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Project GaBE:
Comprehensive Assessment of Energy Systems

Severe Accidents in the Energy Sector

First edition

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Abstract

This report addresses one of the major limitations of the current comparative studies of the environmental and health impacts of energy systems, i.e. the treatment of severe accidents. The work covers technical aspects of severe accidents and thus primarily reflects an engineering perspective on the energy-related risk issues.

The assessments cover fossil energy sources (coal, oil and gas), nuclear power and hydro power. The scope of the work has not been limited to the power production (conversion) step of these energy chains but whenever applicable also includes exploration, extraction, transports, processing, storage and waste disposal. In relative terms more resources were allocated to the analysis of energy chains that currently dominate the Swiss electricity supply, i.e. hydro and nuclear power.

With the exception of the nuclear chain the focus of the work has been on the evaluation of the historical experience of accidents. For hypothetical nuclear accidents the probabilistic technique has also been employed and extended to cover the economic consequences of power reactor accidents. Nevertheless, the report includes a detailed discussion and evaluation of the consequences of the Chernobyl accident.

Within the present work a comprehensive database on severe accidents, with main emphasis on the ones associated with the energy sector, has been established by the Paul Scherrer Institute (PSI). ENSAD (Energy-related Severe Accident Database), which covers all stages of the analysed energy chains, has been developed using a wide variety of sources. This includes among others: major commercial and non-commercial accident databases, journals, newspapers, technical reports, encyclopaedias, relevant books and conference proceedings, and inputs from numerous direct contacts with persons and organisations being in a position to provide crucial information on past accidents.

Currently, ENSAD covers 13,914 accidents, of which 4290 are energy-related. Applying the definition of a severe accident, used in the present work, 1943 severe energy-related accidents are stored in ENSAD. Accidents with at least five fatalities form the largest group (846). Due to the use of a variety of information sources ENSAD exhibits in comparison with other databases a much more extensive coverage of the energy-related accidents. Furthermore, the coverage is well balanced with respect to countries and regions where the accidents took place.

Significant effort has been directed towards the examination of the relevance of the world-wide accident records to the Swiss-specific conditions, particularly in the context of nuclear and hydro power. For example, a detailed investigation of large dam failures and their consequences was carried out. This includes a study of the dependency between the frequency of dam failures on the one hand, and the types of dams and their purposes on the other. Generally, while Swiss-specific aspects are emphasised, the major part of the collected and analysed data, as well as the insights gained, are considered to be of general interest. In particular, three sets of the aggregated results of the evaluation of the past experience are provided, i.e. one based on world-wide occurrence, one valid for OECD-countries, and one for non-OECD-countries. The generic results obtained for OECD are for

the purpose of this report considered to be representative for Switzerland. For fossil fuels allocation schemes were developed, taking into account the flows of these carriers between OECD- and non-OECD-countries.

The evaluations of severe accident frequencies and their consequences were first carried out for each energy carrier covered in this work. These results were then used for comparisons between the various energy sources. The comparisons concern the electricity sector, although within the gas chain also the Liquid Petroleum Gas (LPG) is included. The results were normalised on the basis of energy production by means of each of the sources covered.

As opposed to the previous studies the ambition of the present work has been, whenever feasible, to cover a relatively broad spectrum of damage categories of interest. This includes apart from fatalities also serious injuries, evacuations, land or water contamination, and economic losses. It is, however, acknowledged that the completeness and consistency of the coverage of these categories varies significantly between the different sources.

Informed decisions should be taken in full knowledge of the technical estimates of risks. Being aware of the risk aspects which do affect the socio-political side of the matter, efforts were here directed towards addressing such features of energy-related severe accidents as: delayed effects, the chance of a large number of people being affected and the uncertainties involved in the assessment.

While a variety of damage categories were considered and analysed the conclusions cited in this summary are primarily based on fatality rates. First, the statistical records on fatalities are most complete; second, the fatalities associated with large accidents are regarded as the indicator attracting most attention on the side of the society; third, the patterns for other indicators are in some (but definitely not all) cases quite similar to those characteristic for the fatality rates.

The present work shows that significant differences exist between the aggregated, normalised damage rates assessed for the various energy carriers. One should, however, keep in mind that from the absolute point of view the fatality rates are in the case of fossil sources small when compared to the corresponding rates associated with the health impacts of normal operation. For this reason the evaluation focuses here on the relative differences between the various energy carriers.

The broader picture obtained by coverage of full energy chains leads on the world-wide basis to aggregated immediate fatality rates being much higher for the fossil fuels than what one would expect if power plants only were considered. The highest rates apply to LPG, followed by hydro, oil, coal, natural gas and nuclear. In the case of nuclear, the estimated delayed fatality rate solely associated with the only severe (in terms of fatalities) nuclear accident (Chernobyl), clearly exceeds all the above mentioned immediate fatality rates. However, in view of the drastic differences in design, operation and emergency procedures, the Chernobyl-specific results are considered not relevant for the “Western

World". Given lack of statistical data, results of state-of-the-art Probabilistic Safety Assessments (PSAs) for representative western plants are used as the reference values.

Generally, the immediate failure rates are for all considered energy carriers significantly higher for the non-OECD countries than for OECD countries. In the case of hydro and nuclear the difference is in fact dramatic. The recent experience with hydro in OECD countries points to very low fatality rates, comparable to the representative PSA-based results obtained for nuclear power plants in Switzerland and in USA. With the important exception of hydro in OECD countries, and coal and oil occasionally switching positions, the internal ranking based on the immediate fatality rates remains the same within OECD- and non-OECD countries as the above cited results based on the world-wide evidence. This is valid both for the straight-forward assessment as well as for the estimates employing allocation schemes. Accounting for delayed fatalities along with the immediate ones preserves this ranking when OECD countries are considered but due to the Chernobyl accident nuclear compares unfavourably to the other chains when the experience base is considered for non-OECD countries only.

The allocation procedure considers the trade-based flows of fossil energy carriers between the non-OECD and OECD countries. The OECD countries are net importers of these energy carriers and the majority of accidents occurs within the upstream stages of these chains. Consequently, the reallocation to OECD countries of the appropriate shares of accidents that physically occurred in non-OECD countries leads to smaller differences between the corresponding damage rates for these two groups of countries in comparison with the straight-forward evaluation. The effect is particularly significant in the case of oil.

For damage indicators other than fatalities the results must be interpreted with caution due to the incompleteness problems (particularly for injuries and economic losses) and inconsistencies of boundaries in the evaluation of monetary damages. It is, however, clear in spite of the uncertainties that the economic loss associated with the Chernobyl accident is highly dominant.

The presentation of results is not limited to the aggregated energy chain specific values. Also frequency-consequence curves are provided. They reflect implicitly the above ranking but provide also such information as the observed or predicted chain-specific maximum extents of damages. This perspective on severe accidents may lead to different system rankings, depending on the individual risk aversion.

The limitations of the approach used are discussed in this report. They are related to the database (completeness and recording accuracy, quality, use of historical data), to uses of probabilistic techniques (intrinsic and practical limitations, low probability numbers), and to the scope of the present approach (e.g. coverage of current technologies only, risk perception/aversion not explicitly treated).

Finally, recommendations for future work are provided. These include: (a) Database maintenance and basic extensions; (b) Coverage of renewable energy sources other than hydro power; (c) Consideration of technological advancements and associated safety improvements; (d) Further applications of probabilistic techniques; (e) Estimation of external costs associated with energy-related severe accidents (beyond the nuclear energy chain); (f) Swiss-specific allocation of accidents in external stages of energy chains; (g) Development of site-specific consequence analysis for hydro power; (h) Refinements and broadening of comparative assessment; (i) User-tailored extensions and corresponding result presentations; (j) Explicit consideration of risk perception/aversion.

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1. INTRODUCTION

1.1 Context of the Study

In 1993 the Paul Scherrer Institute (PSI) in co-operation with the Swiss Federal Institute of Technology, Zurich (ETHZ) launched a long term project on "Assessment of Energy Systems" ("Ganzheitliche Betrachtung von Energiesystemen"; GaBE). The ultimate goal of this project is an integrated evaluation covering risk-related, environmental and economic aspects associated with different energy systems, [Hirschberg, 1995b, 1998], [Hirschberg et al., 1993]. The results of this work are intended to serve as a scientific support to the decision-making process concerning energy supply options for Switzerland. The approaches used and a major part of the results being generated are, however, of general interest and are not restricted to the Swiss conditions.

This report addresses severe accidents in the energy sector. In fact, one of the major limitations of the current comparative studies of the environmental and health impacts of energy systems is the unsatisfactory treatment of contributions from severe accidents [Chadwick ed., 1991], [Fritzsche, 1992].

1.2 Severe Accidents Issue

In general terms by severe accidents we understand potential or actual accidents that represent a significant risk to people, property and the environment. A reasonably complete picture of the wide spectrum of health, environmental and economic effects associated with different energy systems can only be obtained by considering damages due to normal operation as well as due to severe accidents.

Of interest are accidents that might occur at fixed installations storing and processing hazardous materials, or when transporting such materials by road, rail, pipelines, open sea and inland waterways. Examples of hazards that need to be considered include fires, explosions, structural collapses and uncontrolled releases of toxic substances outside of the boundaries of the hazardous installations.

A number of earlier more or less comprehensive studies addressed the comparison of risks related to severe accidents and associated with various industrial activities. Below follow some examples of the previously published reports. It is not intended to provide in this chapter a detailed review of the literature. For a more extensive bibliography we refer instead to the lists of references included in the subsequent chapters.

The report on the first full scope Probabilistic Safety Assessment (PSA) for nuclear power plants [Rasmussen, 1975] contained an appendix providing a comparison of nuclear risks with natural catastrophes and man-made disasters resulting from various types of hazardous installations. The purpose of this work was to put the risks of nuclear power into perspective. Later an extended and updated analysis was published [Coppola and Hall, 1981]. Major chemical hazards were outlined in e.g. [Marshall, 1987]. In [Health and

Safety Executive, 1989] a comparison of UK risks from certain types of hazardous activities (such as aircraft, railway, process industry, nuclear power plants), were provided.

Fritzsche addressed the risks of energy production due to the normal operation and due to accidents [Fritzsche, 1988 and 1989]. His results concerning health effects, including the impacts of severe accidents, were adopted within the internationally co-ordinated effort to assess the corresponding impacts [Chadwick ed., 1991]. When the present work was undertaken this constituted the state-of-the-art in the comparative assessment of the risks associated with power generation. In the meantime two major studies on external costs of power production were published [ExternE, 1996a - 1996f], [ORNL&RfF, 1992, 1994a, 1994b, 1995a - 1995e]. While these studies significantly improved the knowledge of environmental and health impacts of electricity generation, and advanced the methodology used for the assessment, the treatment of severe accidents has not been given a high priority. Some progress has been achieved but the overall state of knowledge in this context did not change much. In Switzerland a debate on risks of energy production was intensified in connection with the publication of the Swiss study on external costs of energy production [Ott et al., 1994]. Particularly the issue of economic consequences of nuclear accidents has been the subject of a discussion which also found its way to the media [Hirschberg and Erdmann, 1994], [Zweifel and Nocera, 1994]. Recently a comparative overview of catastrophes and emergencies was published by The Swiss Office of Civil Protection [Bundesamt für Zivilschutz, 1995].

The energy sector has been recognised as one of the main contributors to man-made disasters. According to the previously published data on accidents that occurred world-wide since 1970 the second (after transportation) largest group responsible for man-made disasters is the field of energy production. Fritzsche [1992] concluded in an Editorial in one of the issues of "Risk Analysis" that about 25% of the fatalities caused by severe accidents world-wide in the period 1970-1985 occurred in the energy field. These results were based on the statistics on the disasters, published by the world's second largest reinsurance company Swiss Re in Zurich [Swiss Re, 1986]. In the same Editorial Fritzsche recognised that the level of completeness and the quality of the existing data on severe accidents is not satisfactory. He urged the risk assessment community to undertake an effort of "a systematic collection and analysis of the world-wide statistics on accidents in the energy field and their correlation with the quantity of electrical energy produced". The present report represents a contribution to such an effort. The scope of the work is, however, not limited to the accidents which occurred in the past. In addition, Probabilistic Safety Assessment (PSA) has been employed in some cases where due to several reasons the past experience is not representative.

1.3 Potential Users of Severe Accident Information

The spectrum of potential users includes:

- Architect engineering companies
- Construction industry

- Chemical industry
- Mining industry
- Transportation industry (air, rail, road, water)
- Power plant vendors, utilities, decision makers in the energy sector
- Insurance and reinsurance companies
- Emergency response organisations
- National and international safety and environmental law enforcing organisations
- International and national disaster relief organisations

The needs of the potential users vary widely. **Industrial applications** tend to require actuarial and detailed information on major hazards in order to provide:

- Actuarial material for the training of plant, fire brigade or emergency service personnel.
- Increased understanding of major hazards.
- Background information for the preparation and evaluation of risk assessments.
- The opportunity to understand, digest and utilise the available past experience, to prevent major incidents by designing defensive mechanisms and countermeasures towards such hazards and therefore safer plants.
- Factual information to be used for preparing the necessary evacuation and emergency counter-action plans.

Safety authorities need detailed information on major hazards:

- To assist them in carrying out their duties under national and international regulations.
- For the purposes of developing training and current awareness programs.
- For assisting in the validation of assessments submitted by industry.
- To aid decision makers in their policy development.
- To assist the staff in its advisory role to local planning authorities and to ensure the relevance, validity and consistency of their advice.
- To assist with the cross checking and validation of techniques being developed.
- For uses in own risk assessments.

National governments need to outline information on major hazards to:

- Understand the nature and potential of risks involved in different energy systems so as to make appropriate policy decisions.
- Allocate R&D resources.
- Allocate countermeasure resources.

Despite the fact that the above lists are not exhaustive, they demonstrate that there are major differences between the requirements of potential users of severe accident information, and that at the same time there are areas where the type of information needed is similar.

The areas of common interest can be divided into the following four general but dissimilar types:

A. Information about past accidents, particularly on **what** went wrong and possibly **why**:

- the sequence of events (to the extent known)
- details on casualties, injuries, evacuations, financial damage and other consequences
- consequence ameliorating factors (human, engineered, natural)

B. Information based on applications of predictive methods such as:

- incidence probabilities
- consequence assessment

C. Experimental and investigative data designed to augment and further the understanding of the causes and consequences of incidents:

- large-scale dispersion trials
- radiation from pool fires
- burning rates of flammable vapour clouds
- other

D. Chemical, physical and physiological (e.g. toxicity) properties of substances involved.

This report concentrates on area A and has elements of area B. The focus is on the evaluation of the aggregated accident statistics relevant for policy-oriented uses of the information, and not on the detailed analysis of the propagation and causes of the individual accidents.

1.4 Report Organisation

The objectives and scope of the present work are described in Chapter 2. Chapter 3 summarises the analysis approach that has been used. In Chapter 4 the main sources of information are introduced and commented. Chapter 5 provides the description of the structure and contents of the severe accident database established at PSI. The results of evaluations carried out for the different energy carriers are given in Chapter 6. The information gathered in Chapter 6 serves as an input to comparative evaluations presented in Chapter 7. Chapters 6 and 7 provide the results of the work performed but should not be viewed in isolation from the other parts of the report. In particular, the difficulties and limitations associated with the present work are summarised in Chapter 8. Finally, Chapter 9 includes highlights of the work carried out, conclusions and recommendations for future work. Appendices A-F provide details on severe accidents within the various energy chains. Appendices G and H contain review comments on this report, written by social scientists; finally Appendix I is the response of the authors to this review.

References are provided at the end of each chapter and in one case (Chapter 6) at the end of the sections addressing severe accidents for each energy carrier. The readers interested in specific energy sources may in this way easier identify the relevant literature.

1.5 Dissemination of Project Results

During the course of this project the preliminary results in some of the areas covered were published and presented in different forums [Hirschberg, 1995a, 1995b, 1998], [Hirschberg and Cazzoli, 1994], [Hirschberg and Dones, 1998], [Hirschberg and Erdmann, 1994], [Hirschberg et al., 1994], [Hirschberg and Parlavantzas, 1994], [Hirschberg and Spiekerman, 1996], [Hirschberg et al., 1997], [Kröger and Hirschberg, 1993]. The experience gained has been used within a number of international activities addressing issues related to the analysis of energy systems. This includes the Inter-Agency Joint Project on Databases and Methodologies for Comparative Assessment of Different Energy Sources for Electricity Generation (DECADES), the IAEA Co-ordinated Research Programme (CRP) on "Comparative Health and Environmental Risks of Nuclear and other Energy Systems" and OECD/NEA Expert Group on "Methodologies for Assessing the Economic Consequences of Nuclear Reactor Accidents" [Hirschberg, 1995c, 1995d, 1996]. Parts of this material have been adopted in the present report.

1.6 References

Bundesamt für Zivilschutz (1995), Katastrophen und Notlagen in der Schweiz, Eine Vergleichende Übersicht (in German). Bundesamt für Zivilschutz, Bern, Switzerland.

Chadwick, M. J. ed. (1991), Key Issue Paper No. 3 by International Expert Group 3: Comparative Environmental and Health Effects of Different Energy Systems for Electricity Generation. Proceedings of Senior Expert Symposium on Electricity and the Environment, 13-17 May 1991, Helsinki, Finland.

Coppola, A. and Hall, R. E. (1981), A Risk Comparison. Report NUREG/CR-1916, U.S. Nuclear Regulatory Commission, Washington D.C., USA.

ExternE (1996a), Externalities of Energy, Vol. 1: Summary. Published by the European Commission Directorate General XII, 2 rue Mercier, L-2985 Luxemburg.

ExternE (1996b), Externalities of Energy, Vol.2: Methodology. Published by the European Commission Directorate General XII, 2 rue Mercier, L-2985 Luxemburg.

ExternE (1996c), Externalities of Energy, Vol. 3: Coal & Lignite. Published by the European Commission Directorate General XII, 2 rue Mercier, L-2985 Luxemburg.

ExternE (1996d), Externalities of Energy, Vol. 4: Oil & Gas. Published by the European Commission Directorate General XII, 2 rue Mercier, L-2985 Luxemburg.

ExternE (1996e), Externalities of Energy, Vol. 5: Nuclear. Published by the European Commission Directorate General XII, 2 rue Mercier, L-2985 Luxemburg.

ExternE (1996f), Externalities of Energy, Vol. 6: Wind & Hydro. Published by the European Commission Directorate General XII, 2 rue Mercier, L-2985 Luxemburg.

Fritzsche, A.F. (1988), Gesundheitsrisiken von Energieversorgungssystemen; Von der Kohle bis zu Energien der Zukunft und den Rohstoffen bis zu Entsorgung (in German). Köln: Verlag TÜV Rheinland.

Fritzsche, A. F. (1989), The Health Risks of Energy of Energy Production. Risk Analysis, **9** (1989) 565 - 577.

Fritzsche, A. F. (1992), Editorial, Severe Accidents: Can They Occur Only in the Nuclear Production of Electricity? Risk Analysis, **12** (1992) 327-329.

Health & Safety Executive (1989), Quantified Risk Assessment: Its Input to Decision Making. London: her Majesty's Stationery Office.

Hirschberg, S. (1995a), External Costs of Electric Power Generation - Are Accidents Adequately Treated? Schweizer Ingenieur und Architekt, Nr. 20 (1995) 469-473.

Hirschberg, S. (1995b), Framework for and Current Issues in Comprehensive Comparative Assessment of Electricity Generating Systems. Invited Paper presented at the International Symposium on "Electricity, Health and the Environment: Comparative Assessment in Support of Decision Making", organised by EC, ESCAP, IAEA, IBRD, IIASA, OECD/NEA, OPEC, UNIDO, WMO, 16 - 19 October 1995, Vienna, Austria. In IAEA Proceedings Series (1996).

Hirschberg, S. (1995c), External Costs of Nuclear Reactor Accidents, 28 pp., November 1995. Contribution to the OECD/NEA Report on Methodologies for Assessing the Economic Consequences of Nuclear Reactor Accidents (to be published 1998).

Hirschberg, S., (1995d), Severe Accidents, 12 pp., November 1995. Contribution to the IAEA/World Bank Reference Book on Enhanced Electricity System Analysis for Decision Making (to be published 1998).

Hirschberg, S. (1996), Key Methodological Issues, 33 pp., March 1996. Contribution to the IAEA Guidelines for the Comparative Assessment of Health and Environmental Impacts of Electrical Energy Systems (to be published 1998).

Hirschberg, S. (1998), Integral Assessment of Energy Systems, International Conference on Environment and Nuclear Energy, 27-29 October 1997, Washington D.C., USA. In B.N. Kursonoglu ed., "Environment and Nuclear Energy". New York: Plenum Publishing Corp.

Hirschberg, S. and Cazzoli, E. (1994), Contribution of Severe Accidents to External Costs of Nuclear Power. Proceedings of ENS Topical Meeting on PSA/PRA and Severe Accidents '94, 17-20 April 1994, Ljubljana, Slovenia.

Hirschberg, S. and Dones, R. (1998), Health and Environmental Risk Assessment of Energy Systems in Support of Decision-Making. Proceedings of PSAM 4 International Conference on Probabilistic Safety Assessment and Management, New York City, USA, 13-18 September 1998.

Hirschberg, S., Dones, R. and Kypreos, S. (1994), Comprehensive Assessment of Energy Systems: Approach and Current Results of the Swiss Activities. Invited Paper presented at Jahrestagung Kerntechnik '94, 17-19 May 1994, Stuttgart, Germany.

Hirschberg, S. and Erdmann, G. (1994), Wie hoch sind die Kosten der Stromproduktion? Die Bewertung externer Kosten als heikle Aufgabe (in German). Neue Zürcher Zeitung, No. 192, 6 October 1994.

Hirschberg, S. and Parlavantzas, C. (1994), Severe Accidents in Comparative Assessment of Energy Sources: Current Issues and Actual Experience Data. Invited Paper presented at PSAM-II International Conference Devoted to the Advancement of System-based Methods for the Design and Operation of Technological Systems and Processes, 20-25 March 1994, San Diego, California, U.S.A.

Hirschberg, S. and Spiekerman, G. (1996), Comparative Evaluation of Severe Accident Risks Associated with Electricity Generation Systems. In Cacciabue, P. C. and Papazoglou, I. A., ed., Proceedings of ESREL'96/PSAM-III International Conference on Probabilistic Safety Assessment and Management, 24-28 June 1996, Crete, Greece. London: Springer-Verlag.

Hirschberg, S. et al. (1993), Assessment of Energy Systems (Ganzheitliche Betrachtung von Energiesystemen - GaBE). Detailed Outline of the Project, 2nd Version, Paul Scherrer Institute, Wurenlingen and Villigen, Switzerland, July 1993.

Hirschberg, S., Spiekerman, G. and Dones, R. (1997), Comparative Assessment of Severe Accident Risks in the Energy Sector. 1997 Annual Meeting of the Society for Risk Analysis - Europe, 15-18 June 1997, Stockholm, Sweden. In Drotz Sjöberg, B.-M., ed., Proceedings, New Risk Frontiers, 10th Anniversary of the Society for Risk Analysis - Europe. Stockholm: The Center for Risk Research, Stockholm School of Economics.

Kröger, W. and Hirschberg, S. (1993), Safety Problems in Power Generation. Paper presented at Forum Engelberg, Energy and Environment: A Question of Survival, 16-19 March 1993, Engelberg, Switzerland.

Marshall, V. C. (1987), Major Chemical Hazards. Chichester: Ellis Horwood Limited.

ORNL&RfF (1992), U.S. - EC Fuel Cycle Study: Background Document to the Approach and Issues. Report No. 1, prepared by Oak Ridge National Laboratory and Resources for the Future. ORNL/M-2500, Oak Ridge, Tennessee: Oak Ridge National Laboratory, USA.

ORNL&RfF (1994a), Estimating Fuel Cycle Externalities: Analytical Methods and Issues. Report No. 2, prepared by Oak Ridge National Laboratory and Resources for the Future. Washington D.C.: McGraw-Hill/Utility Data Institute.

ORNL&RfF (1994b), Estimating Externalities of Coal Fuel Cycles. Report No. 3, prepared by Oak Ridge National Laboratory and Resources for the Future. Washington D.C.: McGraw-Hill/Utility Data Institute.

ORNL&RfF (1995a), Estimating Externalities of Natural Gas Fuel Cycles. Report No. 4, prepared by Oak Ridge National Laboratory and Resources for the Future. Washington D.C.: McGraw-Hill/Utility Data Institute.

ORNL&RfF (1995), Estimating Externalities of Oil Fuel Cycles. Report No. 5, prepared by Oak Ridge National Laboratory and Resources for the Future. Washington D.C.: McGraw-Hill/Utility Data Institute.

ORNL&RfF (1995c), Estimating Externalities of Hydro Fuel Cycles. Report No. 6, prepared by Oak Ridge National Laboratory and Resources for the Future. Washington D.C.: McGraw-Hill/Utility Data Institute.

ORNL&RfF (1995d), Estimating Externalities of Biomass Fuel Cycles. Report No. 7, prepared by Oak Ridge National Laboratory and Resources for the Future. Washington D.C.: McGraw-Hill/Utility Data Institute.

ORNL&RfF (1995e), Estimating Externalities of Nuclear Fuel Cycles. Report No. 8, prepared by Oak Ridge National Laboratory and Resources for the Future. Washington D.C.: McGraw-Hill/Utility Data Institute.

Ott, W. et al. (1994), Externe Kosten und kalkulatorische Energiepreiszuschläge für den Strom und Wärmebereich (in German). Bericht 724.270 D, Bundesamt für Konjunkturfragen, Bern, Switzerland.

Rasmussen, N. (1975), Reactor Safety Study - An Assessment of Accident Risks in US Commercial Nuclear Power Plants. Report WASH-1400, U.S. Nuclear Regulatory Commission, Washington D.C., USA.

Swiss Re (1986), International Statistic of Natural Catastrophes and Major Losses 1970 - 1985. Sigma, Economic Studies, 11/86, Swiss Reinsurance Company, Zurich, Switzerland.

Zweifel, P. and Nocera, S. (1994), Was kostet die Vermeidung von Atomrisiken? Fundierte Grundlagen zur Bewertung externer Kosten (in German). Neue Zürcher Zeitung, No. 274, 23 November 1994.

2. OBJECTIVES AND SCOPE OF WORK

2.1 Project Objectives

The **primary objective** of the present work is to address the issue of severe accidents in the energy sector with particular emphasis on the electricity supply. The results of the analysis should be expressed in form of quantitative estimates, whenever this is possible in view of practical limitations.

In order to meet this goal some specific objectives were defined:

1. To collect, organise and analyse data on historical accidents in the energy sector.
2. To supplement the data based on the actual experience with relevant results of probabilistic assessments, essentially for nuclear power.
3. To address the applicability of the available data to the domestic (Swiss) facilities.
4. To compare the estimates obtained for the various energy chains.
5. To identify and comment the methodological issues encountered in comparative analysis of severe accidents.

2.2 Scope of Work

The starting point for this study was the awareness of the existence of major gaps in the current state-of-the-art of the assessment of severe accident potential characteristic for different energy sources. Furthermore, the evidence solely based on accidents that occurred in the past provides only a partial perspective on the risks since:

- Conditions (for example with respect to technology, safety principles and culture, physical and operational environment) characteristic for a specific event, may be such that its applicability to other conditions may be questionable, possibly precluded.
- Actual experience, if available, in most cases only reflects some examples from a wide spectrum of hypothetical accident scenarios.
- For some energy sources and for specific parts of energy chains the statistical evidence is very poor, which may either be due to unsatisfactory reporting or due to high reliability of safety systems.
- Impact of expected advancements in technology, including improvements of safety-specific features, are not taken into account when past events are evaluated.

Thus, a balanced evaluation of severe accident risks associated with systems having extensive built-in safety features calls for the use of predictive approaches employing

Probabilistic Safety Assessment (PSA) techniques. The major problem is, however, that relevant PSA applications are currently available only for few technologies, primarily for nuclear power plants. Consequently, using past experience constitutes for most parts of the various fuel cycle the only feasible option for the evaluation of the associated accident risks. Use of past experience has also definite merits as:

a) supplement to PSA

b) source of information to support PSA and set priorities

The following aspects affecting the scope need to be considered in a comprehensive comparative analysis of severe accidents:

- The comparison should not be made on the basis of consequences of severe accidents in isolation. Also the associated frequencies must be estimated; in fact, this represents the major difficulty and challenge. Generic information on such parameters may have a limited applicability and, if used, must be treated with great care.

- The comparison should not be limited to the power production (conversion) step but preferably also include other steps of the energy chains, i.e. whenever applicable also exploration, extraction, transports, processing, storage and waste disposal. In fact, for some energy chains these other steps may represent a larger hazard than the power plant itself. Based on experience and some earlier analyses, the potential for severe accidents is concentrated to specific parts of the different energy chains. Table 2.2.1 shows an overview of the accidents specific for each energy chain.

- Time and space dimensions of accident consequences are of interest. The following has been suggested in [IAEA, 1992]:

Time:	Short term	(direct impacts - up to 1 year)
	Medium term	(within a persons lifetime - about 70 years)
	Long term	(inter-generational)
Space:	Local	(most impacted area or population)
	Regional	(national, international or continental)
	Global	

- It is acknowledged that the current state of knowledge concerning delayed health effects as well as long term environmental impacts from severe accidents associated with different energy systems is limited. Consequently, the assessment results frequently only cover immediate/acute health effects.

TABLE 2.2.1

Energy chain-specific nature of potential severe accidents (after [Chadwick, ed., 1991]).

Energy Chain	Type of Accident
Coal	Explosions or fires in underground coal mines; collapse of roof or walls in underground or surface mines; tailing dam collapse; haulage/vehicular accidents.
Oil	Off-shore rig accidents; fires or explosions from leaks or process plant failures; well blowouts causing leaks; transportation accidents resulting in fires, explosions or major spills; loss of content in storage farms resulting in fires or explosions.
Natural gas	Same as for oil cycle (except for spills).
Nuclear (LWR)	Loss of coolant water or reactivity transient and reactor meltdown; accidents during shipment of high level radioactive waste.
Hydro	Rupture or overtopping of dam.
Geothermal	Well blowouts, resulting in the release of toxic gases.
Biomass	Not identified.
Wind	Missiles in densely populated areas.
Solar - Photovoltaic	Release of toxic materials during photocell manufacture.
Solar - Thermal	Release of toxic working fluids.

- Not all aspects of severe accidents are amenable to quantification in a straight-forward manner. This applies in particular to environmental effects such as loss of quality, aesthetic values, disturbance of the ecosystem or genetic deterioration, possible irreversibility of damages, and to social impacts of psychological nature. In the context of decision-making qualitative accounting for these effects is essential.

The present work considers all the aspects mentioned above. At the same time a number of scope limitations apply. The following defines the actual scope:

1. With the exceptions of nuclear accidents the focus is on the evaluation of past experience of accidents. For hypothetical nuclear accidents PSA-based approach was also employed.

2. In relative terms more resources were allocated to the analysis of energy chains that currently dominate the Swiss electricity supply, i.e. hydro and nuclear power (together these two sources stand for about 98% of the yearly domestic electricity generation). Significant effort has been directed towards the examination of the relevance of the world-wide records on accidents which involve these two means of electricity generation to the Swiss-specific conditions. While in view of the objectives of this project the focus was on Switzerland, major part of the data collected and analysed as well as the insights gained are of more general interest.

3. Addressing the relevance of the available data means that the representativeness of the data for the population of the Swiss plants is of interest. There is, however, no intention within the present work to address the risk of severe accidents individually for each one of the plants.

4. The scope of the analysis is limited to coal, oil, gas, hydro and nuclear chains. Thus, analysis of accidents associated with renewable energy sources other than hydro power is not included at present.

5. One central objective of this work was the development of the severe accident database for energy sources. The database has been established and is fully operationalised. While the work performed and reflected in this report concerns the energy-related severe accidents, the major part of the database contains information on man-made accidents in other sectors and on natural catastrophes. The level of completeness for the latter mentioned events is, however, much lower than for the energy-related ones. In particular, accidents related to person transport are not included unless the cause of the accident stems from the activities within a specific energy chain of interest for the present work.

6. Comparisons between the various energy sources are in the present work limited to the electricity sector. Nevertheless, the material available either in form of accident lists included in this report or in PSI's database could also be used for comparison of heating systems. This would, however, require a partial reconsideration of the allocation of accidents to the different stages of the energy chains and appropriate normalisation.

7. Most of earlier comparisons of severe accidents were limited to the evaluation of only one type of consequence, namely fatalities. The spectrum of consequences of interest includes apart from fatalities: serious injuries, evacuations, ban on consumption of locally produced food or drinking water, releases of hydrocarbons, enforced clean-up of land or water and direct economic losses. The ambition of the present work has been whenever feasible to cover also these consequence types.

8. The nature of the work on a severe accident database is such that the scope of this task can always be expanded. First, there exists an enormous amount of sources of information on past accidents which taken one by one only cover some aspects of the problem. These sources are of varying quality and depth; they may be partially overlapping or may in other cases contradict each other. Second, there is a flow of new information concerning recent accidents. As a result, the evaluations of severe accidents are constantly changing. The results provided in this report cover accidents that occurred until the end of year 1996. There is always a substantial time lag with respect to the inclusion, accounting for and analysis of the accidents in the multitude of information sources used as the input. According to our judgement acceptable completeness and quality can at this time only be achieved for the period until the end of 1996.

9. **The present work concentrates on a technical comparative analysis of severe accidents.** While the role of sociological and psychological factors in the evaluation of the various energy sources is acknowledged and discussed here mainly in the context of nuclear energy, these aspects were not subjects of the current research.

2.3 References

Chadwick, M. J., ed., (1991), Key Issue Paper No. 3 by International Expert Group 3: Comparative Environmental and Health Effects of Different Energy Systems for Electricity Generation. Proceedings of Senior Expert Symposium on Electricity and the Environment, held in Helsinki, Finland, 13-17 May 1991.

IAEA (1992), Comparative Assessment of the Health and Environment Impacts of Various Energy Systems from Severe Accidents. Working Material, Proceedings of a Technical Committee Meeting Organised by the International Atomic Energy Agency and held in Vienna, Austria, 1-3 June 1992.

3. GENERAL ANALYSIS APPROACH AND METHODOLOGICAL ISSUES

The details of the approach used in the present study will be provided in Chapters 4-6. Here some general principles and the rational for the approach chosen are summarised. Some of the methodological issues anticipated at the time the project was established are shortly outlined. Finally, the strategy chosen for the overall analysis is described.

3.1 Background

The process of collecting and analysing accident-related information for commercial and non-commercial databases is time and resource consuming. Months and years may be spent locating relevant sources, filtering the material, reading reports, organising and analysing data. As a result, the generation of a detailed severe accident database may constitute a very expensive endeavour.

A common misunderstanding of the whole process is the perception of the whole effort as a straight-forward collection of data. While this part may be cumbersome, particularly in view of many restrictions and sensitivities associated with the information on accidents, the difficulties are most prominent in the context of the analysis of the available data. This includes the qualification and interpretation of the available information with view to the objectives of the intended application of the data. Frequently, this leads to a conclusion that the level of detail of the available information is not sufficient or inconsistent, that the quality is questionable or that the uncertainties involved are very large. In such situations efforts need to be made to identify supplementary sources of information. Thus, the process is by nature iterative.

3.2 User-dependent Restrictions

The way in which the information is used to create a database on hazardous incidents will largely be determined by the objectives laid down for the database as determined by user requirements, i.e. WHO wants it and WHY.

Specification of user requirements must take into account:

- availability of data
- cost of computerising, storing and retrieving the information
- availability of suitable software, and
- benefits likely to be derived from a particular need

The user requirements, the expected entry number and detail, and available technical and economic means, determine the structure of the database and the types of software and hardware that are suitable to store and manage the database and retrieve data from it.

In the case of an accident database the information should concentrate on causes and consequences. Although such information may be described in narrative accounts, the appropriate uses of the material are to some extent affected by the fact that there is a variety of ways in which it is possible to describe essentially similar events.

It is necessary to structure the database so as to provide a high degree of “recall” (i.e. ability to retrieve related accidents) coupled with high degree of “focus” (i.e. the amount of information that is not relevant for a specific use should be minimal). The appropriate structure can be provided by including user-defined keywords or classifications in the form of numeric codes which enable the identification of the important accident characteristics.

The extent to which the desirable structure can be implemented in the database is determined by the capability of the software chosen to be used to handle such information and the availability of resources for conducting the associated labour-intensive pre-processing of the data.

Numerically structured (coded) information can be used for readily producing statistical summaries of accidents which would be laborious to produce if the database was in a largely unstructured form. In addition, coded data may be stored much more efficiently on a computer. However, structuring the data in this way presents some problems. It is a source of errors and much professional judgement is required if a consistent approach is to be maintained in classifying information which in the original form is written in a variety of styles and levels of detail. At present, incidents reporting is a subject to extreme variability.

3.3 Implementation

At an early stage it was decided that building a severe accident database from scratch would not be feasible given the actual time and resource constraints. Such an undertaking would, however, have a number of attractive features, allowing more flexibility with respect to the user requirements as well as more extensive quality control. The survey of the existing sources of information, carried out at the beginning of the project, showed that:

a) Numerous sources of information exist; their availability, scope, development status and quality exhibits an enormous variation.

b) Commercial and non-commercial databases are available. They normally cover man-made accidents in a variety of sectors and in some cases also the natural disasters. Very few of the databases deal explicitly with energy-related accidents. If they do, the coverage concerns one specific energy carrier, for example offshore accidents. In most cases energy-related accidents constitute a not explicitly identified subset among other accidents.

c) None of the available individual databases has a satisfactory coverage to form alone a basis for the evaluation of severe accidents within the present project.

d) The information assembled in the available databases even if combined would not be fully adequate for meeting the objectives of this work. It needs to be supplemented by additional sources in order to achieve reasonable completeness and quality.

As a result of these insights the following approach was applied within the project (the implementation has not been fully sequential since some of the steps were performed in parallel and also iterations were necessary):

1. Acquisition of relevant databases. Factors considered when selecting the set of databases were: availability, price, coverage (sectors, time, geographical area) and quality. Among databases which apparently were very similar and more or less totally overlapping only the most representative one was selected. Databases containing accidents for one specific country only were of lower interest.

2. Implementation of the acquired databases on a PC. PC environment was considered as sufficiently flexible and adequate for this application. User requirements concerning the overall database were relatively moderate since the final product was intended exclusively for internal uses at PSI and not for external distribution.

3. Merging of the contents of the various databases within the framework of Microsoft's Access Database. In view of the focus of this project on energy-related accidents not all information was retained when merging the databases into a single structure.

4. Elimination of overlapping events and/or harmonisation of non-consistent information. The latter required consultation of sources beyond the available databases (see also point 7 below).

5. Identification of energy-related accidents and among them of accidents considered as severe (see Chapter 5 for the definition of severe accident as used in this study).

6. Allocation of energy-related accidents to specific fuel cycles and subsequently to specific stages within each fuel cycle.

7. Searches utilising supplementary sources of information and aiming at checks as well as identification of additional events; analysis of the assembled material. This includes: annual publications, general and specialised literature, national and international newspapers, incident lists and reports, and direct contacts with responsible companies and other competent organisations or individuals. Such investigations are extremely time and resource consuming. For this reason within the present effort checks and complementary analyses beyond the main sources of information were concentrated on events which have very severe consequences and/or are subject to major uncertainties with respect to the real extent of consequences. Particular attention has been given in this context to the applicability and transferability of the data (see Section 3.4 and relevant parts of Chapter 6).

8. Application of Probabilistic Safety Assessment (PSA). Consequences of hypothetical nuclear accidents, including the economic losses were analysed using PSA techniques.

Use of a full scope PSA in the context of external costs estimation constitutes a novel application of this methodology. The specific features of this analysis are covered in detail in Chapter 6.

9. Implementation of the additional evidence into the database. Given that new events have been identified this includes also the steps under points 5 and 6 above.

10. Evaluations based on the “final” set of data. The evaluations of severe accident frequencies and various types of consequences were first carried out for each energy carrier. These results were then used for comparisons between the various energy sources. The results were normalised on the basis of energy production by means of each of the sources.

3.4 Some Methodological Issues

Methodological issues related to the scope of the analysis were mentioned in Chapter 2. The present work addresses to a different extent a number of issues considered as difficult and/or unresolved. This includes:

- Definition of a severe accident which could be consistently applied to various energy sources. This definition could include as parameters the resulting health and environmental impacts, the extent of economical damages and of evacuations. Lack of a consistent definition has in the past resulted either in double-counting of contributions (already included in the impacts associated with the “normal” operation) or in underestimating (by not accounting for some effects at all).

- Distinction between the estimates based on the actual experience of accidents and those resulting from predictions based on logical system models. The nature of these two basic sources of data on accident frequency and consequences is different; so are the associated uncertainties. The two approaches may be viewed as complementary but the probabilistic technique can be the only relevant one whenever the experience from past accidents is clearly invalid for the specific analysis context.

- Treatment of source data and the rational for screening. Due to the variety of the actual conditions characteristic for the accidents that occurred in the past and for the facilities that have been subjected to probabilistic assessments, the data need to be carefully examined on a case by case basis with respect to their applicability/transferability to the conditions associated with the case being examined (see also the preceding point). For the data originating from probabilistic assessments limitations of the underlying approach need to be addressed both generally and for the specific analyses that have been performed. This may include parametric-, modelling- and completeness-related aspects.

- Accounting for contributions from all stages of fuel cycles. Completeness requires an inclusive treatment of the potential contributors from the different parts of the various fuel cycles. Risks can originate also from the manufacture of materials used in the different energy systems and from the production of the energy needed to support different parts of the fuel cycles. Within the project GaBE [Hirschberg, 1993], Life Cycle Analysis (LCA) is used to determine detailed material and energy balances for all fuel cycles of interest [Frischknecht et al., 1996], [Dones et al., 1996]. This provides the structure and major input for the corresponding risk considerations. Thus, the structures of the various energy chains used in the present analyses are consistent with the ones employed in the LCA studies. However, consideration of severe accident risks associated with the production of materials other than fuels is beyond the scope of this report. For the energy chains covered here such risks are of secondary importance. Smaller accidents and incidents typical for the corresponding industrial environments are treated within the GaBE project as a part of the health effects (particularly occupational ones) associated with normal operation. On the other hand, for material-intensive energy chains (such as solar Photovoltaic), which are not covered in the present work, a separate treatment of potential severe accidents associated with the material production appears to be necessary due to the expected dominance of such contributions.

- Role of risk aversion. The experience shows that the influence of subjective risk aversion on the behaviour of individuals can be significant. In the context of the issue of severe accident aversion does play a role and is reflected in the attitudes of decision-makers and the public towards some energy sources, particularly nuclear. Specifically, aversion relates to the distinction between high frequency/low consequence accidents and low frequency/high consequence accidents. The present research concentrates fully on the technical (objective) measures of risks, even though risk aversion is discussed in the section dealing with nuclear power.

- Presentation of results. Presentation of results on risks associated with the different energy systems is a matter of ongoing discussions. For the case of electricity generation, the estimated damages are frequently aggregated and normalised by the amount of electricity generated. While this form is valid, alternative and complementary indicators for comparison are necessary, in particular the frequency/consequence diagrams directly illustrating the potential for accidents with extreme consequences. It is desirable (although not feasible in all cases) to cover the different types of damages associated with the different energy systems. In case the results include estimates based on past experience on the one hand and on predictive approaches on the other the origin of the different estimates should be clearly specified.

3.5 Overall Analysis Strategy

In a comprehensive analysis accidents associated with parts of fuel cycles outside of the borders of the country for which the study is being performed should be included. For a specific country various fuel cycles usually have much different structures with respect to their geographical locations. For example, hydro power (which represents a simple cycle) is completely domestic, while for most countries (including Switzerland) in the case of nuclear energy only the power plants and waste storage facilities are within the country with the other parts located abroad. In the oil fuel cycle such accident prone activities as oil extraction and ship transportation are usually totally external but a proper share of these accidents should be allocated to the domestic power production. The analysis of domestic facilities should be based, if feasible, on PSA techniques and supplemented with historical data. Whenever PSAs for other plants and/or past experience are used the applicability/transferability of the results used to the situation being analysed should be considered. The application-oriented screening of the data can lead to reduction of the risks for plants having excellent safety features. In other cases, when these features are worse than average, the plant-specific risk needs to be increased on the basis of careful extrapolation.

Following this strategy the most detailed analysis were performed within this project for the hydro and nuclear chains. This is also reflected in the volume of the documentation on severe accidents in the different chains, provided in Chapter 6 of the present report. Thus, in relative terms much more space is devoted to hydro and nuclear than to the other energy sources.

3.6 References

Dones, R., Gantner, U., Hirschberg, S., Doka, G. and Knoepfel, I. (1996), Environmental Inventories for Future Electricity Supply Systems for Switzerland. PSI Report Nr. 96-07, Paul Scherrer Institute, Wurenlingen and Villigen, Switzerland, February 1996.

Frischknecht R. (Ed.) et al. (1996), Ökoinventare von Energiesystemen - Grundlagen für den ökologischen Vergleich von Energiesystemen und den Einbezug von Energiesystemen in Ökobilanzen für die Schweiz. 3rd Ed. (in German), Swiss Federal Institute of Technology Zurich (ETHZ) / Paul Scherrer Institute (PSI), Zurich, Switzerland, July 1996.

Hirschberg, S. et al. (1993), Assessment of Energy Systems (Ganzheitliche Betrachtung von Energiesystemen - GaBE). Detailed Outline of the Project, 2nd Version, Paul Scherrer Institut, Würenlingen and Villigen, Switzerland, July 1993.

4. INFORMATION SOURCES

4.1 Introduction

In the past, significant efforts have been directed towards the development of databases for historical events with the purpose of understanding the potential hazards confronting industrial designers, insurance companies or decision makers. Efficient risk management and hazard control can be defined and implemented if lessons are learned from previous incidents and accidents [ICOLD, 1974; Baecher et al., 1980; Drogaris, 1993; Beek, 1994]. The experience gained from the analysis of past accidents can be used to avoid design errors, to improve existing facilities, to develop emergency plans, to evaluate specific technologies, etc.

4.2 Overview

The most important information sources for the Energy-related Severe Accidents Database (ENSAD) developed as a part of this work were:

1. *Major commercial and non-commercial accident databases*

2. *Journals, periodicals and books on specific energy systems*

3. *Technical reports issued by manufacturing and insurance companies, or by research institutes*

4. *National and international newspapers*

5. *Other publications, e.g. Conference Proceedings, Encyclopaedias, Annual Reports etc.*

6. *Plant operators*

7. *Consular authorities*

8. *International organisations (UN, OECD, European Community, etc.)*

9. *Organisations providing emergency services (Red Cross, UN, etc.)*

10. *Governmental organisations having an internal reporting system, such as police, fire brigades, labour and environmental inspectorates*

Data sources were selected with a view to their potential to provide a large number of usable records from the energy sector. Most of the databases were not designed for dealing explicitly with accidents associated with the energy sector but rather to address industrial accidents in general. The sources differ in scope, quality and time periods covered. The emphasis of the description of an accident varies from source to source. For instance, newspapers tend to focus on the human consequences of an accident, such as fatalities, injured persons or evacuations. On the other hand, the main emphasis in technical reports is normally directed to probing and identifying the princip al technical causes of accidents.

4.3 Review of Selected Databases and Sources

4.3.1 Databases and some additional sources used in ENSAD

To obtain a comprehensive collection of severe energy-related accidents, different databases (in written or electronic form), and other additional potential sources of severe accident related information were considered. In the case of the databases, the information about the accidents is usually expressed using keywords, making the data easily accessible for risk analyses and risk management.

The important databases which can be accessed by standard database software (such as ACCESS, dBASE, FoxPro, Paradox etc.), or have their own software for database viewing, were:

1. *The Office of US Foreign Disaster Assistance Database*
2. *The Fatal Hazardous Materials Accidents Database of the Resources of the Future Centre (USA)*
3. *The Major Hazards Incidence Data Service of the United Kingdom Atomic Energy Authority*
4. *FACTS Database for Industrial Safety of the TNO Institute of Environmental Sciences, Energy Research and Process Innovation Department of Industrial Safety (The Netherlands).*

The most important databases available in written form were:

1. *The WOAD Offshore Database of Det Norske Veritas (Norway)*
2. *The Major Accident Reporting System of ISPRA (European Commission)*
3. *Materialien 5/83 of the German Federal Office for the Environment*
4. *The SIGMA Publication of the Schweizer Rück Company (Switzerland)*
5. *The Catalogues of Dam Disasters of the International Commission on Large Dams*

4.3.1.1 The OFDA Disaster History Database

The US Office of Foreign Disaster Assistance (OFDA) has compiled a database that provides information on major world-wide disasters which have occurred since 1900 [Mitchell Group, 1996]. The completeness of the information has significantly improved since 1964. OFDA includes ‘‘declared’’ and ‘‘non-declared’’ disasters. Accidents are defined as ‘‘declared’’ if they were declared by the US Diplomatic Mission in an affected country as a disaster. So-called ‘‘non-declared’’ disasters are retained if they fulfil certain criteria. For instance, earthquake and volcanic disasters are included if the incident caused at least 6 fatalities or 25 injured persons or affected 1000 people. Disasters caused by extreme weather, except drought, are included if the number of fatalities or injured persons is at least 25.

The OFDA disaster history database, which contains over 4300 records, is updated quarterly. The information is coded by keywords and free text. The keywords of the OFDA database are:

1) Strike Date	*5) Fatalities*
2) Declaration Date	*6) Affected Persons*
3) Geographical Region	*7) Homeless*
4) Disaster Type	*8) Damage*

Further information on the OFDA database may be obtained from:

Office of US Foreign Disaster Assistance (OFDA)

Mr. Wes Mossburg

Information Support Specialist

320 Twenty-First Street

N.W. Washington

D.C. 20523

USA

4.3.1.2 The Fatal Hazardous Materials Accidents Database

The Fatal Hazardous Materials Accidents database, which in this report is abbreviated as RfF, contains 1068 records of fatal accidents involving a release of hazardous materials. The database was assembled by the Resources for the Future (RfF) Centre in Washington USA and covers the time period 1945-1991 [RfF, 1993]. The sources for this database were encyclopaedias, almanacs, books, reports, articles, newspapers and computer files such as FACTS (Section 4.3.1.4) or the Disaster File [Ferrara, 1979]. The RfF database claims to have assembled nearly every accident that was reported to have occurred during industrial production, storage, handling and transport of hazardous materials, which led to at least one fatality for the USA, or five fatalities for accidents that occurred outside the USA.

The term ‘‘hazardous materials’’ means not just acutely hazardous chemicals. It covers radioactive materials, too.

Three kinds of accidents were not included in the database: firstly, those accidents which occurred during mining and other forms of mineral extraction (e.g. offshore oil drilling); secondly, accidents involving the handling, transportation or storage of munitions, fireworks and manufactured explosives; and thirdly, accidents involving the transmission or distribution of natural gas. The keywords of the database are:

1) Serial Number | *11) Pipeline Site*

2) Date | *12) Pipeline Types*

3) Location | *13) Materials (maximum five materials)*

4) State | *14) Quantities (maximum five quantities)*

5) Country | *15) Release Types*

6) Type of Activity | *16) Min./Max. of reported Fatalities*

7) Facility Type | *17) Min./Max. of reported Injured persons*

8) Products (1-2 products) | *18) Number of Evacuated*

9) Transportation Mode | *19) Min./Max. of US$ Damage*

10) Transportation Phase | *20) Data Sources/Comments*

Further information may be obtained from:

Fatal Hazardous Materials Accidents Database

Resources for the Future

1616 P Street, N.W.

Washington, DC 20036-1400

USA

4.3.1.3 The Major Hazards Incidence Data Service (MHIDAS)

The Major Hazards Incidence Data Service (MHIDAS) was developed by the Safety and Reliability Directorate (SRD) of the United Kingdom Atomic Energy Authority, on behalf of the Major Hazards Assessment Unit of the UK Health and Safety Executive [SilverPlatter Directory, 1998]. The database comprises about 9300 accidents from 95 countries throughout the world, in particular, the USA, the UK, Canada, Germany, France and India. The recorded incidents resulted in, or had the potential to produce, a significant impact on the public at large, but exclude nuclear incidents and events associated with the extraction of materials (mining, oil drilling). The database was started in the early 80s, but also contains earlier events, going back to the beginning of this century. The database is continuously updated. The keywords for the coded information on an accident are:

1) Date	*9) Ignition Source*
2) Quantity of Material	*10) Time*
3) Release	*11) Financial Damage*
4) Material Type	*12) Country*
5) Material Name	*13) Fatalities*
6) Evacuations	*14) Injured persons*
7) Incidence Type	*15) Place*
8) Cause	*16) Abstract*

MHIDAS contains relatively detailed information on accidents and can be used for validating assumptions and judgements in safety assessments.

Further information on the MHIDAS database may be obtained from:

MHIDAS Database Manager

AEA Technology, Consultancy Services (SRD)

Wingshaw Lane, Culteth

Cheshire WA3 4NE

UK

4.3.1.4 The Industrial Safety Database FACTS

The Failure and Accidents Technical Information System (FACTS) database contains world-wide information on more than 20,000 industrial accidents with hazardous materials over the past 90 years. More than 100,000 pages of background information are recorded and, if non-confidential, available for further research purposes. The database is operated by TNO (Institute of Environmental Sciences, Energy Research and Process Innovation in Apeldoorn, The Netherlands) [TNO, 1998]. The key component of FACTS is PC-Facts which contain a subset of 14,000 accidents. All the accidents recorded in PC-Facts are coded in abstracts so as to make the data valuable for the purpose of risk analyses, risk and safety management, damage prevention and emergency response. Accidents are coded by hierarchically structured keywords and free text. The coding is based on accident analysis and also on a time scale. Keywords are readable, so that, in a short time, a complex accident may be understood.

Some keywords of FACTS are:

1) Fatalities	*7) Release of substances*
2) Injured persons	*8) Run-away reactions*
3) Fires	*9) Domino effects or danger for nearby objects*
4) Explosions	*10) Minor damage due to effective actions*
5) Release of toxic materials	*11) Location*
6) Suffocatings	

Incidents involving radioactive materials or munitions, or which occurred during military activities, are not covered by the database.

The incident profile for an accident to be collected in the database should contain at least one of the following items:

1. *Chemicals must be involved.*
2. *Acute injury and/or property damage must be caused, or the potential of danger of this exists.*
3. *The activity was: winning, production or extraction, transport, storage, trans-shipment, use/application (industrial or private), waste treatment, cleaning and research.*
4. *The incident can be categorised as a ''near miss''.*

Figure 4.3.1 shows a distribution of events that occurred during major industrial activities and included in FACTS.

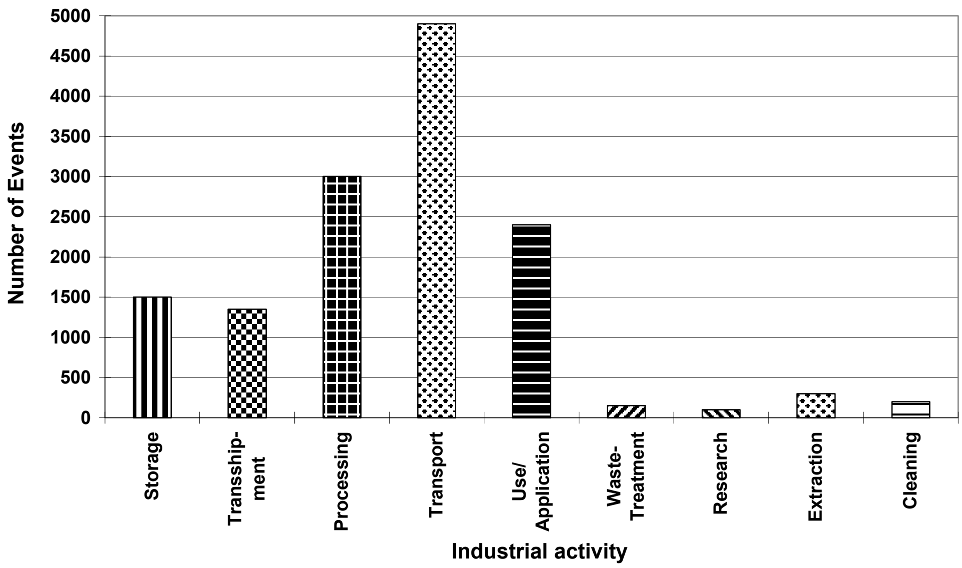

Fig. 4.3.1 Accidents and incidents that occurred during major industrial activities (according to FACTS status in 1998).

The main chemicals involved in accidents and incidents, according to FACTS, are shown in Fig. 4.3.2.

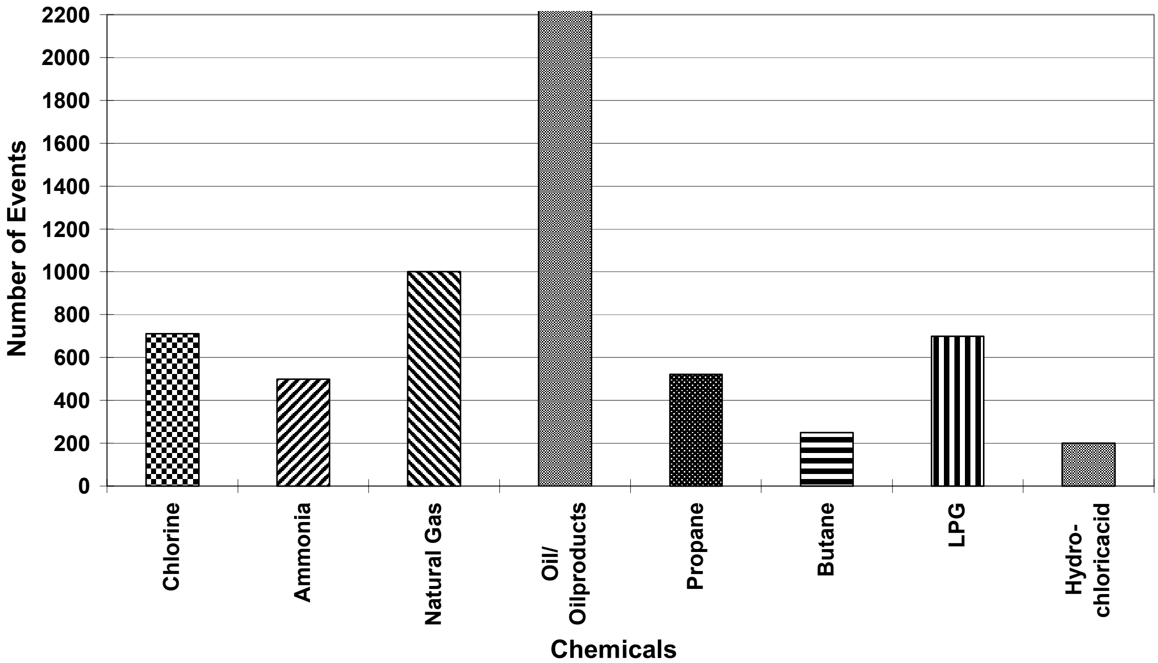

Fig. 4.3.2 Accidents and incidents involving different chemicals (according to FACTS status in 1998).

FACTS uses the following information sources to collect accident data:

1. *Periodicals*
2. *Newspapers from several countries*
3. *Company reports*
4. *Reports from research institutes*
5. *Technical reports*
6. *Governmental organisations such as:*
   - *a) Fire departments*
   - *b) Labour inspectorates*
   - *c) Environmental inspectorates*

Further information can be obtained from:

Pieter van Beek or Koos J.L. Clavel

Laan van Westenenk 501

P.O. Box 342

7300 AH Apeldoorn

The Netherlands

Phone: 31555493810 or 31555493892

Fax: 31555493390 or 31555493201

E-mail:facts@mep.tno.nl

or

P. Roder

AC-Laboratory Spiez

CH-3700 Spiez Switzerland

Phone: 332281771

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4.3.1.5 The WOAD Offshore Database

The World-wide Offshore Accident Databank (WOAD) was established by the Norwegian organisation Det Norske Veritas (DNV) [DNV, 1998]. In the database, information on offshore accidents is collected and systematised to provide information for oil companies, rig owners, drilling operators, authorised consultants and other organisations engaged in offshore safety and reliability. In WOAD over 3500 offshore accidents have been documented on a world-wide basis, involving material damage to fixed and mobile oil platforms, lay barges, offshore helicopters, pipelines and other equipment. All relevant information is coded, grouped and implemented in the database. For instance, one group is ‘‘type of accident’’ (e.g. blow-out, explosion, fire, collision, etc.). Another group is ‘‘type of unit’’ (e.g. mobile unit, fixed unit, pipeline, flare, buoy, etc.). Altogether, there are some 60 groups.

The databank claims to cover all offshore accidents dating from 1970 on, and probably comprises the world’s largest offshore accident databank. New accidents and incidents are being added to the database at a rate of about 200 a year. WOAD also enables users to have access to a database containing US accidents in the Gulf of Mexico, which are being recorded by the Mineral Management Services (MMS) (Section 4.3.2.2).

The keywords used in WOAD are:

1) Degree of damage	*8) Date of accident*
2) Type of accident	*9) Fatalities*
3) Geographical location	*10) Injured persons*
4) Operation mode	*11) Accident sequence*
5) Type of unit	*12) Number of well slots*
6) Type of spill or release	*13) Weather and sea conditions*
7) Spill or release size	*14) Repair time*

Further information can be obtained from:

Det Norske Veritas

Industri Norge AS Technica

Veritasveien 1

N-1322 Høvik

Norway

4.3.1.6 The Major Accident Reporting System

The Major Accident Reporting System (MARS) has been set up by the Commission of the European Communities and is operated by the Institute for Systems Engineering and Information (ISEI) in Ispra (Italy) [Drogaris, 1993]. By the end of 1991, a total of 121 accidents had been assembled in MARS[1]. The accidents were classified according to the parameters:

1) Year of occurrence	*6) Substances involved*
2) Type of accident	*7) Consequences*
3) Type of activity	*8) Description*
4) System involved	*9) Causes*
5) Mode of operation	

MARS collects mainly the most severe accidents from all member states of the European Community. An information flow chain has been established from the manufacturer to the

[1] Currently the MARS database has been extended to 320 major industrial accidents. This is a result of including accidents that occurred between 1992 and the present. The latter accidents have not been considered within the present version of ENSAD.

authorities, and MARS guarantees a high data quality. Chlorine and ammonia are the two substances most often involved in accidents notified to MARS. The Committee of the Competent Authorities of MARS has developed five ‘‘gravity’’ levels. These are: Worthy of note; Important; Severe; Very Severe; Catastrophic. They define the level of danger and the extent of consequences and safety measures.

4.3.1.7 The Accident Handbook ‘‘Materialien 5/83’’

Nearly 1000 accidents and failures were assembled in the handbook ‘‘Materialien 5/83’’, launched by the German Federal Office for the Environment [UBA, 1983]. The information provided in this book is based on the data from the FACTS database. The accidents which were collected in ‘Materialien 5/83’’ occurred mainly in the industrial sector, primarily in the chemical and oil industries. Other accidents in Materialien 5/83 are associated with the storage, handling and distribution of dangerous materials. The evaluation covers events which happened during the period 1900-1983. In the handbook, incidents have been included whenever one or more of the following criteria were fulfilled:

1. *Participation, release, combustion or explosion of dangerous materials*
2. *Releases of energy, such as shock waves or catapulted fragments*
3. *Injury to, or endangering of, people*
4. *Damage to or endangerment of objects of high value*
5. *Circumstances of special importance for the triggering of accidents (e.g. root causes) are described*
6. *Insights for preventing accidents and limiting consequences are provided*

The accidents are coded, using the following keywords:

1) Date

2) Occurrence data (fire, release, vaporisation, dispersion, explosion)

3) Occupancy data (company type, country)

4) Circumstances

5) Chemicals involved

6) Consequences (fatalities, injured persons)

7) Measures

8) Abstract

9) References

Accidents from the handbook ‘‘Materialien 5/83’’ for the time period 1969-1983 have been included in ENSAD.

4.3.1.8 The ‘‘SIGMA’’ Publication of the Schweizer Rück (reinsurance) company

The Swiss reinsurance company Schweizer Rück (Schweizer Re), in Zurich, which is world-wide the second-largest reinsurer, publishes annually the catalogue ‘‘SIGMA’’ [Swiss Re, 1970-1998]. Each year, in January, an overview is given of the largest reported accidents around the world. The summary of the largest catastrophes and damages given in ‘‘SIGMA’’ does not lay claim to completeness. The information comes from different sources (original documents, newspapers, etc.), and is coded in keywords such as:

1) Date

2) Place

3) Reason for the incident

4) Consequences (fatalities, injured persons, homeless, affected people)

5) Insured damage (in US$)

Further information can be obtained from:

Schweizerische Rückversicherungs-Gesellschaft

Sektion Wirtschaftsstudien

Postfach

CH-8022 Zurich

Switzerland

4.3.1.9 Encyclopaedia Britannica

Since 1973, the Encyclopaedia Britannica, Inc., annually publishes ‘‘Book of the Year’’ [Encyclopaedia Britannica, 1973-1998]. Each book in the series contains articles dealing with economic development, the environment and natural resources, food and agriculture, health and diseases, politics, sport and other themes. It also contains a catalogue of the most catastrophic events of the past year, including man-made and natural disasters. A short description of each accident is given, including the date, place and consequences.

4.3.1.10 The ICOLD catalogues of dam disasters

The International Commission On Large Dams (ICOLD) published in 1974 the book ‘‘Lessons from Dam Incidents’’ [ICOLD, 1974], covering 290 dam accidents which occurred world-wide before 1965. They were not, however, evaluated in terms of loss of life or monetary damage. The main effort was to identify and to examine the principal technical causes of failures and accidents. The findings were considered helpful to those responsible for the planning, design, construction and operation of dams.

An updated catalogue was published in 1995 (‘‘Dam Failures Statistical Analysis’’; [ICOLD, 1995]). It contains nearly 160 dam failures world-wide, defined as cases where the dam could not retain all the stored water, and covers the time period 1850-1996.

4.3.1.11 The ‘‘Catalog of Dam Disasters, Failures and Accidents’’

The ‘‘Catalog of Dam Disasters’’ [Babb and Mermel, 1968] contains approximately 600 dam accidents, which are listed alphabetically by countries. In most cases, the height, the length of the dam crest and the year of completion are given along with the reasons for failure. Information includes bibliographical references and the consequences of dam failures, such as fatalities or cost in US$.

4.3.1.12 Marsh & McLennan Study on Gas and Electricity Utilities

The publication ‘‘A 26-Year Study of Large Losses in the Gas and Electric Utility Industry’’ [Hathaway, 1991] was intended to provide individuals and organisations involved in the gas and electric utility industry with technical information covering incidents in the gas and electricity industry. The time period for the 104 reported events is 1965-1990; detailed descriptions of events are given, including the consequences to people.

4.3.2 Examples of some other databases not used in ENSAD

Some additional databases that might be of interest in the context of the present work have been identified. They have neither been evaluated or directly used within this project due to the resource limitations. However for future updates and extensions of the PSI’s database, the potential of these additional sources to enhance the completeness may be worthwhile to consider.

4.3.2.1 The Casualties and Demolition Database

The Lloyd’s Maritime Information Services Company maintains several databases. One of them is the ‘‘Casualties and Demolition Database’‘. This incorporates comprehensive details of reported serious casualties (including total losses) to merchant ships of 100 tonnes gross tonnage and above, which have occurred since 1978. The database claims to include all reported accidents involving tankers since 1976, and comprises 71,000 events [Lloyd’s, 1998]. The input originates from daily reports received from Lloyd’s Agents and Lloyd’s Registered Surveyors. The database also includes published information on reported accidents to drilling rigs and platforms.

The keywords are:

1) Cargo Type

2) Cubic Capacity (gas carriers)

3) Dead weight

4) Date of the accident

5) Event sequence

6) Location

7) Gross tonnage

8) Fatalities, Injured persons

9) Pollution

10) Ship type

11) Abstract

Further information can be obtained from:

Lloyd's Maritime Information Centre

Services Ltd

Collywn House, Sheepen Place

Colchester

Essex

UK

4.3.2.2 Minerals Management Service Accident Database

This database contains accidents in the Gulf of Mexico which occurred up to 1989. The database, which is accessible through WOAD (see Section 4.3.1.5) contains 4600 events.

4.3.2.3 Acute Hazardous Events Database

The Acute Hazardous Events (AHE) database was developed by the Environmental Protection Agency (EPA), in the USA, through its Office of Toxic Substances, Economics and Technology [AHE, 1985]. It was assembled as part of EPA's review of the dangers posed to the US public and industrial workers by sudden, accidental releases of toxic chemicals. The AHE database contains data from various states and federal agencies. It includes summaries of records of 3121 accidental releases of hazardous substances, of which 468 events involve either a death or an injury. The database was constructed from two federal reporting systems, from reports maintained by four states, from news media, and from a published historical summary assembled by the National Response Center (NRC). The sources cover the time period 1980 to 1985. Priority was given to events resulting in deaths or injured persons, due to air releases of toxic chemicals.

Further information can be obtained from:

Industrial Economics, Inc.

2067 Massachusetts Ave.

Cambridge, MA 02140

USA

4.3.2.4 SONATA

In the Italian database SONATA, world-wide events are collected that actually led, or might have led, to an unacceptable deviation of a process from its normal operating conditions. The data is structured according to the following keywords [Salvatore, 1998]:

1) Date, Location, Country

2) Substances (1-4), Quantities (1-4)

3) Type of accident (e.g. events leading to partial or total loss, or which may cause harm to the safety of workers and/or public or the environment)

4) Number of fatalities and/or injured persons

5) Damage (in US$)

6) Type of activity (e.g. storage, transport, production, processing) and plant

7) Documentation

8) Brief description of the accident

The information sources for SONATA were :

1) ENI (Ente Nazionale Idrocarburi) personnel world-wide

2) National press

3) International press

4) Links with major databases, e.g. FACTS (TNO, Netherlands) or WOAD (VERITAS, Norway)

5) Institutions or authorities responsible for fire prevention, public health and civil protection

More information may be obtained from:

Tema S.p.A.

SONATA Database

Via Medici del Vascello

I-20138 Milano

Italy

4.3.2.5 The VARO database

The VARO register is a database operated by the Finnish Technical Inspection Centre. It collects data on accidents and incidents involving pressure vessels, explosives, dangerous substances and mines. Data have been registered since 1978 and the total accident number as of today is about 1717. Registered information includes the following:

1) Accident type and date

2) Names of chemicals

3) Description of the accident

4) Measures taken to prevent the reoccurrence of a similar accident

The Technical Inspection Centre is a state institution, which carries out technical inspection of pressure vessels and dangerous substances. Regulations oblige owners to report immediately any accident and the associated damage connected to their facilities.

This obligation is prescribed by regulations in the following areas:

1. *Pressure vessels, boilers and associated piping*

2. *Use of inflammable liquids, natural gas and LPG*

3. *Oil heating equipment*

Reporting is compulsory if pressure vessel equipment or any other device is damaged, if people are injured, or if material or environmental damages are severe. Also, non-workplace incidents are included, e.g. incidents with oil tanks, heating devices and LPG fires in housing.

Further information may be obtained from:

Finnish Institute of Occupational Health (FIOH)

Department of Occupational Safety

Laajaniityntie 1

FIN-01620 Vantaa

Finland

4.3.3 Additional potential sources of severe-accident related information

4.3.3.1 OSH-ROM

OSH-ROM [SilverPlatter Directory, 1998] contains four databases which provide information on health and safety, hazardous incidents, and on the handling of dangerous materials. One of the databases is MHIDAS, which was presented in Section 4.3.1.3. The other three are: HSELINE (Section 4.3.3.2), NIOSHTIC (Section 4.3.3.3) and CISDOC (Section 4.3.3.4). The four databases contain together over 300,000 citations, taken from over 500 journals and 100,000 monographs. About 20,000 new records are being added annually. The databases cover the time period from 1960 to the present. OSH-ROM is available on compact disc, read-only memory (CD ROM).

4.3.3.2 HSELINE

HSELINE is a UK computerised database of bibliographic references to published documents on health and safety at work. It contains over 100,000 references; about 12,500 new references are added each year. HSELINE is available to the public through the European Space Agency Information Retrieval System, IRS Dialtech, Pergamon Infoline and Data Star. The database was developed by the Health and Safety Executive (UK).

Information on how to access HSELINE may be obtained from:

1) Dept. of Trade and Industry

IRS/Dialtech Room 392 Ashdown House

123 Victoria Street

London SW1E 6RB

UK

2) Data Star

D-S Marketing Ltd.

Plaza Suite

114 Jermyn Street

London SW1 6HJ

UK

3) Pergamon Orbit Infoline Ltd.
Achilles House
Western Avenue
London W3 OVA
UK

4.3.3.3 NIOSHTIC

NIOSHTIC was established in 1970 by the National Institute for Occupational Safety & Health, US Department of Health and Human Services. It contains information on occupational safety and health within the USA. Further information can be obtained from the same addresses as given in Section 4.3.3.2.

4.3.3.4 CISDOC

CISDOC, from the International Occupational Safety & Health Information Centre of the International Labour Organisation, was established in 1959 as the main centre within the UN for collecting and disseminating safety and health information world-wide. It is supported by a network of 52 National Information Centres around the world. Further information can be obtained from the same addresses as in Section 4.3.3.2.

4.3.3.5 The ETDE Energy Database

The ETDE [SilverPlatter Directory, 1998] energy database was assembled by the International Energy Association to increase access to information on energy, such as important developments in fossil and synthetic fuels, solar and renewable energy, energy storage and conversion, environmental sciences and related issues. The database also contains abstracts of accidents in the energy field. The database was developed by 14 member countries from the International Energy Agency (IEA). It includes the International Nuclear Information System (INIS) database on nuclear energy, as well as the IEA Coal Database. ETDE has over 3.6 million records, covers the time period from 1987 to the present, and is increasing by more than 200,000 records annually.

4.4 Summary

Table 4.3.1 gives an overview of major databases described in Sections 4.3.1 and 4.3.2 with their corresponding scopes and geographical areas.

Out of 17 databases in the table, 12 were directly used as a source of information for ENSAD. The code names of these sources are shown in boldface in the table. Possible use of the other databases including the ones described in Section 4.3.3 is not expected to lead to dramatic improvements of the completeness of ENSAD, given the current scope of work. However, some of these sources may include information on accidents associated with renewable sources, not covered here. Furthermore, additional information could certainly enhance the quality of the assessment.

TABLE 4.3.1

Major accident databases of relevance for the present work.

Full Name of the Database (Contact Organisation or Originators)	Country of Origin	Database Code Name[a]	Time Period[b]	Geogra-phical Area	Accidents covered
The US Office of Foreign Disaster Assistance Database (OFDA)	USA	**OFDA**	1900-1998	World-wide	Man-made and Natural Catastrophes
The Fatal Hazardous Materials Accidents Database (RfF)	USA	**RfF**	1945-1991	World-wide	Man-made and Natural Catastrophes
The Major Hazards Incidence Data Service (SRD)	UK	**MHIDAS**	1900-1998	World-wide	Industrial Accidents
The Failure and Accidents Technical Information System (TNO)	Netherlands	**FACTS**	1900-1998	World-wide	Industrial Accidents
The World-wide Offshore Accident Databank (DNV)	Norway	**WOAD**	1970-1998	World-wide	Offshore Accidents
The Accident Handbook (UBA)	Germany	**Handbuch Störfälle**	1900-1986	World-wide	Industrial Accidents
The Major Accident Reporting System (CEC JRC-Ispra)	European Community	**MARS**	1980-1991	Europe	Industrial Accidents
The “SIGMA” Publication (Schweizer Rück)	Switzerland	**SIGMA**	1969-1997	World-wide	Man-made and Natural Catastrophes
Book of the Year (Encyclopaedia Britannica)	UK	**Encyclopaedia Britannica**	1973-1997	World-wide	Man-made and Natural Catastrophes
The ICOLD Catalogues of Dam Disasters (ICOLD)	France	**ICOLD**	1850-1992	World-wide	Dam Accidents
Catalogue of Dam Disasters, Failures and Accidents (Babb and Mermel)	USA	**CDDFA**	1800-1968	World-wide	Dam Accidents
Study on Large Losses in the Gas and Electric Utility Industry (Marsh & McLennan)	USA	**MM**	1965-1990	World-wide	Accidents in Gas and Electric Utility Industry
The Lloyd’s Casualties and Demolition Database (Lloyd’s)	UK	Lloyd’s	1976-1998	World-wide	Offshore Accidents
Minerals Management Service Database (access through WOAD)	USA	MMS	1970-1989	USA	Offshore Accidents
Acute Hazardous Event Database (EPA)	USA	AHE	1900-1985	USA	Chemical Accidents
SONATA Database (TEMA/ENI)	Italy	SONATA	1850-1998	World-wide	Industrial Accidents
VARO Databank (FIOH)	Finland	VARO	1978-1998	Finland	Man-made and Natural Catastrophes

[a] Databases in bold have been used as information sources for ENSAD.

[b] The time period refers to the currently available databases; the actual period considered when using them as information sources within ENSAD may be different in some cases.

4.5 References

AHE (1985), Acute Hazards Database. Industrial Economics Inc., Cambridge, MA 02140, USA.

Baecher, G., Paté, M. and de Neufville R., Risk of Dam Failure in Benefit-Cost Analysis. Water Resources Research, **16** (1980) 449-456.

Babb, A. and Mermel, T. (1968), Catalog of Dam Disasters, Failures and Accidents. US Department of the Interior, Bureau of Reclamation, Washington, D.C., USA.

Beek, P.C. van (1994), Presentation of FACTS, A Database for Industrial Safety, held at the AC-Laboratorium in Spiez, Switzerland.

DNV (1998), World-wide Offshore Accident Databank. Det Norske Veritas Industry AS, DNV Technica, Hovik, Norway.

Drogaris, G. (1993), Major Accident Reporting System, Lessons Learned from Accidents Notified. Prepared for the Commission of the European Communities. Amsterdam: Elsevier Science Publishers B. V.

Encyclopaedia Britannica (1973-1998), Book of the Year. University of Chicago, 1974-1996.

Ferrara, G. M. (1979), The Disaster File: the 1970's. Facts on File, New York, USA.

Hathaway, L. (1991), A 26-Year Study of Large Losses in the Gas and Electricity Utility Industry. Marsh & McLennan Protection Consultants, New York, USA.

ICOLD (1974), Lessons From Dam Incidents. International Commission on Large Dams, CIGB/ICOLD, Paris, France.

ICOLD (1995), Dam Failures Statistical Analysis. Bulletin 99, CIGB/ICOLD, Paris, France.

Lloyd's (1998), Seadata On-line Maritime Information. Lloyd's Maritime Information Services, London, UK.

Mitchell Group (1996), Disaster History, Significant Data on Major Disasters World-wide, 1900 - 1995, prepared for the Office of U.S. Foreign Disaster Assistance Agency for International Development, Washington, Mitchell Group, Inc., Washington, USA.

RfF (1993), Fatal Hazardous Materials Accidents Database. Resources for the Future, 1616 P Street, N.W., Washington D.C. 20036-1400, USA.

Salvatore, A. (1998), SONATA Database (personal communication). Tema S.p.A., Milano, Italy.

SilverPlatter Directory (1998), A Directory of Electronic Information Products. SilverPlatter Information Ltd., Chiswick, London, UK.

Swiss Re (1970-1998), International Statistic of Natural Catastrophes and Major Losses. Sigma, Economic Studies, 11/86, Swiss Reinsurance Company, Zurich, Switzerland.

TNO (1998), FACTS Database for Industrial Safety. Institute of Environmental Sciences, Energy Research and Process Innovation (TNO), Department of Industrial Safety, Apeldoorn, The Netherlands.

UBA (1983), Handbuch Störfälle. Forschungsbericht UBA-FB 83-023, Umweltbundesamt. Berlin: Erich Schmidt Verlag (in German).

5. STRUCTURE AND CONTENT OF ENSAD

5.1 Actual versus Reported Accidents

To establish a database where all energy-related accidents are collected for all countries and where the accidents are described in full detail is an extremely demanding task. For practical reasons, there is a discrepancy between the number of accidents that actually occur and those that are published and analysed in reports or periodicals (Fig. 5.1.1; arbitrary scales).The relatively rare major accidents have a much greater probability of being publicised than the much more frequent accidents which cause less severe damage or danger [Marshall, 1987; Beek, 1994].

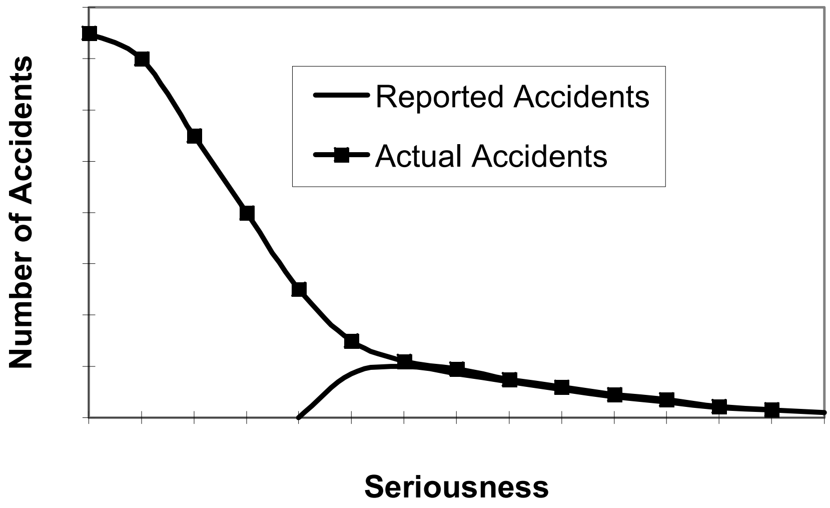

Fig. 5.1.1 Discrepancy between the number of accidents which actually happened and those reported [Beek, 1994].

For accidents with minor consequences, weeks and months may have to be spent to contact the authorised persons and to find the relevant reports. Since severe accidents are better documented than accidents with minor consequences, a high level of completeness was sought for in ENSAD for severe accidents.

5.2 Severe Accident Definitions

Based on the literature, there is no unique definition of a severe accident. All definitions include various consequence (damage) types (evacuees, injured persons, fatalities or costs) and a minimum level for each damage type. The differences between the definitions concern both the set of specific consequence types considered and the damage threshold. The ‘‘World-wide Offshore Accident Database’’ (WOAD) of Det Norske Veritas [DNV, 1992] considers an accident as severe or major, if more than one fatality occurred or if the damaged unit (e.g. oil platform, drill ship or drill barge) experienced total loss.

[Glickman and Terry, 1994] define a significant accident for technological hazard, if it resulted in at least 5 fatalities or if it involved the release of a chemical, petroleum product, hazardous waste or other hazardous material. The SIGMA publication series of Schweizer Rück [Swiss Re, 1997] and [Rowe, 1977] do not use the term ‘‘severe accidents’’. However, they do investigate and collect data on catastrophic events. Table 5.2.1 gives an overview of different criteria for an accident to be considered as severe or catastrophic. The criteria are arbitrary [Rowe, 1977], not standardised and can change with time [Swiss Re, 1988 and 1994].

TABLE 5.2.1

Different definitions of severe accidents.

Damage Categories (OR mode)	**SOURCES**					
	DNV (1992)	**Glickman and Terry (1994)**	**Swiss Re (1997)**	**Rowe (1977)**	**IAEA (1992)**	**ENSAD (this work)**
Fatalities	≥ 1	≥ 5	≥ 20	-	≥ 10	≥ 5
Injured	-	-	≥ 50	-	≥ 10	≥ 10
Evacuees	-	-	-	-	≥ 200	≥ 200
Homeless	-	-	2000	-	-	-
Ban on consumption of food	-	-	-	-	yes	yes
Polluting release of hydrocarbons or chemicals[b]	≥10,000 tonnes	Yes (no minimum specified)	-	-	-	≥10,000 tonnes
Enforced clean-up of land+water	-	-	-	-	≥ 25 km^2	≥ 25 km^2
Economic loss (million US$)	≥ 2	-	≥ 62.3 (total loss) Insured loss[a]: Shipping: ≥12.5 Aviation: ≥24.9 Other: ≥31.1	≥ 3	> 10	≥ 5

[a] The lower limits for the insured damages are increased annually by the inflation rate.

[b] The release levels refer exclusively to hydrocarbons. Other chemicals need to be treated on a case-by-case basis.

The criteria used in ENSAD to define severe accident are shown in the last column of Table 5.2.1. An energy-related severe accident is then defined as:

An accident which occurred in the oil, gas, coal, nuclear or hydro chain and which resulted in:

1) at least 5 fatalities or

2) at least 10 injured or

3) at least 200 evacuees or

4) extensive ban on consumption of food or

5) releases of hydrocarbons exceeding 10,000 tonnes[1] *or*

6) enforced clean-up of land and water over an area of at least 25 km^2 or

7) economic loss of at least 5 million 1996 US$.

In the following chapters of this report the various types of consequences mentioned above are covered to differing extents. This is to a high degree related to the availability and quality of information. At the same time, the users of the present report may have a particular interest in a specific type of consequence, for example number of fatalities. For these reasons, in applicable cases the type of the consequence considered will be indicated in the text. This is done by providing a specification (e.g. "≥ 5 fatalities") after mentioning ‘‘severe’’, whenever such a clarification is considered necessary.

5.3 Data Structure in ENSAD

The circumstances of past severe accidents are coded under more than 50 keywords, which throw light on the different characteristics of the event. Some features are described by only one keyword, others by several. Tables 5.3.1 and 5.3.2 give an overview of all accident characteristics in ENSAD, with the corresponding keywords. The keywords are explained in sections of this chapter, as specified in the last column of Tables 5.3.1 and 5.3.2.

5.3.1 Identification number

The ‘‘Identification number’’ is an integer number, which uniquely identifies each accident in the database. The number allows records in ENSAD to be related to records in other databases.

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[1] Other chemicals need to be considered on a case-by-case basis with view to their toxicity.

TABLE 5.3.1

Accident characteristics and keywords in ENSAD.

Aspect	Keywords	Explanation in Section :
Identification number	Accident number	5.3.1
Timing information and accident site specification	Date of the incident	5.3.2
	Hour	
	Region	
	Country	
	State	
	Province	
	City	
	Nearest city	
	Population density	
Technological characteristics of the accident	(see Table 5.3.2)	5.3.3
Accident analysis	Cause No. 1, Occurrence No. 1, Consequence No. 1.	5.3.4
	Cause No. 2, Occurrence No. 2, Consequence No. 2	
	Cause No. 3, Occurrence No. 3, Consequence No. 3	
	Cause No. 4, Occurrence No. 4, Consequence No. 4	
	Cause No. 5, Occurrence No. 5, Consequence No. 5	
Damages	Immediate fatalities (Max.), Immediate fatalities (Min.)	5.3.5
	Delayed fatalities (Max.), Delayed fatalities (Min.)	
	Immediate injured persons (Max.), Immediate injured persons (Min.)	
	Evacuees	
	Homeless	
	Releases of hydrocarbons, chemicals and radioactive products (tonnes)	
	Enforced clean-up of land or water (km^2)	
	Max. economic loss (US$), Min. economic loss (US$)	

TABLE 5.3.2

The keywords of the technological data of the accident.

Aspect	Specification	Keywords	Explanation in Section
Technological characteristics of the accident	**Energy production**	Energy-related (Yes/No)	5.3.3.1
		Type of energy carrier (coal, oil, gas, nuclear or hydro power)	
		Stage in the energy chain (extraction, power plant, etc.)	
	Coal	Name of the coal mine	5.3.3.2
		Production (tonnes/year)	
		Power level of damaged coal power plant (MW)	
	Oil	Name of oil field	5.3.3.3
		Name of damaged tanker	
		Flag of damaged tanker	
		Pipesite (above- or underground) of the damaged pipeline	
		Power level of damaged oil power plant (MW)	
	Natural Gas	Name of gas field	5.3.3.4
		Pipesite (above- or underground) of the damaged pipeline	
		Power level of damaged gas power plant (MW)	
	Nuclear	Type of nuclear power plant	5.3.3.5
		Power of the nuclear power plant (MW)	
	Hydro	Name of the dam	5.3.3.6
		River	
		Year of dam completion	
		Dam height (m)	
		Length of dam crest (m)	
		Volume of stored water	
		Dam type	
		Power level of damaged power plant (MW)	
	Activity data	Type of activity (storage, process, transfer etc.)	5.3.3.7
	Transport mode information	Transport mode (highway, rail, marine etc.)	5.3.3.8
	Information on the damaged facility	Damaged facility (barge, hose, pipeline, pump, railtanker, etc.)	5.3.3.9
	Information on general causes	General causes for the accident (external, human, mechanical, etc.)	5.3.3.10
	Information on specific causes	Specific causes for the accident (design error, floods, road accident, high winds, etc.)	5.3.3.11

Table 5.3.2 continues on the next page.

TABLE 5.3.2 (continued)

The keywords of the technological data of the accident.

Aspect	Specification	Keywords	Explanation in Section
Technological characteristics of the accident	**Chemicals involved**	Material A involved, Material A type	5.3.3.12
		Material A hazard, Material A code	
		Material A max. quantity, Material A min. quantity, Material A units	
		Material B involved, Material B type	
		Material B hazard, Material B code	
		Material B max. quantity, Material B min. quantity, Material B units	
		Material C involved, Material C type	
		Material C hazard, Material code	
		Material C max. quantity, Material C Min. quantity, Material C units	

5.3.2 Timing information and accident site specification

The timing information is given by the keywords ‘‘Date of the accident’’ and ‘‘Hour’’. In some sources which describe accidents, the day and month are not specified and only the year is provided. In such cases the date was set as 1st January.

The keyword ‘‘Region’’ describes a geographical location including land and sea. The codes used in ‘‘Region’’ have been adopted from the offshore accident databank WOAD [DNV, 1992]. Table 5.3.3 provides an overview.

Some countries (USA, India, Germany) consist of an union of states. Therefore the keyword ‘‘State’’ is introduced.

For some accidents a precise location is not known. Therefore the keyword ‘‘Nearest city’’ is introduced.

For further investigations, the keyword ‘‘Population density’’ could be an important parameter. If the population density is high in the area where accident occurs, the potential for severe consequences to people is high. At the moment only three qualitative indicators of population density are provided. These are: Rural, Town, Village.

TABLE 5.3.3

Codes and explanations for the keyword ''Region''.

Continent	Code	Explanation
Africa	AFW	Africa West, Africa West Coast (Atlantic)
	AFE	Africa East, East Africa (not included Red Sea and Suez)
	AFN	Africa North, Mediterranean (Africa)
	AFS	Africa South
America	ACE	Central America East, Caribbean Sea (not Gulf of Mexico)
	ACW	Central America West, California, Mexico (Pacific)
	AGL	North America Great Lakes
	AGM	Gulf of Mexico
	ANE	North America North East, USA & Canada East Coast (Atlantic), South Greenland
	ANW	North America North West, USA & Canada West Coast (Pacific)
	ARA	Arctic, North America, Alaska, Northwest Territories, West Greenland
	ASE	North America South East, South America East Coast (Atlantic)
	ASW	North America South West, South America West Coast (Pacific)
Antarctic	AAN	Antarctic
Arctic	AIA	Arctic, Asia, Russia North East
	ARC	Arctic, Europe, Norwegian Sea, Barents Sea, Svalbard, Arctic Ocean, East Greenland
Asia	AIE	Asia East, China, Japan South (including ocean in between)
	AIM	Middle East, Red Sea, Arabia, Iran, Iraq
	AIS	Asia South, India
	AUE	Australia East & New Zealand West
	AII	Asia, Indonesia, Malaysia, Thailand, Philippines
	AIN	Asia North, Russia East, Japan North
	AIW	Caspian Sea, Black Sea
Australia	AUS	Australia South
	OCE	Oceania & New Zealand East
	AUN	Australia North & New Zealand West
	AUW	Australia West
Europe	ENS	Europe North Sea, England, Scotland, Norway, Denmark, Netherlands, Germany
	EU	Europe East, Baltic Sea, Gulf of Bothnia
	EUS	Europe South, Mediterranean
	EUW	Europe West, Iceland, Ireland, France, Portugal

5.3.3 Technological accident characteristics of different energy sources

5.3.3.1 Energy production

The keyword ‘‘Energy-related’’ is a flag which indicates whether the accident occurred at facilities involved in energy production. The type of energy production (keyword ‘‘Type of energy production’’) can be based on coal, oil, gas, nuclear or hydro.

5.3.3.2 Coal

The keywords ‘‘Name of coal mine’’ should precisely define the location where the accident took place. The keyword ‘‘Production’’ makes a comparison possible with other collieries.

5.3.3.3 Oil

The keywords ‘‘Name of oil field’’, ‘‘Name of damaged tanker’’ and ‘‘Power level of damaged power plant’’ are self-explanatory. The keyword ‘‘Flag of damaged tanker’’ means the country where the tanker has its home port. The keyword ‘‘Pipesite’’ shows if the pipeline was above- or underground when the accident took place.

5.3.3.4 Gas

The keywords ‘‘Name of gas field’’ and ‘‘Power level of damaged power plant’’ are self-explanatory. The keyword ‘‘Pipesite’’ is explained in Section 5.3.3.3.

5.3.3.5 Nuclear

The keywords ‘‘Type of nuclear power plant’’ and ‘‘Power of the nuclear power plant’’ are self-explanatory.

5.3.3.6 Hydro

The keywords ‘‘Name of the dam’’, ‘‘River’’, ‘‘Year of completion’’, ‘‘Length of dam crest’’ and ‘‘Power level’’ are self-explanatory. The keyword ‘‘Dam height’’ means the height above lowest foundation. The keyword ‘‘Purpose’’ means the purpose of the reservoir, such as irrigation, hydro power, water supply or recreational.

5.3.3.7 Activity data

The keyword ‘‘Activity data’’ gives the activity during which the accident occurred. Table 5.3.4 gives an overview of the abbreviations used in ENSAD and the corresponding meanings. The codes used in ‘‘Activity data’’ have been adopted from in the databank MHIDAS (Section 4.3.1.3).

TABLE 5.3.4

Abbreviations and meanings for the keyword ‘‘Activity data’’.

Abbreviation	Meaning
Dom/Com	Accident originated in domestic or commercial premises
Process	Accident originated in items of process plant or in an area of process plant
Storage	Accident originated in items/area of storage plant
Transfer	Accident originated during loading or unloading
Transport	Accident originated during transport of the material external to plant, including pipelines
Warehouse	Accident originated in a warehouse
Waste	Waste storage or disposal areas, including settling ponds, material dumps, and bulk waste files

5.3.3.8 Transport mode information

There exist different modes for the transportation of goods. The keyword for this is ‘‘Transportation mode’’. The modes are road, rail, pipeline, marine or inland waterways.

5.3.3.9 Information on the damaged facility

The keyword ‘‘Damaged facility’’ describes the facility or facilities damaged by the accident. Table 5.3.5 gives an overview. The codes used in ‘‘Damaged facility’’ have been adopted from the databank MHIDAS (Section 4.3.1.3).

5.3.3.10 Information on general causes

The entries and corresponding meanings for ‘‘General causes of the accident’’ are given in Table 5.3.6. The codes used in ‘‘General causes of the accident’’ have been adopted from the databank MHIDAS (Section 4.3.1.3).

5.3.3.11 Information on specific causes

The entries and corresponding meanings for ‘‘Specific causes of the accident’’ are given in Table 5.3.7. The codes used in ‘‘Specific causes of the accident’’ have been adopted from the databank MHIDAS (Section 4.3.1.3).

TABLE 5.3.5

Entries for the keyword ‘‘Damaged facility’’ and explanations.

Entry for ‘‘Damaged facility’’	Meaning
Asvessel	Atmospheric pressure storage vessel
Barge	Inland waterway vessel
Commtank	Small commercial tank
Firedequip	Fired process equipment, including furnaces
Heatxchang	Heat exchangers, evaporators, condensers, boilers, reboilers
Hose	Hoses and other similar loading/unloading connections
Macdrive	Process machinery drives, including electrical motors, engines, turbines
Package	Portable transport containers, including drums, barrels, jerricans, boxes, bags, composite packagings, cylinders
Pipeline	Pipes, containment used for bulk transport external to plant
Pipework	On-plant pipes and associated valves, joints
Psvessel	Pressurised storage vessels
Pump	Any type of pump, compressor, ejector, fan
Pvessel	Process vessels, including equipment items such as centrifuges, towers, columns, dryers, distillation, absorption, filtration, cyclones, ion-exchange, crystalliser
Railtanker	Pressurised, general purpose
Roadtanker	Single, compartmented or multiple tanks
Ship	Ocean-going vessel
Sizechange	Size reducing/enlarging equipment, including mills
Solidmove	Equipment for moving solid material, e.g. conveyers, belts, elevators, buckets, screw, pneumatic
Tankcontnr	A tank having a capacity of ≥ 50 lt whose shell is fitted with items of service and structural equipment

TABLE 5.3.6

Entries and meanings for ‘‘General causes of the accident’’.

Entries for ‘‘General causes of the accident’’	Meaning
External	External events
Human	Human factor
Impact	Impact failure
Instrument	Instrument failure
Mechanical	Mechanical failure
Procond	Disturbed process conditions
Service	Services failure
Vreaction	Violent reaction

TABLE 5.3.7

Entries and meanings for ‘‘Specific causes of the accident’’.

Entries for ‘‘Specific causes of the accident’’	Meaning
Accvent	Accidental venting
Brittle	Brittle failure
Communicat	Communication systems
Compair	Compressed air or nitrogen
Conexp	Confined explosion
Connect	Failure to connect or disconnect
Construct	Construction error
Control	Controller
Design	Design error
Drainacc	Draining accident
Electric	Electricity
Excavequip	Excavating equipment
Extnlexp	Explosion
Extnlfire	Fire
Flangcoupl	Leaking coupling or flange
Floods	Flooding

Table 5.3.7 continues on the next page.

TABLE 5.3.7 (continued)

Entries and meanings for ‘‘Specific causes of the accident’’.

Entries for ‘‘Specific causes of the accident’’	Meaning
General	General management error
Generalop	General operational
Glandseal	Leaking gland or seal
Ground	Subsidence, soil stress, erosion of support
Highwinds	High winds
Hvyobject	Heavy object
Incompat	Use of incompatible materials
Install	Installation error
Instair	Instrument air
Intnlfire	Internal fire
Isoluncoup	Failure to isolate or drain before uncoupling
Maintain	General maintenance
Metallurg	Other metallurgical failure
Overfill	Overfilling
Overheat	Overheating
Overload	Overloading
Overpres	Overpressure
Reliefvalv	Relief valve failure
Railacc	Rail accident, no other vehicle
Roadacc	Road accident, no other vehicle
Runaway	Runaway reaction
Sabotage	Sabotage or vandalism
Ship/Ship	Ship to ship collision, also barges
Roadtanker	Single, compartmented or multiple tanks (in USA: tank trucks).
Ship	Ocean-going vessel
Sizechange	Size reducing/enlarging equipment, including mills, grinders, crushers; breakers, cutters, agglomerators
Solidmove	Equipment for moving solid material, e.g. conveyers, belts, elevators, buckets, screw, pneumatic
Solidstore	Solids storage, including piles, bins, silos, hoppers.
Ship/Land	Ship to land collision
Tankcontnr	A tank having a capacity of $\geq$ 50 lt, whose shell is fitted with items of service equipment and structural equipment.
Temprture	Temperature extremes
Valve	A leaking·or passing valve
Vehicle	Other vehicle
Water	Water supply
Weldfail	Weld failure

5.3.3.12 Chemicals involved

There are different keywords to cover up to three possible chemicals which are involved in the incident. The keywords are: ‘‘Material A involved’’, ‘‘Material B involved’’, ‘‘Material C involved’’. Their material types (keyword e.g. ‘‘Material A type’’) such as liquid, solid or gaseous and their hazards (keyword e.g. ‘‘Material A hazard’’) can be also given. For the amount of released chemicals there are the keywords e.g. ‘‘Material B max. quantity’’ and ‘‘Material B min. quantity’’, because in some cases the exact amount of released material is not known.

5.3.4 Accident analysis

An incident could be structured by chains of causes, of occurrences and of consequences. In ENSAD, up to five causes, occurrences and consequences can be coded, as shown in Fig. 5.3.1.

Cause chain		Occurrence chain		Consequence chain
Cause No. 1	⇒	Occurrence No. 1	⇒	Consequence No.1
		⇓		⇓
Cause No. 2	⇒	Occurrence No. 2	⇒	Consequence No.2
		⇓		⇓
Cause No. 3	⇒	Occurrence No. 3	⇒	Consequence No.3
		⇓		⇓
Cause No. 4	⇒	Occurrence No. 4	⇒	Consequence No.4
		⇓		⇓
Cause No. 5	⇒	Occurrence No. 5	⇒	Consequence No.5

Fig. 5.3.1 Accident structured in cause, occurrence and consequence chains.

Three examples are given to demonstrate how an accident can be structured according to Fig. 5.3.1.

Example accident (1), based on FACTS [TNO, 1994]

Description of the accident

On June 16th 1966, off the coast of Norway, the five-legged floating platform "Alexander Kielland" overturned in gale-force winds in the North Sea. One hundred and twenty three of the 212 persons aboard were drowned and 45 men injured when one of the anchored legs gave way and caused the platform to overturn.

The structure of this accident is:

Cause chain		**Occurrence chain**		**Consequence chain**
Cause No. 1		**Occurrence No. 1**		**Consequence No. 1**
Gale-force winds	⇒	Leg of the platform gave way	⇒	--
		⇓		
Cause No. 2		**Occurrence No. 2**		**Consequence No. 2**
--	⇒	Overturning of the platform	⇒	123 workers killed, 45 injured

Fig. 5.3.2 Structure of accident No. 1.

The keywords in Fig. 5.3.2 have the following values (Table 5.3.8) in ENSAD:

TABLE 5.3.8

Entries for accident No. 1.

Keyword in ENSAD	Entry
Cause No. 1	Gale-force winds
Cause No. 2	--
Occurrence No. 1	Leg of the platform gave way
Occurrence No. 2	Overturning of the platform
Consequence No. 1	123 workers killed, 45 injured
Consequence No. 2	--

The keywords ‘‘Causes No. 3’’, ‘‘Cause No. 4’’,..., ‘‘Consequences No. 4’’, ‘‘Consequences No. 5’’ have, in this case, no entries.

Example accident (2), based on MHIDAS [SRD, 1993]

Description of the accident

On April 1st 1966, in Feyzin (France) LPG leaked from a spherical tank while sampling. An LPG cloud drifted to a nearby highway. The cloud was ignited by a car passing into the cloud and flashed back to the LPG sphere which blew up, killing twenty one fire-fighters and workers and injuring 52 persons. Two thousand people were evacuated. The blast threw 100 tonnes of fragments over a circle with a diameter of 150 meters. Further explosions occurred as fire spread to other installations.

The structure of this accident is shown in Fig. 5.3.3 and keywords are provided in Table 5.3.9.

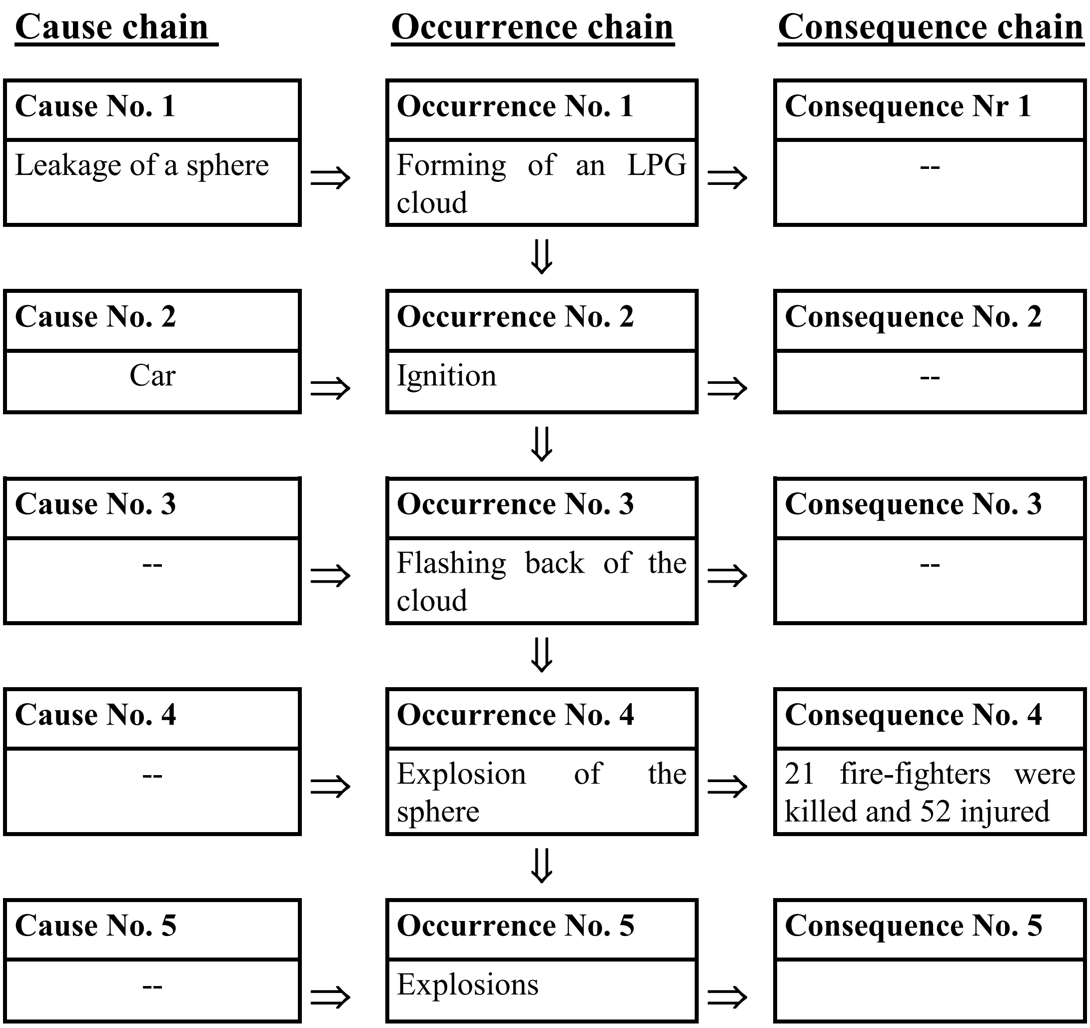

Fig. 5.3.3 Structure of accident No. 2.

TABLE 5.3.9

Entries for accident No. 2.

Keyword in ENSAD	Entries
Cause No. 1	Leakage of a spherical tank
Cause No. 2	Car
Cause No. 3	--
Occurrence No. 1	Forming of an LPG cloud
Occurrence No. 2	Ignition
Occurrence No. 3	Flashing back of the cloud
Occurrence No. 4	Explosion of the sphere
Occurrence No. 5	Explosions
Consequence No. 1	--
Consequence No. 2	--
Consequence No. 3	--
Consequence No. 4	21 fire-fighters killed and 52 injured
Consequence No. 5	

Example accident (3), based on [Encyclopaedia Britannica, 1978]

Description of the accident

A helicopter, attempting to land on the deck of an offshore oil rig during high winds crashed into the rig and dropped after the crash some 130 ft into rough sea. Two oil workers were injured and 17 others aboard were killed. The structure of this accident is:

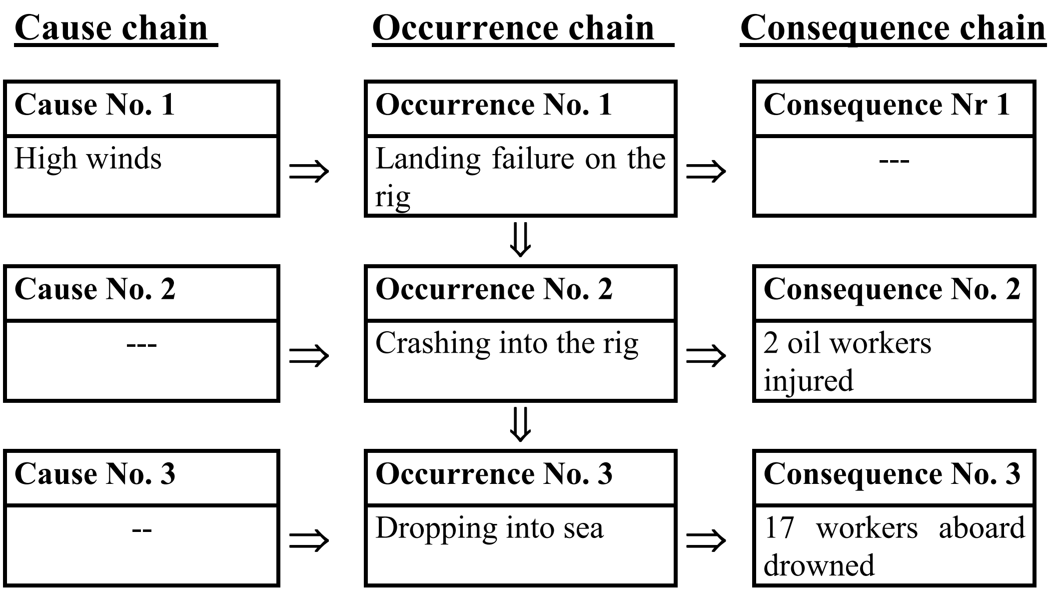

Fig. 5.3.4 Structure of accident No. 3.

The keywords for the accident analysis would have the following entries in ENSAD:

TABLE 5.3.10

Entries for accident No. 3.

Keyword in ENSAD	Entries
Cause No. 1	High winds
Cause No. 2	--
Cause No. 3	--
Cause No. 4	Rough seas
Occurrence No. 1	Insecure landing on the rig
Occurrence No. 2	Crashing into the rig
Occurrence No. 3	Dropping into sea
Consequence No. 1	---
Consequence No. 2	Workers injured
Consequence No. 3	17 workers aboard drowned

5.3.5 Damages

Accidents can cause immediate deaths (keyword ‘‘Immediate Fatalities’’) and, as in the case of Chernobyl, delayed fatalities (keyword ‘‘Delayed Fatalities’’). Sometimes the sources, such as reports or newspapers, give different numbers for the fatalities and other consequences. Therefore the two keywords ‘‘Max. Immediate Fatalities’’ and ‘‘Min. Immediate Fatalities’’ were introduced when different values were given. The corresponding keywords for other types of consequences are: Max./Min. Delayed Fatalities, Max./Min. Immediate Injured, Max./Min. Evacuees, Max./Min. Economic Loss.

5.4 Some Facts about ENSAD

5.4.1 Overall statistical information of ENSAD

Currently the ENSAD database covers 13,914 accidents, of which 4290 (30.8%) accidents are energy-related, i.e. occurred in the coal, oil, gas, hydro power or nuclear chain. Nearly 93% of them occurred during the time period 1945-1996. Ten thousand and sixty four accidents (72.3%) are classified as man-made. The share of energy-related accidents among the man-made accidents amounts to 42.6%. Nearly one third of all man-made and natural severe accidents with five or more fatalities and nearly two thirds of all energy-related severe accidents with five or more fatalities occurred in OECD-countries. An overview of the number of accidents of the different types and within specific damage categories is given in Table 5.4.1.

It must be stressed that non-energy-related accidents are a secondary priority within ENSAD. Consequently, the corresponding data are less reliable than the ones provided for the energy-related accidents.

TABLE 5.4.1

Overview of the number of accidents by type (natural, man-made, man-made energy-related, man-made non-energy-related) and by different damage categories, as included in ENSAD[2].

	Damage Categories							
	No Consequence Threshold	A	B	C	D[a]	E[a]	F	G
All accidents	13914	4736	2118	2273	632	35	1407	8483
Natural	3850	2254	291	1653	0	0	221	3107
Man-made	10064	2482	1827	620	632	35	1186	5376
Man-made energy-related	4290	846	542	174	632	30	309	1943
Man-made Non-energy-related	5774	1636	1285	446	0	5	877	3433

[a] D and E are partially overlapping; within these two categories many additional non-energy related accidents have certainly occurred but have not been implemented in ENSAD.

Damage categories and thresholds:

1) A: ≥ 5 Fatalities
2) B: ≥ 10 Injured
3) C: ≥ 200 Evacuees
4) D: ≥ 10,000 tonnes of pollutive releases of hydrocarbons
5) E: ≥ 25 km^2 area of enforced clean up of land and/or water
6) F: ≥ 5 million 1996 US$ of economic loss
7) G: A or B or C or D or E or F

[2] The table provides the number of unique events represented in ENSAD. This means that whenever there are several records of the same event in ENSAD (due to the discrepancies between the various sources), the event is counted only once here.

5.4.2 Source composition of energy-related accidents in ENSAD

The major contributors to ENSAD, i.e. sources of energy-related accidents which occurred in the energy chains such as coal, oil, natural gas, liquefied petroleum gas (LPG) and hydro power, are shown in Fig. 5.4.1. This should by no means be interpreted as a statement on the relative completeness of the databases used. Many accidents are represented in several databases but were taken only from one of the sources whenever the information was identical. As may be seen the primary sources were MHIDAS, FACTS, RfF, SIGMA and WOAD. However, it should be noted that other sources that were used are of critical importance. This applies in particular to databases covering specific energy chains, such as WOAD (gas & oil offshore) and ICOLD (hydro). The time periods covered and the countries from which the information comes for the different databases, are given in Table 4.3.1 of Section 4.3.4.

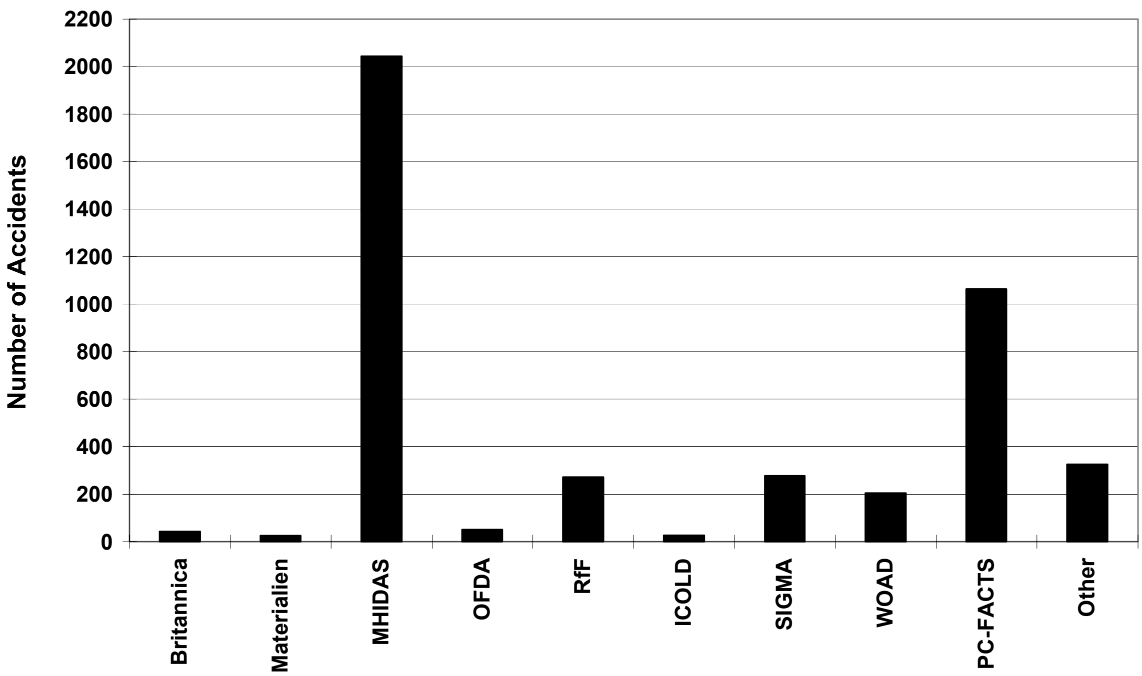

Fig. 5.4.1 Origin of energy-related accidents in ENSAD.

In Table 5.4.2 the number of events in databases MHIDAS, FACTS[3], RfF, SIGMA and WOAD along with the corresponding number of events adopted in ENSAD are shown.

[3] The search conducted in FACTS was limited in scope in the sense that it focused on the accidents in sectors that were potentially not very well represented in other information sources used by ENSAD.

TABLE 5.4.2

Some major databases contributing to ENSAD.

Name of the Database	Number of events in the original database	Number of energy-related events induced in ENSAD
MHIDAS	9319	2043
FACTS	≈20,000	1065
SIGMA	3874	277
RfF	1068	271
WOAD	≈3500	201

In relative terms the database RfF has the highest share of energy-related accidents adopted in ENSAD in relation to the total number of events in the original database.

5.4.3 Source composition of non-energy-related accidents in ENSAD

The databases providing largest contributions to the non-energy-related accidents in ENSAD are shown in Fig. 5.4.2.

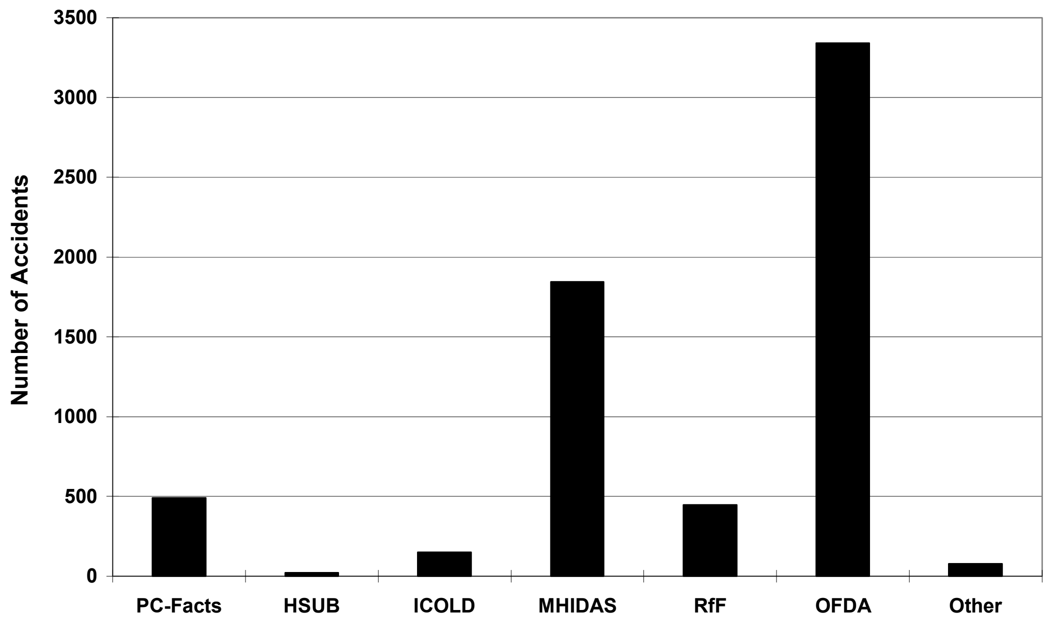

Fig. 5.4.2 Origin of non-energy-related accidents in ENSAD.

Nine thousand six hundred and twenty four non-energy-related accidents are represented in ENSAD, with 8949 of them occurring during 1945-1996. Table 5.4.3 gives an overview of the primary sources of information on non-energy-related accidents, as utilised by ENSAD. Thus, MHIDAS and OFDA provide the largest shares; with regard to FACTS the remark in the footnote on page 58 applies also here.

TABLE 5.4.3

Primary contributors to the non-energy-related accidents in ENSAD.

Name of the Database	Number of non-energy-related events induced in ENSAD
MHIDAS	3416
OFDA	3340
FACTS	497
RfF	446

5.4.4 Distribution of energy-related accidents by years

Four thousand two hundred and ninety energy-related accidents are collected in ENSAD, with 99.1 % of them being man-made events, and 3843 (89.6 %) occurring during the time-period 1969-1996. Eight hundred and forty six energy-related accidents resulted in at least 5 fatalities, with 675 of them occurring during 1969-1996. The distribution of the energy-related accidents in the time-period 1945-1996 is shown in Fig. 5.4.3.

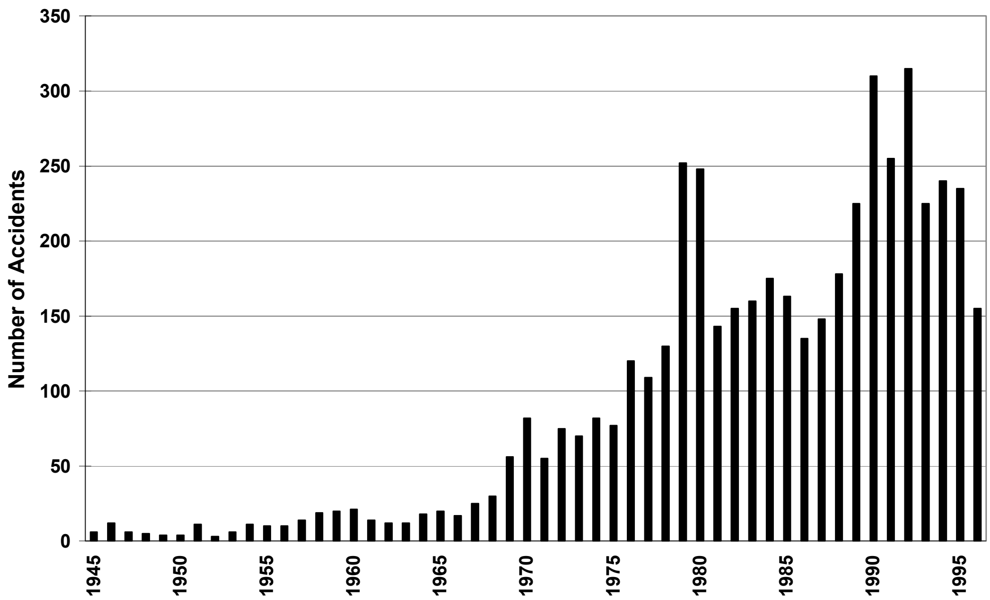

Fig. 5.4.3 Distribution of energy-related accidents in the time-period 1945-1996.

Figure 5.4.3 indicates an increase of the number of energy-related accidents since late sixties, a stabilisation in the eighties, followed by an increase in the early nineties and a possible return to stabilisation again. (It remains to be seen whether this trend will continue beyond 1996; the records for 1996 may be less complete than for the preceding years after 1969.) The years in which the highest number of energy-related accidents occurred were 1990 and 1992. This effect can be attributed to a particularly significant increase of accidents in the oil chain. The increase after 1969 is probably due to two reasons: (a) improved reporting; (b) increased volume of energy-related activities shown in Fig. 5.4.4 for coal, oil, hydro power nuclear energy production and in Fig. 5.4.5 for natural gas and LPG energy production.

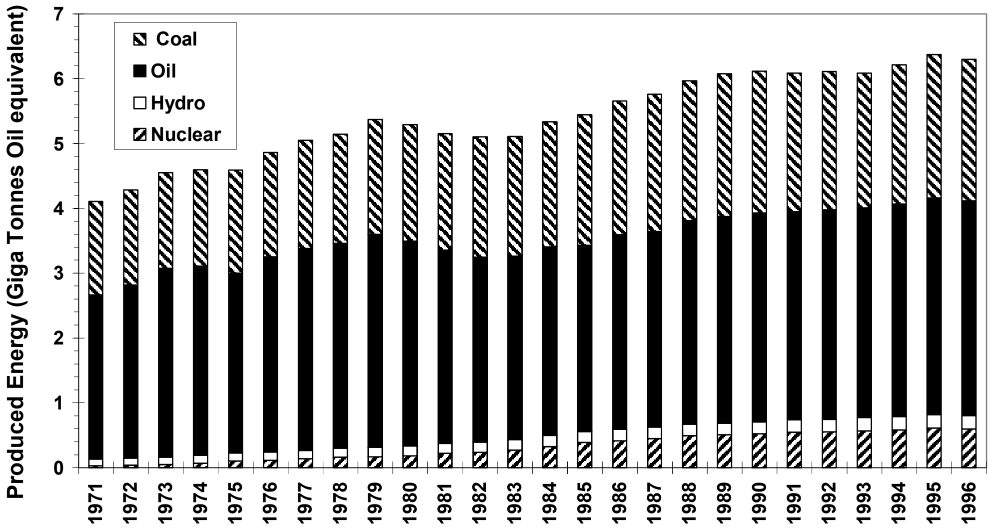

Fig. 5.4.4 World coal, oil, hydro power and nuclear energy production in the period 1971-1996.

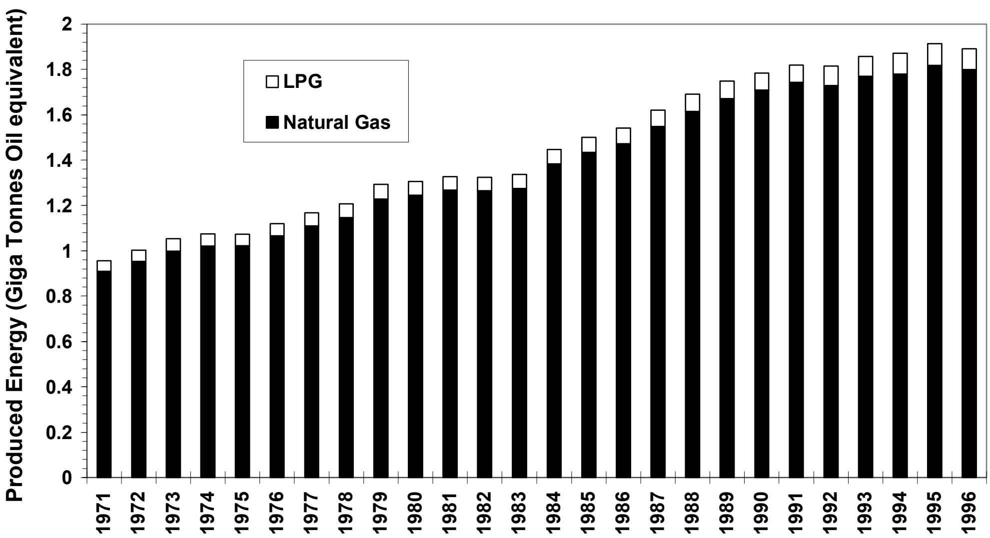

Fig. 5.4.5 World natural gas and LPG energy production in the period 1971-1996.

The distribution of the number of energy-related accidents by year, for four different accident gravity indices (5-20, 21-50, 51-100 or more than 100 fatalities per accident), is shown in Fig. 5.4.6. The figure shows an increase of severe accidents, with at least 5 fatalities, after 1970. The figure proves also that catastrophes with more than 100 fatalities still occur, in spite of world-wide technical improvements of industrial facilities.

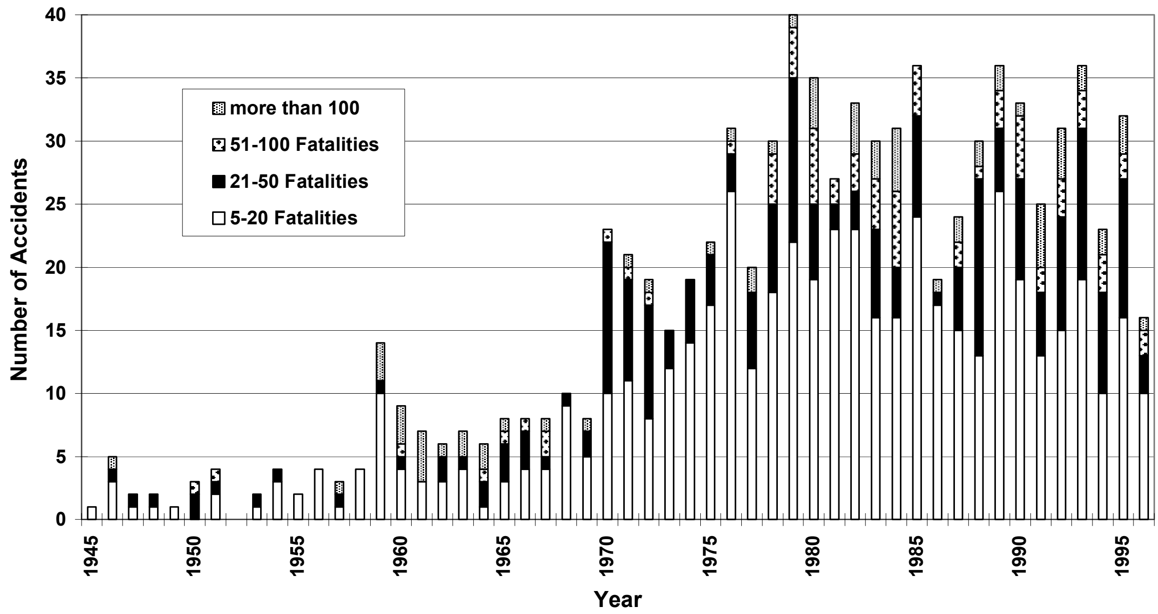

Fig. 5.4.6 Severe energy-related accidents during the period 1945-1996, with different gravity indices for fatalities.

The number of injured for three gravity indices (10-50, 51-100, 101-300 and more than 300 injured persons) is shown in Fig. 5.4.7. The figure indicates an increased number of injured persons due to energy-related accidents since 1966, with peaks in 1978, 1984 and 1985. It should be noted that the injured persons records are more uncertain and less complete than the corresponding fatality records.

5.4.5 Distribution of non-energy-related accidents by years

The number of non-energy-related accidents by years is shown in Fig. 5.4.8, with the distinction between the man-made and non-man-made ones. The figure demonstrates an increase in the number of accidents since about 1964 and then again from 1975. The number of accidents appears to be decreasing since 1993.

The number of non-energy-related severe accidents during the time-period 1945-1996, with different indices of gravity (5-20, 21-50, 51-100 and more than 100 fatalities), is shown in Fig. 5.4.9. As can be seen the number of larger accidents in the late eighties and nineties clearly exceeds the corresponding number in earlier periods.

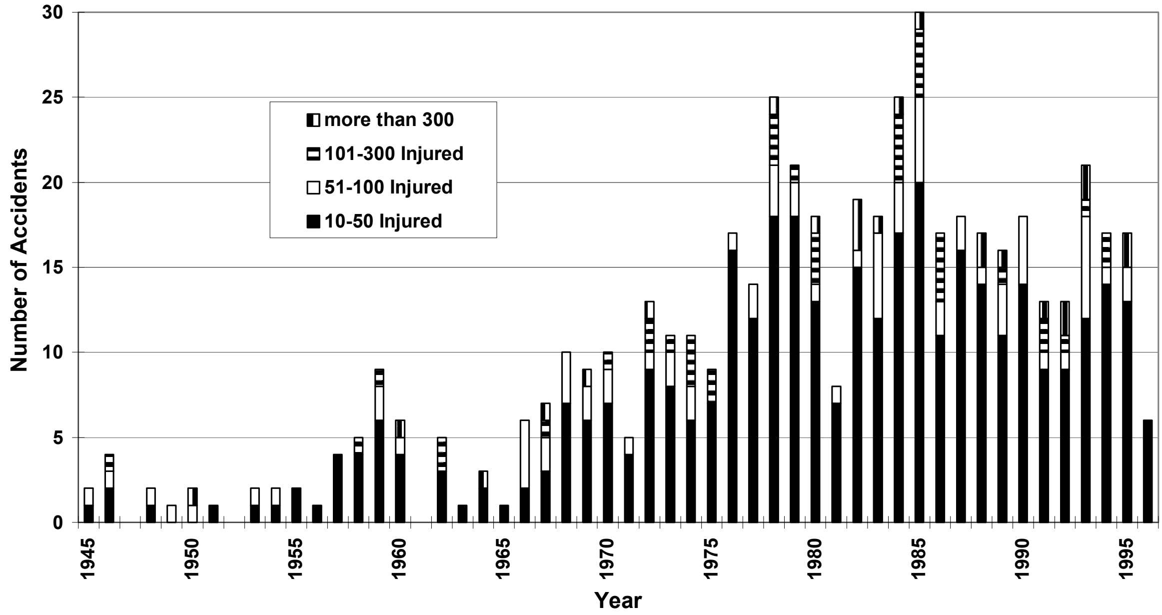

Fig. 5.4.7 Severe energy-related accidents during the period 1945-1996, with different gravity indices for injured.

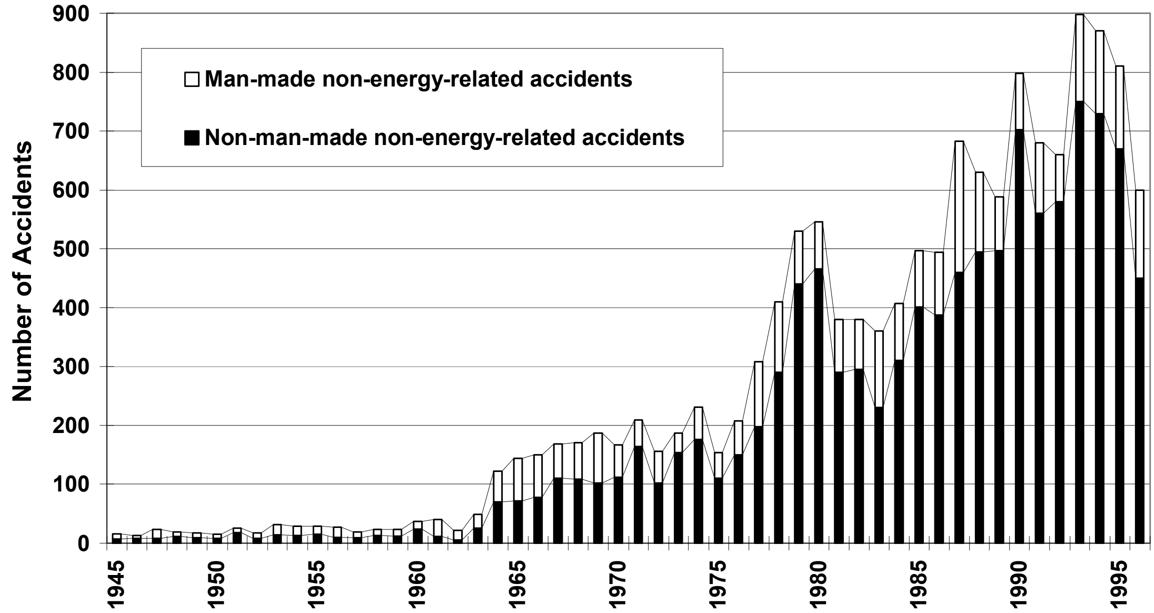

Fig. 5.4.8 Number of non-energy-related accidents (man-made and non-man-made) in the time-period 1945-1996.

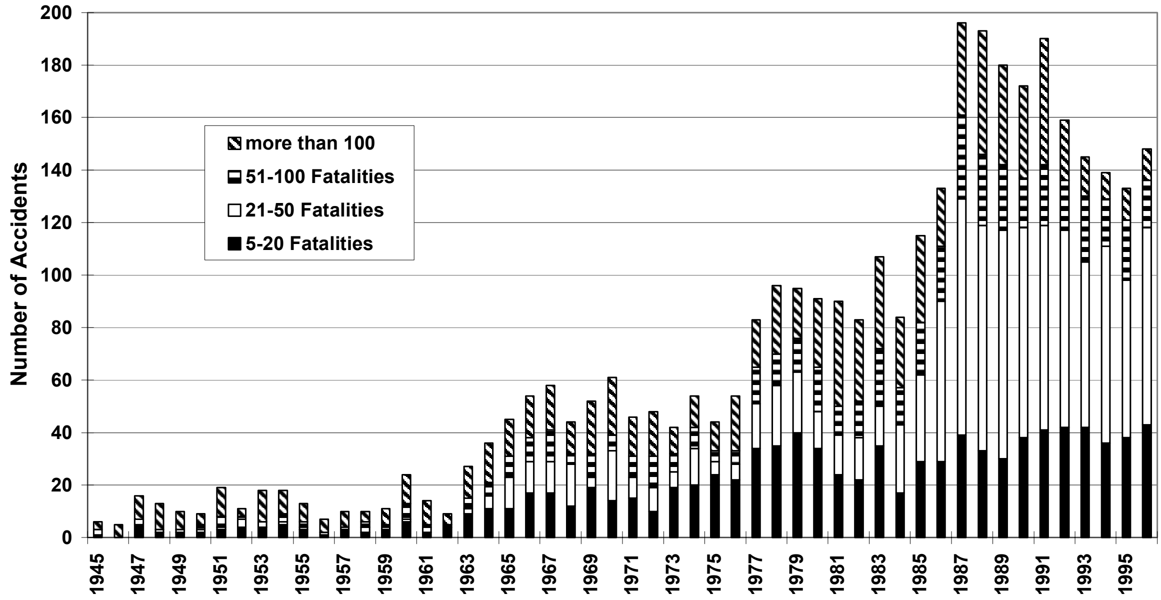

Fig. 5.4.9 Severe non-energy-related accidents during the period 1945-1996 with different gravity indices for fatalities.

The number of injured for four gravity indices (10-50, 51-100, 101-300 and more than 300 injured persons) is shown in Fig. 5.4.10. This figure illustrates recent increase in the observed number of injured people.

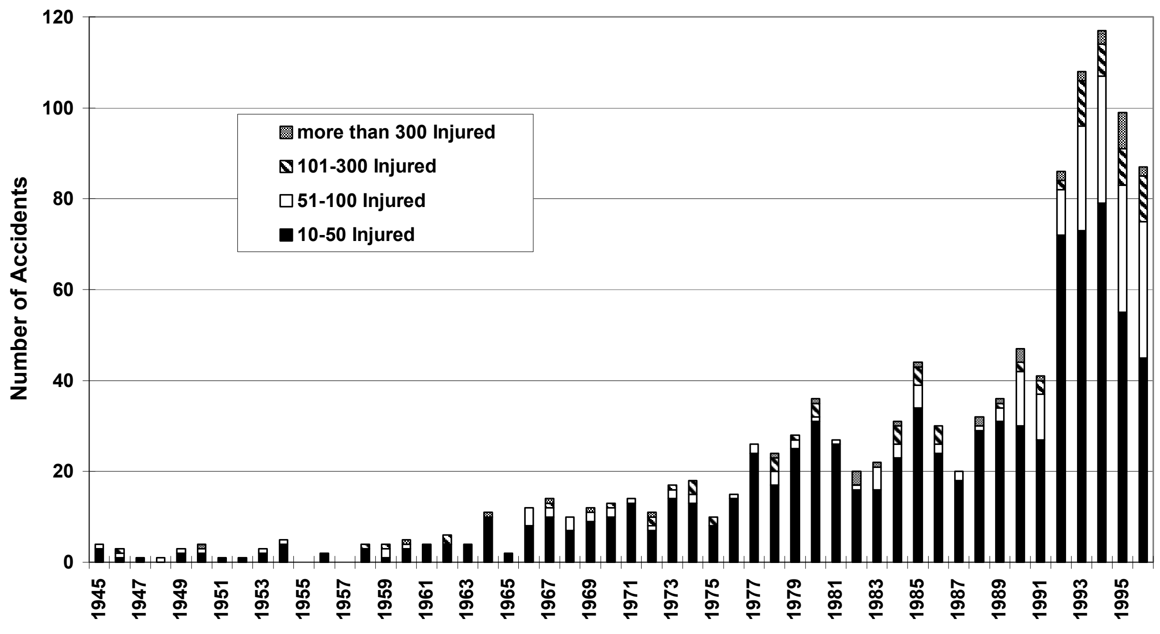

Fig. 5.4.10 Severe non-energy-related accidents during the period 1945-1996, with different gravity indices for injured.

5.4.6 Distribution of severe energy-related accidents by country and continent

The distribution by country for countries in which a minimum of 14 energy-related severe (≥ 5 fatalities) accidents occurred during the period 1945-1996, is shown in Fig. 5.4.11 (The number 14 was chosen for graphical reasons.)

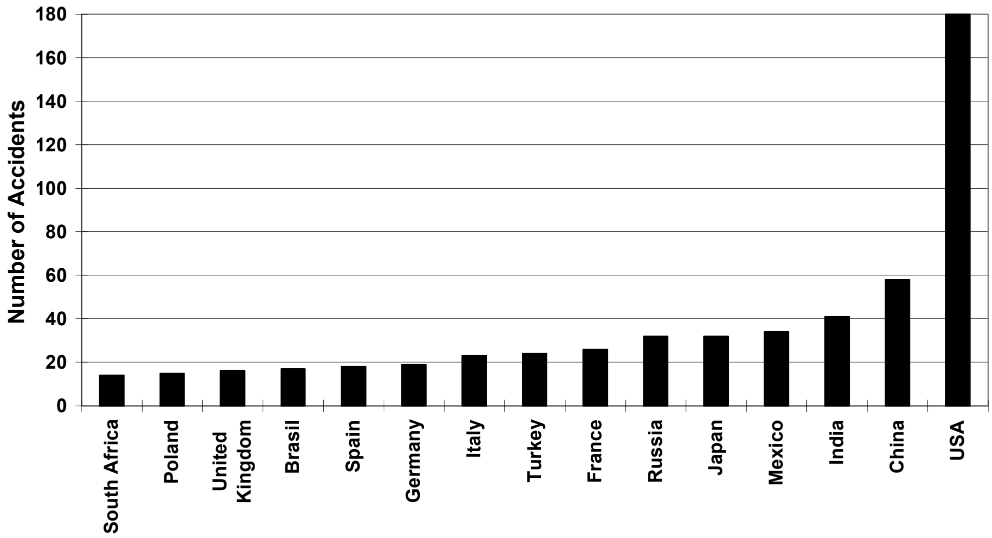

Fig. 5.4.11 Distribution by countries of energy-related severe (≥ 5 fatalities) accidents during 1945—1996, with more than 14 accidents per country.

The distribution of severe (≥ 5 fatalities) energy-related accidents by continent is shown in Fig. 5.4.12. The figure indicates that in the here considered period of time nearly 60% of all severe energy-related accidents included in ENSAD occurred in Europe and America.

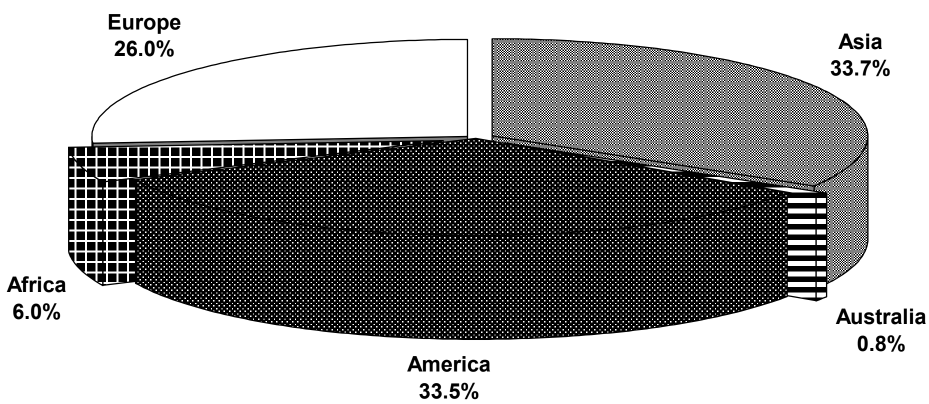

Fig. 5.4.12 Distribution by continent of severe (≥ 5 fatalities) energy-related accidents for the time-period 1945-1996.

5.4.7 Distribution of severe non-energy-related accidents by country and continent

The distribution of non-energy-related man-made severe accidents by countries, where during 1945-1996 more than 16 events occurred, is shown in Fig. 5.4.13. (The number 16 was chosen for the same reason as for Fig. 5.4.11.) The figure demonstrates that third-world countries, as well as industrialised countries, generate a substantial number of non-energy-related man-made severe (≥ 5 fatalities) accidents.

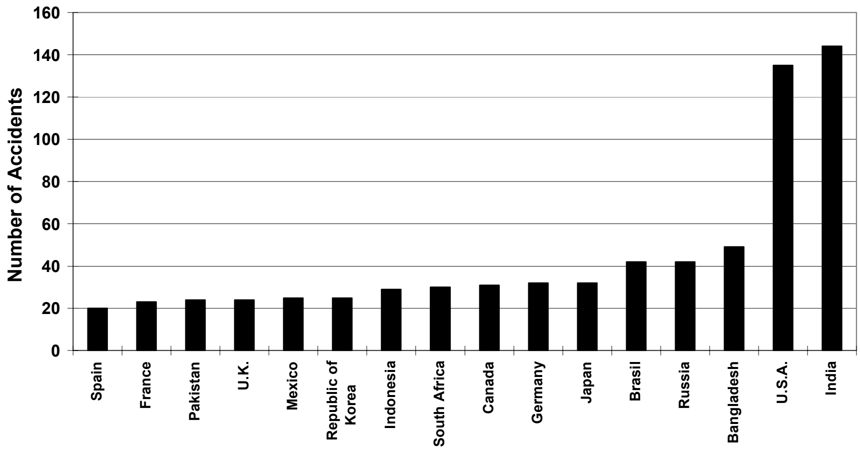

Fig. 5.4.13 Man-made, non-energy-related severe accidents (≥ 5 fatalities) during the time period 1945-1996; includes only countries with more than 16 events.

Figure 5.4.14 shows the distribution of non-energy severe (≥ 5 fatalities) accidents by countries for the time-period 1945-1996 with only countries where more than 42 events occurred being shown. (The number 42 was chosen for the same reason as above.) The figure shows that developing countries tend to have more non-energy-related accidents than developed countries. This is partially due to natural catastrophes.

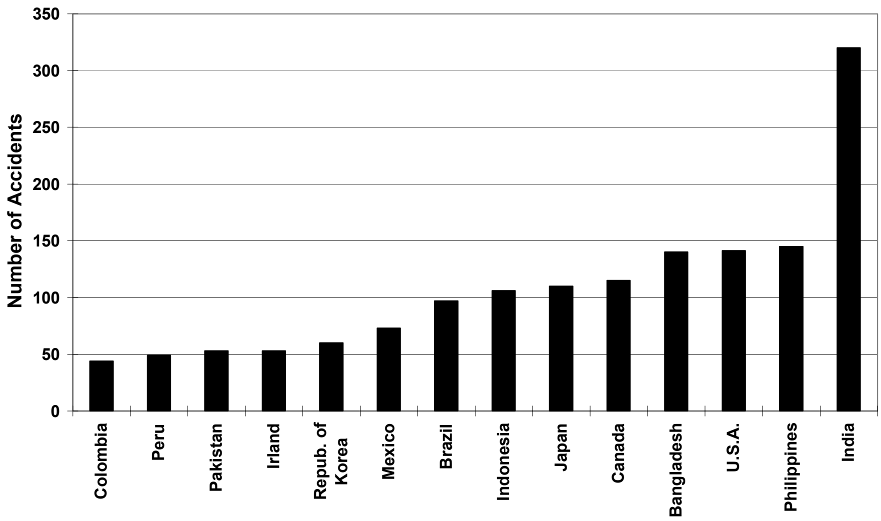

Fig. 5.4.14 Non-energy related severe (≥ 5 fatalities) accidents during the time period 1945-1996; includes only countries with more than 42 events.

Figure 5.4.15 shows the distribution by continent of non-energy-related severe (≥ 5 fatalities) accidents for 1945-1996.

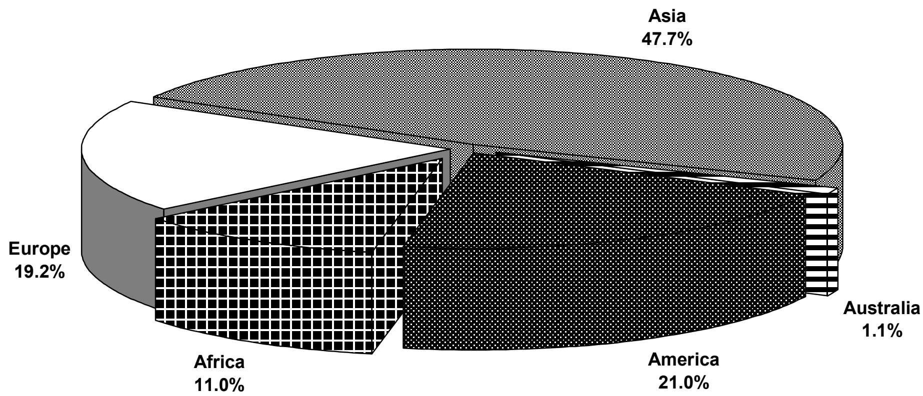

Fig. 5.4.15 Distribution by continent of non-energy-related severe (≥ 5 fatalities) accidents for the time-period 1945-1996.

Figure 5.4.15 displays that nearly half of all non-energy-related severe (≥ 5 fatalities) accidents occurred in Asia.

Figure 5.4.16 shows the distribution by continent of non-energy man-made severe (≥ 5 fatalities) accidents for the time-period 1945-1996. There is some increase of the relative share of non-energy-related man-made severe (≥ 5 fatalities) accidents for the American continent in comparison with the share of the total non-energy-related accidents in the same period, with a corresponding decrease for the Asian, African and European continent.

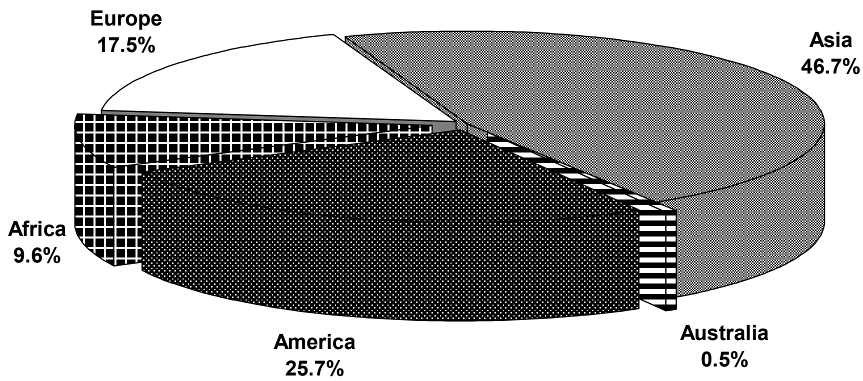

Fig. 5.4.16 Distribution by continent of non-energy-related man-made severe (≥ 5 fatalities) accidents for the time-period 1945-1996.

5.5 Comparison of ENSAD with Other Databases

Figures 5.5.1, 5.5.2 and 5.5.3 reflect the status of the PSI database ENSAD. In Fig. 5.5.1 the number of severe accidents causing X or more fatalities ≥is given for different databases. The figure demonstrates that ENSAD contains the highest number of severe (≥ 5 fatalities) man-made accidents.

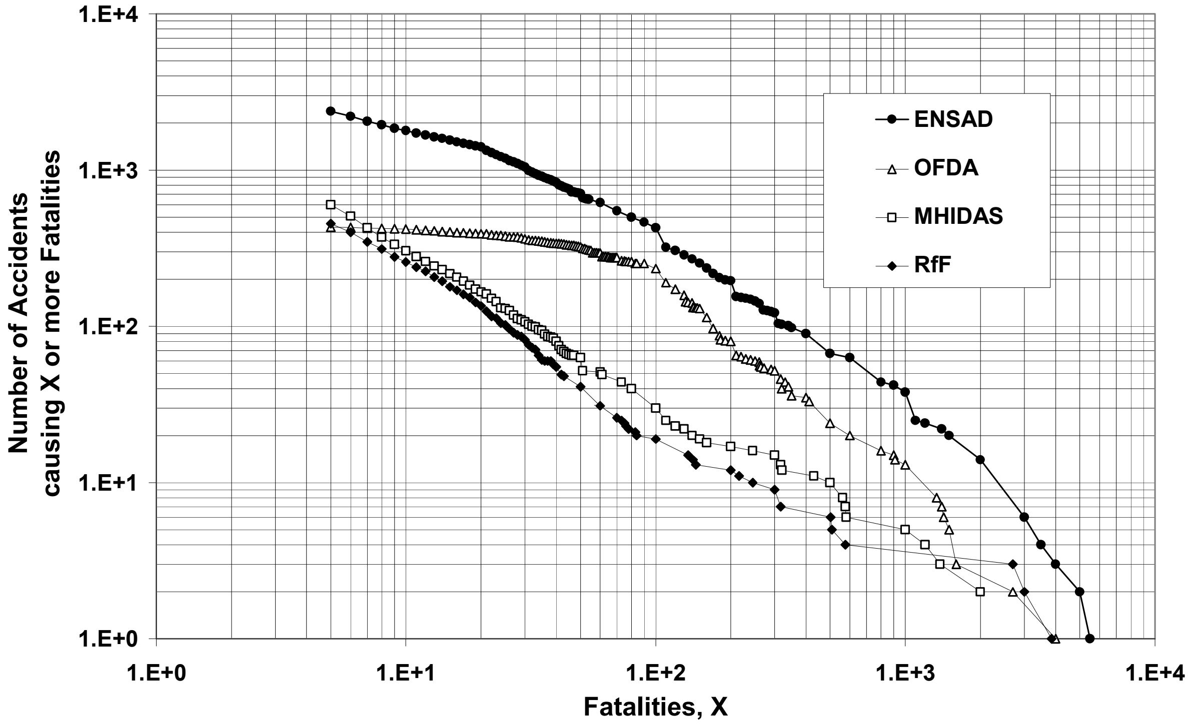

Fig. 5.5.1 Number of man-made severe (≥ 5 fatalities) accidents causing X or more fatalities according to different databases.

In Fig. 5.5.2 the number of severe energy-related accidents is plotted for ENSAD, SIGMA and MHIDAS. The figure shows that the number of such accidents stored in ENSAD widely exceeds the coverage in MHIDAS and SIGMA. It should be noted that the SIGMA database only covers the time period 1969-1996.

The distribution by continent for different databases is given in Fig. 5.5.3. The figure shows that ENSAD has a more balanced distribution by geographical area than the databases OFDA and RfF.

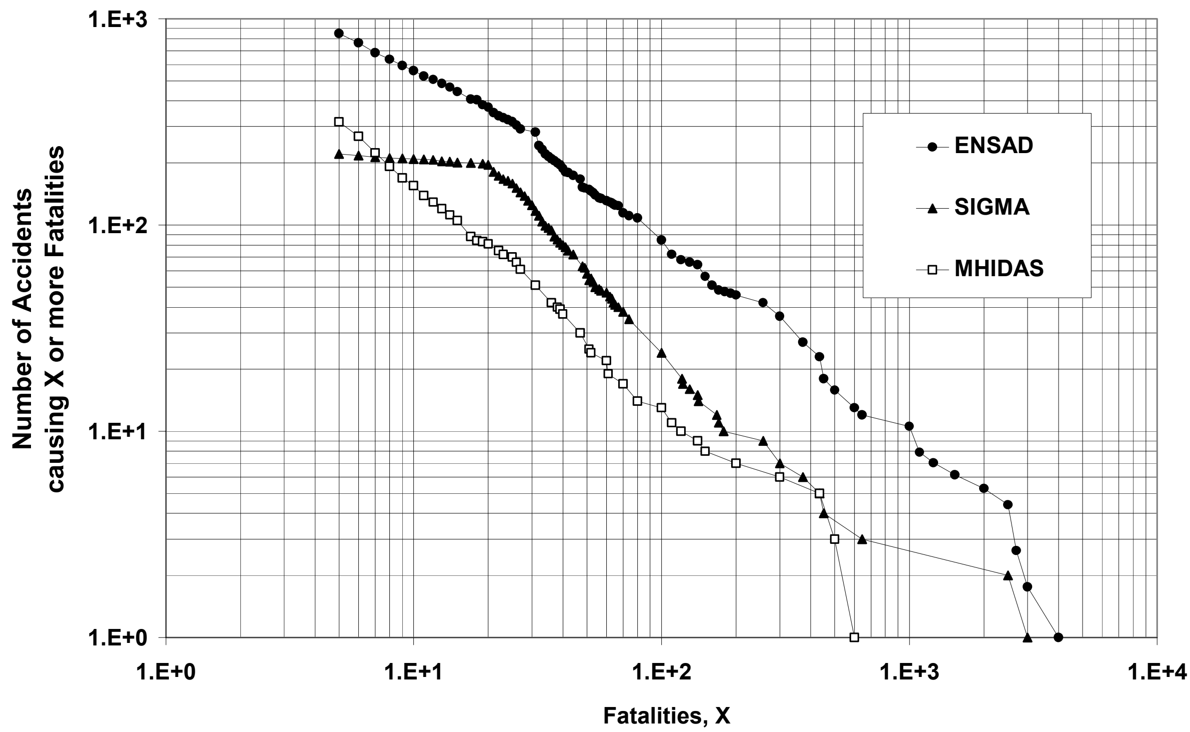

Fig. 5.5.2 Number of energy-related severe (≥ 5 fatalities) accidents causing X or more fatalities according to the databases ENSAD, SIGMA and MHIDAS.

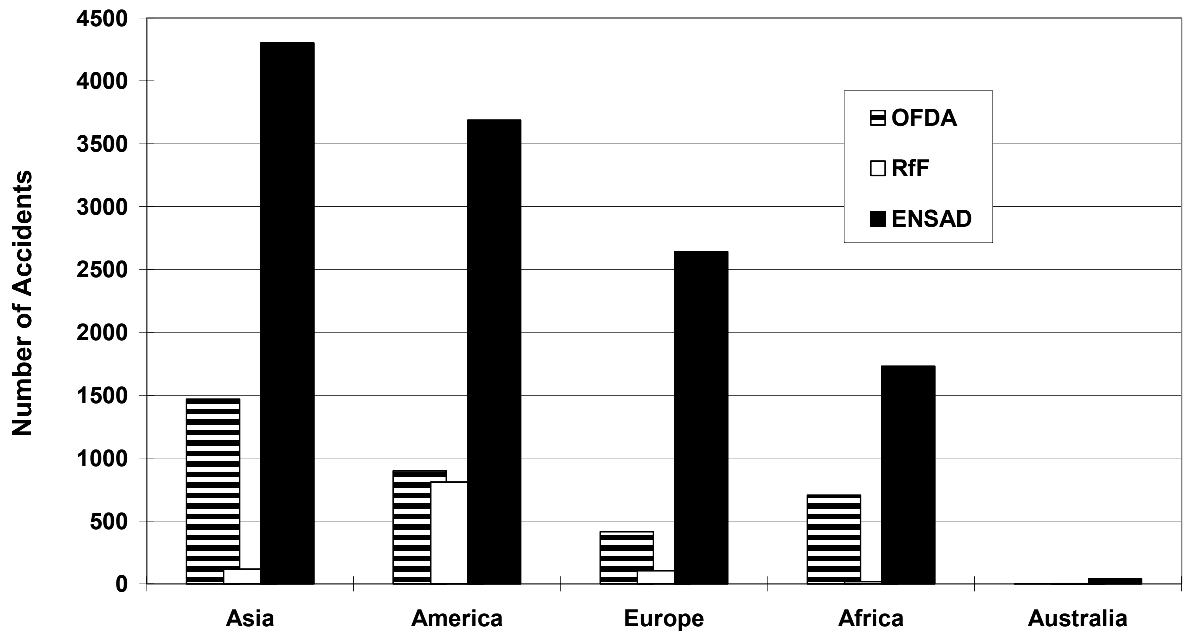

Fig. 5.5.3 Distribution of the number of accidents by continent according to different databases.

5.6 Summary

1. Data on severe accidents are coded in ENSAD using more than 50 keywords to categorise different aspects of the events.

2. The sources that provided the largest number of energy-related accidents as input to ENSAD were MHIDAS, FACTS, SIGMA, RfF and WOAD. Numerous additional sources of information were used to enhance the completeness and quality of the PSI's database.

3. Four thousand two hundred ninety energy-related accidents have been collected in ENSAD, with nearly 89.6% occurring within the time period 1969-1996.

4. Applying the definition of severe accident, established in the present work, 1943 severe energy-related accidents are stored in ENSAD. Furthermore, 846 of the energy-related accidents caused five or more fatalities per accident, with 675 of them occurring during 1969-1996.

5. Nearly one third of all man-made and natural severe accidents with five or more fatalities and nearly two thirds of all energy-related severe accidents with five or more fatalities occurred in OECD-countries.

6. Due to the use of a wide variety of information sources ENSAD enhances a balanced coverage with respect to countries and regions where the accidents took place. This resulted also in a much more extensive coverage of man-made accidents in comparison with other databases.

5.7 References

Beek, P.C. van (1994), Presentation of FACTS, A Database for Industrial Safety, held at the AC-Laboratorium in Spiez, Switzerland.

DNV (1992), World-wide Offshore Accident Databank. Det Norske Veritas Industry AS, DNV Technica, Hovik, Norway.

Encyclopaedia Britannica (1978), Book of the Year. University of Chicago.

Glickman, T. and Terry K. (1994), Using The News to Develop a World-wide Database of Hazardous Events. Center for Risk Management, Resources for the Future, Washington, D.C., USA.

IAEA (1992), Comparative Assessment of the Health and Environmental Impacts of Various Energy Systems from Severe Accidents. Proceedings of the IAEA Technical Committee Meeting, 1-3 June 1992, International Atomic Energy Agency, Vienna Austria.

Marshall, V. C. (1987), Major Chemical Hazards. Chichester: Ellis Horwood Limited.

Rowe, W. (1977), An anatomy of Risk. New York: John Wiley & Sons.

SRD (1993), The Major Hazards Incidence Data Service. AEA Technology, Consultancy Services (SRD), Cheshire, UK.

Swiss Re (1988), Sigma. Swiss Reinsurance Company, No. 1/2, January/February 1988.

Swiss Re (1994), Sigma. Swiss Reinsurance Company, No. 1/2, January/February 1994.

Swiss Re (1997), Sigma. Swiss Reinsurance Company, No. 1/2, January/February 1997.

TNO (1994), FACTS Database for Industrial Safety. Institute of Environmental Sciences, Energy Research and Process Innovation (TNO), Department of Industrial Safety, Apeldoorn, The Netherlands.

6 EVALUATIONS FOR SPECIFIC ENERGY CHAINS

6.1 Principles and Assumptions for Evaluation

6.1.1 Energy chain stages

The risks to the public and the environment, associated with various energy systems, arise not only within the power plant stage of the energy production. Investigations of past accidents show that accidents occur at all stages of energy chains. The stages can be categorised as: exploration, extraction, long-distance, regional and local transport, storage, power generation, heating systems, transmission, local distribution, waste treatment and waste disposal. Note that not all these stages are applicable for all energy systems. In Table 6.1.1 an overview of distinct stages for the coal, oil, gas, nuclear and hydro chains is given.

TABLE 6.1.1

Stages of different energy chains.

Stage of Energy Chain	Energy Carriers								
	Coal		Oil		Natural Gas		LPG	Nuclear	Hydro
Exploration	Exploration		Exploration		Exploration		--	Exploration	
Extraction	Mining and Coal Preparation		Extraction		Extraction and Processing		--	Mining / Milling	
Transport	Transport to Conversion Plant		Transport to Refinery		Long Distance Transport (pipeline)		--	Transport	
Processing	Conversion Plant		Refinery				• Refinery • Natural gas processing Plant	Upstream Processing [a]	
Transport	Transport		Regional Distribution		Distribution: • Long Dist. • Regional • Local		Distribution : • Long Dist. • Regional • Local	Transport [b]	
Power / Heat Generation	Power Plant	Heating Plant	Power Plant	Heating Plant	Power Plant	Heating Plant	Heating Plant	Power Plant	Power Plant
Transport								Transport to Reprocessing Plant	
Processing								Reprocessing	
Waste Treatment	Waste Treatment							Waste Treatment	
Waste Disposal	Waste Disposal							Waste Disposal	

[a] Includes: Conversion, Enrichment, Fuel Fabrication.

[b] Includes transports between the processing stages mentioned in note a.

Severe accidents attributable to raw materials and production of parts used in energy-systems (turbines, boilers, reactors) [Frischknecht et al., 1996; Dones et al., 1996], are beyond the scope of this work.

6.1.2 LPG chain

Liquefied Petroleum Gas (LPG) chain is treated in this report as a separate energy chain although LPG is derived by refinery processes and natural gas processing plants. There are several reasons why the LPG chain is treated as an independent chain and not covered as a part of the oil chain. First, LPG is a highly hazardous substance. Large amounts of LPG represent a considerable potential danger to people, to a higher extent than any other substances derived from crude oil. An evaluation of 1000 accidents involving chemical substances showed that LPG accidents constitute 9.5% of all accidents, i.e. the dominant contributor [Bützer, 1985]. Among the world largest industrial accidents two involved LPG (Section 6.4.4). Second, the handling of LPG requires, in comparison to other products of crude oil, particularly high safety standards with special means of transport because it is flammable and asphyiant [Gerhartz and Elvers, eds., 1990].

6.1.3 Allocation of damages to energy and non-energy uses of energy carriers

Normally an energy carrier passes through several stages before it is transformed into saleable products with defined characteristics. The new products can be used for the generation of energy but can also find application in non-energy uses. Figure 6.1.1 gives an example for the coal chain [Gerhartz, ed., 1986].

When coal leaves the mine it passes different conversion processes (combustion, gasification, liquefaction, etc.) before it reaches energy end users (electric power, heat, heating gas, automotive fuels, etc.) and non-energy end users (reducing gas, chemicals, etc.). The question which arises is as follows: Is the share of the consequences (e.g. fatalities, injured, costs, etc.), which are associated with the non-energy uses of coal and oil, so significant that this needs to be taken into account in the allocation procedure?

For the allocation of consequences to energy and non-energy uses of coal and oil the matter can be easily resolved. Figures 6.1.2 and 6.1.3 show the share of coal and oil products during the time-period 1971-1996 for OECD and Non-OECD countries.

Figure 6.1.2 displays that the non-energy use of coal does not exceed 1.2% while according to Fig. 6.1.3 the corresponding share for oil is less than 8%. Therefore, it is a reasonable approximation for the purpose of this work to treat all oil and coal accidents as energy-related ones. Thus, the accidents at the stages before and at the refinery for oil (respectively treatment plant for coal, if any) can be fully allocated to the energy sector.

In the case of natural gas the end use is practically limited to heating and power generation. Here again all accidents are allocated to energy end uses.

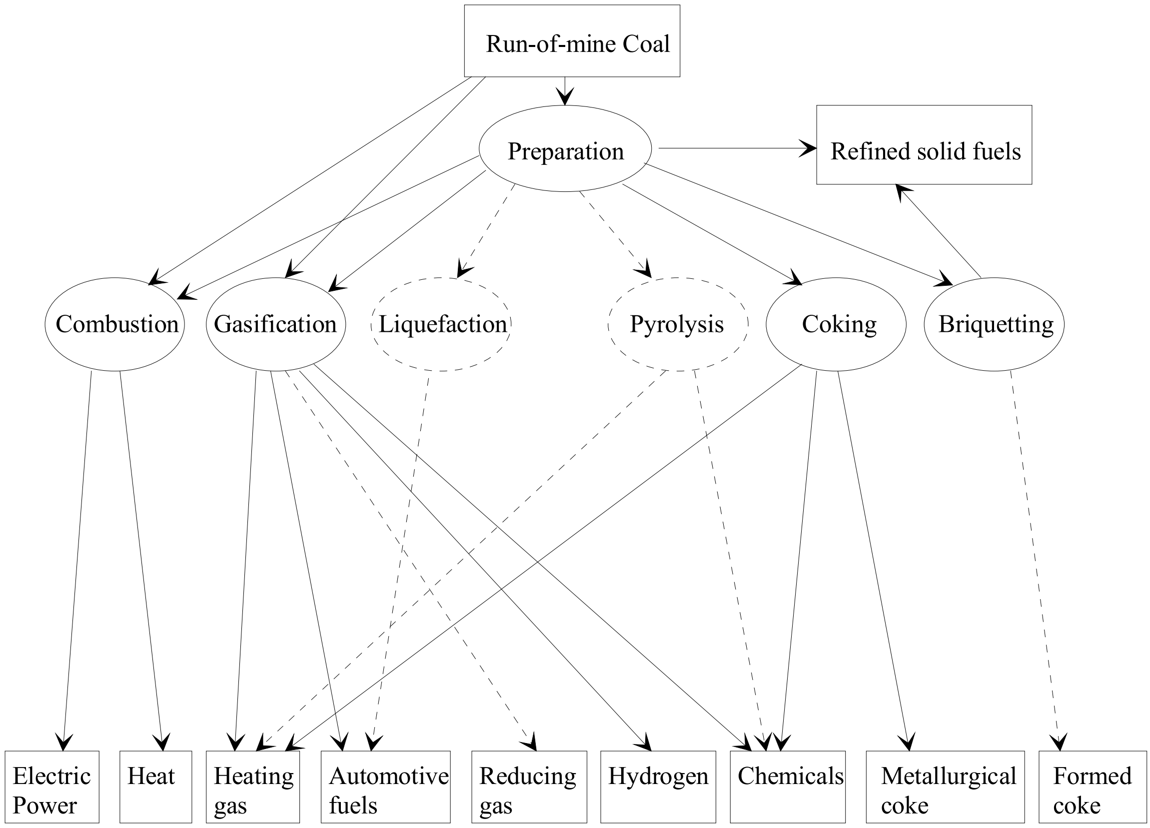

Fig. 6.1.1 Coal conversion processes and end uses.

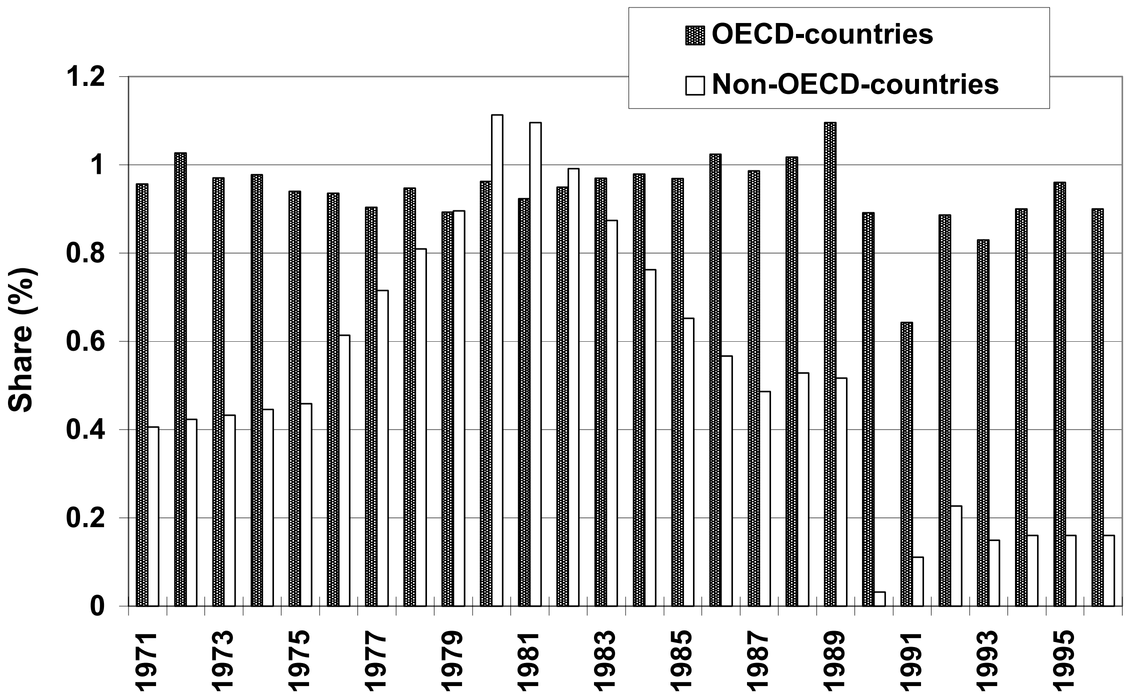

Fig. 6.1.2 Share of coal-products in non-energy applications.

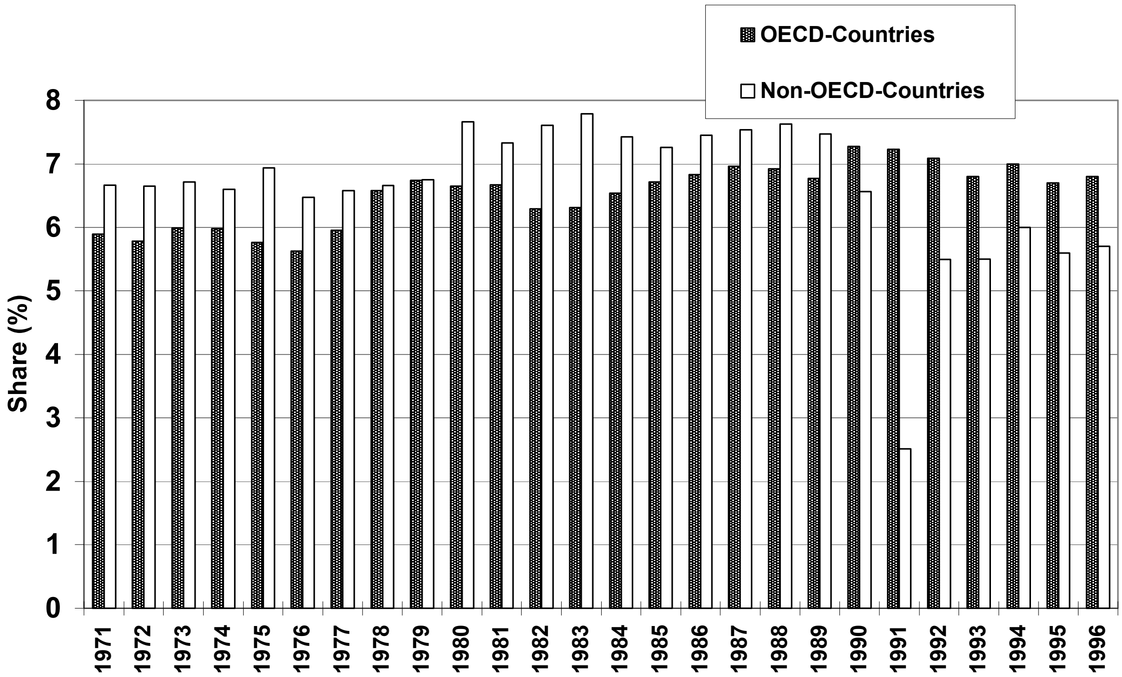

Fig. 6.1.3 Share of oil-products in non-energy applications.

LPG provides a clean fuel for cooking, heating and automobiles. LPG is also used in refining and in petroleum industries to increase the volatility and octane number of the fuel. A non-energy end application of LPG is the use as a chemical feedstock in the production of intermediates for polymers. The quantities involved are not significant. Therefore, all accidents which occurred in the LPG chain were allocated to energy uses.

In the case of nuclear and hydro chains the allocation problem mentioned above does not arise at all.

6.1.4 Allocation of damages to countries exporting or importing energy carriers

In Chapter 9 aggregated, normalised, energy-related severe accident records are compared. In this context distinction is made between OECD and non-OECD countries[1]. OECD countries import from non-OECD countries a large fraction of their total consumption of crude oil and LPG, a small fraction of natural gas and a negligible fraction of coal. Fig. 6.1.4 shows that in OECD countries the imports are higher than the indigenous production of oil for the time period 1969-1996. The net import from non-OECD countries is also relatively high for LPG but negligible for hydro and nuclear power.

[1] Few countries currently being members of OECD were for the purpose of this report not included among OECD countries. The most essential comparative evaluations included in this report are based on the statistical material covering a period of nearly 30 years and stretching until the end of 1996. For this reason countries which acceded OECD between 1994 and 1996, i.e. Mexico, Czech Republic, Hungary, Poland and Republic of Korea are here not included among the OECD countries.

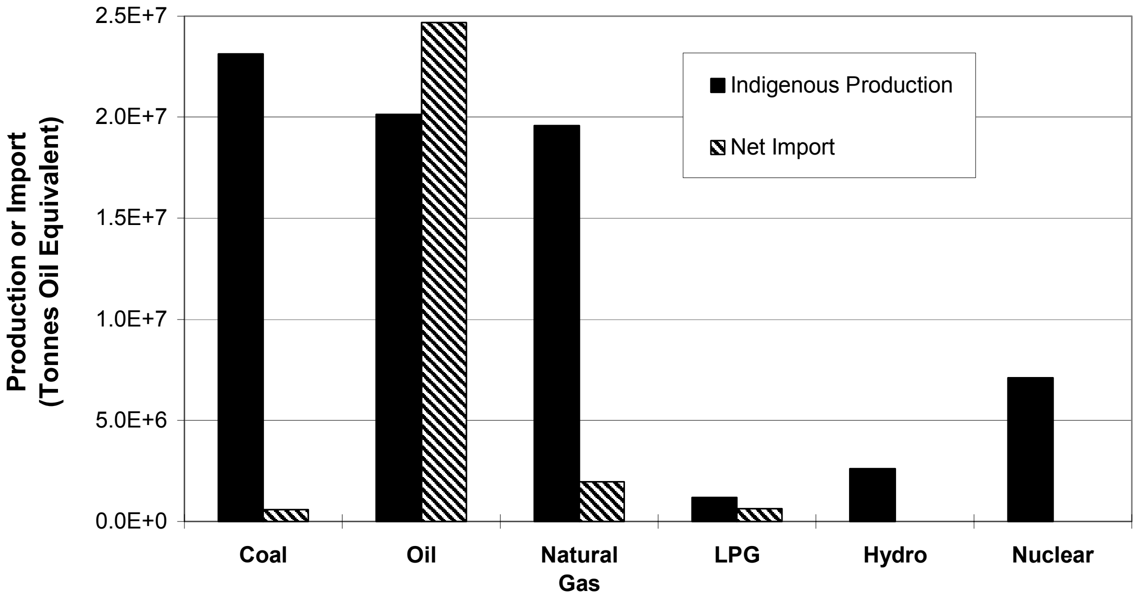

Fig. 6.1.4 Indigenous production and net import of different energy carriers in OECD-countries in the time period 1969-1996.

A difficulty which arises in comparative studies with aggregated normalised severe accident records is that a large number of severe accidents occurs in non-OECD countries at stages in the energy chain relevant for the export to OECD countries. In the case of the oil chain the stages are: “Exploration”, “Extraction”, “Transport to the Refinery” (see Section 6.3.2); “Exploration”, “Extraction”, “Long Distance Transport” for natural gas (see Section 6.4.1); and in the case of the LPG chain the stage “Refinery” and “Natural Gas Processing Plant” (see Section 6.4.1). An appropriate share of the consequences of accidents that occurred at these stages in non-OECD countries should be added to the damages which physically occurred in OECD countries, considering the net amounts of energy carriers imported to OECD countries from non-OECD countries. The consequences of accidents that occurred in non-OECD countries were allocated to the consequences in OECD countries according the following formula, which is a linear function of the amounts of imported energy carriers from non-OECD countries:

$$\overline{C}_{OECD}(i) = C_{OECD}(i) + C_{non-OECD}(i) * \frac{I_{non-OECD}(i)}{P_{non-OECD}(i)} \qquad (6.1.1)$$

where:

$\overline{C}_{OECD}(i)$: consequence indicator such as total number of fatalities, injured or evacuees in a time period (A, B) to be allocated to OECD countries for an energy carrier i (i = oil, natural gas or LPG) considering the imports from non-OECD countries;

$C_{OECD}(i)$: consequence indicator such as number of fatalities, injured or evacuees in a time period (A, B) physically occurring in OECD countries for energy carrier i (i = oil, natural gas or LPG);

$C_{non-OECD}(i)$: consequence indicator such as number of fatalities, injured or evacuees in a time period (A, B) in non-OECD countries, occurred at the stages: “Exploration”, “Extraction”, or “Transport to the Refinery” for oil; “Exploration”, “Extraction” or “Long Distance Transport” for natural gas; and “Refinery”, “Natural Gas Processing Plant” or “Long Distance Transport” for LPG;

$I_{non-OECD}(i)$: imported amount of an energy carrier i (i = oil, natural gas or LPG) to OECD countries from non-OECD countries in time period (A, B);

$P_{non-OECD}(i)$: produced amount of an energy carrier i (i = oil, natural gas or LPG) in non-OECD countries in time period (A, B);

The total damages for non-OECD countries are then:

$$\overline{C}_{non-OECD}(i) = C_{non-OECD}(i) - C_{non-OECD}(i) * \frac{I_{non-OECD}(i)}{P_{non-OECD}(i)} = C_{non-OECD} * (1 - \frac{I_{non-OECD}(i)}{P_{non-OECD}(i)}) \tag{6.1.2}$$

The normalised damage rate (in terms of fatalities, injured or evacuees) per unit of consumed energy is then for OECD-countries:

$$R_{OECD}(i) = \frac{\overline{C}_{OECD}(i)}{F_{OECD}} \tag{6.1.3}$$

where:

$F_{OECD}(i)$: consumed amount of energy carrier i (i = oil, natural gas or LPG) in OECD countries in the time period (A, B);

and for non-OECD-countries:

$$R_{non-OECD} = \frac{\overline{C}_{non-OECD}}{F_{non-OECD}} = \frac{C_{non-OECD} * (1 - \frac{I_{non-OECD}(i)}{P_{non-OECD}(i)})}{(P_{non-OECD} - I_{non-OECD})} = \frac{C_{non-OECD}}{P_{non-OECD}} \tag{6.1.4}$$

where:

$F_{non-OECD}$: consumed amount of energy carrier i (oil, natural gas or LPG) in non-OECD countries in the time period (A, B).

6.1.5 References

Bützer, P. (1985), Zwischenfälle mit chemischen Stoffen - eine statistische Auswertung, Chem. Labor. Betr., 235.

Dones, R., Gantner, U., Hirschberg, S., Doka, G. and Knoepfel, I. (1996), Environmental Inventories for Future Electricity Supply Systems for Switzerland. PSI Report Nr. 96-07, Paul Scherrer Institute, Würenlingen and Villigen, Switzerland, February 1996.

Frischknecht R. (Ed.) et al. (1996), Ökoinventare von Energiesystemen - Grundlagen für den ökologischen Vergleich von Energiesystemen und den Einbezug von Energiesystemen in Ökobilanzen für die Schweiz. 3rd Ed. (in German), Swiss Federal Institute of Technology Zurich (ETHZ) / Paul Scherrer Institute (PSI), Zurich, Switzerland, July 1996.

Gerhartz, W., ed. (1986), Ullmann's Encyclopaedia of Industrial Chemistry, Vol. A7. 5th Ed., VCH Verlagsgesellschaft mbH, Weinheim, Germany.

Gerhartz, W. and Elvers, B., ed. (1990), Ullmann's Encyclopaedia of Industrial Chemistry, Vol. A15. 5th Ed., VCH Verlagsgesellschaft mbH, Weinheim, Germany.

6.2 Coal Chain

6.2.1 Trends in severe accidents in the coal chain

Figure 6.2.1 shows that the number of severe (≥ 5 fatalities) accidents slightly decreased in OECD- and increased in non-OECD-countries in the last two decades. The former trend may be due to an improvement of safety regulations in OECD-countries. The latter trend may be due to the improved reporting coverage in non-OECD countries.

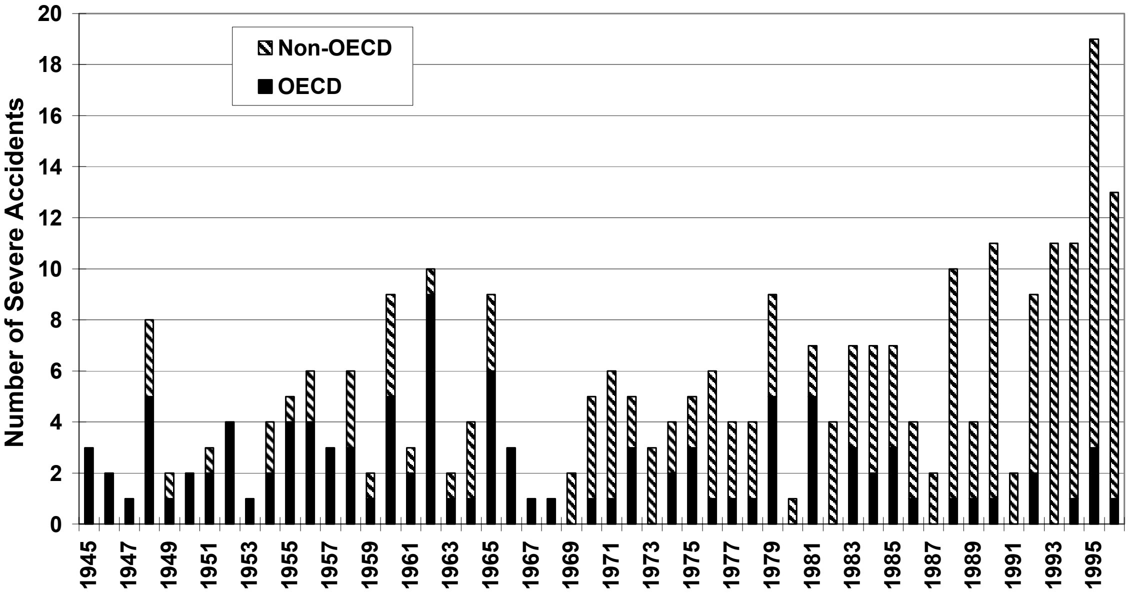

Fig. 6.2.1 Number of severe (≥ 5 fatalities) accidents in the coal chain in OECD- and non-OECD-countries.

The decrease of the number of severe (≥ 5 fatalities) accidents in OECD-countries cannot be explained by a reduced coal production. On the contrary: in the last 20 years the total coal production increased continuously (Fig. 6.2.2) although some countries reduced their coal output and the number of employed people in the coal industry (e.g. the UK).

The reasons for the decrease of the fatality rates in OECD-countries are manifold and depend on the specific country. An overview of the fatalities which occurred in the UK mining industry in relation to the number of employees in the coal sector is given in Table 6.2.1 [Clifton, 1992].

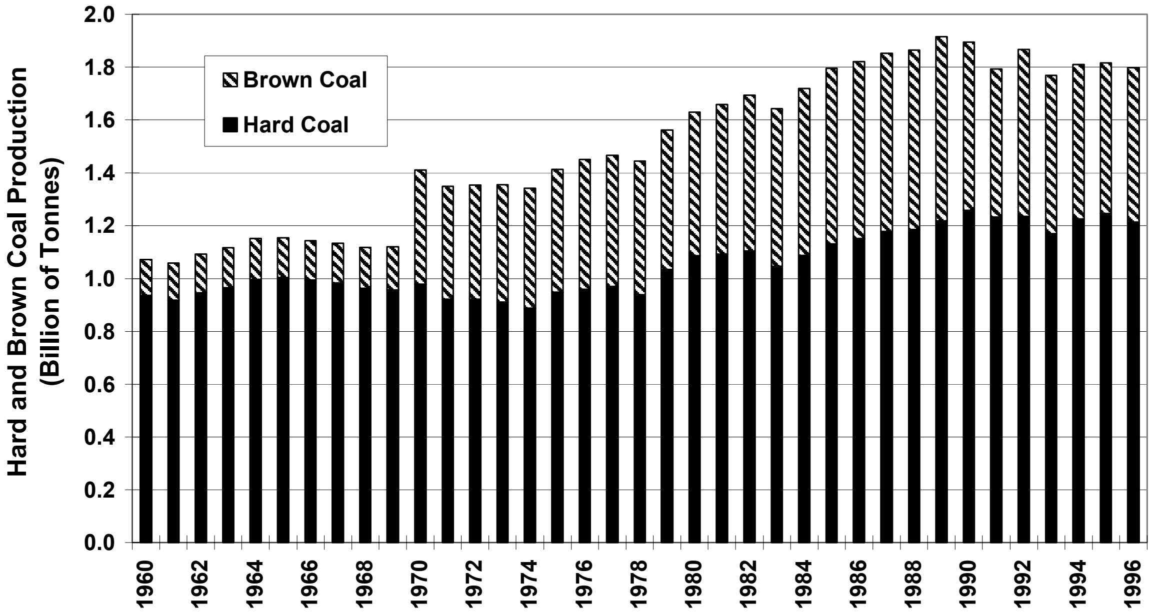

Fig. 6.2.2 Coal production in OECD-countries for the time period 1960-1996.

TABLE 6.2.1
Number of fatal accidents in relation to the number of employees by years for UK coal mines [Clifton, 1992].

Year	Thousands employed	Number of fatal accidents	Number of fatal accidents per employed
1932/33	770	877	$1.0\ 10^{-3}$
1946/47	729	618	$8.3\ 10^{-4}$
1956/57	734	396	$5.4\ 10^{-4}$
1966/67	445	151	$3.4\ 10^{-4}$
1975/76	255	50	$2.0\ 10^{-4}$
1985/86	155	28	$1.7\ 10^{-4}$
1986/87	125	15	$1.1\ 10^{-4}$
1987/88	104	9	$8.7\ 10^{-5}$
1988/89	87	18	$1.9\ 10^{-4}$
1989/90	70	18	$2.6\ 10^{-4}$

The table shows that in the last 60 years the number of employees decreased by a factor of 11 but the number of fatal accidents decreased by a factor of about 50. The fatality rate in the last column of the table decreases with increasing number of years with the exception of the years 1988/89 and 1989/90. In the UK the legislation has had a major impact on the reduction of the fatality rates along with research findings on gas and coal-dust explosions, fires and inundations; other reasons for the decrease of the fatality rates were mechanisation, use of powered supports, the employment of steel roadway-supports, training and safety programmes [Clifton, 1992; NMHSA, 1993], but also closure of old unsafe mines [Fritzsche, (1996)].

Table 6.2.2 shows the number of fatalities and the production by years for US coal mines [Coleman, 1995]. The table demonstrates how the production was increased in the last 30 years by a factor of 2.4 and the number of fatal injuries was reduced due to the impact of safety regulations by a factor of about 5. In the last column of Table 6.2.2 the fatality rate per produced tonne is given. This shows how the rate could be steadily reduced over a period of 30 years.

TABLE 6.2.2

Number of fatalities and production by years for US coal mines.

Year	Production (million tonnes)	Number of fatal accidents	Number of fatal accidents per produced tonne
1960	393.9	325	0.7
1970	555.6	260	0.5
1980	751.5	133	0.2
1990	933.3	66	0.1

For non-OECD countries the situation is different. In this case the production has increased in the last 20 years by a factor of almost 2 (Fig. 6.2.3); this increase is larger than in OECD-countries. At the same time the number of severe accidents has not been reduced.

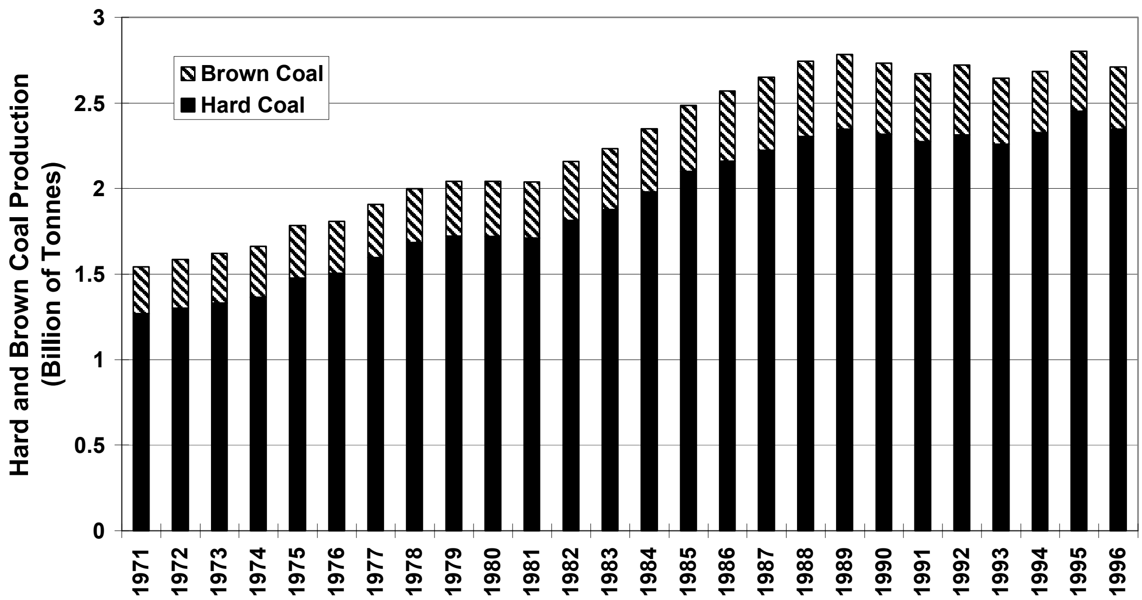

Fig. 6.2.3 Coal production for non-OECD-countries for the time period 1971-1996.

The number of fatalities due to severe accidents in non-OECD and OECD countries is given in Fig. 6.2.4. The figure shows a peak in the year 1952 when some 4000 people died of the smog in London in December 1952 due to a mixture of sulphur dioxide and coal smoke. In terms of consequences and their manifestation in time this smog catastrophe can be regarded as a severe accident. Nevertheless, one has to assure that this type of events is not double-counted by accounting for it also in the analysis of the impacts of "normal" operation. Furthermore, such extreme smog situations are currently not representative although on a smaller scale their occurrence in less developed countries cannot be excluded. Figure 6.2.4 also demonstrates that after 1965 most fatalities occurred in the coal industry of non-OECD countries.

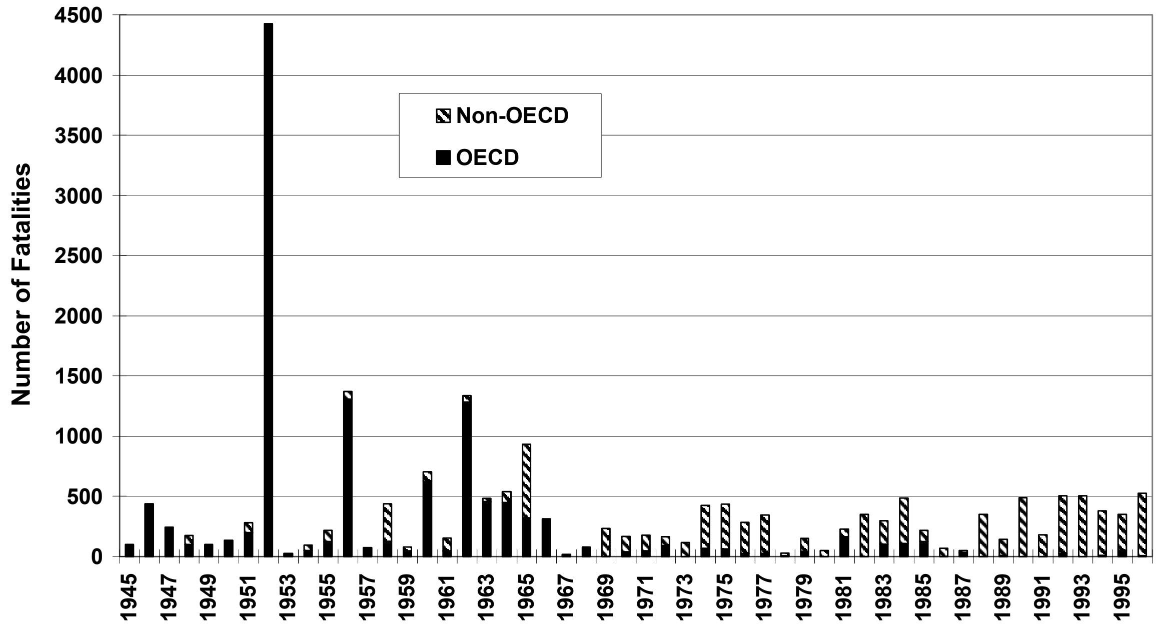

Fig. 6.2.4 Number of fatalities due to severe (≥ 5 fatalities) accidents for the coal chain in OECD- and non-OECD-countries.

A comprehensive list of severe (≥ 5 fatalities) coal accidents collected in ENSAD is given in Appendix A. In the case of coal accidents the number of injured or economic losses associated with accidents were seldom available. The number of evacuees is in most cases practically zero. For this reason no information on evacuees is provided in the list in Appendix A.

6.2.2 Breakdown into coal chain stages

6.2.2.1 The "Exploration" and "Extraction" stages

During the exploration stage no severe accidents have been recorded. However, the total number of workers killed during the extraction stage is enormous. Records show that since

1850 over 100,000 people have been killed in the extraction stage in the UK only, as a direct result of accidents. According to recent reports in 1997 more than 10,000 workers were killed in China's coal mining industry despite of a series of government directives on occupational safety [Occupational Safety and Health Reporter, 1998]. Miners who died as a result of contracting pneumoconiosis due to the dust in coal mines are not included in this number. In Table 6.2.3 the worst accidents in coal mining are given.

TABLE 6.2.3

Some large severe accidents in coal mining.

Date	Name of colliery	Location	Number of fatalities	Number of employed people underground	Causes
12.2.1931	Fushun	Manchuria	3000	Not known	-
26.4.1942	Honkeiko	Manchuria	1527	4400	Poisoning by CO and ignitions of coal dust and methane
10.3.1906	Courrieres	Pas de Calais/France	1099	7594	Coal dust explosion
10.6.1895	Upper Silesia	Not available	550	Not known	-
9.11.1963	Mikawa	Japan	458	2080	Poisoning by CO and coal dust explosion
6.6.1972	Wankie Colliery	Rhodesia	427	Not known	Three gas explosions
7.2.1962	Luisenthal	Saar coal basin	299	Not known	Ignition of methane
3.3.1992	Turkey	Kozlu	272	Not known	Methane explosion
16.7.1984	Mei Shan	Taiwan	121	Not known	Fire in coal mine

6.2.2.2 The "Transport" stage

Accidents in the transport stage within the coal chain are rare. The worst accident occurred on February 12th 1983 and involved a coal freighter carrying 27,000 tonnes of coal; the freighter capsized and sank in storm-battered seas off the coast of Chincoteague Virginia, USA. Only three of the 36 crewmen aboard survived.

6.2.2.3 The "Conversion Plant" stage

Crude coal extracted from the mine is practically useless until it is processed. It contains various types of accompanying minerals and interstrafications which must be removed to obtain coal that complies with market demands. Only a small part of the prepared coal is directly used for heating. The largest part of coal is refined by means of thermal processes to higher valued energy carriers or coal products. The coal conversion processes may be divided into three groups: first, mechanical conversion processes include coal preparation and briquetting; second, processes for transforming coal into secondary fuels include coking, gasification, liquefaction and combustion; and third, processes for the conversion of coal for purposes other than the generation of fuels (e.g. coal tar for chemical industry and production of activated carbon [Gerhartz and Elvers, 1990].

Accidents in the processing stage rarely result in multiple fatalities. The worst recorded severe accident in terms of economic losses occurred in the UK on July 13th 1983 when a fire damaged a coal process plant. The monetary loss was 12 million pounds.

6.2.2.4 The "Heating" & "Power Station" stage

One of the worst disasters in the "Heating" or "Power Station" stage was the smog catastrophe in London in December of 1952. A warm air mass covered the city. Under this mass there was a cold layer of air containing an exceptionally great concentration of sulphur dioxide and coal smoke. More than 4000 people died of the smog and eventually another 8000 persons from its prolonged effects [Nash, 1976]. There were other episodes originating from coal-fired power stations and coal-burning devices which caused severe harm to public under adverse weather conditions. Table 6.2.4 gives an overview of the worst past accidents [ACNS, 1989].

TABLE 6.2.4

Worst catastrophes caused by coal-burning devices and coal-fired power plants emissions under adverse weather conditions.

Date	Location	Fatalities
1930	Meuse Valley, Belgium	60
1948	Donora, Pennsylvania, USA	17
1952	New York	≈360
1952	London	≈4000
1956	London	≈1000
1962	London	≈850
1962	Osaka	≈60
1966	New York	168

Severe air pollution catastrophes of this type have not occurred in industrialised countries since 1966 due to more strict emission and air pollution regulations [ACNS, 1989].

In the stage “Power Station” only two severe accidents with large number of fatalities are known. One occurred in former Democratic Republic of Germany in May 1948 when coal dust was ignited. An explosion killed 50 and injured 76 people. The other accident, an explosion that caused 45 fatalities, occurred in Shandong, in China on July 13th 1990. In Table 6.2.5 the economic consequences of some accidents in coal power plants are listed. These costs are in Table 6.2.5 also expressed in 1996 US$, used in this report for most of the cited monetary losses in order to facilitate comparisons.

Table 6.2.5

Some accidents in the stage “Power Station” with large monetary losses.

Location	**Date**	**Monetary loss**		**Causes**
		million US$	**million 1996 US$**	
USA	4.1.1975	11.5	29.4	Fire and mechanical damage
USA	17.1.1975	11.3	28.8	Fire in an air heater
USA	21.11.1976	21.3	52.0	Fire in coal conveyor
USA	07.07.1977	45.0	103.5	Computer problem
USA	14.10.1980	27.0	48.8	Explosion and fire
USA	28.07.1986	24.6	33.4	Tornado

6.2.2.5 “Waste storage and disposal” stages

Coal refuse is a waste material generated in the mining and preparation of coal. Substantial quantities of coal refuse are produced every year (roughly 150 million tonnes per year in the USA). The effective disposal of this material presents an increasingly important problem for the coal industry in terms of safety, economics and environmental acceptability [Usmen and Cheng, 1987]. One of the worst accidents at the disposal stage occurred on February 2nd 1972 at the Buffalo Creek (Tailings) Dam in West Virginia. The dam failure caused a flood that killed 125 people. The embankment which consisted of a pile of coal mine waste lacked the features of an engineered dam [Jansen, 1983]. Heavy rains made the water level rise. The water level was 0.3 meters below the crest before the dam collapsed. A flood wave estimated as high as 6 meters moved down the Buffalo Creek valley.

Very often coal waste is piled into huge slag tips. Parts of these tips can slip down the mountains and destroy villages [Clifton, 1992]. A large accident at the waste storage stage occurred in Aberfan in South Wales on September 21st 1966. The accident caused 144 fatalities due to a slag tip which slid down a slope and destroyed a primary school

[Bignell and Peters, 1977]. Tip slides are not new phenomena. Although not frequent they have happened throughout the world and particularly in South Wales [Kletz, 1993]. Another disaster at the waste storage stage occurred in 1982 when an avalanche of coal waste engulfed 284 workers in China.

6.2.3 Causes of coal accidents

An evaluation of severe (≥ 5 fatalities) coal accidents showed that the most frequent reason for severe accidents during the extraction stage was explosion of methane in mines. In non-OECD countries nearly every third severe accident during the extraction stage is a gas explosion in a coal mine (Fig. 6.2.5).

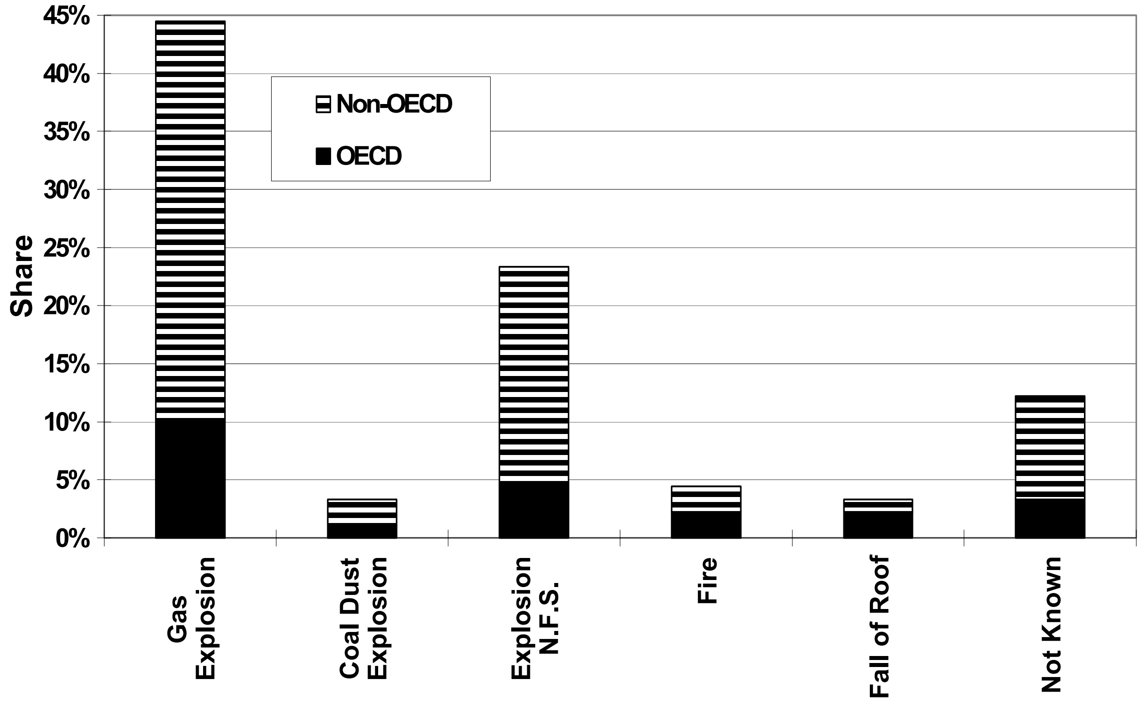

Fig. 6.2.5 Causes of severe (≥ 5 fatalities) accidents in the period 1969-1996 in OECD and non-OECD countries (N.F.S. means no further specification).

For US mines gas explosions play a secondary role in causing accidents with fatalities (Fig. 6.2.6) in underground mining due to improved ventilation safety regulations in US coal mines. For comparison the causes for surface mining fatal accidents are given in Fig. 6.2.7.

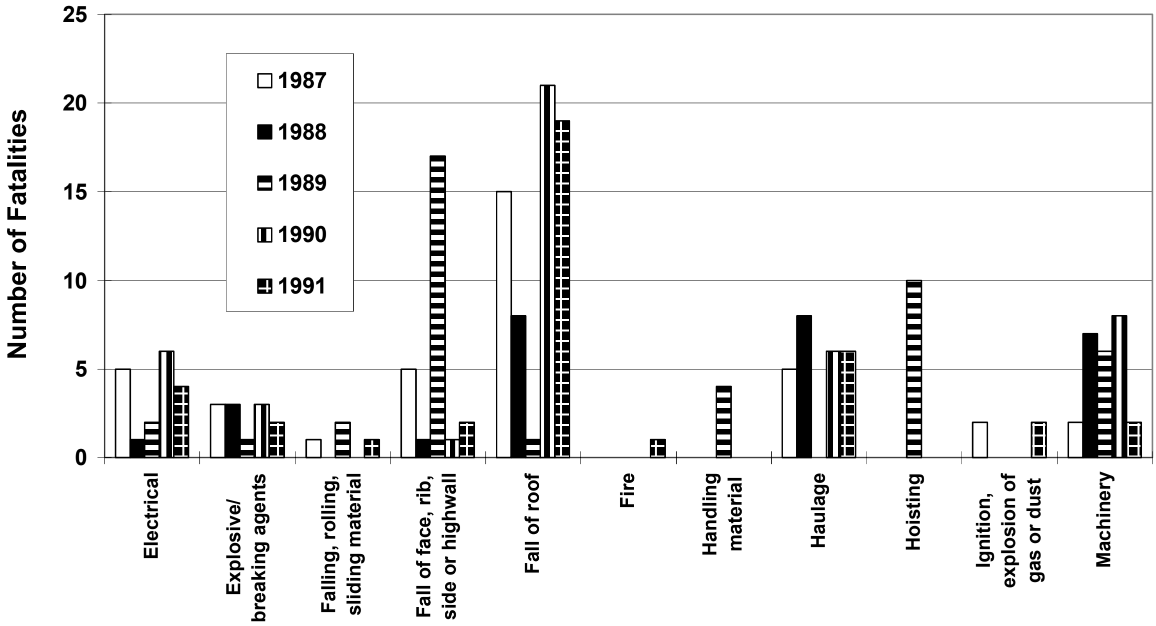

Fig. 6.2.6 Fatal US accidents in underground mining (1987-1991) and their causes [Coleman, 1992].

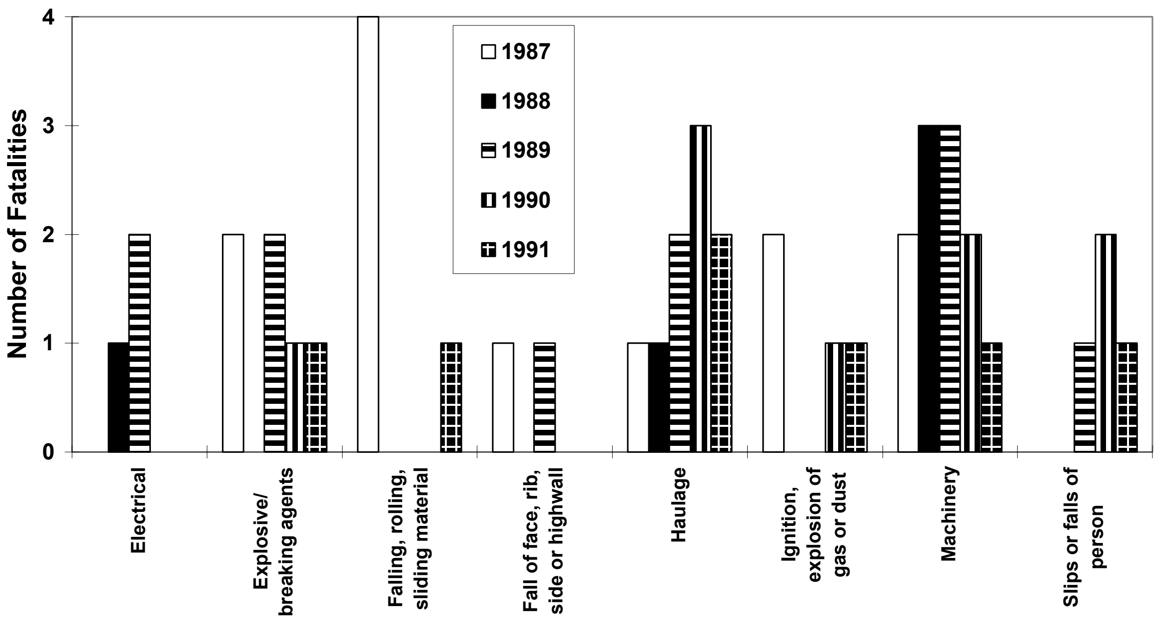

Fig. 6.2.7 Fatal US accidents in surface mining (1987-1991) and their causes [Coleman, 1992].

6.2.4 Some highlights

1. The overall number of severe (≥ 5 fatalities) accidents decreased slightly in OECD-countries in the last two decades as opposed to non-OECD countries.

2. The number of fatalities in OECD countries decreased significantly. While the coal production was increased there has been a simultaneous reduction of severe accidents due to legislation, research findings concerning the prevention of gas and coal-dust explosions, fires and inundations, as well as closure of old unsafe mines

3. The stage with by far most fatalities is “Extraction”. The “Heating Plant” and “Power Plant” stages are currently relatively small contributors to severe accidents. In the industrialised world some smog catastrophes which have features of severe accidents occurred in the 50s and 60s and have not been repeated since.

4. The main cause for world-wide severe (≥ 5 fatalities) coal accidents are methane gas explosions in underground mining. Their relative contribution in OECD-countries is, however, three times lower than in non-OECD countries.

6.2.5 References

ACNS (1989), Alternative Electrical Energy Systems - A comparison of the Risks of Occupational and Public Fatalities. ACNS-10, Advisory Committee on Nuclear Safety, Ottawa, Canada.

Bignell, V. and Peters, G. (1977), Catastrophic Failures. New York: The Open University Press, Milton Keynes.

Clifton, J. J. (1992), The Historical Record of Major Accidents in the Energy Industries. Applied Energy **42** (1992) 17-32.

Coleman, L. (1992), Coal Data 1992. The National Coal Association, Washington D.C., USA.

Coleman, L. (1995), (Director Statistical Services, National Mining Association, Washington D.C., USA). Personal communication by fax.

Fritzsche A. (1996). Personal communication.

Gerhartz, W. and Elvers, B., eds. (1990), Ullmann’s Encyclopaedia of Industrial Chemistry, Vol. A15. 5th Ed., VCH Verlagsgesellschaft mbH, Weinheim, Germany.

Jansen, R. (1983), Dams and Safety, A Water Resources Technical Publication. US Department of the Interior, Bureau of Reclamation, Washington D.C., USA.

Kletz, T. (1993), Lessons from Disasters. Houston: Gulf Publishing Company.

Nash, R. J., (1976), Darkest Hours. Chicago: Nelson-Hall.

NMHSA (1993), Catalog of Training Products for the Mining Industry - 1993. US Department of Labour, Mine Safety and Health Administration, National Mine Health and Safety Academy.

Occupational Safety and Health Reporter (1998), China logs one of worst safety records, 28. Jan. 1998, Vol. 27, No. 34, 1320. (Author anonymous).

Usmen, M. and Cheng S. (1987), Reliability and Risk Assessment of Coal Refuse Disposal Facilities. Published in Carlson, C., Swisher, J. (eds.), Innovative Approaches to Mined Land Reclamation, pp. 693-717, Southern Illinois University, Carbondale, Il., USA.

6.3 Oil Chain

6.3.1 Crude oil products and trends in consumption

Crude oil is a mixture of gaseous, liquid and solid hydrocarbons. In its crude state oil is practically useless [Encyclopaedia Britannica,€1972]. When refined it supplies fuels, lubricants, illuminants, solvents, surfacing materials and other products. Nearly 90% of oil products are used as transportation and combustion fuels [Gerhartz and Elvers, eds., 1991]. The fuels derived from oil account for half the world's total supply of energy. Table 6.3.1 gives an overview of gas and liquid fuels and their applications.

TABLE 6.3.1

Most important oil products and their applications.

	Name	**Components**	**Boiling range**	**Application**
Gas fuels	Refinery gas	Methane, ethane	-	Refinery furnaces
	Liquefied petroleum gas (LPG)	Hydrogen, propane, butane and olefins	-47-69 ^{o}C	Heating, motor fuel or other products
Liquid fuels	Motor gasolines	Light and heavy cracker and reformer gasolines	40-200 ^{o}C	Motor fuels
	Kerosene	Refined petroleum distillate intermediate in volatility between gas-line and gas/diesel oil	150-250 ^{o}C	Jet fuels, lighting oil
	Gas oils	Heavy and light oil fractions	250-350 ^{o}C	Diesel fuels
	Heavy fuel oils	Residuals from distillation and conversion processes	-	Marine fuels, power stations, industrial furnaces

In Fig. 6.3.1 trends are shown with regard to the consumption of some oil products such as LPG, gas/diesel oils, jet fuels, motor gasoline in OECD-countries (The consumption of refinery gas is not shown in Fig. 6.3.1 because it is very small in comparison to other oil products.) The figure shows an increase of the consumption of oil products in the period 1960-1979, a decrease after 1979 and a slight increase again since 1984.

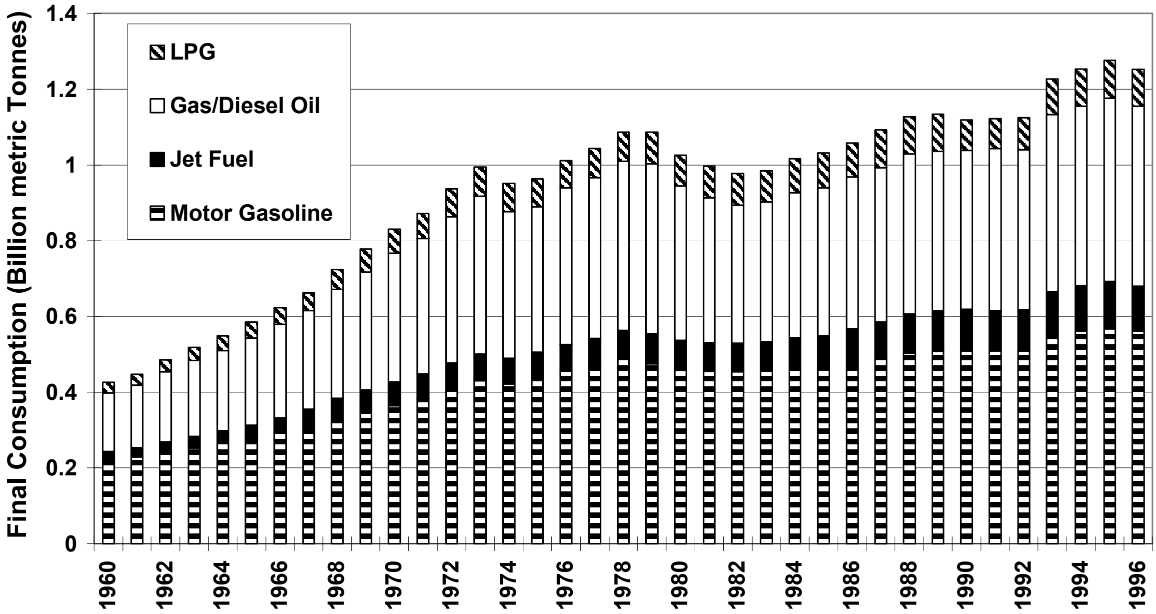

Fig. 6.3.1 Trends in final consumption of some oil products in OECD-countries.

In Fig. 6.3.2 the liquid fuel based electricity output in OECD-countries is shown for the period 1960-1996. The figure shows an increase in the period of 1960-1973 (as in Fig. 6.3.1), a stagnation between 1973-1979 due to the dramatic increase of the oil price by the OPEC cartel, a strong decrease between 1979-1985, followed by a slight increase since 1986.

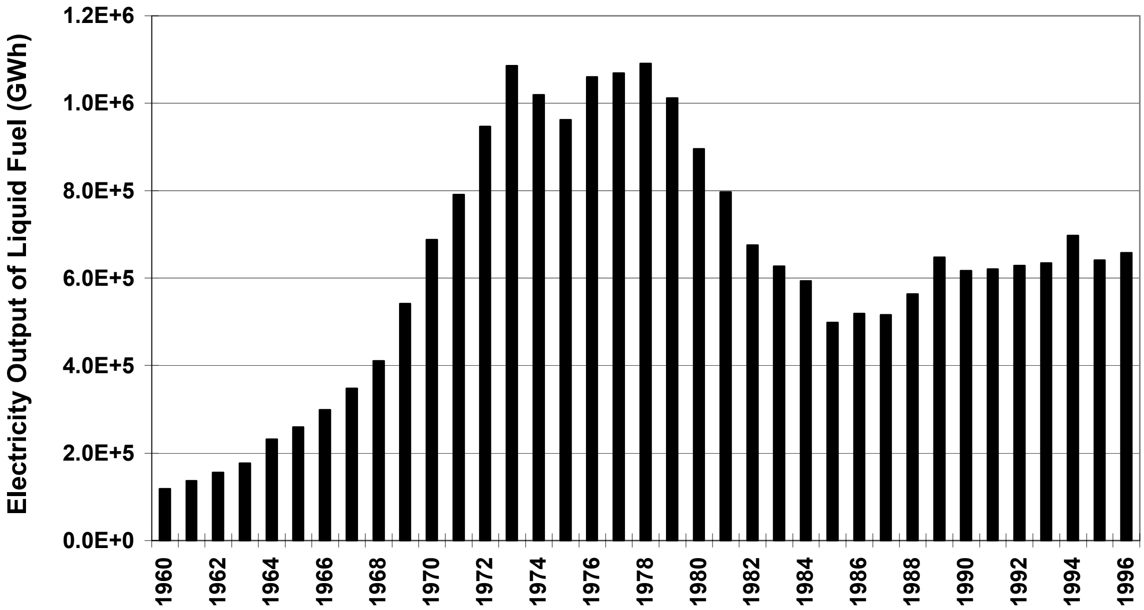

Fig. 6.3.2 Liquid fuel based electricity output between 1960 and 1996 in OECD-countries.

6.3.2 Breakdown of the oil chain into stages

Figure 6.3.3 shows the preliminary products from the fractionating tower in a refinery, the following processes or the facilities where the processes occur and the final products. The final products have non-energy end uses such as asphalt, petrochemicals, greases etc. and energy-related end uses such as LPG, bunker oil, marine diesel etc.. In the context of energy-related oil products the oil chain can be roughly characterised by Fig. 6.3.4 [Frischknecht et al., 1996]. For non-energy-related end uses of petroleum, heavy petroleum and long residue, the stage "Regional Distribution" is replaced by other stages such as "Transport to Lubricant Plant" in the case of long residue or "Transport to Petrochemical Industry" in the case of petroleum.

The transport of oil between the stages in Fig. 6.3.4 is characterised by a multitude of transport means.

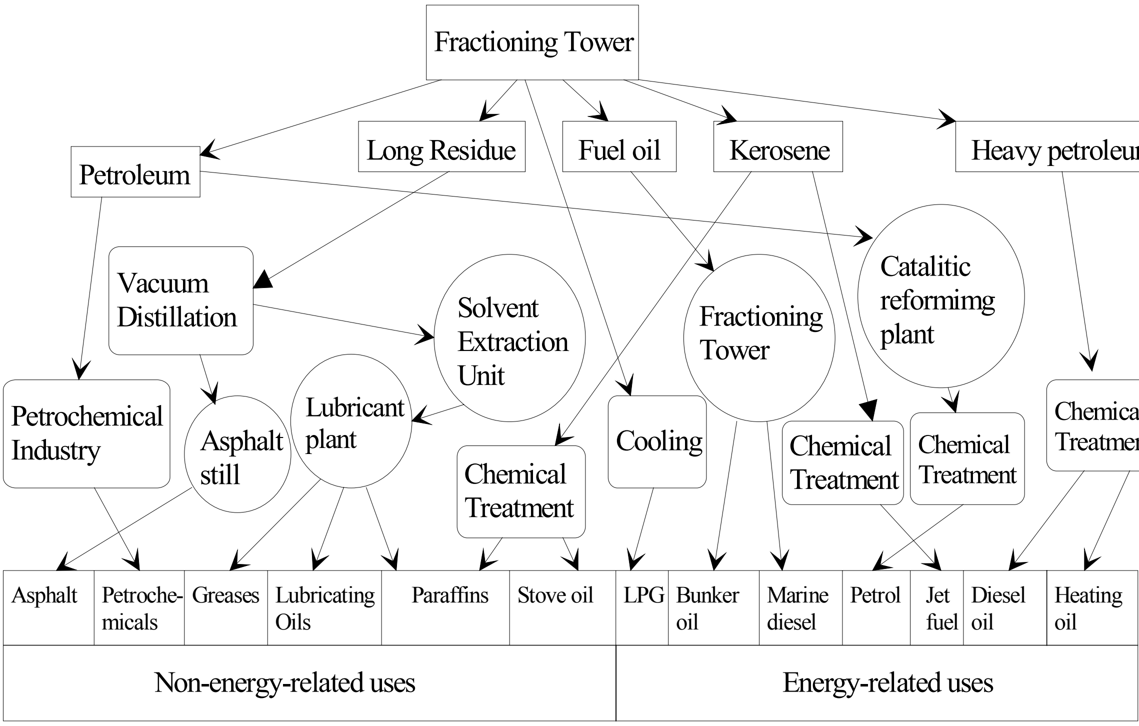

Fig. 6.3.3 Overview of products from the refinery, the subsequent processes or the facilities where the processes occur, and energy-related and non-energy-related end uses of oil products.

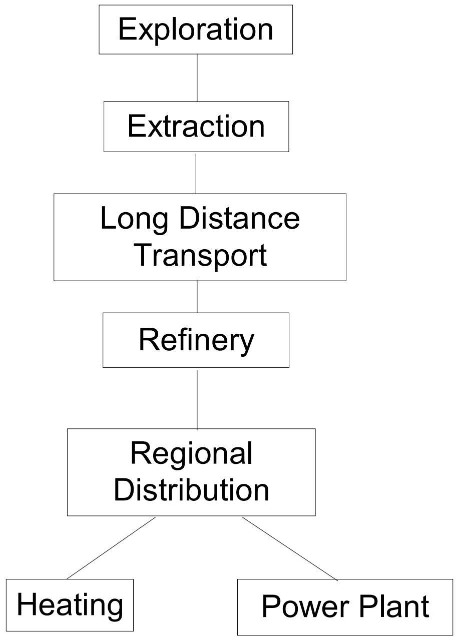

Fig. 6.3.4 Rough breakdown of the oil chain into different stages.

6.3.3 Accidents in the oil chain

6.3.3.1 Severe oil accidents involving fatalities

In Fig. 6.3.5 the number of world-wide severe (≥ 5 fatalities) accidents in the oil chain for the period 1950-1996 is shown. The figure illustrates a dramatic increase of accidents after 1965. One of the reasons could be the growing consumption of oil products since the sixties (Fig. 6.3.6), with the corresponding increase of exploration, extraction, refining and transportation activities.

A clear increase of accidents can be observed in the period of 1965-1979. The years in which the most accidents occurred were 1979, 1980 and 1989. Between 1984 and 1992 the curve begins to scatter very strongly with a clearly decreasing trend after 1992. It remains to be seen whether the number of severe oil accidents will stabilise at this lower level. One possibility is that due to the delays in the implementation the reporting completeness is less satisfactory for the last few years.

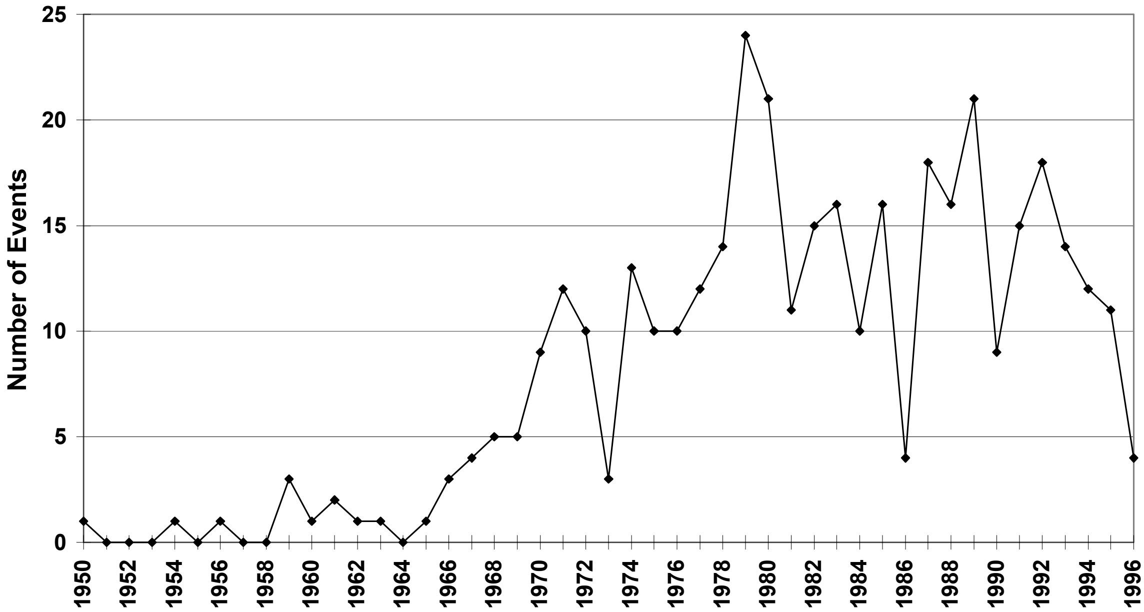

Fig. 6.3.5 World-wide number of severe (≥ 5 fatalities) accidents for the oil chain in the period 1950-1996.

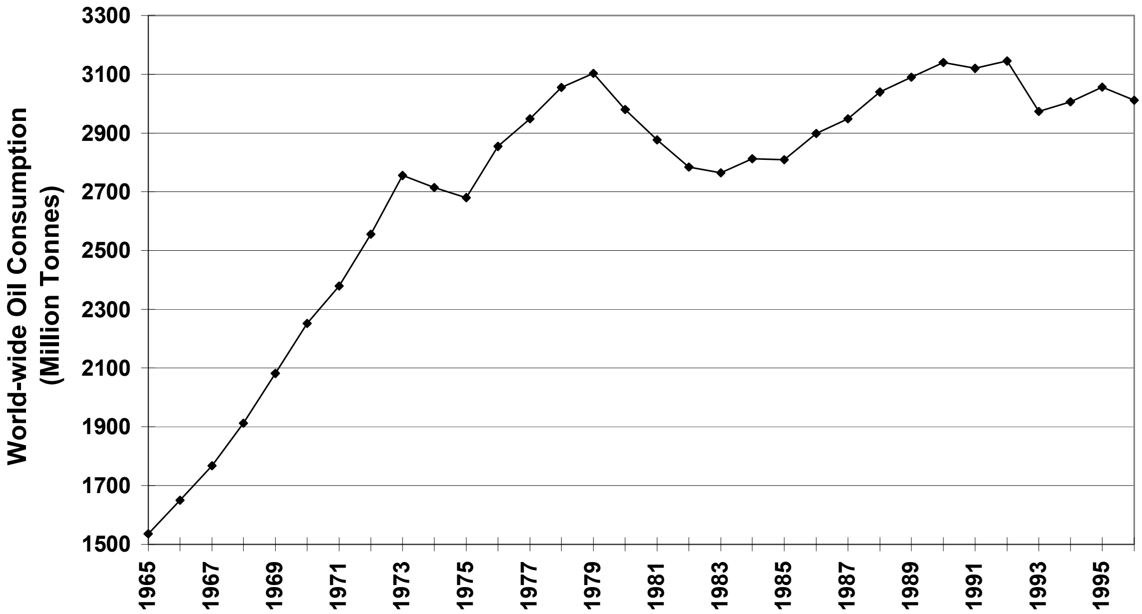

Fig. 6.3.6 Development of world-wide oil consumption.

In Fig. 6.3.7 the number of fatalities in world-wide severe (≥ 5 fatalities) accidents within the oil chain is shown by years.

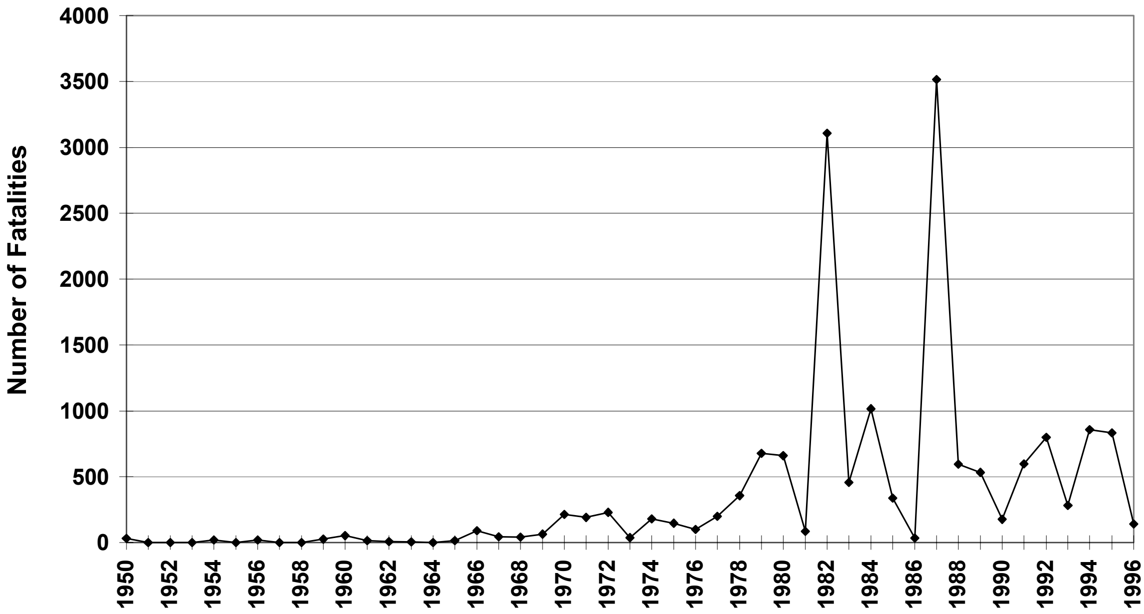

Fig. 6.3.7 World-wide number of fatalities in severe (≥ 5 fatalities) accidents within the oil chain in the period 1950-1996.

Two extremely severe accidents are responsible for the two high peaks in Fig. 6.3.7 in years 1982 and 1987. In 1982 in Afghanistan, a collision of a Soviet fuel truck and another vehicle caused 2700 fatalities (see Section 6.3.4.2). The other extreme accident that caused 3000 fatalities in 1987 occurred off the coast of Mindoro in the Philippines (see Section 6.3.4.2).

These two events represent the largest oil accidents and have at the same time quite untypical features. This applies in particular to the accident in Afghanistan since it occurred during a war and among its victims were Soviet soldiers (along with Afghan civilians). At the same time the accident did not result from acts of war.

In Fig. 6.3.8 the number of fatalities (Data) and the trendline (Trendline) are shown with the two above mentioned disasters in 1982 and in 1987 excluded. The trendline is based on a polynomial of second degree. Eventhough in years 1981, 1986, 1990, 1993 and 1996 the number of fatalities was very low, there is a clearly growing trend.

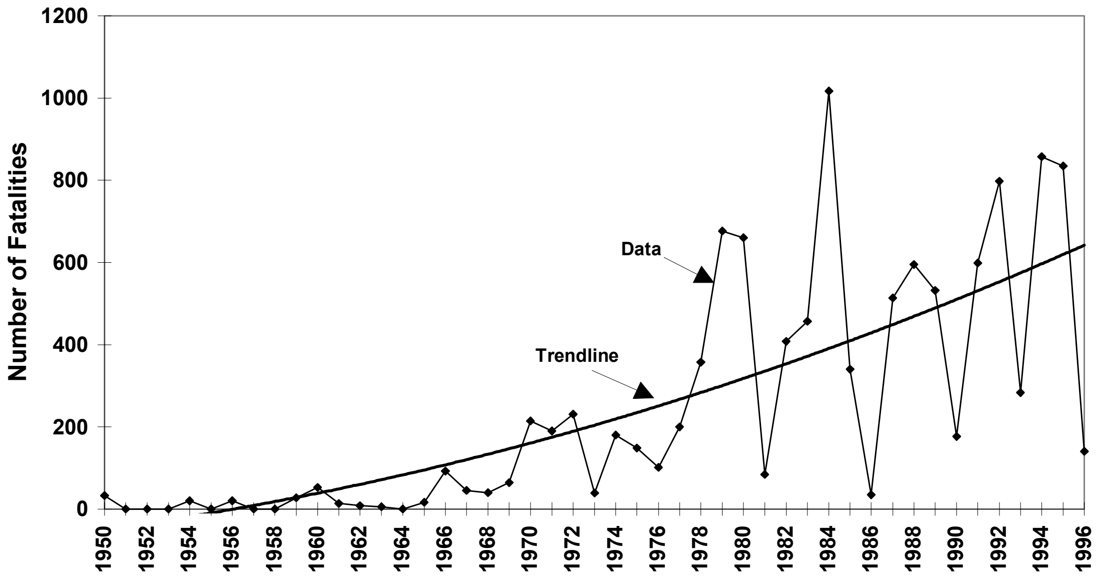

Fig. 6.3.8 World-wide number of fatalities and trendline for severe (≥ 5 fatalities) accidents within the oil chain in the period 1950-1996; the extreme accidents in Afghanistan and Philippines are here excluded.

6.3.3.2 Severe oil accidents involving injured

Figure 6.3.9 illustrates an increase of world-wide severe (≥ 10 injured) oil accidents since 1965. The figure shows that the average number of severe (≥ 10 injured) accidents per year amounted to 8 for the period 1976-1996.

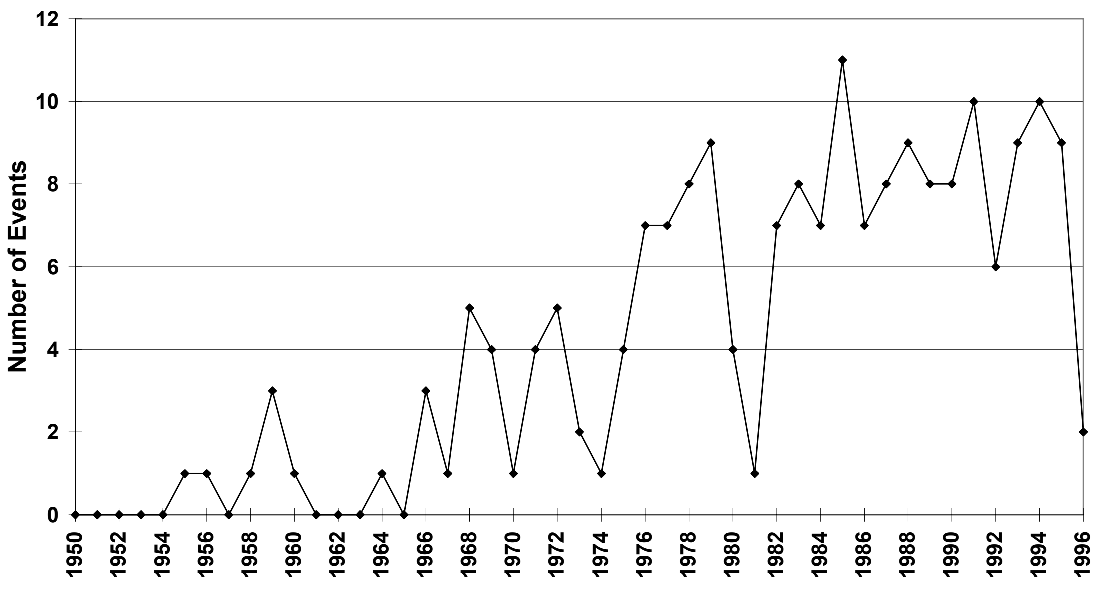

Fig. 6.3.9 World-wide number of severe (≥ 10 injured) accidents within the oil chain in the period 1950-1996.

Figure 6.3.10 shows the number of injured in severe (≥ 10 injured) oil accidents. The peak in 1980 with about 3000 injured persons corresponds to the blow out of the well Funiwa-5 off the Nigerian coast, where on January 17th 1980 apart from the injured 180 persons were killed . The figure shows that between 1982 and 1996 the number of injured scattered very strongly in comparison to other time periods.

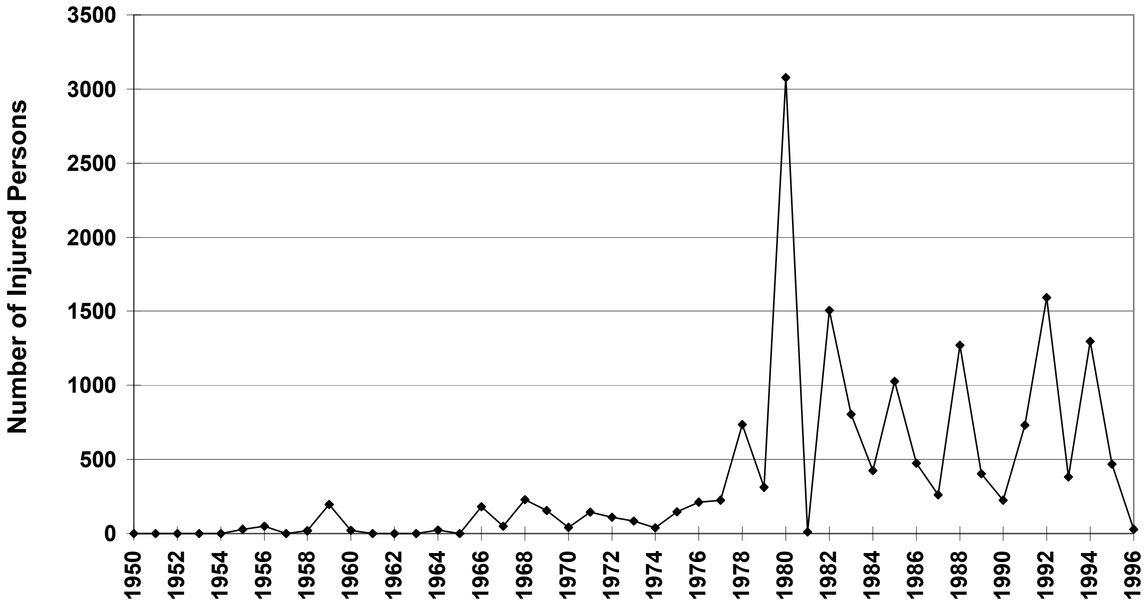

Fig. 6.3.10 World-wide number of injured in severe (≥ 10 injured) accidents within the oil chain in the period 1950-1996.

A list of severe (≥ 5 fatalities, ≥ 10 injured, ≥ 200 evacuees, ≥ 5 million US$ of economic losses) oil accidents is given in Appendix B.

6.3.4 Fatal accidents in different oil chain stages

In Fig. 6.3.11 the number of world-wide severe (≥ 5 fatalities) accidents for different stages in the oil chain and the period 1969-1996 is shown, including the most severe accidents which occurred in Afghanistan and in the Philippines. The figure demonstrates that "Regional Distribution" and "Transport to the Refinery" are the stages where most severe accidents occurred. This is followed by "Extraction", "Refinery" and "Exploration". "Heating" and "Power Plant" do not contribute essentially to the number of events.

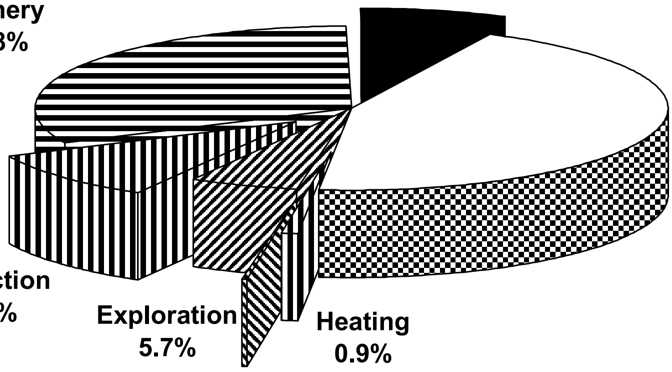

Fig. 6.3.11 Distribution of the number of severe (≥ 5 fatalities) accidents throughout the oil chain in the period 1969-1996.

In figures 6.3.12 and 6.3.13 the number of fatalities in the period between the years 1969 and 1996 is shown. In Fig. 6.3.13 the oil disasters in the Philippines and in Afghanistan mentioned in Section 6.3.3.1 have been excluded with view to their atypical character.

In conclusion the figures show that regional distribution and transport to the refinery are associated both with most events (Fig. 6.3.11) and with most fatalities (Fig. 6.3.12).

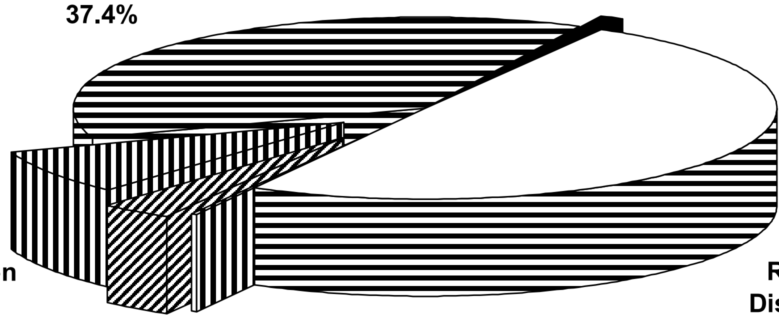

Fig. 6.3.12 Distribution of the number of fatalities in severe accidents (≥ 5 fatalities) throughout the oil chain in the period 1969-1996.

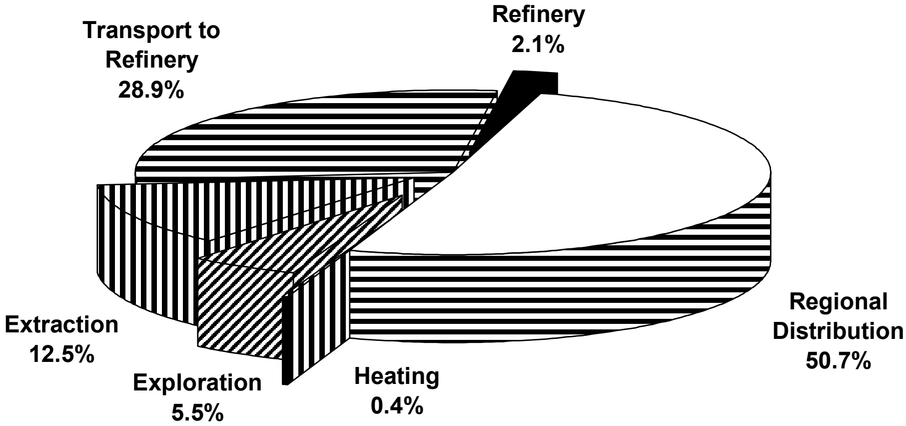

Fig. 6.3.13 Distribution of the number of fatalities in severe accidents (≥ 5 fatalities) throughout the oil chain in the period 1969-1996, excluding the two largest disasters in the Philippines and Afghanistan.

6.3.4.1 "Exploration" and "Extraction" stages

In the period between 1969 and 1996 nearly all severe accidents associated with these stages occurred offshore. There has been a clear trend of increasing offshore drilling and exploring activities since the late seventies [Brown, 1981]. A contributing reason is the longer distance from the rigs to the coast. Thus, working conditions and living accommodation for a large number of workers are being provided in an unfriendly environment.

In Table 6.3.2 the worst accidents at the "Exploration" and "Extraction" stages are given.

TABLE 6.3.2

Worst accidents in the "Exploration" and "Extraction" stages.

Date	Stage	Type of unit	Name of Unit	Number of Fatalities
6.7.1988	Extraction	Jacket	Piper Alpha	167
27.3.1980	Exploration	Semisubmersible	Alexander Kielland	123
11.3.1989	Exploration	Drilling Ship	Seacrest	91
15.2.1982	Extraction	Semisubmersible	Ocean Ranger	84
25.10.1983	Exploration	Drilling Ship	Glomar Java Sea	81
25.11.1979	Extraction	Jackup	Bohai II	72

A "Jacket" is the substructure of an oil rig. The legs of the substructure are placed on the sea bottom and fix the oil rig. Normally the substructure is built from steel. In recent years in the North Sea concrete has been used as the construction material for the "Jackets" in order to save costs. Normally jackets are used if the oil field guarantees an exploitation of at least 25 years otherwise production ships are put into action.

A "Jackup" mentioned in Table 6.3.2 is a movable installation consisting of a large deck with legs which may be jacked up. During operation, the legs are resting on the seabed, and the vessel is "jacked up", leaving the deck in secure position high above the surface of the sea. When moved, the legs are retracted and the installation floats. Normally, a "Jackup" is used as a drilling rig in water depths of maximum 100 to 120 metres and it is not equipped with own propulsion machinery.

A "Semisubmersible" is a movable installation consisting of a deck on stilts, fastened to two or more pontoons; it is usually fitted with own propulsion machinery and used in water depths of maximum 600 - 800 metres. When in operation, the pontoons are filled with water and lowered beneath the surface. The installation is normally kept in position by a number of anchors, but may also be fitted with dynamic positioning equipment (DPE).

A "Drillship" is a ship equipped with drilling rig and its own propulsion machinery. It is kept in position by DPE and operates in waters with a maximal depth of 2,000 metres.

The worst exploration accident occurred off the coast of Norway on March 27th 1980. The five-legged floating oilfield platform "Alexander Kielland" overturned in gale-force winds in the North Sea. One hundred twenty-three of the 212 people aboard drowned when one of the anchored legs gave way. The platform was being used as a hotel for oil workers.

The worst oil-production accident occurred off the east cost of Scotland on July 6th 1988. The accident started during the evening with a major gas leak in the compression module. A subsequent explosion and fire splitted the towering oil platform "Piper Alpha" into a tangle of fallen metal. Two thirds of the installation collapsed into 144 m deep water. 167 lives were lost.

In Fig. 6.3.14 the number of fatalities in severe (≥ 5 fatalities) accidents is shown by geographical regions. The figure shows that in the North Sea where offshore oil activities are carried out under hard conditions, the number of fatalities is significantly higher than in other regions.

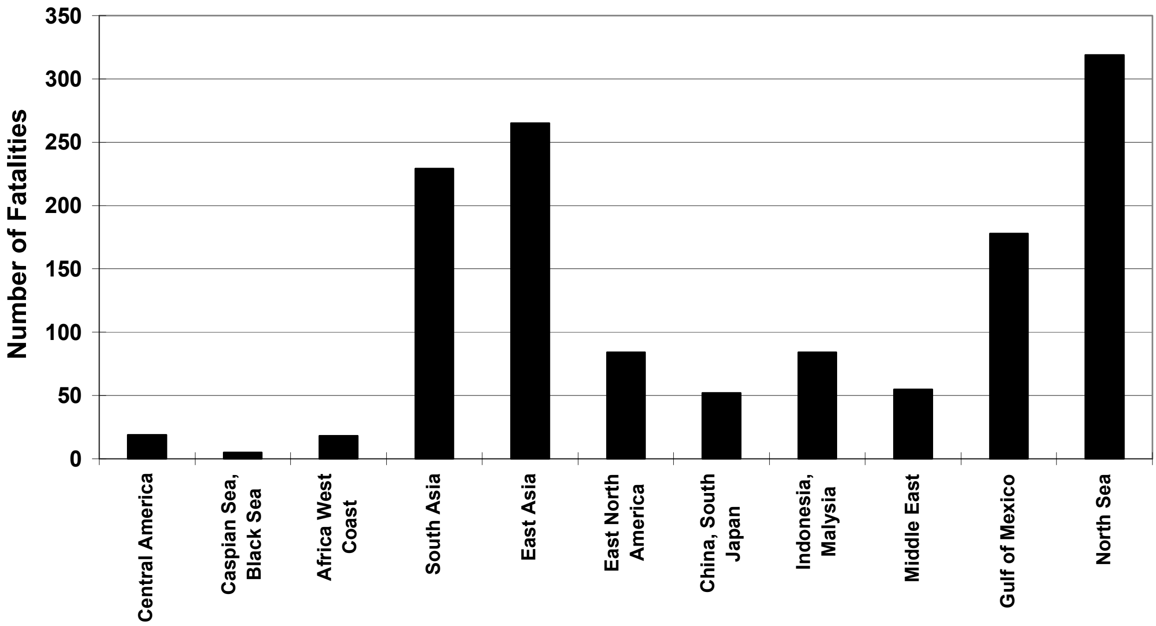

Fig. 6.3.14 Number of fatalities in severe (≥ 5 fatalities) offshore accidents in the period 1969-1996.

In Fig. 6.3.15 the causes for severe (≥ 5 fatalities) offshore accidents are shown. The figure demonstrates that blow-out, in which gas, oil or other fluids flow uncontrolled from the reservoir and collisions, constitute the main causes for the accidents.

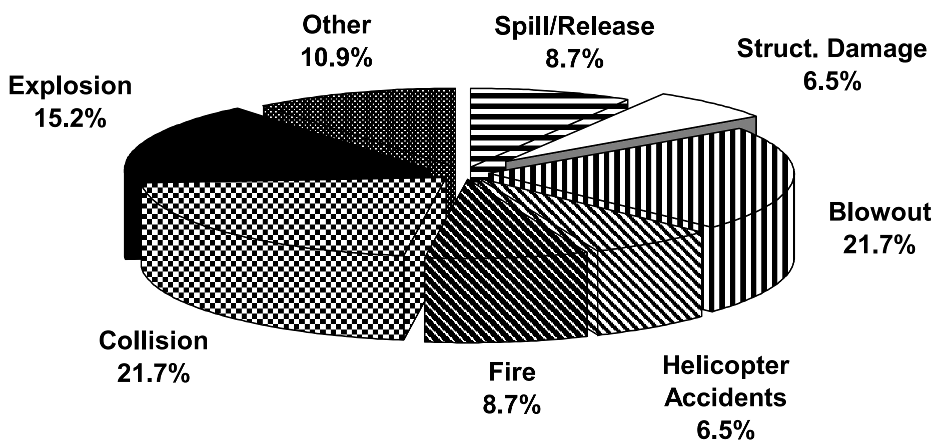

Fig. 6.3.15 Main causes for offshore severe (≥ 5 fatalities) accidents in the period 1969-1996.

6.3.4.2 "Transport to Refinery" and "Regional Distribution" stages

In Table 6.3.3 the most severe accidents in the "Transport to Refinery" and the "Regional Distribution" stages are shown. The worst severe accident in the "Transport to Refinery" stage occurred on December 12th 1987 off the coast of Mindoro in the Philippines. A ferry packed with as many as 3000 passengers and crewmen collided with an oil tanker. Both ships exploded and sank. Only 26 badly burned persons survived.

The worst severe accident in the "Regional Distribution" stage happened in early November in 1982. A Soviet fuel truck collided with another vehicle in the Salang Tunnel in the northern part of Afghanistan and exploded into flames, sending noxious fumes throughout the 2.7 km long tunnel. Soviet soldiers and Afghan civilians died from burns and asphyxiation.

TABLE 6.3.3

Worst severe (≥ 60 fatalities) accidents in the "Transport to Refinery" and "Regional Distribution" stages in 1969-1996.

Date	Country	Stage	Fatalities
20.12.1987	Philippines	Transport to Refinery	3000
01.11.1982	Afghanistan	Regional Distribution	2700
2.11.1994	Egypt	Regional Distribution	580
25.02.1984	Brazil	Regional Distribution	508
05.03.1987	Ecuador	Transport to Refinery	300
22.4.1992	Mexico	Regional Distribution	200
15.10.1984	Romania	Regional Distribution	150
10.04.1991	Italy	Regional Distribution	141
08.03.1989	Vietnam	Transport to Refinery	130
26.06.1991	Malaysia	Transport to Refinery	124
08.03.1992	Thailand	Transport to Refinery	112
12.3.1995	India	Regional Distribution	110
22.11.1978	Nigeria	Regional Distribution	100
22.11.1991	India	Regional Distribution	90
11.05.1972	Uruguay	Transport to Refinery	84
15.11.1979	Turkey	Transport to Refinery	75
24.01.1990	China	Transport to Refinery	70
12.10.1978	Singapore	Transport to Refinery	64
7.11.1993	Nigeria	Regional Distribution	60
4.11.1994	Nigeria	Regional Distribution	60

In Fig. 6.3.16 the transport modes involved in severe accidents for the oil chain stages "Transport to Refinery" and "Regional Distribution" are shown.

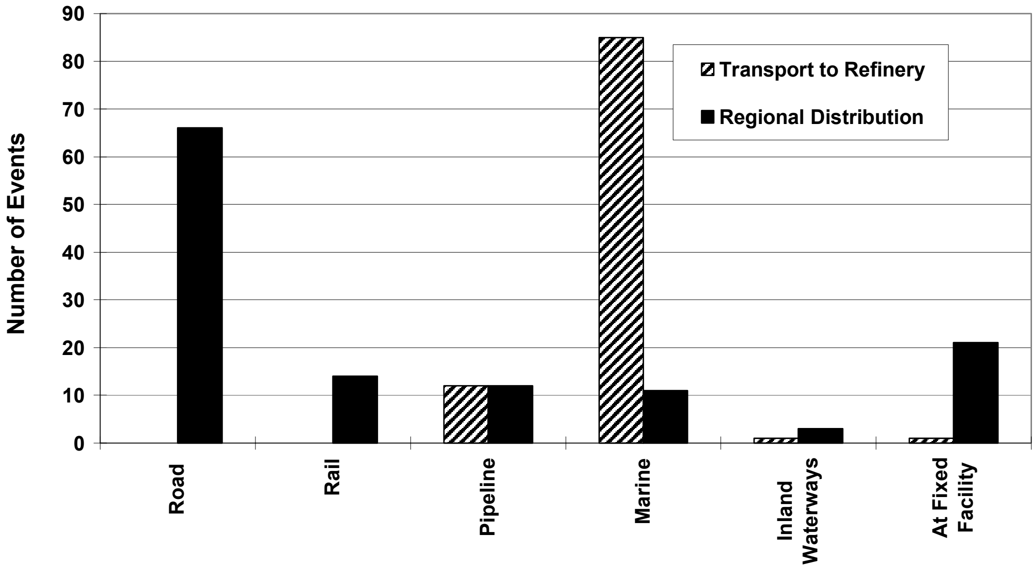

Fig. 6.3.16 Modes of transport involved in severe (≥ 5 fatalities) accidents in the oil chain in the period 1969-1996.

The figure shows that the dominant accidents within the "Transport to Refinery" stage were maritime accidents. The main circumstances include tankers that exploded, caught fire, or collided with each other. For the stage "Regional Distribution" most accidents occurred on the road. The main causes of road accidents in the period of 1969-1996 were collisions of road tankers with other vehicles (52%) and overturning of road tankers (10%).

6.3.4.3 "Refinery" stage

Accidents at refineries resulted in a relatively low number of fatalities in comparison with the previously described oil stages. Table 6.3.4. depicts the most severe accidents at the "Refinery" stage during the period 1969-1996. The worst disaster occurred in 1983 in Teleajen in Romania. More than 30 persons died after an explosion. The second worst refinery accident occurred in 1988 in Shanghai, China. Explosions and fires killed 25 persons.

An examination of the refinery accidents collected in ENSAD showed that in nearly all cases an explosion was followed by fire. Explosions occurred with little warning and destroyed large areas [Munich Re, 1991]. At the centre of the explosion, there is usually total damage. A single, specific part of the refinery that gives rise to frequent accidents has not been identified. The units of the refinery, where the accidents were initiated were the desulphuring plant, pipes, pipeworks, compressor station, reformer unit, catalytic cracker unit, distillation unit and fractionating tower.

TABLE 6.3.4

Worst severe (≥ 5 fatalities) accidents in the "Refinery" stage.

Date	Country	Number of Fatalities
06.12.1983	Romania	>30
22.10.1988	Shanghai	25
08.10.1992	USA	16
01.09.1992	Greece	14
12.08.1976	USA	13
24.07.1984	USA	13
28.08.1988	Mexico	12
?.3.1984	Nigeria	10
10.07.1971	Netherlands	9
16.10.1992	Japan	9
11.11.1969	Mexico	8
3.6.1993	Italy	7
17.3.1977	USA	7
5.5.1988	USA	7
26.8.1972	France	6
12.12.1991	Netherlands	6
9.11.1992	France	6
11.8.1990	Russia	6
6.3.1969	Venezuela	5
1970	Japan	5
7.4.1972	South Korea	5
30.5.1987	Nigeria	5

6.3.4.4 "Power plant" and "Heating" stages

Only few accidents occurred at these stages. The worst accident happened in 1978 when an oil oven exploded and killed nine people.

6.3.5 Cost of oil accidents

In the following Tables 6.3.5 through 6.3.10 some major financial losses in different stages in the oil chain are shown. The costs in the tables are in applicable cases composed of damage to property, clean-up work and possibly loss of production. In the last column of the tables the costs are expressed in 1996 US$.

6.3.5.1 "Exploration" and "Extraction" stages

Table 6.3.5 shows that the recorded losses at the stage "Exploration" range up to nearly 2000 million 1996 US$ (last column in Table 6.3.5). The accident with the largest losses occurred on January 28th 1969 offshore California due to a blow-out during drilling activities. The accident with the second largest losses occurred on June 3rd 1979 offshore Mexico (see Section 6.3.7.2). The total compensation sought in the United States was in the region of 400 million US$ but the actually paid amount was about 18 million US$. The cost of the clean-up of the coast of Mexico was 34 million US$ and the cost to regain control of the well another 100 million US$.

TABLE 6.3.5

Costs of the worst (in monetary terms) accidents with costs larger than 20 million 1996 US$ in the "Exploration" stage as collected in ENSAD.

Date	Country	Facility	Name	Costs (million US$)	Costs (million 19962 US$)
28.01.1969	USA	Platform	-	560	1947
03.06.1979	Mexico	Platform	Ixtoc-I	152	310.9
15.02.1982	Canada	Platform	Ocean Ranger	86	132.2
22.10.1980	USA	Platform	Dan Prince 2	36	65.0
22.09.1990	UK	Platform	Ocean Odyssey	50	56.7
12.01.1977	Taiwan	Platform	Scan Sea	21	51.5
01.03.1976	Norway	Platform	Deep Sea Driller	18	47.1
16.08.1984	Brazil	Platform	Enchova	30	44.5
16.10.1983	South China Sea	Drilling ship	Glomar Java Sea	30	44.8
27.08.1981	Indonesia	Drilling ship	Petromar V	26	42.4
18.09.1985	Malaysia	Platform	South Sea III	24	33.1
20.03.1989	Venezuela	Well	-	20	25.1
01.08.1982	India	Exploration plant	Sagar Vikas	14	21.5

Table 6.3.6 gives the costs in US$ for some of the worst accidents in monetary terms, which occurred during the "Extraction" stage. The most expensive disaster was the explosion and fire on the Piper Alpha rig in the North Sea, followed by the disaster on the oil platform Enchova No. 1 in Brazil, where a blow-out and a fire caused 42 fatalities. The third most costly accident was the total loss of the Sleipner A oil platform due to loss of buoyancy caused by leakage of water into the unit.

TABLE 6.3.6

Costs of the worst (in monetary terms) accidents with costs larger than 12 million 1996 US$ in the "Extraction" stage according to ENSAD.

Date	Country/ Area	Facility	Name	Costs (million US$)	Costs (million 1996 US$)
07.07.1988	UK	Platform	Piper Alpha	1200-1500	1440-1800
24.04.1988	Brazil	Platform	Enchova No: 1	330	419.8
23.08.1991	Norway	Platform	Sleipner A	334.5	365.2
16.04.1978	Saudi Arabia	Gas/oil separation plant	-	54	123.1
27.03.1980	Norway	Platform	Alexander Kielland	66.2	119.5
01.10.1984	Indonesia	Oil and gas well	Bekapai Well BC7	55	81.6
01.09.1983	Australia	Platform	Key Biscayne	50	74.7
24.10.1986	USA	Platform	Mexico II	53	72.0
22.10.1980	USA	Platform	Dan Prince	36	64.9
21.04.1979	USA	Platform	Solar Energy I	26	53.2
11.12.1980	Egypt	Platform	Ocean Champion	25	45.1
28.05.1981	Angola	Platform	Sedco 250	22	36.0
15.04.1976	Iraq	-	-	12	31.5
20.08.1990	North Sea	Platform	West Gamma	24	27.2
15.08.1975	USA	Motor tanker	Globtik Sun	10	27.7
28.01.1996	Egypt	Platform	-	25.7	25.7
20.07.1988	Venezuela	Platform	-	20	25.4
22.02.1988	USA	Platform	Keyes 302	15	19.1
06.07.1993	Egypt	Platform	-	15	15.9
14.07.1982	USA	Platform	Rig 52	8	12.3

6.3.5.2 "Transport to Refinery" stage

Table 6.3.7 lists the accidents with highest economic losses at the stage "Transport to Refinery" with their corresponding costs. The most costly accident at this stage occurred on March 24th 1989, when the tanker Exxon Valdez as a result of changing the course run aground on Blight Reef near the Valdez Harbour in Alaska [Sharples, 1992]. About 35,000 tonnes of crude oil was spilled into the sea [OECD, 1991]. The ship was loaded with 158,000 tonnes crude oil. The Exxon Valdez Oil Spill was the largest tanker spill in the history of United States.

TABLE 6.3.7

Costs of the worst (in monetary terms) accidents with costs larger than 20 million 1996 US$ in the "Transport to Refinery" stage according to ENSAD.

Date	Country/ Area	Facility	Name	Costs (million US$)	Costs (million 1996 US$)
24.03.1989	USA	Tanker	Exxon Valdez	1200-2000	1360-2260
11.05.1977	Saudi Arabia	Pipeline	-	100	244.9
?.?.1976	France	-	-	83	217.3
20.07.1979	Trinidad	Tankers	Aegean Captain & Atlantic Empress	100	204.6
15.03.1978	France	Tanker	Amoco Cadiz	75.0	171.1
02.09.1979	USA	Tanker	Chevron Hawaii	68	139.1
24.01.1976	Pacific	Tanker	Olympic Bravery	50	130.9
16.04.1978	Saudi Arabia	Separation plant	-	54	123.1
05.01.1993	UK	Tanker	Braer	115	121.9
06.08.1983	South Africa	Tanker	Castillo de Bellver	72	107.6
27.03.1971	USA	Tanker	Texaco Oklahoma	24	87.8
08.07.1977	USA	Pipeline	-	35	85.8
15.11.1979	Turkey	Tanker	Independenta	40	81.8
17.10.1976	France	Tanker	Boehlen	31	79.5
05.11.1973	Canaries	Tanker	Golar Patricia	22.7	75.9
22.02.1974	Pacific	Tanker	Giovanna Lolli Ghetti	23.1	69.5
20.09.1992	Indonesia	Tanker	Nagasaki Spirit	60	63.6
14.10.1982	(Black Sea)	Tanker	Unirea	39.7	61
15.12.1969	Quatar	Tanker	Marpressa	15.067	60.8
?.?.1979	Canada	Tanker	Kurdistan	30	58.3
12.05.1976	Spain	Tanker	Urquiola	18.7	49.0
03.04.1980	Tanzania	Tanker	Albahaa B.	27	48.7
24.07.1969	France	Tanker	Silja	11.6	47.1
18.02.1971	Atlantic	Tanker	Ferncastle	12.6	46.3
19.12.1972	Golf of Oman	Tanker	Sea Star	12.0	42.8
23.02.1978	Colombia	Tanker	Cassiopeia	14	31.9
15.04.1977	Papua New Guinea	Tanker	Universe Defiance	11	26.9
04.06.1977	Saudi Arabia	Loading terminal	-	11	26.9
21.03.1978	Indonesia	Tanker	Aegis Leader	9	20.6

6.3.5.3 "Refinery" stage

Table 6.3.8 lists some of the worst (in terms of economic losses) accidents in the "Refinery" stage. The most expensive refinery disaster occurred on May 30th 1987 in Nigeria. A tanker was loaded with fuel for Lagos when it was struck with a lightning as it was departing the refinery. Five crew members were killed by the explosion.

TABLE 6.3.8

Costs of the worst (in monetary terms) accidents with costs larger than 25 million 1996 US$ in the "Refinery" stage according to ENSAD.

Date	Country	Costs (million US$)	Costs (million 1996 US$)
30.05.1987	Nigeria	700	916.4
09.11.1992	France	370	392.2
28.01.1989	Nigeria	300	360
17.09.1989	USA	272	326
23.07.1984	USA	203.2	301.6
20.08.1981	Kuwait	175	286.2
05.12.1970	USA	69	266.6
10.12.1991	Germany	184.6	201.5
16.10.1992	Japan	157.8	167.3
10.12.1975	Belgium	50	137.8
24.07.1994	UK	106	106
11.03.1991	Mexico	90	102.1
22.06.1992	Spain	87	92.2
06.12.1981	UK	52	84.9
13.04.1991	USA	75	85.1
26.03.1985	USA	50.5	69.6
08.10.1992	USA	55	58.3
03.10.1978	USA	22	50.1
10.07.1971	Netherlands	13.5	49.5
04.08.1971	Italy	12.0	43.8
22.03.1987	UK	26.7	35.0
22.02.1990	France	29	32.9
25.04.1974	Romania	10.2	30.3
21.12.1985	Italy	20	27.6
03.03.1991	USA	23	26.13

6.3.5.4 "Regional Distribution" stage

Table 6.3.9 lists the worst (with regard to economic losses) accidents within the stage "Regional Distribution". The most expensive disaster occurred on November 14th 1981. Seven persons died when a truck carrying gasoline sideswiped a trailer. The truck caught fire leaving a wall of flames for 300 m.

TABLE 6.3.9

Costs of the worst (in monetary terms) accidents with costs larger than 15 million 1996 US$ in the "Regional Distribution" stage according to ENSAD.

Date	Country	Facility	Costs (million US$)	Costs (million 1996 US$)
14.11.1981	USA	Tanker	350	571.3
19.01.1981	USA	Tanker	280	457.1
24.02.1986	Greece	Tank farm	300	407.3
09.03.1972	USA	Tank vehicle	100	355.5
22.04.1992	Mexico	-	300	318
02.11.1994	Egypt	-	140	140
03.10.1993	South Korea	-	100	106
07.03.1980	France	Tanker	30	54
06.03.1993	Chile	-	50	53
10.10.1983	Nicaragua	-	25	37.4
30.08.1983	UK	Storage Plant	15	22.5
25.10.1972	USA	-	5	17.8
20.11.1969	Netherlands	Storage tank	4.9	17.1
20.10.1994	USA	-	15	15

6.3.5.5 "Heating/Power Plant" stage

Table 6.3.10 shows the worst (in monetary terms) accidents in the last stage of the oil chain. The most expensive accident occurred on December 19th 1982 in Venezuela where a violent boilover of a 240,000 barrel fixed roof tank spread burning oil over a distance of 400 m destroying nearby buildings. The total costs amounted to 61.5 million 1996 US$.

TABLE 6.3.10

Costs of the worst (in monetary terms) accidents in the "Heating/Power Plant" stage according to ENSAD.

Date	Country	Facility	Costs (million US$)	Costs (million 1996 US$)
19.12.1982	Venezuela	Power plant	40	61.5
15.02.1992	Germany	Power Plant	46.5	49.3
09.08.1985	USA	Power Plant	24.8	34.1
10.04.1982	USA	Power plant	19.7	28.9
18.07.1976	USA	Tank	25	65.5
03.02.1989	France	Power plant	11.5	14.6
01.10.1979	Germany	Storage plant	2.6	5.3

6.3.6 Oil products involved in accidents

In the "Exploration/Extraction" and "Transport to Refinery" stages the main product involved in severe accidents is crude oil. In the "Exploration/Extraction" stage the ignition of released gases such as propane, butane or methane from the well caused severe accidents in the past. For instance, the total loss of rigs such as Piper Alpha or Trintoc Atlas was caused by explosions of leaking gas. The petrochemicals that were involved in major refinery accidents were manifold. A dominant material type cannot be specified.

In Fig. 6.3.17 the share of petrochemicals, which were involved in severe (≥ 5 fatalities) accidents in the period 1969-1996 is shown for the stage "Regional Distribution". The figure shows that petrol was involved in almost half of all major accidents.

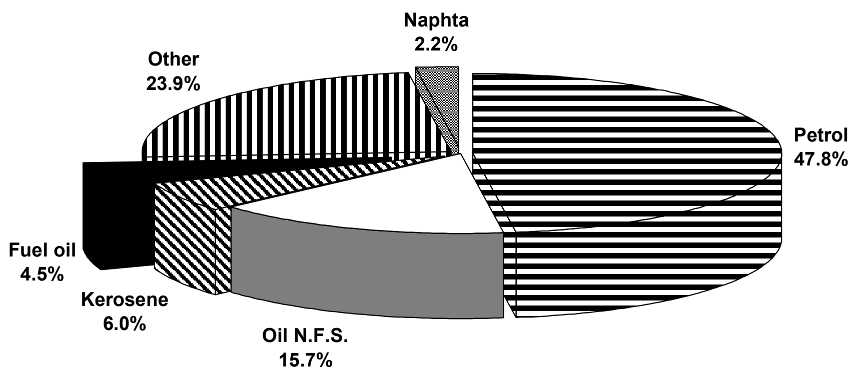

Fig. 6.3.17 Oil products involved in severe (≥ 5 fatalities) accidents in the period 1969-1996 for the stage "Regional Distribution" (N.F.S. = Not Further Specified).

6.3.7 Oil spills

6.3.7.1 Oil spilled in "Exploration/Extraction" and "Transport to Refinery" stages

The largest oil spill in the stage "Exploration/Extraction" occurred on June 3rd 1979 due to the blow-out of the Ixtoc 1 well offshore Mexico (Section 6.3.7.2). The worst case of ship-borne pollution was the accident of the Greek tanker "Atlantic Empress" in 1979. The vessel sank after a disastrous collision with another tanker. The quantity of crude oil that was spilled amounted to 258,750 tonnes [Sharples, 1992]. The oil dispersed into the sea. The London insurance market paid about 100 million US$ for this loss. Two other tankers involved in extremely large oil spills were Castillo de Bellver (250,000 tonnes of spilled oil) in 1983 and Amoco Cadiz (230,000 tonnes of spilled oil) in 1978.

Figure 6.3.18 shows the number of major offshore and onshore spills of crude oil exceeding 25,000 tonnes for the period of 1969- 1996. The figure demonstrates a trend of increase of major oil spills between 1969 and 1979, followed by a decrease to at most four spills per year.

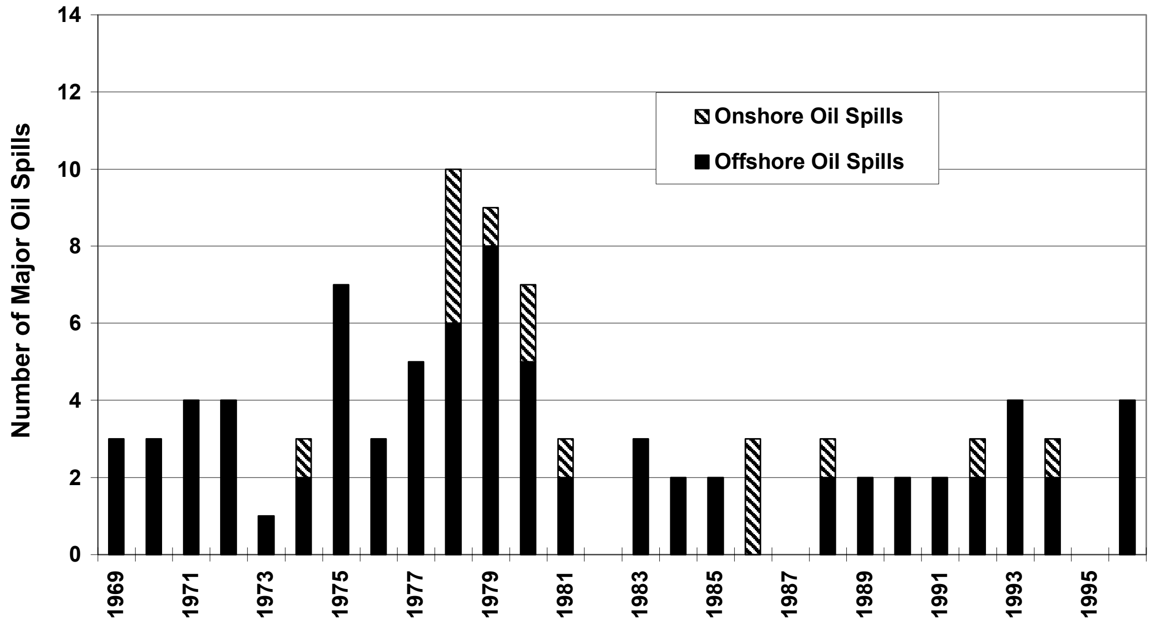

Fig. 6.3.18 Number of major offshore and onshore spills exceeding 25,000 tonnes in the period 1969-1996.

A list of major onshore and offshore oil spills exceeding 25,000 tonnes is given in Appendix B.

The total spill into the world's oceans is difficult to determine. The best estimates cite a value somewhere between 3 and 4 million tonnes per year. The major sources for oil pollution are industrial river runoff discharges, tanker operational discharges, sewage disposal, atmospheric releases and non-tanker maritime transport [OECD, 1991]; shipping accidents are quantitatively less important. Table 6.3.11 gives the shares of oil discharged into the various types of marine environment. As discussed in Section 6.3.7.3 the quantity of spilled oil is not necessarily directly correlated with the extent of the resulting damages.

TABLE 6.3.11

Oil discharged into the marine environment [OECD, 1991].

Source	Percentage of discharged oil into the marine environment (%)
River run-off (particularly in areas with industries along the banks)	26.1
Tanker operational discharges (reducing recently)	22.5
Natural seeps (over 200 are known; some up to 25 tonnes/day)	9.8
Atmospheric (oil released from vehicles and industry falls as rain)	9.6
Non-tanker marine transportation(bilge oil and fuel oil sludge)	7.4
Coastal, municipal, industrial waste dumping via city drains)	5.0
Non-refining industrial waste	5.0
Urban run-off	5.0
Coastal refineries	3.4
Tanker accidents (locally significant and attract media attention)	1.6
Offshore production (exploration, development and pipeline transportation)	1.2
Other	3.4

6.3.7.2 Claimed and awarded costs of oil spills

An evaluation of the costs of oil spills shows that there exists a large discrepancy between the claimed and settled costs, which can amount to more than a factor of 30. It should be noted that the real costs, which may include the partially not directly quantifiable ecological damages, may be still higher. Below two cases of oil spills are discussed with regard to the evaluation of the costs.

Ixtoc 1

The largest oil-spill recorded in history occurred after the blow-out of the Ixtoc 1 well offshore Mexico. It is estimated that 375,000 tonnes of crude oil were spilled over a time-period of 7 months into the sea. The resulting oil slick was 800 kilometres long and 80 kilometres wide. The damage to the tourist industry and commercial fishery due to the oil spill was initially estimated in the US at 2000 million US$ and 600 million US$, respectively. Months later the total damages sought in the US were in the region of about

400 million US$. Table 6.3.12 gives an overview of the components of these damages [Sharples, 1992].

TABLE 6.3.12

Sought costs by property owners for the Ixtoc 1 accident.

Property owners	Sought cost (million US$)
Fishermen, crabbers, oystermen	155
Hotel, motel, condominium, property and restaurant owners	100
Persons who own, rent, lease, operate property that depends on tourism	100
City and state entities for loss of taxes	50
US Department of Justice clean-up	6
Total	411

The settlement costs for the US ended up being 12 million US$. Thus the discrepancy between the sought and the compensation awarded by the courts amounts to a factor of 33.

The total (uninsured) cost for the oil company amounted to 152 million US$. Costs due to long-term effects which were claimed by the fishermen and compensations for suffering the smell from beaches and loss of profits were not paid. Although the courts did not recognise long-term adverse effects of the oil, there is an evidence for long-term environmental effects [Seymour, Geyer (1992)].

Amoco Cadiz

The Amoco Cadiz tanker was wrecked off the coast of Brittany and spilled 230,000 tonnes of crude oil onto the beaches of north-western France. The cost of the oil spill was according to the newspapers initially estimated at 2000 million US$. The claimed and awarded costs are summarised in Table 6.3.13 [Sharples, 1992].

In the following court proceedings claims amounted to 202 million US$. Ten years later the settlement costs were 45 million US$ plus interests. This sum was later increased by 30 million US$ because of errors in the courts' understanding of some of the accounting. In this case the discrepancy between the settled costs and the awarded costs amounts to a factor of three. The US National Oceanic and Atmospheric Administration (NOAA) launched a study of the Amoco Cadiz and concluded that the real economic losses were between 190 and 290 million US$.

TABLE 6.3.13

Summary of claimed and awarded costs of the Amoco Cadiz tanker accident(in US$) [Sharples, 1992].

Recipient	Impacts	Claimed	Awarded
Clean-up	Government	66,406,000	30,007,000
	Communes	111,582,000	8,449,000
	Bird clean-up and lost profit in bird sanctuary	668,000	54,000
Fishermen	Fishermen/oystermen	7,779,000	4,326,000
	Transport oysters, shellfish/mussels	446,000	329,000
	Restore beds	464,000	393,000
	Seaweed harvest	31,000	31,000
	Miscellaneous	172,000	112,000
	Oyster growers	1,399,000	0
Economic loss	Government (sports and leisure)	660,000	315,000
	Brittany ferries	1,493,000	360,000
	Other	8,425,000	604,000
Other	Ministry of labour (unemployment programmes)	283,000	147,000
	Ministry of industry (research)	1,915,000	585,000
	Fish products	87,000	38,000
	Total	201,810,000	45,750,000

Also Grundlach et al. [1983] investigated the effects of the oil spill of the Amoco Cadiz in 1978. The most important change was the reduction of the flatfish population. It was, however, concluded that after three years the population of flatfish reached natural variability.

6.3.7.3 Oil spills and ecological impacts

The percentage of oil discharged into the marine environment by means of tanker accidents amounts to only 1.6% of the total but the impacts to marine environment can be very disastrous and expensive. For instance, the resource damage figures of the tanker Exxon Valdez, which grounded on March 23rd 1989 indicate that over 90,000 sea birds, 1000 sea otters and 150 bald eagles perished. The costs are anticipated to be between 1.2 to 2 billion US$.

An evaluation of 18 tanker and offshore oil production accidents showed that weather and current conditions, the sensitivity to damage of coastal ecosystems and the distance to the coast were the most important factors for impacts to the marine environment. In many cases, the amount of spilled oil into the sea is of secondary importance. For instance, in the case of the Exxon Valdez tanker accident a comparatively small amount of oil was spilled into the sea (last line of Table 6.3.14) but because the accident occurred near to the coast and wind and current pushed the oil slick to the beaches the result was an ecological disaster. Oil moved along the coastline of Alaska, contaminating portions of the shoreline of Prince William Sound, the Kenai Peninsula, lower Cook Inlet, the Kodiak Archipelago, and the Alaska Peninsula. Oiled areas included a national forest, four national wildlife refuges, three national parks, five state parks, four state critical habitat areas, and a state game sanctuary. Oil eventually reached shorelines nearly 600 miles south-west from Bligh Reef where the spill occurred. An estimated 1,000 miles of shoreline was oiled.

TABLE 6.3.14

Selected major oil spills.

Shipname	Year	Location	Oil lost (tonnes)
Atlantic Empress	1979	off Tobago, West Indies	287,000
Castillo de Bellver	1983	off Saldanha Bay, South Africa	252,000
Amoco Cadiz	1978	off Brittany, France	223,000
Haven	1991	Genoa, Italy	144,000
Odyssey	1988	700 naut. miles off Nova Scotia, Canada	132,000
Torrey Canyon	1967	Scilly Isles, UK	119,000
Urquiola	1976	La Coruña, Spain	100,000
Hawaiian Patriot	1977	300 naut. miles off Honolulu	95,000
Independenta	1979	Bosphorus, Turkey	95,000
Jakob Maersk	1975	Oporto, Portugal	88,000
Braer	1993	Shetland Islands, UK	85,000
Khark 5	1989	120 naut. miles off Atlantic coast of Morocco	80,000
Aegean Sea	1992	La Coruña, Spain	74,000
Sea Empress	1996	Milford Haven, UK	72,000
Katina P.	1992	off Maputo, Mozambique	72,000
Assimi	1983	55 naut. miles off Muscat, Oman	53,000
ABT Summer	1991	700 naut. miles off Angola	51,000
Metula	1974	Magellan Straits, Chile	50,000
Wafra	1971	off Cape Agulhas, South Africa	40,000
Exxon Valdez	1989	Prince William Sound, Alaska, USA	37,000

Table 6.3.15 gives an overview of the amount of spilled oil, the distance from the place of each accident to the coast, the weather conditions, the ecological impacts and the costs. The case of the tanker Castillo de Bellver shows that farmland can be polluted by tanker accidents even if the beaches remain clean.

TABLE 6.3.15

Claimed costs, amount of spilled oil, ecological impacts, distance from the coast, and weather and current conditions for some severe oil tanker and platform accidents.

Date	Name of the unit	Spilled oil (tonnes)	Distance from the coast (km)	Weather and current conditions	Ecological impacts	Claimed Costs (million US$)
1979	Atlantic Empress	258,750	16-500	good weather conditions	Not extensive (no specific impacts known)	100
1983	Castillo de Bellver	255,000	71	wind pushed the 150 km^2 oil slick out to sea	No pollution of beaches but damaging of large areas of farmland due to black oil rain	NA
1978	Amoco Cadiz	230,000	0.5-1	Currents and wind pushed the oil slick to the beaches	Polluted beaches, fishing grounds and oyster beds	75
1979	Burmah Agate	37,500	6	Currents and wind pushed the oil slick to the coast	Pollution of 260 km of the Texas coastline	NA
1989	Exxon Valdez	32,500	0.5-1	Loss of control of the oil due to bad weather	90,000 sea birds, 1000 sea otters and 150 bald eagles perished. Polluted beaches and fishing grounds	1200-2000
1977	Ekofisk B	20,000	NA	Currents and wind pushed the oil slick to the open sea	No polluted beaches or fishing grounds	NA
1976	Argo Merchant	17,500	0.5-1	Bad weather broke up the oil slick and offshore winds dispersed the slick seaward preventing an ecological disaster	Dead sea birds	NA
1969	Santa Barbara	10,000	1-2	Currents and wind pushed the oil slick to the coast	4000 sea birds, 150 sea lions and 5 whales perished	560

NA = Not Available.

6.3.8 Some highlights

1. Along with higher oil consumption there has been a trend of increasing number of severe accidents resulting in fatalities within the oil chain.

2. The most risk prone stages in the oil chain are “Regional Distribution” and “Transport to Refinery”. Slightly more than 75% of all severe (≥ 5 fatalities) accidents in the oil chain occurred in these two stages.

3. Maritime accidents are the most frequent accidents during the stage “Transport to Refinery” while road accidents are the most frequent accidents during the stage “Regional Distribution”. In the latter mentioned stage petrol is the primary oil product involved.

4. The North-Sea is the most unfriendly environment for offshore activities and consequently has a high share of severe offshore accidents.

5. In the period of 1969-1996 more than 40 refinery accidents occurred. None of them caused more than 40 fatalities per accident.

6. In terms of the quantities released oil spills as a consequence of shipping and platform accidents are less significant than oil spills caused by industrial river runoff discharges, tanker operational discharges, sewage disposal and non-tanker maritime transportation. However, factors other than the quantity released (distance from the coast, weather and current conditions, time profile of the discharges and sensitivity of the areas exposed to oil pollution), contribute to and may in fact be decisive in the context of the ecological disasters caused by some tanker and platform accidents.

7. Table 6.3.16 lists the most expensive oil accidents in different stages of the oil chain, based on the information stored in ENSAD.

TABLE 6.3.16

Largest economic losses due to accidents at various stages of the oil chain.

Stage	Costs (million 1996 US$)
Exploration	1947
Extraction	1440-1800
Transport to Refinery	1360-2260
Refinery	916
Regional Distribution	571.3
Heating/Power Plant	61.5

6.3.9 References

Brown, R. (1981), Health and Environmental Effects of Oil and Gas Technologies: Research Needs. MTR-81W77, Mitre Corporation, July 1981.

Corbeil, J., Archambault A. (1992), Ponds Bildwörterbuch, Ernst Klett Verlag, Stuttgart, Dresden.

Encyclopaedia Britannica (1972). Book of the Year, Vol. 17, p. 758. University of Chicago.

Frischknecht R. (Ed.) et al. (1996), Ökoinventare von Energiesystemen - Grundlagen für den ökologischen Vergleich von Energiesystemen und den Einbezug von Energiesystemen in Ökobilanzen für die Schweiz. 3rd Ed. (in German), Swiss Federal Institute of Technology Zurich (ETHZ) / Paul Scherrer Institute (PSI), Zurich, Switzerland, July 1996.

Gerhartz, W. and Elvers, B., ed. (1991), Ullmann's Encyclopaedia of Industrial Chemistry. Vol. A18. 5th Ed., VCH Verlagsgesellschaft mbH, Weinheim, Germany.

Grundlach, E., Boehm, P., Marchand, M., Atlas, R. and Ward, D. (1983). The Fate of the Amoco Cadiz Oil. Science, 221: 122 - 29.

Munich Re (1991), Losses in the Oil, Petrochemical and Chemical Industries - A Report. A Publication of the Munich Reinsurance Company, Munich, Germany.

OECD (1991), The State of the Environment. OECD, Paris.

Seymour, R., Geyer, R. (1992), Fates and Effects of Oil Spills. Annual Review of Energy and the Environment, Vol. 17, pp. 261-83, California, USA.

Sharples, B. (1992), Oil Pollution by the Offshore Industry Contrasted with Tankers: An Examination of the Facts. Proceedings Institutional Mechanical Engineers, **206** (1992) 3-14.

6.4 Gas Chain

6.4.1 Gas chain structure

Natural gas is a mixture of gaseous hydrocarbons and is composed mainly of methane. It passes through several treatment steps before it can be transported by pipeline [Gerhartz and Elvers, eds., 1991]. The treatment (deposition of elemental sulphur, introduction of corrosion inhibitors, separation of liquids, mercury or nitrogen removal, etc.) can take place at the well or in centralised processing plants. Another important factor is the recovering of a proportion of the ethane and heavier component content in natural processing plants to meet product specifications which yield additional products such as ethane, Liquefied Petroleum Gas (LPG) and higher boiling hydrocarbons (natural gasoline).

A complex transportation system lies between the extraction of the natural gas deposits and the consumer. After the gas has been treated, so-called trunklines are connected with pipeline head stations. In this part the pressure amounts to 70-100 bar. Afterwards the natural gas is pumped into long distance pipelines and is transported under an average pressure of 65-70 bar to the take-over stations of the consumers. From there the gas is transported under a pressure of 25-40 bar to the control station of the regional distribution system. Next the gas goes under a pressure of 20 mbar to industrial customer(s), and/or households [Bartholomé et al., eds., 1975]. In the context of energy-related applications the natural gas chain can be roughly characterised by Fig. 6.4.1 [Frischknecht et. al., 1996].

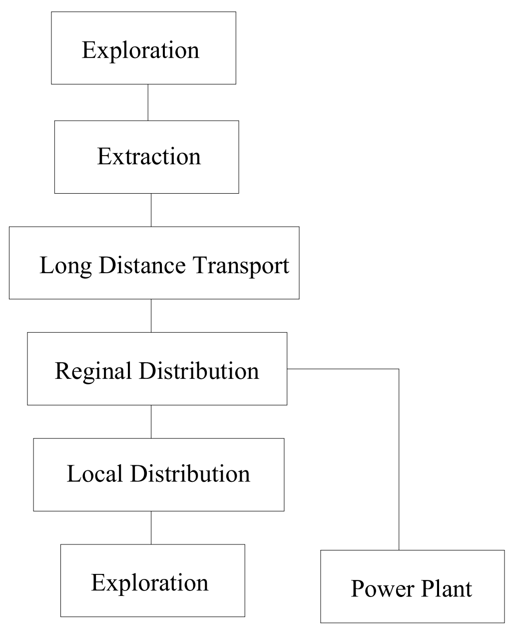

Fig. 6.4.1 Rough breakdown of the natural gas chain into different stages.

Another important gas resource is LPG. LPG can be produced primarily in two ways. The first is by extraction from crude oil and natural gas streams at or close to the point of production from the reservoir. Alternatively, LPG can also be obtained by processing crude oil in refineries [Gerhartz and Elvers, eds., 1990]. LPG can also be produced in refinery conversion processes. LPG consists of hydrocarbons mixtures in which the main components are propane ($CH_3CH_2CH_3$), butane (C_4H_{10}), isobutane ($(CH_3)_3CH$), propene ($CH_3CH{=}CH_2$) and butene (C_4H_{10}) [Gerhartz and Elvers, eds., 1990]. At a normal temperature and pressure these components and mixtures thereof are gaseous. But they can be liquefied by cooling or compression.

The transport means depend on the location of LPG production plants in relation to the markets. LPG may be transported by pipeline, sea, road or rail, in pressurised ships as well as trucks and rail cars. Large volumes, particularly within the USA, are transported by pipelines [Gerhartz and Elvers, eds., 1990]. For transportation to the consumers cylinders and bulk vehicles of various sizes are used.

LPG may be stored in three ways pressurised storage at ambient temperature, refrigerated storage at ambient pressure or semirefrigerated partially pressurised product storage [Gerhartz and Elvers, eds., 1990].

In Table 6.4.1 an overview of the differences in transport of natural gas and LPG is given [Bützer, 1988].

TABLE 6.4.1

Simplified representation of transport and storage systems for natural gas and LPG.

Gas	Transport stage	Transport means	Storage
LPG	Long distance	Tank wagon/Pipeline	Tankyard
	Regional	Tank wagon/Pipeline	Interim storage/ Filling stations
	Local	Road tanker	Tanks
	Customer	Pipelines	-
Natural Gas	Long distance	Large-diameter high pressure transmission pipelines	-
	Regional	High pressure pipelines	Storage pipe arrays/ Spherical gas tanks
	Local	Pressure pipelines	Storage pipe arrays/ Spherical gas tanks
	Customer	Low pressure pipelines	-

LPG finds a wide area of uses. Mainly it is used for cooking and heating. LPG is also an attractive automobile fuel because of the low exhaust emissions. LPG is employed in the refining and petroleum industries for the production of gasoline and the increase of the volatility and octane number of the fuel. Another use of LPG is in the manufacture of intermediate for polymers such as polyethylene ($(-CH_2-CH_2-)_n$), ployvinylchloride ($(-CH_2-CHCl-)_n$) and polypropylene ($(-CH(CH_3)CH_2-)_n$). In the pipeline gas industry specially propane is injected in the pipeline close to the consumer in the case when the pipeline is overloaded [Gerhartz and Elvers, 1990]. In the context of energy-related LPG applications the LPG chain can be roughly characterised as shown in Fig. 6.4.2. In contrast to natural gas no LPG is burned in power plants.

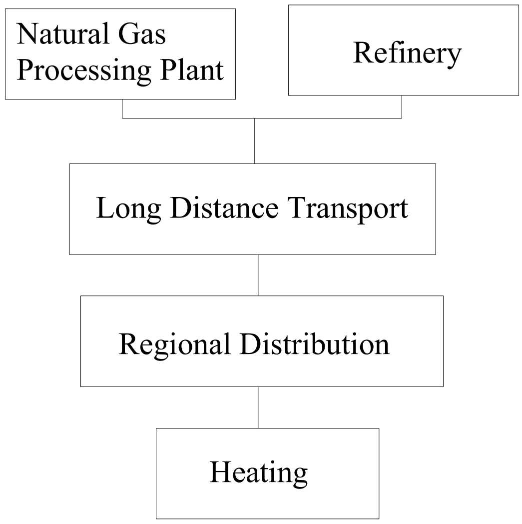

Fig. 6.4.2 Rough breakdown of the LPG chain into different stages.

Other gases that find a wide area of applications are: Gas works gas, coke oven gas and blast furnace gas. Gas works gas is produced in lighting gas factories [Falbe and Regitz, 1990]. Coke oven gas is produced as the name implies in coke ovens. The percentage of CO amounts up to 6%. The furnace gas is produced in blast furnaces. It contains 28-33% CO, 6-12% CO_2, 2-4% H_2, some methane and 55-60% N_2. Gas works, coke oven and blast furnace gases lost their importance for heating purposes and are not considered in the consequence evaluations included in the present report.

6.4.2 World-wide consumption and trends for combustible gases

In Fig. 6.4.3 the consumption of natural gas in OECD countries for the period 1960-1996 and the consumption of non-OECD countries and world-wide for the period 1971-1996 is shown [IEA, 1997]. The figure shows that for OECD-countries the consumption of natural gas doubled between 1960 and 1972 and then continued to grow at a lower rate. The figure shows also that for non-OECD countries the natural gas consumption increased constantly between 1971 and 1992 and began to decrease after 1992.

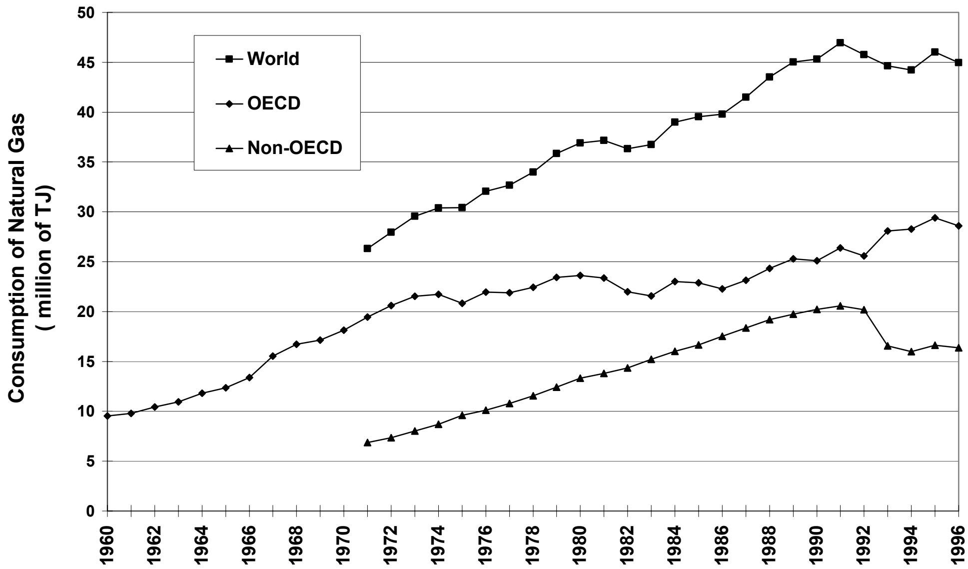

Fig. 6.4.3 Natural gas consumption in OECD and non-OECD countries [IEA, 1997].

In Fig. 6.4.4 the LPG consumption in OECD and non-OECD countries is shown. The figure demonstrates that the growth-rate of the consumption of LPG in OECD countries was higher during the period 1960-1973 than during 1974-1996. In non-OECD countries LPG is of increasing importance. In these countries the consumption of LPG was quadrupled between 1971 and 1996.

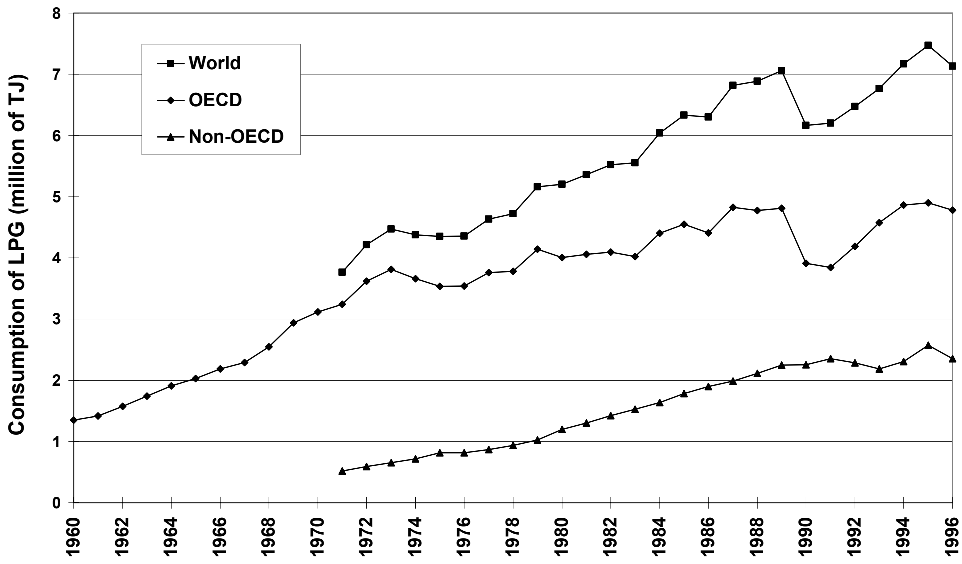

Fig. 6.4.4 LPG consumption in OECD and non-OECD countries [IEA, 1997].

The consumption in OECD countries of other gases such as gas works gas, coke oven gas and blast furnace gas is shown in Fig. 6.4.5. They partially lost their importance for heating due to their toxicity and found applications in other areas (see Section 6.4.3).

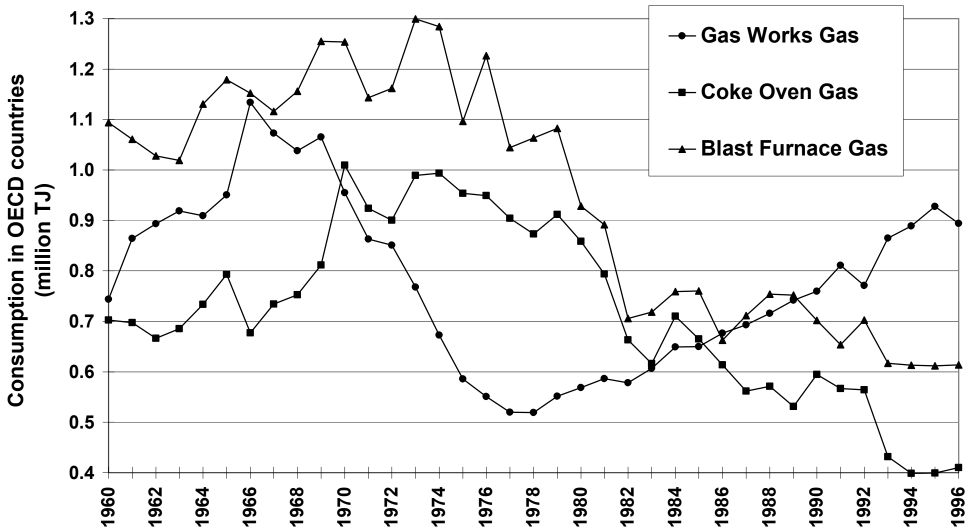

Fig. 6.4.5 Consumption of gas works gas, coke oven gas and blast oven gas in OECD countries [IEA, 1997].

For non-OECD countries only coke oven gas is of increasing importance (Fig. 6.4.6). The total consumption of gases such as gas works gas, coke oven gas and blast oven gas is lower than that of LPG. In Fig. 6.4.6, the consumption of coke oven gas shows a steep increase in 1980 when China began to report on energy consumption (the consumption prior to 1980 does not include data for China). In the same figure a large decrease in the consumption of blast furnace gas is seen because the former USSR did not report data beyond 1990.

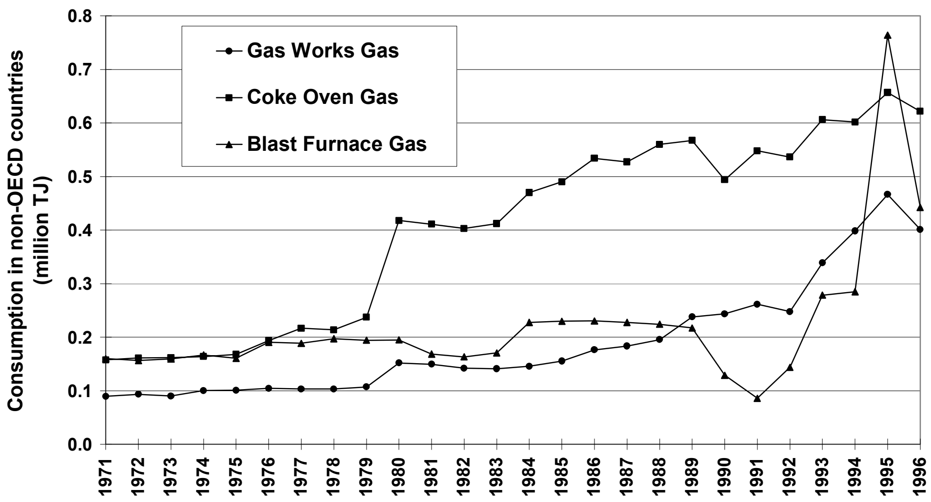

Fig. 6.4.6 Consumption of gas works gas, coke oven gas and blast oven gas in non-OECD countries [IEA, 1997].

6.4.3 Non-energy uses of various gases

Natural gas is used mainly for heating [Gerhartz and Elvers, eds., 1991]. LPG has different non-energy uses such as welding, lighting, propellant in sprays and as chemical raw material. The amount of combustible gases for non-energy uses is insignificant compared to the quantities used in energy applications [IEA, (1997)]. Therefore, it is a reasonable approximation to regard severe LPG accidents as energy-related.

Other gases such as gas works gas, coke oven gas and blast oven gas have lost their importance for heating since the seventies due to the toxicity of these gases containing a particularly great percentage of carbon monoxide. Other important application areas of these gases are the large-scale production of methanol, hydrocarbons and the reduction of ores [Bartholomé et al., eds., 1975].

6.4.4 Accidents, fatalities and injured in the gas chain

6.4.4.1 Severe natural gas and LPG accidents involving fatalities

In Fig. 6.4.7 the number of severe (≥ 5 fatalities) accidents in the gas chain world-wide is shown for the period 1950-1996. In the same figure a polynomial trendline of fourth degree is provided demonstrating a decreasing trend after 1984 even though the consumption of LPG and natural gas have been increasing (Section 6.4.2). The figure also shows that the yearly number of severe accidents scatters very strongly since 1970.

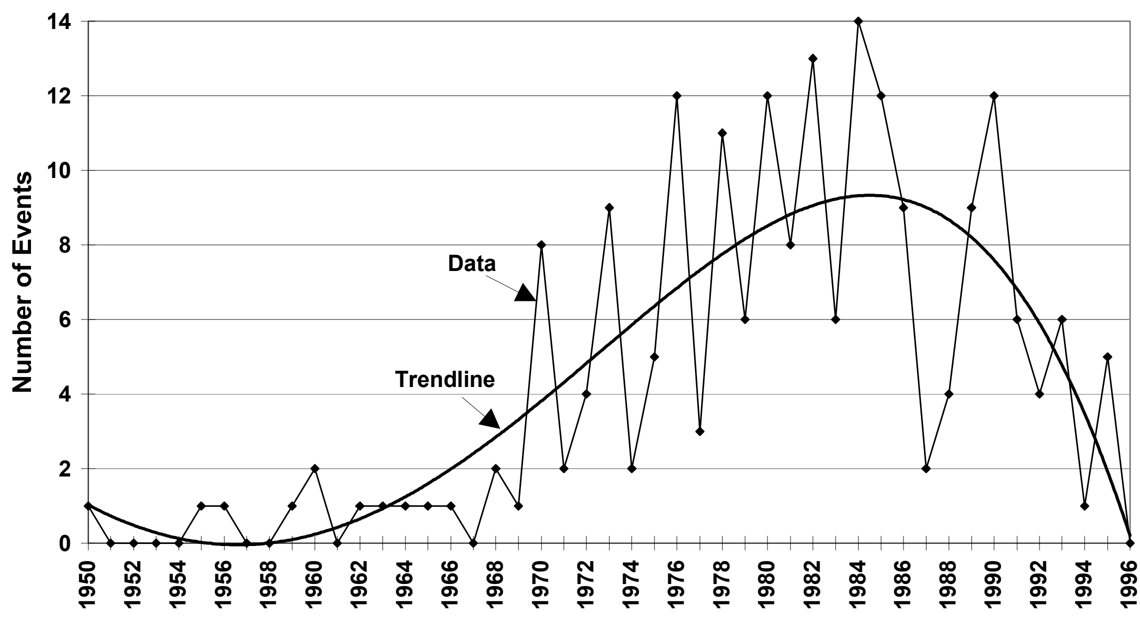

Fig. 6.4.7 World-wide number of severe (≥5 fatalities) gas accidents.

A clear explanation for this large scatter cannot be given; from Fig. 6.4.8 it can be seen that there is a large scatter from year to year in the number of severe accidents with natural gas as well as with LPG.

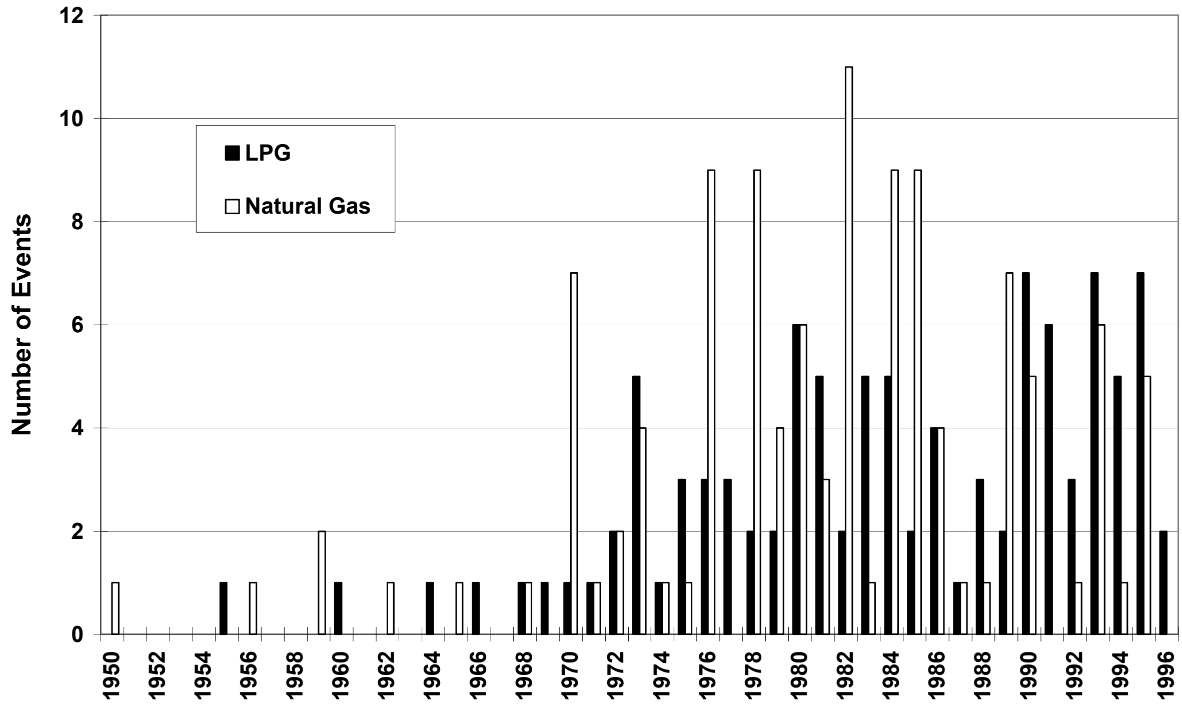

Fig. 6.4.8 World-wide number of severe (≥ 5 fatalities) LPG and natural gas accidents.

The worst disaster years in terms of the number of severe (≥ 5 fatalities) accidents were 1982 for natural gas and 1990, 1993 and 1995 for LPG.

In Fig. 6.4.9 the number of fatalities in severe (≥ 5 fatalities) LPG and natural gas accidents is shown. The worst years in terms of number of fatalities were 1984 and 1989 for LPG and 1978 and 1982 for natural gas. Two among the world's largest industrial accidents involved LPG. On June 4th 1989 about 600 people were killed and more than 700 injured by the massive explosion and fire between Asha and Ufa in Russia. Sparks from a passing train ignited a gas cloud originating from a leaking pipeline carrying 30% gasoline and 70% LPG. The second largest accident with LPG occurred on November 19th 1984 in San Juan Ixhuatepec in Mexico. About 500 people were killed when leaking LPG was ignited possibly by a gas burner. Within minutes two spheres exploded simultaneously. Numerous further boiling liquid expanding vapour explosions (BLEVE) occurred in the next 75 minutes. Only 4 out of 54 vessels remained intact.

The worst disasters with natural gas occurred on December 2nd 1984 and on April 8th 1970. One of these accident happened in Tbilisi in Georgia, where a fire caused about 100 fatalities. The other occurred in Osaka in Japan, where a fire also caused about 100 fatalities.

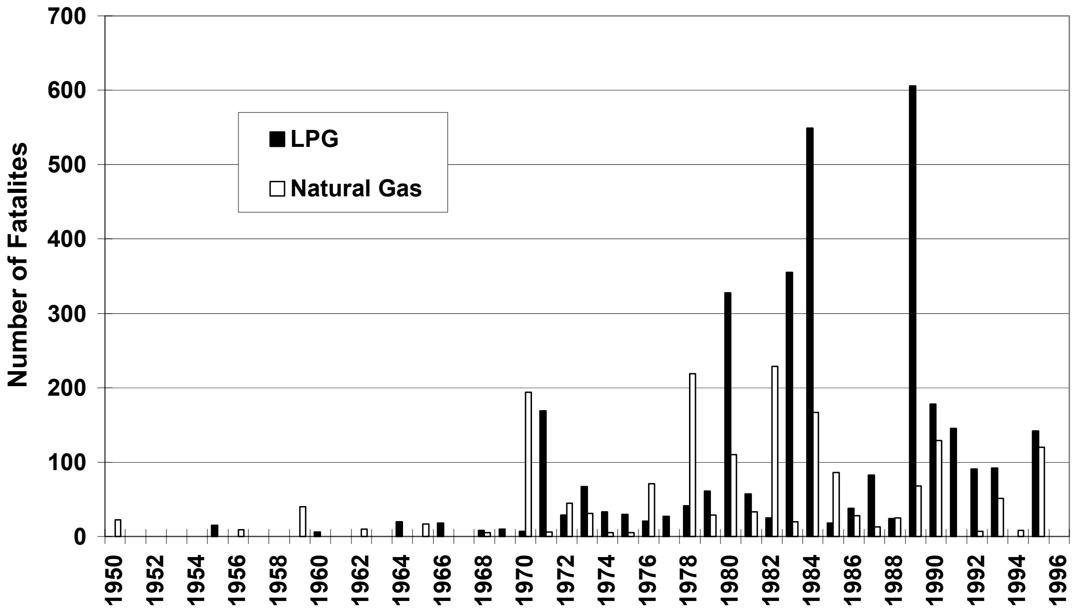

Fig. 6.4.9 World-wide number of total yearly fatalities in severe (≥ 5 fatalities) LPG and natural gas accidents.

In Appendix C lists of severe (≥ 5 fatalities, ≥ 10 injured, ≥ 200 evacuees, ≥ 5 million US$) natural gas and LPG accidents are given.

6.4.4.2 Severe natural gas and LPG accidents involving injured

In Fig. 6.4.10 the number of severe (≥ 10 injured) LPG and natural gas accidents is shown.

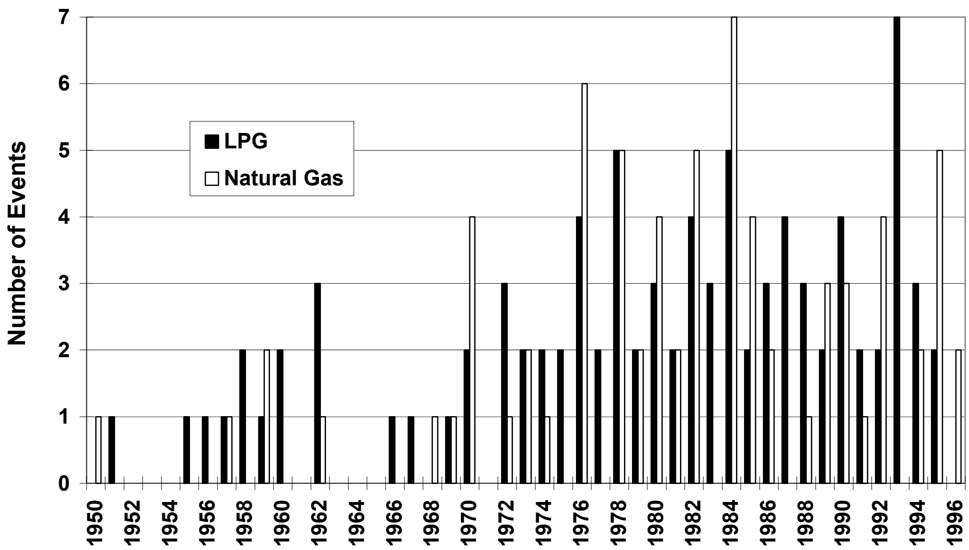

Fig. 6.4.10 World-wide number of severe (≥ 10 injured) LPG and natural gas accidents.

The figure illustrates that after 1972 severe LPG and natural gas accidents involving injured occurred more regularly. The years when most such events occurred were 1993 for LPG and 1984 for natural gas.

In Figure 6.4.11 the total yearly number of injured persons in severe (≥ 10 injured) and natural gas accidents is shown. The worst disaster year was 1984 with 7456 injured, mainly due to the LPG accident in San Juan Ixhuatepec (Mexico City) on November 19th. The number of injured persons never exceeded 1000 for other years both for natural gas and for LPG chain.

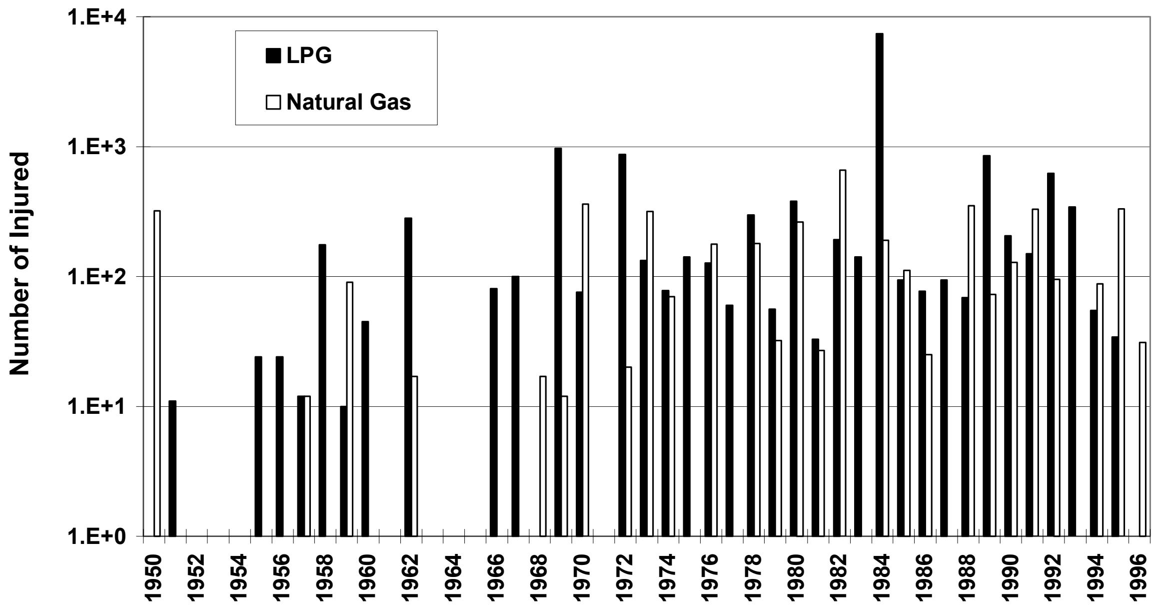

Fig. 6.4.11 World-wide number of injured persons in severe (≥ 10 injured) LPG and natural gas accidents.

6.4.4.3 Severe natural gas and LPG accidents involving evacuations

In Fig. 6.4.12 the total yearly number of severe (≥ 200 evacuees) LPG and natural gas accidents is shown. The figure demonstrates that more such accidents occurred with LPG than with natural gas.

The number of evacuees by year is given in Fig. 6.4.13. The two peaks for LPG in years 1979 and 1984 are mainly due to the accidents which happened on November 11th 1979 in Mississauga (Canada) and on November 19th 1984 in San Juan Ixhuatepec (Mexico). The first accident caused the evacuation of about 220,000 persons. In the second accident 200,000 persons were evacuated. The worst (in the evacuation context) severe natural gas accident occurred on January 20th 1982 in La Venta (Mexico) where 40,000 persons were evacuated.

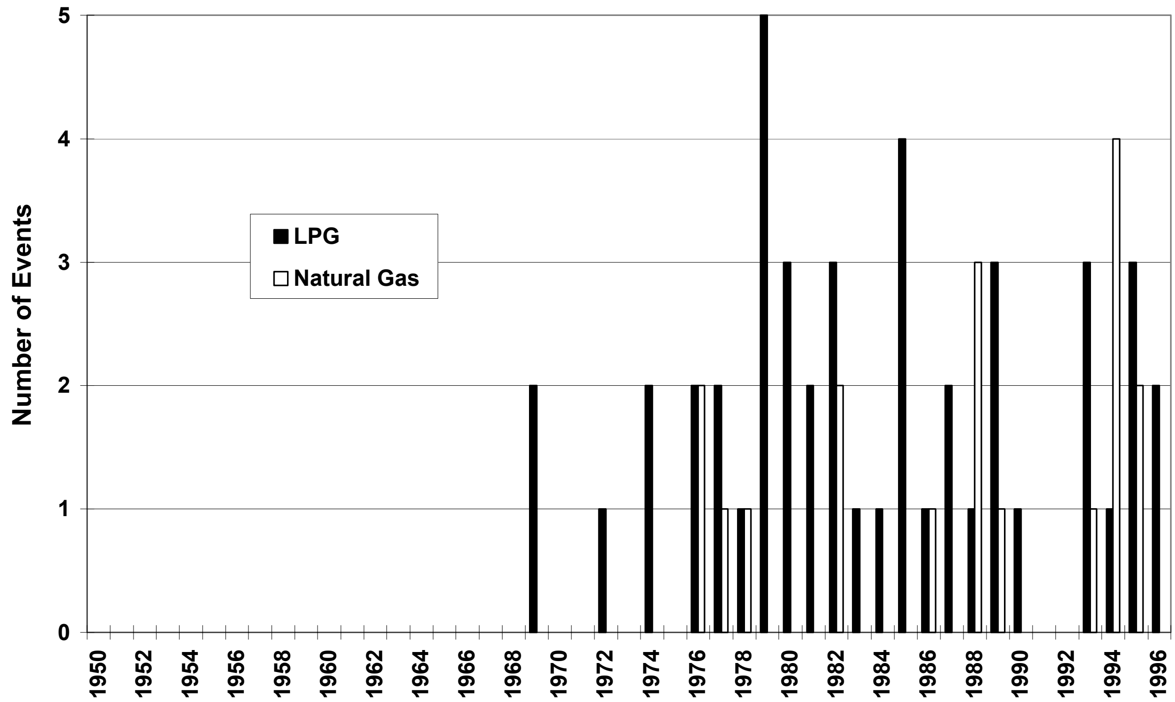

Fig. 6.4.12 World-wide number of severe (≥ 200 evacuees) LPG and natural gas accidents.

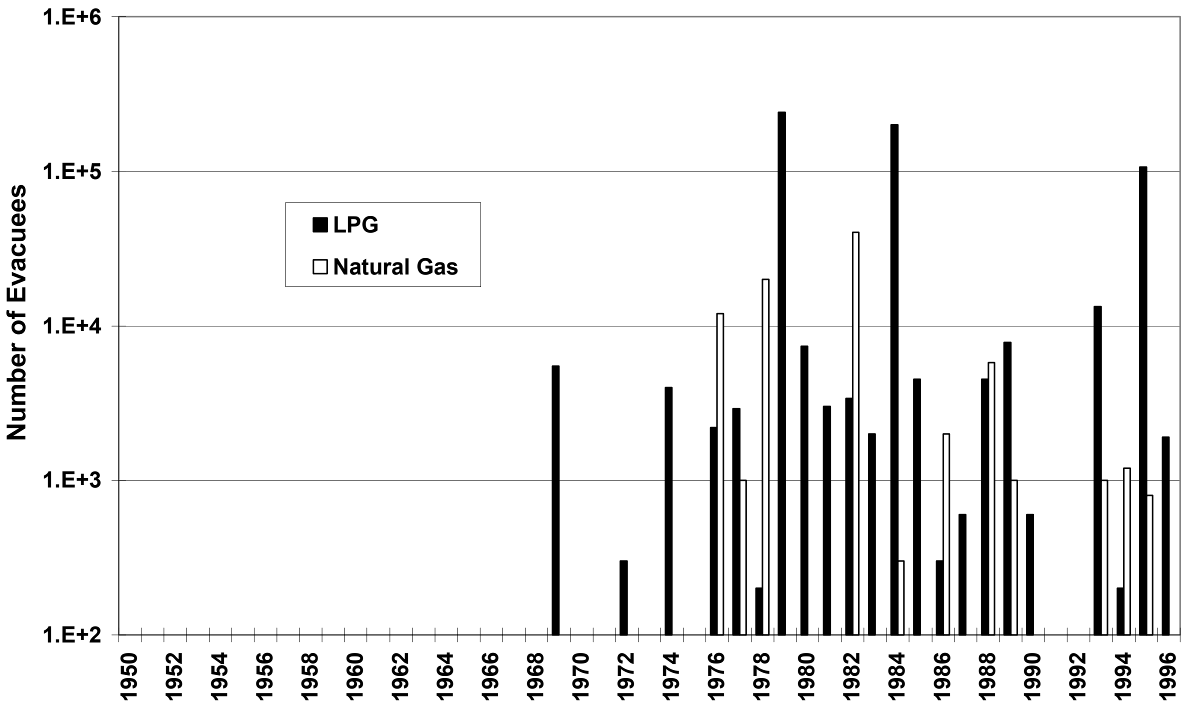

Fig. 6.4.13 World-wide number of severe (≥ 200 evacuees) LPG and natural gas accidents.

6.4.5 Breakdown into natural gas and LPG chain stages

6.4.5.1 Natural gas chain

Figure 6.4.14 shows the share of the different stages of the natural gas chain in severe (≥ 5 fatalities) accidents. The figure illustrates that most severe accidents occur in stages “Long Distance Transport”, “Local Distribution” and “Regional Distribution”.

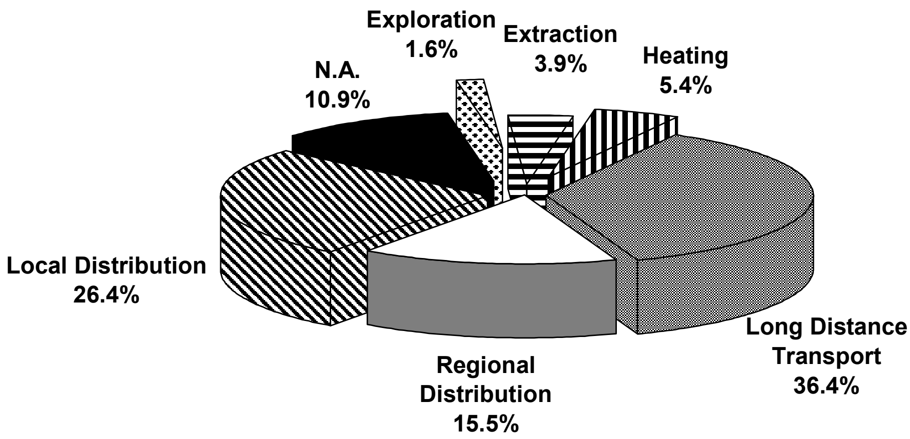

Fig. 6.4.14 Share of different stages of the natural gas chain in severe (≥ 5 fatalities) accidents in the period 1969-1996 (N.A. = information not available).

It may be of interest to investigate the causes of severe (≥ 5 fatalities) accidents which occurred in the stages “Long Distance Transport”, “Local Distribution” and “Regional Distribution” of the natural gas chain. A difficulty in this evaluation is that not all severe accidents are sufficiently well described. A closer look at 70 severe (≥ 5 fatalities) accidents from 1969-1996, collected and well documented in ENSAD, showed that 74% of these occurred during the transport of the natural gas through pipelines, 10% occurred during storage and 6% during the road transport with tank vehicles.

One of the main reasons for severe (≥ 5 fatalities) accidents due to failures of pipelines were mechanical failures and impact failures such as damage of the pipeline by vehicles or groundworks. The share of mechanical failures in all severe (≥ 5 fatalities) accidents with pipelines amounts to 35%. The corresponding share for impact failures is 36%. In the context of mechanical failures the main reason for the accidents was the leakage of natural gas from corroded pipelines. The escaping natural gas was ignited leading to considerable damages.

In Fig. 6.4.15 an evaluation of all 288 natural gas accidents collected in ENSAD is shown. Not all accidents are severe ones. This evaluation aims at investigating whether the same activities (transport by tank vehicles or pipelines, storage, etc.) and causes (impact, mechanical failures, etc.) dominate when all accidents are considered. Table 6.4.2 explains the terminology used in Fig. 6.4.15.

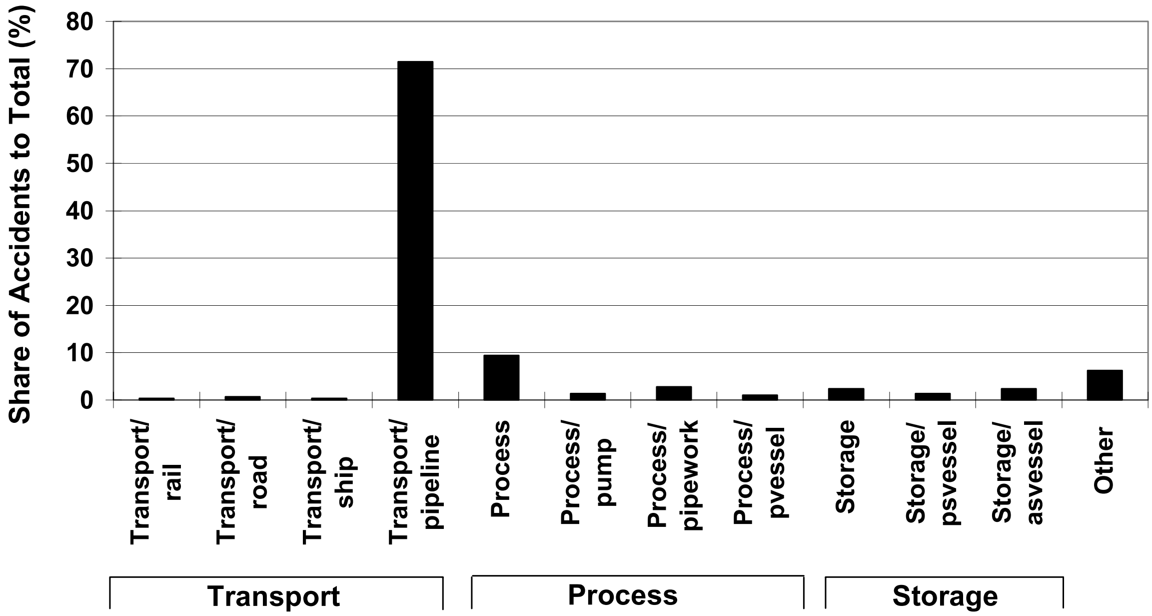

Fig. 6.4.15 Natural gas accidents and conditions of their occurrence (transport, process, storage) in the period 1969-1996.

TABLE 6.4.2

Overview of the terminology used in Fig. 6.4.15 and Fig. 6.4.18.

Abbreviation	Meaning
Dom/com	Incident originated in domestic or commercial premises
Process	Incident originated in not specified items of a process plant or in an area of a process plant
Process/pipework	Incident originated in on-plant pipes and associated valves or joints of a plant or in an area of it
Process/pump	Incident originated in any pump or compressor or ejector or fan of a plant or in an area of it
Process/pvessel	Incident originated in process vessels of a plant or in an area of it
Storage	Incident originated in a not specified part of a storage plant
Storage/asvessel	Incident originated in atmospheric pressure storage vessels of a storage plant
Storage/psvessel	Incident originated in pressurised storage vessels of a storage plant
Transfer	The incident originated during loading or unloading
Transport/pipeline	Transport in pipelines
Transport/rail	Transport in tank wagons
Transport/road	Transport in road tankers
Transport/ship	Transport in ocean going vessels
Waste	Waste storage or disposal areas

Figure 6.4.15 shows that accidents that occurred during the transport by pipelines represent the largest part of all accidents. This is fully consistent with the result that was obtained for severe (≥ 5 fatalities) accidents.

In Fig. 6.4.16 the main causes for pipeline accidents are shown. The figure shows that nearly 45% are mechanical and impact failures.

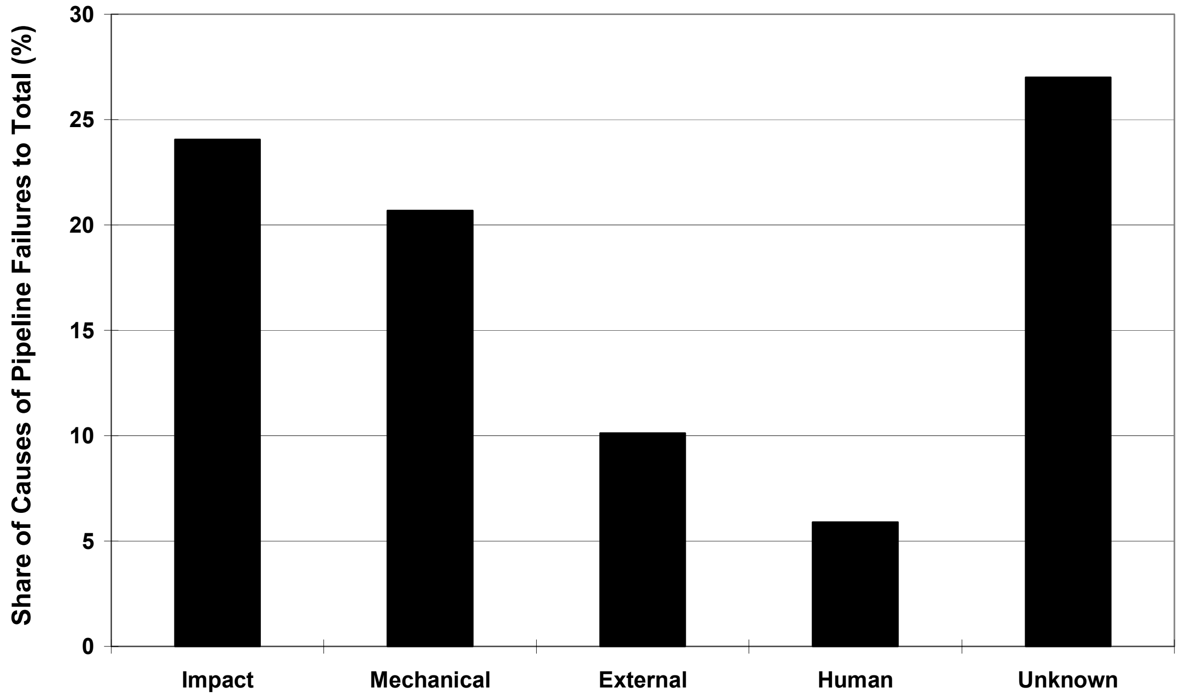

Fig. 6.4.16 Causes of pipeline failures in natural gas accidents between 1969 and 1996.

6.4.5.2 LPG chain

Figure 6.4.17 shows that nearly 65% of all severe (≥ 5 fatalities) accidents in the LPG chain occurred in the stage "Regional Distribution" and nearly 11% in "Long Distance Transport". At the stage "Natural Gas Processing Plant" several accidents caused by fires and explosions could be found but no one was severe in the context of fatalities, injured or evacuees.

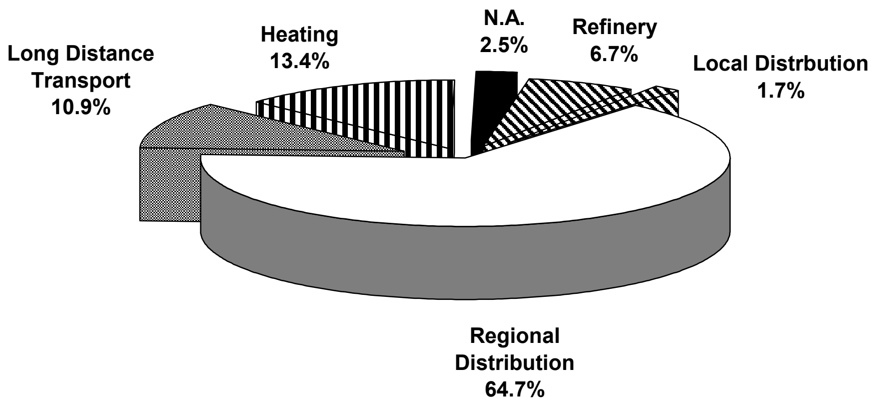

Fig. 6.4.17 Share of different stages of the LPG chain in severe (≥ 5 fatalities) accidents (N.A. = information not available).

The database ENSAD contains 26 well documented severe (≥ 5 fatalities) LPG accidents during the period 1969-1996. For the following statistical evaluations , where different accident characteristics such as the conditions of the occurrences and the causes of the accidents are considered, this number is too small. Therefore, the whole spectrum of 165 well documented LPG accidents was evaluated, including the non-severe ones. The conditions of the occurrence of the accidents are shown in Fig. 6.4.18. Approximately 50% of all accidents occurred during transport, particularly by rail and road tankers. Other areas where accidents relatively frequently happened are storage (15.8%), process (10.3%) and transfer (15.2%). The abbreviations on the x-axis in Fig. 6.4.18 were explained in Table 6.4.2.

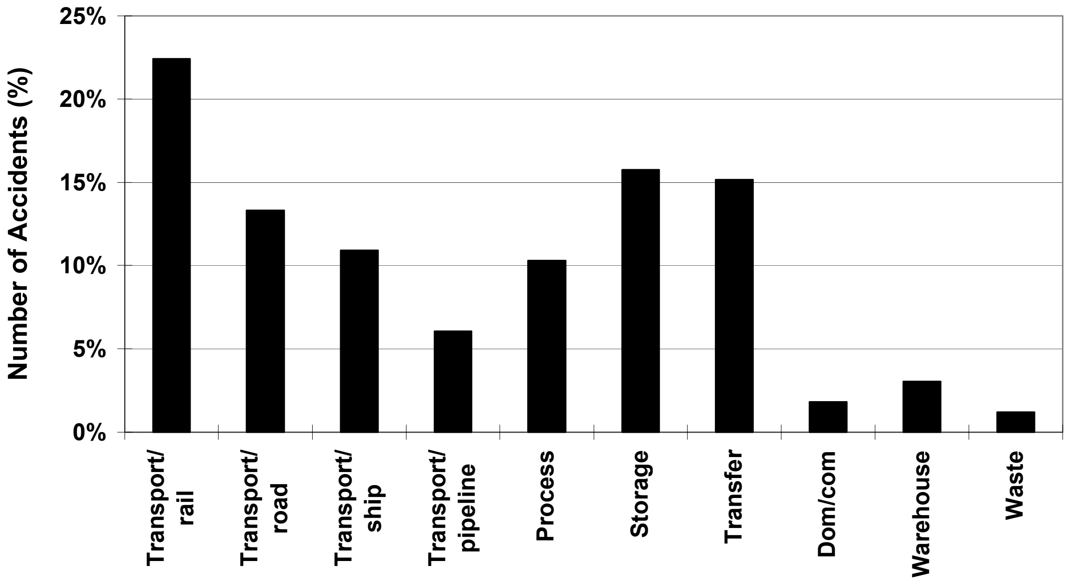

Fig. 6.4.18 LPG accidents and conditions of their occurrence (transport, process, storage, transfer, domestic or commercial premises) in the period 1969-1996.

The causes of the accidents in Fig. 6.4.18 are outlined in Fig. 6.4.19. The figure shows that impact failures are the most important cause for LPG accidents during the transport with road- and rail-tankers. Mechanical failures are the most frequent cause for LPG accidents during the process, transfer and storage activities.

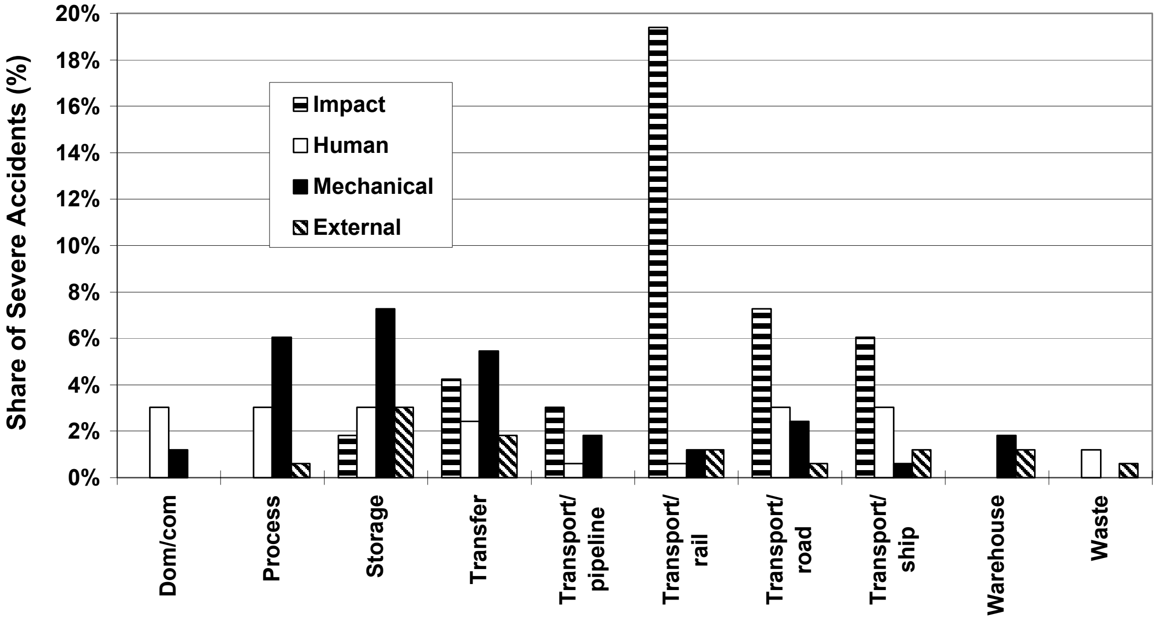

Fig. 6.4.19 Causes of accidents in the LPG chain in the period 1969-1996.

6.4.6 Country-specific distribution of severe natural gas and LPG accidents

In Fig. 6.4.20 the numbers of severe (≥ 5 fatalities) accidents in some OECD and non-OECD countries per consumed TJ of natural gas and LPG are given. The number of severe (≥ 5 fatalities) accidents per consumed TJ of LPG or natural gas does not exceeded the value of $3.0 \cdot 10^{-6}$ for OECD and non-OECD countries.

For the normalised number of fatalities a somewhat different picture is obtained (Fig. 6.4.21) for some of the countries (particularly for Mexico and the former USSR which had few LPG accidents but with a large number of fatalities involved).

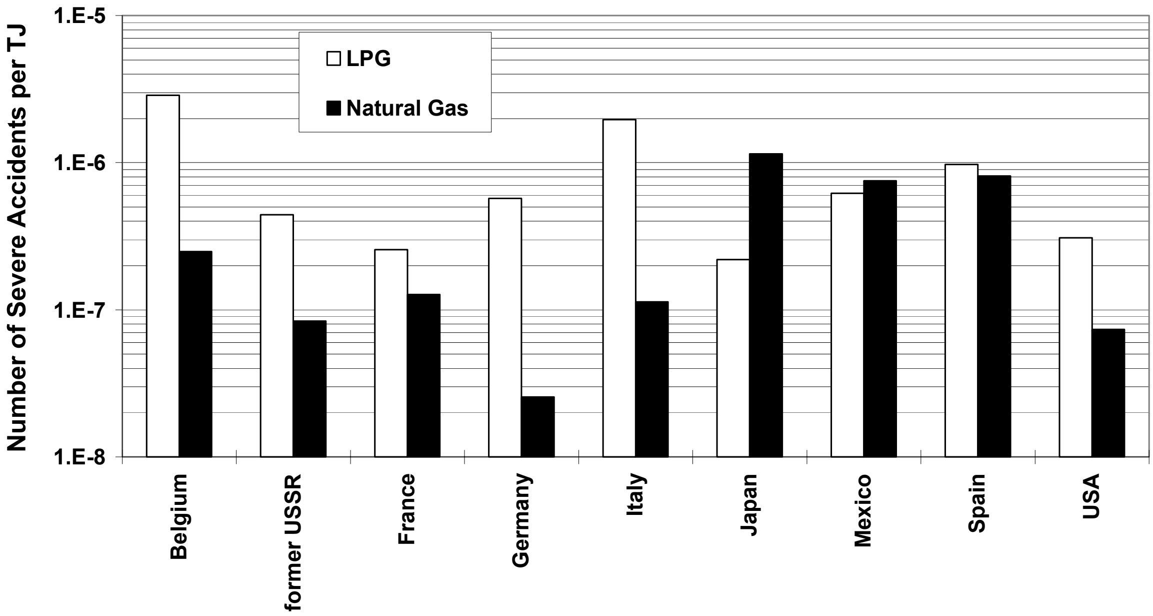

Fig. 6.4.20 Number of severe (≥ 5 fatalities) accidents per TJ of consumed natural gas and LPG in the period 1969-1996 for some OECD and non-OECD countries.

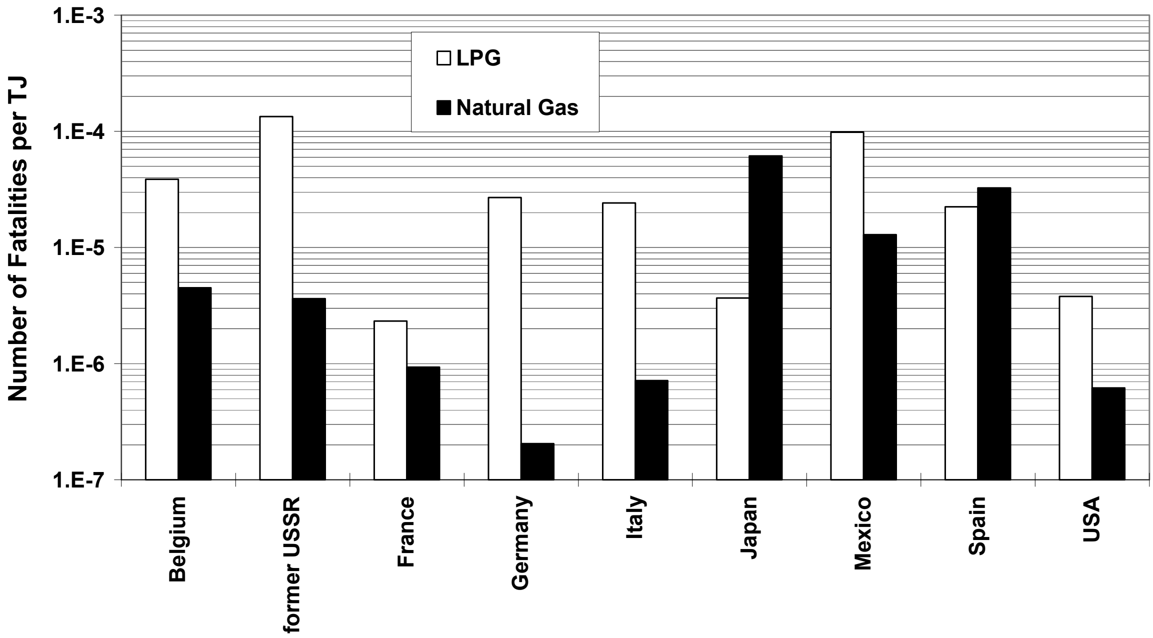

Fig. 6.4.21 Number of fatalities in severe (≥ 5 fatalities) accidents per TJ of consumed natural gas and LPG in the period 1969-1996 for some OECD and non-OECD countries.

6.4.7 Some highlights

1. The yearly number of LPG and natural gas severe (≥ 5 fatalities) accidents significantly increased after 1970. However, since 1985 there is a decreasing trend in the number of severe gas accidents. At the same time there is a large scatter in the number of accidents from year to year.

2. The stages in which most of the severe (≥ 5 fatalities) accidents occurred are "Long Distance Transport", "Local Distribution" and "Regional Distribution" for natural gas and "Regional Distribution" for LPG.

3. Nearly 72% of 288 natural gas accidents (not all are severe ones) which are collected in ENSAD occurred in 1969-1996 during the transport by pipelines, nearly 15% in a process plant or in an area of a process plant and only 6% in a storage plant. About 21% of all natural gas accidents involving pipelines were caused by mechanical failures and 24% by impact failures.

4. Nearly 53% of 165 LPG accidents (not all are severe ones) which are collected in ENSAD occurred in 1969-1996 during the transport by road- or rail-tankers, pipelines or by ship. The dominant cause was impact failure.

6.4.8 References

Bützer, P. (1988), Gefährdungsanalyse von Flüssiggas (Propan, Butan) und Erdgas (in German).

Bartholomé, E., Biekert, E., Hellmann, H., Ley, H. and Weigert, M., eds. (1975), Ullmann's Encyklopädie der technischen Chemie. 4th Ed., Verlag Chemie, Weinheim, Germany.

Falbe, J. and Regitz, M. (1991), Römpp-Chemie-Lexikon. Thieme Verlag, Stuttgart.

Frischknecht R. (Ed.) et al. (1996), Ökoinventare von Energiesystemen - Grundlagen für den ökologischen Vergleich von Energiesystemen und den Einbezug von Energiesystemen in Ökobilanzen für die Schweiz. 3rd Ed. (in German), Swiss Federal Institute of Technology Zurich (ETHZ) / Paul Scherrer Institute (PSI), Zurich, Switzerland, July 1996.

Gerhartz, W., Elvers, B., eds. (1990), Ullmann's Encyclopaedia of Industrial Chemistry, Vol. A15, 5th Ed., VCH Verlagsgesselschaft mbH, Weinheim, Germany.

Gerhartz, W., Elvers B., eds. (1991), Ullmann's Encyclopaedia of Industrial Chemistry, Vol. A17, 5th Ed., VCH Verlagsgesselschaft mbH, Weinheim, Germany.

IEA (1997), Energy Statistics and Balances, OECD (1960 - 1995), Non-OECD (1971 - 1995). International Energy Agency Diskette Service, OECD, Paris.

6.5 Nuclear Chain

This section has a somewhat different structure and content in comparison with the sections covering other energy chains. When addressing the issue of nuclear reactor accidents probabilistic technique was actively employed in addition to the consideration of past accidents. Furthermore, the much debated issue of external costs associated with hypothetical severe nuclear accidents was investigated in detail as a part of the present research. The accident-related nuclear external costs, as cited in the literature, differ by several orders of magnitude. For this reason the necessary background concerning external costs is summarised in the nuclear section although as the present study demonstrates the severe accidents issue is relevant for all major energy chains.

6.5.1 Trends in nuclear-based electricity production

Figure 6.5.1 shows the development of the nuclear electricity production in OECD and non-OECD countries in the period 1960 to 1996 inclusive. Major expansion took place in the eighties and was followed by a stagnation in the nineties. This is further illustrated by Fig. 6.5.2 showing the number of new nuclear power plants taken into commercial operation in the same period of time. After a peak occurred in 1985 with 38 new plants taken into operation, the number decreased to seven in year 1996. Without any doubt the Chernobyl accident in 1986 has had a strong impact on this development.

According to a recent press release of the IAEA [1997] 442 commercial nuclear power plants were in operation in 30 countries at the end of 1996; additional 45 are under construction in 16 countries and should go into operation in the next 14 years [IAEA, 1997]. The total installed power was 349,813 MW_e (net).

According to the same source 17 countries cover at least one fourth of their electricity demand using nuclear-based electricity; Switzerland is among them (43%). In eight countries - Lithuania (83%), France (77%), Belgium (55%), Sweden (50%), Bulgaria (48%), Slovak Republic (45%), Ukraine (44%) and Hungary (41%) - the contribution of nuclear power to the total electricity generation is over 40% [SVA, 1997].

In 1996 the world-wide nuclear electricity production was 2300 TWh, corresponding to 17% of the global electricity generation. The cumulated operational experience for nuclear power plants in operation at the end of 1996 amounted to 7259 reactor-years; the cumulated electricity production in the period 1969-1996 (here used as the evaluation period) was about 3685 GW_e*a.

6.5.2 Historical nuclear accidents

Two major accidents with high impact on the debate concerning the role of nuclear power as a major contributor to electricity generation occurred in the past, the core melts at the nuclear power plants Three Mile Island 2 (TMI-2, USA, 28 March 1979) and at Chernobyl 4 (former Soviet Union, 26 April 1986).

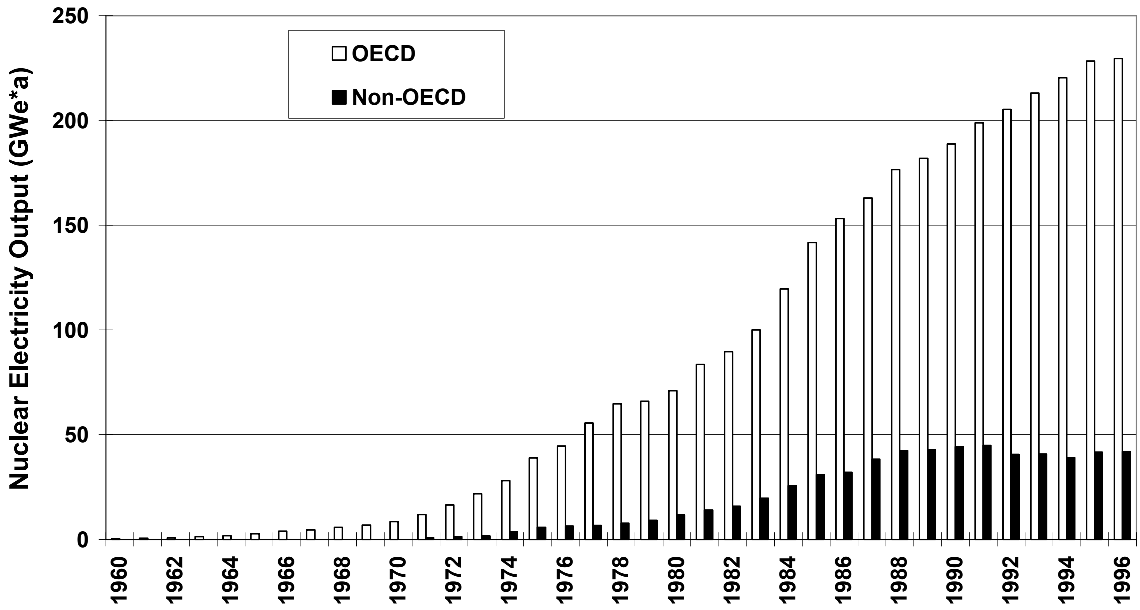

Fig. 6.5.1 Nuclear electricity production in OECD and non-OECD countries between 1960 and 1996.

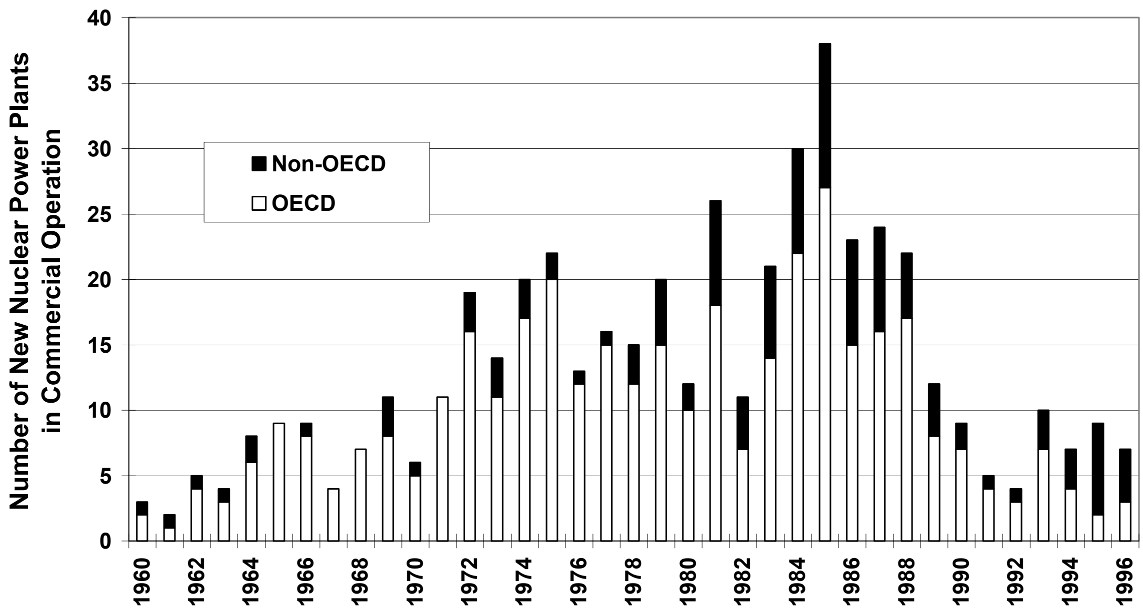

Fig. 6.5.2 New nuclear power plants taken into commercial operation in OECD and non-OECD countries between 1960 and 1996.

Appendix D provides a detailed discussion of the consequences of the Chernobyl accident and a survey of nuclear accidents (including TMI-2), as well as a number of other accidents with varying severity at nuclear power plants as well as other stages of the nuclear chain. Here only short summaries of the assessed consequences of the TMI-2 and Chernobyl accidents are provided.

The TMI-2 accident occurred at a 843 MWe PWR as a result of equipment failures combined with human errors. Due to small release of the radioactivity the estimated collective effective dose to the public was about 40 person-Sv. The individual doses to members of the public were extremely low, <1 mSv in the worst case [UNSCEAR, 1993]. On the basis of the collective dose one extra cancer fatality was estimated. 144,000 people were evacuated from the area around the plant [Sorensen et al., 1987]. Cleanup work at the site continues to date. [Komanoff, 1986] estimated the total cost of the TMI accidents to be about 130 billion US$, thereof 4 billion US$ are on-site costs due to the damage of the plant, clean-up and replacement power (under a limited period of time). The remaining 126 billion US$ are side effects of the accident on the nuclear (particularly PWR) programme in the USA. This includes the delays in plant building and financing, and the need of extra fossil fuels. Other costs may be considered as investments since they support improvements in operation, maintenance and safety. Side effects were observed world-wide in countries having nuclear power programmes; some of them adopted a moratorium on this technology. Recently, [Sørensen, 1994] estimated the cost of the TMI accident as 40 billion ECU. Also in this case side effects were included.

The Chernobyl accident happened at a 1000 MWe RBMK type of plant. The RBMK reactors are water-cooled and graphite-moderated. This type of plant is operated exclusively in some countries of the former Soviet Union. The accident revealed in an utmost dramatic way the deficiencies of the design of this reactor type, and the insufficient preparation and unsatisfactory safety culture of the plant management and staff.

The most up-to-date results concerning this accident have been emerging during the last few years. The current estimation of the consequences is as follows (primarily based on [EC/IAEA/WHO, 1996]):

- 237 individuals, all belonging to the reactor crew or to the emergency team, suspected of suffering from acute radiation sickness (ARS) were hospitalised. The diagnosis of ARS was confirmed in 134 cases. In the acute phase 28 persons died due to radiation exposure, two due to non-radiation causes at the accident site and one probably due to a coronary thrombosis. After the acute phase, 14 additional patients have died over the last ten years. Their deaths do not correlate with the original severity of ARS and may therefore not be directly attributable to the radiation exposure.

- The overall response to the accident was conducted by a large number of *ad hoc* workers, including operators of the plants, emergency volunteers such as fire-fighters, and military personnel, as well as many non-professional people. These people became known as “liquidators”. Approximately 200,000 liquidators worked in the region of Chernobyl during the period 1986 - 1987, when the radiation exposures were most significant. In total some 600,000 to 800,000 persons took part in the cleanup activities.

The predicted number of potential fatal cancers due to radiation exposure in the group of 200,000 is 2000 which for this group represents an excess of 5% of the normal number of cancer deaths. Additionally, 200 cases of leukaemia were predicted, an excess of 20%. According to the current models, 150 of these 200 excess leukaemia cases among the liquidators, would have been expected to have been seen in the first ten years. However, the numbers actually observed are consistent with the spontaneous incidence of leukaemia for this period.

- 135,000 members of the public were evacuated soon after the accident to protect them against high levels of radiation. A so called “exclusion zone” of 30 km was established on the most contaminated territories, to which access was prohibited to the general public. This zone was continued into the succeeding three independent countries and covers in total 4300 km^2. The predicted number of potential excessive fatal cancers among the evacuees is 150 (0.1% excess) and the number of corresponding leukaemia cases is 10 (2% excess).

- Among the residents of the so called “strict control zone” defined by activity level exceeding 555 kBq/m^2 (typically within a few hundred kilometres of the Chernobyl plant; total number of residents 270,000), the predicted number of potential excessive fatal cancer cases is 1500 (3% excess) and the number of corresponding leukaemia cases is 100 (9% excess). In other “contaminated” areas in Belarus, Russia and Ukraine having a population of 6,800,000 the predicted number of potential excessive fatal cancers amounts to 4600 (0.4% excess) and the number of corresponding leukaemia cases is 200 (1.5% excess).

- There has been a dramatic increase in the incidence of thyroid cancer, especially in young children. Thyroid cancer in individuals who were children at the time of the accident will be the form of cancer most likely to be clearly associable with the accident. The number of reported cases in Belarus, Russia and Ukraine up to the end of 1995 are close to 1000 in children between 0 - 15 years old; nearly 400 of these cases were observed in Belarus. According to the information available in 1996 ten children died of this disease. The expected survival rate within the group is 90 - 95%. The overall estimate of the number of thyroid cancers that are likely to occur in the most affected population (about 1,000,000 children) is 4000 - 8000 cases (100 - 400 times normal), thereof 200 - 800 fatal cancers.

- Between 1990 and the end of 1995, owing to ever-increasing societal pressure and the political situation following clarification of the radiological situation, there was further resettling of people in Ukraine (about 53,000 persons), Belarus (about 107,000 persons) and Russia (about 50,000 persons). Evacuation and resettling created a series of serious social problems, linked to the hardships of adjusting to the new living conditions.

- There are significant non-radiation-related health disorders and symptoms, such as anxiety, depression and various psychosomatic disorders attributable to mental stress among the population in the region. Psychosocial effects, unrelated to radiation exposure, resulted from the lack of information immediately after the accident, the stress and trauma of compulsory relocation, the breaking of social ties, and the fear that radiation exposure is damaging and could damage their and their children's health in the future. The psycho-social effects due to the accident are extremely difficult to distinguish from effects associated with the collapse of the USSR and economic hardship.

- In comparison with other European countries, relatively high levels of contamination were recorded in Bulgaria, Austria, Greece and Romania, followed by other countries of central, south-east and northern Europe. UNSCEAR estimated that outside the former Soviet Union the highest national average first year individual dose due to the accident has been 0.8 mSv and the highest regional average committed individual dose over the 70 years to 2056 is expected to be 1.2 mSv. These doses are in absolute sense very low and any effects of the exposure would be undetectable. For perspective, the global annual average radiation dose from natural background is 2.4 mSv, with considerable geographical variation. Hence in a lifetime an individual accrues on average 2.4 x 70 = ~170 mSv.

- While the risk to individuals receiving very small doses is very small, a huge number of people in space and time is affected. When the large collective dose (resulting from summing millions of very small doses) is combined with a linear dose response function with no threshold for the individual exposure, the thus estimated health effects may become dominant. For a discussion of the aggregation problem we refer to [Hirschberg, 1996]. Using the total collective dose due to the Chernobyl accident estimated by [UNSCEAR, 1993], reducing it by the above mentioned estimate of the number of latent fatalities among the public in the former Soviet Union, and using no threshold for the radiation exposure, leads to approximately 23,000 potential additional fatal cancers among the population of the entire northern hemisphere. These cancers will not be detectable since 650 million naturally occurring cancers are expected in the same population over the next 60 years. In a recent position statement [Mossman et al., 1996] the Health Physics Society[2] points out that: (a) Biological mechanisms including cellular repair of radiation injury, which are not accounted for by the linear, no-threshold model, reduce the likelihood of cancers and genetic effects; (b) Epidemiological studies have not demonstrated adverse health effects in individuals exposed to small doses (less than 10 rem (100 mSv)). With reference to the observability of radiogenic health effects, the Society has recommended to limit the estimates of risk to individuals receiving a dose of at least 5 rem (50 mSv) in one year or a lifetime dose of at least 10 rem in addition to natural background. Below this limit zero health effects is considered the most likely outcome. The average individual doses outside of the earlier accounted of

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2 The Health Physics Society is a US-based non-profit scientific organisation dedicated exclusively to the protection of people and the environment from radiation. Since its formation in 1956, the Society has grown to more than 6800 scientists, physicians, engineers, lawyers and other professionals representing academia, industry, government, national laboratories, trade unions, and other organisations. The Society's objective is the protection of people and the environment from unnecessary exposure to radiation, and its concern is understanding, evaluating, and controlling the risks from radiation exposure relative to the benefits derived from the activities that produce the exposures.

"contaminated areas" are clearly below this limit. For this reason the above mentioned estimate of 23,000 potential additional fatal cancers is subject to strong reservations.

- The total estimate of the number of fatal latent cancers due to the Chernobyl accident is roughly in the range 9000 - 33,000, with the upper range including the 23,000 cases based on the aggregation of small doses. When regarding the upper range of this interval the above discussed perspective of the Health Physics Society should not be forgotten.

- The estimated costs of the Chernobyl accident cited in [Nucleonics Week, 1994] range between 20 and 320 billion US$ (the range depends on the assumed exchange rate for roubles). It is not clear which cost elements are covered by these estimates. In [Sørensen, 1994] the estimated cost of the Chernobyl accident is 600 billion ECU. As in his corresponding estimate for TMI this includes side effects and monetised health effects.

Due to the radical differences in the plant design and operational environment the Chernobyl accident is essentially irrelevant for the evaluation of the safety level of the Swiss (and most Western) nuclear power plants. More specifically we note the following major differences:

- **Engineering.** Engineering differences between Russian- and western-built nuclear power plants have been studied and clearly identified in many sources (e.g. [EU-RF, 1996]). Serious deficiencies have been identified in the Russian PWRs design in general. With regard to the graphite moderated RBMKs, the lack of stable physical behaviour under accident conditions, lack of relevant safety studies and consequently lack of knowledge about this behaviour, lack of containment, deficiencies in separation of safety systems, are some examples of the weaknesses. In contrast, the recent studies conducted by the operators and the competent Swiss authority (HSK) demonstrate the Swiss plants meet stringent safety requirements.

- **Regulatory requirements.** Until 1988-1989 there was no regulatory body in the (then) USSR. The plants had no operating license since no licensing criteria existed, nor legislation, and design/construction were of a self-regulatory nature. All Western NPPs are strictly regulated by governmental bodies, with rules which conform to the IAEA standards. Consensus on regulatory requirements is being reached [EC, 1996].

- **Safety culture.** Safety culture and quality assurance were highly problematic in (then) USSR). In addition, written Emergency Procedures (EOPs) are still not generally implemented at Russian sites, and safety in the case of a severe accidents relies heavily on individual operator experience. In Western plants EOPs are implemented at each site and reviewed by the regulators.

- **Results of PSAs.** In general, PSAs performed for Western plants show core damage frequencies in the order of 10^{-5}. Those performed for Russian designs have core damage frequencies up to 10^{-2}.

The distinctions above are also important in the context of the external costs associated with severe nuclear reactor accidents.

6.5.3 Consequences and external costs of severe nuclear reactor accidents[3]

In the following the concept of external costs is introduced and their treatment in the context of energy sources is discussed with emphasis on severe nuclear accidents. The methodology used for the assessment of physical impacts of accidents (which according to some studies are among the main contributors to the external costs), and the results obtained as a part of this work, are presented.

6.5.3.1 The concept of externalities and its implications

Background and definitions

By **externalities** we understand economic consequences of an activity (such as energy production) that accrue to society, but are not explicitly accounted for in the decision making of activity participants. In the literature externalities are alternatively called side effects, spillover effects, secondary effects and external economies/diseconomies. In economic terms detrimental consequences are called **“external costs”**; positive consequences are called **“external benefits”**.

The concept of externalities has a long tradition in the economic literature (see e.g. [Kula, 1992]), starting with [Marshall, 1890]. Marshall addressed exclusively the advantages (benefits) enjoyed by businessmen without payment and outside the market. Later [Pigou, 1920] pointed out that externalities can also be of negative character and lead to costs. Apart from the outside of the market influence on the production conditions of the third parties also the welfare of private persons can be seriously affected both in cost and benefit terms. Kapp [1950] anticipated the far reaching consequences of economic growth on the environment and introduced the concept of **“social cost”**, which is defined as all direct and indirect burdens imposed on third parties or the general public by the participants in economic activities. He explicitly mentions all costs emanating from production processes that are passed on to outsiders by way of air and water pollution, which harms health, reduces agricultural yield, accelerates corrosion of materials, endangers aquatic life, flora and fauna and creates problems in the preparation of drinking water.

Two fundamental types of externalities can be distinguished: environmental and non-environmental. Examples of environmental externalities include impacts on public and occupational health (mortality, morbidity), impacts on agriculture and forests, biodiversity

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[3] The remaining part of this chapter is a modified and extended version of one of the authors’ contribution [Hirschberg, 1995b] to the forthcoming OECD/NEA Report on Methodologies for Assessing the Economic Consequences of Nuclear Reactor Accidents.

effects, aquatic impacts (ground water, surface water), impacts on materials (such as buildings, cultural objects), and global impacts (greenhouse effect). Among non-environmental externalities are public infrastructure, security of supply of strategic goods, and government actions (such as R&D expenditures).

Externalities arise due to the imperfections and/or non-existence of markets. For instance, there is no market for clean air and water. In a system of perfect competitive markets and in the absence of externalities, prices constitute the instrument for efficient resource allocation both on the production and consumption sides of the economy. Externalities are the source of misalocation of resources thus generating welfare losses to the society. Since the central theorem of modern welfare economics is that of Pareto efficiency, the relevance of an externality may be compared with this optimality condition. Accordingly, an externality is defined to be a **Pareto-relevant externality** when the extent of the activity may be modified in such a way that the externality-affected party can be made better off without the acting party being made worse off.

From the economic point of view complete elimination of externalities is neither practical nor desirable. For example, there is an optimum level of environmental degradation and this is not at zero level. From the point of view of the society as a whole the industry should reduce its discharge of pollution to the point where the sum of the cost of pollution and cost of pollution control is a minimum. In other words, beyond some point the cost of reducing pollution exceeds the benefits.

Internalisation of external costs

The impact of every industrial activity in a society includes, on one side, external costs like pollution, and also external benefits like improvement of the standard of living, employment generation or economic development. From society's point of view the price of a product should reflect all the involved external costs and benefits. When this is the case the costs and benefits are considered as **"internalised"**.

Most attention has been directed towards internalisation of external costs. With respect to external benefits the major ones are usually considered as already internalised by the existing market processes. There is, however, no general consensus about this point of view.

OECD defined **"the polluter pays principle"** as a fundamental principle of cost allocation. According to the "Guiding Principles" [OECD, 1975] the polluters should bear the expenses of preventing and controlling pollution to ensure that the environment is in an acceptable state. The principle is conceptually not limited to pollution control. In order to correct for externalities three types of environmental policy instruments exist: (1) taxes (fees, charges) and subsidies; (2) property-rights approaches (bargaining, tradable pollution permits); (3) direct regulation. There is a widespread controversy about which approaches are to be preferred.

6.5.3.2 External Costs and Electricity Generation

Role of health and environmental externalities in the electricity sector

Electricity generation like other industrial activities is not free from health and environmental impacts. Several of these impacts are traditionally not accounted for in the price of electricity. It is only recently that the issue started to receive the attention it deserves. In fact, since the late eighties the energy sector in particular has been subject to a debate (and in some cases to specific steps) concerning internalisation of external impacts, i.e. creating conditions where the damages from production and consumption are taken into account by those who cause these effects. The current trend is clear - externalities play an increasingly important role in decision-making and planning of utilities and other actors in the energy market. For example, a number of state public utility commissions in the US have begun to implement or consider monetised externality surchargers (adders) for air emissions and other environmental impacts from power plants. These environmental externality adders are charged for emissions not already covered by current emissions standards. They are intended to give utilities an incentive to reduce emissions beyond current requirements, including in some cases, currently unregulated emissions such as carbon dioxide. Consideration of external costs is particularly beneficial for electric utilities when considering the alternatives for the future. Accounting for environmental externalities may help to avoid costs of future environmental controls and reduce the uncertainties in utility resource planning. Full Cost Accounting (FCA), which is equivalent to accounting for both internal and external costs is one of the cornerstones of Ontario Hydro's sustainable energy development strategies.

It is worth noting that prior to this development a substantial number of potential external impacts has been effectively internalised through regulation and standards to which the power industry must comply. Thus, the damages associated with power generation are implicitly minimised. However, it needs to be acknowledged that the standards applicable to the different energy sources and to the various steps of energy chains (such as extraction, processing, transportation, power generation, waste management), are not homogeneous and not everywhere implemented to the same extent. Notably, when considering a specific energy chain, these activities may be taking place in different countries.

Current state of knowledge on external costs

Four basic approaches to the estimation of environmental external costs can be distinguished (see e.g. [Krupnick et al., 1993]):

- **"Top-down"** approach (pioneered by [Hohmeyer, 1988]). For example, in order to estimate damages from fossil fuels three steps are executed: (1) Identification of other studies' estimates of the total health costs attributed to air pollution; (2) Estimation of the fraction of the total emissions that originates from electric power generation from fossil fuels; (3) Multiplication of the total health costs according to (1) by the fraction according to (2). The method is obviously quite rough, relies on previous estimates of total damages, does not account for the different steps of energy chains and has no capability to account for site-specific effects.

- **Pollution control costs as a surrogate for damages** (e.g. [Bernow et al., 1990]). The rationale for this simple and thus attractive approach are the difficulties and uncertainties associated with the estimation of damage costs. The method is based on two not generally valid (actually frequently flawed) assumptions: (1) The marginal costs of abating emissions equal the marginal damages; (2) Environmental regulation is economically efficient. The assumptions are arbitrary since the regulators can not decide on optimal policies without knowing the damage costs. Nevertheless, the approach is particularly useful in the context of analysing external costs of Greenhouse Gas (GHG) emissions, a global problem characterised by overwhelming uncertainties when attempting to estimate the "true" damage costs. Extensive critical comments on the use of control costs are provided in [Pearce, 1995].

- **Limited "Bottom-up"** approaches (e.g. [Ottinger et al, 1990; Pearce et al., 1992]). Five steps were included in the Ottinger study (also referred to as Pace study; the study by Pearce is similar in spirit): (1) Estimate of emissions; (2) Estimate of dispersal of pollutants; (3) Determination of the population, flora and fauna exposed to the pollutants; (4) estimation of the impacts from exposure to the pollutants; (5) Calculation of the monetary cost of the impact. When calculating damages the method relies heavily on the estimates from previous studies; thus, no data are collected on the primary level. The account for different steps of energy chains is more extensive than in "top-down studies but still limited. Finally, the site-specific effects are not considered.

- **Full scope "Bottom-up"** approach of the EC/US study on external costs of energy chains ([ExternE, 1996a - 1996f; ORNL&RfF, 1992, 1994a, 1994b, 1995a - 1995e]. The damage function approach employed in these studies tracks the pathway from activities to emissions to ambient concentrations to impacts to costs. Estimation of the impacts relies almost entirely on the use of dose response functions to evaluate physical damages. The approach has been applied to specific sites (typically one or two per study for each energy source) and the different steps of energy chains were covered. Depending on the context of application of the results the single plant focus may be problematic. Different damage valuation approaches were used. These include market values, contingent valuation, travel cost and hedonic methods. The application concerns current technologies at existing (or in few cases hypothetical) sites. Lessons learned from the EC/US studies are summarised in [Krupnick et al., 1995]; the authors consider the damage function approach as superior to other methods.

Some recent studies exhibit elements from the different approaches above. One example is the Swiss study by INFRAS & PROGNOS [Ott et al., 1994] where, however, the use of the full scope "Bottom-up" approach is limited.

A number of difficulties and limitations are associated with the estimation of external costs [Hirschberg and Erdmann, 1994; Hirschberg, 1995a]:

- Estimation of physical impacts is a complicated and resource-demanding task. Among many factors affecting these estimations we may mention physical characteristics of the emissions (e.g. rate, duration, location), meteorological and topographical conditions, pollutant interactions and transformations. Dose-response functions for estimation of health and environmental effects are "known" for only few major pollutants and are frequently subject to large uncertainties.

- Transferability of results obtained for a specific environment may be questionable or not valid for the environment being examined. Ideally the full scope "bottom-up" approach should not be subject to this limitation. However, from practical point of view it may not be feasible to simulate from scratch all environmental damages for all energy chains on a location-specific basis. Consequently, it is customary to use to some extent data from different studies and attempt to correct for the differences between the source and application environments by introduction of systematic factors (scaling). Bearing in mind the complexity of the estimation (see the point above), this process is normally associated with large uncertainties.

- The effects of incremental loads may be non-linear, i.e. depending on the baseline level of environmental quality a small increment could lead to substantial damage or none at all.

- Establishment of boundary conditions, particularly time and space limits, for environmental damage estimation is not straight-forward. Thus, the time scales for manifestation of environmental damage can vary; transboundary effects and contributions of parts of energy chains in foreign countries may be very important and it is an open question how deep in the structure of energy chains one should go in order to account for all significant contributions (e.g. material manufacturing). The focus of many studies has been on the production facilities, while such parts of specific energy chains as transportation or storage may constitute potentially important, but unaccounted for contributors. The effects can be local, regional or global. Usually, local and regional impacts can be assessed with more confidence than the global ones.

- Explicit monetisation of damages allows to express the cost of a specific damage per unit of energy produced. Advantages of such representation are clear - the detrimental effects are expressed in a manner which allows direct and consistent comparisons between internal and external costs, between different contributors to external costs and between various energy chains. Monetisation is carried out using different approaches, particularly since some of the commodities are marketable and others are not. The use of discounting, i.e. placing a lower value on damages that occur in the future as compared to the present ones, is a debatable issue with large potential impact on the numerical results.

- Scope and depth of the analyses addressing the contribution of severe accidents to external costs is inadequate. This is partially due to the inhomogeneous state of knowledge concerning the risks associated with different energy chains and partially due to the use of non state-of-the-art or even flawed approaches.

Estimation of external costs is clearly subject to large uncertainties; some of them are inherent and will stay with us, other are matters of practice and are bound to be reduced with the increased state of knowledge and prospective agreements on procedures for carrying out balanced evaluations. Incidentally, treatment and representation of uncertainties, which appears to be central in the support of decision-making, is another weak point of current studies.

In no way the deficiencies and difficulties currently being experienced should be viewed as disqualifying the efforts to estimate the costs of environmental damage. Firstly, the discipline is extremely young, and tries to penetrate partially unexplored terrain. Secondly, we know for certain that environmental damages occur, although we may have difficulties in estimating them with the desired precision. Assigning to them a value of zero, as was practised in the past, appears to be the worst possible solution.

At first look the results of the different external cost studies show large discrepancies (up to orders of magnitude) between the estimates by the different authors. Earlier studies (particularly [Hohmeyer, 1988 and 1990]; to some extent [Ottinger et al., 1990]) tend to exhibit high overall results for fossil and nuclear sources; in view of his results Hohmeyer [1990] claimed that given a full account of external costs for fossil and nuclear, solar and wind energy would be fully competitive today. The latest, more detailed and comprehensive studies (EC/US study in particular) when applied to modern (i.e. clean) technologies, and excluding Greenhouse Gas effects and risk aversion to nuclear accidents, produce much more moderate estimates (in most cases clearly below 1 (US)cent per kWh). Consequently, given use of modern technologies, the ranking of the different electricity generation sources based on private costs is not much affected by consideration of external costs unless the highly uncertain and controversial costs of aversion and of potential impacts of global warming are considered.

<u>External costs and severe accidents in the energy sector</u>

There is no disagreement that the external costs associated with normal operation of nuclear power plants are small, i.e. typically below 0.1 cents per kWh. With regard to severe accidents the past external cost studies concentrate on hypothetical nuclear reactor accidents. Notably, accidents in energy chains other than nuclear have been mostly ignored in external cost studies or have been treated in a very simplistic manner. This is a deficiency since accidents do occur in various steps of the different energy chains as demonstrated in the present report. It needs to be said that the Chernobyl accident has a special "prominence" in this context in view of the very high number of estimated delayed fatalities and other serious health, environmental and social impacts.

Use of past experience to evaluate external costs is subject to serious limitations (further discussed in the next section). In the nuclear case the statistical material consists of only two accidents, i.e. Three Mile Island (TMI) in 1979 and Chernobyl in 1986.

In Section 6.5.2 estimates of the economic losses associated with the TMI accident were provided in [Komanoff Energy Associates, 1986; Sørensen, 1994]. Corresponding estimates for Chernobyl may be found in [Nucleonics Week, 1994; Sørensen, 1994]. Using these values and considering that the total commercial nuclear experience until the end of 1996 corresponds to about 3680 GW_e*a, we obtain the normalised cost of past nuclear accidents to be in the range of 0.3 to 2.9 cents per kWh. These numbers are provided here only as the background to the estimates based on the different approaches, presented in the next section. They are not representative for current plants with good safety standards (from design and operational point of view), since neither TMI nor Chernobyl in particular were designed to meet these standards. Moreover they contain side effects and some cost elements that already are internalised.

6.5.3.3 Studies of External Costs of Nuclear Reactor Accidents

Historical background

The primary objective of early studies was in most cases the estimation of off-site financial consequences of nuclear reactor accidents, without consideration of the probability of occurrence of such accidents. The first very rough attempt in this direction was undertaken by the US Atomic Energy Commission [USAEC, 1957]. The "Reactor Safety Study" [USNRC, 1975], on the other hand, was the first comprehensive application of Probabilistic Safety Assessment (PSA) techniques to estimate the risks to the public from the operation of nuclear power plant. This included the assessment of economic risks using the Calculation of Reactor Accident Consequence (CRAC) model. Using an improved version of CRAC the offsite financial costs of five types of accidents for 91 nuclear power plant sites in the US were estimated in [Strip, 1982]. Economic effects labelled "property damage" included: lost wages, relocation expenses of the evacuated population, decontamination costs, loss of crops and milk, and interdicted land costs. In addition, three types of major types of public health effects were estimated, i.e. prompt fatalities, early injuries, and latent cancer fatalities; financial costs were attached to these effects using empirical values of society's willingness to expend resources to avert a death. Burke et al. [1984] developed a new set of models based on the original CRAC model, which allowed for more flexibility in operation and accuracy in supplying input data for the offsite cost estimations. The models were applied to the Surry site.

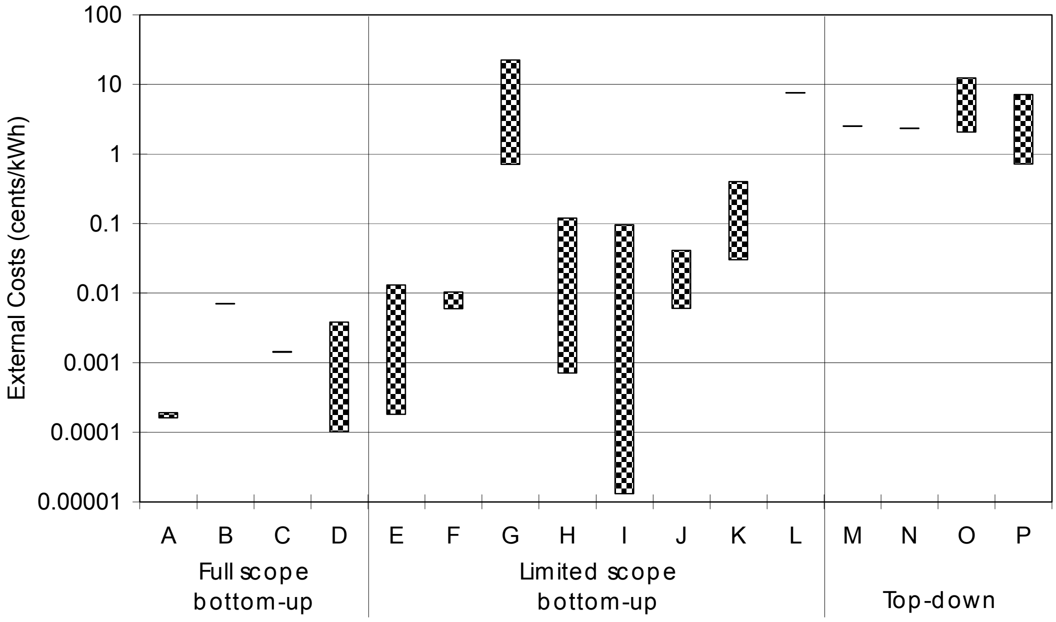
Later applications reflect the improvements in consequence modelling as well as better knowledge of source terms. Thus, code systems such as UFOMOD [Erhardt et al., 1988], MACCS [Jow et al., 1990], COSYMA [Ehrhardt and Jones, 1991], COCO-1 [Haywood et al., 1991] and MECA2 [Gallego, 1989] were developed. Economic consequence models in all these codes were expanded and upgraded in relation to the earlier approaches. With respect to source terms calculations major advancements were achieved and implemented in the latest severe accident risk study by USNRC [USNRC, 1990a], leading to less conservative source terms than these used by [Burke et al., 1984]. Economic accident consequence analyses were also carried out for non light water reactors (for example Canadian CANDU; [Lonergan et al., 1990]). This was followed by numerous calculations of external costs associated with severe nuclear accidents.

Relatively simple atmospheric dispersion models (unidimensional, without contours such as mountains) are used in all the above mentioned consequence codes. Accuracy of results beyond 70-80 km is quite poor. Although economic models have improved they rely on expert judgement. Uncertainties are treated to a limited extent, i.e. only uncertainties in releases and release frequencies are included.

In the following we concentrate on studies of external costs of severe accidents. A survey of a number of such studies can be found in [Hirschberg, 1995a]. Since additional studies have been identified an extended survey will be presented in this section.

Summary of results of external cost studies

Figure 6.5.3 shows the estimates of contributions of severe accidents to external costs of nuclear power, obtained in different studies in recent years. All costs are expressed in cents per kWh, based on exchange rates in March 1994.



A	Wheeler & Hewison (UK) 1994	B	Hirschberg & Cazzoli (CH) 1994: Zion (mean)
C	Hirschberg & Cazzoli (CH) 1994: Peach Bottom (mean)	D	Hirschberg & Cazzoli (CH) 1994: Mühleberg
E	CEPN (F) 1994	F	Fisher & Williams (USA) 1994
G	Masuhr & Oczipka (CH) 1994 (under “risk awareness”)	H	Masuhr & Oczipka (CH) 1994 (under “risk neutrality”)
I	ERG (Can) 1993	J	Friedrich & Voss (D) 1993
k	Pearce (UK) 1992 (risk aversion included)	L	Ferguson (UK) 1991 (risk aversion included)
M	Ewers & Rennings (D) 1992	N	Ottinger (USA) 1990
O	Hohmeyer (D) 1990	P	Hohmeyer (D) 1988

Fig. 6.5.3 Span of estimated external costs of severe reactor accidents; the estimate for Mühleberg includes external events.

The values in the figure cover a range of some six orders of magnitude. No attempt to express the prices in terms of present values was made here; this would actually, in most cases, further increase the differences.

Types of studies

The calculation of external costs associated with rare severe accidents includes the same basic steps as the estimation of external costs in general. There are, however, some specific characteristics related to the random nature of the events, which require special treatment.

The main steps are:

1. Identification of externalities (types of accidents) specific for the activity.

2. Evaluation of resulting physical impacts. For effects that originate from rare events rather than from continuous releases of pollutants this step necessarily involves the assessment of frequencies associated with consequences of different magnitudes.

3. Monetisation of damages.

As evident from point 2 above any estimate of external costs will need to use some input from Probabilistic Safety Assessment (PSA). This is actually the case with all studies cited in this section. However, the extent to which the PSA results have been used and consistency of the application varies significantly. For this reason the studies considered here have been grouped with respect to the weight given to PSA on the one hand and to past experience of severe nuclear accidents (equivalent to Chernobyl) on the other hand. In reality there are some mixtures of the different approaches; in applicable cases the allocation is made on the basis of the dominance of one factor over the others. Using the same categories as applied to the external cost studies in general (see Section 6.5.3.2), this leads to the following groups of studies:

A. **"Top-down"** studies, based on (and driven by) the Chernobyl-specific total dose to the population.

B. **Limited "Bottom-up"** studies, extrapolating PSA results obtained for a specific plant in a specific environment to the case of interest and/or using few PSA-based scenarios.

C. **Full scope "Bottom-up"** studies, fully based on a plant-specific PSA or on an alternative, detailed, plant-specific probabilistic consequence analysis.

Some of the results are driven by risk aversion, independently of the type of the study according to the classification above. Since the treatment of risk aversion is from the methodological point of view a central but simultaneously an open issue, it will be treated separately in Section 6.5.4.

Short survey of selected nuclear accident external cost studies

A. "Top-down" studies

- **[Hohmeyer, 1988 and 1990].** Since other studies of this type follow in their spirit the work of Hohmeyer, more space is given here to the description of his studies. Hohmeyer estimated external costs of accidents at a German plant (Biblis), using the Chernobyl-specific collective dose to the world population (pessimistic estimate, available at that time) as the starting point and upgrading it by a factor supposed to reflect the higher population density in Germany. In the study of 1990 an additional factor (of five) was introduced to represent the largest possible release for the Biblis plant. This was combined with the **total** core damage frequency which, however, was assigned to the maximum source term (whose frequency is only a share of the total); accident mitigation measures which further reduce this frequency were not credited. The upper result for a Chernobyl accident in Germany was in the 1988 study obtained as follows:

[2.4 10^6 person-Sv (collective dose from Chernobyl) x 10 (higher population density) x 100 000 cancers/10^6 person-Sv (dose-response factor) x 0.75 10^6 DM (cost of each cancer case) x 5 10^{-4} accidents/reactor-year (accident frequency)] : 7.5 TWh (energy produced/reactor-year) = 12.0 Pf/kWh

For the lower band an accident frequency lower by a factor of 10 was used, resulting in a corresponding reduction. However, the author concludes that the upper value is in his opinion closer to the expected costs of the corresponding accident in Germany. Using the current best estimate of the collective Chernobyl-specific dose, actual difference in population density and range of accident frequencies valid for a plant with good safety standard and for the Chernobyl type of accident (in terms of a comparable source term), the above estimated external costs would be reduced by three orders of magnitude. In Hohmeyer's study of 1990 the collective dose was further increased by a factor of five in order to reflect possibly higher source terms for the German plant. The resulting external costs were 3.48 - 21.0 Pf/kWh.

- **[Ottinger et al., 1990].** The approach is very similar to Hohmeyer. There is, however, no correction factor for the differences in population density and much higher monetary values are used for fatal cancers. In addition to the costs of health effects farm production losses were included. The assessed external cost is 2.3 cents/kWh.

- **[Ewers and Rennings, 1992].** Also in this case the basic approach of Hohmeyer has been adopted. The differences include somewhat lower correction factor for population density, lower dose-response factor and the accident frequency slightly lower than the lower value in the studies by Hohmeyer. This results in an external cost of 4.3 Pf/kWh.

Apart from specific problems in the implementation, common limitations of "Top-down" studies are as follows:

1. Only the "worst case" is examined while the assigned frequencies are not representative for such a case. One extreme accident which occurred at a plant with specific (flawed) design, operating in a specific environment (low safety culture) and located at a specific site, is chosen to represent the whole spectrum of hypothetical accidents with varying consequences.

2. The path leading to estimation of consequences conditional on specific releases is purely deterministic (Chernobyl case); different weather conditions, accident management strategies, sheltering conditions and evacuation practices are not considered.

B. Limited "Bottom-up" studies

- **[Friedrich and Voss, 1993].** The estimate by these authors is based on the work of [Burke et al., 1984]. Adjustments were made for the higher population density in Germany in comparison with the US sites. The authors point out that the results of Burke et al. can only be transferred to a limited extent to Germany. The basic difference between this study and the ones belonging to "Top-down" type is that instead of the Chernobyl accident a PSA (for a US plant) was used as a reference for evaluating a hypothetical accident in Germany. The resulting external costs are 0.008 to 0.07 Pf/kWh.

- **Energy Research Group, Inc. [ERG, 1993].** This study concerning CANDU plants is based on the input provided by Ontario Hydro and covering the frequencies, population doses and off-site financial damages for five categories of reactor accidents. It is stated that these categories cover the full range of design basis and catastrophic accident consequences. The frequencies and consequences used were considered to be bounding estimates, pending the publication of the results of station-specific risk assessment. The accident category representations were those used in the Darlington Probabilistic Safety Evaluation and were assumed to apply to both Pickering and Bruce plants. ERG increased all probabilities of occurrence by a factor of 2 to account for external events. High and low cases were considered based on the application of a ±20 factor of error. The range of results is between 0.000013 and 0.096 cents/kWh.

- **[Masuhr and Oczipka, 1994].** This work was a contribution to the Swiss INFRAS & PROGNOS external cost study [Ott et al., 1994]. The approach shares with "Top-down" studies the use of the Chernobyl-specific collective dose. However, the major improvement is that the lower range of consequences is based on some release frequencies from the Swiss regulatory review of the PSA for the Mühleberg plant [HSK, 1991]. The same frequencies were then applied to the other four Swiss nuclear power plants which have very different designs. An additional extremely high release category was assumed. Furthermore, an arbitrary set of much higher frequencies was postulated in order to estimate the upper range of consequences. The analysed consequences were limited to health effects and some losses in agricultural production (the latter were based on [Ottinger et al., 1990]). The results are in the range between 0.001 - 0.17 Rp/kWh. Another set of results (1.0 - 31.8 Rp/kWh) reflects the use of subjective risk aversion. This will be further elaborated in Section 6.4.

- **Centre d'étude sur l'Evaluation e la Protection dans le domaine Nucléaire [CEPN; Volume 5 in ExternE, 1996e].** CEPN postulated four different source terms, assigned a core melt probability considered representative for a large PWR, based on NUREG-1150 [USNRC, 1990a] assumed conditional containment failure or bypass probability, and carried out consequence calculations for a hypothetical site in Germany using COSYMA (i.e. the calculations concern all cost elements in COSYMA). The range of the results, 0.0023 to 0.104 mECU/kWh, corresponds to the different source terms. Health effects dominate, followed by cost of food bans, while evacuation and relocation costs are relatively small.

- **[Fisher and Williams, 1994].** This work was carried out as a part of the EC/US study on external costs of energy chains. The approach used is very similar to that employed by CEPN. A large, hypothetical Westinghouse PWR was sited at two US locations. Also in this case four accident scenarios were analysed and the conditional probability for containment failure or bypass was based on the Zion plant analysis within NUREG-1150 [USNRC, 1990a]. For consequence calculations MACCS was used. The results are 0.0059 cents/kWh for one of the sites and 0.0103 cents/kWh for the other. As opposed to CEPN, non-health effects are dominant.

Limited “Bottom-up” studies are more diversified with respect to the approaches used than the more homogenous “Top-down” studies. A common feature is use of extrapolations on different levels of the analysis. Furthermore, a very limited number of scenarios has been analysed; these scenarios are in several cases postulated rather than derived; this may or may not include the worst possible case (in terms of source terms). Some studies use hypothetical sites.

C. Full scope “Bottom-up” studies

- **[Hirschberg and Cazzoli, 1994].** This study, which primarily concerns the Swiss BWR plant Mühleberg, is based on a state-of-the-art full scope PSA that covers the full spectrum of initiating events (including the external ones such as fires, earthquakes, floods, aircraft crashes, etc., which frequently dominate the core damage frequency profile). The Mühleberg PSA was extended by calculations of economic consequences, using the economic effect models of the MACCS code. The consequence analysis used 31 representative source terms derived from the overall number of 3000 source terms reflecting all the credible end-states of the containment matrix for Mühleberg. The analysis includes a systematic propagation of uncertainties and an integration of the full spectrum of contributing release scenarios. The estimated external costs for Mühleberg are as follows: 0.0012 cents/kWh (mean); 0.0001 cents/kWh (5-th percentile); 0.0004 cents/kWh (50-th percentile); 0.0038 cents/kWh (95-th percentile). They are dominated by health effects and according to a sensitivity analysis are moderately sensitive to the costs of land and property. In addition to the Swiss Mühleberg plant external costs were calculated for two US plants, Peach Bottom (BWR) and Zion (PWR), using information from reports [USNRC, 1990b] and [USNRC, 1993] prepared as supporting documentation to NUREG-1150 [USNRC, 1990a]. The estimated mean value for Peach Bottom is 0.0014 cents/kWh and for Zion 0.0069 cents/kWh. Further details concerning this study will be provided in Section 6.5.3.4.

- **[Wheeler and Hewison, 1994].** The report addresses external costs related to the proposal for a PWR located at Hinkley Point in United Kingdom. Although in the available report there is no reference to a PSA, the information given indicates that plant specific accident frequencies were used as the basis for the calculations. Twelve degraded core accidents, eight containment by-pass accidents and three design basis accidents were analysed. Consequences were first estimated using the MARC-1 computer program. Later the accident consequence code CONDOR [NRPB et al., 1993] was used in order to cover two aspects not included in MARC-1 (long-term relocation of people from contaminated land and food restrictions). The total external cost based on CONDOR was 0.00011 p/kWh and 0.00013 p/kWh based on MARC-1. Health effects dominate in both cases.

Table 6.5.1 summarises the main characteristics of the studies described above. Limitations of Type C studies will be discussed in Section 6.5.3.4.

Result driving factors

It is worthwhile to consider which factors may have the primary influence on the numerical discrepancies between the different studies [Hirschberg, 1995a]:

Accident frequency. The frequencies used in the different studies were either plant-specific, adopted from other plants, or considered generic. There are cases where relatively high frequencies were allocated to specific very severe consequences (corresponding to the Chernobyl accident), possibly due to misunderstanding of the reference set of data used. Only this can explain differences of three orders of magnitude.

Magnitude of consequences. The amount of radioactivity released was either assumed, estimated on plant-specific basis or simply adopted from the Chernobyl accident. The extent of the consequences was then either calculated for the specific location or extrapolated using results obtained for other plants. Alternatively, Chernobyl-specific consequences were used with very limited adjustments for site-specific characteristics. In some cases the implementation of extrapolations and adjustments is subject to errors.

Scope. The scope of the different studies ranges from consideration of one specific accident (typically Chernobyl) to systematic modelling of the full spectrum of hypothetical accidents; the latter approach, when properly implemented, provides a set of consequences with specific magnitudes and the associated frequencies. Some studies are limited to coverage of only one type of consequence, i.e. radiation-induced health effects, other also provide estimates of costs of a wide spectrum of short- and long-term countermeasures (including the related effects such as losses of land and property).

Risk integration. Risks are integrated by combining the consequences with specific magnitude and the associated frequencies. In most cases the so called “product formula” was used, where frequency of an accident is simply multiplied by the magnitude of its consequences. Some studies consider risk aversion by explicit or implicit allocation of extra weights to events with very large consequences. As an example, the results of Masuhr and Oczipka [1994] show an increase by two to three orders of magnitude when such an approach is adopted.

Economic parameters. Depending on the scope of the economic analysis the results are particularly sensitive to the monetary values assigned to loss of life, land and property. The degree of sensitivity may in turn be highly dependent on the plant-specific spectrum of accidents and on local conditions. In recent studies quite similar values were used for loss of life.

TABLE 6.5.1

Characteristics of selected studies of external costs of nuclear reactors.

Type of Study	Author(s)	Object	Estimated External Costs	Some Key Analysis Characteristics	Risk Aversion Considered	External Events Included	Uncertainty Propagation	Full Set of Source Terms	Computer Code for Uncertainty Analysis	Cost Elements	Remarks
"Top-down"	Hohmeyer (1988 and 1990)	Biblis, Germany (PWR)	1.2 - 12.0 3.48 - 21.0 (Pf/kWh)	Use of Chernobyl consequences (further increased) CDF= "Worst" case freq.	No	No	No (two CDFs used)	"Worst" case	Not applicable	Health effects	Correction for population density (overestimated)
"Top-down"	Ottinger (1990)	US plant (unspecified)	2.3 (cents/kWh)	Same as Hohmeyer (1988)	No	No	No	"Worst" case	Not applicable	Health effects and farm production losses	-
"Top-down"	Ewers and Rennings (1992)	Biblis, Germany (PWR)	4.3 (Pf/kWh)	Same as Hohmeyer (1988)	No	No	No	"Worst" case	Not applicable	Health effects	Correction for population density (lower than Hohmeyer's)

Table 6.5.1 continues on the next page.

Table 6.5.1 (continued)

Type of Study	Author(s)	Object	Estimated External Costs	Some Key Analysis Characteristics	Risk Aversion Considered	External Events Included	Uncertainty Propagation	Full Set of Source Terms	Computer Code for Uncertainty Analysis	Cost Elements	Remarks
Limited "Bottom-up"	Friedrich and Voss (1993)	German plant	0.008 - 0.07 (Pf/kWh)	Based on PSA analysis for a US plant (Burke et al., 1984)	No	Yes	No	Yes (for US plant; conservative)	CRAC (in Burke et al., 1984)	Broad set of health effects and counter-measures	Correction for population density
Limited "Bottom-up"	ERG (1993)	Darlington, Bruce and Pickering, Canada (CANDUs)	0.000013 - 0.096 (cents/kWh)	Five categories of accidents for Darlington (frequencies assumed to represent bounding estimates)	No	Yes (arbitrary factor of two)	No (arbitrary factor of 20 included)	No (but bounding cases represented)	Not clear	Health effects and property damage	Extrapolation of Darlington results to Bruce and Pickering
Limited "Bottom-up"	Masuhr and Oczipka (1994)	Swiss plants (BWRs and PWRs)	0.001 - 0.17 1.0 - 31.8 (Rp/kWh)	Use of Chernobyl consequences as reference value; Mühleberg source term freq. for lower bound and arbitrary for higher	Yes, in the second case	Yes (implicit)	No (arbitrary set of frequencies postulated to reflect uncertainty)	No (but bounding cases represented)	Not applicable	Health effects and some losses in agricultural production	Mühleberg source term freq. used for all other Swiss plants

Table 6.5.1 continues on the next page.

Table 6.5.1 (continued)

Type of Study	Author(s)	Object	Estimated External Costs	Some Key Analysis Character-istics	Risk Aversion Consid-ered	External Events Included	Uncer-tainty Propa-gation	Full Set of Source Terms	Computer Code for Uncer-tainty Analysis	Cost Elements	Remarks
Limited "Bottom-up"	CEPN (1994)	French PWR	0.0023 - 0.104 (mECU/kWh)	Assumed CDF and rough conditional containment failure proba-bilities; based on US PWR (NUREG-1150); hypo-thetical site in Germany	No	No	No	No (four source terms)	COSYMA	Full set in CO-SYMA	Domi-nance of health effects
Limited "Bottom-up"	Fisher and Williams (1994)	Large hypothe-tical US PWR	0.0059 - 0.0103 (cents/kWh)	CDF and containment probabilities as in CEPN analysis; two sites in US	No	No	No	No (four source terms)	MACCS	Full set in MACCS plus health effects	Domi-nance of non-health effects

Table 6.5.1 continues on the next page.

Table 6.5.1 (continued)

Type of Study	Author(s)	Object	Estimated External Costs	Some Key Analysis Character-istics	Risk Aversion Consid-ered	External Events Included	Uncertain-ty Propa.-gation	Full Set of Source Terms	Computer Code for Uncer-tainty Analysis	Cost Elements	Remarks
Full scope "Bottom-up"	Hirschberg and Cazzoli (1994)	Mühleberg, Switzer-land (BWR)	0.0012 (mean) 0.0001 (5-th) 0.0004 (50-th) 0.0038 (95-th) (cents/kWh)	Fully based on state-of-the-art Level 3 PSA	No	Yes	Yes (LHS method)	Yes	MACCS	Full set in MACCS plus health effects	Domi-nance of health effects
		Peach Bottom, US (BWR)	0.0014 (mean) (cents/kWh)	As above	No	No	Yes (but not fully available)	Yes	MACCS	As above	As above
		Zion, US (PWR)	0.0069 (mean) (cents/kWh)	As above	No	No	As above	Yes	MACCS	As above	As above
Full scope "Bottom-up"	Wheeler and Hewison (1994)	Hinkley Point, UK (proposed PWR)	0.00011 - 0.00013 (p/kWh)	Plant-specific (unclear ori-gin)	No	Unclear	No	Broad (23 source terms)	CONDOR and MARC-1	Full set in CON-DOR Limited set in MARC-1	Domi-nance of health effects

6.5.3.4 State-of-the-art Methodology and its Limitations

Approach overview

The state-of-the-art approach encompasses two elements:

- Use of a well-established, reviewed, full scope plant-specific PSA; the PSA should preferably cover a very broad range of initiating events, including the external ones. Propagation of uncertainties through the model (normally using a Monte Carlo method) is highly desirable. The rationale for the preference for using a plant-specific PSA as the most relevant basis for estimating the economic consequences of nuclear accidents is the demonstrated strong dependence of the results on plant-specific features (including site characteristics).
- Use of economic models of established consequence codes such as COCO-1, CONDOR, COSYMA, MACCS or MECA2. Improvements/extensions of these models are desirable and in several cases are being implemented.

An open point is whether risk aversion should be incorporated into the assessment of external costs. For this reason risk aversion is addressed separately. Also the limitations of the current state-of-the-art methodology are discussed towards the end of this section.

The basic steps involved in a Level 3 PSA include:

- Assessment of Plant Damage States (PDS) frequencies
- Accident progression evaluation for these PDSs
- Source terms evaluation for each of the end-states of the accident progression
- Conditional consequence evaluation for a representative set of source terms
- Integration of risk measures

Figure 6.5.4 shows the overview of the PSA methodology as applied in the study for the Swiss plant Mühleberg, including the flow of data in the entire process. The approach is similar to the methodology applied in the NUREG-1150 studies [USNRC, 1990a].

The starting point of a PSA is the establishment of a set of initiating events (about 80 in the Mühleberg case). In the next step millions of accident sequences were generated, based on event trees developed for the different initiating events. The sequences add to the **total core damage frequency**. Among them 8000 (those having frequencies exceeding 10^{-10} per reactor-year) were binned into 20 **plant damage states**, defined by a list of descriptors that identify the characteristics important to containment failure and radionuclide transport (e.g. status of the primary system and the containment, pressure in the primary system at time of core degradation, pressure and temperature in the containment at the time of core degradation, status of AC power, status of heat removal). The Level 2 calculation was performed with all 20 plant damage states. The accident progression event tree constructed for the Level 2 analysis led to several thousands sequences binned into 15 to 20 **release categories** (i.e. groups having similar accident progression histories).

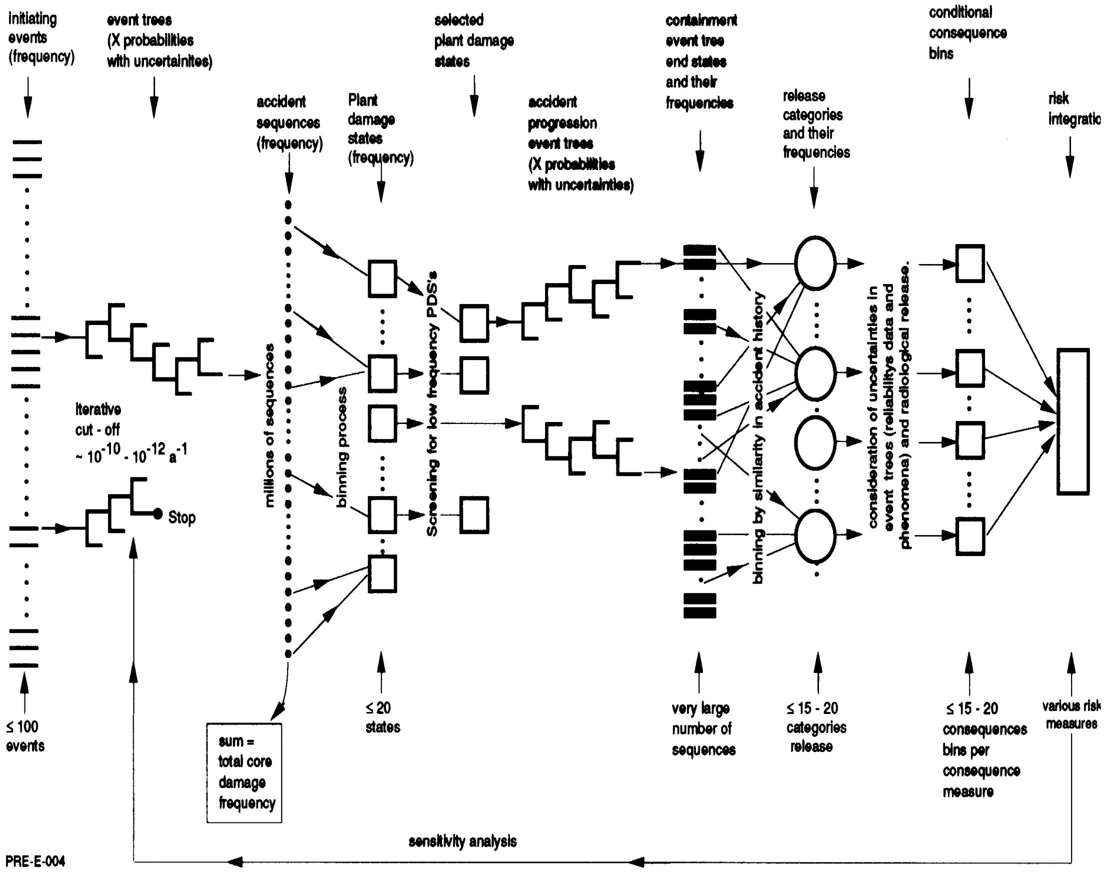


Fig. 6.5.4 PSA methodology [Cazzoli et al., 1993a].

A set of "source term clusters" was then established taking into account physical and chemical phenomena acting after the containment failure. The **source terms** and the associated frequencies constitute the input to the consequence analysis which together with the preceding steps constitutes Level 3 PSA. Conditional consequences are calculated for a representative set of the source terms. Finally, the risk measures are integrated.

The elements of probabilistic consequence assessment are depicted in Figure 6.5.5. The main types of release and site specific input data are shown on the left of the figure, whilst the more general input data requirements are shown to the right. In the centre of the figure, the main calculational steps are identified. The following comments on the tasks within probabilistic consequence analysis are based on [NEA, 1994].

For the radionuclide **dispersion** (i.e. transport and diffusion processes) calculations, the Gaussian plume model is widely used in Level 3 PSAs; the Gaussian shape of the concentration profile has been found to be approximately valid in many situations. Typically, the Gaussian dispersion model will be run around a hundred or more times with different weather samples and, in some cases, each plume profile is rotated over a number of azimuthal sectors to generate a large statistical set of consequence estimates. Deposition mechanisms ("dry and wet") for removal of radioactive material from the plume are considered in consequence calculations.

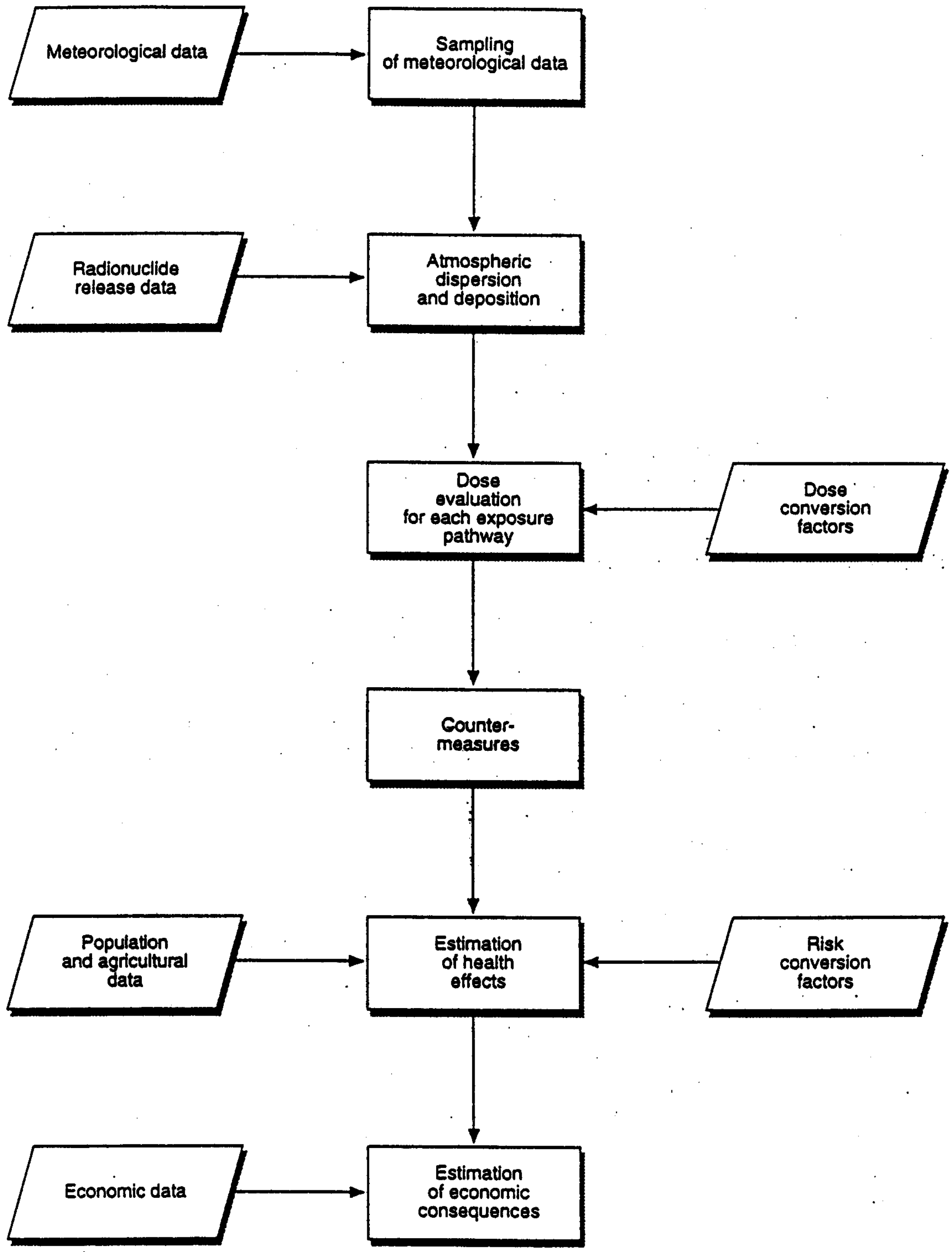


Fig. 6.5.5 Basic elements of probabilistic consequence assessment (from [NEA, 1994]).

The choice of **meteorological data** often represents a compromise between the ideal, the available and what is adequate for a particular assessment. Thus, normally data from the meteorological station nearest to the release point are used but also data compiled at other stations may be used if they are found representative. Data from one or more years is sampled and a representative set of weather sequences is selected, each of these having an assigned probability of occurrence.

The **exposure pathways** by which people can accumulate a radiation dose after an accidental release are:

- **external irradiation** from radioactive material in the passing plume, deposited on the ground, or deposited on the skin and clothing

- **internal irradiation** from radioactive material inhaled directly from the passing plumed, inhaled following resuspension of the ground deposit, or ingested due to contamination of foodstuffs or drinking water

For each pathway a **dosimetric model** is used to convert the distribution of radioactive material in the atmosphere and on the ground, to distributions of dose in man.

Data on the **spatial distribution of population** and **agricultural production** are necessary for evaluating the collective dose and health effects, and if required for calculating the economic impact of implementing countermeasures, such as relocation and food bans.

Typical **offsite consequences** calculated in Level 3 PSA include:

- number of early (acute) fatalities and injuries
- number of latent (chronic) cancer fatalities
- total population dose from all pathways
- individual risk of death and individual probability of latent cancer fatality
- interdicted and condemned land area

The cost elements to be included in the economic consequence analysis are associated with early protective (emergency response) actions, long-term protective actions and costs resulting from these actions. They specifically include:

- Cost of countermeasures
  a) population movement (transport away from the affected area, temporary accommodation and food, loss of income, loss of capital)
  b) agricultural restrictions and countermeasures (e.g. food bans)
  c) decontamination (e.g. cleaning process, labour, health effects induced in workforce)

- Cost of radiation-induced health effects (early cancers, hereditary)
  a) direct health care costs
  b) indirect costs (lost income)

Indirect or secondary effects as well as intangible effects will be further commented in the context of the limitations of the current methodology.

Swiss-specific application

In the following the approach that has been used in the present work to estimate the external costs of nuclear reactor accidents is further commented on and the results are presented in more detail (this part was originally published in [Hirschberg and Cazzoli, 1994].

As an extension of the authority reassessment of the Mühleberg PSA [PLG, 1990], a Level III risk study was also performed, using a Mühleberg-specific site model (in [Cazzoli et al., 1993b]). The methodology adopted for the analysis is similar to the one employed in the NUREG-1150 study [USNRC, 1990a]. Uncertainties of relevant parameters are propagated using a Monte Carlo method (LHS), starting from the frequencies of Plant Damage States (PDS), then evaluating the accident progression for these PDSs, source terms for each of the end-states of the accident progression, and finally conditional consequences for a representative set of the source terms. In the final step of the analysis, the risk measures are integrated. Conditional consequences for all source terms have been calculated with the MACCS computer code [Chanin et al., 1987], developed at Sandia National Laboratories. The Mühleberg-specific weather and population data have been used. For the emergency countermeasures conditions best approximating the current Swiss offsite protective action strategies have been modelled.

A number of different types of offsite consequences were calculated. Figures 6.5.6 through 6.5.10 show frequency of exceedance of: population dose to 800 km, number of latent cancer fatalities to 800 km, risk of individual latent cancer fatalities to 20 km, interdicted area[4] and condemned area[5], respectively. In Table 6.5.2 estimated mean risk measures are shown; for comparison the corresponding measures are also given for two US plants, based on the results provided in NUREG-1150 [USNRC, 1990a]. In the context of latent cancer fatalities, the old dose-response factor implemented in the available version of MACCS, was used for all three plants; this means that in order to compensate for the associated underestimation the corresponding risk measure should be multiplied by roughly a factor of three [ICRP, 1990].

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[4] Interdicted area is defined as an area interdicted for up to 30 years following the accident.

[5] Condemned area is defined as an area which can not be decontaminated before 30 years.

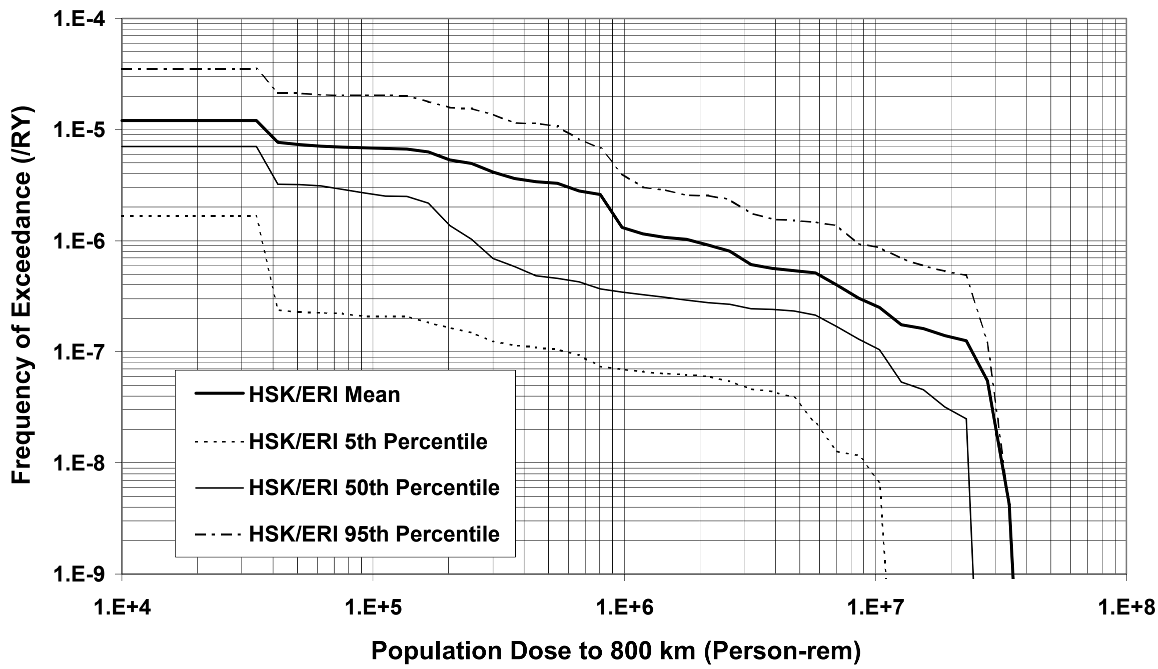

Fig. 6.5.6 Frequency of exceedance of population dose to 800 km [Cazzoli et al., 1993b].

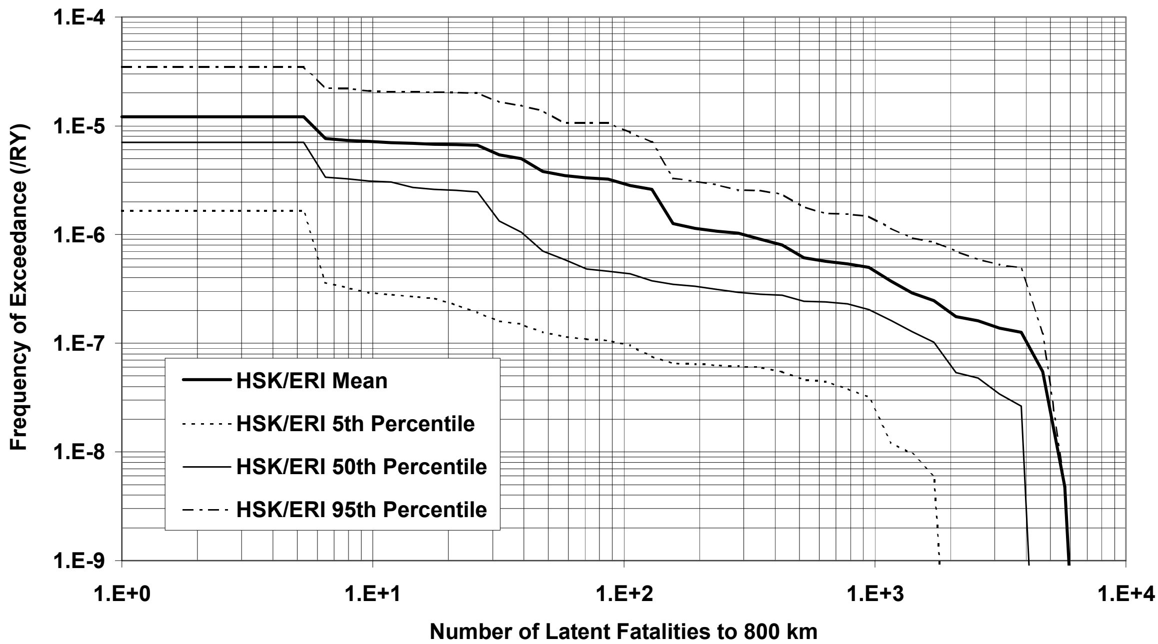

Fig. 6.5.7 Frequency of exceedance of latent cancer fatalities to 800 km [Cazzoli et al., 1993b].

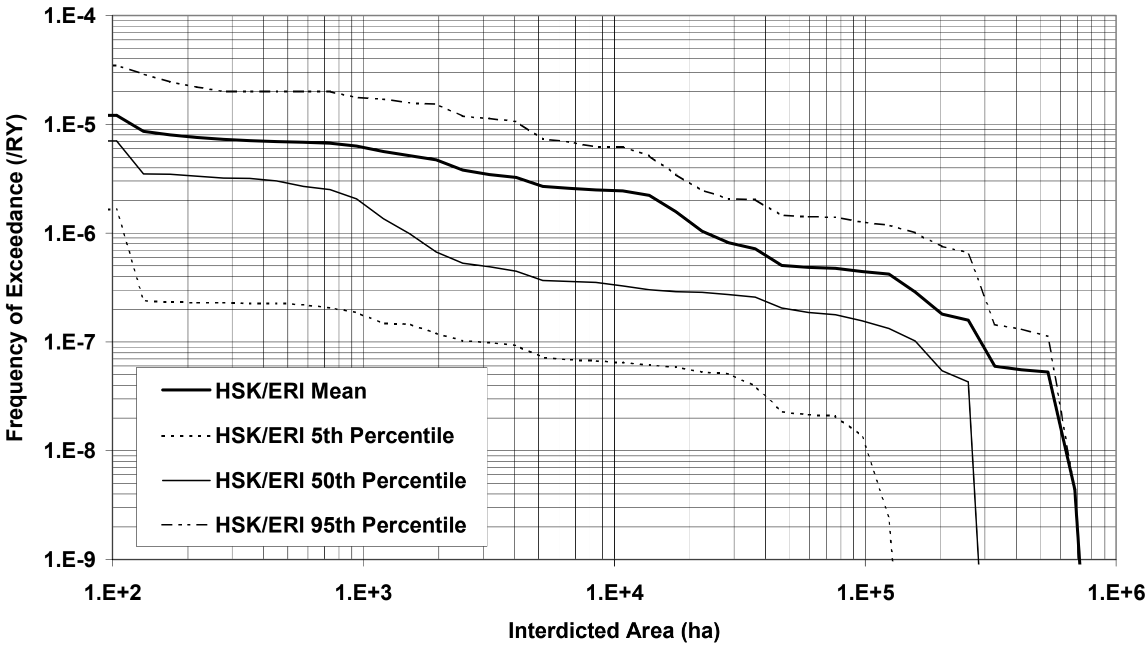

Fig. 6.5.8 Frequency of exceedance of interdicted area [Cazzoli et al., 1993b].

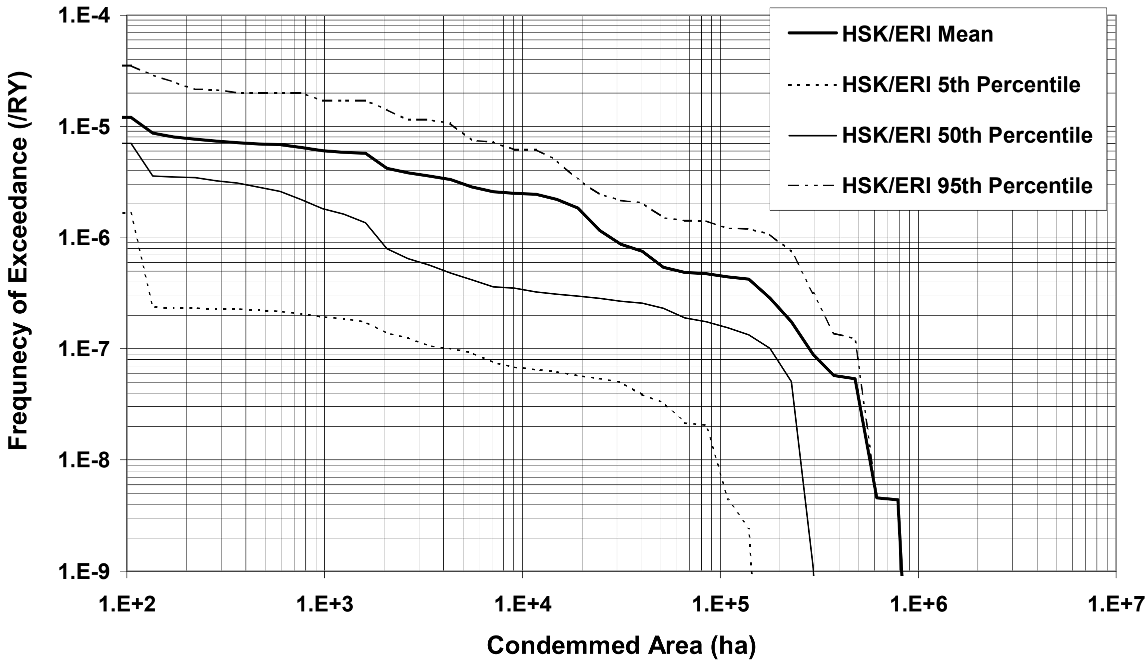

Fig. 6.5.9 Frequency of exceedance of condemned area [Cazzoli et al., 1993b].

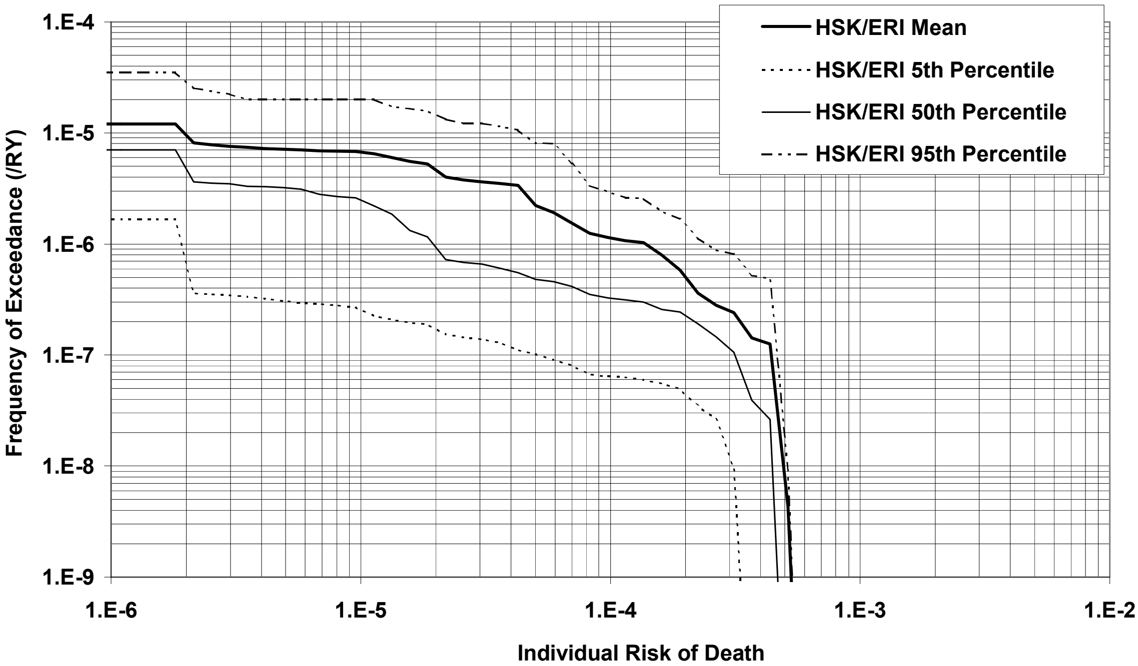

Fig. 6.5.10 Frequency of exceedance of individual latent cancer fatalities to 20 km [Cazzoli et al., 1993b].

Since the results given for Mühleberg include the contributions from external events, it is worth noting that in this particular case the internal events contribute roughly 50% to the total risk measures. To illustrate the uncertainty in the estimation, in the case of the Mühleberg plant the 5-th and 95-th percentiles for latent cancer fatalities to 800 km are 1.7×10^{-4} and 7.2×10^{-2} per $GW_e a$, respectively; here the current dose-response factor according to [ICRP, 1990] was used.

Economic consequences of hypothetical severe accidents were calculated for Mühleberg by the authors, using the economic effect models in MACCS. US economic data for 1980 were used; for land value the highest data applicable to USA were chosen to represent the Swiss-specific conditions. However, for these conditions this may still be an underestimation whose effects will be addressed below. The rationale for using data from 1980 was the consistence with the Swiss population data (employed in the health consequence analysis), which originate from the 1980 census.

TABLE 6.5.2

Examples of estimated mean risk measures based on plant-specific PSAs.

Mean Risk Measure (per $GW_e a$)	Mühleberg	Peach Bottom*	Zion*
Early fatalities	$<10^{-12}$	$3.5x10^{-8}$	$1.0x10^{-5}$
Latent cancer fatalities to 800 km	$6.7x10^{-3}$	$6.2x10^{-3}$**	$2.4x10^{-2}$**
Population dose to 800 km (person-rem)	40.4	40.2**	161.8**
Individual risk of cancer death	$1.6x10^{-9}$	$6.7x10^{-10}$	$9.4x10^{-9}$
Condemned area (km^2)	$5.9x10^{-3}$	$1.5x10^{-2}$***	$1.2x10^{-1}$***
Risk of large release	$<1x10^{-9}$	$1.3x10^{-9}$	$7.5x10^{-7}$

* Only internal events ** Calculation to 1600 km

*** Not shown in NUREG-1150; calculation based on extrapolation.

Two types of costs are modelled in MACCS: costs resulting from early protective (emergency response) actions and costs resulting from long-term protective actions. The following specific costs are covered:

- food and lodging costs for short-term relocation of people who are evacuated or relocated during the emergency phase of the accident,
- decontamination costs for property that can be returned to use if decontaminated,
- economic losses incurred while property (farm and nonfarm) is temporarily interdicted by a period of time following decontamination to allow for radioactive decay to reduce ground concentrations to acceptable levels,
- economic losses resulting from milk and crop disposal, and
- economic losses due to permanent interdiction of property.

The estimation of costs associated with the number of radiation-induced deaths, injuries, and cancers has not been included in the MACCS economic model.

Figure 6.5.11 shows the frequency of exceedance of external costs for Mühleberg, based on the total core damage frequency obtained for the full spectrum of internal events (including external ones), and calculated to 800 km.

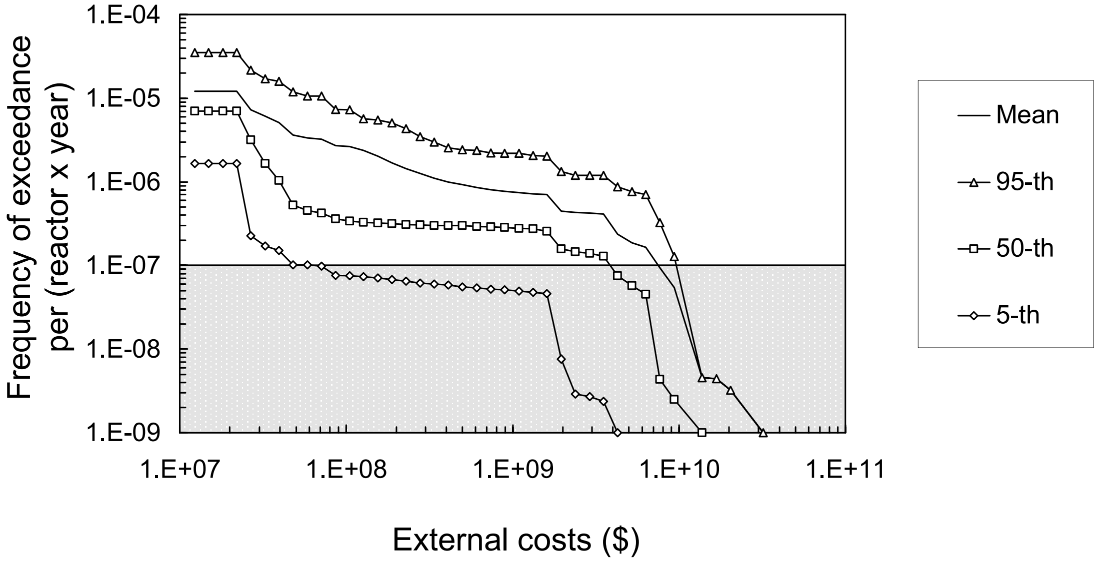

Fig. 6.5.11 Mühleberg-specific frequency of exceedance of external costs of severe accidents with radiation-induced health effects excluded [Hirschberg and Cazzoli, 1994]. The mean can be regarded as the main reference, while the 95-th percentile can be interpreted as providing a bounding value.

A line was introduced over the shadowed area at the frequency level of 10^{-7}/year, in order to emphasise that the large damages predicted at and below this level are associated with extremely small probability of occurrence. The resolution and completeness of PSA-technique in this domain are disputable. In fact, some experts (e.g. [Farmer, 1990]) advocate the use of cut-off values at the level of 10^{-7}/year or even 10^{-6}/year in non-engineering PSA applications (assessment of external costs belongs to this category). The main argument for a cut-off at this level is the heavy burden to demonstrate validity when the probabilities become extremely small.

Table 6.5.3 summarises the external costs (excluding radiation-induced health effects), calculated for Mühleberg and for the two US plants, Peach Bottom and Zion. The results for US plants were derived using information from reports prepared as a support to NUREG-1150, but published later. Also for the US plants MACCS economic model was used.

The estimated external costs are apparently very low in the absolute sense but in spite of the use of the same evaluation methodology and application to plants of "western" design, the relative differences are substantial. The differences would be further amplified were the external events for the US plants and the radiation-induced health effects for all plants included.

TABLE 6.5.3

External costs of severe accidents for three nuclear power plants (radiation-induced health effects not included).

Plant	External costs (cents/kWh)			
	5-th	**50-th**	**Mean**	**95-th**
Mühleberg	0.00002	0.00006	0.0002	0.0005
Peach Bottom*	NA**	NA**	0.0004	NA**
Zion*	0.00007	0.0006	0.003	0.006

* Only internal events

** NA = Data not available

In order to arrive at the total external costs the costs of radiation-induced health effects (totally dominated by latent cancers) were quantified separately and added to those implicitly covered in Figure 6.5.11 and explicitly given in Table 6.5.3. For the value of statistical life 4 million US$ was assigned (based on hedonistic price analysis) and for each non-fatal cancer or case resulting in genetic effects 400 thousands US$ (based on human-capital-method). Most of the current external cost studies (including [ExternE, 1996a - 1996f; Hohmeyer, 1988 and 1990 ORNL&RfF, 1992, 1994a, 1994b, 1995a - 1995e; Ott et al., 1994; Ottinger et al., 1990]) adopted similar or identical values; consequently, these parameters are of secondary importance when addressing the discrepancies between the results of the different studies. Using these values, the current dose-response factors [ICRP, 1990], the population dose to 800 km (mean value given in Table 6.5.2) and the numbers given in Table 6.5.3, we obtain the following estimates of the external costs associated with hypothetical severe accidents at Mühleberg:

5-th percentile:	0.0001 cents/kWh
50-th percentile:	0.0004 cents/kWh
Mean:	0.0012 cents/kWh
95-th percentile:	0.0038 cents/kWh

For comparison the external costs associated with hypothetical severe accidents at two US plants were estimated as a part of the present work. The results are based on a similar approach. However, the work was in this case only limited to processing of the relevant information available in Appendices to the NUREG-1150 report [USNRC, 1990a; USNRC, 1990b; USNRC, 1993]. The mean values are: 0.0014 cents/kWh for Peach

Bottom (BWR) and 0.0069 cents for Zion (PWR). As opposed to the Mühleberg results, the values given for the US plants do not cover the contributions from external events, which may dominate the risk profile. Given the monetisation parameters used for health effects, this part dominates the estimate (particularly in the Mühleberg case). Based on the detailed specification of the contributors to the economic costs, provided in MACCS, the land-related costs constitute in the Mühleberg case roughly 50% of the costs given in Table 6.5.3. Thus, an increase of land values by a factor of ten leads to a corresponding increase of the Mühleberg-specific costs (health effects excluded) by a factor of five. This would in turn lead to an increase of the total (including monetised health impacts) external costs associated with hypothetical severe accidents at Mühleberg by less than a factor of two. Consequently, the above mentioned uncertainties in economic parameters assigned to property values do not have a dramatic impact on the results. However, the presently used values are probably underestimated and should be revised.

Role and quantification of risk perception and aversion

Expert-based risk estimates (using for example PSA techniques) ignore public perception of risks. Thus, in the PSA context risks are integrated by simple multiplication of consequences with specific magnitude by the corresponding frequencies; all such terms are then added to obtain the overall risk. In reality, subjective aversion towards the possibility of very high damages/losses can have a substantial influence on the behaviour of individuals. Economists and social scientists emphasise the relevance of risk aversion by pointing out to the empirical evidence. Thus, in the context of financial investments the strategy chosen by individuals is clearly affected by the extent of possible losses and not only by the expectation value of the gains.

The issue of risk aversion is definitely important when discussing the role of nuclear power. Extreme nuclear accidents which potentially could lead to severe land contamination of long duration, would also result in social detriment beyond the quantifiable components of health and economic detriments. Considerations of the societal dimensions related to post-accident situations with large scale and heavy land contamination are discussed in [Lochard and Prêtre, 1993]. Figure 6.5.12 illustrates symbolically the possible relative importance of the different types of detriments as a function of accident severity. Obviously, the currently used economic models do not cover the social detriment. Some analysts view the explicit inclusion of risk aversion in the estimate of the economic consequences of accidents as a compensation (or surrogate) for lack of representation of the social dimension. Clearly, such a compensation is artificial.

The forthcoming IAEA Guidelines for the Comparative Assessment of Health and Environmental Impacts of Electrical Energy Systems [IAEA, to be published 1998] discusses the role of the experts' estimates of the probability of an accident and of the accounting for public perception. It is pointed out that these two perspectives are **complementary** and should **not** be considered as **alternative** views. From an engineering standpoint, the expected damage approach provides the most scientifically justifiable estimate of the risk. It is further stated that the "analysts may wish to consider the issue of public perception and aversion in a comparative assessment but are cautioned to keep impacts associated with perceived risks separate from the engineering-based estimates of risk. Any such approach should be careful to ensure consistent application to all risks for which it may be relevant. It should also be recognised that the same opinions and perceptions may influence any subsequent decision process on alternative energy systems to which the results of comparative assessment provide input."

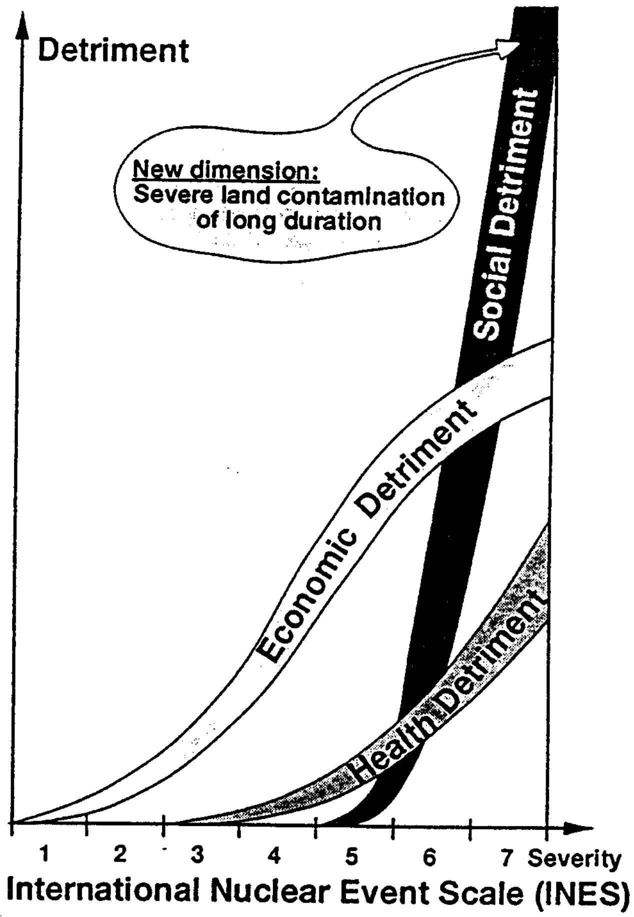

Fig. 6.5.12 Possible relative significance of social and other detriments versus accident severity [Lochard and Prêtre, 1993].

Some studies account for risk aversion by explicit or implicit allocation of extra weights to events with very large consequences. Per definition, aversion factors, when expressed as exponents of the magnitude of consequences, are equal or greater than one and in most published cases smaller or equal to two. Taking the "square" approach one event causing 10 deaths is valued the same as 100 events with one death each.

Quantification of risk aversion remains to be a controversial matter. A complete review of the different approaches to the quantification of risk aversion is beyond the scope of this report. Here we predominantly limit the scope to some approaches which have been employed in the context of external cost studies. Thus, aversion has been quantitatively addressed in [Ferguson, 1991; Pearce, 1992; Masuhr and Oczipka, 1994]. Ferguson employed the “square” rule while Pearce used different functions including a multiplication factor (as opposed to an exponent) of 300. There is no empirical foundation for these functions and factors.

Masuhr and Oczipka [1994] considered the standard deviation of the damages as a measure of aversion. Zweifel and Nocera [1994] referred to the “revealed preference analysis” developed in [Pratt, 1964; Arrow, 1974] and pointed out that following the spirit of this method PROGNOS should have used the variance instead of the standard deviation as well as individual willingness to pay rather than collective. Given this correction and employing an empirical “price for risk” parameter[6] based on conditions on capital and insurance markets, external cost of nuclear accidents (including risk aversion) estimated by Zweifel and Nocera amounts to 1.1 Rp/kWh for the upper bound case (31.8 Rp/kWh in the PROGNOS study). The approach assumes that the probability distribution for the monetised losses is symmetrical (which does not apply). Another concern is the applicability of parameters reflecting the conditions on financial markets to quantify the aversion towards accidents. Erdmann [1997] discusses a number of methodological problems associated with applications of the revealed preference approach to large scale energy risks. In this context he provides an estimate of external costs for Mühleberg (including aversion) in the range 0.03 to 0.06 Rp/kWh, using the identical set of values for the economic consequences as in the PROGNOS study.

Recently, an approach which accords with economic theory and aims at estimating the difference between the results based on the “expert expected damage” (EED) approach and on the “expected utility” (EU) approach was proposed [Krupnick et al., 1993]. The term “expected utility” is used because individuals are assumed to maximise the expected value of their utility over a state with, and a state without the accident while accounting for the probability of each state occurring (“ex ante” approach). In the EED approach one estimates the loss in satisfaction from the consequence of an accident if it occurred with certainty and then multiplies the amount by the probability that the accident will occur (“post ante” approach). The authors show that the ratio between the results based on the EU approach and the EED approach is greater the greater the risk aversion, the smaller the probability of the event and the greater the loss if the event occurs. Also in this case reliable empirical information is lacking, particularly with regard to the appropriate utility function and degree of risk aversion.

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[6] This parameter represents the degree of acceptance of variance (uncertainty) on the part of decision makers. [Masuhr and Oczipka, 1992] used two extreme values of this parameter, i.e. zero (corresponding to risk neutrality) and one (corresponding to total aversion).

Limitations of current methodology

The following limitations have been identified [Hirschberg, 1995a]:

- **Limitations of PSA techniques.** Specific limitations of PSA methodology and the progress achieved in handling them have been discussed elsewhere (see for example [Hirschberg, 1992]. Some specific issues concern reliability data, common cause failures, human interactions, external events, phenomena related to accident progression and source terms, and containment performance. Nevertheless, the physical impact models employed in the state-of-the-art PSAs are by and large adequate as a basis for estimation of external costs.

- **Limitations of economic models.** The current economic models connected to the consequence codes are still relatively primitive. Consideration of ecological damages is limited to agriculture while recreational value of land or impacts on tourism are not considered. Generally, the analyses performed in the context of external cost estimations are limited to the land areas that are directly affected by the accident. For accidents which lead to long disruption periods there will be impacts on other areas and many sectors of the economy are likely to be affected. To simulate such effects, both at regional and national level, the input-output methodology that accounts for the interactions between the economic sectors, could be employed. A recent example of such application is the Spanish analysis of an agricultural scenario [Hidalgo et al., 1994]; other scenarios in mainly industrial and tourist areas are being assessed. Applications of the input-output approach are in turn subject to limitations associated with standard problems of input-output analysis and the difficulties to achieve compatibility between the regional economic data and the area impacted by the accident.

  Within the limited scope of the economic consequence models that have been applied, the most important cost-driving parameters in the case of an accident with very extensive external consequences are: the value of life and the price of interdicted/condemned land. Both these parameters may be assigned according to different principles and the absolute levels are disputable. There is a particularly large potential variability with respect to the assigned prices of rural and urban land. In this context it is important to emphasise that cost parameters may be interdependent. For example, based on success of decontamination within a given period of time, land may be classified as habitable (relocation is necessary for a short period of time), temporarily interdicted (relocation is necessary for a protracted time), or permanently interdicted (condemned, the population will not be able to return for an indefinite period). Given a relatively low price of land (typical for rural land), high contamination levels and high decontamination costs, cost effectiveness criterion (as employed in several models) will lead to abandonment of the decontamination effort and condemnation of the land from the beginning. On the other hand, for more expensive land (such as urban areas), the habitability criterion is going to weigh very heavily in the definition of interdiction and condemnation.

- **Limitations in the treatment of subjective risks.** The issue of risk aversion in the context of external costs associated with severe accidents remains unresolved. The empirical foundation for aversion factors that have been employed remains to be weak and needs to be strengthened. This is necessary independently of the debate on external costs. While risk aversion certainly plays a role in the public debate (acceptability of specific technology), there is no general consensus that it should be reflected in external cost estimates.

6.5.4 Some highlights

1. In the historical experience of nuclear reactor accidents two events are clearly dominant, namely the TMI-2 and Chernobyl accidents. While the first mentioned accident had practically negligible health and environmental consequences, the latter resulted in disastrous impacts. Current, preliminary estimates of these impacts are provided in the present report. Having in mind their partially latent nature the definite assessment cannot be made at this stage.

2. Due to the radical differences in the plant design and operational environment the Chernobyl accident is essentially irrelevant for the evaluation of the safety level of the Swiss (and most western) nuclear power plants.

3. Use of a plant-specific PSA, if available, is the most rationale basis for the estimate of consequences of severe accidents and the associated external costs. The results obtained from such an approach are by definition representative for the case being studied. In addition, it enables treatment of uncertainties in a transparent and disciplined way. In case this approach is not feasible, any extrapolation of results obtained for a specific plant in a specific environment must be done with great care; the reference case should be carefully selected with view to similarities in the design philosophy and in the operating environment. Some earlier published applications do not exhibit such a care.

4. Estimates of external costs of severe nuclear accidents show the largest discrepancies in the past studies and are considered controversial. Independently of the numerical results, use of the Chernobyl accident as the only reference for the assessment of environmental consequences is more than questionable. Generally, state-of-the-art, rationale and defensible methodological approaches, based on full scope PSAs, have not been used extensively in this context.

5. The results obtained for western plants using predominantly PSA-based approaches show low (quantifiable) contributions of severe accidents to external costs of nuclear power. This contrasts with some estimates based on simplistic, limited in scope and arbitrary approaches discussed in this work. Low (absolute) contributions are to be expected as a reflection of the defence in depth design philosophy. In the particular case of Mühleberg the early offsite risks are negligible due to relatively low radionuclide inventory and low population density in the immediate proximity of the plant. The extensive backfitting has been generally efficient in terms of reduction of the applicable risk measures. Generalisations should, however, be avoided - the indication is applicable to plants with good safety standards and within the limited boundaries of the analyses

performed. The relative differences between the various applications can still be large since the risks are expected to be strongly plant- and site-specific.

6. External costs associated with rare severe accidents are of interest primarily for comparison, which in turn may support the decision-making process. There appears to be a disputable rationale behind internalisation of costs of events which with a very high probability will not occur during the life-time of the plants being examined. In contrast, detrimental impacts associated with normal operation and with operational incidents, are not hypothetical but deterministic.

6.5.5 References

Arrow, K. J. (1974), Essays in the Theory of Risk Bearing. Amsterdam: North Holland.

Bernow, S., Biewald, B. and Marron, D. (1990), Environmental Externalities Measurement: Quantification, Valuation and Monetization. Tellus Institute, Boston, Massachussets, USA.

Burke, R. P., Aldrich, D. C. and Rasmussen, N. C. (1984), Economic Risks of Nuclear Power Reactor Accidents. NUREG/CR-3673, U.S. Nuclear Regulatory Commission, Washington D.C.,USA.

Cazzoli, E., Khatib-Rahbar, M., Schmocker, U., and Isaak, H. P. (1993a), Approach to Quantification of Uncertainties in Probabilistic Safety Assessment. Proceedings of the European Safety and Reliability Conference, 10 - 12 May 1993, Munich, Germany.

Cazzoli E. et al. (1993b), A Regulatory Evaluation of the Mühleberg Probabilistic Safety Assessment, Volume II: Level 2. ERI/HSK 93-304, HSK 11/356 (Limited Distribution).

Chanin D. I. et al. (1987), MACCS Accident Consequence Code System, Vol. I User's Guide. NUREG/CR-4691, Sandia National Laboratories, USA.

EC (1996), 1995 Consensus Document on Safety of European LWR. Report EUR 16803EN, European Commission, Nuclear Science and Technology.

EC/IAEA/WHO (1996), EC/IAEA/WHO International Conference: “One Decade after Chernobyl - Summing up the Consequences of the Accident”, 8 - 12 April 1996, Vienna, Austria.

Erdmann, G. (1997), Assessment of Nuclear Power Plant Risk under Risk Aversion. Jahrestagung Kerntechnik ‘97, 13 - 15 May 1997, Aachen, Germany.

ERG (1993), Calculation of Environmental Externalities for Ontario Hydro’s Nuclear Power Plants. Energy Research Group, Inc., Waltham, MA, USA.

Erhardt, J., Burkhart, K., Hasemann, I., Matzerath, C., Panitz, H.-J. and Steinhauer, C. (1988), The Program System UFOMOD for Assessing the Consequences of Nuclear Accidents. Report KfK 4330, Kernforschungszentrum Karlsruhe.

Erhardt, J. and Jones, J. A. (1991), An Outline of COSYMA, a New Program for Accident Consequence Assessments. Nuc. Tech., Vol. 94, No. 2 (1991) pp. 196.

ExternE (1996a), Externalities of Energy, Vol. 1: Summary. Published by the European Commission Directorate General XII, Luxemburg.

ExternE (1996b), Externalities of Energy, Vol. 2: Methodology. Published by the European Commission Directorate General XII, Luxemburg.

ExternE (1996c), Externalities of Energy, Vol. 3: Coal & Lignite. Published by the European Commission Directorate General XII, Luxemburg.

ExternE (1996d), Externalities of Energy, Vol. 4: Oil & Gas. Published by the European Commission Directorate General XII, Luxemburg.

ExternE (1996e), Externalities of Energy, Vol. 5: Nuclear. Published by the European Commission Directorate General XII, Luxemburg.

ExternE (1996f), Externalities of Energy, Vol. 6: Wind & Hydro. Published by the European Commission Directorate General XII, Luxemburg.

EU-RF (1996), Joint EU-RF Analysis of European Challenges and Solutions in Nuclear Safety (Phase 1 and 2). RISKAUDIT Report No. 34, EDF/MINATOM, February 1996.

Ewers, H.-J. and Rennings, K. (1992), Abschätzung der Schäden durch einen sogennanten “Super-GAU”; in: Prognos-Schriftenreihe Identifizierung und Internalisierung externer Kosten der Energieversorgung, Band 2, Prognos, Basel, Switzerland.

Farmer, R. (1990), An Appreciation of the Santa Fe Workshop Contribution to the Question of Cut Off Criteria for Low Probability Sequences (and Numbers). In Final Report to CSNI, Note on the Outcome of a Workshop on “Applications and Limitations of Probabilistic Safety Assessment”, 4 - 6 September 1990, Santa Fe, New Mexico, USA.

Ferguson, R. (1991), Environmental Costs of Energy Technologies - Accidental Radiological Impacts of Nuclear Power (Draft Report).

Fisher, S. E. and Williams, K. A. (1994), Social Costing Approach for Nuclear Power Plant Accidents. Proceedings of ANS Winter Meeting, 13 - 17 November 1994, Washington D.C., USA.

Friedrich, R. and Voss, A. (1993), External Costs of Electricity Generation. Energy Policy, 21 (1993) pp. 114 - 122.

Gallego, E. (1989), MECA2. Model for Economic Consequence Assessment, Version 2. Reference Guide. Report CTN-43/92, Catedra de Tecnologia Nuclear, Universidad Politecnica de Madrid, Spain.

Haywood, S. M., Robinson, C. A. and Heady, C. (1991), COCO-1: Model for Assessing the Cost of Offsite Consequences of Accidental Release of Radioactivity. Report NRPB-R243, National Radiological Protection Board, UK.

Hidalgo, A., Gallego, E., Munoz, A., Pavón, J. (1994), Evaluacion del Impact Economico Externo de los Accidentes Nucleares (in Spanish). Catedra de Economia, Catedra de Tecnologia Nuclear, Universidad Politecnica de Madrid, Spain.

Hirschberg, S. (1992), Prospects for Probabilistic Safety Assessment. Nuclear Safety, Vol. 33, No. 3, (1992) pp. 365 - 380.

Hirschberg, S. (1995a), External Costs of Electric Power Generation: Are Accidents Adequately Treated? (in German) Schweizer Ingenieur und Architekt, Nr. 20, 11 May 1995, pp. 469 - 473.

Hirschberg, S. (1995b), External Costs of Nuclear Reactor Accidents, 28 pp., November 1995. Contribution to the OECD/NEA Report on Methodologies for Assessing the Economic Consequences of Nuclear Reactor Accidents (to be published 1998).

Hirschberg, S. (1996), Key Methodological Issues, 33 pp., March 1996. Contribution to the IAEA Guidelines for the Comparative Assessment of Health and Environmental Impacts of Electrical Energy Systems (to be published 1998).

Hirschberg, S. and Cazzoli, E. (1994), Contribution of Severe Accidents to External Costs of Nuclear Power. ENS Topical Meeting on PSA/PRA and Severe Accidents '94, 17 - 20 April 1994, Ljubljana, Slovenia.

Hirschberg, S. and Erdmann, G. (1994), Wie hoch sind die Kosten der Stromproduktion? Die Bewertung externer Kosten als heikle Aufgabe (in German). Neue Zürcher Zeitung, No. 192, 6 October 1994.

Hohmeyer, O. (1988), Social Costs of Energy Consumption: External Effects of Electricity Generation in the Federal Republic of Germany. New York: Springer-Verlag.

Hohmeyer, O. (1990), Latest Results of the International Discussion on the Social Costs of Energy - How Does Wind Compare Today? The European Commission's Wind Energy Conference, September 1990, Madrid, Spain.

HSK (1991), Gutachten zum Gesuch um unbefristete Betriebsbewilligung und Leistungserhöhung für das Kernkraftwerk Mühleberg (in German). Bericht HSK 11/250 (KSA 11/150). Hauptabteilung für die Sicherheit der Kernanlagen, Würenlingen.

IAEA (1996), Press Release, 19 April 1996. International Atomic Energy Agency, Vienna, Austria.

IAEA (to be published 1998), Guidelines for the Comparative Assessment of Health and Environmental Impacts of Electrical Energy Systems. International Atomic Energy Agency, Vienna, Austria.

ICRP (1990), Recommendations of the International Commission on Radiological Protection. Oxford, New York.

Jow, H.-N., Sprung, J. L., Rollstin, J. A., Ritchie, L. T. and Chanin, D. I. (1990), MELCOR Accident Consequence Code System (MACCS). Model Description. Report NUREG/CR-4691 (SAND86-1562), Vol. 2, Sandia National Laboratories, Albuquerque, New Mexico, USA.

Kapp, K. W. (1950), The Social Costs of Private Enterprise. Cambridge: Cambridge University Press.

Komanoff Energy Associates (1986), Costs of the Three Mile Island Accident. In Le vrai coût d'un accident nucléaire, Science et Vie, No. 829 (1986) pp. 36 - 39.

Krupnick, A., Burtraw, D. and Palmer, K. (1995), The Social Benefits of Social Costing Research. Prepared for the European Commission, International Energy Agency and Organization for Economic Cooperation and Development Workshop on the External Costs of Energy, 30 - 31 January 1995, Brussels, Belgium.

Krupnick, A., Markandya, A., Lee, R. and Valette, P. (1993), The Evaluation of External Costs from Energy Sources: The EC-US Fuel Cycle Study. Proceedings of International Symposium on Power Generation Choices: Costs, Risks and Externalities, 23 - 24 September 1993, Washington D.C., USA.

Krupnick, A. J., Markandya, A. and Nickell, E. (1993), The External Costs of Nuclear Power: Ex Ante Damages and Lay Risks. American Journal of Agricultural Economics, 75 (1993) pp. 1273 - 1279.

Kula, E. (1992), Economics of the Natural Resources and the Environment. London, New York, Tokyo, Melbourne, Madras: Chapman&Hall.

Lochard, J. and Prêtre, S. (1995), Return to Normality after a Radiological Emergency. Health Physics, Vol. 68, No. 1 (1995) pp. 21 - 26.

Lochard, J. and Prêtre, S. (1993), Intervention after Accident: Understanding the Social Impact. In Radiation Protection on the Threshold of the 21st Century, Proceedings of the NEA/OECD Workshop, 11 - 13 January 1993, Paris, France, pp. 197 - 209.

Lonergan, S. C., Goble, R. L. and Cororaton, C. (1990), Estimating the Financial Consequences of a Severe Nuclear Accident in Canada. Energy, Vol. 15, No. 6 (1990) pp. 507 - 522.

Marshall, A. (1890), Principles of Economics. London: Macmillan.

Masuhr, K. P. and Oczipka, T. (1994), Die externen Kosten der Stromerzeugung aus Kernenergie (in German). Materialen zu PACER, Bericht 724.270.2d, Bundesamt für Konjunkturfragen, Bern, Switzerland.

Mossman, K. L., Goldman, M., Massé, F., Mills, W. A., Schiager, K. J. and Vetter, R. J. (1996), Health Physics Society Position Statement: Radiation Risk in Perspective. HPS Newsletter, Volume XXIV, Number 3, March 1996.

NEA (1994), Probabilistic Accident Consequence Assessment Codes, Second International Comparison. Overview Report. Paris: OECD/NEA.

NRPB et al. (1993), CONDOR 1: A Probabilistic Consequence Assessment Code Applicable to Releases of Radionuclides to the Atmosphere. NRPB (NRPB-R258), AEA (SRD R598), Nuclear Electric (TD/ETB/REP/7021).

Nucleonics Week (1994), Outlook on International Nuclear Liability. Special Report to the Readers of Nucleonics Week, Inside N.R.C., and Nuclear Fuel. Nucleonics Week, 29 September 1994, Inside N. R. C., 3 October 1994, Nuclear Fuel, 10 October 1994.

OECD (1975), The Polluter Pays Principle. Paris: OECD.

ORNL&RfF (1992), U.S. - EC Fuel Cycle Study: Background Document to the Approach and Issues. Report No. 1, prepared by Oak Ridge National Laboratory and Resources for the Future. ORNL/M-2500, Oak Ridge, Tennessee: Oak Ridge National Laboratory, USA.

ORNL&RfF (1994a), Estimating Fuel Cycle Externalities: Analytical Methods and Issues. Report No. 2, prepared by Oak Ridge National Laboratory and Resources for the Future. Washington D.C.: McGraw-Hill/Utility Data Institute.

ORNL&RfF (1994b), Estimating Externalities of Coal Fuel Cycles. Report No. 3, prepared by Oak Ridge National Laboratory and Resources for the Future. Washington D.C.: McGraw-Hill/Utility Data Institute.

ORNL&RfF (1995a), Estimating Externalities of Natural Gas Fuel Cycles. Report No. 4, prepared by Oak Ridge National Laboratory and Resources for the Future. Washington D.C.: McGraw-Hill/Utility Data Institute.

ORNL&RfF (199b), Estimating Externalities of Oil Fuel Cycles. Report No. 5, prepared by Oak Ridge National Laboratory and Resources for the Future. Washington D.C.: McGraw-Hill/Utility Data Institute.

ORNL&RfF (1995c), Estimating Externalities of Hydro Fuel Cycles. Report No. 6, prepared by Oak Ridge National Laboratory and Resources for the Future. Washington D.C.: McGraw-Hill/Utility Data Institute.

ORNL&RfF (1995d), Estimating Externalities of Biomass Fuel Cycles. Report No. 7, prepared by Oak Ridge National Laboratory and Resources for the Future. Washington D.C.: McGraw-Hill/Utility Data Institute.

ORNL&RfF (1995e), Estimating Externalities of Nuclear Fuel Cycles. Report No. 8, prepared by Oak Ridge National Laboratory and Resources for the Future. Washington D.C.: McGraw-Hill/Utility Data Institute.

Ott, W. et al. (1994), Externe Kosten und kalkulatorische Energiepreiszuschläge für den Strom und Wärmebereich (in German). Bericht 724.270 D, Bundesamt für Konjunkturfragen, Bern, Switzerland.

Ottinger, R. L., Wooley, D. R., Robinson, N. A., Hodas, D. R. and Babb, S. F. (1990), Environmental Costs of Electricity. Pace University Center for Environmental Legal Studies, New York: Oceana Publications.

Pearce, D., Bann, C. and Georgiou, S. (1992), The Social Costs of Fuel Cycles. Centre for Social and Economic Research on the Global Environment, University College London, UK.

Pearce, D. (1995), The Development of Externality Adders in the United Kingdom. Prepared for the European Commission, International Energy Agency and Organization for Economic Cooperation and Development Workshop on the External Costs of Energy, 30 - 31 January 1995, Brussels, Belgium.

Pigou, A. C. (1920), The Economics of Welfare. London: Macmillan.

PLG (1990), Mühleberg Level 2 Probabilistic Safety Assessment. Prepared for Bernische Kraftwerke AG, PLG-0744, November 1990.

Pratt, J. W. (1964), Risk Aversion in the Small and in the Large. Econometrica, 32 (1964) pp. 19 - 22.

Strip, D. R. (1982), Estimates of the Financial Consequences of Nuclear Power Reactor Accidents. Report NUREG/CR-2723, U.S. Nuclear Regulatory Commission, Washington D.C., USA.

Sorensen, J. et al. (1987), Impacts of Hazardous Technology - The Psychosocial Effects of Restarting TMI-1. State University of New York Press.

Sørensen, B. (1994), Impacts of Major Nuclear Accidents. Private Communication to N. Eyre, M. Dreicer and A. Rabi.

SVA (1997), Kernkraftwerke der Welt. Schweizerische Vereinigung für Atomenergie, Bern, Switzerland.

USAEC (1957), Theoretical Consequences of Major Accidents in Large Nuclear Power Plants. Report WASH-740, U.S. Atomic Energy Commission, Washington D.C., USA.

USNRC (1975), Reactor Safety Study. Report NUREG-075/14, U.S. Nuclear Regulatory Commission, Washington D.C., USA.

USNRC (1990a), Severe Accident Risks: An Assessment for Five U.S. Nuclear Power Plants. Final Summary Report. Report NUREG-1150, U.S. Nuclear Regulatory Commission, Washington D.C., USA.

USNRC (1990b), Evaluation of Severe Accident Risks: Peach Bottom, Unit 2. Report NUREG/CR-4551, Appendices, Vol. 4, Rev. 1, Part 2, U.S. Nuclear Regulatory Commission, Washington D.C., USA.

USNRC (1993), Evaluation of Severe Accident Risks: Zion, Unit 1. Report NUREG/CR-4551, Vol. 7, Rev. 1, Part 2B, U.S. Nuclear Regulatory Commission, Washington D.C., USA.

UNSCEAR (1993), 1993 Report to the General Assembly, with Scientific Annexes. United Nations Scientific Committee on the Effects of Atomic Radiation, United Nations Sales Publication E.94.IX.2, New York, USA.

Wheeler, G. and Hewison, R. C. (1994), The External Costs of Accidents at a UK PWR. Report IS3538-2, Version 2.0, Intera Information Technologies, Oxfordshire, UK.

Zweifel, P. and Nocera, S. (1994), Eine Replik. Was kostet die Vermeidung von Atomrisiken? Fundierte Grundlagen zur Bewertung externer Kosten (in German). Neue Zürcher Zeitung, Nr. 274, 23 November 1994.

6.6 Hydro Chain

The risks associated with hydro power may arise during dam construction and during operation. Here only the risk of severe accidents is addressed although the construction and normal operation of dams result in environmental impacts. Stored water covers large areas, changes the natural water balance, disturbs existing ecosystems and can induce earthquakes [König, 1984; Gupta, 1992]. On the other hand, hydro power dams can protect villages and towns from floods [Neue Zürcher Zeitung, 1985]. They can also be used for water supply and irrigation.

6.6.1 Trends in the production of electricity by hydro power

The production of electricity by hydro power increased in OECD-countries in the period 1971-1983 and stagnated afterwards. (Fig. 6.6.1). For non-OECD countries the trend is different. In the period 1971-1996 the electricity output from hydro power has been steadily growing.

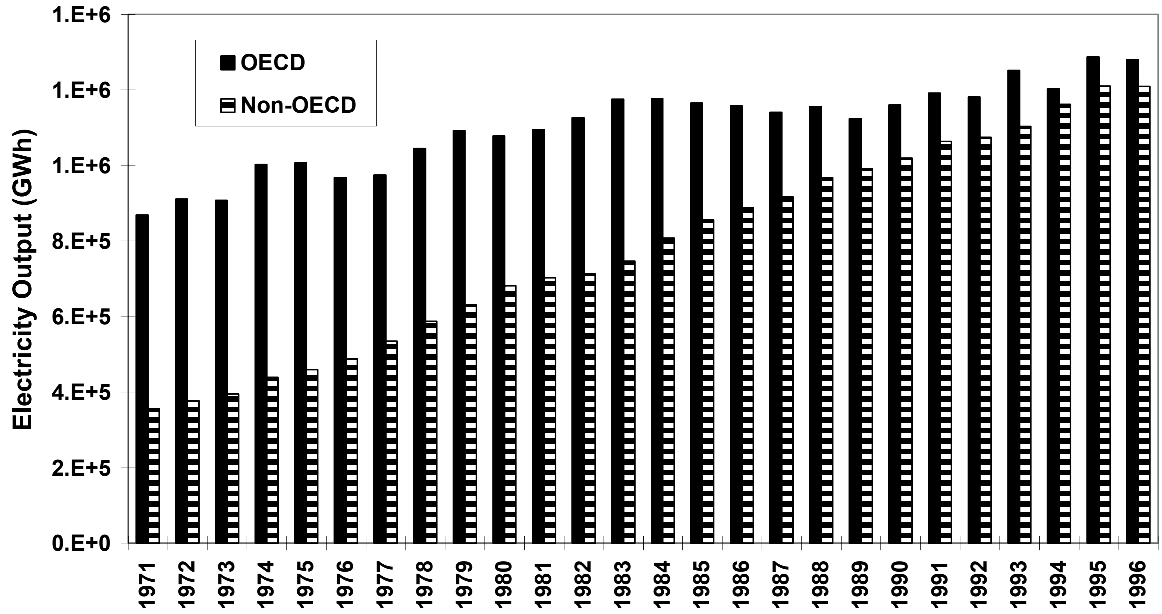

Fig. 6.6.1 Hydro power electricity output for OECD and non-OECD countries. The output includes contributions from dams and run-of-river plants.

6.6.2 Trends in the construction of hydro power dams by type

The number of hydro power dams built each year remained roughly constant during the period 1960-1971, at an average number of 120 dams a year, and decreased in the period 1972-1987 for all dam types with the remarkable exception of year 1984 (Fig. 6.6.2).

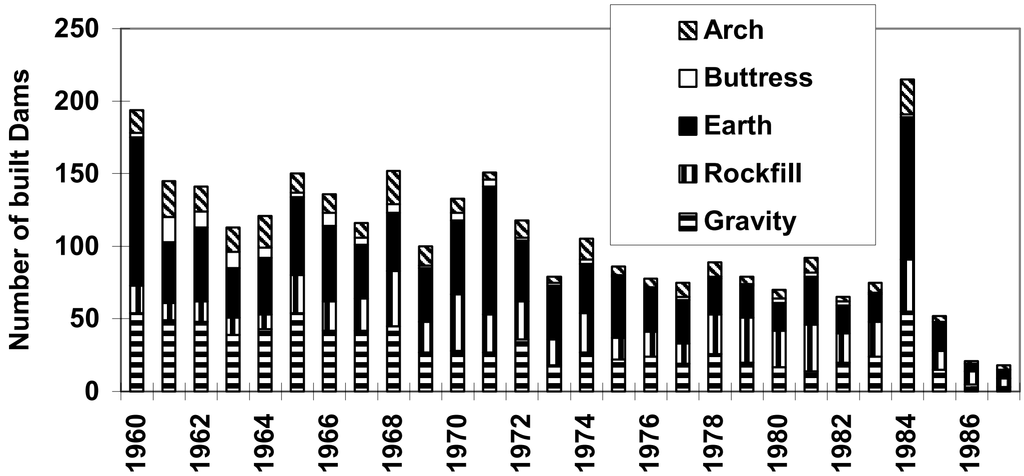

Fig. 6.6.2 World-wide number of hydro power dams of different types built each year [ICOLD 1984, 1988].

Dams of type earth or rockfill are embankment dams whose fill material is earth or rock. They are placed with sloping sides and their length is greater than the height. An embankment is generally higher than a dike. Dams of type gravity are constructed of concrete and/or masonry which rely on their weight for stability. An arch dam is built of concrete or masonry which are curved in plan so as to transmit the major part of the water load to the abutments. A dam of buttress type consists of a watertight part supported at intervals on the downstream side by a series of buttresses. Buttress dams can take many forms. Table 6.6.1 provides a list of dam purposes and the associated abbreviations for later use in this section.

TABLE 6.6.1

Abbreviations for dam types and dam purposes.

Dam Type		Dam Purpose	
Abbreviation	**Meaning**	**Abbreviation**	**Meaning**
Te	Earth	H	Hydro power
Er	Rockfill	I	Irrigation
Pg	Gravity	C	Flood control
Pg(M)	Gravity dam built of masonry	S	Water supply
Va	Arch	N	Navigation
Cb	Buttress	R	Recreational purposes
Mv	Multi-Arch	-	-

Dams of mixed type such as Arch/Earth or Earth/Rockfill were accounted for in Fig. 6.6.2 as one arch and one earth dam in the first case, and as one earth and one rockfill dam in the latter. There exist also dams of mixed type with three different sections such as Gravity/Rockfill/Earth. In this case they were accounted three times as one gravity, one rockfill and one earth dam. However, dams with a higher number than two of different types are very rare. Dams of mixed type are composed of different sections strung end-to-end to control a wide river. The mid-section may be a gravity part containing the power station and the spillway; this may be combined with long earth or rockfill wings. An example of a dam of mixed type is the Itaipu dam at the border between Brazil and Argentina. The type classification of this dam is Pg/Er/Te. In this case one wing is of the gravity type (Pg) containing the spillway and the power plant; the middle section is of the rockfill type (Er) and the other wing is of the earth type (Te). Another example for a dam of mixed type is the Roselend Va/Cb dam in France. Its both wings are of the buttress type (Cb) and the middle section is of the arch type (Va).

In Fig. 6.6.3 the total number of world-wide hydro power dams is depicted for the period 1920-1988. The abbreviations in Fig. 6.6.3 such as Cb, Er, Mo, Mv, etc. were explained in Table 6.6.1.

In Fig. 6.6.3 the X-axis defines the type of the main part of the dam; the Y-axis specifies the other type of the same dam. Pg/Pg, Cb/Cb, Te/Te, etc. mean just Pg-, Cb-, Te-dams, respectively. As illustrated by Fig. 6.6.3 the most common hydro power dam types are gravity dam followed by earth dam.

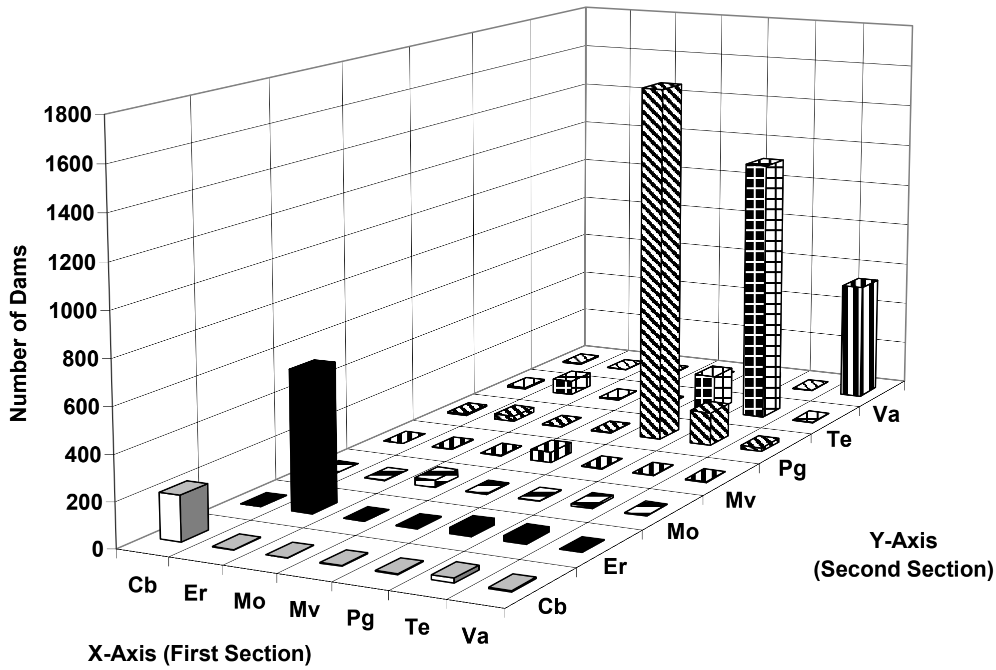

Fig. 6.6.3 Number of large hydro power dams of different types built world-wide in the period 1920-1987 [ICOLD 1988].

6.6.3 Dam accidents and dam failure rates

6.6.3.1 Risk of accidents during the construction of dams

A risk to the workers and to the public may arise during the building phase of dams, because of the extreme conditions (mudslides, avalanches, falling rocks) in mountainous areas. In Table 6.6.2, a list is given of some accidents which involved fatalities during the construction phase of dams or hydro power schemes including dams.

Table 6.6.2 shows that in most cases the reasons for the death of the dam workers were pure external initiators such as typhoons, mudslides or as in the case of Mattmark an ice slide. It is clear that from the point of view of the judicial responsibility the causes of such accidents are external events. Nevertheless, it is the construction of the dam which necessitates the presence of the workers at the site. According to the evaluation principles applied in this work to all energy chains, the consequences of such accidents were attributed to hydro power.

In some countries, accidents during the construction phase of dams have been a quite significant contributor to the overall risk. [Charles and Boden 1985] mention that 17% of all dam accidents in the UK happened during construction.

6.6.3.2 Evaluation of dam failure rates on the basis of historical data

There are two basic ways to estimate risks associated with dam failure :

1) Statistical studies based on historical failure records. The validity of such studies depends on the availability of data and their transferability.

2) Probabilistic analysis of accident scenarios leading to a dam failure (e.g. earthquakes, landslides or floods causing a dangerous overtopping), and of possible damages to property and people.

[Serafim, 1981] pointed out that statistical studies based on the historical records of dam failures could lead to incorrect conclusions because the data are not homogenous. He emphasised that dam design and construction have improved in the course of the years. Therefore, dams are not directly comparable. Furthermore, in many cases, the causes of dam failures were difficult to determine because either the information available from different sources was contradictory or it was missing. On the other hand, use of probabilistic technique to estimate dam failure risks also faces difficulties. [Baecher et al., 1980] state, that dams can fail through an infinite number of modes, which cannot be fully enumerated. Although the approach to determine the probability of a dam failure based on historical frequencies is subject to limitations, this technique has been used by different organisations like Corps of Engineers, the Bureau of Reclamation in the USA or Basler & Hofmann in Switzerland. In the present study the effort was made to take into account the type of dams and the technological developments in dam construction.

TABLE 6.6.2

Selected incidents occurring during construction of dams or hydro power schemes including dams resulting in fatalities[a].

Name/ Project	Country	Year of failure or construction period	People killed	Injured Persons	Cause	Reference
Mauvoisin	Switzer-land	1954	6	not available	Tower crash	Private communication with an employee of Mauvoisin
Vorderrhein	Switzer-land	1956-1961	22	not available	Avalanches, falling rocks	[Kraftwerke Vorderrhein, 1963]
Oros	Brazil	1960	40	not available	Flood	[Schweizerischer Wasserwirtschafts-verband, 1986]
Limmern	Switzer-land	1960-1963	19	not available	not available	[Kraftwerke Linth Limmern, 1965]
Mattmark	Switzer-land	1965	88	not available	Ice slide	[Engineering News Record, 1965]
Torrejon Tajo	Spain	1965	30	not available	Tunnel gate failure	[Babb and Mermel, 1968]
Hongrin	Switzer-land	1966	6	not available	Gas in hydro tunnel	[Engineering News Record, 1966]
Sempor	Indonesia	1967	200	not available	Monsoon, poor foundation	[Engineering News Record, 1967]
Sarganserland	Switzer-land	1974	≥2	not available	not available	[Kraftwerke Sarganserland, 1978]
Guavio	Colombia	1983	70	33	Two mudslides	[Encyclopaedia Britannica, 1984]

[a] Construction accidents are considered here following the general principles established in the present work for the comparison of severe accidents associated with all energy chains. This means that the severe accidents (if any), occurring within all stages of the chains and within all phases of the life cycles of the relevant facilities are considered. In the table above the Swiss accidents are clearly over-represented. This is due to the availability of information and due to the particular interest of this study for the Swiss conditions. Nevertheless, the Swiss construction accidents have in practice no impact on the final results of the comparative evaluations (Chapters 7 and 9) since their occurrence was almost exclusively prior to the chosen evaluation period.

6.6.3.3 Earlier dam failure studies based on historical records

In the past, several dam safety studies based on historical records of dam accidents have been published [Schnitter, 1976], [Basler & Hofmann, 1978], [Baecher et al., 1980], [Hoffmann et. al., 1984]. Table 6.6.3 shows some failure rates for dam accidents, where water was partially or completely released, based on historical events. For comparison, in the last three rows of the table the probability of dam failures due to different causes are provided; these results originate from analytical risk assessment. [Gruetter and Schnitter (1982)] assessed the probability for a gravity or arch dam in an alpine region whereas [Johansen et al. (1997)] and [Hartford and Lampa (1997)] estimated the probability for specific dams in Norway respectively in Canada.

TABLE 6.6.3

Examples of dam failure rates according to different sources.

Author/Company	Failure rate [per dam-year]	Cause of failure	Dam type	Region/ Country
[Basler & Hoffmann (1978)]	$3 \cdot 10^{-5}$ - $3 \cdot 10^{-4}$	not specified	Gravity, Arch	Europe
[Baecher et. al. (1980)]	$2 \cdot 10^{-4}$-$5 \cdot 10^{-4}$	not specified	all types	USA
[Baecher et. al. (1980)]	$4 \cdot 10^{-5}$	not specified	all types	Japan
[Baecher et. al. (1980)]	$6 \cdot 10^{-4}$	not specified	all types	Spain
[Baecher et. al. (1980)]	$2 \cdot 10^{-4}$	not specified	all types	World
[Gruetter and Schnitter (1982)]	$1.8 \cdot 10^{-5}$	overtopping	Gravity, Arch	alpine region
[Johansen et al. (1997)]	$6.3\ 10^{-5}$-$5.6\ 10^{-4}$	hydrologic, seismic, internal erosion	Rockfill	Norway
[Hartford (1996)]	$2.8\ 10^{-6}$-$6.9\ 10^{-6}$	hydrologic	Earth	Canada

The International Commission On Large Dams (ICOLD) sent, in 1986, questionnaires to national committees world-wide with the intention of collecting data on dam failures and clarifying their causes. The resulting list of failed dams was reported in [ICOLD, 1995]. Using this material, knowledge about the processes causing dam failures could be improved. The list contains occurrences of dam failures but no consequences such as fatalities, injured, evacuees or costs of accidents. No specification of the purpose of the failed dams (such as irrigation, flood control, water supply, hydro power) is provided.

As a part of the present study many organisations and individuals (including a number of chairmen of national committees of ICOLD), as well as numerous books and journals dealing with dam construction and safety, were consulted to establish the consequences of historical dam failures. Frequently, the consequences cited in specific source(s) needed to be compared with other information sources since inconsistencies were observed or suspected. For instance, in [Jansen, 1983] it is mentioned that overtopping of the Swiss dam Palagnedra caused 24 fatalities. Later investigations which among other sources utilised national and local newspapers showed that the 24 fatalities were caused by floods in Italy and Switzerland on the same date and should not be attributed to overtopping of Palagnedra.

The dam purposes were in most cases identified from the "World Register of Dams" issued by ICOLD [ICOLD, 1984, and 1988].

In some cases allocation problems arise in the context of the evaluation. For instance, the Macchu II dam had multiple purposes namely irrigation, hydro power and water supply. In August 1979 the dam failed due to overtopping during exceptionally high floods. The loss of human life during the ensuing flood caused by the dam failure was about 2500 fatalities. To which extent should the fatalities be attributed to the various dam purposes? In this study all 2500 fatalities were fully attributed to hydro power. Consequently, the generic assessment of hydro power specific fatality rates is in this respect conservative. On the other hand, for a number of historical hydro power accidents the consequences were not accounted for due to lack of information, which should balance this particular conservatism.

Lists of dam failures represented in ENSAD with the corresponding dam purposes, dates of the accidents, consequences in terms of fatalities and economic losses is given in Appendix E.

6.6.3.4 Boundaries in the evaluation of dam accident rates on the basis of historical data

Failed dams exhibit a wide variation in terms of the level of engineering design, maintenance, control and other factors such as type, purpose, height, capacity. Care must be also taken in the context of failure definition. Some failure listings define "failure" as an accident that destroys the dam and renders the dam useless. In other surveys "failure" means a catastrophic accident which releases most or all of the impounded water. In the following subsections the boundaries used in the evaluations of failure rates are presented.

Geographical area

The detailed evaluations of dam failure rates were in the present work restricted to dams in countries in the Western World(here defined as USA, Canada, Western Europe, Australia and New Zealand). The reasons for this restriction are good failure reporting systems in this area and similarities to the conditions characteristic for Switzerland with respect to the technology and regulatory requirements.

Definition of a large dam

In the enquiry launched by the ICOLD to obtain a catalogue of all dam failures around the world, only large dams are considered.

A large dam is defined in [ICOLD, 1974] as:

1) *Height above 15 m measured from the lowest portion of the general foundation area to the crest;*

or

2) *Height between 10 - 15 m and at least one of the following conditions:*

   a) length of crest not less than 500 m;

   b) capacity of the reservoir not less than 1 million cubic metres;

   c) maximum flood discharge more than 2000 cubic metres per second;

   d) dam of unusual design;

   e) dam with special foundation problems.

Definition of a failure

In the ICOLD catalogue a failure is defined as follows [ICOLD, 1995]:

Collapse or movement of part of a dam or its foundations so that the dam cannot retain the stored water.

This definition does not address partial dam failures. The dam is considered failed when <u>all</u> stored water is released. Complete dam failures represent the largest threat to the population living downstream the dam.

Within this work the evaluation of the frequency of dam failures was based on consideration of complete dam failures only. However, this restriction does not apply to the generic evaluation of the consequences of accidents, where the full spectrum of historical data was used.

The catalogue issued by ICOLD also contains information about dam accidents during construction. They are considered as failures when:

1) a large amount of water was released downstream by a river flood which caused partial or total destruction of the dam. The height of the dam in construction when the overtopping began should have at least a height of 15 m;

or

2) reservoir filling had commenced before dam completion.

Dam types and point of time of failure

From Fig. 6.6.4 it can be seen that there are large differences with respect to the numbers of operating dams of various types. This is also reflected in the shares of the different dam types among the failed dams. Therefore, a differentiation by dam type is essential. In the figure the share of constructed dams of specific types is given for the Western World and Switzerland for comparison, too. This shows that Switzerland has a different distribution of dam types with a relatively small share of Earth/Rockfill dams and much higher percentage of Gravity and Arch dams. It should be noted that for the estimation of failure rates the central parameter is not the number of dams of a certain type but rather the corresponding operation time.

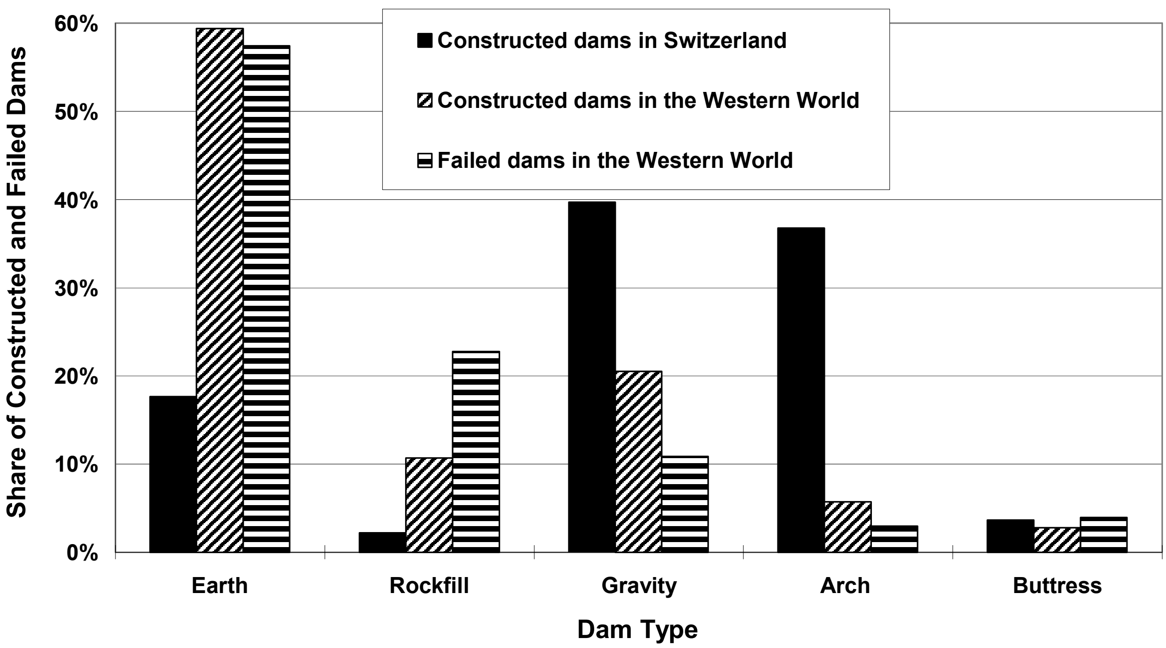

Fig. 6.6.4 Share of constructed and failed dams to the total by dam type in the Western World (USA, Canada, Western Europe, Australia and New Zealand). The time period is 1850-1996.

Another important characteristics is the point of time at which the failure occurred. Four occasions of failure are distinguished in ICOLD. These are [ICOLD, 1995]:

1) During construction;

2) During the first filling;

3) During the first five years of operation;

4) After five years of operation;

Figure 6.6.5 shows the occasions of failure occurred world-wide for two periods 1850-1996 and 1930-1996. The figure shows that roughly 50% of the failures occur before, during or within five years after the first filling.

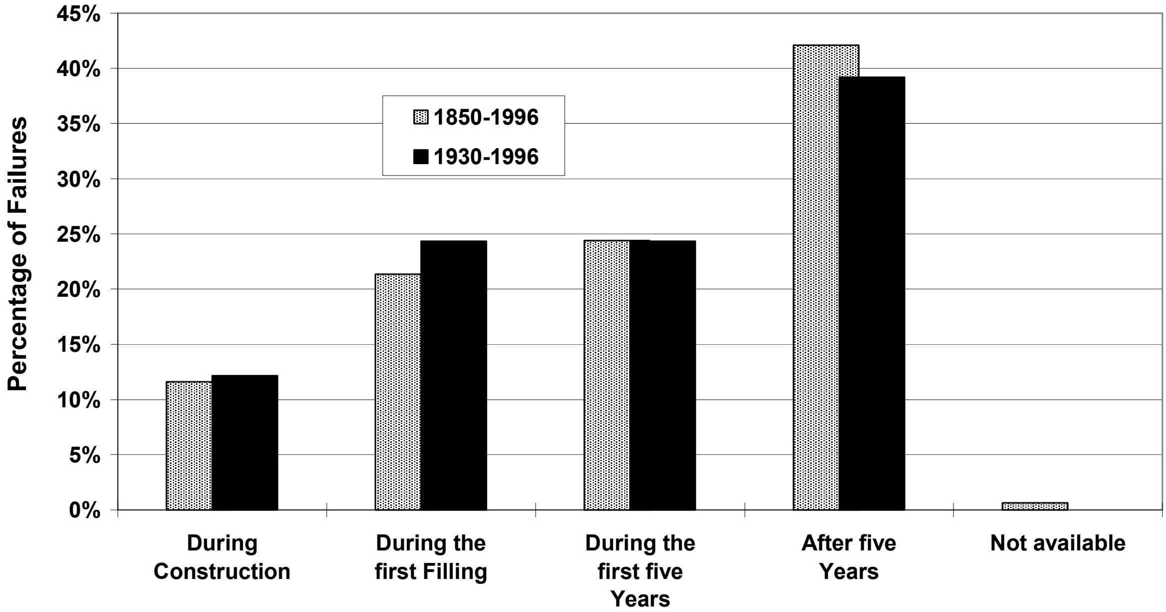

Fig. 6.6.5 Percentage of dams constructed and failed in 1850-1996 and 1930-1996. The failures occurred at different points of time dam life cycle, based on world-wide experience.

Most Swiss dams were built before the seventies and no failure of a large dam occurred during the first five years of operation or during the first filling. Therefore a for the purpose of the present study a differentiation between failures which occurred within the first *5 years after the first filling* on the one hand, and those which occurred later was made. Other characteristics like dam height or capacity were not taken into consideration.

6.6.3.5 Failure rates and years between failures for different dam types, time periods and times of failure

In the next subsections the failure rate (per dam-year) (*fr*) and the mean time between failures (*MTBF*), are calculated for:

1) Different dam types (Earth, rockfill, arch, gravity and buttress);

2) Different time periods (1850-1996 and 1930-1996);

3) Different times of failure (no restriction and 5 years after the first dam filling).

The failure rate fr_k is given by:

$$fr_k = \frac{k}{OT_k} \tag{6.6.1}$$

where:

k: failure number given in the first column of Tables 6.6.4 through 6.6.21
(If in the same table for the same year several accidents occurred, the total number of accidents was taken into account until the next year with failures.)

OT_k: operation time

The operation time (OT_k) is defined as :

OT_k = Operation time in years of all dams between 1850 (or 1930) and the year of the k-th failure

The mean time between failures *(MTBF)* is calculated as:

$$OT_k \approx \frac{ND_k}{2} \cdot k \cdot MTBF_k \qquad (6.6.2)$$

where:

ND_k = *total* number of constructed dams beginning from 1850 (or 1930) up to the year of the k-th failure; this number is divided by factor 2 to obtain the average number of dams operating during these periods; thus it is assumed that the number of dams grows linearly in time.

Combining eq. (6.6.1) and eq. (6.6.2) fr_k can be written as:

$$fr_k = \frac{k}{OT_k} \approx \frac{k}{\left(\frac{ND_k}{2} \cdot k \cdot MTBF_k\right)} = \frac{1}{\left(\frac{ND_k}{2} \cdot MTBF_k\right)} \qquad (6.6.3)$$

or from eq. (6.6.3):

$$MTBF_k \approx \frac{1}{fr_k \cdot \frac{ND_k}{2}} \qquad (6.6.4)$$

In cases when the operation time cannot be reasonably well approximated by eq. (6.6.2), eq. (6.6.4) can lead to inconsistent results.

In Appendix E (Table E.1) a list of failed dams in North America, Western Europe, Australia and New Zealand is given. The information in this list served as a basis for the evaluation of failure rates. The purposes, types of the dams and the number of fatalities due to floodwaters after dam failure are listed in the table. In some cases, the exact number of fatalities is not known. Apart from general reporting uncertainties the reason is that intense rainstorms can also cause floodwaters which result in deaths. After a dam failure it is then often very difficult to attribute the correct number to the floodwater deaths caused by the dam failure [Jansen, 1983]. Therefore, both the recorded maximum and minimum number of fatalities caused by the dam failure are given.

Several issues arise when evaluating the material. First, in order to carry out the evaluations the operation time of dams is needed. Both World Register of Dams [ICOLD 1984 and 1988] list dams whose completion years were up to 1983 and 1987, respectively. Therefore, approximation curves for the operation time and number of dams were used for all dam types and the period 1987-1996. It was found that a polynom of second order was adequate to approximate both operation time and number of dams.

Another issue is the inexplicable removal of all US dams less than 30 m of height in the new registers [ICOLD 1984, 1988] although this is not consistent with ICOLD's definition of large dams. All US large dams have been catalogued in [ICOLD 1973 and 1977] for the period 1850-1976. For these reasons the operation time and the number of US dams were approximately determined for US dams during the period 1977-1996 by a polynom of second order.

As shown in Fig. 6.6.4 gravity dams form the most common dam type in Switzerland. Not all failures in Table E.1 of Appendix E are applicable to the Swiss conditions. In Switzerland, all gravity, arch and buttress dams were built using concrete; in no case masonry, a weaker material than concrete, was used. On the other hand, in [ICOLD, 1984 and 1988] there are no details provided which would allow to decide whether in applicable cases concrete or masonry were used. According to a number of sources (e.g. [Hauenstein, 1995]), starting from about 1930 most dams of type Pg, Va and Cb world-wide were built using concrete. Therefore, within the evaluation period 1930-1996 masonry dams were excluded.

Sometimes the types of dams are mixed, such as for example Pg/Er, Te/Pg or Te/Pg/Er. In these cases the question arises to which dam type the failure should be assigned. If a dam of type Pg/Er failed, because the earth section of the dam was destroyed, then the failure was classified as an Er dam failure. The description of the accident must be studied carefully before a decision can be taken.

In the statistical evaluation of failure rates the Lower Bound (5%) and Upper Bound (95%) were calculated based on the records (number of failures and total operational time) at the end of year 1996, and using the Gamma distribution. The mean value was then obtained using direct estimation (total number of failures/total operation time) or employing the Lognormal approximation whenever the number of failures is 0.

Failures of gravity (Pg) dams for all occasions of failure (evaluation period 1850-1996).

In Table 6.6.4, gravity dam failures used for the evaluations are shown for all occasions of failure during the period 1850-1996. In the last two columns the failure rate and the estimated mean years between failures (rounded to full digit) are given. The last row of the table provides the estimate at the end of 1996.

TABLE 6.6.4

Failures of dams of type gravity (Pg) in the Western World; the failed dams were built of masonry (Pg(M)) or concrete and the evaluation period is 1850-1996.

Failure No. K	Country	Dam name	Type	Year of failure	Operation time ΔOT_k [years]	Failure rate [per dam-year]	Number of dams	Years between failures
1	USA	Austin I	Pg(M)	1893	675	$1.5\ 10^{-3}$	51	26
2	France	Bouzey	Pg(M)	1895	782	$2.6\ 10^{-3}$	61	13
3	USA	Bayless	Pg	1911	2641	$1.0\ 10^{-3}$	235	9
4	USA	Elwha River	Pg	1912	2876	$1.4\ 10^{-3}$	262	5
5	USA	St. Francis	Pg	1928	9633	$5.2\ 10^{-4}$	675	6
6	Italy	Zerbino	Pg	1935	15095	$4.0\ 10^{-4}$	886	6
7	Spain	Xuriguera	Pg	1944	23732	$3.4\ 10^{-4}$	1056	6
8	USA	Gallinas	Pg(M)	1957	39730	$2.8\ 10^{-4}$	1526	5
9	USA	Hauser Lake II	Pg	1969	60677	$1.5\ 10^{-4}$	1989	7
10	USA	Lower Idaho Falls	Er/ Pg(M)	1976	75128	$1.2\ 10^{-4}$	2150	8
	-	-	Pg or Pg(M)	1996[a]	120625	$8.3\ 10^{-5}$	2300	10.5/5.2[b]

[a] No failure occurred in 1996; the reliability parameters are here calculated at the end of 1996.

[b] Two different times between failures are given. The first is based on the average number of operating dams during the evaluation period while the second is a projected time based on the assumption that the population of dams of specific types will remain at the same level as in 1996.

For 1996 the 5% Lower Bound (LB) is $5.1\ 10^{-5}$ and the 95% Upper Bound (UB) is $1.4\ 10^{-4}$.

For the time period 1987-1996 an approximation polynom of second order was used for the operation time (eq. 6.6.5) and for number of dams (eq. 6) of type Pg :

$$OT = 7.0 \cdot (x\text{-}1970)^2 + 2050 \cdot (x\text{-}1970) + 62593 \qquad (6.6.5)$$

where:

OT = Operation time of dams in the Western World for type Pg built from concrete or masonry

x = Year of construction ($x \geq 1987$)

$$ND = -0.44 \cdot (x\text{-}1970)^2 + 21.8 \cdot (x\text{-}1970) + 2027 \qquad (6.6.6)$$

where:

ND = Number of dams

x = Year of construction ($x \geq 1987$)

Table 6.6.4 shows that the failure rate has decreased with time down to $8.3 \cdot 10^{-5}$ at the end of 1996.

Failures of gravity (Pg) dams built of concrete for all occasions of failure (evaluation period 1930-1996).

In the next step, Pg-dams completed during the time period 1930-1996 were chosen. Only dams built of concrete were considered. For the dams Zerbino, Xuriguera, Hauser Lake II in Table 6.6.4 the failures occurred after 1930. However, they are not listed in Table 6.6.5 because these dams were completed before year 1930. In addition, the dams Gallinas and Lower Idaho Falls in Table 6.6.4 are not considered because these dams were built of masonry. Therefore in Table 6.6.5 no specific dam is listed.

TABLE 6.6.5

Gravity (Pg) dam failures (evaluation period 1930 - 1996).

Number of failures	Country	Dam name	Type	Year of failure	Operation time ΔOT_k [years]	Failure rate [per dam-year]	Number of dams	Years between failures
0	-	-	Pg	1996[a]	62814	$1.3\ 10^{-5}$	1620	95.0/47.5[b]

[a] No failure occurred in 1996; the reliability parameters are here calculated at the end of 1996.

[b] Two different times between failures are given. The first is based on the average number of operating dams during the evaluation period while the second is a projected time based on the assumption that the population of dams of specific types will remain at the same level as in 1996.

For 1996 the 5% Lower Bound (LB) is $8.2\ 10^{-7}$ and the 95% Upper Bound (UB) is $4.8\ 10^{-5}$.

For evaluations after 1987, the following polynomial approximations of second order for the operation time (eq. 6.6.7) and the number of dams (eq. 6.6.8) up to 1996 are used:

$$OT = 7.0 \cdot (x\text{-}1970)^2 + 1341 \cdot (x\text{-}1970) + 23216 \qquad (6.6.7)$$

$$ND = -\ 0.33 \cdot (x\text{-}1970)^2 + 20.44 \cdot (x\text{-}1970) + 1322 \qquad (6.6.8)$$

Failures of gravity (Pg) dams occurred later than 5 years after the first filling (evaluation period 1850-1996).

Table 6.6.6 shows the dam failures taken from Table 6.6.4 but restricted to the accidents that occurred after the first five years following the first filling. The approximations for the number of dams and operation time were the same as those used for Table 6.6.4.

TABLE 6.6.6

Failures occurred later than 5 years after the first filling of dams of type gravity (Pg) in the Western World; the building material was masonry (Pg(M)) or concrete (evaluation period 1850-1996).

Failure No. K	Country	Dam name	Type	Year of failure	Operation time ΔOT_k [years]	Failure rate [per dam-year]	Number of dams	Years between failures
1	France	Bouzey	Pg(M)	1895	782	$1.3\ 10^{-3}$	61	25
2	Italy	Zerbino	Pg	1935	15095	$1.2\ 10^{-4}$	886	19
3	Spain	Xuriguera	Pg	1944		$1.3\ 10^{-4}$	1056	7
4	USA	Gallinas	Pg(M)	1957	39730	$1.0\ 10^{-4}$	1526	13
5	USA	Hauser Lake II	Pg	1969	60677	$8.1\ 10^{-5}$	1989	12
6	USA	Lower Idaho Falls	Er/ Pg(M)	1976	75128	$8.0\ 10^{-5}$	2150	12
-	-	-	Pg or Pg(M)	1996 [a]	120625	$5.0\ 10^{-5}$	2300	17.4/8.7 [b]

[a] No failure occurred in 1996; the reliability parameters are here calculated at the end of 1996.

[b] Two different times between failures are given. The first is based on the average number of operating dams during the evaluation period while the second is a projected time based on the assumption that the population of dams of specific types will remain at the same level as in 1996.

For 1996 the 5% Lower Bound (LB) is $2.7\ 10^{-5}$ and the 95% Upper Bound (UB) is $9.8\ 10^{-5}$.

Failures of gravity (Pg) dams built of concrete and whose failures occurred later than 5 years after the first filling (evaluation period 1930-1996).

The results for failure rates and years between failures for the case where the time period 1930-1996 was chosen is the same as in Table 6.6.5.

Failures of arch (Va) dams for all occasions of failure (evaluation period 1850 - 1996).

Table 6.6.7 shows the selected failures of dams of type Va. In general all Va dams are built of concrete.

For the operation time, *OT*, and the number of dams *ND*, the following approximations were used:

$$OT = 1.9 \cdot (x\text{-}1970)^2 + 565 \cdot (x\text{-}1970) + 13579 \qquad (6.6.9)$$

$$ND = -0.06 \cdot (x\text{-}1970)^2 + 5.0 \cdot (x\text{-}1970) + 562 \qquad (6.6.10)$$

TABLE 6.6.7

Failures of dams of type arch (Va) in the Western World; the failed dams were built of concrete (evaluation period 1850 - 1996).

Failure No. K	Country	Dam name	Type	Year of failure	Operation time ΔOT_k [years]	Failure rate [per dam-year]	Number of dams	Years between failures
1	USA	Moyie River	Va	1926	952	$1.1\ 10^{-3}$	97	19
2	USA	Vaughn Creek	Va	1926	952	$2.1\ 10^{-3}$	97	10
3	France	Malpasset	Va	1959	8213	$3.7\ 10^{-4}$	405	13
-	-	-	Va	1996 [a]	29553	$1.0\ 10^{-4}$	651	30.7/15.4 [b]

[a] No failure occurred in 1996; the reliability parameters are here calculated at the end of 1996.

[b] Two different times between failures are given. The first is based on the average number of operating dams during the evaluation period while the second is a projected time based on the assumption that the population of dams of specific types will remain at the same level as in 1996.

For 1996 the 5% Lower Bound (LB) is $4.6\ 10^{-5}$ and the 95% Upper Bound (UB) is $2.6\ 10^{-4}$.

Failures of arch (Va) dams for all occasions of failure (evaluation period 1930-1996).

In the next step the period 1930-1996 is chosen to account for the improved technical developments in concrete dam construction.

TABLE 6.6.8

Failures of dams of type arch (Va) in the Western World; the failed dam was built of concrete (evaluation period 1930-1996).

Failure No. K	Country	Dam name	Type	Year of failure	Operation time ΔOT_k [years]	Failure rate [per dam-year]	Number of dams	Years between failures
1	France	Malpasset	Va	1959	3243	$3.1\ 10^{-4}$	282	23
-	-	-	Va	1996 [a]	20032	$5.0\ 10^{-5}$	528	75.8/37.9[b]

[a] No failure occurred in 1996; the reliability parameters are here calculated at the end of 1996.

[b] Two different times between failures are given. The first is based on the average number of operating dams during the evaluation period while the second is a projected time based on the assumption that the population of dams of specific types will remain at the same level as in 1996.

For 1996 the 5% Lower Bound (LB) is $1.8\ 10^{-5}$ and the 95% Upper Bound (UB) is $2.4\ 10^{-4}$.

For the operation time, OT, and the number of dams, the following approximations were used:

$$OT = 1.9 \cdot (x\text{-}1970)^2 + 442 \cdot (x\text{-}1970) + 7256 \qquad (6.6.11)$$

$$ND = -0.06 \cdot (x\text{-}1970)^2 + 5.0 \cdot (x\text{-}1970) + 439 \qquad (6.6.12)$$

Failures of arch (Va) dams occurred later than 5 years after the first filling (evaluation period 1850-1996).

The failure at Malpasset is not included in Table 6.6.9 because it occurred within 5 years after the first filling. Therefore the value for the failure rate based on year 1996 is lower than the value calculated in Table 6.6.7.

TABLE 6.6.9

Arch (Va) dam failures, occurred later than 5 years after first filling (evaluation period 1850-1996).

Number of failures	Country	Dam name	Type	Year of failure	Operation time ΔOT_k [years]	Failure rate [per dam-year]	Number of dams	Years between failures
0	-	-	Va	1996[a]	29553	2.8 10^{-5}	651	110.0/55.0[b]

[a] No failure occurred in 1996; the reliability parameters are here calculated at the end of 1996.

[b] Two different times between failures are given. The first is based on the average number of operating dams during the evaluation period while the second is a projected time based on the assumption that the population of dams of specific types will remain at the same level as in 1996.

For 1996 the 5% Lower Bound (LB) is 1.7 10^{-6} and the 95% Upper Bound (UB) is 1.0 10^{-4}.

Failures of arch (Va) dams occurred later than 5 years after the first filling (evaluation period 1930-1996).

During 1930-1996 no failure occurred after the first filling.

TABLE 6.6.10

Arch (Va) dam failures, occurred later than 5 years after first filling (evaluation period 1930-1996).

Number of failures	Country	Dam name	Type	Year of failure	Operation time ΔOT_k [years]	Failure rate [per dam-year]	Number of dams	Years between failures
0	-	-	Va	1996[a]	20032	4.2 10^{-5}	528	90.2/45.1[b]

[a] No failure occurred in 1996; the reliability parameters are here calculated at the end of 1996.

[b] Two different times between failures are given. The first is based on the average number of operating dams during the evaluation period while the second is a projected time based on the assumption that the population of dams of specific types will remain at the same level as in 1996.

For 1996 the 5% Lower Bound (LB) is 2.6 10^{-6} and the 95% Upper Bound (UB) is 1.5 10^{-4}.

The failure rate in 1996 is somewhat higher than that calculated in Table 6.6.9 due to the shorter time interval.

Failures of buttress (Cb) dams for all occasions of failure (evaluation period 1850-1996).

In Table 6.6.11 the failures of dams of buttress type are shown. Most failures occurred at dams built of masonry. The approximations for the operation time and the number of dams were:

$$OT = 0.70 \cdot (x\text{-}1970)^2 + 283.32 \cdot (x\text{-}1970) + 6928 \qquad (6.6.13)$$

$$ND = -0.046 \cdot (x\text{-}1970)^2 + 2.20 \cdot (x\text{-}1970) + 281 \qquad (6.6.14)$$

TABLE 6.6.11

Failures of dams of buttress type (Cb) in the Western World; the dams were built of concrete (Cb) or masonry (Cb(M)) (evaluation period 1850-1996).

Failure No. K	Country	Dam name	Type	Year of failure	Operation time ΔOT_k [years]	Failure rate [per dam-year]	Number of dams	Years between failures
1	USA	Ashley	Cb	1909	40	$2.5\ 10^{-2}$	8	10
2	USA	Austin II	Cb(M)	1915	168	$1.2\ 10^{-2}$	37	5
3	Sweden	Selfors	Cb(M)	1943	2055	$1.5\ 10^{-3}$	103	13
4	Spain	Vega de Terra	Cb(M)	1959	4247	$7.1\ 10^{-4}$	204	14
-	-	-	-	1996 [a]	14759	$2.7\ 10^{-4}$	307	24.1/12.1 [b]

[a] No failure occurred in 1996; the reliability parameters are here calculated at the end of 1996.

[b] Two different times between failures are given. The first is based on the average number of operating dams during the evaluation period while the second is a projected time based on the assumption that the population of dams of specific types will remain at the same level as in 1996.

For 1996 the 5% Lower Bound (LB) is $1.3\ 10^{-4}$ and the 95% Upper Bound (UB) is $6.2\ 10^{-4}$.

Failures of buttress (Cb) dams for all occasions of failure (evaluation period 1930 - 1996).

In the next step the period 1930-1996 is chosen to reflect the technical improvements in dam construction. During this period no applicable failure occurred. (Selfors and Vega de Terra of Table 6.6.11 are excluded in this part of analysis because they are built of masonry). The approximations for the operation time and the number of dams during 1987-1996 are:

$$OT = 0.70 \cdot (x\text{-}1970)^2 + 211.32 \cdot (x\text{-}1970) + 3100 \qquad (6.6.15)$$

$$ND = -0.045 \cdot (x\text{-}1970)^2 + 2.20 \cdot (x\text{-}1970) + 209.41 \qquad (6.6.16)$$

TABLE 6.6.12

Buttress (Cb) dam failures (evaluation period 1930 - 1996).

Number of failures	Country	Dam name	Type	Year of failure	Operation time ΔOT_k [years]	Failure rate [per dam-year]	Number of dams	Years between failures
0	-	-	-	1996[a]	9067	9.3 10^{-5}	236	91.1/45.6[b]

[a] No failure occurred in 1996; the reliability parameters are here calculated at the end of 1996.

[b] Two different times between failures are given. The first is based on the average number of operating dams during the evaluation period while the second is a projected time based on the assumption that the population of dams of specific types will remain at the same level as in 1996.

For 1996 the 5% Lower Bound (LB) is 5.7 10^{-6} and the 95% Upper Bound (UB) is 3.3 10^{-4}.

Failures of buttress (Cb) dams occurred later than 5 years after the first filling (evaluation period 1850-1996).

In Table 6.6.13 the failures of dams of type Cb are shown. During the period 1850-1996 there is only the Austin failure.

TABLE 6.6.13

Failures of dams of type Buttress (Cb) in the Western World; the dams were built from concrete(Cb) or masonry (Cb(M)) (evaluation period 1850-1996).

Number of failures	Country	Dam name	Type	Year of failure	Operation time ΔOT_k [years]	Failure rate [per dam-year]	Number of dams	Years between failures
0	-	-	-	1996[a]	14759	5.7 10^{-5}	307	114.3/57.1[b]

[a] No failure occurred in 1996; the reliability parameters are here calculated at the end of 1996.

[b] Two different times between failures are given. The first is based on the average number of operating dams during the evaluation period while the second is a projected time based on the assumption that the population of dams of specific types will remain at the same level as in 1996.

For 1996 the 5% Lower Bound (LB) is 3.5 10^{-6} and the 95% Upper Bound (UB) is 2.0 10^{-4}.

Failures of buttress (Cb) dams occurred later than 5 years after the first filling (evaluation period 1930-1996).

The results are the same as calculated in Table 6.6.12.

Failures of earth (Te) dams for all occasions of failure (evaluation period 1850-1996).

In Table 6.6.14 the failures of earth (Te) dams are shown. For evaluations beyond 1986 the following approximations for the operation-time (*OT*) and the number of dams (*ND*) until 1996 are used :

$$OT = 32.77 \cdot (x\text{-}1970)^2 + 4718 \cdot (x\text{-}1970) + 101073 \qquad (6.6.17)$$

$$ND \approx 5704 \qquad (6.6.18)$$

TABLE 6.6.14

Failures of dams of earth (Te) type in the Western World (evaluation period 1850-1996).

Failure No. K	Country	Dam name	Type	Year of failure	Operation time ΔOT_k [years]	Failure rate [per dam-year]	Number of dams	Years between failures
1	UK	Rhodes-worth	Te	1852	23	4.3 10^{-2}	15	3
2	UK	Torside	Te	1854	54	3.7 10^{-2}	21	3
3	UK	Dale Dike	Te	1864	367	8.2 10^{-3}	46	5
4	USA	Cuba	Te	1868	579	6.8 10^{-3}	67	4
5	USA	South Fork	Te/Er	1889	3645	1.4 10^{-3}	233	6
6	USA	Chambers Lake I	Te	1891	4122	1.5 10^{-3}	251	5
7	USA	Avalon I	Te/Er	1893	4634	1.5 10^{-3}	265	5
8	USA	Snake Ravine	Te	1898	6044	1.3 10^{-3}	312	5
9	USA	Lake Francis I	Te	1899	6356	1.4 10^{-3}	317	4
10	USA	Utica	Te	1902	7344	1.4 10^{-3}	355	4
11	USA	Avalon II	Te/Er	1904	8069	1.4 10^{-3}	381	4
12	USA	Greenlick	Te	1904	8069	1.5 10^{-3}	381	4

Table 6.6.14 continues on the next page.

TABLE 6.6.14

Failures of dams of earth (Te) type in the Western World (evaluation period 1850-1996). *(continued)*

Failure No. K	Country	Dam name	Type	Year of failure	Operation time ΔOt_k [years]	Failure rate [per dam-year]	Number of dams	Years between failures
13	USA	Chanbers Lake II	Te	1907	9280	$1.4\ 10^{-3}$	444	3
14	USA	Zuni	Te/Er	1909	10187	$1.4\ 10^{-3}$	480	3
15	USA	Jumbo	Te	1910	10667	$1.4\ 10^{-3}$	505	3
16	USA	Hatchtown	Te	1914	12851	$1.2\ 10^{-3}$	608	3
17	USA	Hebron I	Te	1914	12851	$1.3\ 10^{-3}$	608	2
18	USA	Horse Creek	Te	1914	12851	$1.4\ 10^{-3}$	608	2
19	USA	Owen	Te	1914	12851	$1.5\ 10^{-3}$	608	2
20	USA	Lyman	Te	1915	13459	$1.5\ 10^{-3}$	624	2
21	USA	Lake Toxaway	Te	1916	14083	$1.6\ 10^{-3}$	638	2
22	USA	Lookout Shoals	Te	1916	14083	$1.6\ 10^{-3}$	638	2
23	USA	Sweetwater Main	Te	1916	14083	$1.7\ 10^{-3}$	638	2
24	USA	Mammoth	Te	1917	14721	$1.7\ 10^{-3}$	644	2
25	USA	Schaeffer	Te	1921	17365	$1.4\ 10^{-3}$	696	2
26	Canada	Log Falls	Te	1923	18772	$1.4\ 10^{-3}$	735	2
27	USA	Apishaba	Te	1923	18772	$1.4\ 10^{-3}$	735	2
28	USA	Graham Lake	Te	1923	18772	$1.5\ 10^{-3}$	735	2
29	USA	McMahon Gulch	Te	1925	20260	$1.4\ 10^{-3}$	777	2
30	USA	Lake Hemet	Te	1927	21840	$1.4\ 10^{-3}$	835	2
31	USA	Balsam	Te	1929	23543	$1.3\ 10^{-3}$	891	2
32	USA	Corpus Christi	Te	1930	24434	$1.3\ 10^{-3}$	925	2
33	USA	Lake Francis II	Te	1935	29309	$1.1\ 10^{-3}$	1064	2

Table 6.6.14 continues on the next page.

TABLE 6.6.14

Failures of dams of earth (Te) type in the Western World; (evaluation period 1850-1996). *(continued)*

Failure No. K	Country	Dam name	Type	Year of failure	Operation time ΔOt_k [years]	Failure rate [per dam-year]	Number of dams	Years between failures
34	USA	Wagner Creek	Te	1938	32600	$1.0\ 10^{-3}$	1169	2
35	USA	Anaconda	Te	1938	32600	$1.1\ 10^{-3}$	1169	2
36	USA	Hebron II	Te	1942	37466	$9.6\ 10^{-4}$	1298	2
37	USA	Sinker Creek	Te	1943	38764	$9.5\ 10^{-4}$	1318	2
38	USA	Fred Burr	Te	1948	45493	$8.4\ 10^{-4}$	1425	2
39	USA	Torenson	Te	1953	53267	$7.3\ 10^{-4}$	1793	2
40	Canada	Battle River	Te	1956	58879	$6.8\ 10^{-4}$	2060	1
41	USA	Mill Creek	Te	1957	60939	$6.7\ 10^{-4}$	2166	1
42	USA	Alamo Royo Site2	Te	1960	67808	$6.2\ 10^{-4}$	2598	1
43	Australia	Lake Cawndilla	Te	1962	73168	$5.9\ 10^{-4}$	2959	1
44	USA	Baldwin Hills	Te	1963	76127	$5.8\ 10^{-4}$	3130	1
45	USA	Little Deer Creek	Te	1963	76127	$5.9\ 10^{-4}$	3130	1
46	USA	Swift	Te/Er	1964	79257	$5.8\ 10^{-4}$	3295	1
47	USA	English W. Supply	Te	1965	82552	$5.7\ 10^{-4}$	3502	1
48	USA	Wesley E. Seale	Te	1965	82552	$5.8\ 10^{-4}$	3502	1
49	USA	Emery	Te	1966	86054	$5.7\ 10^{-4}$	3679	1
50	USA	Sheep Creek	Te	1970	101919	$4.9\ 10^{-4}$	4324	1
51	USA	Lake Barcroft	Te	1972	110719	$4.6\ 10^{-4}$	4642	1

Table 6.6.14 continues on the next page.

TABLE 6.6.14

Failures of dams of earth (Te) type in the Western World (evaluation period 1850-1996) *(continued).*

Failure No. K	Country	Dam name	Type	Year of failure	Operation time ΔOt_k [years]	Failure rate [per dam-year]	Number of dams	Years between failures
52	USA	Whitewater Brook Upper	Te	1972	110719	$4.7\ 10^{-4}$	4642	1
53	USA	Caulk Lake	Te	1973	115361	$4.6\ 10^{-4}$	4843	1
54	USA	Walter Bouldin	Te	1975	125226	$4.3\ 10^{-4}$	5122	1
55	USA	Teton	Te/Er	1976	130348	$4.2\ 10^{-4}$	5236	1
56	Canada	Hinds Lake	Te	1982	162578	$3.4\ 10^{-4}$	5523	1
57	Sweden	Noppikoski	Te	1985	179250	$3.2\ 10^{-4}$	5611	1
58	USA	Quail Creek	Te	1988	196187	$3.0\ 10^{-4}$	5689	1
-	-	-	Te	1996 [a]	245803	$2.4\ 10^{-4}$	5704	2.7/1.4 [b]

[a] No failure occurred in 1996; the reliability parameters are here calculated at the end of 1996.

[b] Two different times between failures are given. The first is based on the average number of operating dams during the evaluation period while the second is a projected time based on the assumption that the population of dams of specific types will remain at the same level as in 1996.

For 1996 the 5% Lower Bound (LB) is $1.9\ 10^{-4}$ and the 95% Upper Bound (UB) is $2.9\ 10^{-4}$.

Failures of earth (Te) dams for all occasions of failure (evaluation period 1930-1996).

In Table 6.6.15 the time period 1930-1996 was selected for the evaluation. Consequently, both dam failures before 1930 and failures of dams constructed before 1930 are excluded. For evaluations beyond 1986 the following approximations for the operation-time (*OT*) and the number of dams (*ND*) are used:

$$OT = 32.76 \cdot (x\text{-}1970)^2 + 3827 \cdot (x\text{-}1970) + 40999 \qquad (6.6.19)$$

$$ND \approx 4813 \qquad (6.6.20)$$

TABLE 6.6.15

Failures of dams of earth (Te) type in the Western World (evaluation period 1930-1996).

Failure No. K	Country	Dam name	Type	Year of failure	Operation time ΔOT_k [years]	Failure rate [per dam-year]	Number of dams	Years between failures
1	USA	Corpus Christi	Te	1930	34	$2.9\ 10^{-2}$	34	2
2	USA	Fred Burr	Te	1948	5021	$4.0\ 10^{-4}$	534	9
3	USA	Battle River	Te	1956	11279	$2.7\ 10^{-4}$	1169	6
4	USA	Alamo Royo Site 2	Te	1960	16644	$2.4\ 10^{-4}$	1707	5
5	Australia	Lake Cawndilla	Te	1962	20222	$2.5\ 10^{-4}$	2068	4
6	USA	Baldwin Hills	Te	1963	22290	$2.7\ 10^{-4}$	2239	3
7	USA	Little Deer Creek	Te	1963	22290	$3.1\ 10^{-4}$	2239	3
8	USA	Wesley E. Seale	Te	1965	26933	$3.0\ 10^{-4}$	2611	3
9	USA	English Water Supply	Te	1965	26933	$3.3\ 10^{-4}$	2611	2
10	USA	Sheep Creek	Te	1970	41845	$2.4\ 10^{-4}$	3433	2
11	USA	Whitewater Brook Upper	Te	1972	48863	$2.3\ 10^{-4}$	3751	2
12	USA	Caulk Lake	Te	1973	52614	$2.3\ 10^{-4}$	3952	2
12	USA	Walter Bouldin	Te	1975	60697	$2.0\ 10^{-4}$	4231	2
13	USA	Teton	Te/Er	1976	64928	$2.0\ 10^{-4}$	4345	2
14	Canada	Hinds Lake	Te	1982	91812	$1.5\ 10^{-4}$	4632	3
15	Sweden	Noppikoski	Te	1985	105811	$1.4\ 10^{-4}$	4720	3
16	USA	Quail Creek	Te	1988	120075	$1.3\ 10^{-4}$	4798	3
-	-	-	Te [a]	1996[a]	162647	$9.8\ 10^{-5}$	4813	4.2/2.1[b]

[a] No failure occurred in 1996; the reliability parameters are here calculated at the end of 1996.

[b] Two different times between failures are given. The first is based on the average number of operating dams during the evaluation period while the second is a projected time based on the assumption that the population of dams of specific types will remain at the same level as in 1996.

For 1996 the 5% Lower Bound (LB) is $6.7\ 10^{-5}$ and the 95% Upper Bound (UB) is $1.5\ 10^{-4}$.

Failures of earth (Te) dams occurred later than 5 years after the first filling (evaluation period 1850-1996).

The failures which occurred 5 years after the first filling are shown in Table 6.6.16.

TABLE 6.6.16

Failures of dams of earth (Te) type in the Western World occurred later than 5 years after the first filling (evaluation period 1850-1996).

Failure No. K	Country	Dam name	Type	Year of failure	Operation time ΔOT_k [years]	Failure rate [per dam-year]	Number of dams	Years between failures
1	USA	Cuba	Te	1868	579	$1.7\ 10^{-3}$	67	17
2	USA	South Fork	Te	1889	3645	$5.5\ 10^{-4}$	233	16
3	USA	Chambers Lake I	Te	1891	4122	$7.3\ 10^{-4}$	251	11
4	USA	Utica	Te	1902	7344	$5.4\ 10^{-4}$	355	10
8	USA	Avalon II	Te/Er	1904	8069	$9.9\ 10^{-4}$	381	5
9	USA	Chambers Lake II	Te	1907	9280	$9.7\ 10^{-4}$	444	5
10	USA	Jumbo	Te	1910	10667	$9.4\ 10^{-4}$	505	4
11	USA	Hatchtown	Te	1914	12851	$8.6\ 10^{-4}$	608	4
13	USA	Sweetwater Main	Te	1916	14083	$9.2\ 10^{-4}$	638	3
14	USA	Lake Toxaway	Te	1916	14083	$9.9\ 10^{-4}$	638	3
15	USA	Schaeffer	Te	1921	17365	$8.6\ 10^{-4}$	696	3
16	USA	Lake Francis II	Te	1935	29309	$5.8\ 10^{-4}$	1064	3
17	USA	Wagner Creek	Te	1938	32600	$5.5\ 10^{-4}$	1169	3
18	USA	Anaconda	Te	1938	32600	$5.8\ 10^{-4}$	1169	3
19	USA	Hebron II	Te	1942	37466	$5.3\ 10^{-4}$	1298	3

Table 6.6.16 continues on the next page.

TABLE 6.6.16

Failures of dams of earth (Te) type in the Western World occurred later than 5 years after the first filling (evaluation period 1850-1996) *(continued)*.

Failure No. K	Country	Dam name	Type	Year of failure	Operation time ΔOT_k [years]	Failure rate [per dam-year]	Number of dams	Years between failures
20	USA	Sinker Creek	Te	1943	38764	$5.4\ 10^{-4}$	1318	3
21	USA	Torenson	Te	1953	53267	$4.1\ 10^{-4}$	1793	3
22	USA	Mill Creek	Te	1957	60939	$3.8\ 10^{-4}$	2166	2
23	USA	Baldwin Hills	Te	1963	76127	$3.2\ 10^{-4}$	3130	2
24	USA	Swift	Te/Er	1964	79257	$3.2\ 10^{-4}$	3295	2
25	USA	Wesley E. Seale	Te	1965	82552	$3.1\ 10^{-4}$	3502	2
26	USA	Emery	Te	1966	86054	$3.1\ 10^{-4}$	3679	2
27	USA	Lake Barcroft	Te	1972	110719	$2.5\ 10^{-4}$	4642	2
28	USA	Whitewater Brook Upper	Te	1972	110719	$2.6\ 10^{-4}$	4642	2
29	USA	Caulk Lake	Te	1973	115361	$2.6\ 10^{-4}$	4843	2
30	USA	Walter Bouldin	Te		125226	$2.5\ 10^{-4}$	5122	2
31	Sweden	Noppikoski	Te	1985	179250	$1.8\ 10^{-4}$	5611	2
32	-	-	Te	1996 [a]	245803	$1.3\ 10^{-4}$	5702	2.7/1.3 [b]

[a] No failure occurred in 1996; the reliability parameters are here calculated at the end of 1996.

[b] Two different times between failures are given. The first is based on the average number of operating dams during the evaluation period while the second is a projected time based on the assumption that the population of dams of specific types will remain at the same level as in 1996.

For 1996 the 5% Lower Bound (LB) is $9.5\ 10^{-5}$ and the 95% Upper Bound (UB) is $1.7\ 10^{-4}$.

Failures of earth (Te) dams occurred 5 years after the first filling (evaluation period 1930-1996).

In Table 6.6.17 the time period 1930-1996 was selected. Six failures occurred.

TABLE 6.6.17

Failures of dams of type earth (Te) in the Western World occurred later than 5 years after the first filling (evaluation period 1930-1996).

Failure No. K	Country	Dam name	Type	Year of failure	Operation time ΔOT_k [years]	Failure rate [per dam-year]	Number of dams	Years between failures
1	USA	Baldwin Hills	Te	1963	22290	$4.5\ 10^{-5}$	2239	20
2	USA	Wesley E. Seale	Te	1965	26933	$7.4\ 10^{-5}$	2611	10
3	USA	Whitewater Brook Upper	Te	1972	48863	$6.1\ 10^{-5}$	3751	9
4	USA	Caulk Lake	Te	1973	52614	$7.6\ 10^{-5}$	3952	7
5	USA	Walter Bouldin	Te	1975	60697	$8.2\ 10^{-5}$	4231	6
6	Sweden	Noppikoski	Te	1985	105811	$5.7\ 10^{-5}$	4720	7
-	-	-	Te	1996 [a]	162647	$3.7\ 10^{-5}$	4813	11.2/5.6 [b]

[a] No failure occurred in 1996; the reliability parameters are here calculated at the end of 1996.

[b] Two different times between failures are given. The first is based on the average number of operating dams during the evaluation period while the second is a projected time based on the assumption that the population of dams of specific types will remain at the same level as in 1996.

For 1996 the 5% Lower Bound (LB) is $2.0\ 10^{-5}$ and the 95% Upper Bound (UB) is $7.3\ 10^{-5}$.

Failures of rockfill (Er) dams for all occasions of failure (evaluation period 1850-1996).

In Table 6.6.18 the failures of dams of type rockfill (Er) are shown. For evaluations beyond 1986 the following approximations for the operation-time (*OT*) and the number of dams (*ND*) until 1996 are used:

$$OT = 12.56 \cdot (x\text{-}1970)^2 + 607 \cdot (x\text{-}1970) + 11997 \qquad (6.6.21)$$

$$ND = -0.40 \cdot (x\text{-}1970)^2 + 31.52 \cdot (x\text{-}1970) + 599.82 \qquad (6.6.22)$$

TABLE 6.6.18

Failures of dams of rockfill (Er) type in the Western World for all occasions of failures (evaluation period 1850-1996).

Failure No. K	Country	Dam name	Type	Year of failure	Operation time ΔOT_k [years]	Failure rate [per dam-year]	Number of dams	Years between failures
1	USA	English	Er	1883	185	$5.4\ 10^{-3}$	12	31
2	USA	Wallnut Grove	Er	1890	281	$7.1\ 10^{-3}$	17	17
3	USA	Goose Creek	Er	1900	497	$6.0\ 10^{-3}$	27	12
4	USA	Lake Vera	Er	1905	643	$6.2\ 10^{-3}$	35	9
5	USA	Wisconsin Dells	Er	1911	898	$5.6\ 10^{-3}$	57	6
6	USA	Lower Otay	Er	1916	1220	$4.9\ 10^{-3}$	72	6
7	USA	Overholser	Er	1923	1754	$4.0\ 10^{-3}$	89	6
8	Canada	Scott Falls	Pg/Er	1923	1754	$4.6\ 10^{-3}$	89	5
9	USA	Littlefield	Er	1929	2344	$3.8\ 10^{-3}$	112	5
10	Australia	Briseis	Er	1929	2344	$4.3\ 10^{-3}$	112	4
11	USA	Castlewood	Er	1933	2818	$3.9\ 10^{-3}$	124	4
12	USA	Stockton Creek	Er	1950	5484	$2.2\ 10^{-3}$	191	5
13	USA	Jennings Creek 3	Er	1963	8842	$1.5\ 10^{-3}$	375	4
14	USA	Jennings Creek 16	Er	1964	9217	$1.5\ 10^{-3}$	391	3
15	USA	Hell Hole	Er	1964	9217	$1.6\ 10^{-3}$	391	3
16	USA	Swift	Er	1964	9217	$1.7\ 10^{-3}$	391	3
17	USA	Cazadero	Er	1965	9608	$1.8\ 10^{-3}$	423	3
18	Spain	Odiel	Er	1968	10962	$1.6\ 10^{-3}$	525	2

Table 6.6.18 continues on the next page.

TABLE 6.6.18

Failures of dams of rockfill (Er) type in the Western World for all occasions of failures (evaluation period 1850-1996) *(continued)*.

Failure No. K	Country	Dam name	Type	Year of failure	Operation time ΔOT_k [years]	Failure rate [per dam-year]	Number of dams	Years between failures
19	USA	Van Norman Lake	Er	1971	12631	$1.5\ 10^{-3}$	628	2
20	USA	Lower Idaho Falls	Er	1976	16097	$1.2\ 10^{-3}$	769	2
21	New Zealand	Ruahihi	Er	1981	20185	$1.0\ 10^{-3}$	909	2
22	Spain	Tous	Er	1982	21094	$1.0\ 10^{-3}$	634	3
-	-	-	Er	1996 [a]	36270	$6.1\ 10^{-4}$	1150	2.8/1.4 [b]

[a] No failure occurred in 1996; the reliability parameters are here calculated at the end of 1996.

[b] Two different times between failures are given. The first is based on the average number of operating dams during the evaluation period while the second is a projected time based on the assumption that the population of dams of specific types will remain at the same level as in 1996.

For 1996 the 5% Lower Bound (LB) is $4.3\ 10^{-4}$ and the 95% Upper Bound (UB) is $8.7\ 10^{-4}$.

Failures of rockfill (Er) dams for all occasions of failure (evaluation period 1930-1996).

Table 6.6.19 summarises the results. Several dams of Table 6.6.18, which failed after 1930 are not listed in Table 6.6.19 because they were built before 1930. For evaluations beyond 1986 the following approximations for the operation-time (*OT*) and the number of dams (*ND*) are used:

$$OT = 12.56 \cdot (x\text{-}1970)^2 + 495 \cdot (x\text{-}1970) + 5061 \qquad (6.6.23)$$

$$ND = -0.40 \cdot (x\text{-}1970)^2 + 31.52 \cdot (x\text{-}1970) + 487.77 \qquad (6.6.24)$$

TABLE 6.6.19

Failures of dams of rockfill (Er) type in the Western World for all occasions of failures (evaluation period 1930-1996).

Failure No. K	Country	Dam name	Type	Year of failure	Operation time ΔOT_k [years]	Failure rate [per dam-year]	Number of dams	Years between failures
1	USA	Stockton Creek	Er	1950	788	$2.5\ 10^{-3}$	191	4
2	USA	Jennings Creek 3	Er	1963	2690	$1.1\ 10^{-3}$	375	5
3	USA	Jennings Creek 16	Er	1964	2953	$1.4\ 10^{-3}$	391	4
4	USA	Hell Hole	Er	1964	2953	$1.7\ 10^{-3}$	391	3
5	Spain	Odiel	Er	1968	4250	$1.6\ 10^{-3}$	525	2
6	USA	Lower Idaho Falls	Er/Pg	1976	8489	$1.1\ 10^{-3}$	769	2
7	New Zealand	Ruahihi	Er	1981	12017	$8.3\ 10^{-4}$	909	3
8	Spain	Tous	Er	1982	12814	$8.6\ 10^{-4}$	934	2
-	-	-	Er	1996 [a]	26422	$3.0\ 10^{-4}$	1037	6.4/3.2 [b]

[a] No failure occurred in 1996; the reliability parameters are here calculated at the end of 1996.

[b] Two different times between failures are given. The first is based on the average number of operating dams during the evaluation period while the second is a projected time based on the assumption that the population of dams of specific types will remain at the same level as in 1996.

For 1996 the 5% Lower Bound (LB) is $1.8\ 10^{-4}$ and the 95% Upper Bound (UB) is $5.5\ 10^{-4}$.

Failures of rockfill (Er) dams occurred later than 5 years after the first filling (evaluation period 1850-1996).

Table 6.6.20 shows the failures of dams of type rockfill (Er) within the above specified boundaries.

TABLE 6.6.20

Failures of dams of rockfill (Er) type in the Western World occurred later than 5 years after the first filling (evaluation period 1850-1996).

Failure No. K	Country	Dam name	Type	Year of failure	Operation time ΔOT_k [years]	Failure rate [per dam-year]	Number of dams	Years between failures
1	USA	Lake Vera	Er	1905	643	$1.6\ 10^{-3}$	35	37
3	USA	Castle-wood	Er	1933	2818	$1.1\ 10^{-3}$	124	15
4	USA	Cazadero	Er	1965	9608	$4.2\ 10^{-4}$	423	11
5	USA	Van Norman Lake	Er	1971	12631	$4.0\ 10^{-4}$	628	8
6	USA	Lower Idaho Falls	Er/Pg	1976	16097	$3.7\ 10^{-4}$	769	7
-	-	-	Er	1996 [a]	36270	$1.7\ 10^{-4}$	1150	10.2/5.1 [b]

[a] No failure occurred in 1996; the reliability parameters are here calculated at the end of 1996.

[b] Two different times between failures are given. The first is based on the average number of operating dams during the evaluation period while the second is a projected time based on the assumption that the population of dams of specific types will remain at the same level as in 1996.

For 1996 the 5% Lower Bound (LB) is $9.1\ 10^{-5}$ and the 95% Upper Bound (UB) is $3.3\ 10^{-4}$.

Failures of rockfill (Er) dams occurred later than 5 years after the first filling (evaluation period 1930-1996).

In this period no failure occurred (Table 6.6.21).

TABLE 6.6.21

Rockfill (Er) dam failures occurred later than 5 years after the first filling (evaluation period 1930-1996).

Number of failures	Country	Dam name	Type	Year of failure	Operation time ΔOT_k [years]	Failure rate [per dam-year]	Number of dams	Years between failures
0	-	-	Er	1996[a]	26422	3.2 10^{-5}	1037	30.1/60.3[b]

[a] No failure occurred in 1996; the reliability parameters are here calculated at the end of 1996.

[b] Two different times between failures are given. The first is based on the average number of operating dams during the evaluation period while the second is a projected time based on the assumption that the population of dams of specific types will remain at the same level as in 1996.

For 1996 the 5% Lower Bound (LB) is 1.9 10^{-6} and the 95% Upper Bound (UB) is 1.1 10^{-4}.

6.6.3.6 Summary of the study of dam failures in the Western World

Figure 6.6.6 shows the failure rates for different dam types (Pg, Va, Cb, Te, Er), time periods (1850-1996, 1930-1996) and manifestations of failures (five years after the first filling of the reservoir or before).

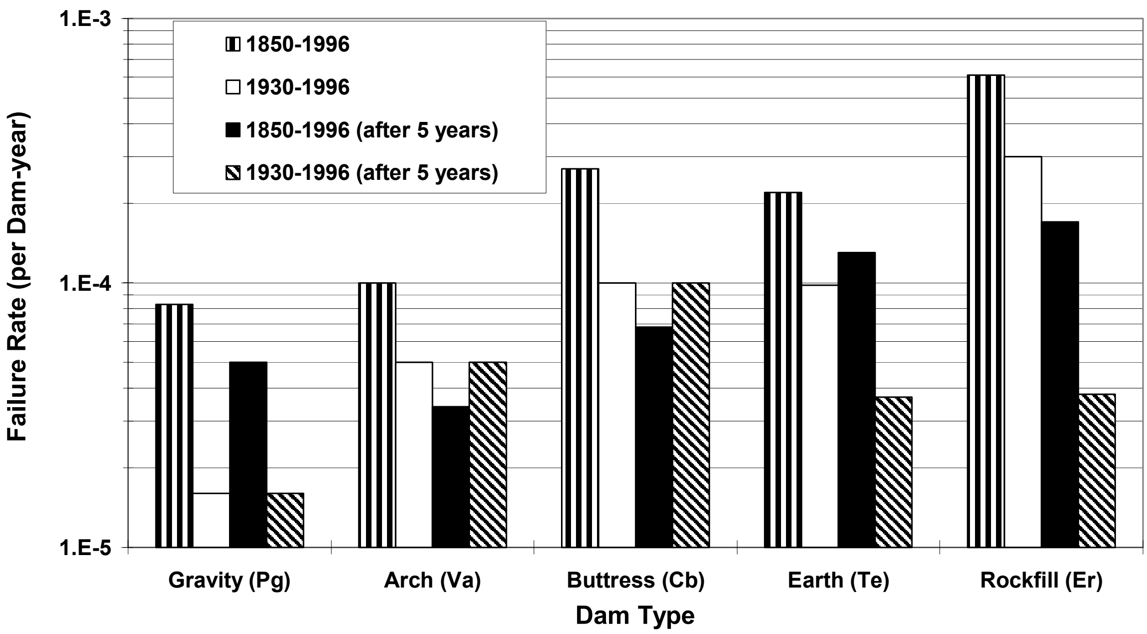

Fig. 6.6.6 Failure rates for different dam types and time periods.

The figure shows that for gravity, earth and rock fill dam types, and for all occasions of failure the failure rate decreases significantly when the evaluation is limited to the time period 1930-1996. This does not apply to arch and buttress dam failures that occurred later than 5 years after the first filling. In these cases the failure rate increases for the period 1930-1996 in comparison to 1850-1996. The reason is that no dam failure occurred for these two dam types during the period 1850-1996 and under the restriction to the time beyond 5 years after the first filling. Due to the longer operation time the failure rate is then smaller for the period 1850-1996 in comparison to 1930-1996.

The figure indicates also that within the evaluation period 1850-1996 most failures occurred before the dam had a lifetime of five years. For the period 1930-1996 and with the boundary condition to account only for the failures that occur later than five years after the first filling, the failure rates for gravity, arch, buttress and rockfill dams are based on zero failures (and substantial but varying operation times); this leads to the correspondingly large confidence intervals (not shown in the figure).

6.6.4 Characteristics of and accidents at Swiss dams

The calculation of risk of dam failure for Swiss conditions, on the basis of historical world-wide failures, encounters several difficulties:

a) Data on world-wide dams which failed are not homogeneous. Design features, quality of materials used for dam construction, and degree of control and supervision can vary from dam to dam.

b) Swiss dams show somewhat different characteristics than typical failed dams in other countries.

6.6.4.1 Supervision

In the past, many dam failures occurred because there was no or poor inspection. Several failed dams represented a significant and unacceptable danger to people living downstream and were erected regardless of theory or practice [Moore, 1912]. For this reason laws were passed in many countries in order to assure adequate protection. The state should exercise jurisdiction over the design, construction, operation, alteration and repair to prevent the construction of any insecure dams.

An example of how supervision and careful design of dams could lead to a considerable reduction of dam failures follows. In Great Britain before 1930, the reservoir building owner could choose anyone he liked as dam engineer. After failures of three small dams occurred in 1925 and 19 persons lost their lives, the British Government enacted the "Reservoirs Safety Provisions Act". One of its provisions [British National Committee on Large Dams, 1983] was that design, construction and statutory inspections must be under the direction of a qualified engineer appointed to one of the Panels created under the Act. After this legislation, no other dam failure resulting in loss of life has ever been reported in Great Britain.

In 1929, the collapse at St. Francis, where floodwaters killed 420 people, led the Government of California to introduce a similar legislation. The State of California regulates the design, construction, repair and surveillance of all legally built dams. Several foreign countries followed, enacting laws for the supervision of the safety of dams. The results are noteworthy. Since 1930, a remarkable decrease in the failure rate of dams is noticeable [Blind, 1983].

In Switzerland, all dams are supervised during the construction and operation [Schnitter and Mörgli, 1995]; over 200 dams are under the surveillance of the Swiss government. The ambitious safety concept for dams as applied in Switzerland is described in [Biedermann, 1997]. This emphasises the question whether it makes sense to consider dam failures from the past that occurred in countries which at the time of failure had poor or none dam supervision.

6.6.4.2 Dam types at Swiss reservoirs

As already discussed in Section 6.6.3.4 Swiss dams have a different distribution than dams in other countries around the world with respect to type, height and capacity. Fig. 6.6.7 shows the distribution of three ratios (T_1^k, T_2^k, T_3^k) for different dam types (k ε {earth, rockfill, gravity, buttress, arch, multi-arch}); here world-wide dam population is used as the reference while Fig. 6.6.4 was based on the situation in the Western World. The ratios are :

T_1^k* : *(Number of dams of type* k *in Switzerland) / (Total number of dams in Switzerland)

T_2^k* : *(Number of world-wide existing dams of type* k*) / (Total number of world-wide dams)

T_3^k* : *(Number of dams failed world-wide of type* k*) / (Total number of failed dams)

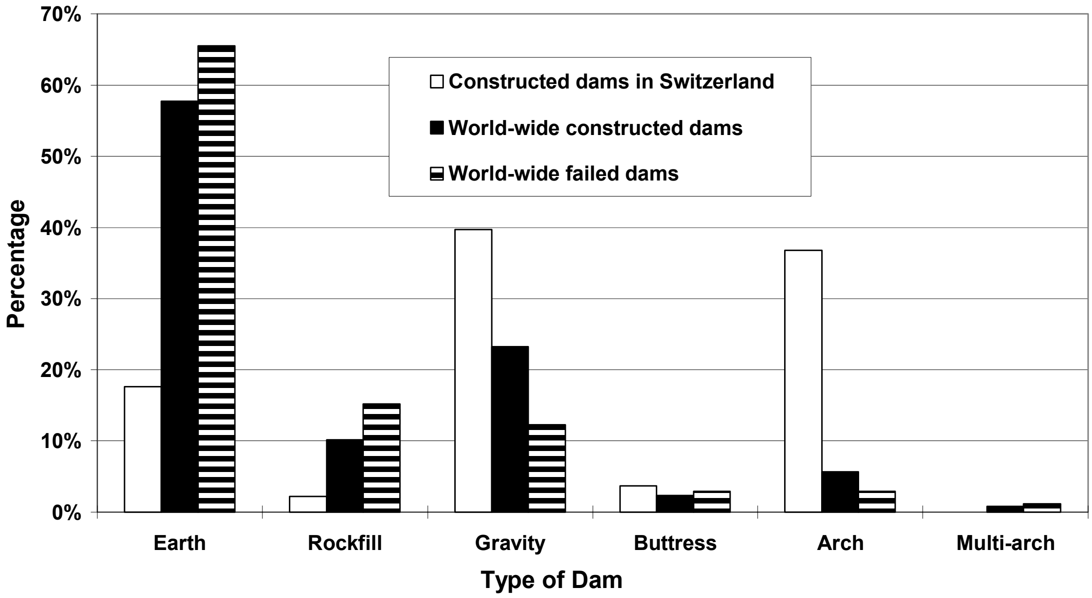

Fig. 6.6.7 Percentage of constructed dams by type world-wide and in Switzerland versus failed dams world-wide in 1850-1996.

Figure 6.6.7 shows that the ratio, for world-wide constructed and failed dams are roughly the same for every dam type, and that the world-wide failed dams are mostly of the embankment type (earth and rockfill). On the other hand, Switzerland has a completely different distribution of dam types, with more than 70% being concrete dams of the gravity and arch types.

6.6.4.3 Heights of Swiss dams

Swiss dams are higher than most dams around the world. In Fig. 6.6.8, three ratios are shown:

R_1^c **:** *(Number of dams of height h in Switzerland / (Total number of dams in Switzerland)*

R_2^c **:** *(Number of dams of height h world-wide) / (Total number of dams world-wide)*

R_3^c **:** *(Failed dams of height h world-wide) / (Total number of failed dams)*

where ***c*** stands for three selected categories :

a) $h < 30m$ *b)* $30m \leq h < 60m$ *c)* $h \geq 60m$

According to the figure about 70% of the failed dams had a height lower than 30 m. In Switzerland roughly two thirds of all dams are higher than 30 m.

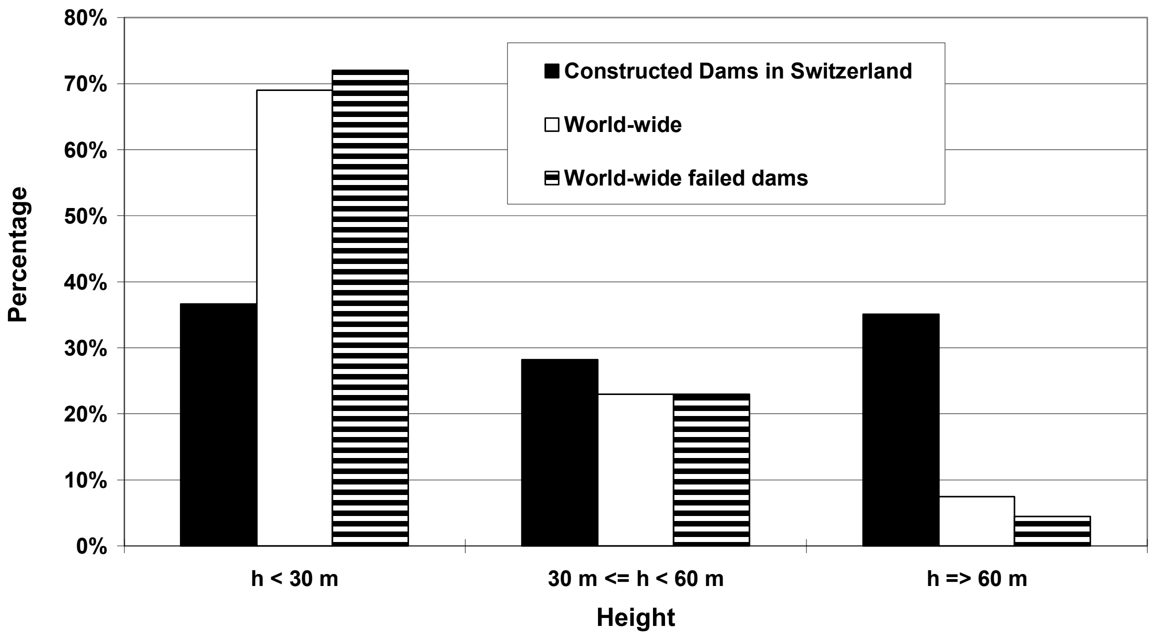

Fig. 6.6.8 Percentage of constructed dams in Switzerland and world-wide and world-wide failed dams as a function of dam height in the period 1850-1996.

6.6.4.4 Capacities and influxes of Swiss reservoirs

In 1978, anomalous deformations and, later, cracks in the “Zeuzier” dam were observed. Thanks to continuous monitoring and rapid emptying of the reservoir, failure was avoided [Schweizer. Wasserwirtschaftsverband, Kraftwerke Brusio, 1986]. This example shows that the capacity of a dam and the amount of river water influx play an important part in dam safety. If both quantities do not exceed certain limits, rapid emptying of a reservoir is possible. The capability of emptying a reservoir quickly, before a possible incident, is an essential safety feature. Many failed dams outside Switzerland had higher reservoir capacities than those of existing Swiss dams. Figure 6.6.9 shows the distribution of the capacities of failed earth dams around the world and of the present Swiss earth dams. The x-axis is divided into capacity intervals in million m^3. The figure shows that the distributions are completely different. Thus, one has to be aware that the probability of dam failure leading to very severe consequences could for a Swiss earth dam be significantly lower than the generic values, due to continuous monitoring and differences in capacity.

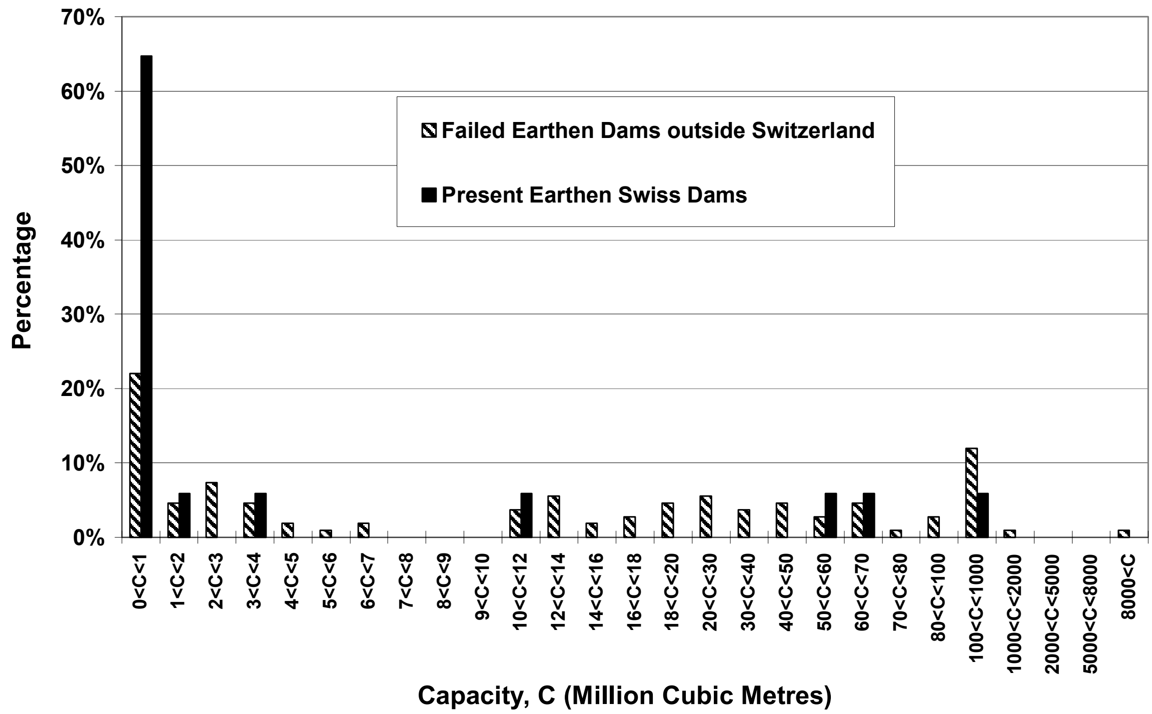

Fig. 6.6.9 Dam capacity distribution for the Swiss earth dams versus world-wide failed dams over the time period 1850-1996.

Figure 6.6.9 shows that more than 60% of all Swiss earth dams have a reservoir capacity not exceeding 1 million m^3. More than 50% of failed dams world-wide, however, had capacities higher than 10 million m^3.

These comparisons demonstrate that Swiss dams have atypical characteristics in terms of dominant dam types dam heights and reservoir capacity.

6.6.4.5 Dam incidents and accidents in Switzerland

Table 6.6.22 gives an overview of events that occurred in the past 120 years. As may be seen, in Switzerland, the most serious accidents to people occurred not after the bursting of dams but during construction; this is due to the difficult working conditions in the Alps. The cases of dam accidents where water was partially or completely released were Joux-Verte, Baslerweiher, Crapaly, Lac Rond, Prafleuri, Risi, Grob, and Oberalpsee. It must be mentioned that none of these dams is large, according to the definition given in Section 6.6.3.4. The only dangerous situation for a large dam, which could have resulted in dam failure, was the overtopping at Palagnedra in 1978, where a side wall of the dam could have been destroyed by the flood [Martini, publication year unknown]. Table 6.6.22 also shows that most of the dams which experienced incidents were earth dams.

6.6.4.6 Applicability of historical data to the Swiss conditions

In the preceding sections failure rates and projected years to the next failure were calculated for different dam types, time periods and times of failure. Under which restrictions can these results be applied to Swiss dams? In Switzerland, dams are thoroughly supervised. Concrete and not masonry is the generally used construction material. Furthermore, no serious failure of a large dam has occurred during operation since 1930 after the first 5 years of operation. Therefore, the corresponding failure rates for Western World dams, time period 1930-1996, failures occurring later than 5 years after the first filling were chosen as the most representative for the Swiss gravity, earth and rockfill dams. For the Swiss arch and buttress dams the value of the failure rate for Western World dams within the period 1850-1996, again excluding the accidents occurring within 5 years after the first filling, is considered more representative due to the features of the statistical data (Table 6.6.13). The failure rates are listed in the second column of Table 6.6.23. The third column of the table reports the number of dams of the corresponding type in Switzerland. The projected years between failures, given in the last column in Table 6.6.23, are calculated using only *ND* and not *ND/2* because the number of dams in Switzerland is currently not increasing with time but remains roughly constant.

The failure rates given in Table 6.6.23 may be regarded as Swiss generic values based on the experience. It should be noted that these (mean) values are relatively close to the estimated upper bounds (95%), while the lower bands (5%) are up to two orders of magnitude lower for all dams except those of earth type. Thus, given the continued error-free operation of the Swiss dams the best estimates (which are mostly based on zero failures) may be significantly reduced. At the same time it cannot be excluded that some dams among those operating in Switzerland may have higher failure rates. As mentioned in Section 6.6.4.4, for many Swiss dams, due to their rather low capacities, the option of rapid emptying can be implemented as emergency measure thus preventing serious consequences which may occur following a hypothetical dam failure.

TABLE 6.6.22

Dam incidents and accidents in Switzerland[a]
(GP: Gravel pit; WT: Wood transport, FF: Fish farming; GW: Gravel washing; H: Hydroelectric; S: Water supply; C: Flood control).

Dam name	Type	Height (m)	Year of completion	Year of failure	Fatalities	Type of failure	Purpose	Sources
Albigna	Pg	115	1959	1962	0	Crack	H	[ICOLD, 1983]
Arnensee	Te	17	1942/56	NA[b]	0	Seepage	H	[ICOLD, 1983]
Baslerweiher	Te	10	NA[b]	1871	0	Overtopping during construction	S, C	[Wackernagel, 1981]
Crapaly	Te	5	1877	1877	0	Inner erosion	FF	[Salis, 1877]
Gigerwald	Va	147	1976	1974	≥ 2	Accident during construction	H	[Kraftwerke Sarganserland, 1978]
Grob	Te	5	NA[b]	1987	0	NA[b]	GP	[Schnitter, 1994]
Joux-Verte	Va	13	1695	1945	0	Flood	WT	[Schnitter, 1994]
Klöntal	Te	21.5	1910	NA[b]	0	Seepage	NA[b]	[ICOLD, 1983]
Kraftwerke Vorderrhein (Napls, Curnera, Sta. Maria)	Va	127	1962	1958-1962	22	Accidents during construction	H	[Kraftwerke Vorderrhein, 1963]
Lac Rond	Te	NA[b]		1951	0	Overtopping by flood	NA[b]	[Wasser u. Energiewirtschaft, 1956]
Les Toules	Va	86	1963	NA[b]	0	Seepage	NA[b]	[ICOLD, 1983]
Limmern [c]	Va	145	1963	1960-1963	19	Accident during construction	H	[Kraftwerke Linth-Limmern, 1965]
Maggia project	NA	NA[c]	1950	1966	17	Gas in tunnel	H	[Eng. News Record, 1966]
Mattmark	Te	NA[c]	1967	1965	88	Ice fell on workers	H	[Eng. News Record, 1965]

[a] Construction accidents are included in the table. For the rationale of this scope and the overall impact of this inclusion on the comparative results we refer to the footnote to Table 6.6.2.

[b] NA: not available

[c] The only hydropower scheme, where the total number of fatalities during construction is available.

Table 6.6.22 continues on the next page

TABLE 6.6.22

Dam incidents and accidents in Switzerland[a]
(GP: Gravel pit; WT: Wood transport; FF: Fish farming; GW: Gravel washing; H: Hydroelectric; S: Water supply; C: Flood control) *(continued).*

Dam name	Type	Height (m)	Year of comple-tion	Year of failure	Fata-lities	Type of failure	Pur-pose	Sources
Mauvoisin	Te	237	1957	1954	6	Accident during construction	H	Personal communication
Oberalpsee	Pg	5	1961	1965	0	Foundation Failure	H	[Babb and Mermel, 1968]
Palagnedra	Va/Pg /Te	72	1952	1978	0	Overtopping	H	[Charles and Boden, 1985]
Parfleuri	Te	8	1954	1963	0	Failure	GW	[Schnitter, 1994]
Punt Dal Gal	Va	130	1969	NA[b]	0	Seepage	H	[ICOLD, 1983]
Räterichsboden	Pg	94	1950	1962	0	Overtopping	H	[ICOLD, 1983]
Riau	NA[b]	NA[b]	NA[b]	1950	0	Erosion		[Babb and Mermel, 1968]
Risi	Te	8	1983	1985	0	Sliding	GP	[Schnitter, 1994]
Santa Maria	Va	118	1968	NA	0	Formation of foundation	H	[ICOLD, 1983]
Sonzier	NA[b]	10	NA[b]	1888	5	NA[b]	S	[Mantel, 1888]
Spitallamm	Va/ Pg	114	1931	NA[b]	0	Seepage	H	[ICOLD, 1983]
Zevreila	Va	151	1957	NA[b]	0	Break in foundation	H	[ICOLD, 1983]
Zöt	Va	37	1967	NA[b]	0	Foundation problems	H	[ICOLD, 1983]

[a] Construction incidents and accidents are included in the table. For the rationale of this scope and the overall impact of this inclusion on the comparative results we refer to the footnote to Table 6.6.2. Furthermore, it should be noted that the vast majority of the events in this table did not lead to failure of the dam walls as such. According to our knowledge the only exceptions are: Crapaly, Joux-Verte, Lac Rond, Parfleuri, Risi and Sonzier.

[b] NA: not available

TABLE 6.6.23

Failure rates and projected years between failures for different dam types for Switzerland, based on generic estimates for the Western World and time period 1930-1996.

Dam type	Failure rate [dam year] $^{-1}$	Number of dams in Switzerland	Projected years between failures
Gravity (Pg)	$1.3\cdot10^{-5}$	53	1451
Arch (Va)	$2.8\cdot10^{-5}$	50	714
Buttress (Cb)	$5.7\cdot10^{-5}$	5	3508
Earth (Te)	$3.7\cdot10^{-5}$	24	1126
Rockfill (Er)	$3.2\cdot10^{-5}$	3	10417

6.6.5 Frequency-consequence curves for dam accidents

6.6.5.1 Fatalities

The Table E.1 in Appendix E was taken as a basis for generating frequency-consequence curves for dam accidents. It should be noted that this material reflects exclusively dam failures in the Western World, with associated **total** loss of stored water. The percentage of dam failures leading to X or more fatalities is shown in Fig. 6.6.10 for the two periods 1900-1969 and 1900-1996. The points in the graph correspond to actual accidents. There are only a small differences between the data sets. This reflects the fact that in the last 30 years no dam failure with total loss of the stored water led to large consequences in the Western World. The same is not true for a number of accidents involving partial loss of water.

In Fig. 6.6.11 the corresponding frequency-consequence curves are shown. As expected, when the consequences of accidents are normalised by the operation time the effect of the absence of major accidents with total loss of the stored water in the last 30 years is clearly manifested in the curve for the period 1900-1996.

In Fig. 6.6.12, the number of accidents causing X or more fatalities is shown for the Western World and Asia together with Africa, over two time-periods. The figure demonstrates a decrease of the frequencies for the time-period 1900-1996, showing that dams have become safer. The figure also shows that the frequencies for western countries are lower for consequences larger than 40 fatalities. This difference is certainly underestimated since the completeness of the records on dam accident consequences in Asia and Africa is not satisfactory. The accident with 230,000 fatalities in Fig. 6.6.12 corresponds to the failures of the Banqiao and Shimantan dams in China on 5th August 1975. Estimates of the immediate death toll ranged from the official count of 85,600 to the unofficial count of 230,000 [Qing, 1998]. [Human Rights Watch/Asia, 1995] said that separate publications refer up to 230,000 deaths.

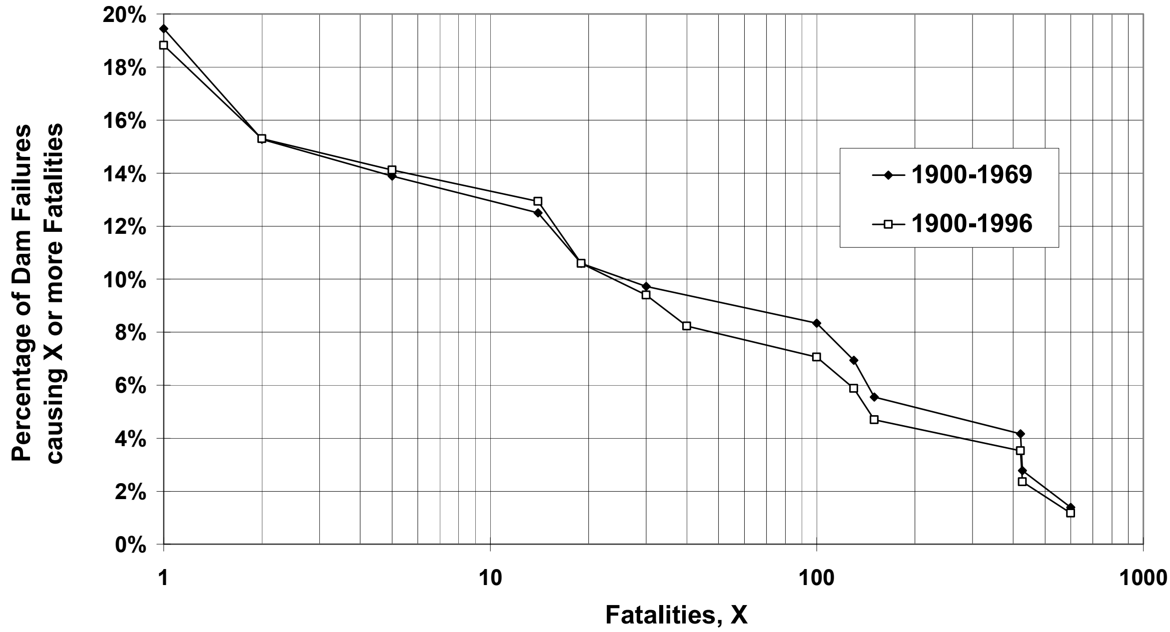

Fig. 6.6.10 Percentage of accidents involving fatalities based on dam failures in the USA, Canada, Australia, New Zealand and Western Europe. All dam types and two time periods are covered; only accidents with **total** loss of stored water are considered.

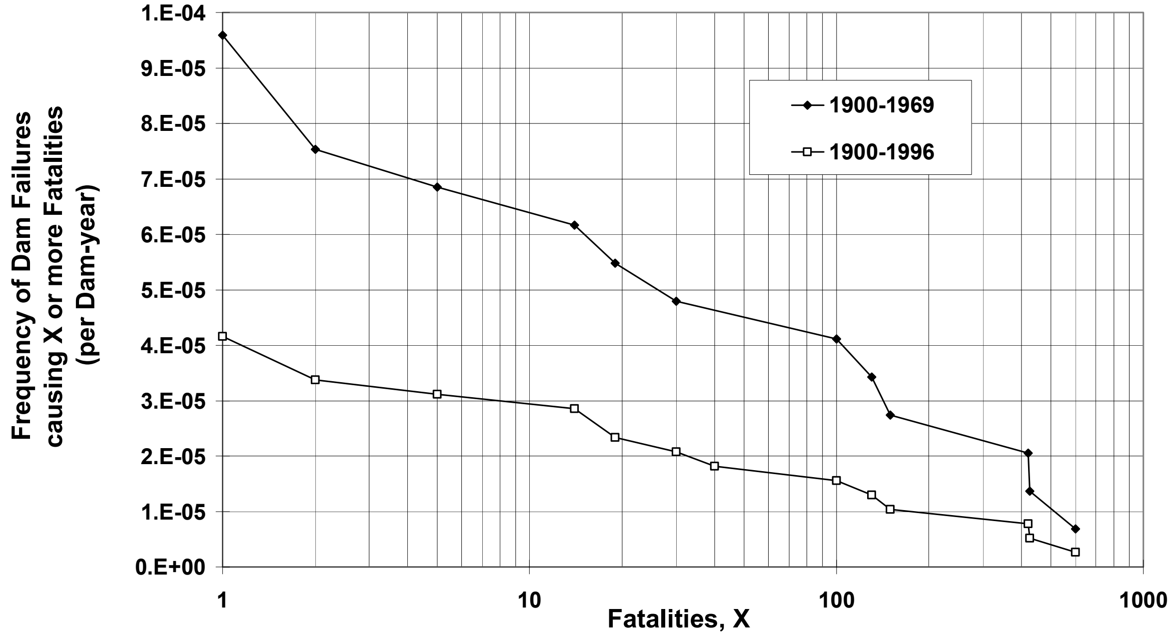

Fig. 6.6.11 Frequency-consequence (fatalities) curves for dam failures in the USA, Canada, Australia, New Zealand and Western Europe for all dam types. All dam types and two time periods are included; only accidents with **total** loss of stored water are considered.

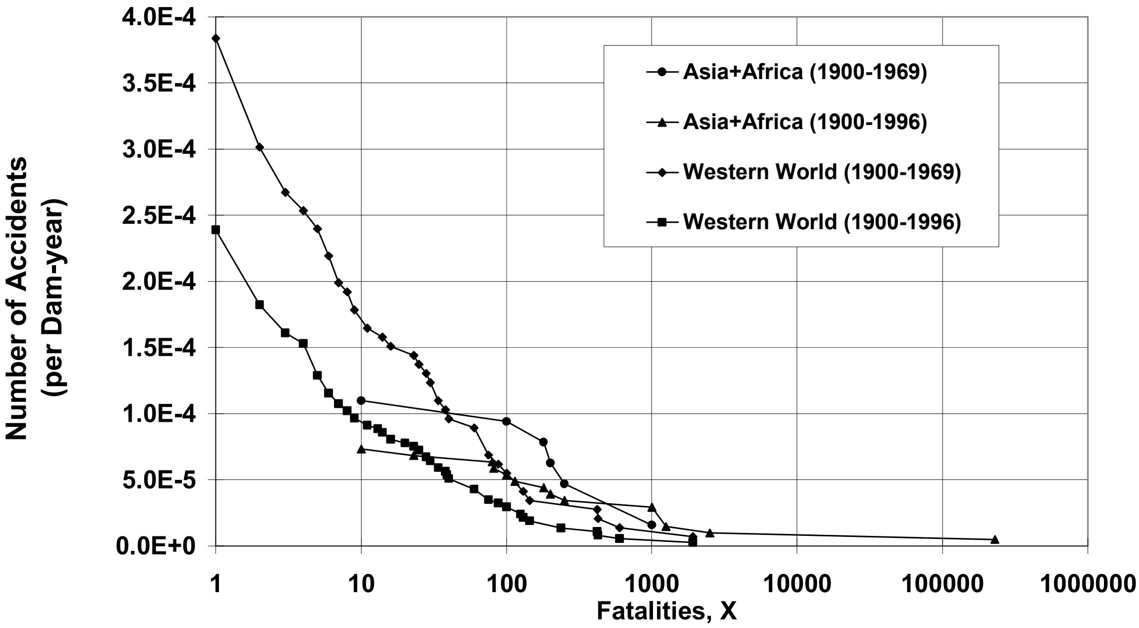

Fig. 6.6.12 Percentage of dam accidents causing X or more fatalities for two time periods and two geographical areas (Asia+Africa and Western World excluding South America).

In Fig. 6.6.13, the percentage of dam failures causing X or more fatalities is shown, using data from [Schnitter, 1976] and data collected in ENSAD for the period 1900-1969. Additionally, in the same figure the results for the time-period 1900-1996 for data assembled in ENSAD are also included.

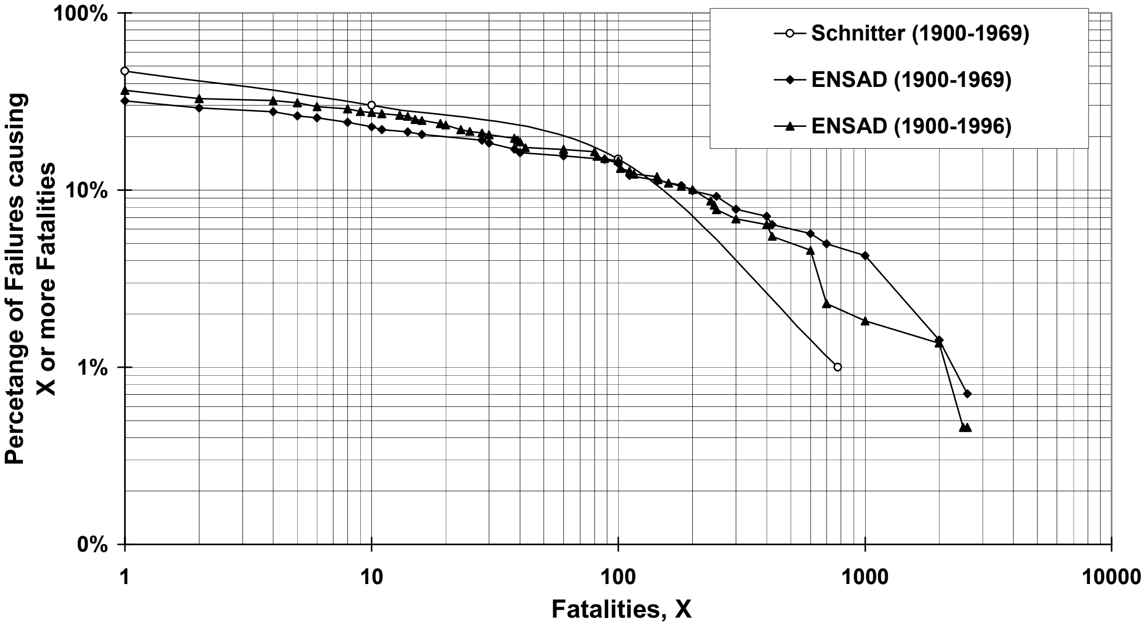

Fig. 6.6.13 Comparison of three sets of data on dam failures causing X or more fatalities; world-wide experience is used as the basis.

For the two curves obtained using the data assembled in ENSAD only the maximal numbers for consequences of the accidents were considered. The figure shows that, for accidents world-wide causing less than 100 fatalities, all three sets of data lead to similar results. Only for accidents causing more than about 200 fatalities does the data diverge.

6.6.5.2 Costs of dam failures

This section provides some estimates of the average costs to property of severe (≥ 5 million 1996 US$) dam accidents. In these costs the rebuilding costs of the failed dam are included. Other costs such as temporary interruptions of income to individuals due to the inundated commercial, agricultural and industrial areas are not considered. Losses to cultural heritage or environmental damage are not included either.

In the case of hydro power the loss of power during the repair outage of the dam can cost as much as the costs to property after the failure. For instance, in the case of the failure of the Walter Bouldin dam, the reconstruction of the dam has been estimated to cost about 40 million US$. The loss of about 1840 million kWh of electric energy during the 4-year outage of the dam corresponds to an estimated cost of 60 million US$ [Federal Energy Regulatory Commission, 1978].

In Table E.5 of Appendix E a list of world-wide severe (≥ 5 million 1996 US$) dam accidents collected in ENSAD is given. The period covered is 1900-1996. In the third column of this table the economic losses in 1996 US$ are depicted.

Figure 6.6.14 gives the frequency-consequence (costs) curve for the period 1945-1996. The figure is a partial evaluation of the list in Table E.5. In the same figure a trendline, calculated as the least squares fit through the points, is provided. It is based on the following function:

$$y = 114.54 \cdot x^{-0.602} \qquad (6.6.25)$$

where:

x: Costs in million 1996 US$
y: Number of accidents causing x or more costs

Other regression trendlines were tried, such as the linear, logarithmic, polynomial or exponential equation [Microsoft Excel, 1993]. However, the above power function gave the best fit.

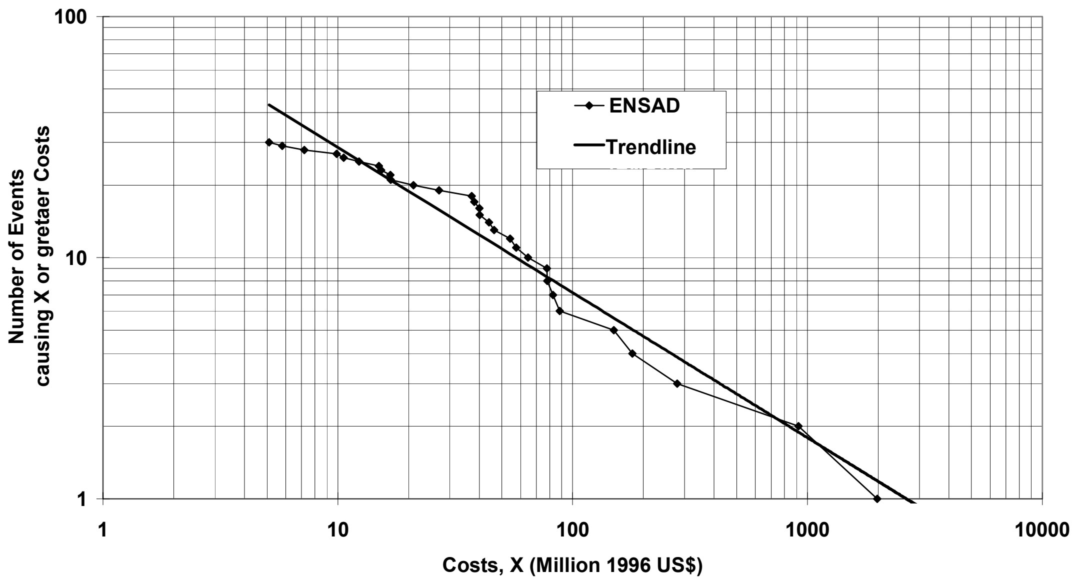

Fig. 6.6.14 Number of events causing X or more costs (in 1996 US$).

6.6.6 Are hydro power dams safer than dams with other purposes?

Figure 6.6.15 shows that the average frequency of dam failures where the dam cannot retain all the stored water in the Western World to some extent depends on the purpose of the dams. The lowest frequency applies to dams used for flood control, followed by hydro power, irrigation and water supply dams. The figure is based on the list of dam failures given in Table E.1. The time period covered in the figure is 1930-1996.

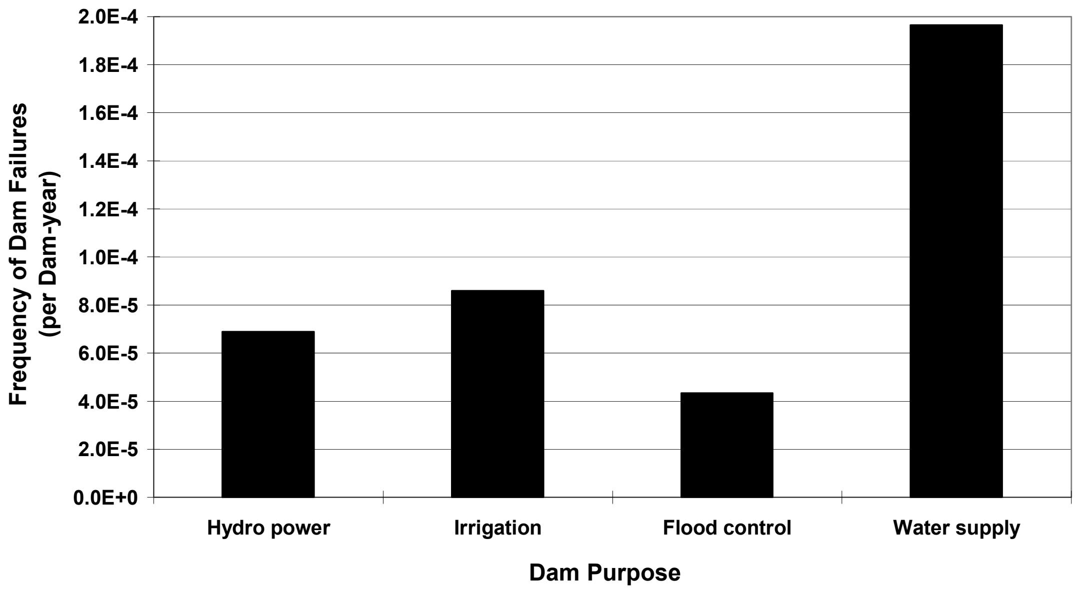

Fig. 6.6.15 Frequency of dam failures (where the dam cannot retain all the stored water) by purpose for dams in the in the Western World and time period 1930-1996. The dams were constructed in the same time period.

More details are provided in Fig. 6.6.16. Here the frequency of failures by type (rockfill, earth, gravity, arch, buttress and multi-arch) and purpose is given. In addition to reflecting the same perspective as Fig. 6.7.15 this figure shows also that for a given dam type the failure rates are of the same order independently of the purpose. It should be noted that here in cases with no statistical evidence of failure for the specified boundary conditions of the evaluation a zero failure rate was assigned (in contrast to the approach used in Section 6.6.3.5). This explains zero failure rate estimates for gravity and buttress dams.

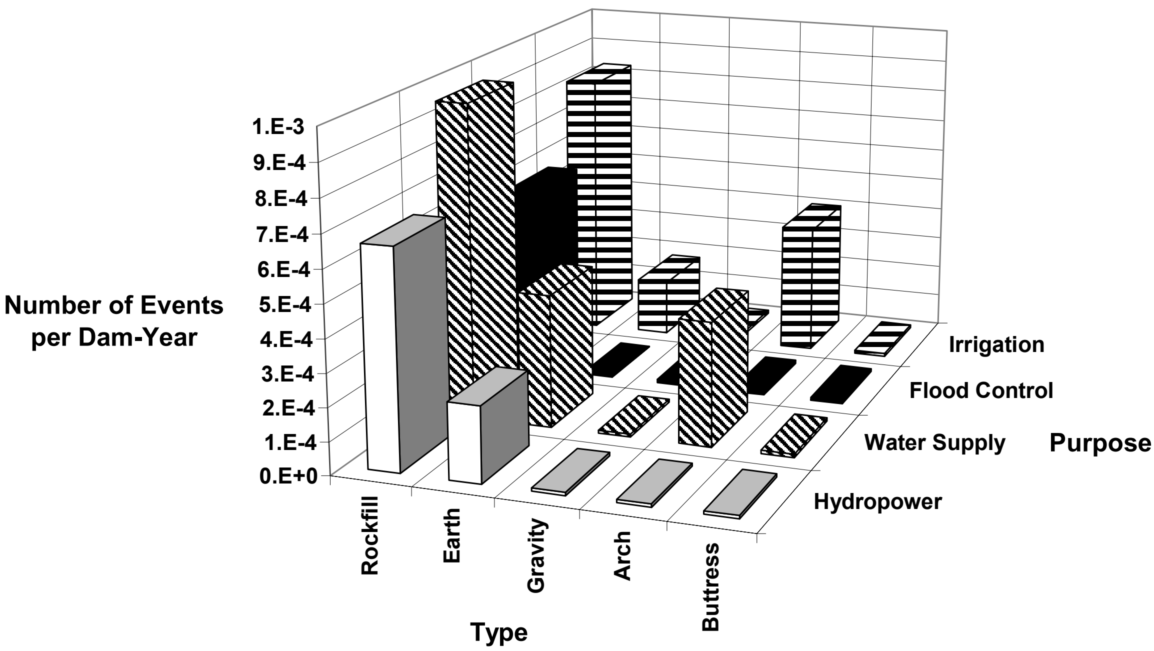

Fig. 6.6.16 Frequency of failures by type (rockfill, earth, gravity, arch, buttress) and purpose (hydro power, water supply, flood control, irrigation) for the Western World and the period 1930-1996.

6.6.7 Some highlights

1. Tables 6.6.24 and 6.6.25 summarise dam failure rates obtained for all occasions of failures and for operation later than five years after the first filling. The estimates are based on historical evidence of total loss of the stored water in dams for all purposes in the Western World. Failure rates considered as generically applicable to Switzerland are given in bold.

   Depending on the evaluation time period and the related boundary conditions the variation between the failure rates (mean values) for the different dam types corresponds to a factor of 6 to 23.

   With only few exceptions, the dam failure rates have decreased significantly in time. This is due to a combined effect of technological developments (including replacement of masonry by concrete as the primary construction material around 1930 and on) and the impact of regulatory requirements.

TABLE 6.6.24
Dam failures rates [a] [per dam-year] for all failure occasions, various dam types and two time periods.

Time period	Dam type				
	Gravity (Pg)	**Arch (Va)**	**Buttress (Cb)**	**Earth (Te)**	**Rockfill (Er)**
1850 - 1996	MV: 8.3 10^{-5} LB: 5.1 10^{-5} UB: 1.4 10^{-4}	MV: 1.0 10^{-4} LB: 4.6 10^{-5} UB: 2.6 10^{-4}	MV: 2.7 10^{-4} LB: 1.3 10^{-4} UB: 6.2 10^{-4}	MV: 2.4 10^{-4} LB: 1.9 10^{-4} UB: 2.9 10^{-4}	MV: 6.1 10^{-4} LB: 4.3 10^{-4} UB: 8.7 10^{-4}
1930 - 1996	MV: 1.3 10^{-5} LB: 8.2 10^{-7} UB: 4.8 10^{-5}	MV: 5.0 10^{-5} LB: 1.8 10^{-5} UB: 2.4 10^{-4}	MV: 9.3 10^{-5} LB: 5.7 10^{-6} UB: 3.3 10^{-4}	MV: 9.8 10^{-5} LB: 6.7 10^{-5} UB: 1.5 10^{-4}	MV: 3.0 10^{-4} LB: 1.8 10^{-4} UB: 5.5 10^{-4}

[a] MV = Mean Value; LB = Lower Bound (5%); UB = Upper Bound (95%)

TABLE 6.6.25

Dam failures rates [a] [per dam-year] for operation five years after the first filling, various dam types and two time periods.

Time period	Dam type				
	Gravity (Pg)	**Arch (Va)**	**Buttress (Cb)**	**Earth (Te)**	**Rockfill (Er)**
1850-1996	MV: 5.0 10^{-5} LB: 2.7 10^{-5} UB: 9.8 10^{-5}	**MV: 2.8 10^{-5}** **LB: 1.7 10^{-6}** **UB: 1.0 10^{-4}**	**MV: 5.7 10^{-5}** **LB: 6.7 10^{-5}** **UB: 1.5 10^{-4}**	MV: 1.3 10^{-4} LB: 9.5 10^{-5} UB: 1.7 10^{-4}	MV: 1.7 10^{-4} LB: 9.1 10^{-5} UB: 3.3 10^{-4}
1930-1996	**MV: 1.3 10^{-5}** **LB: 8.2 10^{-7}** **UB: 4.8 10^{-5}**	MV: 4.2 10^{-5} LB: 2.6 10^{-6} UB: 1.5 10^{-4}	MV: 1.0 10^{-4} LB: 3.5 10^{-6} UB: 2.0 10^{-4}	**MV: 3.7 10^{-5}** **LB: 2.0 10^{-5}** **UB: 7.3 10^{-5}**	**MV: 3.2 10^{-5}** **LB: 1.9 10^{-6}** **UB: 1.1 10^{-4}**

[a] MV = Mean Value; LB = Lower Bound (5%); UB = Upper Bound (95%)

In most cases there is a significant decrease in failure rates when the first five years of operation after filling the dam are excluded from the evaluation. This observation is important since a majority of current dams have long operating history, far beyond five years.

2. The Swiss dams exhibit a number of favourable safety-related features. Of particular importance are the typically relatively low capacity of earth dams which is a positive factor for the mitigation of accidents and for the limitation of the extent of potential damages.

   The generic estimates (mean values) provided in Table 6.6.25 considered as the most representative for the Swiss conditions (in bold), show a variation by a factor of at most 4.3 between the various dam types. The lowest estimate was obtained for gravity dams. For gravity, arch, buttress and rockfill dams the mean values are close to the estimated upper bounds, while lower bands are up to two orders of magnitude lower. The available statistical material is most comprehensive for earth dams.

3. Dam failure rates are not only subject to variation with respect to the type of dam but depend also to some extent on the purpose of the dam. This may partially reflect the different safety standards within the various areas of dam applications but is also a result of the differences in the distributions of dam types within these diverse applications. In this context flood control and hydro power dams appear on average to be the best performers. The water supply dams have the highest average failure rates.

6.6.8 References

Babb, A. and Mermel, T. (1968), Catalog of Dam Disasters, Failures and Accidents. US Department of the Interior, Bureau of Reclamation, Washington, D.C., USA.

Baecher, B., Paté, M. E. and de Neufville R. (1980), Risk of Dam Failure in Benefit-Cost Analysis. Water Resources Research, **16** (1980)**, pp.** 449-456.

Basler & Hofmann (1978), Überlegungen zur Autretenswahrscheinlichkeit von Talsperrenbrüchen (in German). Report TB 645-ASK-14, Basler & Hofmann, Zurich, Switzerland, July 1978.

Biedermann, R. (1997), Safety Concept for Dams: Development of the Swiss Concept since 1980. Wasser, Energie, Luft - Eau, Énergie, Air, 89. Jahrgang, Heft 3/4, pp. 55-63.

Blind, H. (1983), The Safety of Dams. Water Power & Dam Construction, pp. 17-20, May 1983, London, UK.

British National Committee On Large Dams (1983), Dams In The UK, 1963-1983. The Institution of Civil Engineers, London, UK.

Charles. J. and Boden, J. (1985), The Failure of Embankment Dams in the United Kingdom. Earthwork Failures and Repair, pp. 133-153.

Engineering News Record (1965), Glacier Smashes Swiss Damsite. Engineering News Record, pp. 30-31, 9 September 1965.

Engineering News Record (1966), Mysterious Gas Kills 17 In Swiss Hydro Tunnel. Engineering News Record, p. 19, 24 February 1966.

Encyclopaedia Britannica (1984), Book of the Year. University of Chicago.

Federal Energy Regulatory Commission (1978), Walter Bouldin Dam Failure and Reconstruction, DOE/FERC-0017, Office of Electric Power Regulation, Washington, D.C., USA.

Gruetter, F. and Schnitter, N.J. (1982), Analytical Risk Assessment for Dams. Q.52, R.039, Vol. 1, ICOLD 14, International Commission on Large Dams, Rio de Janeiro, 1982.

Gupta, H. K. (1992), Reservoir Induced Earthquakes. New York: Elsevier.

Hartford (1996), Risk-based Safety Evaluation of Wahleach Dam Spillway, BC Hydro, Report No. MEP 11-4, March 1996.

Hauenstein W. (1995), Schweizerisches Komitee für grosse Talsperren. Personal Communication.

Hoffmann, H.-J., Oedekoven, L. and Ott, K. O. (1984), Statistical Trend Analysis of Dam Failures Since 1850. Special Report No. 245, Kernforschungsanlage Jülich, Jülich, Germany.

Human Rights Watch/Asia (1995), The Three Gorges Dam in China: Forced Resettlement, Suppression of Dissent and Labor Rights Concerns, Vol. 7, No. 2.

ICOLD (1973), World Register of Dams. International Commission on Large Dams, Paris, France.

ICOLD (1974), Lessons from Dam Incidents. International Commission on Large Dams, Paris, France.

ICOLD (1977), World Register of Dams (update). International Commission on Large Dams, Paris, France.

ICOLD (1983), Deterioration of Dams and Reservoirs. Members of the Committee on Deterioration of Dams and Reservoirs, International Commission on Large Dams, Paris, France.

ICOLD (1984), World Register of Dams. International Commission on Large Dams, Paris, France.

ICOLD (1988), World Register of Dams (update). International Commission on Large Dams, Paris, France.

ICOLD (1995), Dam Failures Statistical Analysis. Bulletin 99, International Commission on Large Dams, Paris, France.

Jansen R.(1983), Dams and Public Safety. US Government Printing Office, Washington D.C., USA.

Johansen P., S. Vick, C. Rikartsen (1997), Risk Analyses of three Norwegian Rockfill Dams, Hydropower'97, Broch, Lysne, Flatabo & Helland-Hansen (eds) © 1997 Balkema, Rotterdam, ISBN 90 54 10 888 6.

Kraftwerke Linth-Limmern AG (1965), Die Kraftwerke Linth-Limmern im Kanton Glarus, p. 58.

Kraftwerke Sarganserland AG (1978), Die Kraftwerke Sarganserland im St. Galler Oberland, p. 8.

Kraftwerke Vorderrhein AG Disentis (1963), Die Kraftwerke Vorderrhein im Bündner Oberland, p. 28.

König, M. (1984), Geologische Katastrophen und ihre Auswirkungen auf die Umwelt : Vulkane, Erdbeben, Bergstürze (in German). Ott Verlag Thun.

Mantel, G. (1888), Die Stabilitätsverhältnisse des Reservoirs in Sonzier (in German). Schweizerische Bauzeitung, Vol. 12, 1988.

Martini O. (publication year unknown), Die Hochwasserkatastrophe 1978 am Ausgleichungsbecken Palagnedra (in German). Maggia Kraftwerke AG, Locarno, p. 6.

Microsoft Excel (1993), User's Guide, Version 5.0. Microsoft Corporation.

Moore, J. (1912), Safe Dam Construction in New York. Engineering News, 27 June 1912, p. 1235.

Neue Zürcher Zeitung (1985), Acht Tage nach der Umwetterkatastrophe im Tessin. Neue Zürcher Zeitung, Nr. 187, p. 23.

Qing Dai (1998), The River Dragon Has Come! The Three Gorges Dam and the Fate of China's Yangtze River and its People. Probe International. International Rivers Network. M.E. Sharpe, Armonk, New York, London, England.

Salis (1877), Jahresbericht der naturforsch. Gesellschaft Graubündens (1877/1878), p. 3 (in German).

Schnitter, N. (1976), Statistische Sicherheit von Talsperren (in German). Wasser, Energie, Luft - Eau, Énergie, A ir, 68. Jahrgang, Heft 5, pp. 126-129.

Schnitter N. (1994). Personal Communication.

Schnitter, N. and Mörgeli, H (1995), Staumauern und Staudämme (in German). Schweizerisches Nationalkommitee für grosse Talsperren, Verband Schweizerischer Elektrizitätswerke, Informationsstelle für Elektrizitätsanwendung.

Schweizerischer Wasserwirtschaftsverband, Kraftwerke Brusio AG (1986). Sicherheit von Schweizer Talsperren (in German), Baden, Schweiz.

Serafim, J. (1981), Safety of Dams Judged from Failures. Water Power & Dam Construction, p. 32.

Wackernagel, A., (1981), Longterm Behaviour of a Dam in a Period of 108 Years. 10thInt. Congr. Soil Mech. and Foundation Engineering, Stockholm, Sweden, **3** (1981) pp. 561-563.

Wasser und Energiewirtschaft (1956), p. 251, Schweizerisches Monatsschrift, Guggenbühl & Huber, Zürich.

7. COMPARATIVE EVALUATIONS

This chapter provides the numerical comparisons of severe accident risks associated with the energy systems covered in the present report. Limitations of the approach used will be addressed in Chapter 8. The results of the comparison and their implications are extensively discussed in Chapter 9 where also qualitative aspects and issues in comparative assessment of severe accidents are covered.

7.1 Scope of and Prerequisites for Comparative Evaluations

The evaluations presented in the following concern different severe accident indicators such as the number of accidents, fatalities, injured, evacuees and the extent of monetary damages. Other consequence categories (such as released amounts of hydrocarbons and chemicals, or enforced clean-up of land and water) can not be compared over all systems since they are either associated with a subset of the analysed systems or the completeness of data differs so much between the systems that a comparison does not appear to be meaningful given the present state of knowledge. For this type of consequences the relevant energy source-specific sections in Chapter 6 should be consulted.

In fact, it needs to be acknowledged that for some of the categories that are compared in this chapter the completeness is quite heterogeneous across the various options. In relative terms the fatality records show the best completeness and are reasonably homogeneous in this respect. Probably the least complete and perhaps the most uncertain information concerns costs of accidents. Furthermore, in this context the material is not consistent due to the partially uncontrolled differences in the cost definition, coverage (frequently not specified in the original sources) and interpretation (e.g. claimed, settled and real costs). The cost elements that have been included in the various estimates may include different components, which makes the comparison quite unbalanced.

Nevertheless, the authors decided to include also comparisons of economic losses since they reflect the current state of knowledge. The above reservations should, however, be kept in mind when viewing the results.

All comparisons were carried out using two time periods for the evaluations, namely 1969 to 1986 and 1969 to 1996. There are three reasons for choosing year 1969 as the lower time limit for the evaluation. First, going further back in time would create problems with respect to the applicability of the data (at least for some of the energy sources) to the present situation. Second, as demonstrated in Chapter 5, the number of recorded energy-related accidents started to increase at the end of the sixties as a result of the improved reporting as well as due to the increasing volume of energy-related activities. Third, a major recent comparative study of severe accidents[1] [Chadwick, ed., 1991], conducted by a number of international organisations under the leadership of United Nations, covered the

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[1] The study (based on [Fritzsche, 1988 and 1989]) is limited to comparison of fatality rates and does not address other consequence categories. When citing results directly adopted in [Chadwick, ed., 1991] from [Fritzsche, 1989] we will here used the latter work as the (original) reference. The results derived in [Chadwick, ed., 1991] using accident data from [Fritzsche, 1989] as input will be referred to as "UN-estimate".

period 1969-1986. This explains also the choice of the upper time limit for one of the periods studied here; in this way comparisons with the previous work are possible. Furthermore, presenting the results for the two periods enables identification of possible changing trends (if any) as the result of the inclusion of additional years of operational experience.

An essential parameter used for the normalisation of the results is the total energy produced by each energy source. For comparison purposes the data in terms of number of accidents, various indicators for accident consequences and cumulative frequency distribution of consequences were normalised on the basis of the unit of electricity production for the different energy sources. For nuclear and hydro power the normalisation is straight-forward since in both cases the generated product is electrical energy. In the case of coal, oil, natural gas and LPG the thermal energy was converted to an equivalent electrical output using a factor of 0.35.

The results of the comparison are presented below in form of diagrams. The exact numbers behind the figures are provided in Appendix F. It should be noted that while most severe accidents result in simultaneous damages of various types (e.g. fatalities, injuries, economic losses, etc.), the following presentation describes these effects in separate sections.

7.2 Severe Accidents Involving Fatalities

7.2.1 Number of severe accidents

In Fig. 7.2.1 the number of severe (≥ 5 fatalities) accidents associated with the various energy sources (coal, oil, natural gas, LPG, hydro power and nuclear) is shown for the two time periods examined. For comparison, the results from [Fritzsche, 1989] are shown.

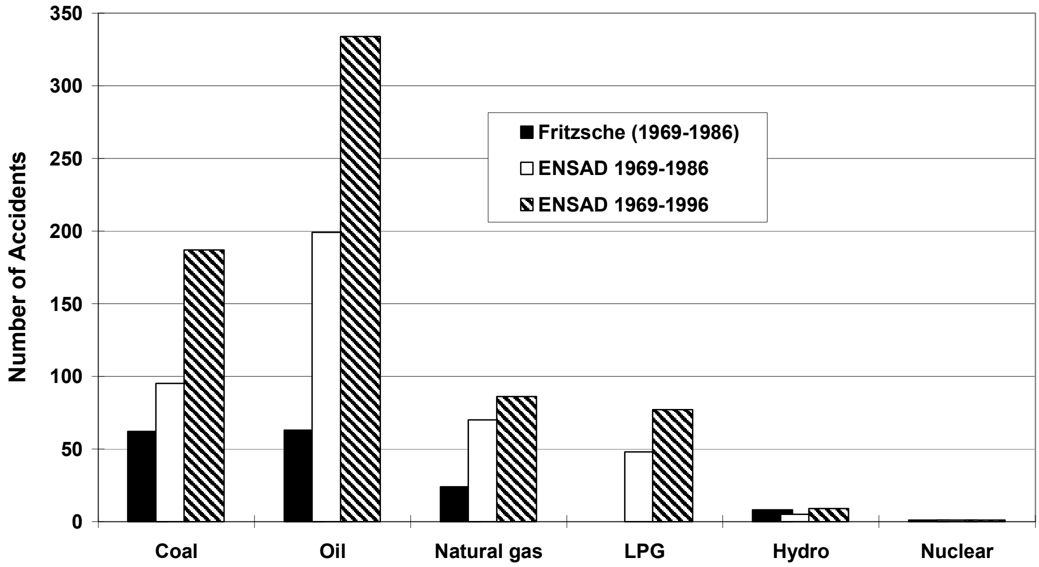

Fig. 7.2.1 Comparison of severe (≥ 5 fatalities) accident records: Total number of events in examined time periods according to ENSAD and [Fritzsche, 1989].

According to ENSAD the largest number of severe accidents involving fatalities occurred in the oil chain, followed by coal, natural gas, LPG, hydropower and nuclear chains.

In contrast to coal, oil and to a smaller extent LPG, severe accidents involving natural gas show only a small increase within the period 1987-1996.

The figure reflects the better coverage of ENSAD in comparison to [Fritzsche, 1989]. Particularly dramatic are the improvements of the completeness of the records for oil and gas accidents. But also significantly larger number of coal accidents has been identified in the current work.

According to the present findings some severe accidents attributed to the natural gas chain in [Fritzsche, 1989] did not in fact involve natural gas. For instance, the failed lorry which caused more than 200 fatalities in an accident near San Carlos in Spain in 1978 transported propylene [SRD, 1993] and not natural gas. Another major gas accident which occurred on June 4th 1989 between Asha and Ufa (Russia) and caused about 600 fatalities, involved LPG instead of natural gas [SRD, 1993].

In the case of hydropower two dam accidents cited in [Fritzsche, 1989] are either not associated with hydro power or have been double-counted [Jansen, 1983]. The first of these accidents occurred on June 9th 1972 in Rapid City (USA); about 200 people drowned. In this case the purpose of the dam was other than power generation. The second accident cited in [Fritzsche, 1989] occurred in India in 1979 and caused about 15,000 fatalities. The latter accident seems to have been mixed up with the Machhu II accident in the state Gujarat in India which caused about 2500 fatalities. Correction for these two cases explains why the ENSAD-based bar for hydro power and the period 1969-1986 in Fig. 7.2.1 is smaller than that based on [Fritzsche, 1989].

In the case of the nuclear energy chain the Chernobyl accident represents the single case accounted for in Fig. 7.2.1.

7.2.2 Number of immediate fatalities

Fig. 7.2.2 shows the number of **immediate** fatalities associated with energy-related severe accidents in the period 1969-1986. For the ENSAD-based results the minimal and maximal number of reported fatalities is given in the figure.

As shown, the oil chain had the highest number of **immediate** fatalities, followed by coal, hydro, LPG and natural gas. Delayed fatalities, particularly relevant for the Chernobyl accident, will be discussed separately in the context of comparisons of fatality rates normalised by the electricity-equivalent output.

The difference of about 3300 fatalities between the minimum and maximum number of immediate fatalities for the oil chain is mainly due the oil accident in Afghanistan in November 1982. The database of Resources for the Future [RfF, 1993] gives for the immediate fatalities caused by this accident a number ranging between 100 and 2700 fatalities.

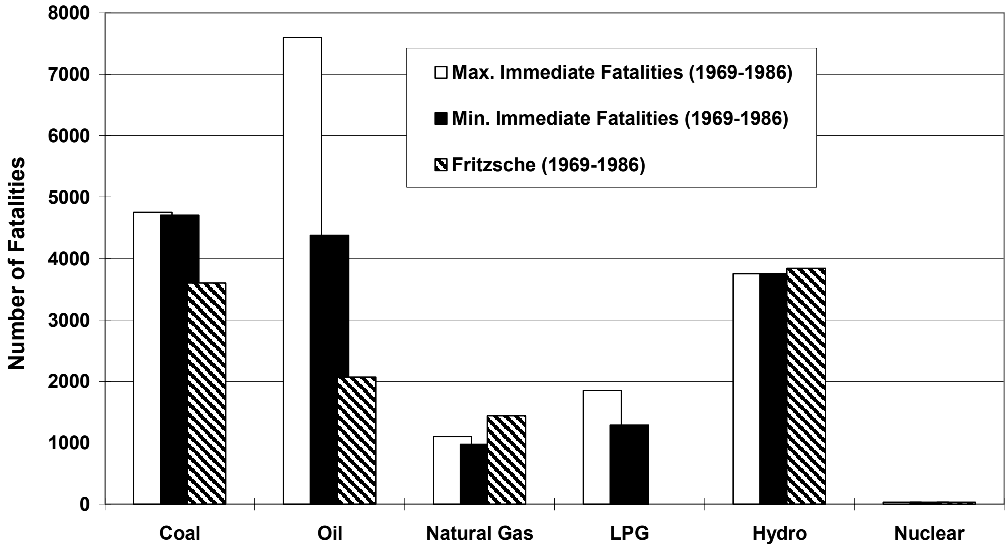

Fig. 7.2.2 Comparison of severe (≥ 5 fatalities) accident records: Total number of **immediate** fatalities in 1969-1986 according to ENSAD and [Fritzsche, 1989].

The similarity between the results for natural gas according to ENSAD- and [Fritzsche, 1989] is due to a pure coincidence. The reason seems to be the earlier mentioned allocation of propylene and LPG accidents to the natural gas chain, as implemented in [Fritzsche, 1989].

Fig. 7.2.3 shows the minimum and maximum number of immediate fatalities in severe accidents for two time periods. The fatalities associated with oil and coal accidents increased drastically in the relatively short period 1987-1996. For natural gas, LPG and hydro power chains there has been a relatively small to moderate increase of fatalities.

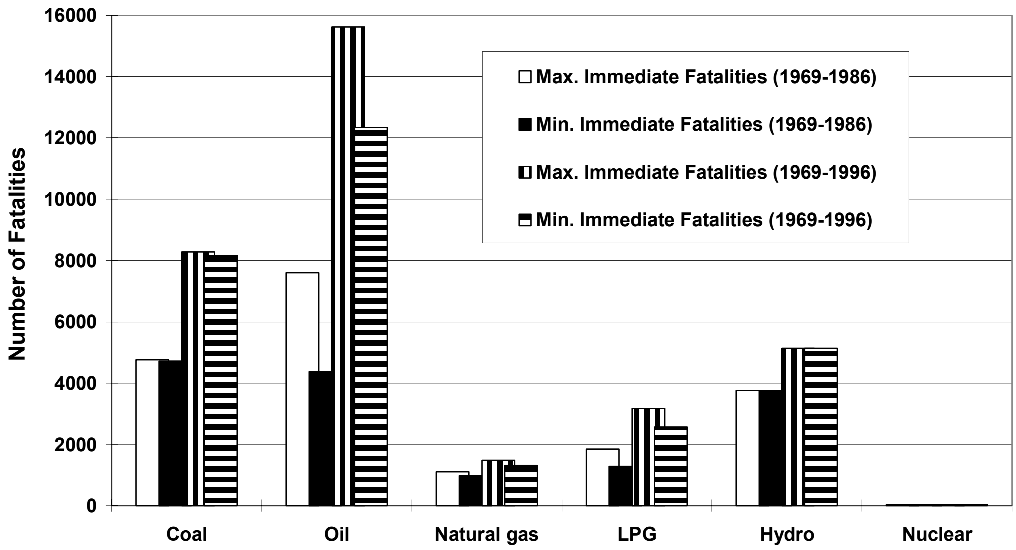

Fig. 7.2.3 Comparison of severe (≥ 5 fatalities) accident records: Total number of **immediate** fatalities in 1969-1986 and 1969-1996 according to ENSAD.

7.2.3 Number of immediate fatalities per event

Figures 7.2.4 and 7.2.5 show the number of **immediate** fatalities per event for the time periods 1969-1986 and 1969-1996, respectively. Hydro power exhibits by far the highest number of **immediate** fatalities per event (but it is decreasing with time), followed by coal, LPG and oil, nuclear and natural gas.

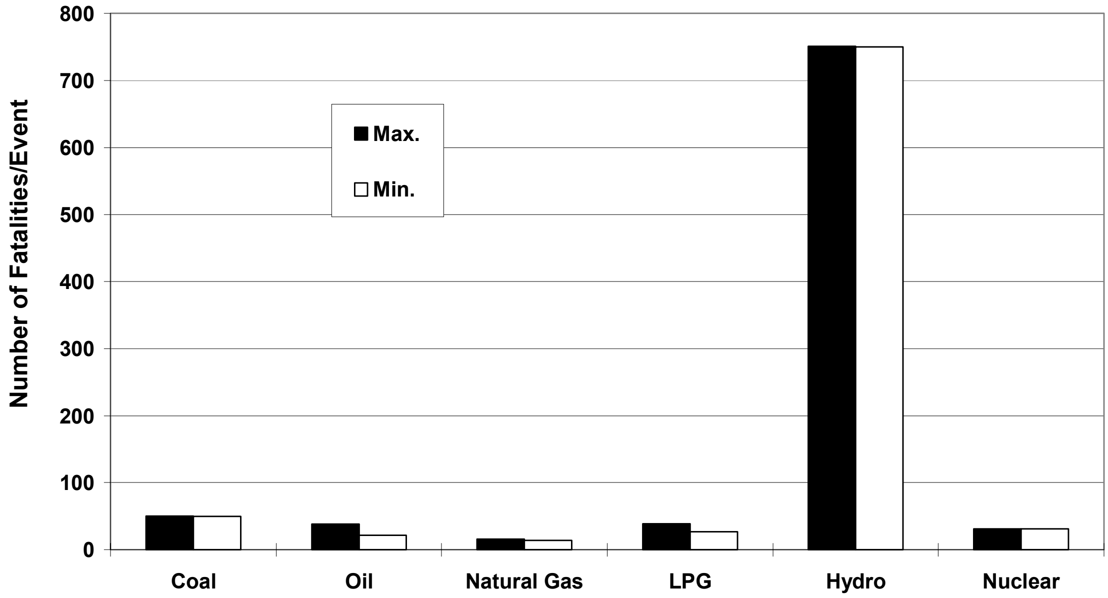

Fig. 7.2.4 Comparison of severe (≥ 5 fatalities) accident records: Number of **immediate** fatalities per event in the period 1969-1986 according to ENSAD.

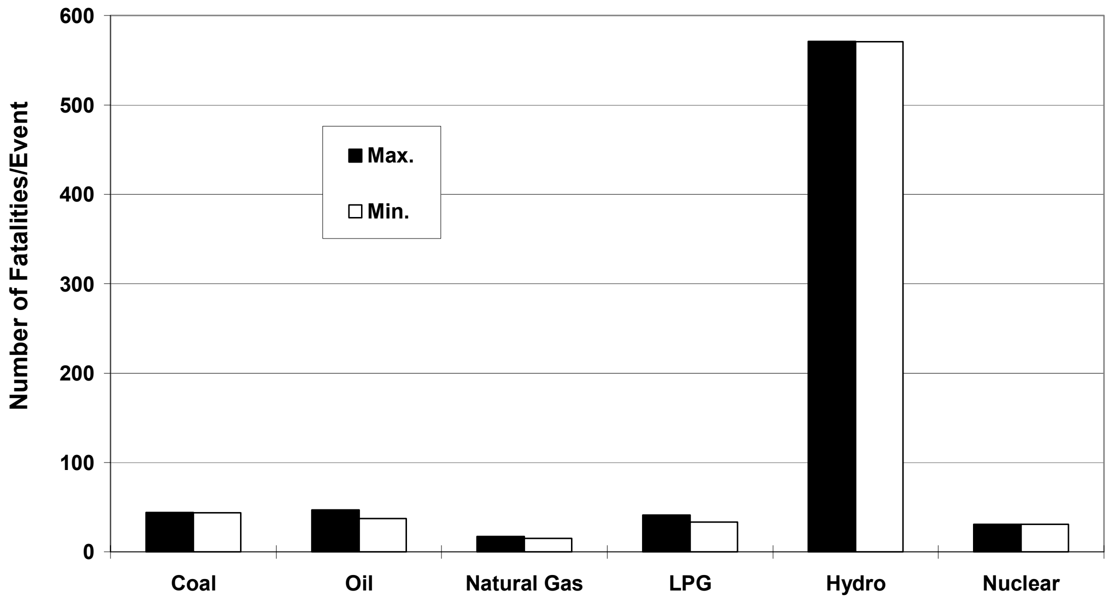

Fig. 7.2.5 Comparison of severe (≥ 5 fatalities) accident records: Number of **immediate** fatalities per event in the period 1969-1996 according to ENSAD.

7.2.4 Immediate fatality rates

The indicators provided in the preceding sections are of limited value for comparative studies since they do not take into account the production volume characteristic for the various energy sources. For this reason the fatality rates based on the normalisation of the accident records by the energy produced are shown here. The approach used in this context was explained in Section 7.1.

In Fig. 7.2.6 the **immediate** fatality rates per "gigawatt(electric)-year" (denoted as GWe*a in figures)[2] are given for different energy options. The values estimated in [Chadwick, ed., 1991] are provided for comparison.

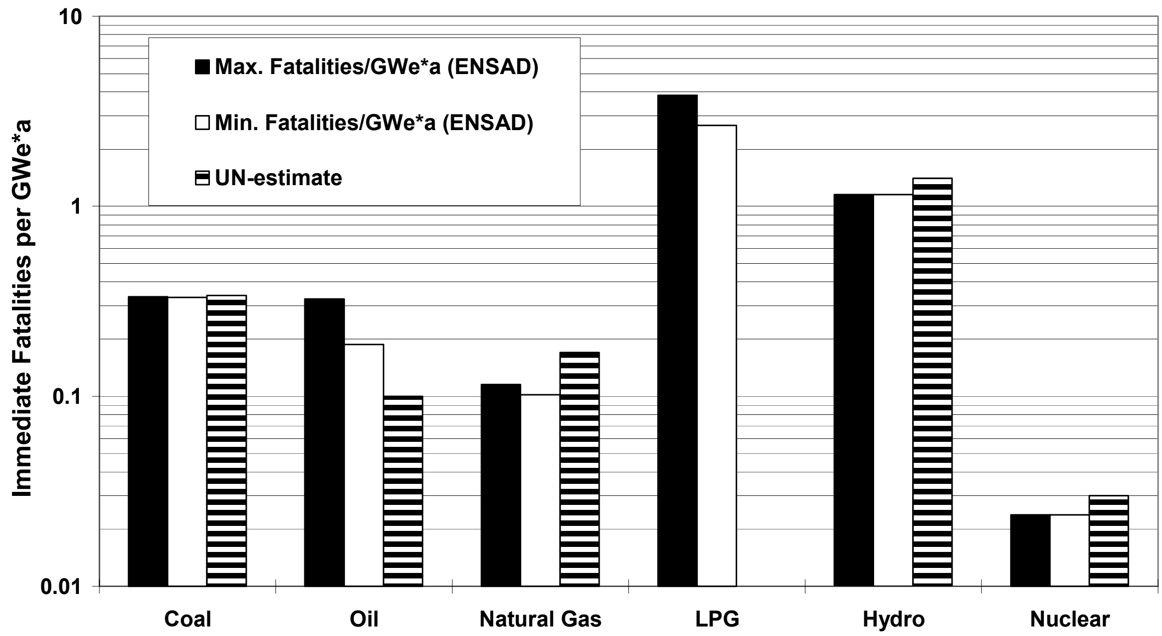

Fig. 7.2.6 Comparison of severe (≥ 5 fatalities) accident records: **Immediate** fatality rates in the period 1969-1986 according to ENSAD and [Chadwick, ed., 1991].

The figure shows that according to ENSAD, LPG has the highest **immediate** fatality rate, followed by hydro power, coal and oil, natural gas and nuclear.

For oil, the ENSAD-based number of immediate fatalities per GWe·a is significantly higher than the UN-estimate; this is clearly due to improved completeness in the present work. For coal and natural gas the ENSAD-based numbers are slightly lower. In the case of coal an evaluation of the statistical energy reviews of BP [BP, 1994] and IEA [IEA, 1993] showed that the total world coal consumption amounted to 1.4 GWe·a instead of 1 GWe·a, which was used to generate the UN-estimate. Therefore, the ENSAD number for **immediate** fatalities per GWe·a for coal is slightly lower than that in [Chadwick, ed., 1991], in spite of a significantly larger number of coal accidents stored in ENSAD. In the case of natural gas

[2] Note that some references use the equivalent notations GWe·a, GWe-a, GWe-yr.

the **immediate** fatality rate according to the present work is lower than the UN-value due to the allocation problems discussed earlier. The same explanation applies also to the differences in the estimates obtained for hydro power.

The normalisation was also performed for the period 1969-1996 as shown in Fig. 7.2.7. The figure demonstrates that the **immediate** fatality rate per GWe·a has increased in the case of the oil chain in comparison to the period 1969-1986, decreased for the natural gas, LPG and hydro and nuclear chains, while the results for coal remain quite stable. The immediate fatality rate for the nuclear chain decreased due to absence of catastrophic events with large number of fatalities during the period 1987-1996.

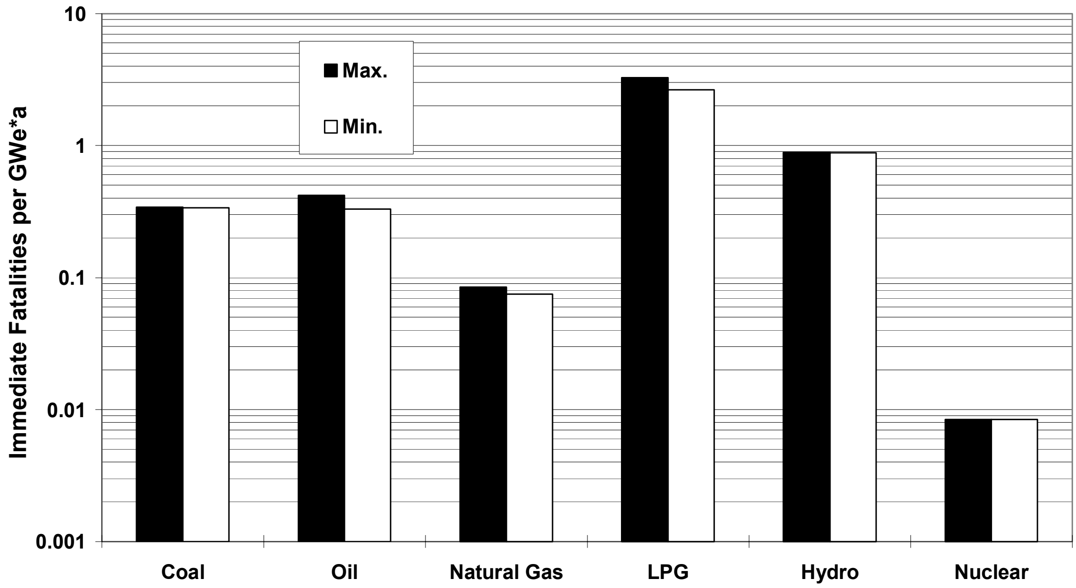

Fig. 7.2.7 Comparison of severe (≥ 5 fatalities) accident records: **Immediate** fatality rates in the period 1969-1996 according to ENSAD.

7.2.5 Delayed fatality rates

The **delayed** fatalities are particularly relevant for nuclear power as manifested by the Chernobyl accident (the **immediate** 31 fatalities associated with this accident are reflected in the figures provided in the preceding sections of this chapter). For other fuel cycles the potential delayed fatalities due to severe accidents are of different nature and not possible to estimate based on the current state of knowledge but are at the same time expected to be of secondary importance.

Figure 7.2.8 summarises the present state of knowledge with regard to the Chernobyl-specific **latent** fatalities. For the detailed background information we refer to Section 6.5 and Appendix D (part D.2). It needs to be emphasised that the consequences shown in the figure are primarily based on estimates governed by the **assessed** occupational ("liquidators") and public radiation doses. This applies fully to predicted cancers expected to occur in the future and also partially to the results concerning fatalities in the period

1987-1996. For the latter case there is, however, an excessive number (in comparison with spontaneous incidence) of thyroid cancers among children in Ukraine and Belarus. For latent cancer fatalities after 1996 the impact on the total of using cut-off criteria (recently recommended by Health Physics Society [Mossman et al., 1996]) can be clearly seen in the figure. The results below are not relevant for western reactors.

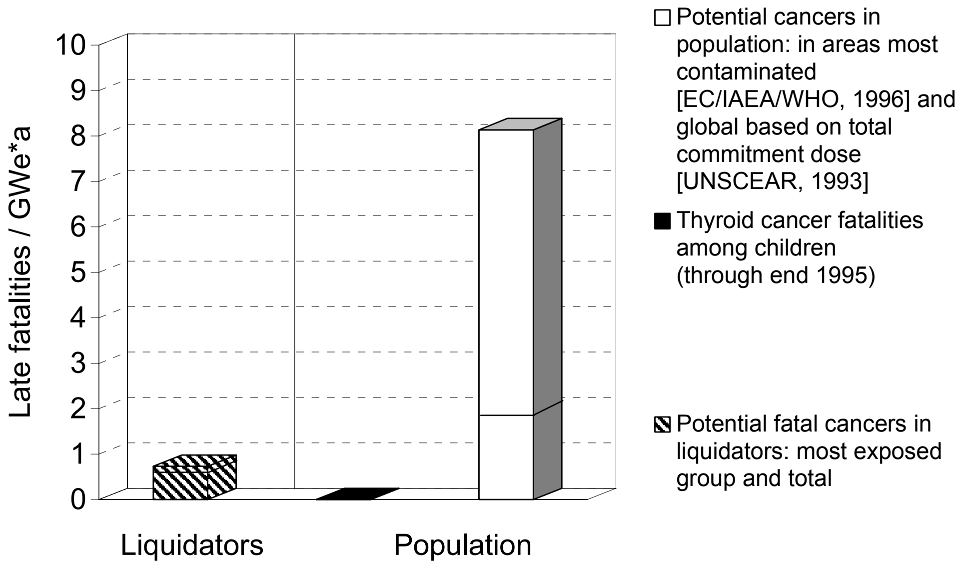

Fig. 7.2.8 Estimated **delayed** fatalities associated with the Chernobyl accident normalised by the unit of electricity; the dividing line in the bar showing potential cancers in population corresponds to the dose cut-off.

Figure 7.2.9 shows three examples of estimated number of **delayed** cancer fatalities per GWe*a for the Swiss nuclear plant Mühleberg [Cazzoli et al., 1993] and for two US plants [USNRC, 1990], including the associated uncertainty measures (5-th and 95-th percentiles). These estimates are based on Probabilistic Safety Assessments (PSAs).

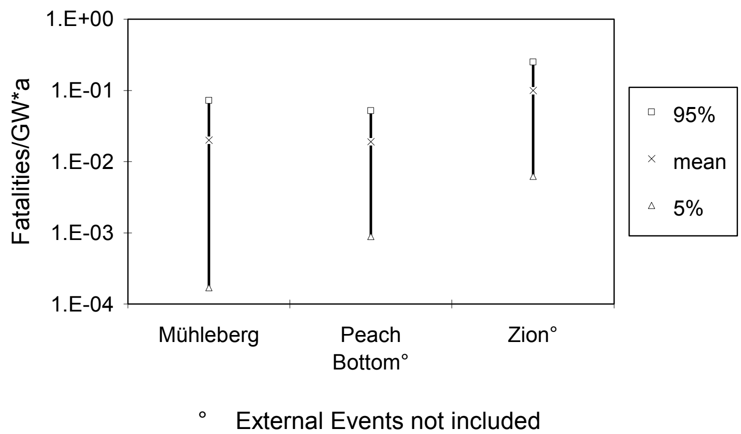

Fig. 7.2.9 Estimated **latent** cancer fatalities due to hypothetical severe accidents (per GWe*a) for the Swiss nuclear power plant Mühleberg and two US plants.

The calculated risk measures are based on the integration of the full analysed spectrum of accidents. For Mühleberg the contribution of the frequently dominant external events (such as fires, earthquakes, floods, aircraft crashes) is included while the US studies only cover the internal events. No dose cut-offs were used in the calculations; for the US plants the consequences were calculated to 1600 km and for Mühleberg to 800 km.

The large difference between Chernobyl-based estimates (Fig. 7.2.8) and probabilistic plant-specific estimates for Mühleberg and US plants (Fig. 7.2.9) illustrates the limitations in applicability of past accident data to cases which are radically different in terms of technology and operational environment.

7.2.6 Frequency-consequence curves for severe accidents involving fatalities

In Fig. 7.2.10 frequency-consequence curves for the time period 1969-1986 and different energy sources are given. The LPG curve has the highest frequency of exceedance of the number of fatalities. Up to the level of about 40 - 60 fatalities the frequency-consequence curve for hydro power is lower than those for coal and oil. Above this level the situation is reversed. Natural gas exhibits in relative terms a favourable picture at least above the level of 20 fatalities. For nuclear there is only one point (Chernobyl).

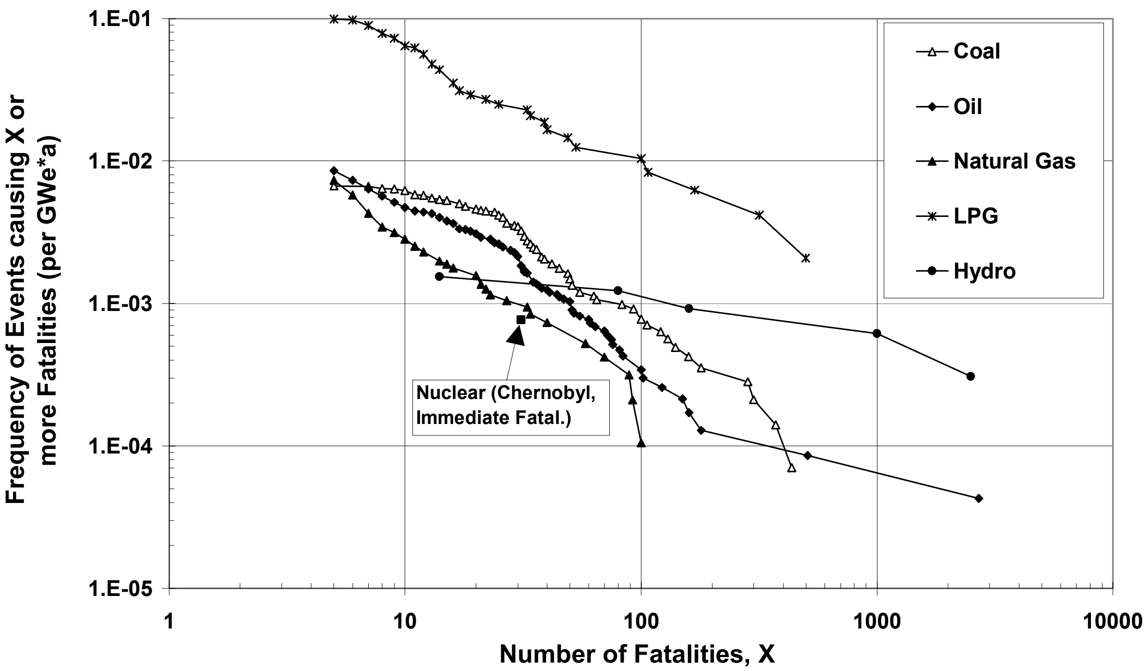

Fig. 7.2.10 Comparison of severe (≥ 5 fatalities) accident records: ENSAD-based frequency-consequence curves for different energy chains and the period 1969-1986; only **immediate** fatalities are considered.

In Fig. 7.2.11 the corresponding frequency-consequence curves for the time period 1969-1996 are provided.

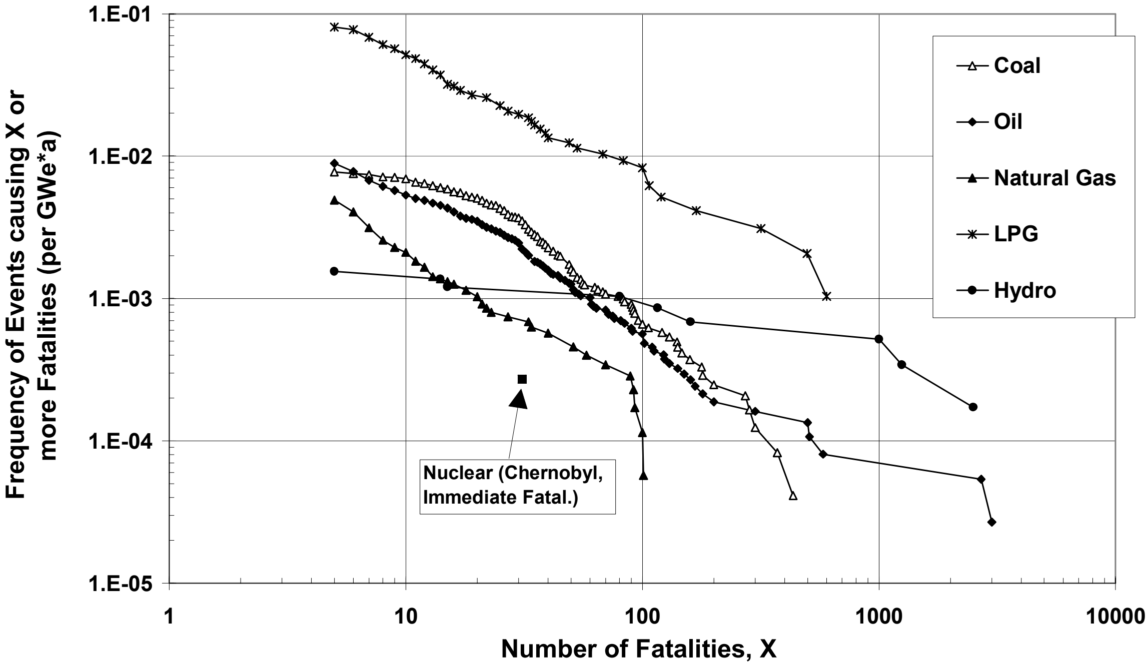

Fig. 7.2.11 Comparison of severe (≥ 5 fatalities) accident records: ENSAD-based frequency-consequence curves for different energy chains and the period 1969-1996; only **immediate** fatalities are considered.

Although the number of fatalities increased for the larger period 1969-1996 (Fig. 7.2.11) in comparison to 1969-1986 (**F**ig. 7.2.10), the frequency-consequence curves are in all cases, except for the oil chain, on a slightly lower level than in the first case. The reason is that in the period 1987-1996, depending on which energy chain is considered there has been a decrease in the number of severe accidents with large number of fatalities and/or an increase of the produced energy with respect to 1969-1986.

In Figures 7.2.10 and 7.2.11 only one point for the nuclear chain is depicted since in the time period 1969-1996 only one severe (≥ 5 fatalities) nuclear accident (Chernobyl) occurred. The accident resulted in 31 **immediate** fatalities which in the figure above is represented as a single point with a frequency value of about $2.7 \cdot 10^{-4}$ events per GWe*a. For comparison, the Chernobyl-specific **delayed** fatalities, on the other hand, have been estimated in the present work (based on a number of sources) to be roughly in the interval 9000-33,000.

Figure 7.2.12 shows the normalised frequency-consequence curves based on the PSA for the damage category **latent** fatalities to 800 km for the Swiss nuclear power plant Mühleberg [Cazzoli et al., 1993; Hirschberg and Cazzoli, 1994]. Different confidence levels (5%, 50% and 95%) are shown in the figure; the mean value can be regarded as the main reference, while the 95-th percentile can be interpreted as providing a bounding value. No credible accident scenarios leading to immediate fatalities among the public have been identified for Mühleberg.

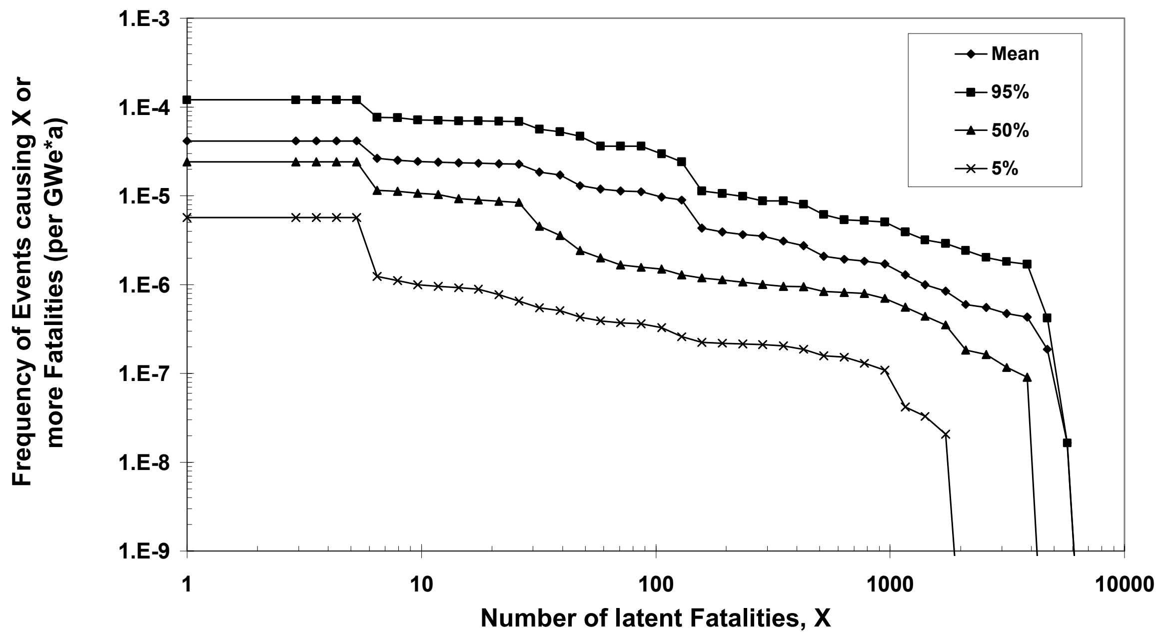

Fig. 7.2.12 PSA-based frequency of exceedance of **latent** cancer fatalities to 800 km for the Swiss nuclear power plant Mühleberg.

The above PSA-based Mühleberg-specific frequency-consequence (mean value) curve for **latent** fatalities is typically at the frequency level by two orders of magnitude lower than the generic experience-based frequency curves for **immediate** fatalities within coal, oil, natural gas and hydro energy chains. For the extreme consequences involving several thousands of fatalities this difference becomes even larger (in relation to oil and hydro chains; the other chains do not exhibit any historical events at this level of consequences).

One remark is here in place concerning hydro power. The hydro-specific curves given in Fig. 7.2.10 and Fig. 7.2.11 are generic and based on world-wide experience. The regional dependence is here substantial and the applicability of the generic hydro curves to the situation in the Western World and in Switzerland in particular is clearly restricted. This is a parallel case to the irrelevance of the Chernobyl experience for the assessment of the safety level of the Swiss nuclear power plants (in spite of the higher statistical significance in the hydro case due to the occurrence of several events). The matter has been elaborated in detail in Section 6.6, demonstrating that the range of the generic Swiss-specific frequencies (in terms of mean values) for dam rupture is expected to be in the interval $1.3 \cdot 10^{-5}$-$5.7 \cdot 10^{-5}$ per dam-year, depending on the type of dam. The frequency of the serious consequences for the public would then be expected to be on a lower level, depending on site-specific conditions. According to the knowledge of the authors no site-specific probabilistic studies are at this stage publicly available to demonstrate this. In Chapter 9 this issue is further discussed and the difference between the generic curves versus the ones obtained for the Western World within the evaluation period 1969-1996, is shown. The result is that the aggregated, normalised immediate fatality rate for the western hydro dams and for the time period 1969-1996 is comparable to that estimated for latent fatalities within the PSA for the Mühleberg plant.

7.3 Severe Accidents Involving Injured

7.3.1 Number of severe accidents

In Fig. 7.3.1 the number of severe (≥ 10 injured) accidents for two time periods (1969-1986 and 1969-1996) is shown. According to the figure the oil chain represents the option with the largest number of severe accidents involving injured. Furthermore, the oil chain showed the largest increase of such accidents during the period 1987-1996 in comparison to 1969-1986. The coal and hydro energy chains have in contrast to other chains a comparatively small number of severe (≥ 10 injured) accidents; in both cases the database completeness problems are suspected in this context. For the nuclear chain there is only one event (Chernobyl) with about 370 injured during the early emergency operation of the failed plant.

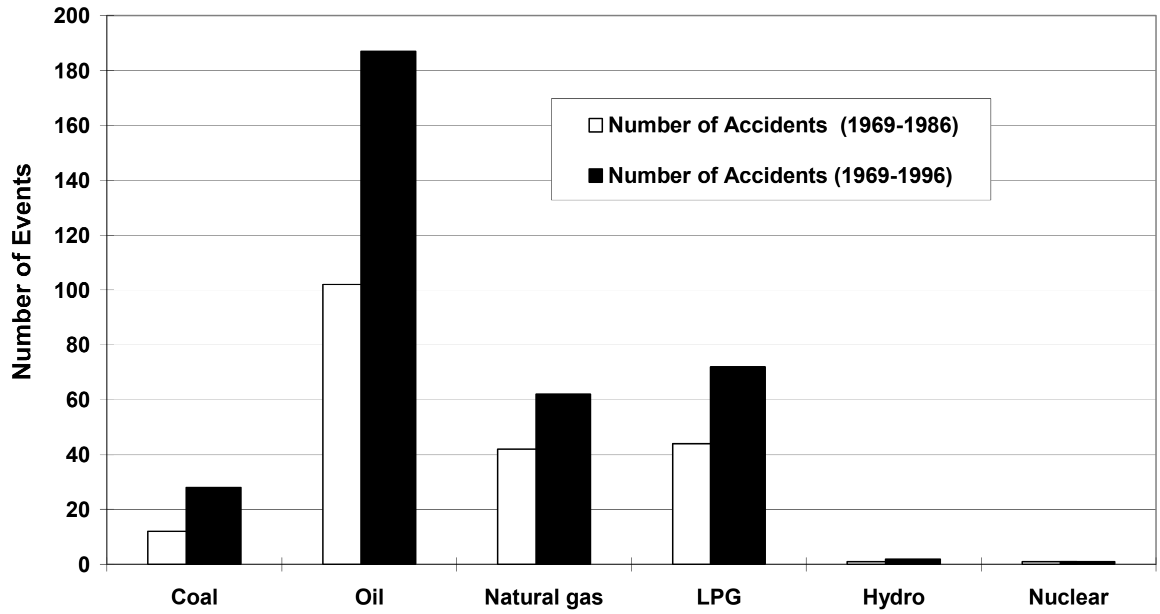

Fig. 7.3.1 Comparison of severe (≥ 10 injured) accident records: Total number of events in examined time periods according to ENSAD.

7.3.2 Number of injured

In Fig. 7.3.2 the number of injured in severe (≥ 10 injured) accidents for two time periods and for different energy options is given. The oil chain exhibits the highest number of injured followed by LPG, natural gas, coal, hydro power and nuclear.

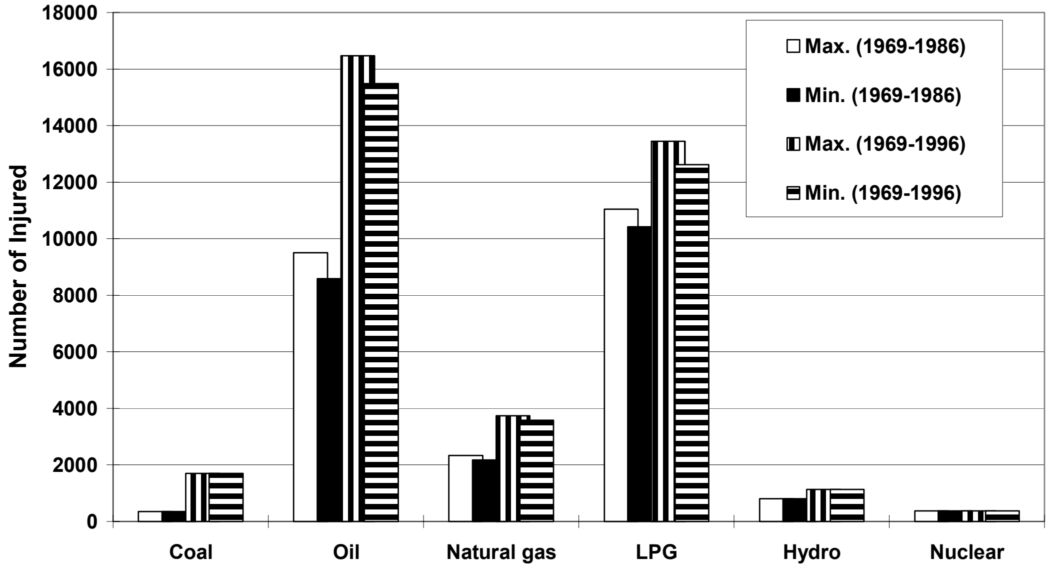

Fig. 7.3.2 Comparison of severe (≥ 10 injured) accident records: Total number of injured in examined time periods according to ENSAD.

7.3.3 Number of injured per event

In Fig. 7.3.3 the number of injured people per event is shown for different energy chains. The hydro option has the highest number of injured per event followed by nuclear, LPG, oil, natural gas and coal.

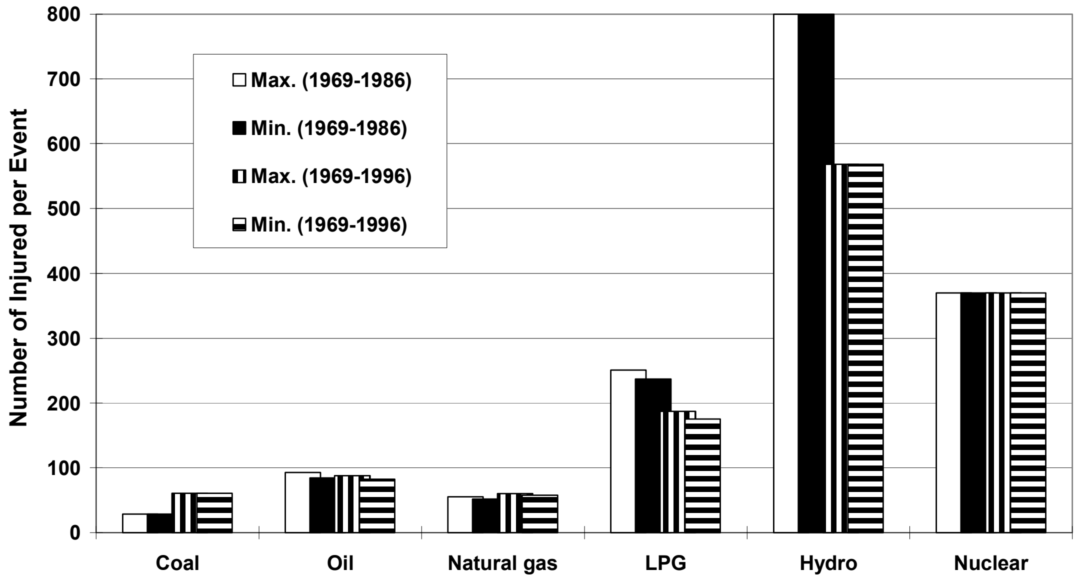

Fig. 7.3.3 Comparison of severe (≥ 10 injured) accident records: Number of injured per event in examined time periods according to ENSAD.

7.3.4 Number of injured per unit of produced energy

In Fig. 7.3.4 the number of injured per produced energy is given for the different energy chains. The figure shows that the LPG chain has in comparison to other energy sources a much higher number of injured per unit of produced energy.

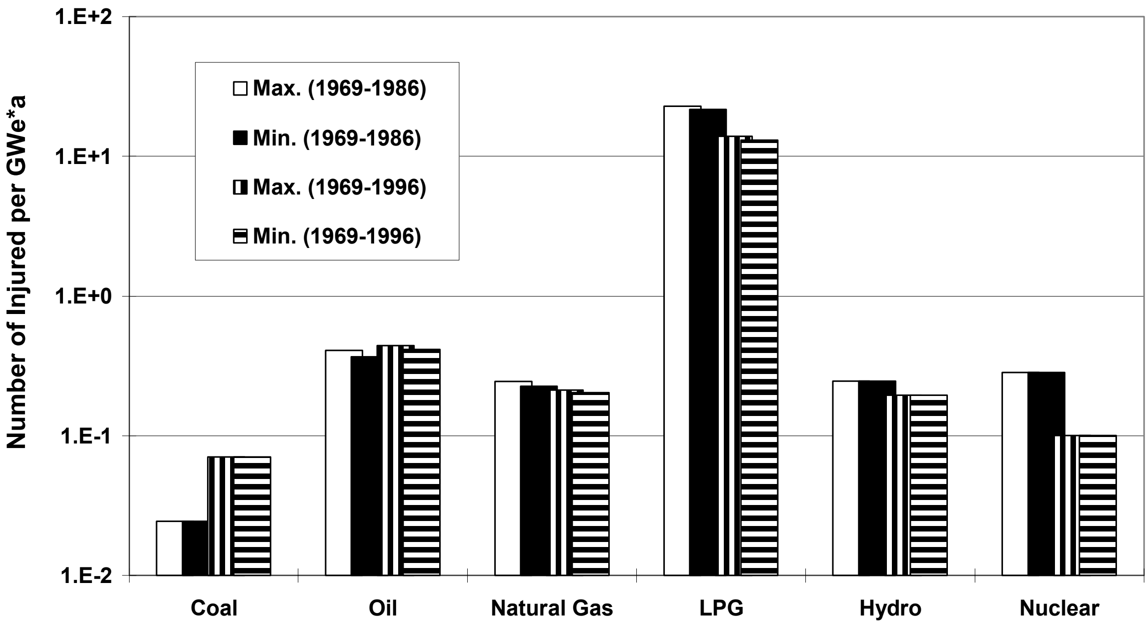

Fig. 7.3.4 Comparison of severe (≥ 10 injured) accident records: Number of injured per unit of produced energy in examined time periods according to ENSAD.

7.3.5 Frequency-consequence curves for severe accidents involving injured

In Figures 7.3.5 and Fig. 7.3.6 the frequency-consequence curves associated with severe (≥ 10 injured) accidents are provided for the two time periods, respectively. The worst disasters with 7200 injured in the LPG and 3000 injured in the oil chain occurred in San Juan Ixhuatepec, Mexico City (Section 6.4.4.2) respectively in the Atlantic Ocean during offshore activities (Section 6.3.3.2). LPG has the highest frequency of exceedance of the number of injured. Except for the region with a vast number of injured, there is some resemblance between the oil and the natural gas curves. The differences between the curves obtained for the two time periods are relatively small.

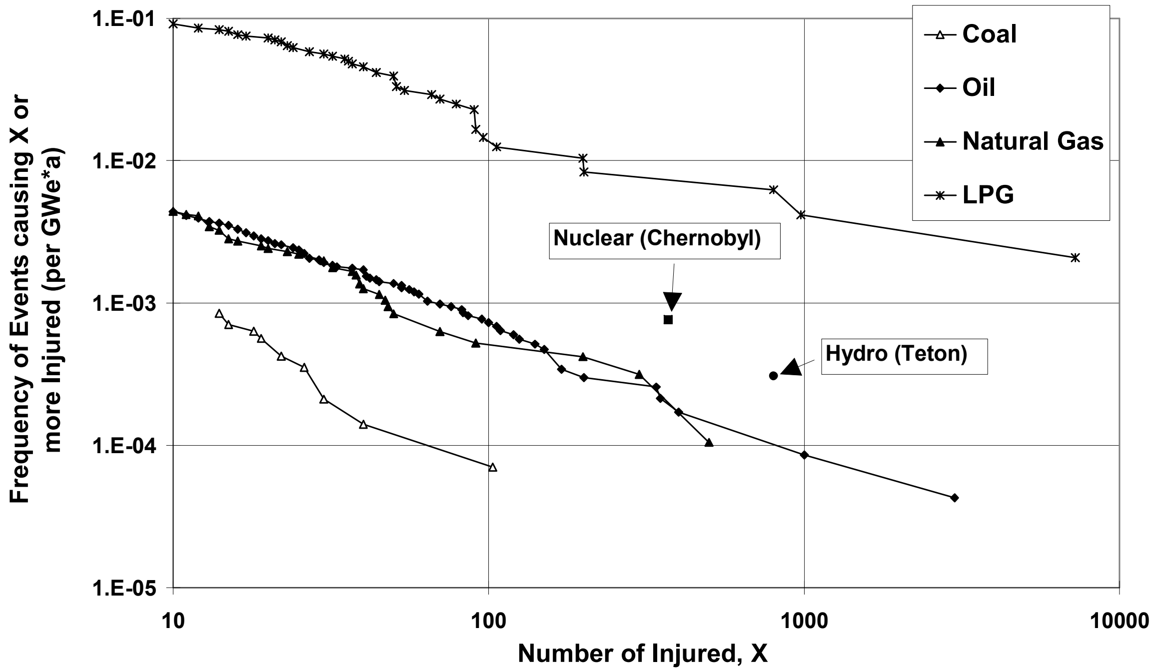

Fig. 7.3.5 Comparison of severe (≥ 10 injured) records: ENSAD-based frequency-consequence curves for different energy chains and the period 1969-1986.

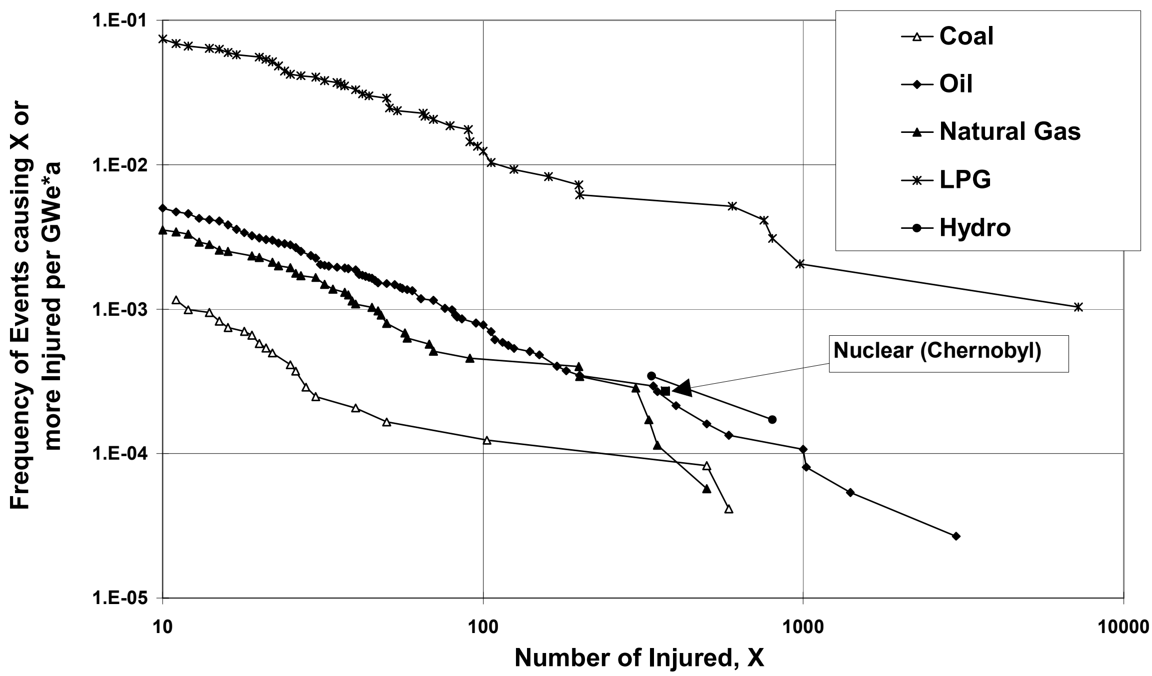

Fig. 7.3.6 Comparison of severe (≥ 10 injured) records: ENSAD-based frequency-consequence curves for different energy chains and the period 1969-1996.

7.4 Severe Accidents Involving Evacuees

7.4.1 Number of severe accidents

Figure 7.4.1 shows the number of severe (≥ 200 evacuees) accidents for the different energy chains and two time periods. The largest number of evacuations has been experienced within the oil chain, followed by the LPG, natural gas, nuclear and hydro chains. Generally, the duration of evacuations is an important parameter, not evident from the figures provided in Section 7.4 due to the lack of detailed information. For the nuclear chain two very large evacuations took place. The first was associated with the Three Mile Island accident on March 28th 1979. One hundred forty four thousand persons were evacuated but once the acute phase of the accident was over they could return home. In connection to the Chernobyl accident between 115,000 and 135,000 persons were permanently evacuated. The coal chain shows no evacuated persons. For the latter energy source the accidents are predominantly in the mining stage and normally only affect the workers. Thus, no evacuation records were identified.

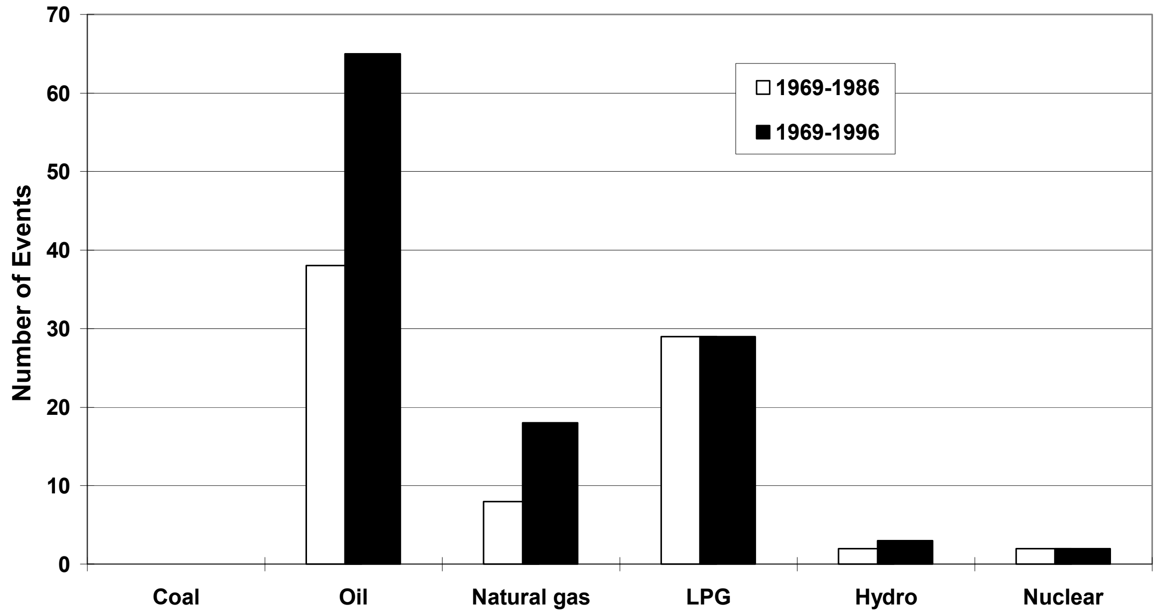

Fig. 7.4.1 Comparison of severe (≥ 200 evacuees) accident records: Total number of evacuations in examined time periods according to ENSAD.

7.4.2 Number of evacuees

Figure 7.4.2 shows the number of evacuees for two time periods and different energy chains. LPG has the highest number of evacuees, followed by nuclear, oil, hydro and natural gas.

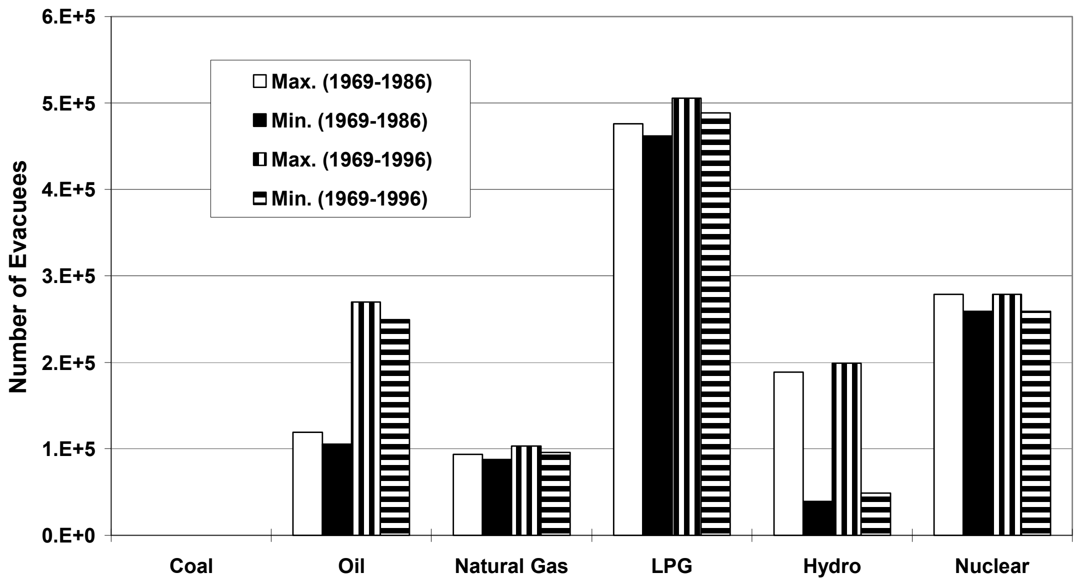

Fig. 7.4.2 Comparison of severe (≥ 200 evacuees) accident records: Total number of evacuees in examined time periods according to ENSAD.

7.4.3 Number of evacuees per event

In Fig. 7.4.3 the number of evacuees per event for two time periods and different energy options is given. The figure demonstrates that nuclear has the highest number of evacuees per event followed by hydro, LPG, natural gas and oil.

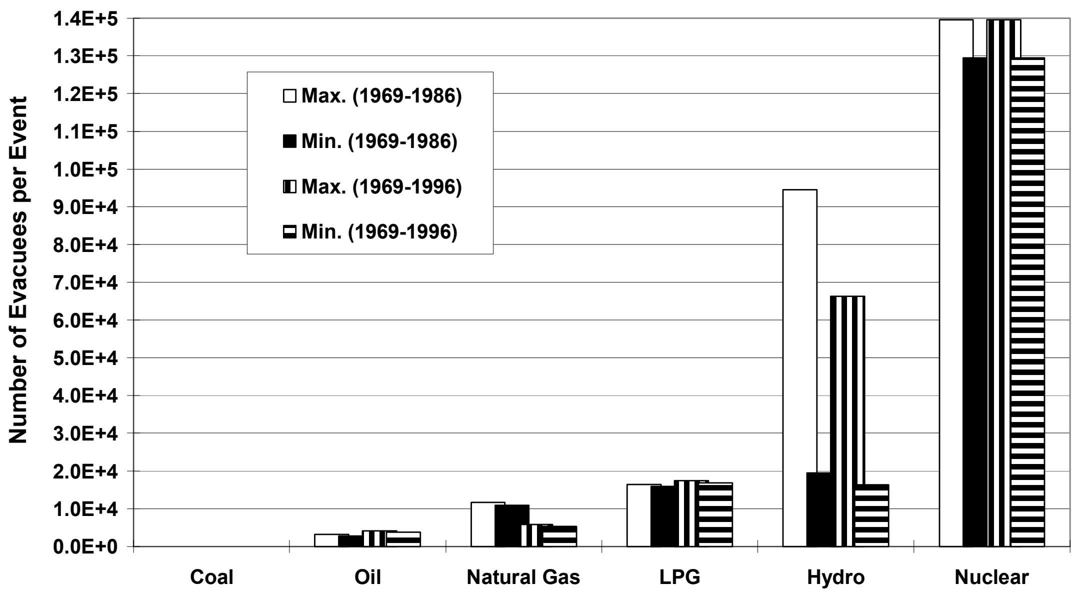

Fig. 7.4.3 Comparison of severe (≥ 200 evacuees) accident records: Number of evacuees per event in examined time periods according to ENSAD.

7.4.4 Number of evacuees per unit of produced energy

Figure 7.4.4 shows the number of evacuees per unit of produced energy for two time periods and different energy chains. The LPG chain has the highest number of evacuees per produced energy, followed by nuclear, hydro, oil and natural gas.

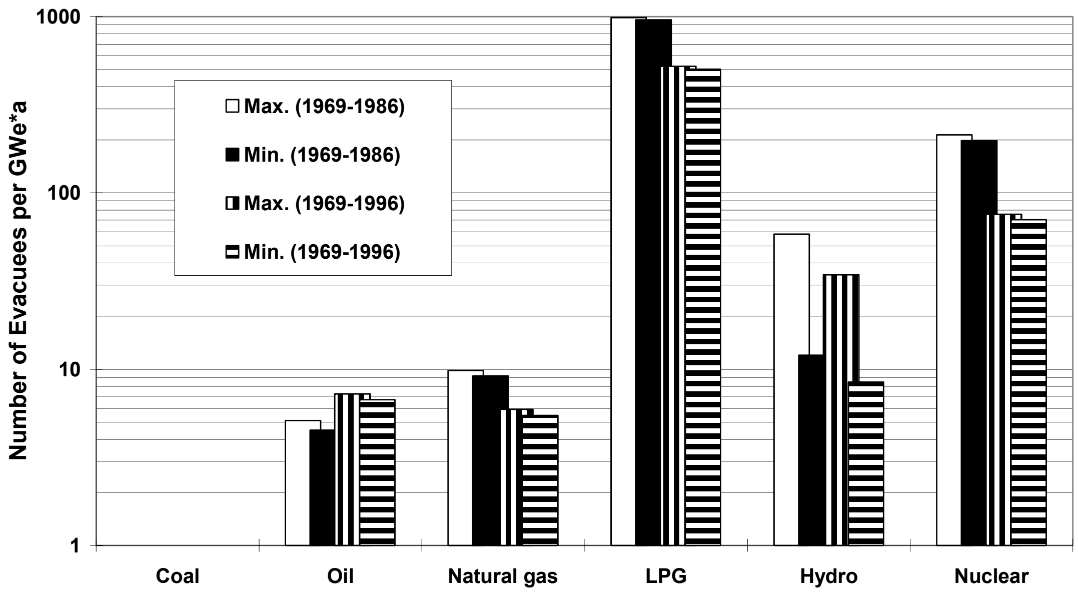

Fig. 7.4.4 Comparison of severe (≥ 200 evacuees) accident records: Number of evacuees per unit of produced energy in examined time periods according to ENSAD.

7.5 Severe Accidents Involving Economic Losses

7.5.1 Number of severe accidents

Figure 7.5.1 shows the number of severe (≥ 5 million 1996 US$) accidents for different energy options and two time periods. Most of such accidents occurred in the oil chain, followed by the LPG, natural gas, hydro, hydro, coal and nuclear chains.

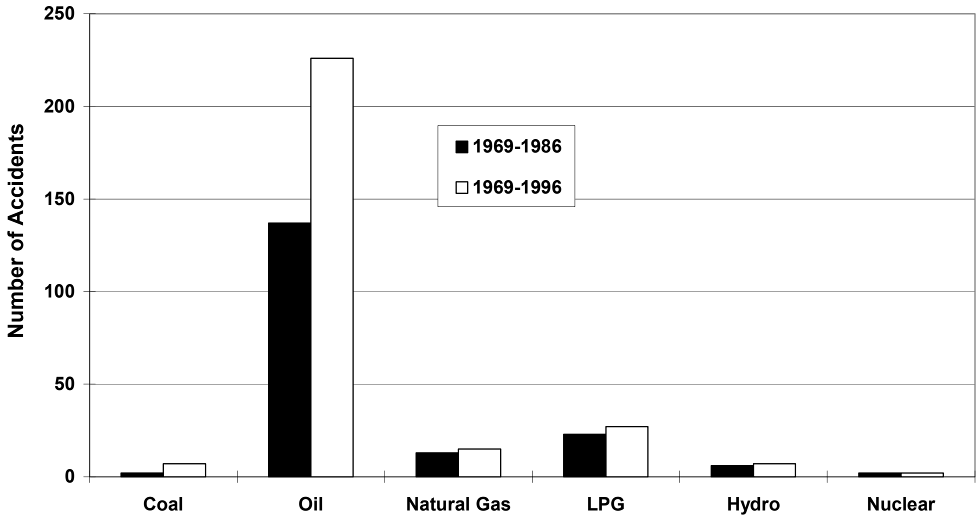

Fig. 7.5.1 Comparison of severe (≥ 5 million 1996 US$) accident records: Number of accidents in examined time periods according to ENSAD.

7.5.2 Total damage costs

Figure 7.5.2 shows the total monetary damage for different energy options and two time periods. The monetary damage for the nuclear chain shows the highest amount in comparison to other energy options followed by the oil, hydro, LPG, natural gas and coal chains.

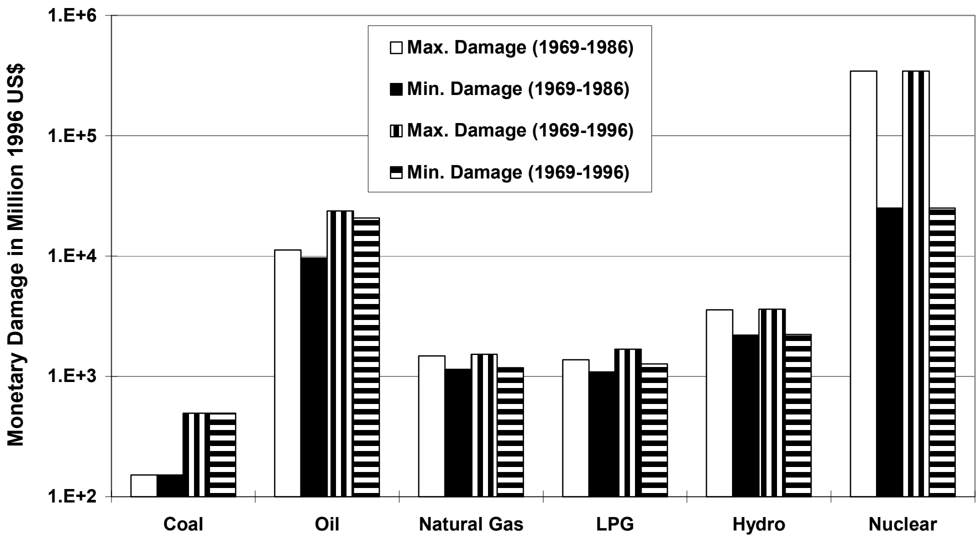

Fig. 7.5.2 Comparison of severe (≥ 5 million 1996 US$) accident records: Total damage costs in examined time periods according to ENSAD.

7.5.3 Damage costs per accident

Figure 7.5.3 shows the monetary damage per severe (≥ 5 million 1996 US$) accident for different energy options and two time periods. For coal, oil, natural gas and LPG the damage costs per severe accident remain on average at a value between 50 and slightly above 100 million 1996 US$. For the nuclear chain the costs are totally dominated by the Chernobyl accident and are two to three orders of magnitude higher. The uncertainties are very large in the nuclear case as illustrated by the difference between the minimum and maximum values.

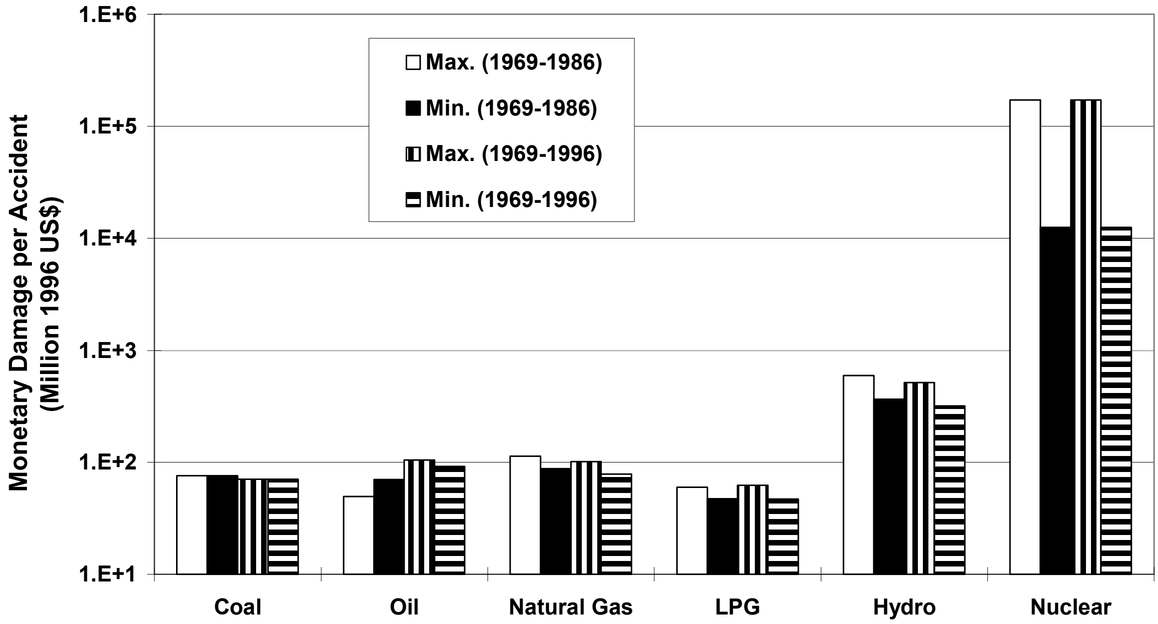

Fig. 7.5.3 Comparison of severe (≥ 5 million 1996 US$) accident records: Damage costs per accident in examined time periods according to ENSAD.

7.5.4 Damage cost rates

Figure 7.5.4 provides the monetary damage per GWe·a for severe (≥ 5 million 1996 US$) accidents. The nuclear energy chain shows the highest results for both time periods followed by the LPG, hydro, oil, natural gas and coal chains.

For comparison, the PSA-based external costs of hypothetical severe accidents at the Swiss nuclear power plant Mühleberg have been estimated in the present work to be in the range $2 \cdot 10^{-3}$-$44 \cdot 10^{-3}$ million US$ per GWe·a and $9 \cdot 10^{-3}$-$333 \cdot 10^{-3}$ million US$ per GWe·a, depending on whether the radiation-induced health effects are included or not.

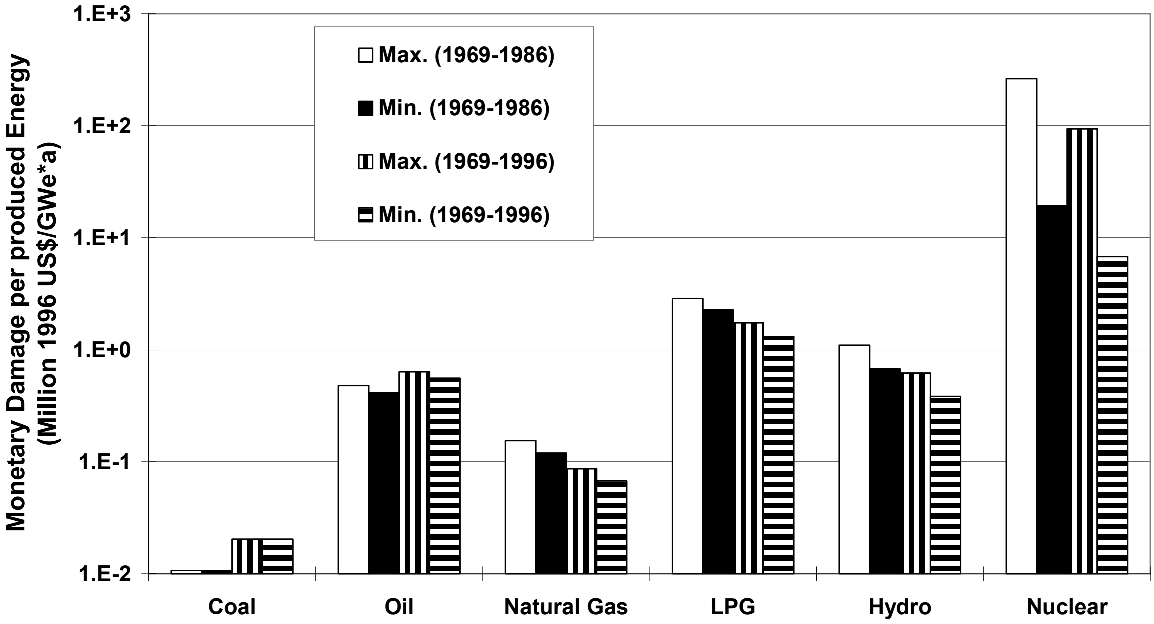

Fig. 7.5.4 Comparison of severe (≥ 5 million 1996 US$) accident records: Damage costs per unit of produced energy in examined time periods according to ENSAD.

7.6 Overview of Person-related Consequence Indicators

Below the results obtained for person-related indicators are summarised in Fig. 7.6.1 through 7.6.4. For the damage category "**immediate** fatalities" only maximum values are considered. "**Delayed** fatalities" are not shown in the figures (for the Chernobyl-specific delayed fatalities we refer to the results and the discussion in Section 7.2.5).

As expected, the number of evacuees exceeds the number of injured and fatalities for all energy chains except for coal (Figures 7.6.1 and 7.6.2). In the case of oil, LPG, natural gas and nuclear chains the number of injured exceeds the number of fatalities. For hydro power and coal the number of injured was significantly lower than the estimate of fatalities. This, however, may be a consequence of database incompleteness.

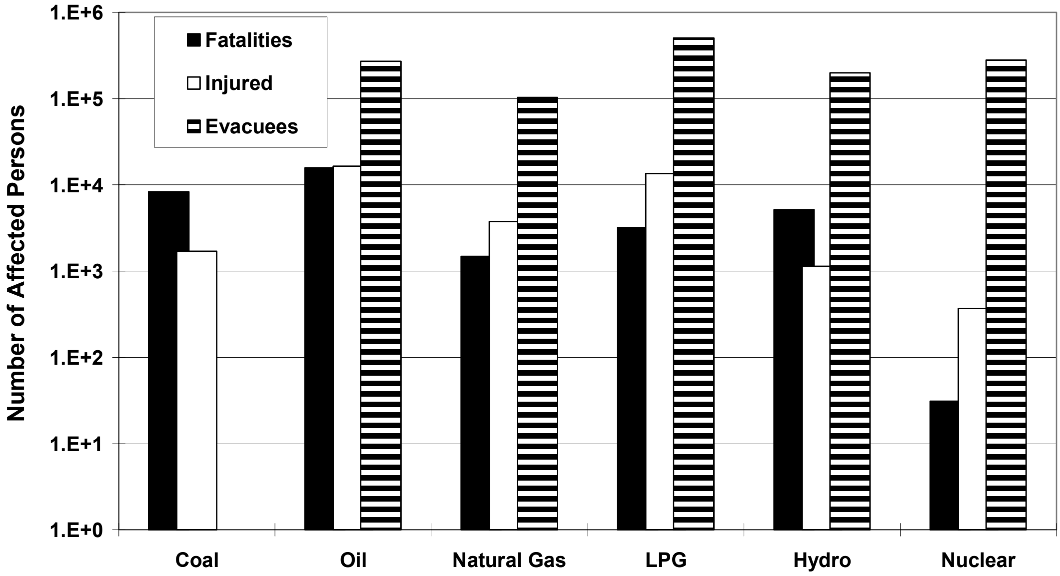

Fig. 7.6.1 Comparison of severe accident records: Number of affected people (evacuees, injured and immediate fatalities) for different energy options and time period 1969-1986 according to ENSAD.

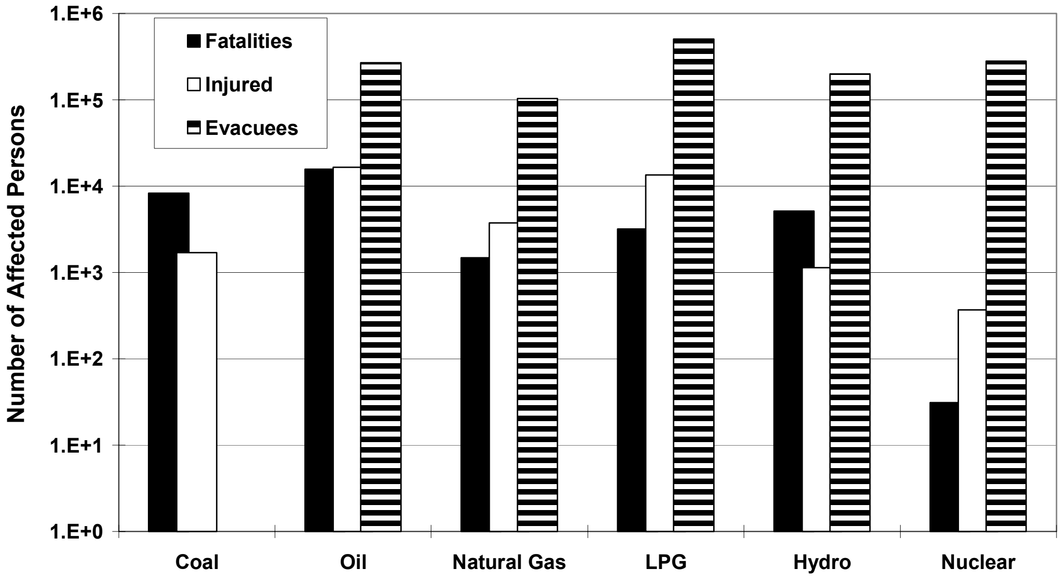

Fig. 7.6.2 Comparison of severe accident records: Number of affected people (evacuees, injured and immediate fatalities) for different energy options and time period 1969-1996 according to ENSAD.

In Figures 7.6.3 and Fig. 7.6.4 the number of affected persons per unit of produced energy is given for different energy options and two time periods. Both figures show that LPG has the highest rates for evacuees, injuries and fatalities per unit of produced energy. The rates for oil and natural gas chains have similar profiles but are clearly lower in the case of natural gas with regard to fatalities and injuries. Hydro has the second largest rate for fatalities and nuclear for evacuees. Except for coal the rate for the category “evacuees” is higher for all energy options than the rates for the categories “injured” and “immediate fatalities”. In the case of hydro power and coal the rate for “fatalities” is higher than that for “injured”.

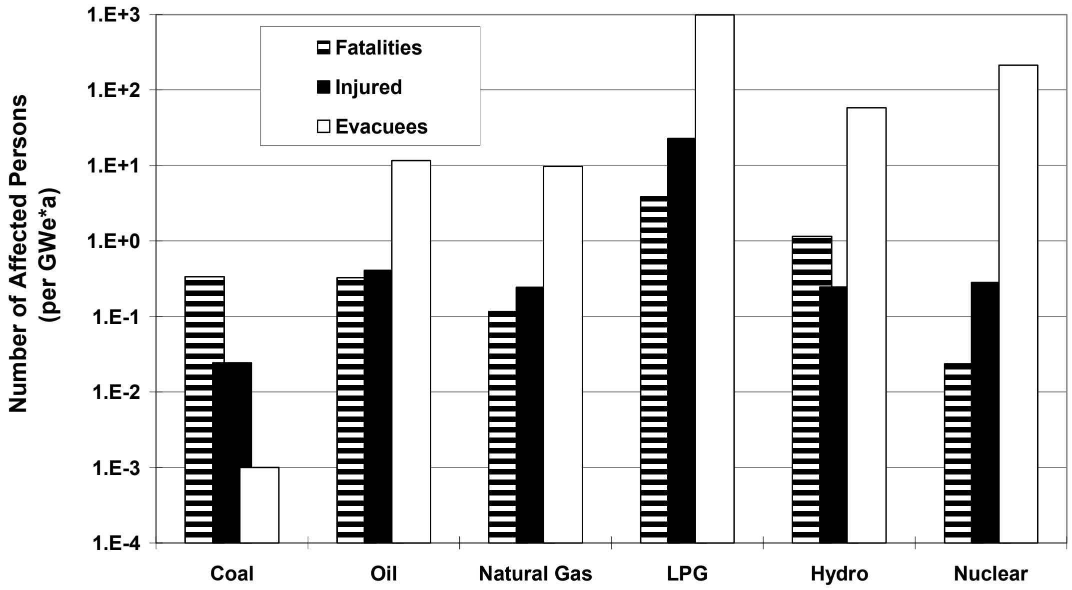

Fig. 7.6.3 Comparison of severe accident records: Normalised rates for the number of affected persons (evacuees, injured and immediate fatalities) for different energy options and time period 1969-1986 according to ENSAD.

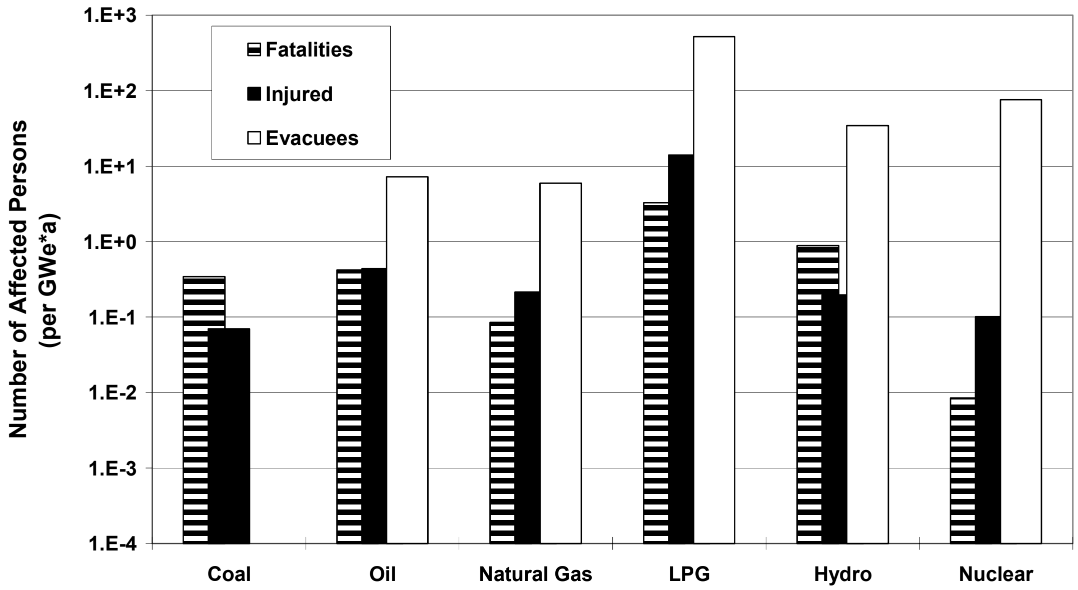

Fig. 7.6.4 Comparison of severe accident records: Normalised rates for the number of affected persons (evacuees, injured and immediate fatalities) for different energy options and time period 1969-1996 according to ENSAD.

It needs to be emphasised that the results presented above are generic and utmost caution should be exercised when using them for specific applications. Some differentiation of the chain-specific results will be provided in Chapter 9.

7.7 References

BP (1994), Statistical Review of World Energy (1994). British Petroleum Company, Disk1 and 2, June 1994.

Cazzoli, E. et al. (1993), A Regulatory Evaluation of the Mühleberg Probabilistic Safety Assessment, Volume II: Level 2. ERI/HSK 93-304. HSK 11/356 (Limited Distribution).

Chadwick, M. J. ed. (1991), Key Issue Paper No. 3 by International Expert Group 3: Comparative Environmental and Health Effects of Different Energy Systems for Electricity Generation. Proceedings of Senior Expert Symposium on Electricity and the Environment, 13-17 May 1991, Helsinki, Finland, IAEA, Vienna, 1991.

Fritzsche, A. F., (1988), Gesundheitsrisiken von Energieversorgungssystemen; Von der Kohle bis zu Energien der Zukunft und den Rohstoffen bis zu Entsorgung (in German). Köln: Verlag TÜV Rheinland.

Fritzsche, A. F. (1989), The Health Risks of Energy Production. Risk Analysis, 9 (1989), pp. 565-577.

Hirschberg, S. and Cazzoli, E. (1994), Contribution of Severe Accidents to External Costs of Nuclear Power. Proceedings of ENS Topical Meeting on PSA/PRA and Severe Accidents '94, 17th-20th April 1994, Ljubljana, Slovenia.

IEA (1993), Energy Statistics and Balances, OECD (1960-1991), Non-OECD (1971-1991). International Energy Agency, Diskette Service, OECD, Paris.

Jansen R. (1983), Dams and Public Safety. U.S. Department of the Interior, Bureau of Reclamation, Washington D.C., USA.

Mossman, K. L., Goldman, M., Massé, F., Mills, W. A., Schiager, K. J. and Vetter, R. J. (1996), Health Physics Society Position Statement: Radiation Risk in Perspective. HPS Newsletter, Volume XXIV, Number 3, March 1996.

RfF (1993), Fatal Hazardous Materials Accidents Database. Resources for the Future, Washington D.C. 20036-1400, USA.

SRD (1993), The Major Hazards Incidence Data Service. AEA Technology, Consultancy Services (SRD), Cheshire, UK.

USNRC (1990), Severe Accident Risks: An Assessment for Five U.S. Nuclear Power Plants. Final Report. Report NUREG-1150, U.S. Nuclear Regulatory Commission, Washington D.C., USA.

8. MAIN LIMITATIONS

This chapter deals with the major limitations and difficulties encountered in the present analysis, which to a large extent are characteristic for the present state-of-the-art of comparative assessment of energy-related severe accidents. Some of these limitations are of practical nature and, consequently progress can be expected; other are inherent with small chances for clear improvements in the short to medium term perspective. The limitations are here discussed separately in the context of databases and probabilistic analyses, respectively. Finally, scope limitations of the present work are summarised. Difficulties and relevant issues that arise when comparing the results will be addressed in Chapter 9.

8.1 Limitations of the Database and its Uses

8.1.1 Completeness and recording accuracy

The incompleteness of the database refers primarily to the discrepancy between the number of accidents that actually occurred and the number of recorded events over the given period. Furthermore, given that a certain accident has been recorded the information on relevant consequence parameters may be not be available or sufficiently detailed.

In the "Handbuch Störfälle" [UBA, 1983] the completeness issue is addressed as follows:

"The question whether the Handbook gives a complete account of events in the considered time span can only be qualitatively treated because an objective criterion for comparison is not available."

With respect to the information recorded there is in relative terms much more material available on the types of damage considered to be most serious and having rather straightforward numerical indicators. Thus, the completeness of data concerning fatalities is superior in comparison to the records on injured or economic costs. Furthermore, the number of fatalities resulting from an accident is directly available in its aftermath while, for example, the assessment of environmental consequences caused by a major oil spill is a complex task associated with large uncertainties.

Recording accuracy relates to the difference between the entries originating from the different sources.

There is often a wide mini-max range in the number of fatalities or injured reported. For example in the case of the hydro power accident at Vaiont dam in Italy, which occurred in October 1963, the number of fatalities reported in different sources is between 1189 and 2600. In the Fatal Hazardous Materials Accidents Database [RfF, 1993] the ratio (Maximum/Minimum) varies from 1 to 27 over 1068 entries that contain fatality figures and from 1 to 400 over 635 entries that incorporate injury figures.

The reporting discrepancies and completeness problems are illustrated by Table 8.1.1 showing the number of fatalities and injured for the large LPG accident in Mexico City in 1984, based on the records in the Failure and Accidents Technical Information System (FACTS [TNO, 1998]), Major Hazard Incidence Data Service (MHIDAS [SilverPlatter Directory, 1998]), the OFDA Disaster History Database [Mitchel Group, 1996], the Fatal Hazardous Materials Accidents Database [RfF, 1993] and the SIGMA publication of the Swiss Reinsurance Company [Swiss Re, 1986]. Since some databases only provide one consequence number for each damage category (i.e. do not distinguish between "minimum" and "maximum"), in such cases the same number is used for both "minimum" and "maximum".

TABLE 8.1.1

Reporting discrepancies concerning the LPG accident in Mexico City in 1984.

Database	Maximum Number of Fatalities	Minimum Number of Fatalities	Maximum Number of Injured	Minimum Number of Injured	Number of Evacuees
FACTS	498	498	7000	7000	NA
MHIDAS	500	500	2500	2500	200,000
OFDA	452	452	4248	4248	NA[a]
RfF	503	452	7231	4248	320,000
SIGMA	452	452	2000	2000	250,000

[a] NA = not available

Clearly, there will always be a discrepancy between the number of accidents that actually occur and those that are recorded.

As a rule of thumb:

- Accidents with minor consequences are not recorded (with the exception of the nuclear industry).
- Accidents that have news value may be recorded as fillers in newspapers and magazines.
- Accidents that involve extremely severe damage are normally publicised, analysed and documented.

The reasons for the incompleteness and recording accuracy problems may be external or internal to the organisation developing a database.

External causes include:

1. Policy decisions in the country of origin.

   The accessibility of information from different areas of the world has varied greatly over the decades. For example, the information on severe coal mining accidents arising in the Peoples Republic of China is currently improving, whereas practically no information on accidents in this country has been available on events occurring ten years ago or earlier. In the past the communist countries tended not to report anything that was not already known.

   Reports originating from poor countries being recipients of international aid may occasionally overreport the consequences of the accidents. On the other hand, developed countries do not usually report accidents to the relief agencies, such as the ones supported by the UN.

2. Policy decisions on behalf of the country receiving the information

   Information from consular sources on accidents occurring in third countries is made available to the public through government departments only in ad hoc circumstances. The OFDA database [Mitchel Group, 1996], which represents a cornerstone for a number of other databases, defines an emergency to be any event that the US government semi-arbitrarily declares to be one and decides to respond to with financial aid. It is likely that a severe accident in a country currently being favoured finds its way into the database whereas another accident resulting in comparable damages but occurring in a country that due to various reasons does not qualify for the assistance, does not.

3. Commercial and military confidentiality.

   Accident and incident information from a number of potential sources such as the police, fire departments, safety authorities, government agencies, and industry may be confidential in nature. In a number of instances, fragments of information are only made available to third parties if anonymity can be guaranteed. It needs to be said, however, that as a rule applicable to most countries, accidents need to be reported to the safety authorities as a matter of requirements placed on the companies by law.

   Information on accidents in or affecting the military sector is rarely disclosed in details. Such accidents, unless extremely severe, may go unrecorded in the international journals and in databases.

4. News value.

   “Professional” reporting organisations, particularly local ones, tend to contemplate the market value of the “news” and treat information as a product. The selection of events that are reported and the space given to them does not necessarily harmonise with the severity of accidents but rather reflect the expected preferences (or biases) of the readers. Moreover, nation-wide newspapers may ignore foreign catastrophes in favour of news of local interest.

Organisation internal causes of incompleteness and recording accuracy problems include:

1. Human factors.

   Constructing and actualising a database of this nature involves a considerable personal commitment and alertness over an extended period of time.

2. Organisational factors.

   The staff involved in the work needs a considerable degree of motivation (the conviction that their work is important), as well as the necessary resources (financial and organisational) over the long term.

3. Language barriers

   In the process of examining a variety of databanks we have established the insight that events occurring in say Japan, Korea, Pakistan and even Germany, France and Italy are consistently underreported in databases originating in the UK and the USA, basically as a result of the local availability of information which in turn is subject to constraints due to language and other cultural barriers. On the other hand the databases originating in the UK and the USA give good coverage of the events in both countries.

8.1.2 Quality of databases

As previously outlined information on accidents derives from a variety of sources ranging from police, fire brigades, industrial companies, insurance and governmental organisations and public inquiries to press cuttings and eye witness accounts.

The available information can, in general, be divided into three broad types:

- textual (narrative accounts)
- numeric (dates, times, quantities, etc.)
- illustrative (pictures, diagrams, films, videos, etc.)

This material is not unexpectedly of variable quality and depends on the reporting resources available at source. In the case of public enquiries, the information is likely to be detailed and verbose; in press cuttings the data may be incomplete, sometimes biased, unreliable or inadequate and erroneous.

As a result, care must be taken to ensure that data is of acceptable standard. In the present work profit has been taken in this context from the use of redundant and diverse sources of information and the possibilities to cross-check the information.

8.1.3 Use of historical data

To the policy maker interested in evaluating options for the future, historical data on societal risk levels are of interest but may not be fully relevant. Furthermore, the use of historical data to estimate current risk is not an all too complete measure of the risks posed by the different hazards. Events which could, but have not yet occurred are inevitably excluded. In addition, the presentation of aggregated world-wide data does not give information on the variability between countries, regions and sites. Homogeneity in both time and geographic space is implicitly assumed. For some technologies the lack of homogeneity is so pronounced that the validity of aggregated, generic estimates is very limited.

These difficulties in comparative exercises are not the only limitation of historical data. The compilation of the information itself involves sources of potential errors and major uncertainties.

<u>Severe accident definition and event allocation</u>

By way of an example; frequency-consequence (F-N) curves are sensitive to categorisation decisions made at the data collection source. This is particularly problematic in two specific cases:

- Where interactions between hazards occur, double-counting can take place since the same fatalities are recorded under more than one category.

- The definitions of the severity of the consequence vary between the sources.

Care has been taken in the present work to eliminate the circumstances with double-counting and to consequently apply the definition of a severe accident as established in this project. Since the definition is rather inclusive some of the sources used did not include certain types of consequences to be covered, and/or the accidents close to the severity threshold chosen were in some cases outside of the scope of these sources.

As a part of the implementation procedure applied in this work (Section 3.3), energy-related accidents were identified and allocated to specific energy sources and appropriate stages in the associated chains. This process unavoidably involves the use of engineering judgement. As elaborated in Section 6.1 some simplifying assumptions were also introduced in the allocation process.

Temporal changes

When using historical figures as a representation of future risk the assumption is made that no systematic variation with time occurs. This is, however, unlikely to be the case.

In F-N curves the frequency of occurrence presented is averaged over the time period concerned. Systematic changes in the frequency, that occur over time within the time period covered by the curve are not evident from its shape. Such changes can be attributed to several causes. These include:

1. Technological changes leading over time to an improved safety record for an industry and reduction of the associated risk potential. It may therefore be important to consider whether a technology being examined is likely to be developing quickly over time when comparing its overall risk figure to those of other more established technologies.

2. Changes in safety regulations result in changes and improvements in industrial risk management.

3. Improvements in the efficiency of emergency services and an increased awareness of hazards result in casualty reductions.

4. Sociological, economic and habit changes result in changes in exposure to risk (changing consumer habits). For example, in some countries air travel has increased at a time when rail travel has decreased. Similarly population density patterns have changed over time and influence the risk measures.

5. The so called “kill size”, i.e. the maximum potential number of persons that can die in any one accident can change (this applies also to other damage categories). For example, larger aircraft and smaller passenger ships are now in use. It is important to note that the “kill size” can vary widely between hazards.

6. The degree of underreporting may change in time. The overall trend is that the completeness of the records has been improving with time due to the growing interest in risks as such and raising public demand to reduce them.

The temporal change issue has been addressed in the present project by investigating trends in accident rates over time The impacts of specific technological improvements have been explicitly considered in some cases. These comparative evaluations have concentrated on the period 1969-1996. While the latter constraint reduces somewhat the statistical material used, it also screens out cases which are highly unrepresentative for the currently used technologies and for the operational standards as applied today.

8.2 Limitations of Probabilistic Safety Assessment

PSA techniques were primarily developed within the nuclear industry. In a relatively short time (about 25 years) PSA has been transformed from a research topic into an established tool for safety work. Subject to suitable modifications and frequently under the name of

Quantitative Risk Assessment (QRA), PSA has also been adopted within the space, offshore and process industries. However, this has been subject to substantial country-to-country variation and to a much more narrow range of applications. This stems partially from the fundamental differences between the nuclear industry (where the highest risks are associated with essentially one process) and the other ones (where a multitude of interdependent processes may be at work within the same plant). Many facilities within the different energy chains exhibit similarities with the process industry. In a number of countries (particularly the Netherlands, UK and USA) the QRA applications within the process industry are extensive and steadily growing.

8.2.1 Intrinsic and practical PSA limitations

As a background to the limitations some clarifications are in place [Kröger and Hirschberg, 1993]:

- PSA does not replace deterministic analyses - it complements them.

- Uncertainties are implicitly represented in all analyses. PSA approach makes them visible.

- PSA has a capacity to identify potential vulnerabilities. Once engineering insights have been obtained, the numerical precision of the predicted frequencies is of lesser importance. The associated uncertainties usually do not undermine such results and the insights concerning the potential impact of design or procedures modifications may be fully valid (given relevant scope, use of appropriate modelling approaches and performance of an adequate review).

- In case of comparison of quantitative PSA results with Probabilistic Safety Criteria (PSC) one should keep in mind that this is only meaningful if there is a compatibility between the definition of criteria/goals on the one hand, and the scope, assumptions and the boundary conditions of the PSA on the other hand.

The limitations of PSA techniques contribute to the overall uncertainty of the results. Some of the limitations are **intrinsic** and difficult or impossible to overcome, while other are **matters of practice** and thus bound to be resolved as understanding of phenomena and level of knowledge improve, and as operating experience grows [Lewis, 1984]. In some cases (e.g. human interactions) there may exist potential for an improved treatment of an intrinsic limitation.

Typical intrinsic limitations include: incompleteness, database, human interactions, common cause failures, uncertainty.

Typical practical limitations include: consistency, conservatism, human interactions, system-related dependencies, external events, time dependencies, uncertainty, documentation.

An account of some of the current PSA limitations (as well as merits) and of the significant progress that has been made in handling some of them, can be found in [Hirschberg, 1992]. The most significant limitations are related to the treatment of human interactions, common cause failures, external events, phenomenological aspects of accident progression and to source term issues. For details we refer to the review paper and its numerous references on the specific modelling topics. It is a common misunderstanding that the existence of limitations such as the treatment of human interactions automatically leads to an underestimation of the frequency of accidents. While uncertainties are generally driven by such limitations the modelling of the associated contributors within the scope of the analysis tends to be conservative. At the same time certain types of interactions are normally outside of the scope of current PSAs. Thus, on the one hand, exclusion of operator errors of commission leads to an underestimation and, on the other, not taking credit for improvised operator actions such as recoveries that are not guided by available procedures represents a conservatism.

In the case of nuclear PSA (the only industry where some generalisation of PSA uses is feasible), the degree of state-of-the-art maturity is as follows [Hirschberg, 1994]:

Identification and quantification of accidence sequences leading to core damage
(PSA Level I): medium to high

Accident progression, containment response, fission product transport
(PSA Level II): low to medium (currently converging towards medium)

Consequence analysis
(PSA Level III): medium

The above reflects implicitly the degree of confidence in the results of the different levels of analysis. However, depending on what we mean by "results" (which in turn depends on the nature of the specific PSA application), the insights may still be quite robust, even in the case of relatively low level of maturity.

8.2.2 Low probability numbers and cut-off values

Low numbers produced by PSAs may be credible or not, depending on how they are arrived at. Low numbers can result due to multiplications of probabilities, each corresponding to a basic event, with the product representing a failure path. Some experts believe that it is not meaningful to perform the quantifications at extremely low probability levels (what exactly is the "extremely low level" is a matter of a dispute). The argument here is that below a certain probability level it is not practically possible to consider all hypothetical initiators; on the other hand, some evaluations at such levels can be excessively conservative. Therefore, below a certain low probability limit, both conservative and non-conservative errors are possible. It is generally true that as the numbers become lower the burden to demonstrate the validity of such numbers becomes greater (in view of the completeness of the analysis).

To overcome the problem above, cut-off values have been proposed and sometimes applied; typical level is 10^{-6} or 10^{-7} per year. The main rational behind this is the impossibility to demonstrate validity beyond the frequency at which accident analyses can be carried out. While this may be a valid argument for the assessment aiming at comparison with specific numerical criteria/goals (although the numerical level can be questioned in some applications), no generalised cut-offs are needed for engineering applications of PSA. In fact, their application could lead to loss of valid and potentially important insights.

8.2.3 Implications for the uses of PSA

One of the important capabilities of PSA lies in the possibility of representing design- and site-specific features which may have a decisive impact on the results of the studies evaluating the potential of severe accidents. The view of the industry and of a vast majority of regulators is that the most important insights provided by a PSA are the engineering ones. The use of the results in the "relative" sense (e.g. identification and ranking of the dominant accident sequences) is considered to be more robust and mature than the direct use of "absolute" results which are of interest in comparative evaluations. The latter is subject to larger uncertainties and places a greater burden on the completeness of the analysis. The fact that more confidence can be placed in "relative" insights by no means disqualifies the (cautious) "absolute" uses. If used properly, the "absolute" PSA results have an indisputable merit as one indicator among others in comparative studies of e.g. various energy systems.

8.3 Scope Limitations of the Present Work

The scope of work was defined in Section 2.2 and includes a detailed account of scope limitations. Here the most essential points are repeated in a concise form:

- In relative terms the efforts were primarily concentrated on the evaluation of past accidents. PSA was only applied to nuclear power plants. The same applies to the consideration of the contribution of severe accidents to external costs.

- The results are applicable to current technologies. Analysis of the impact of prospective advancements in safety was outside of the scope of the present work.

- The assessments concern fossil energy sources, nuclear and hydro power. Renewable energy sources other than hydro were not covered.

- Comparative analysis was focused on the electricity sector. However, some comparisons with other sectors were performed (see Chapter 9).

- Comparisons between the different energy sources, based on historical data, were mainly carried out using the statistical material for the period 1969-1996. The lower limit was chosen with view to the temporal changes discussed in Section 8.1. The upper limit reflects the availability of reliable input at the time the database was implemented. For specific energy sources the records also include accidents which occurred prior to

1969 (in some cases in the 19th century). The completeness of very old data is, however, problematic.

- Risk aversion was not a topic of research in the present study. Its role and issues in the treatment were, however, addressed in the context of nuclear power.

The above limitations will be reflected in the recommendations for future work, provided in Chapter 9.

8.4 References

Hirschberg, S. (1992), Prospects for Probabilistic Safety Assessment. Nuclear Safety, **33** (1992) 365-380.

Hirschberg, S. (1994), Role of Probabilistic Approach in the Context of Safety Evaluation. Paper presented at the Seminar "Warscheinlichkeit", 27 April 1994, Swiss Federal Institute of Technology Zurich (ETHZ).

Kröger, W. and Hirschberg, S. (1993), Safety Problems in Power Generation. Forum Engelberg, Energy and Environment: A Question of Survival. 16-19 March 1993, Engelberg, Switzerland.

Lewis, H. W. (1984), Probabilistic Risk Assessment: Merits and Limitations. Proceedings of 5th International Meeting on Thermal Nuclear Safety, 10-13 September 1984, Karlsruhe, Federal Republic of Germany.

Mitchell Group (1996), Disaster History, Significant Data on Major Disasters World-wide, 1900 - 1995, prepared for the Office of U.S. Foreign Disaster Assistance Agency for International Development, Washington, Mitchell Group, Inc., Washington, USA.

RfF (1993), Fatal Hazardous Materials Accidents Database. Resources for the Future, 1616 P Street, N.W., Washington D.C. 20036-1400, USA.

SRD (1993), The Major Hazards Incidence Data Service. AEA Technology, Consultancy Services (SRD), Cheshire, UK.

Swiss Re (1986), International Statistic of Natural Catastrophes and Major Losses 1970-1985. Sigma, Economic Studies, 11/86, Swiss Reinsurance Company, Zurich, Switzerland.

TNO (1998), FACTS Database for Industrial Safety. Institute of Environmental Sciences, Energy Research and Process Innovation (TNO), Department of Industrial Safety, Apeldoorn, The Netherlands.

SilverPlatter Directory (1998), A Directory of Electronic Information Products. SilverPlatter Information Ltd., Chiswick, London, UK.

UBA (1983), Handbuch Störfälle (in German). Forschungsbericht UBA-FB 83-023, Umweltbundesamt. Berlin: Erich Schmidt Verlag.

9. SUMMARY, CONCLUSIONS AND OUTLOOK

9.1 Summary of Research Results and Insights

This section provides first the summary of the achieved progress in compiling energy-related accident data. This is followed by an overview of insights gained from the analysis of specific energy sources. In the last part of this section the results of the comparative assessment are surveyed and the key issues are discussed.

9.1.1 PSI database and its merits

The present work established a comprehensive database on severe accidents, with main emphasis on the ones associated with the energy sector[1]. ENSAD (Energy-related Severe Accidents Database), which covers all stages of the analysed energy chains, has been established using a variety of sources. This includes among others: major commercial and non-commercial databases covering accidents, journals, newspapers, technical reports, encyclopaedias, conference proceedings and inputs from direct contacts with persons and organisations being in a position to provide relevant information on past accidents.

Numerous checks and complementary analyses beyond the main sources of information were carried out. In view of the resource consuming character of such investigations, they were concentrated on events which had very severe consequences and/or are subject to major uncertainties with respect to the real extent of consequences. Particular attention has been given in this context to the applicability and transferability of the data.

Currently, the ENSAD database covers 13,914 accidents, of which 4290 (30.8%) are energy-related; 10,064 (72.3%) accidents were classified as man-made and the remaining 3850 (27.7%) as natural. The percentage of energy-related accidents among the man-made ones amounts to 42.6%. This number is, however, not fully representative (i.e. the share of energy-related accidents is overestimated) since at present ENSAD does not cover transportation and traffic accidents unless they belong to a specific fuel chain or the accident resulted due to an interaction with a fuel chain.

As shown in Fig. 5.4.6, in the period 1975-1996 typically about 30 energy-related accidents with at least five fatalities occurred each year world-wide. Among them 1-5 accidents (per year) had consequences exceeding 100 fatalities. Nearly 93% of the energy-related accidents collected in ENSAD occurred in the time period 1945-1996. This dominance is mainly due to the larger volume of activities; however, improved reporting coverage probably also plays here an important role.

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1 The name of the database reflects the focus and priorities of this work. Although the non-energy accidents in terms of numbers constitute the major part of ENSAD, as opposed to the energy-related ones no efforts were made to increase the completeness and examine the quality of these data.

An inclusive definition of what constitutes a severe accident was established and consequently applied to coal, oil, gas, nuclear and hydro power energy chains. Thus, an accident is considered to be severe if it is characterised by one or several of the following consequences:

1. at least five fatalities;

2. at least ten injured;

3. at least 200 evacuees;

4. extensive ban on consumption of food;

5. releases of hydrocarbons exceeding 10,000 tonnes;

6. enforced clean-up of land and water over an area of at least 25 km^2;

7. economic loss of at least 5 million 1996 US$.

Various types of consequences are covered to different extent, depending on the availability and quality of the data. These factors differ between the various energy sources. Generally, the completeness and accuracy of the data concerning fatalities resulting from accidents is superior to the ones covering other types of consequences.

Figure 9.1.1 shows the content of ENSAD in terms of the number of accidents of the different types and within specific consequence categories.

Applying the definition of a severe accident, established in the present work, 1943 severe energy-related accidents are stored in ENSAD. Accidents with at least five fatalities form the largest group (846 events). There is also in descending order a large number of energy-related accidents involving major releases of hydrocarbons and chemicals, injuries, large economic losses and evacuations. This distribution is quite similar to the one generally valid for man-made events, while for the natural accidents no large pollutant releases are reported[2].

Below follow some facts with respect to the consequences (here limited to fatalities) of the accidents represented in ENSAD:

- 52.4% of all accidents with at least five fatalities are man-made;

- 17.9% of all accidents with at least five fatalities are energy-related;

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[2] Such releases may constitute a secondary effect of natural accidents. Their severity is, however, normally small in comparison with the overall consequences of natural disasters. For that reason, although the large releases are likely to have occurred in connection with the natural accidents, they tend to be ignored in the reports.

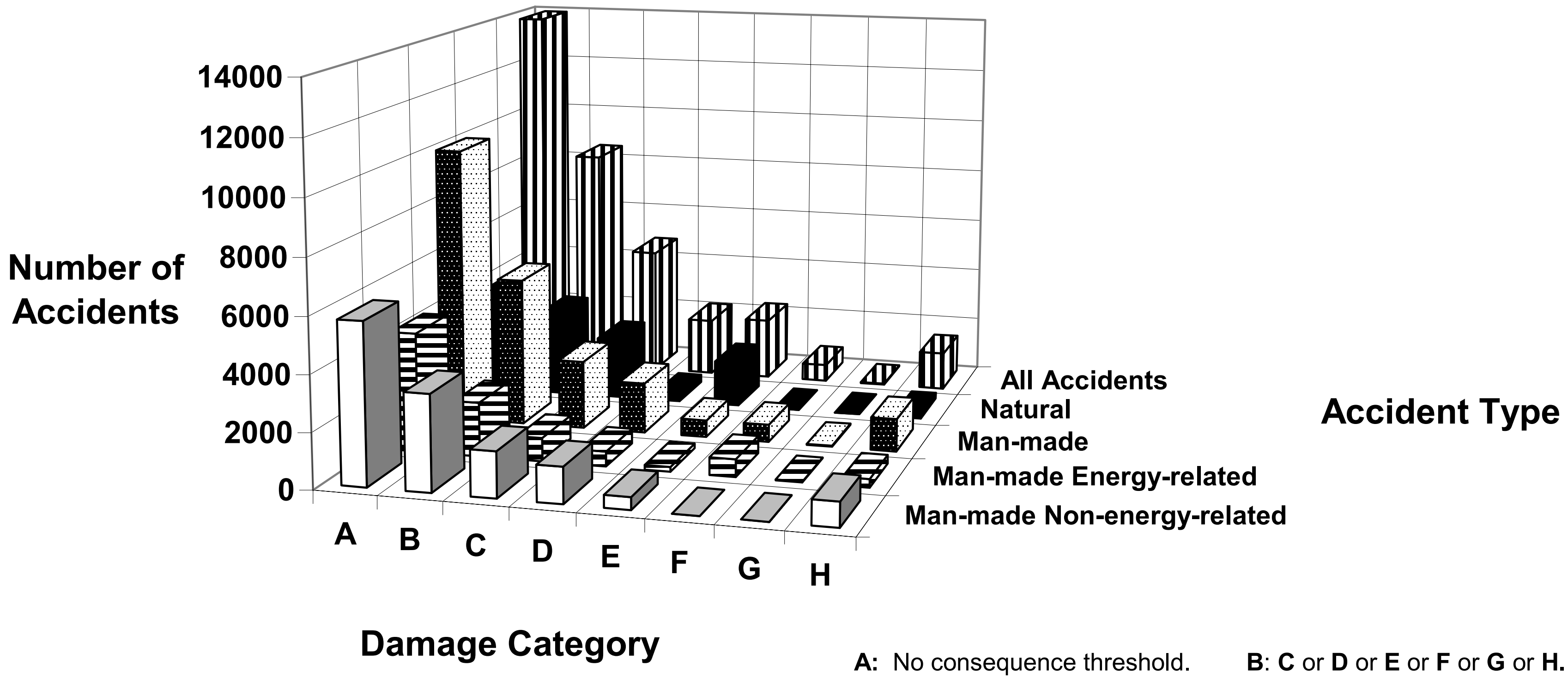
- 34.1% of man-made accidents with at least five fatalities are energy-related;
- 21.7% of all accidents with at least 100 fatalities are man-made;
- 5.1% of all accidents with at least 100 fatalities are energy-related;
- 18.3% of man-made accidents with at least 100 fatalities are energy-related.

These numbers show that the share of man-made accidents and energy-related ones in particular decreases when the very large accidents are considered. This is due to the fact that natural disasters frequently have extremely severe consequences and dominate among the accidents with very high consequences. Summing all fatalities due to accidents in the period 1969-1996 as covered by ENSAD amplifies this picture. Thus, the energy-related accidental fatalities constitute only 1.2% of all fatalities resulting from the accidents covered in this period. This does not include the potential delayed fatalities associated with the Chernobyl accident, which may be manifested over a 70 year period after the accident. Inclusion of the estimate of the predicted latent fatalities and allocation of these consequences to the above period of time would increase the relative contribution of the accidental energy-related fatalities to between 1.5 and 2.3% (depending on whether a radiation dose cut-off is used or not), i.e. still a relatively small share. Implementation of all transport and traffic accidents would further reduce this number.

Nearly two thirds of all recorded energy-related severe accidents with at least 5 fatalities occurred in OECD countries. Similar to the registered increase (in relation to the past) of the number of energy-related accidents during the last 20 years this is primarily caused by the higher level of activities but some impact of underreporting from the developing countries cannot be excluded.

Due to the use of a variety of information sources, including databases established in various countries, ENSAD has a balanced coverage with respect to countries and regions where the accidents took place (Section 5.4). This eliminates a problem encountered in many other accident databases driven by the local availability of information which in turn is subject to constraints due to language and other cultural barriers.

Access to and implementation of the very diversified input resulted also in a much more extensive coverage of man-made accidents in ENSAD in comparison with other databases (Section 5.5). In particular, while there are 846 of energy-related accidents with at least five fatalities in ENSAD, MHIDAS [SilverPlatter Directory, 1998] contains 316 such events and SIGMA [Swiss Re, 1970-1996] 221 accidents with consequences at or exceeding this level. In Fig. 5.5.2 it has been shown that also when exceedance of higher damage levels is considered ENSAD provides a superior coverage of energy-related accidents.



A: No consequence threshold. **B**: **C** or **D** or **E** or **F** or **G** or **H.**
C: at least 5 fatalities. **D:** at least 10 injured. **E**: at least 200 evacuees.
F: more than 10,000 t of hydrocarbons released.
G: at least 25 km^2 area of enforced clean up of land+water.
H: at least 5 Million 1996 US$ of economic loss.

Fig. 9.1.1 Content of ENSAD-number of accidents by type and damage category.

9.1.2 Evaluation of severe accidents for specific energy sources

In this section concise summaries of the insights gained are provided for each of the energy carriers covered in the present report. For details we refer to Chapter 6. In relative terms more resources were allocated to the analysis of energy chains that currently dominate the Swiss electricity supply, i.e. hydro and nuclear power. Significant effort has been directed towards the examination of the relevance of the world-wide records on accidents associated with these two means of electricity generation to the Swiss-specific conditions. Due to the risk profile (in terms of the most risk prone stages of the fuel cycles) in the case of fossil chains, the generic accident statistics are considered to be more relevant.

9.1.2.1 Coal chain

Accidents in the coal chain are currently concentrated to the mining stage. In the past coal-burning devices and coal-fired power plants caused smog catastrophes in big cities under adverse weather conditions. These events, which in one case (London, 1952) led to thousands of fatalities, can be seen as severe accidents in terms of the consequences. However, last time such episodes occurred in the Western World was more than thirty years ago.

The mining accidents are local, constitute essentially an occupational risk and normally do not affect the public. In this respect they are different in their nature from the dominant modes of accidents associated with most other energy chains. The impacts of mining accidents are immediate.

There has been a decreasing trend with respect to the number of severe mining accidents in OECD countries while the opposite applies to the non-OECD countries. In both cases the overall coal production increased in the period following the Second World War. Notably, the number of mining fatalities per year has clearly decreased in OECD countries. This is due to changes in legislation and safety improvements based on increased knowledge concerning gas and coal dust explosions, fires and inundations. Since 1966 the number of fatalities per year due to severe accidents in the coal energy chain world-wide did not exceed 600. For comparison, the largest coal mining accident ever, happened in Manchuria in 1931 and resulted in 3000 fatalities.

Records on injured in coal mining accidents are very scarce. It is likely that most large accidents occur under conditions of low survival rate among the victims. No evacuations have been reported in connection with coal accidents. The economic consequences of coal accidents are also seldom available, except for some accidents at power plants which exhibit moderate monetary losses (not in any of the cases exceeding 100 million US$ at the time the accidents happened).

9.1.2.2 Oil chain

Severe accidents involving fatalities occur in the oil chain predominantly in the “Regional Distribution”, “Transport to Refinery” and “Extraction” stages. In the period 1969-1996 the first two of these stages exhibit 87.0% of all fatalities in the oil chain. Major oil spills are associated with the “Exploration/Extraction” and “Transport to Refinery” stages.

As with coal mining the fatal accidents in the “Exploration/Extraction” stage are occupational, local and their effect is immediate. The health consequences of accidents in “Transport to Refinery” and “Regional Distribution” stages are local and occur immediately. The victims of accidents in the “Regional Distribution” stage include to a high extent the public. In the “Transport to Refinery” stage a vast majority of accidents have occupational risk character but due to few very large accidents with high number of fatalities among the public the picture is mixed. Oil spills result in environmental damages (as opposed to personal), have local and regional impacts and the damage process is distributed in time.

Since late sixties there has been a growing trend in the number of accidents and recorded fatalities in the oil chain. At the same time the consumption of oil clearly increased world-wide. For the preceding period of time there are very few records of oil accidents, which implies serious reporting coverage problems.

With the exception for two peak years the number of fatalities per year, resulting from severe accidents in the oil energy chain world-wide, did not exceed 1000. The peaks occurred due to the two largest oil accidents which resulted in 2700 and 3000 fatalities, respectively (Afghanistan, 1982; Philippines, 1987). The allocation of the Afghan accident can be discussed since it occurred during a war and its victims were Soviet soldiers (along with Afghan civilians). At the same time the accident did not result from acts of war.

During the period 1969-1996 there have been 80 offshore and 15 onshore oil spills exceeding 25,000 tonnes mainly due to tanker accidents and incidents in offshore production. In terms of the total quantities of oil discharged into the marine environment these offshore accidents contribute only about 2.8% of the total spills. These are dominated by river run-off (26.1%; particularly significant in areas with industries along the banks) and tanker operational discharges (22.5%). However, the amount of oil spilled into the sea is not necessarily the primary driving factor for the resulting ecological impacts. Due to the fact that in the most serious accidental spills from tankers large amounts of oil have usually been released in a short time in areas with sensitive fauna and flora, the damages may be disastrous. At the same time the impacts of offshore oil spills characterised by comparable quantities released may differ significantly. This depends on the local weather and current conditions as well as on the distance of the accident site to the coast. The largest recorded spill was estimated at 375,000 tonnes of crude oil and occurred at the coast of Mexico (Ixtoc 1, 1979) not from a tanker but from an oil platform. Notably, in the renown Exxon Valdez spill in Alaska in 1989 “only” 32,500 tonnes of oil were released but the ecological impacts were disastrous.

The records on injuries are not as extensive as on fatalities but exist for a rather large number of oil accidents with the highest number of injured being 3000 in connection to a well blow-out (“FUNIWA-5”, Atlantic, 1980; 180 fatalities). The most extensive evacuation associated with the oil chain affected 100,000 persons (Chihuahua, Mexico, 1988).

The highest costs of oil accidents appear in the “Transport to Refinery” and “Exploration/Extraction” stages. Thus, the costs of the Exxon Valdez spill (1989) were 1360-2260 million 1996 US$ and of the Piper Alpha rig explosion and fire (UK, 1988) 1480-1800 million 1996 US$. None of the accident costs in the Heating/Power Plant” stage exceeds 100 million US$. It should be noted that there is a discrepancy between real costs, claimed costs and awarded compensation. The above quoted costs are a mixture of these three classes.

9.1.2.3 Gas chain

A distinction needs to be made between the natural gas chain and the Liquefied Petroleum Gas (LPG) chain since the accident patterns as well as the uses are different for these two.

In the natural gas chain severe accidents resulting in fatalities occur predominantly in the “Long Distance Transport” (36.4%), “Local Distribution” (26.4%) and “Regional Distribution” (15.5%) stages while for the LPG chain the major contributors are “Regional Distribution” (64.7%) and “Long Distance Transport” (10.9%).

Public is highly exposed to the consequences from gas accidents. The damages occur immediately and are local.

Very few severe natural gas and LPG accidents have been recorded before 1970. After this year the number of severe LPG accidents ranges between one and seven per year and of natural gas severe accidents between one and eleven per year. The overall trend shows an increase until 1982 and then a decrease for natural gas and an increase since 1970 for LPG. At the same time the consumption of both natural gas and LPG has been growing (in both cases almost doubled).

There is a strong scatter from year to year between the world-wide number of fatalities associated with severe gas accidents. In the case of natural gas it does not exceed 250 in any year, with the worst accident (Tbilisi, Georgia, 1984) exhibiting 100 fatalities. The number of fatalities in the natural gas chain has been typically relatively small - since 1969 there have been 17 accidents with more than 20 fatalities. In the case of LPG the number of fatalities due to severe accidents varies in the same period between 0 and 606 per year. The worst accident (Asha-Ufa, Russia, 1989) resulted in 600 fatalities.

The completeness of the records on injuries appears to be rather satisfactory both for natural gas and LPG. In the natural gas accident in La Venta (Mexico, 1982) with 33 fatalities 500 persons were injured and 40,000 evacuated. For LPG between 4248 and 7231 persons were injured according to one source [RfF, 1993] in the Mexico City accident (1984), which also resulted according to the same source in 452 to 503 fatalities. The largest number of evacuees (220,000) in the LPG chain was recorded in the accident in Mississauga (Canada, 1979) which had no fatalities or injured persons; the second largest (200,000) in the above mentioned accident in Mexico.

Estimates of economic consequences of severe gas accidents are available for only few of them. The largest accidents in terms of damage expressed in 1996 US$ occurred in

Trondheim (Norway, 1985; 622 million US$) in the natural gas chain and in Umm Said (Quatar, 1977; 245 million US$) in the LPG chain.

9.1.2.4 Nuclear chain

Severe accident risks associated with the nuclear chain are dominated by nuclear power plants. Other stages in the nuclear chain, including mining, enrichment, fuel fabrication, transport of spent fuel, reprocessing and waste management exhibit significantly lower risk level, although few studies addressed this issue. Within "Externe Project" [ExternE, 1996a-1996f] the risks associated with the transport stage were addressed with considerable detail and found to be low. Nevertheless, a more systematic study of all stages, based whenever feasible on Probabilistic Safety Assessment (PSA) techniques, would be meaningful.

The nuclear chain differs from the other since only two major accidents occurred in the past at commercial nuclear power plants (Three Mile Island, USA, 1979; Chernobyl, Ukraine, 1986). In the first of these accidents the plant itself was damaged and 144,000 persons were evacuated for a short time but otherwise due to the appropriate containment function there were practically no health or environmental impacts. The Chernobyl accident, on the other hand, led to catastrophic health and environmental consequences whose analysis has been a subject of extensive research efforts.

Severe nuclear accidents may result in both local and regional damages. Acute health effects can occur within a distance of few kilometres from the plant. Delayed cancers, however, may appear within a large distance of several hundred kilometres from the place of an accident and with a delay up to several decades. Children are more sensitive to certain forms of cancer risks due to radiation than the adults. Evacuation may be necessary within an area of few thousands square kilometres around the plant. Long-term ground contamination may lead to condemnation of an area of comparable size for many years after the accident had taken place. Restrictions for agriculture, hunting and fishing may be necessary within the most affected areas.

The above concerns extreme nuclear accidents which for western nuclear power plants with high safety standards can be regarded as highly hypothetical. On the other hand, the description applies to the Chernobyl accident. The evaluation of the consequences of the Chernobyl accident is subject to large uncertainties and new insights are continuously emerging as discussed in detail in Appendix D. A short summary of the consequences of the Chernobyl accident according to the current state of knowledge, primarily based on [EC/IAEA/WHO, 1996], is given below.

237 persons among the plant crew and emergency workers were hospitalised. Among them Acute Radiation Sickness (ARS) was diagnosed in 134 cases. 31 persons died in the acute phase, thereof 28 due to ARS. 14 additional persons from this group died over 10 years after the accident; their deaths do not correlate with the original severity of ARS and may therefore not be directly attributable to the radiation exposure.

200,000 “liquidators” worked in the region of Chernobyl during the period 1986-1987, when the radiation exposures were most significant. In total some 600,000 to 800,000 persons took part in the cleanup activities. The predicted number of potential fatal cancers due to radiation exposure in the group of 200,000 is 2200 including 200 cases of leukaemia. In the larger group of liquidators who received smaller doses, about 300-500 potential excessive fatal cancer cases may be predicted on the basis of the collective dose and no dose cut-off. Thus, the total expected number of fatal cancers among the liquidators amounts up to about 2700.

The sum of the estimated number of potential cancers among the 135,000 persons evacuated from the “exclusion zone” of 4300 km^2, among the 270,000 living in the “strict control zone” and among the population of 6,800,000 in other “contaminated” areas in Belarus, Ukraine and Russia amounts to about 6700 cases, including nearly 500 leukaemias. In addition, a dramatic increase of thyroid cancers among children is expected and has already been manifested. Until the end of 1995 close to 1000 cases have been observed and 10 children died. The total number of expected thyroid cancers amounts to 4000-8000, thereof 200-800 may show to be fatal.

Individual doses outside the former Soviet Union have been small (less than 1% of the corresponding lifetime dose for the highest regional average committed individual dose over 70 years). In this situation an aggregation problem arises - the risk to individuals is very small but a huge number of individuals in space and time is affected. When the resulting large collective dose (obtained by summing millions of very small doses) is combined with a linear dose response function with no threshold for the individual exposure, the thus estimated health effects may become dominant. Using the total collective dose due to the Chernobyl accident estimated by [UNSCEAR, 1993], reducing it by the above estimated number of latent fatalities among the most exposed public in the former Soviet Union, and using no threshold for the radiation exposure, we arrive at an estimate of about 23,000 potential additional fatal cancers among the population of the entire northern hemisphere. These cancers will not be detectable since 650 million naturally occurring cancers are expected in the same population over the next 60 years.

Apart from evacuation directly following the accident, between 1990 and the end of 1995 there was further resettling of totally 210,000 people in Ukraine, Belarus and Russia.

There are significant non-radiation-related health disorders and symptoms, such as anxiety, depression and various psychosomatic disorders attributable to mental stress among the population in the region.

The estimated costs of the Chernobyl accident cited in [Nucleonics Week, 1994] range between 20 to 320 billion US$ (the range depends on the assumed exchange rate for roubles). It is not clear which cost elements are covered by these estimates.

The limitations in applicability of past accident data to cases that are radically different in terms of technology and operational environment are evident in the case of the nuclear cycle. Given the scarceness and non-transferability of such data, representative results for the western plants with state-of-the-art safety standards can only be obtained through PSA applications.

In the present work available PSA studies were utilised as sources of information on the plant-specific health risks of one Swiss nuclear power plant (Mühleberg) and two representative US plants (Peach Bottom and Zion). As expected, there is a difference of several orders of magnitude between Chernobyl-based estimates of the frequency of delayed fatalities and probabilistic plant-specific estimates for Mühleberg and US plants. Several other estimated risk measures are provided in [Hirschberg and Cazzoli, 1994]. This includes the condemned land area (long-term highly contaminated area).

The consequence analysis for Mühleberg was extended by calculation of economic consequences [Hirschberg and Cazzoli, 1994]. Three types of costs were modelled - costs resulting from radiation-induced health effects, from early protective (emergency response) actions and from long-term protective actions. The results obtained reflect what appears to be the first published attempt to assess external costs for a specific plant, based on state-of-the-art full scope PSA for this plant. Results provided for Peach Bottom and Zion were obtained through elaboration of information from recent studies [USNRC, 1990].

Recent studies of external costs associated with severe reactor accidents, carried out in Switzerland and elsewhere, were examined and compared with own approach. Although the values originating from the different studies cover a range of some six orders of magnitude, all recent analyses (which as opposed to several older ones do not use Chernobyl as the reference for the consequence assessment) show results below 0.1 US cents per kWh, unless risk aversion is included. Different approaches to risk aversion were briefly discussed, illustrating the problems encountered in its quantification. The factors and features which have the primary influence on the results are: approaches used for the estimation of accident frequency and of magnitude of consequences, scope of analysis and nature of risk integration (in particular risk aversion).

Eleven published studies on external costs of reactor accidents were categorised into one of the three types of analysis used in the context of the overall external cost assessment ("top-down", limited "bottom-up" and full scope "bottom-up"). The full scope "bottom-up" approach, utilising modern and comprehensive PSA represents the current state-of-the-art. However, among the published studies only two, including [Hirschberg and Cazzoli, 1994], fully implemented this approach.

9.1.2.5 Hydro chain

Similarly to the nuclear chain the accidents in the hydro chain are concentrated to the plant (dam[3]) producing power. Within the present work accidents at dams having a variety of purposes were examined. Thus, the data includes dams which serve for one or several of

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[3] Run-of-river plants are here considered whenever failures of the associated dams are involved. Other failure modes of run-of-river plants are not likely to result in severe accidents.

such purposes as: power generation, sweet water supply, irrigation, flood control and recreation. This allowed a significant extension of the available statistical material. An investigation of the variation of the dam failure frequency with dam purpose has shown that flood control and hydro power dams are the best performers while sweet water supply dams are the worst (in relative terms). The difference is at most a factor of three. This variation, although quite significant, does not affect the robustness of the overall conclusions.

Dam accidents occurred in the past during construction and operation. During the construction phase extreme conditions such as mudslides, avalanches, falling rocks may arise. Such accidents happened also in Switzerland. However, world-wide severe accidents during the operation phase have been more frequent and have had in many cases much more serious consequences.

Accidents during construction are local and may affect both the workers and the population. The operational accidents are primarily local but can also result in regional consequences; the victims are to be found in the first place among the public. In both cases the impacts occur shortly after the accident. Apart from fatalities and injuries extensive ecological damage can result.

The largest dam accidents were Vajont (Italy, 1963) with 1917 fatalities and Machhu II (India, 1979) with 2500. Both dams were used for power generation although Machhu II also served for other purposes. The records concerning injured and evacuees are generally extremely poor for dam accidents. Estimates of economic damages are available for a relatively large number of accidents. The most economically devastating accident occurred at the Teton dam (USA, 1976) with an estimated cost in the range 986-2219 million US$ (1996 value).

When evaluating hydro accidents a number of essential dam characteristics were considered. Critical dam failure rates were estimated for two time periods. For the period 1850-1996 all known dam accidents were included while for the period 1930-1996 the accidents involving dams taken into operation before 1930 were excluded; the background for choosing this time boundaries is that after 1930 the structurally stronger concrete replaced the previously used masonry as the dominant construction material. Many other safety-related improvements have been continuously introduced. A separate evaluation was made excluding accidents that occurred within five years after the first filling of the reservoir. The results show significant differences between the various types of dams, lower failure rates for dams built from 1930 and on, and lower susceptibility to accidents after five years of operation. Other evaluations have shown differences between frequency-consequence (F-N) curves for dams in Asia and Africa on the one hand and dams in the western world on the other. The latter show lower risks; this difference is still clearly underestimated in view of the lack of information on the consequences of many recorded accidents in Asia and Africa and expected gaps in reporting of accidents in these continents. These differences are further pronounced when the evaluation is limited in time to the last 25 years. The estimated rates of dam failures with a complete loss of the stored water are for western dams in the range 10^{-5}-10^{-4} events per dam-year, depending on the type of dam.

The Swiss dams were examined with respect to a number of characteristics that are important in the context of evaluating the potential severe accidents. Examples include: type of dam (gravity and earth dams constitute a majority in Switzerland at the same time exhibiting the lowest failure rates), height, capacity, and quality of supervision. In most cases the prevailing characteristics of the Swiss dams are favourable from the risk point of view.

9.1.2.6 Most severe accidents with respect to various damage categories

Appendices to this report provide information on the full set of severe energy-related accidents identified in the course of this work. Tables 9.1.1 through 9.1.4 provide the lists of ten worst accidents in the period 1969-1996 within damage categories “immediate fatalities”, “injured”, “evacuees” and “costs”. While one specific indicator (shown in bold face) is in focus of each table, also other parameters characterising the consequences are provided. “Latent fatal and non-fatal cancers”, particularly relevant for the Chernobyl accident, constitute a separate category not shown in the tables. The cited costs are in many cases very uncertain and due to the differences in definitions subject to major inconsistencies. For all indicators, whenever a range of values is available for a specific damage category only the highest number is provided in the table.

TABLE 9.1.1

Ten energy-related severe accidents with the highest number of immediate fatalities in the period 1969-1996.

Energy carrier	**Date**	**Country**	**Energy chain stage**	**Fatalities**	**Injured**	**Evacuees**	**Costs (10^6 US$1996)**
Oil	20.12.87	Philippines	Transport to Refinery	**3000**	26	0	-
Oil	01.11.82	Afghanistan	Regional Distribution	**2700**	400	0	-
Hydro	11.08.79	India	Power Plant	**2500**	-	150,000	1024
Hydro	27.08.93	China	Power Plant	**1250**	336	-	27
Hydro	18.09.80	India	Power Plant	**1000**	-	-	-
LPG	04.06.89	Russia	Long Distance Transport	**600**	755	0	-
Oil	02.11.94	Egypt	Regional Distribution	**580**	-	0	140
Oil	25.02.84	Brazil	Regional Distribution	**508**	150	2500	-
Oil	29.06.95	South Korea	Regional Distribution	**500**	952	0	-
LPG	19.11.84	Mexico	Regional Distribution	**498**	7231	200,000	2.9

TABLE 9.1.2

Ten energy-related severe accidents with the highest number of injured in the period 1969-1996.

Energy carrier	Date	Country	Energy chain stage	Fatalities	Injured	Evacuees	Costs (10^6 US$1996)
LPG	19.11.84	Mexico	Regional Distribution	498	**7231**	200,000	2.9
Oil	17.01.80	Nigeria	Extraction	180	**3000**	0	-
Oil	22.04.92	Mexico	Regional Distribution	200	**1400**	5000	318
Oil	04.10.88	Russia	Regional Distribution	5	**1020**	0	-
Oil	19.12.82	Venezuela	Power Plant	160	**1000**	40,000	61.5
LPG	25.01.69	USA	Regional Distribution	2	**976**	100	12.9
Oil	29.06.95	South Korea	Regional Distribution	500	**952**	0	-
Hydro	05.06.76	USA	Power Plant	14	**800**	35,000	2219
LPG	01.07.72	Mexico	Regional Distribution	8	**800**	300	3.6
LPG	04.06.89	Russia	Long Distance Transport	600	**755**	0	-

TABLE 9.1.3

Ten energy-related severe accidents with the highest number of evacuees in the period 1969-1996.

Energy carrier	Date	Country	Energy chain stage	Fatalities	Injured	Evacuees	Costs (10^6 US$1996)
LPG	11.11.79	Canada	Regional Distribution	0	0	**220,000**	20.5
LPG	19.11.84	Mexico	Regional Distribution	498	7231	**200,000**	2.9
Hydro	11.08.79	India	Power Plant	2500	-	**150,000**	1024
Nuclear	28.03.79	USA	Power Plant	0	0	**144,000**	54,27.2
Nuclear	26.04.86	Ukraine	Power Plant	31	370	**135,000**	339,200
Oil	25.05.88	Mexico	Regional Distribution	0	70	**100,000**	-
Oil	19.12.82	Venezuela	Power Plant	160	1000	**40,000**	61.5
Natural Gas	20.01.82	Mexico	Long Distance Transport	33	500	**40,000**	84.9
Hydro	05.06.76	USA	Power Plant	14	800	**35,000**	2219
Oil	10.10.83	Nicaragua	Regional Distribution	0	17	**25,000**	37.4

TABLE 9.1.4

Ten energy-related severe accidents with the highest monetary damages in the period 1969-1996.

Energy carrier	Date	Country	Energy chain stage	Fatalities	Injured	Evacuees	Costs (10^6 US$1996)
Nuclear	26.04.86	Ukraine	Power Production	31	370	135,000	**339,200**
Nuclear	28.03.79	USA	Power Production	0	0	144,000	**5427.2**
Oil	24.03.89	USA	Transport to Refinery	0	0	0	**2260**
Hydro	05.06.76	USA	Power Production	14	800	35,000	**2219**
Oil	28.01.69	USA	Extraction	0	0	0	**1947**
Oil	07.07.88	UK	Extraction	167	0	0	**1800**
Hydro	11.08.79	India	Power Production	2500	-	150,000	**1024**
Oil	30.05.87	Nigeria	Refinery	5	-	0	**916.4**
Oil	20.12.90	Bahamas	N.A.	0	0	0	**742**
Natural Gas	06.10.85	Norway	Exploration	0	0	0	**622**

9.1.3 Comparative assessment

Apart from summarising and discussing the content of Chapter 7 this section provides a detailed analysis of the numerical differences between the results for OECD- and non-OECD countries[4], a comparison with the risks associated with other large scale activities and an outline of a number of issues in the current state of comparative assessment. In order to avoid repetitions only a selection of aggregated results is provided here. The comparisons reflect the scope of the present study and address exclusively the technical estimates of risks associated with energy systems. Consequently, the social aspects which are important for the acceptance of specific technologies are not explicitly a part of comparisons supplied in this report and summarised here.

9.1.3.1 Energy chain comparisons

Comparisons between the different energy sources, based on the statistical evidence, were carried out for the period 1969-1996. The choice of the lower limit was guided by two

4 Few countries currently being members of OECD were for the purpose of this report not included among OECD countries. The most essential comparative evaluations included in this report are based on the statistical material covering a period of nearly 30 years and stretching until the end of 1996. For this reason countries which acceded OECD between 1994 and 1996, i.e. Mexico, Czech Republic, Hungary, Poland and Republic of Korea are here not included among the OECD countries.

factors which imply that going too far back in time may lead to results which lack relevance for the present situation. These are as follows:

1. Temporal changes such as technological advancements, more extensive safety regulations, general improvements in industrial risk management, increased hazard awareness, etc.

2. Improved reporting completeness and quality. There are clear indications that the situation has been improving along with the growing societal interest in industrial risks.

One additional reason supporting the choice of year 1969 as the lower limit of the evaluation time period is that the most relevant previous work comparing the risks associated with electricity generation [Chadwick et al., 1991][5], used the period 1969-1986.

The upper limit of the evaluation period (year 1996) has been chosen here with view to a substantial time lag in reporting, database implementation and possible analysis of the accidents in the numerous sources that were used as the input to the present work.

In the context of the establishment of the lower boundary for the consequences of the accidents a decision was made at an early stage to choose the cut-off at a relatively low level (as evident from the definition of a severe accident applied in this study). For example, when comparing fatality rates all known accidents with five or more fatalities are included. The authors are aware that the completeness of the records becomes more questionable the lower the consequence level. Thus, it is acknowledged that particularly the results provided for fossil energy chains are probably significantly underestimated at the lower end of the consequence spectrum. Nevertheless, an inclusive approach was chosen having in mind that these events when added may substantially contribute to the overall damage and are not covered by other activities in the comparative assessment within the GaBE project.

The results obtained in the present work reflect the better coverage and extended scope of the PSI database as compared to the previous comparative analyses. In addition, in relation to [Chadwick et al., 1991] the examined time period was extended to include years 1987 to 1996. Thus, the number of oil accidents with at least five fatalities exceeds in the PSI database the corresponding number of records in [Chadwick et al., 1991] by more than a factor of five. In the context of hydro power and also in the gas chain some allocation inconsistencies were identified when examining the earlier studies. Correction of these inconsistencies would further increase the differences in the statistical evidence. Furthermore, as opposed to previous analyses the present comparison covers a number of damage categories beyond fatalities, including injuries, evacuees and economic damages. Clearly, for these damage categories the completeness of the data is inferior in comparison with the fatality records and the associated uncertainties are substantial. The comparability is here affected by the fact that the quality of the material is not homogeneous over all

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5 This reference in turn bases the comparative evaluation of severe accidents on [Fritzsche, 1988 and 1989].

energy chains. Also in this case the view of the authors is that in spite of the higher uncertainties the comparisons are meaningful and will hopefully stimulate further efforts aiming at reducing the inconsistencies. Some other types of consequences are not covered in the present comparisons since they do not occur over all chains or the basis for the comparison is so weak that there is no point in doing it. Examples include oil spills or ground contamination. For the treatment of these impacts we refer to the results obtained for the specific chains.

A series of aggregated results is shown in Figures 9.1.2 through 9.1.4 and 9.1.6 through 9.1.8. The full set of data behind these figures can be found in Appendix F. In addition, data providing the most central end results are summarised in Tables 9.1.5 through 9.1.7. The numbers represent maximum values unless explicitly stated.

Figure 9.1.2 shows the estimated number of **immediate** fatalities, injured and evacuated persons per unit of energy for six energy chains. Only accidents with at least 5 fatalities, 10 injured and 200 evacuated, respectively, have been included. With the exception of LPG all other energy chains represent different means for electricity production. The results are based on world-wide accident statistics assembled within the present work. For normalisation data on energy production by different means were used, expressed in terms of equivalent electrical output. These data originate primarily from [IEA, 1996], except for few years for which other sources were consulted. Comments on the relative completeness of the data concerning the three damage categories in the context of the different chains may be found in chain-specific summaries in Section 9.1.2.

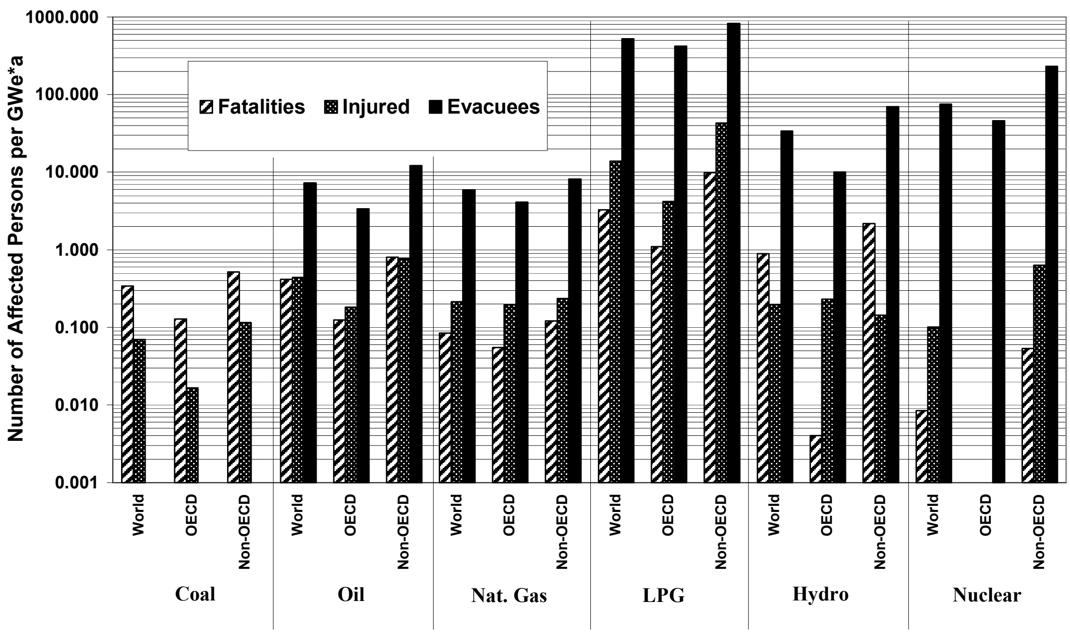

Fig. 9.1.2 Comparison of aggregated, normalised, energy-related damage rates, based on severe accidents that occurred world-wide, in OECD and in non-OECD countries in the period 1969-1996; immediate fatalities, injured and evacuated persons per unit of energy.

In comparison with the normalised immediate fatality rates in [Chadwick et al., 1991] the present results with world-wide records are practically identical for the coal chain, significantly lower for natural gas, nuclear and hydro, and significantly higher for oil. This is due to the combined effect of the extension of the evaluation period by additional ten years of operating experience, higher level of completeness, use of more up-to-date statistical data for the energy production, and consistent assignment of accidents associated with specific energy carriers. The differences in this assignment affect particularly the gas chain (in this work natural gas and LPG are treated separately) and hydro power (some dam accidents accounted for in [Fritzsche, 1988] occurred at dams having purposes other than power production).

When evaluating the fatality rates for the fossil energy carriers in OECD and non-OECD countries, shown in Figure 9.1.2, consumption data were used for both OECD and non-OECD countries for normalisation. This is consistent with the allocation scheme defined in Section 6.1. Consumption is here defined as the total production within the respective block of countries, reduced by exports to OECD in the non-OECD case and increased by imports from non-OECD in the OECD case. There is no difference between the production and consumption numbers in the case of hydro and nuclear. Also for coal the difference is practically negligible. Figure 9.1.3 shows the differences arising from the different bases for the normalisation.

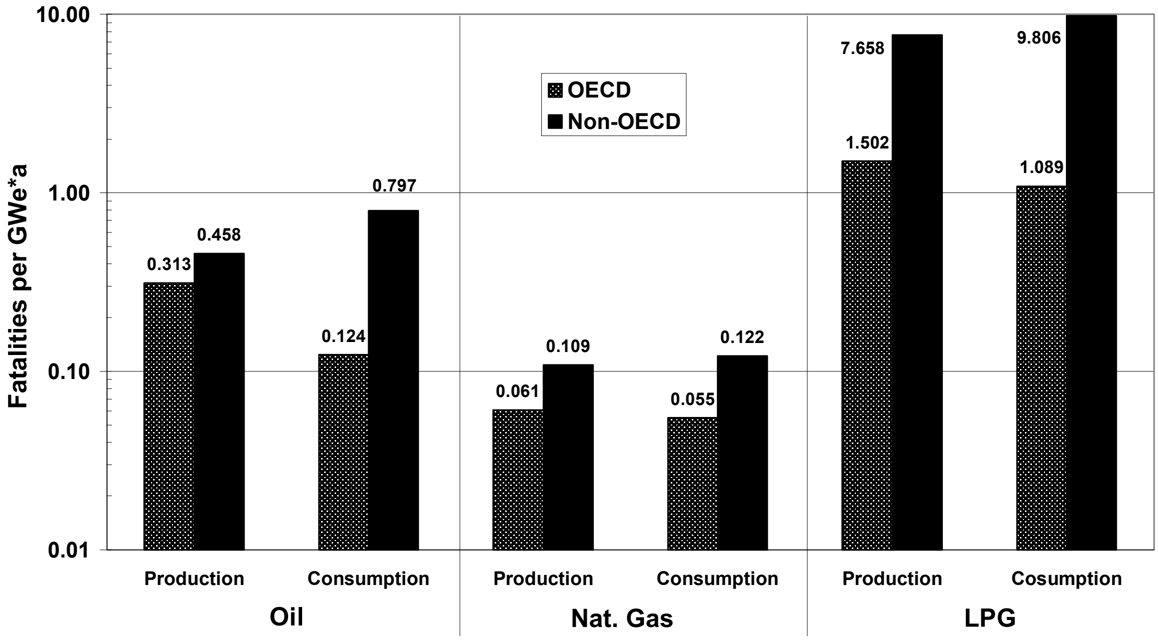

Fig. 9.1.3 Impact of two alternative bases for the normalisation on the estimated fatality rates associated with severe (≥ 5 fatalities) accidents that occurred in OECD and non-OECD countries within the oil, natural gas and LPG chains in the period 1969-1996. Normalisation is here either based on energy production or consumption.

Particularly for oil, but also for LPG, the differences are large. In agreement with the allocation scheme we use the consumption as the basis for all the following evaluations, whenever the separation between OECD and non-OECD is of interest.

When making distinction between OECD and non-OECD countries in Fig. 9.1.2 the flows of fossil energy carriers were considered only when normalising. Thus, so far no redistribution of the consequences of the accidents, taking into account these flows, was carried out. Figure 9.1.4 shows the numbers of immediate fatalities, injured and evacuated persons per unit of energy, based on the weighted allocation of damages that occurred in non-OECD countries within the fossil energy chains to the corresponding damages in OECD countries. The allocation scheme was developed in Section 6.1.3.

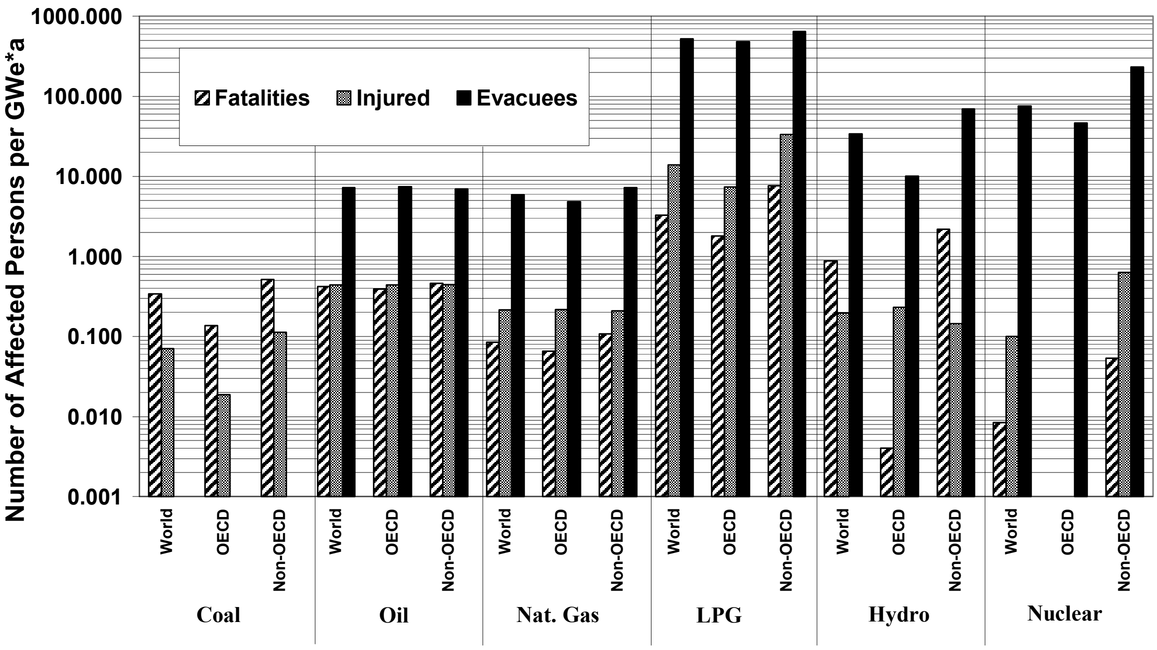

Fig. 9.1.4 Comparison of aggregated, normalised, energy-related damage rates, based on severe accidents that occurred world-wide, in OECD and in non-OECD countries in the period 1969-1996; <u>immediate</u> fatalities, injured and evacuated persons per unit of energy were estimated based on the partial reallocation of damages to OECD countries taking into account imports of fossil energy carriers from non-OECD countries.

The figure shows that the rates for the oil chain quite dramatically increase for OECD countries and decrease for non-OECD countries in comparison to those shown in Fig. 9.1.2; this is due to the large imports of crude oil to OECD countries. The changes for the LPG and natural gas chains are significant but much less dramatic, and practically negligible for the coal chain.

Figures 9.1.2 through 9.1.4 present in the context of mortality results only the rates associated with **immediate** fatalities. The **delayed** (also referred to as **latent**) fatalities, particularly relevant for the Chernobyl accident, need to be treated separately. The current best estimate of the Chernobyl-specific delayed fatalities, primarily based on the assessed doses received by the emergency workers and by the public, is in the range 2.5 to 8.9 fatalities per GWe*a produced by the nuclear energy; the upper bound has been obtained using no exposure threshold, an approach not recommended by the Health Physics Society [Moossman et al., 1996].

It is important to emphasise the differences in the extent of the statistical material available for the different energy sources. Thus, the number of accidents with five or more fatalities is according to ENSAD for the period 1969-1996:

Coal:	187
Oil:	334
Natural gas:	86
LPG:	77
Hydro:	9
Nuclear:	1

The statistical evidence available for severe nuclear accidents resulting in fatalities is limited to one accident. Also for hydro power the statistical basis is relatively poor. The applicability of the "generic" results was discussed in Sections 9.1.2.4 and 9.1.2.5 addressing nuclear and hydro chains, respectively. In the nuclear case the Chernobyl-specific results were contrasted with probabilistic estimates typically obtained for western reactors, demonstrating that naive uses of the historical data may be crude and sometimes evidently unsuitable. Also in the hydro case the estimates presented in Figures 9.1.2 and 9.1.4 show that the generic results obtained for the whole world or for non-OECD countries are not representative for western dams. Figure 9.1.5 shows in a different manner that the regional differences are decisive in the hydro case, particularly in terms of the number of fatalities, given that the evaluation is limited to the period 1969-1996.

Using the records for the western world only we obtain the normalised fatality rate for hydro to be $4.0 \cdot 10^{-3}$ immediate fatalities per GWe*a, i.e. an estimate which is lower by a factor of more than 200 than the generic world average given in Fig. 9.1.2. This result is by a factor of five lower than the corresponding PSA-based estimate of $2.0 \cdot 10^{-2}$ latent fatalities per GWe*a, obtained for the nuclear power plant Mühleberg. Both estimates illustrate one of the pitfalls in uncritical use of the generic experience.

The regional dependence applies also to coal, oil, natural gas and LPG chains as shown in Fig. 9.1.2. However, here the applicability of the generic data may be much more reasonable also for developed countries, particularly when the country where the study is being performed is an importer of coal, oil and/or gas (applies fully to Switzerland) and the impacts associated with the external parts of various fuel cycles are to be accounted for. The reason for this is that for these chains the extraction, and/or long transport steps exhibit high, frequently dominant relative risk importance. The implementation of the allocation scheme (Fig. 9.1.4) shows that accounting for the flows of the fossil energy carriers between OECD and non-OECD countries brings the estimates obtained for these two blocks for the fossil chains closer to one another.

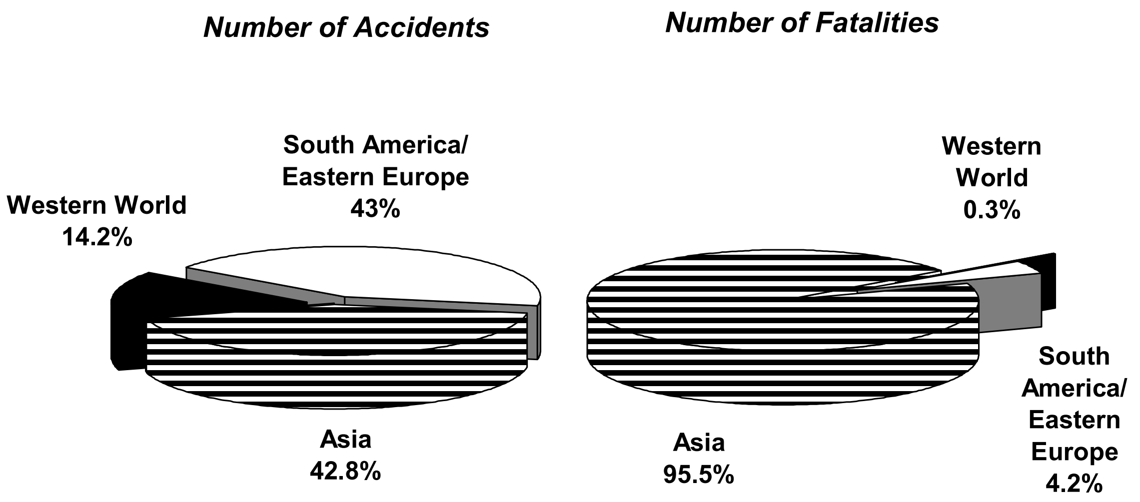

Fig. 9.1.5 Distribution of hydro power accidents and their consequences in terms of fatalities in different world regions (period 1969-1996).

The comparison of economic damages is limited by incompleteness and some serious inconsistencies. First, the estimates of monetary losses are not available for a major part of non-nuclear accidents. Second, the cost elements covered, i.e. the boundaries of the calculation, are normally not documented and may vary widely from case to case. Third, the nature of the reported costs may be different - there is normally a large discrepancy between the compensation paid by insurance companies, claimed damages, real damages, direct costs and indirect costs. In the nuclear case the costs of two accidents have been included, namely TMI and Chernobyl. They are dominated by the latter accident with more than one order of magnitude discrepancy between the lower and higher bound of this estimate.

Figure 9.1.6 shows the aggregated, normalised minimum and maximum values for monetary damages world-wide for each of the energy chains, normalised by the produced energy and based on the currently available information. As may be seen there is a very large range of values for the nuclear chain, depending on the large uncertainties associated with the economic consequences of the Chernobyl accident. In this context the boundaries for the estimation play a central role.

In Figures 9.1.7 and 9.1.8 the distinction is made between OECD and non-OECD countries, using no allocation and full allocation for the fossil energy carriers, respectively.

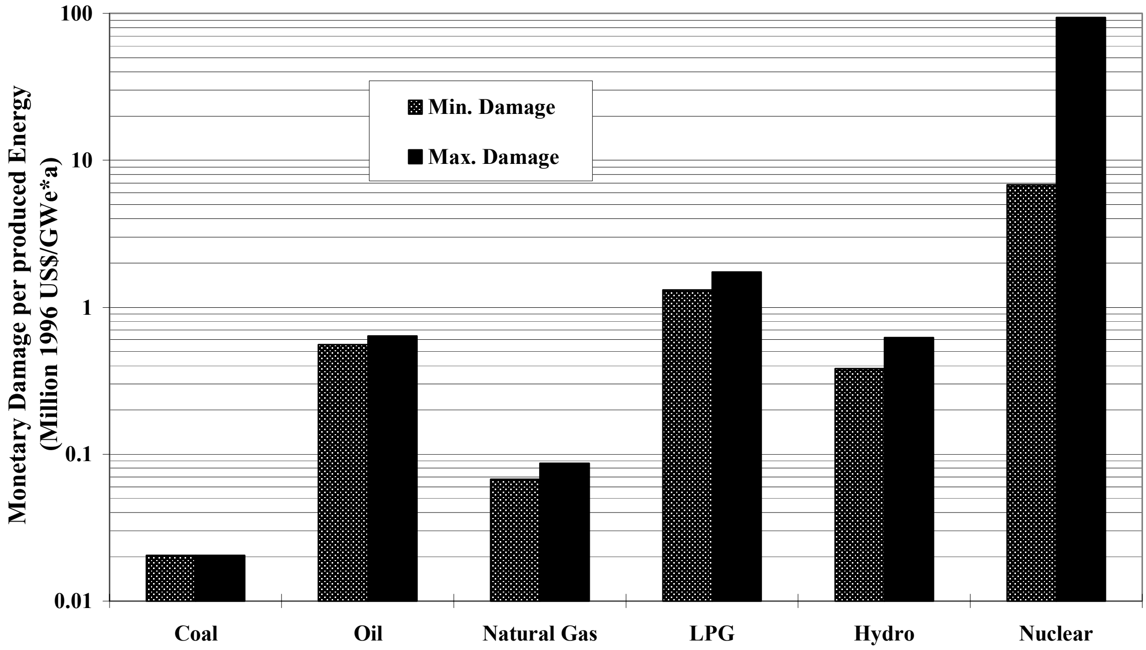

Fig. 9.1.6 Comparison of aggregated, normalised economic losses due to energy-related severe accidents occurred world-wide in the period 1969-1996; minimum and maximum values are shown.

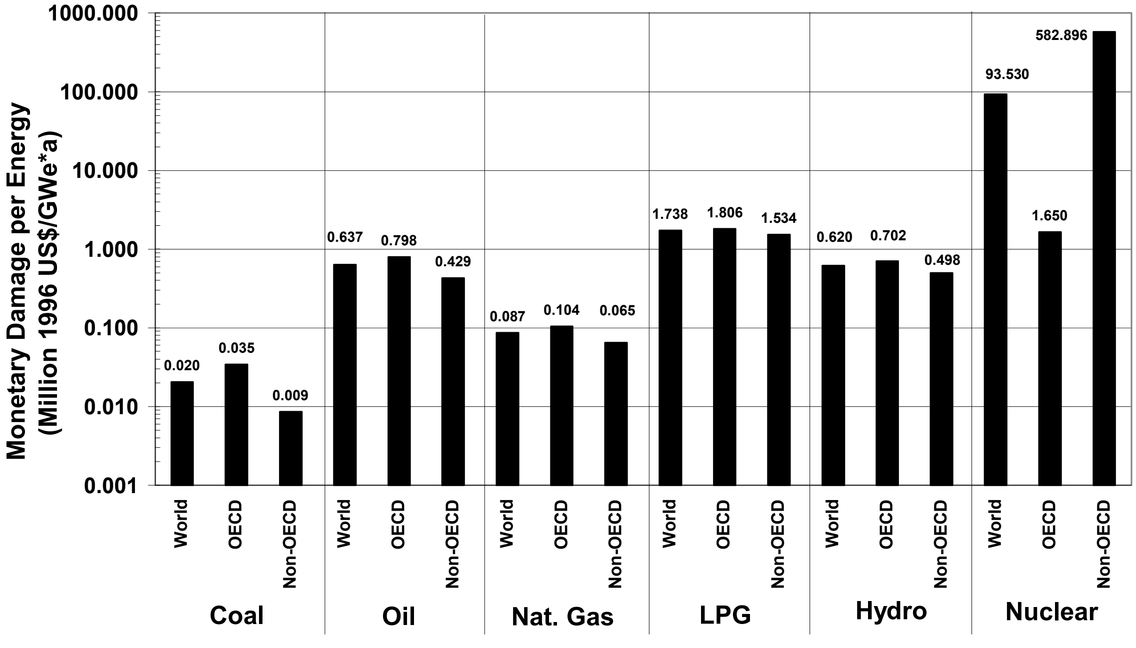

Fig. 9.1.7 Comparison of aggregated, normalised, energy-related economic losses, based on severe accidents that occurred world-wide, in OECD and in non-OECD countries in the period 1969-1996; no reallocation of damages between OECD and non-OECD countries was used in this case.

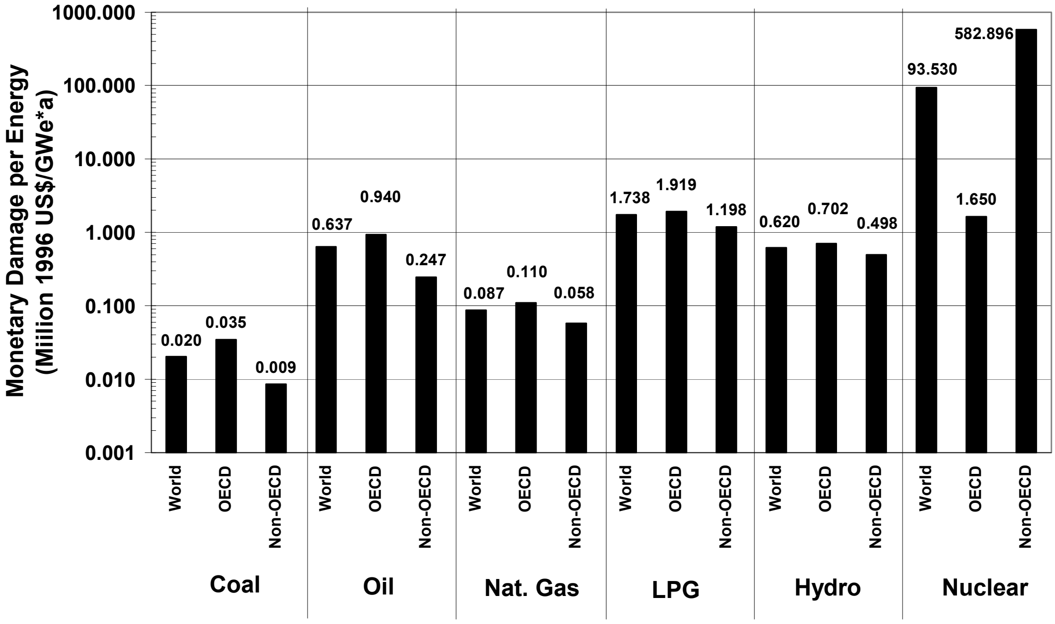

Fig. 9.1.8 Comparison of aggregated, normalised, energy-related economic losses, based on severe accidents that occurred world-wide, in OECD and in non-OECD countries in the period 1969-1996; these results are based on the full reallocation of damages to OECD countries taking into account imports of fossil energy carriers from non-OECD countries.

The results obtained for economic losses and their interpretation are subject to the serious reservations mentioned above. Due to the devastating damages associated with the Chernobyl accident the normalised monetary damages are clearly highest for the nuclear chain, followed by LPG, oil, hydro, natural gas and coal. Consideration of the regional distribution of accidents leads to a somewhat different ranking for the most developed countries. It is also worthwhile to note that the partially artificial limitation of the evaluation period strongly influences the results. For example, according to the records some of the hydro accidents that occurred further back in time resulted in extremely high damages.

The aggregated end results shown in Figures 9.1.2, 9.1.4, 9.1.7 and 9.1.8 are summarised in numerical form in Tables 9.1.5 through 9.1.7.

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TABLE 9.1.5

Severe accident damage indicators based on world-wide records for the period 1969-1996.

Damage Indicator	Energy Carrier					
	Coal	Oil	Natural Gas	LPG	Hydro	Nuclear
Number of Immediate Fatalities (per GWe*a)	3.42E-01	4.18E-01	8.46E-02	3.28E+00	8.83E-01	8.41E-03
Number of Injured (per GWe*a)	7.02E-02	4.41E-01	2.13E-01	1.39E+01	1.95E-01	1.00E-01
Number of Evacuees (per GWe*a)	0	7.22E+00	5.90E+00	5.22E+02	3.42E+01	7.57E+01
Monetary Damage (million 1996 US$ per GWe*a)	2.04E-02	6.37E-01	8.68E-02	1.74E+00	6.20E-01	9.35E+01

TABLE 9.1.6

Severe accident damage indicators for OECD countries based on records for the period 1969-1996.

Damage Indicator	Energy Carrier									
	Coal		Oil		Natural Gas		LPG		Hydro	Nuclear
	A	B	A	B	A	B	A	B		
Number of Immediate Fatalities (per GWe*a)	1.28E-01	1.37E-01	1.24E-01	3.87E-01	5.49E-02	6.55E-02	1.09E+00	1.81E+00	4.03E-03	0
Number of Injured (per GWe*a)	1.67E-02	1.86E-02	1.83E-01	4.39E-01	1.95E-01	2.16E-01	4.20E+00	7.34E+00	2.30E-01	0
Number of Evacuees (per GWe*a)	0	0	3.39E+00	7.41E+00	4.13E+00	4.83E+00	4.20E+02	4.81E+02	1.01E+01	4.64E+01
Monetary Damage (million 1996 US$ per GWe*a)	3.45E-02	3.47E-02	7.98E-01	9.40E-01	1.04E-01	1.10E-01	1.81E+00	1.92E+00	7.02E-01	1.65E+00

A = No reallocation of damages between OECD and non-OECD for fossil chains

B = Full reallocation of damages between OECD and non-OECD for fossil chains

TABLE 9.1.7

Severe accident damage indicators for non-OECD countries based on records for the period 1969-1996.

Damage Indicator	Energy Carrier									
	Coal		Oil		Natural Gas		LPG		Hydro	Nuclear
	A	B	A	B	A	B	A	B		
Number of Immediate Fatalities (per GWe*a)	5.21E-01	5.14E-01	7.97E-01	4.58E-01	1.22E-01	1.09E-01	9.81E+0	7.66E+00	2.19E+00	5.32E-02
Number of Injured (per GWe*a)	1.15E-01	1.13E-01	7.72E-01	4.44E-01	2.36E-01	2.10E-01	4.27E+01	3.34E+01	1.43E-01	6.35E-01
Number of Evacuees (per GWe*a)	0	0	1.21E+01	6.98E+00	8.12E+00	7.23E+00	8.26E+02	6.45E+02	7.00E+01	2.32E+02
Monetary Damage (million 1996 US$ per GWe*a)	8.65E-03	8.53E-03	4.29E-01	2.47E-01	6.48E-02	5.77E-02	1.53E+00	1.20E+00	4.98E-01	5.83E+02

A = No reallocation of damages between OECD and non-OECD for fossil chains

B = Full reallocation of damages between OECD and non-OECD for fossil chains

Figure 9.1.9 shows the frequency-consequence curves for the different energy chains: The results for coal, oil, natural gas, LPG and hydro chains are based on world-wide accidents and concern **immediate** fatalities. For the nuclear chain apart from immediate fatalities associated the Chernobyl accident results from the Probabilistic Safety Assessment (PSA) for the Swiss nuclear power plant Mühleberg are provided. In the latter case the **latent** fatalities are shown since none of the credible scenarios leads to acute fatalities among the public. The Mühleberg results include also the uncertainty bounds but in the figure only the curve based on mean values is shown.

Figure 9.1.10 shows the enlarged curves for the coal, oil, natural gas and hydro chains. This enables the appreciation of the differences between the results obtained for the various chains.

Among the fossil chains natural gas has the lowest frequency of severe accidents involving fatalities. Apart from LPG, coal and oil exhibit the highest frequencies of accidents up to the level of about 70 fatalities while hydro has the lowest. For higher levels of consequences the situation becomes reversed. It should be noted that the fatalities in the coal chain are predominantly occupational as opposed to the other energy carriers. Consideration of accidents in the western world results in a hydro curve with only one point at the low end of the consequence spectrum (see Figure 9.1.11, which also for comparison shows the frequency-consequence curve for the nuclear power plant Mühleberg as well as the Chernobyl-based historical experience). For the evaluation period used there is only one severe (with respect to fatalities) hydro accident in OECD countries. In Section 6.6 a difference was shown between the frequencies of exceedance of the number of fatalities due to dam accidents in Asia and Africa on the one hand and western world on the other, based on much more extensive statistical material due to the longer evaluation time and use of accidents at dams for all purposes.

Concluding remarks on energy chain comparisons

While a variety of damage categories were considered and analysed the conclusions given here are primarily based on fatality failure rates. First, the statistical records on fatalities are most complete; second, the fatalities associated with large accidents are regarded as the indicator attracting most attention on the side of the society; third, the patterns for other damage indicators are in some (but definitely not all) cases quite similar to those characteristic for the fatality rates.

The present work shows that significant differences exist between the aggregated, normalised damage rates assessed for the various energy carriers. One should, however, keep in mind that from the absolute point of view the fatality rates are in the case of fossil sources small when compared to the corresponding rates associated with the health impacts of normal operation. For this reason the evaluation focuses here on the relative differences between the various energy carriers.

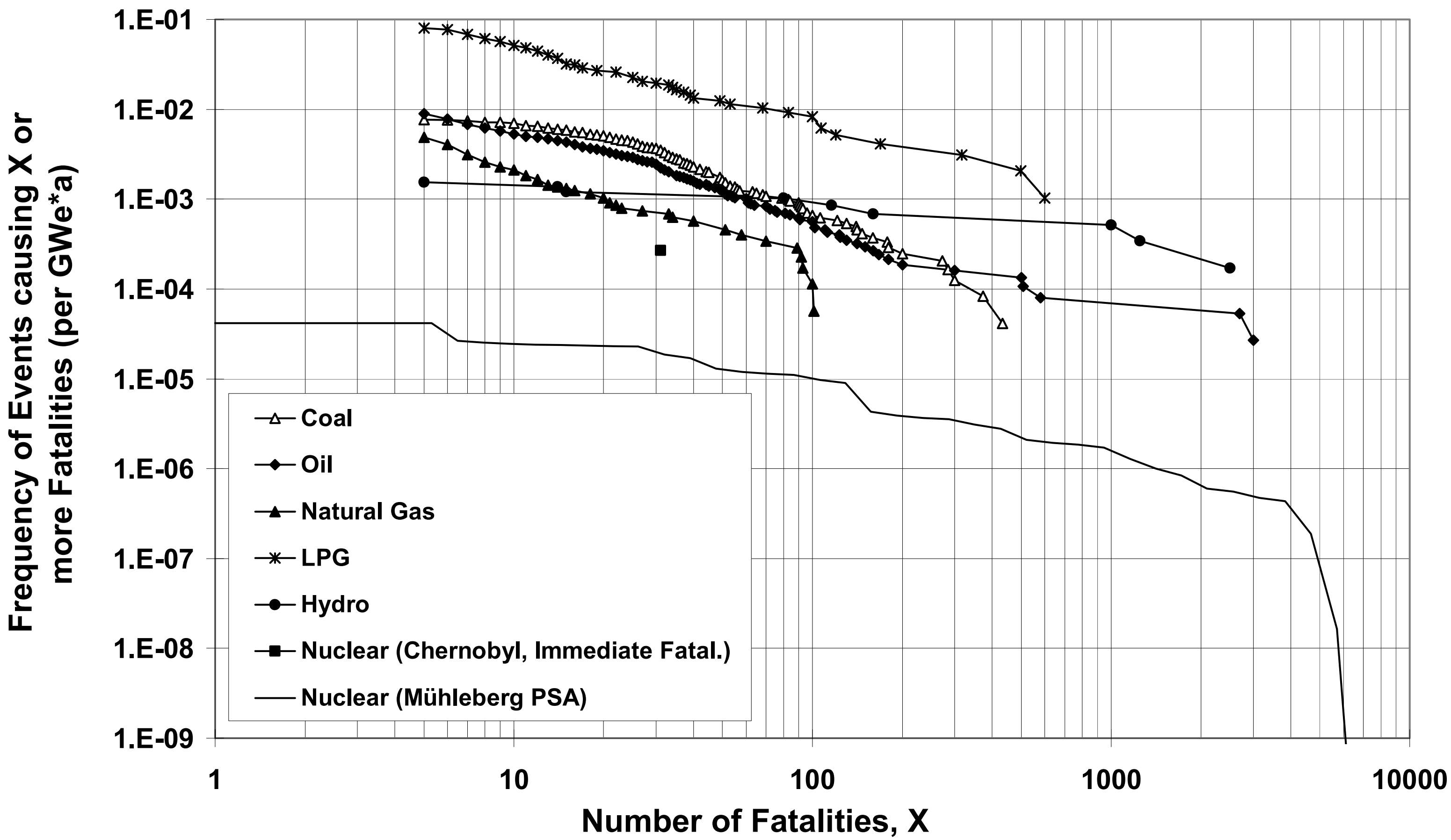


Fig. 9.1.9 Frequency-consequence curves for different energy chains. The curves for coal, oil, natural gas, LPG and hydro chains are based on historical accidents world-wide in the period 1969-1996 and show <u>immediate</u> fatalities. For the nuclear chain the <u>immediate</u> fatalities are represented by one point (Chernobyl). The results for the nuclear power plant Mühleberg originate from the plant-specific Probabilistic Safety Assessment (PSA) and reflect <u>latent</u> fatalities.

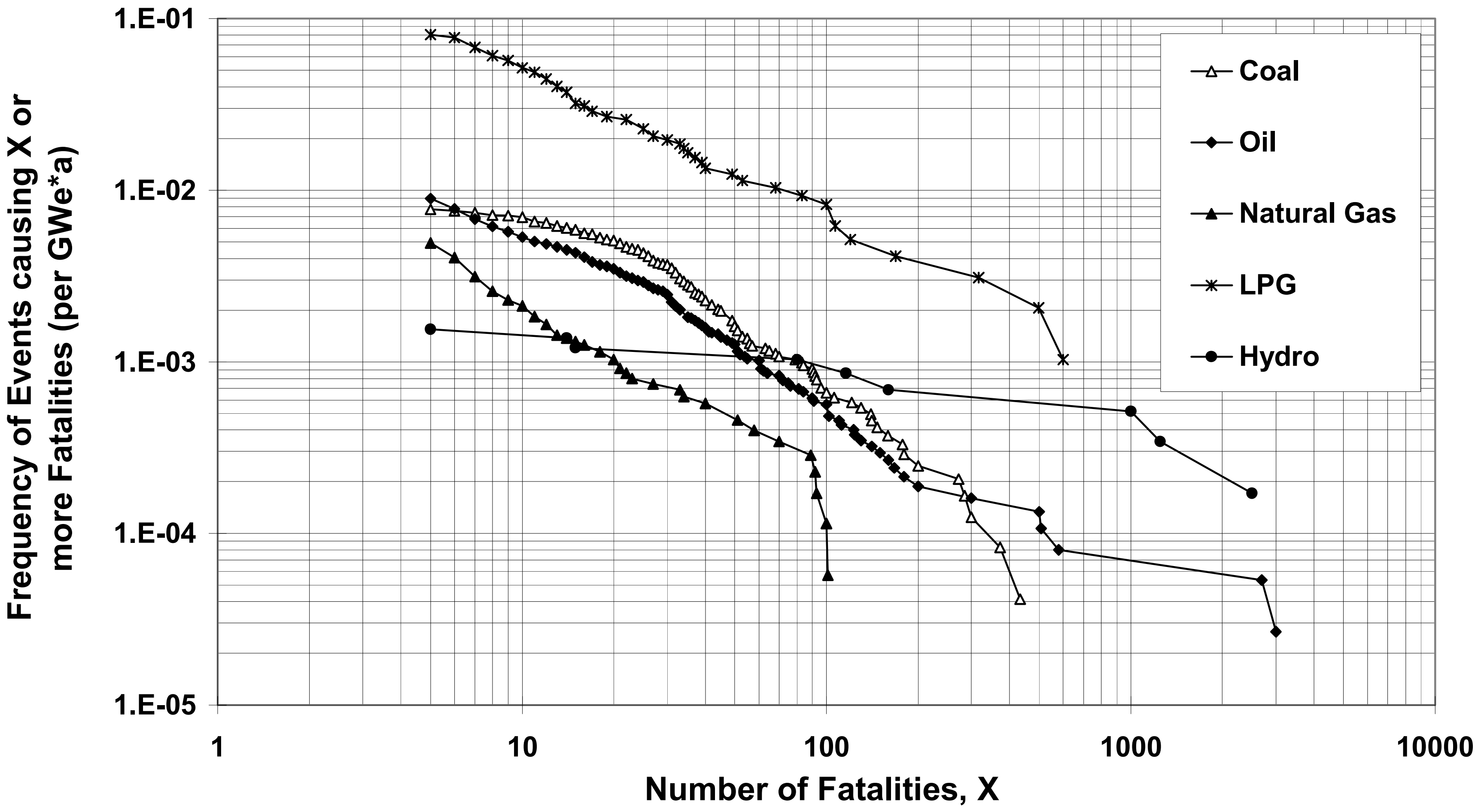


Fig. 9.1.10 Frequency-consequence curves for LPG, coal, oil, natural gas and hydro energy chains (an enlargement of Fig. 9.1.9 (with the nuclear chain excluded)). The curves are based on historical accidents world-wide in the period 1969-1996 and show <u>immediate</u> fatalities.

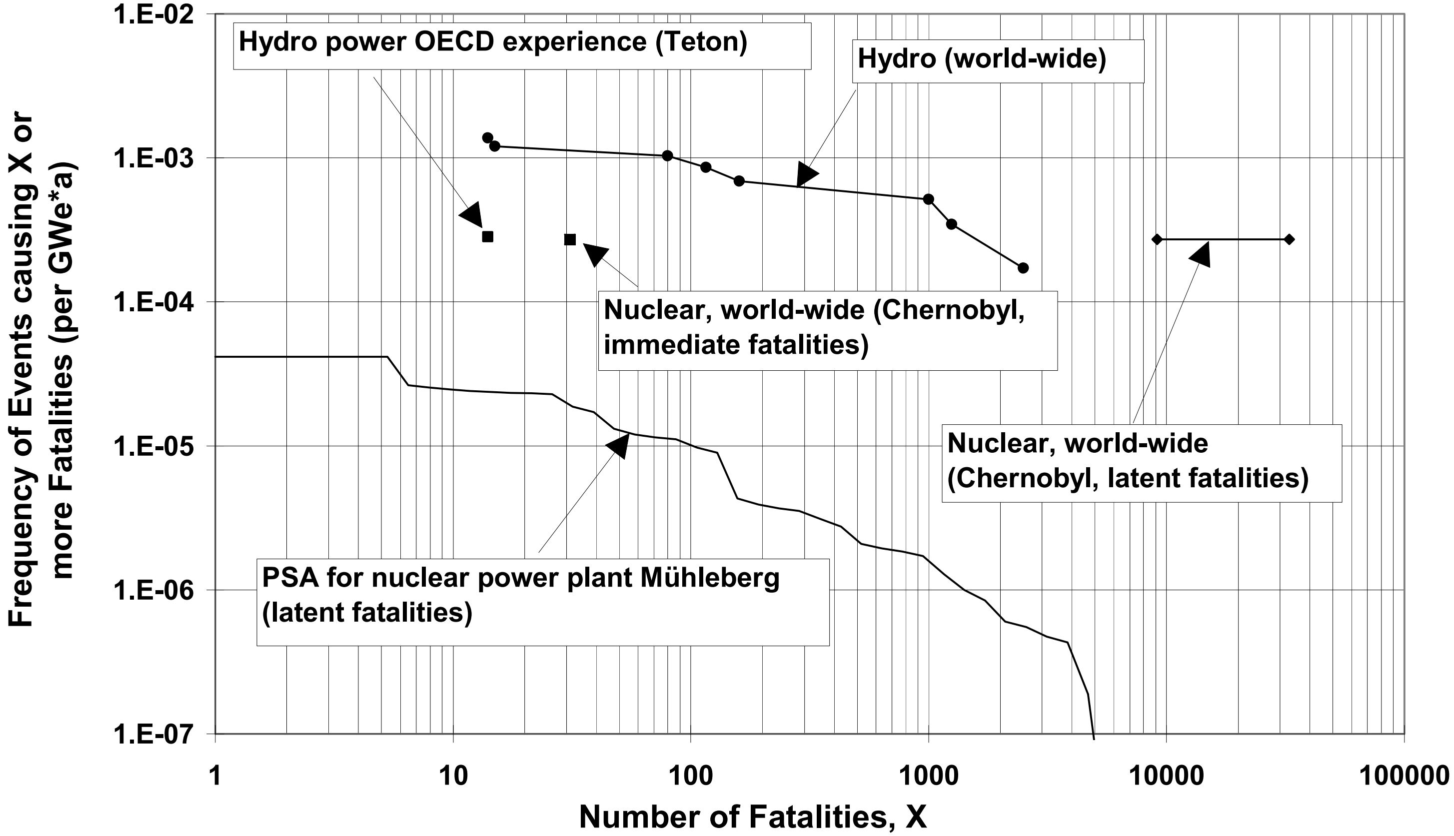


Fig. 9.1.11 Frequency-consequence curves for hydro and nuclear chains. The curves for hydro are based on historical accidents world-wide and in the western world in the period 1969-1996 and show <u>immediate</u> fatalities. The results for the nuclear power plant Mühleberg originate from the plant-specific Probabilistic Safety Assessment (PSA), represent <u>latent</u> fatalities and are based on mean values. Nuclear is also represented in this comparison by the Chernobyl accident; both immediate fatalities and an interval for the consequences based on the assessments of potential latent fatalities with and without dose cut-off, are depicted.

The broader picture obtained by coverage of full energy chains leads on the **world-wide** basis to aggregated **immediate** fatality rates being much higher for the fossil fuels than what one would expect if power plants only were considered. The highest rates apply to LPG, followed by hydro, oil, coal, natural gas and nuclear. In the case of nuclear, the estimated **delayed** fatality rates solely associated with the only severe (in terms of fatalities) nuclear accident (Chernobyl), clearly exceed all the above mentioned immediate fatality rates. However, in view of the drastic differences in design, operation and emergency procedures, the Chernobyl-specific results are considered not relevant for the "Western World". Given lack of statistical data, results of state-of-the-art Probabilistic Safety Assessments (PSAs) for representative western plants are used as the reference.

Generally, the immediate failure rates are for all considered energy carriers significantly higher for the **non-OECD** countries than for **OECD** countries. In the case of hydro and nuclear the difference is in fact dramatic. The recent experience with hydro in OECD countries points to very low fatality rates, comparable to the representative PSA-based results obtained for nuclear power plants in Switzerland and in USA. With the important exception of hydro in OECD countries, and coal and oil occasionally switching positions, the internal ranking based on the **immediate** fatality rates remains the same within OECD- and non-OECD countries as the above cited results based on the world-wide evidence. This is valid both for the straight-forward assessment as well as for the estimates employing allocation schemes. Accounting for **delayed** fatalities along with the immediate ones preserves this ranking when OECD countries are considered but due to the Chernobyl accident nuclear compares unfavourably to the other chains if the experience base is limited to non-OECD countries.

The allocation procedure considers the trade-based flows of fossil energy carriers between the non-OECD and OECD countries. The OECD countries are net importers of these energy carriers and the majority of accidents occurs within the upstream stages of these chains. Consequently, the reallocation to OECD countries of the appropriate shares of accidents that physically occurred in non-OECD countries leads to smaller differences between the corresponding damage rates for these two groups of countries in comparison with the straight-forward evaluation. The effect is particularly significant in the case of oil.

For damage indicators other than fatalities the results must be interpreted with caution due to the incompleteness problems (particularly for injuries and economic losses) and inconsistencies of boundaries in the evaluation of monetary damages. It is, however, clear in spite of the uncertainties that the economic loss associated with the Chernobyl accident is highly dominant.

Along with the aggregated results frequency-consequence curves have been provided. They reflect implicitly the above ranking but provide also such information as the observed or predicted chain-specific maximum extents of damages. This perspective on severe accidents may lead to different system rankings, depending on individual risk aversion.

Table 9.1.8 shows the overview of the risk-dominant energy chains based on the **world-wide** historical accidents in the period 1969-1996. Only accidents with at least 5 fatalities, or 10 injured, or 200 evacuees, or 5 million 1996 US$ economic damages are considered. Table 9.1.9 shows the corresponding results for OECD countries.

The following evaluation categories are used in the table:

I Largest number of accidents having consequences exceeding the above threshold values.

II Largest aggregated number of fatalities, injured, evacuees, and highest aggregated economic losses.

III Largest number of fatalities, injured, evacuees, and highest economic loss in a single accident.

IV Largest aggregated number of fatalities, injured, evacuees, and highest aggregated economic losses, averaged per accident.

V Largest aggregated number of fatalities, injured, evacuees, and highest aggregated economic losses, per unit of energy produced.

TABLE 9.1.8

Risk-dominant energy chains based on world-wide historical severe accidents in the period 1969-1996.

Evaluation Category	Immediate Fatalities	Latent Health Impacts[a]	Injured	Evacuees	Economic Losses
I	Oil	Nuclear	Oil	Oil	Oil
II	Oil	Nuclear	Oil	LPG	Nuclear
III	Oil	Nuclear	LPG	LPG	Nuclear
IV	Hydro	Nuclear	Nuclear	Nuclear	Nuclear
V	LPG	Nuclear	LPG	LPG	Nuclear

[a] Latent health impacts are here equivalent to latent fatal and non-fatal cancers.

TABLE 9.1.9

Risk-dominant energy chains based on historical severe accidents within OECD in the period 1969-1996.

Evaluation Category	Immediate Fatalities	Latent Health Impacts[a]	Injured	Evacuees	Economic Losses
I	Oil	-	Oil	LPG	Oil
II	Oil	-	Oil	LPG	Oil
III	Coal	-	LPG	LPG	Nuclear
IV	Coal	-	Oil	Nuclear	Nuclear
V	LPG	-	LPG	LPG	LPG

[a] Latent health impacts are here equivalent to latent fatal and non-fatal cancers. No severe accidents (in terms of latent fatalities) occurred in OECD.

It is interesting to note that natural gas is the only energy carrier among the analysed ones not represented in the above tables. The presence of nuclear in this tables is primarily due to the Chernobyl accident, with a contribution from the TMI accident to the economic losses and evacuation. Estimates of latent fatalities and latent cancers are only available for the nuclear chain for which they are of particular relevance. Delayed fatalities are likely to have occurred for the other chains with no records available; their significance should, however, be incomparably smaller in comparison with the Chernobyl accident.

Generally, the historical evidence reflected in the tables above does not account for the applicability of these data. Thus, for country-specific uses of the generic experience application-oriented screening, preferably combined with probabilistic approaches, is necessary.

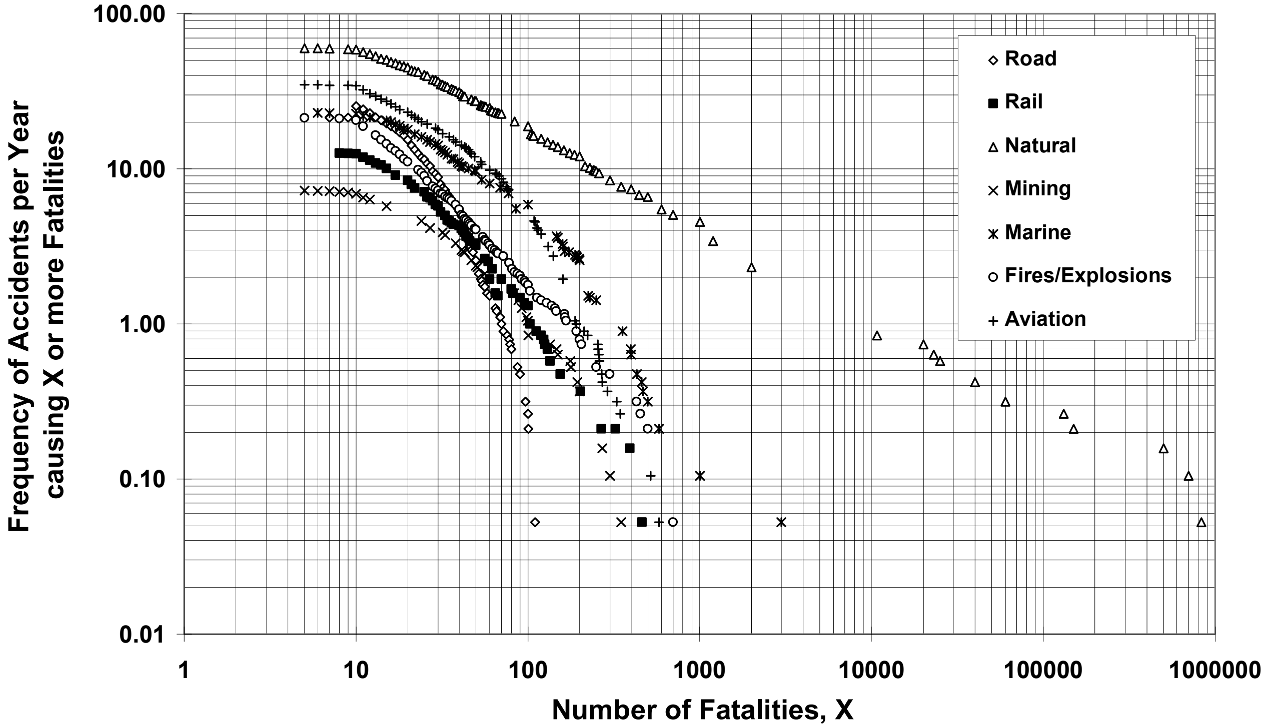
9.1.3.2 Comparison with other large scale activities and natural disasters

Risk comparisons may help to place the risk estimate in perspective. However, attention must be paid whether the type of risk comparison used is relevant. In the guide to risk comparisons [Sandman et al., 1988], different types of risk comparisons are ranked; comparisons with unrelated risks are considered as least acceptable. In the same reference the authors reportedly warn in connection to a table providing risk estimates for quite diverse activities that “USE OF DATA IN THIS TABLE CAN SEVERELY DAMAGE YOUR CREDIBILITY” (capitals in the original).

Consequently, reservations can be made towards any comparison of risks of different nature. Here we limit ourselves to comparing experience-based frequency-consequence curves for energy chains on the one hand, and for different means of person and goods transport, fires/explosions, mining and natural disasters on the other hand. Figure 9.1.12 shows the results of this comparison; in Figure 9.1.13 only the lower consequence part is shown to enable appreciation of the differences between the various activities.

There is a certain overlap since the groups mining and fires/explosions include also contributions from energy chains. For energy chains the records in the figures originate from ENSAD, while the data for the various activities and natural disasters were all taken from [Encyclopaedia Britannica, 1973-1997]. This is due to the fact that at present ENSAD does not contain non-energy-related transport accidents. Nuclear is represented in this comparison by one accident (Chernobyl) with the interval for consequences based on the assessments of potential latent fatalities with and without dose cut-off.

Not unexpectedly the natural disasters are the dominant ones. The energy-related curves are mostly comparable or lower than those representing other activities, with the exception of few points at the high end of the spectrum representing the extreme hydro, oil and nuclear accidents.



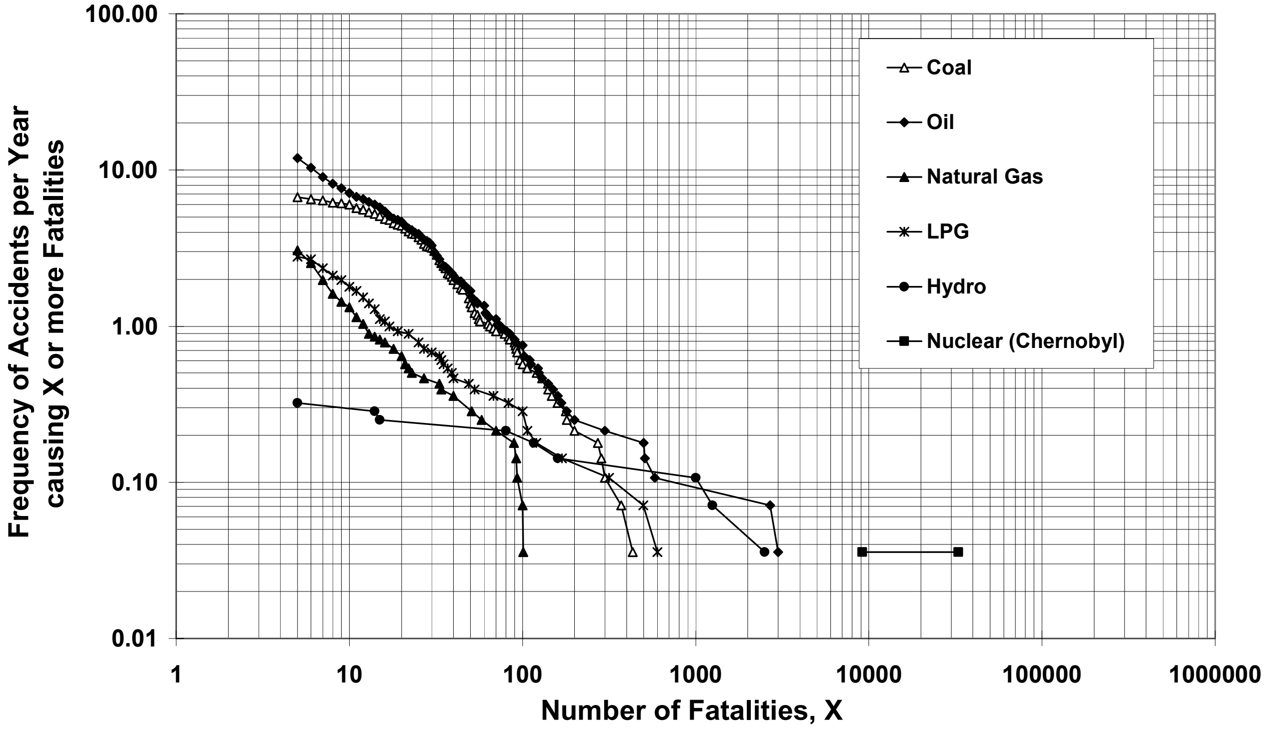
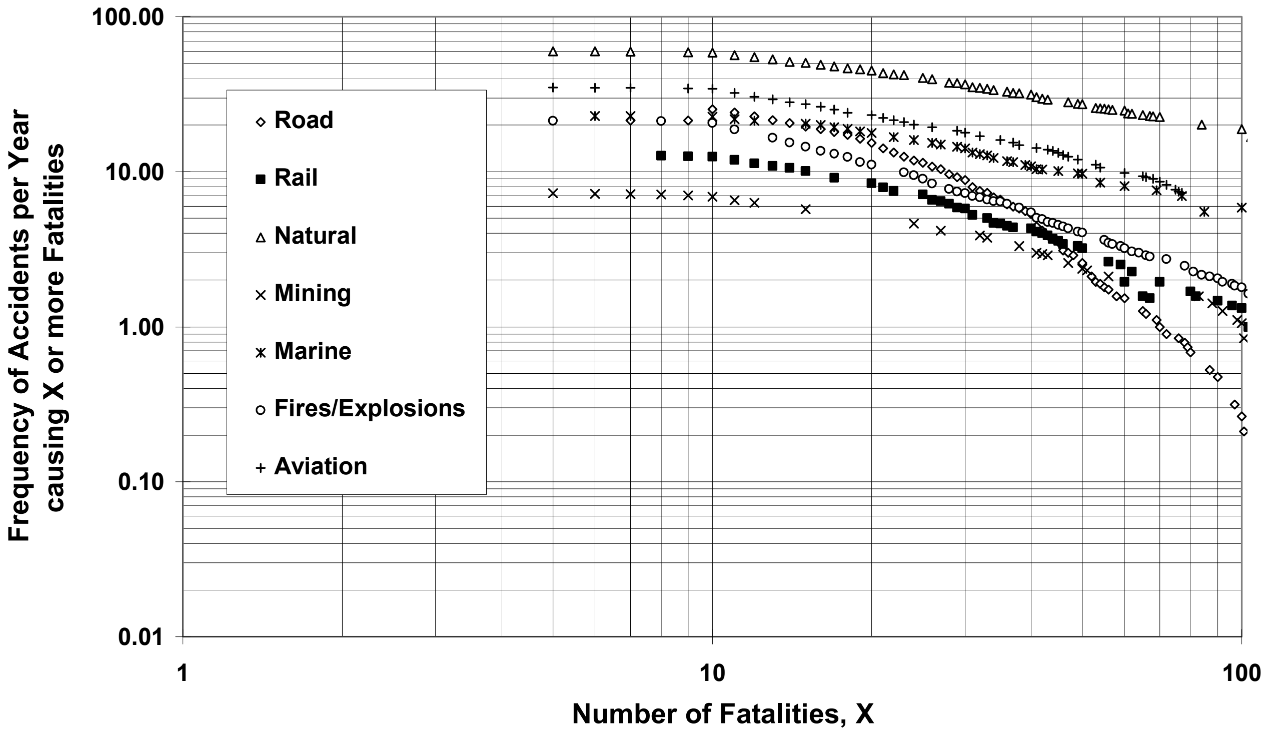


Fig. 9.1.12 Frequency-consequence curves for various activities world-wide (upper figure; period 1973-1996) and for different energy chains (lower figure; period 1969-1996). The results for nuclear reflect the Chernobyl accident and represent delayed fatalities that may occur over a period of 70 years after the accident.



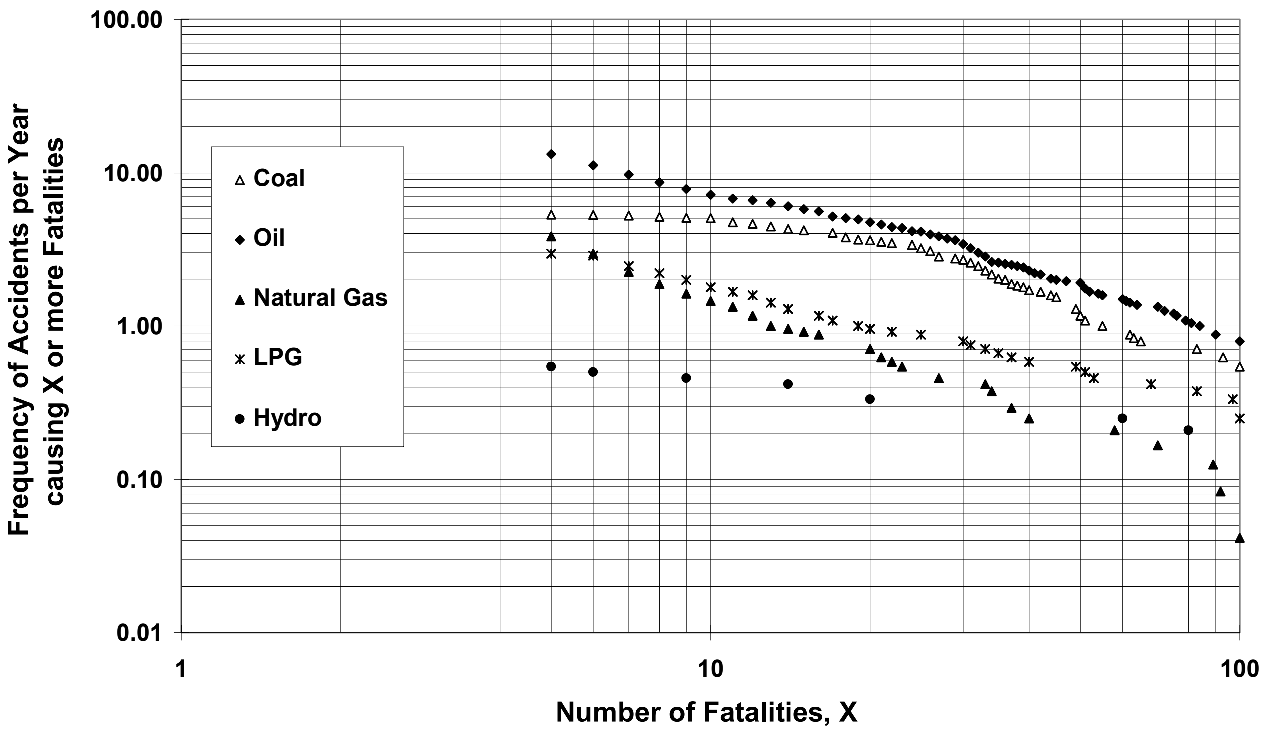


Fig. 9.1.13 Lower (in terms of consequences) part of frequency-consequence curves for various activities world-wide (upper figure; period 1973-1996) and for different energy chains (lower figure; period 1969-1996).

9.1.3.3 Issues in comparative assessment of energy-related severe accidents[6]

The following points summarise the issues related to the comparative assessment of severe accidents, which to some extent are considered as open:

- Non-uniform level of knowledge and limited scope of applications of risk analysis. Few comprehensive PSAs have been performed for energy chains other than nuclear although there is a steadily growing number of applications for offshore, fuel transport, refineries, gas storage etc. Regrettably, such studies are seldom published and made available to potential users. In the context of external costs studies, relatively little attention has been given to severe accidents within energy chains other than nuclear.

- Difficulties to cover a wide range of consequences in a consistent manner. There is a discrepancy between the wide range of consequence categories covered by the definition of severe accident[7] and the current possibilities to quantify their extent and the associated likelihood for different energy technologies. Typically reported risk measures in nuclear PSAs are: number of early (acute) fatalities and injured, number of latent cancer fatalities, total population dose from all pathways, individual risk of death and individual probability of latent cancer fatality, interdicted and condemned land area. For other energy systems, due to the scarcity of information, poor statistical evidence and lack of accuracy of historical data, the evaluation of consequences in the context of comparative analysis is currently meaningful only for a more limited spectrum of damage categories.

- Uncertainties involved in PSA. Uncertainty is an inherent feature of probability. While uncertainties are implicitly represented in all analyses including the deterministic ones, PSA makes them visible. However, the uncertainty range associated with the results of probabilistic assessment of consequences of nuclear accidents is much larger than the corresponding one for the outcome of the quantification of accident sequences leading to core damage. The most significant limitations of nuclear PSA, which affect the uncertainties, are related to the treatment of human interactions, common cause failures, external events, phenomenological aspects of accident progression and to source term issues. Many of these limitations (such as the treatment of human interactions) are also characteristic for non-nuclear QRAs; however, in this context due to the multitude of processes involved generalisations are not possible. A review of the current PSA limitations (as well as merits), and of significant progress that has been made in handling some of them, can be found in [Hirschberg, 1992].

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[6] A somewhat modified version of the text in this section has been included in the contribution of one of the authors [Hirschberg, 1996] to the forthcoming IAEA Guidelines for the Comparative Assessment of Health and Environmental Impacts of Electrical Energy Systems.

[7] The spectrum of consequences of interest includes: fatalities and serious injuries, number of evacuees, ban on consumption of locally produced food or drinking water, releases of hydrocarbons and chemicals, enforced clean-up of land or water and direct economic losses.

- Treatment of the distribution of impacts in time and space. Given the increased uncertainty of the long range assessments there is a need to agree on reasonable analysis boundaries that reflect the priorities of decision makers. This issue is open also in the context of impacts of normal operation.

- Applicability and transferability of severe accident data. The existing data material is not homogeneous. This may be due to: technological variability, country-to-country or region-to-region variability, temporal changes, differences in definition and categorisation of severe accidents, and underreporting. Any use of generic or plant-specific data (available for a plant other than the one being examined) must take into account these differences. This inevitably involves use of engineering judgement.

- Treatment of risk aversion and non-quantifiable social detriments associated with extreme accidents. No consensus exists with respect to the appropriate methods and data to be used to quantify risk aversion, and whether risk aversion should at all be included in the estimates of external costs. There is, on the other hand, a wide agreement that aversion is an indicator for the social acceptance of specific technologies, particularly nuclear. The Chernobyl accident demonstrates that non-radiation-related health disorders and symptoms, such as anxiety, depression and various psychosomatic disorders attributable to mental stress among the population can be a side-effect of extreme accidents. Psychosocial effects and breaking of social ties are not amenable to quantification within the currently used approaches but may under certain conditions be of comparable or even greater concern than the direct damages.

9.2 Recommendations for Future Work

The ambition of the present work was to extend the knowledge about severe accidents in the energy sector, structure this information and provide a consistent comparison of the technical risks. As summarised in Section 8.3 there are a number of scope limitations of interest to address in the near future. Specifically the following are recommended:

- Database Maintenance and Basic Extensions. The data included in ENSAD cover the time until the end of year 1996. Coverage of more recent accidents and those that unfortunately are likely to occur in the near future is the natural follow-up step. Furthermore, it is possible that additional sources of data could become available in the meantime. A new version of the database that could be made available say in year 2003 would include accidents until the end of year 2001. This extension would further improve the statistical basis and allow investigations of time trends that reflect current implementations of state-of-the-art technologies. Some updating of the present material is also desirable, particularly for the very large accidents where the current evaluations are far from definite (especially Chernobyl). Due to resource constraints it has not been possible within the present work to pursue further searches of information in all areas where the primary sources contained scarce or unreliable data. Furthermore, some inquiries remained unanswered and need to be followed up. Consequently, there is a good chance that further work would improve the situation where at present the completeness and consistency of the data are not satisfactory (e.g. economic damages).

This would probably enable a more homogeneous treatment of the various types of consequences.

- Coverage of renewable energy sources other than hydro power. Particularly relevant is the consideration of accidents in the solar energy chain. The fabrication of photovoltaic cells requires large quantities of gases [USDOE, 1988]. Many of them are highly toxic (e.g. arsine, phosphine, silicon tetrafluoride) or flammable (e.g. silane, hydrogen, methane). Some of the gases likely to be used in thin-film cell production are used in other industries, but the quantities and application modes will differ. The volumes needed for cell production may much exceed those used for other purposes. The risks to populations near the facilities could be substantial, although the overall hazard potential is probably rather limited. Some pioneering work on the physical and chemical hazards associated with the solar energy chain has been carried out in the eighties by Brookhaven National Laboratory.

- Consideration of technological advancements and associated safety improvements. The present analysis addresses only the currently operating technologies. Of interest is to investigate what improvements may be expected for the future options. Such an analysis needs to consider the development trends in close co-operation with the leading vendors. In an analogous effort within the GaBE project this approach was recently used in the context of the establishment of environmental inventories for future electricity supply options for Switzerland [Dones et al., 1996].

- Further applications of the predictive approach. Probabilistic techniques were in the present work applied only to hypothetical nuclear reactor accidents. A systematic review of existing applications for other energy chains and for other steps of the nuclear chain should be carried out. While the availability of such full scope studies is quite limited probabilistic reasoning has been frequently applied in this context in a relatively crude and sometimes qualitatively oriented manner.

- Estimation of external costs associated with energy-related severe accidents. This work includes a state-of-the-art assessment of the external costs for hypothetical nuclear reactor accidents. The application concerns the Swiss nuclear power plant Mühleberg although for comparison some results for two US plants were also provided. Some central limitations of this analysis are associated with the scope of the economic analysis and with the assumptions concerning some of the key cost parameters. Currently, the economic parts of some major consequence codes are being expanded which could enable the investigation of indirect impacts of large accidents. Sensitivity analyses may be performed to assess the implications of the interdependencies between some of the cost driving parameters. Applications to Swiss nuclear power plants other than Mühleberg could also be of interest. Relative differences are expected to be quite significant. Finally, it is feasible but not straight-forward to address external costs associated with severe accidents in non-nuclear energy chains. By necessity the approach would have to be much more primitive than for the nuclear case.

- Swiss-specific allocation of accidents in external stages of energy chains. Following the approach employed in Life Cycle Analysis [Frischknecht et al., 1996; Dones et al., 1996] the Swiss-specific allocation of accidents could be implemented, reflecting the present or projected fuel import situation. Due to the relative scarcity of disaggregated data such an approach would not be fully based on country-specific evidence but would rather aim at reflecting regional differences.

- Development of site-specific risk analysis for hydro power. The present analysis is generic but includes the consideration of regional variation. On the level of the assessment of the frequency of dam rupture a number of features which may affect the frequency were considered, including the Swiss-specific conditions. However, no attempt has been made to connect this part with the consequence assessment. Furthermore, the estimation of the break frequency solely based on the past experience is subject to serious limitations. It is fully feasible to investigate the influence of site- and situation-specific factors (e.g. warning time, population at risk, flooding forcefulness), using the findings to predict the likely local consequences of a rupture [DeKay and McClelland, 1993]. PSI has recently carried out a limited evaluation of alternative models for the consequence assessment of hypothetical hydro accidents and has performed a simulation of wave propagation following a postulated break (partial and full) at a specific site. Furthermore, carrying out full or limited scope PSA for hydro dams, using state-of-the-art methodology, is considered fully feasible.

- Refinements and broadening of comparative assessment. Further comparisons between the various chains, including additional investigations of the impact of regional characteristics and studies of time trends may be carried out. Of interest may also be a full inclusion in ENSAD of severe transport accidents, which would allow more consistent comparisons of all energy-related risks.

- User-tailored extensions and corresponding result presentations. The assembled data represent a very extensive source of information. This has been exploited only to a limited extent in the present study. The interests and needs are highly dependent on the users of the information and the context of applications. Thus, the interests and priorities of a public agency are different from those of an insurance company or a vendor. Based on the explicit definition of needs on the side of a variety of users the data analysis could be extended and the form of presentation adjusted to the specifications.

- Consideration of risk perception/aversion. Risk comparison undertaken in the present work does not explicitly deal with how people perceive risks (in accordance with the intended limitation of the scope). Informed decisions should, however, be taken in full knowledge of the technical risk estimates. Being aware about the risk aspects which do affect the socio-political side of the matter, efforts were here directed towards addressing such features as delayed effects, the chance of a very large number of people being affected and the uncertainties involved in the assessment. Attempts to quantify risk aversion have been made in the past but suffer in the context of severe accidents from lack of relevant empirical basis. Efforts to improve the situation could be undertaken. Most essential in view of the authors of this report is the intensification and concretisation of the dialogue between the technical disciplines on the one hand and economy, sociology, environmental sciences, etc. on the other. This work and its extensions can hopefully serve as an input in this context. The socio-political and economic aspects have been addressed in a recent project sponsored by the Swiss Federal Office of Energy [Berg et al., 1995]. We refer also to the work at the University of St. Gallen and in Germany, highly relevant in this context ([Haller and Maas, 1995] and [Königswieser et al., 1996]). Apart from extensive technical reviews of the present work also two reviews focusing on the socio-economic aspects were carried out ([Mohr, 1997] and [Zweifel, 1997]). They provide a different, highly interesting perspective on the issue of severe accidents, and might possibly serve as an opening for future extensions of the scope of the present study towards integrating the technical views with those of social scientists. Practical implementation of the combination of the two perspectives on risk could be pursued within the overall framework for decision support, regarding the problem of accidental risks separately or along with other aspects of importance for energy policy (such as costs, impacts of normal operation, security of supply etc.). Developments regarding the framework and tools for decision-support are presently in progress within the GaBE Project. Input from and participation of policy makers (the intended users) would be highly desirable.

9.3 References

Berg, M., Erdmann, G., Leist, A., Renn, O., Schaber. P., Scheringer, M., Seiler, H. and Wiedenmann, R. (1995), Risikobewertung im Energiebereich (in German). Polyprojekt Risiko und Sicherheit Dokumente, Nr. 7, VDF Hochschulverlag AG an der ETH Zürich.

Chadwick, M. J. ed. (1991), Key Issue Paper No. 3 by International Expert Group 3: Comparative Environmental and Health Effects of Different Energy Systems for Electricity Generation. Proceedings of Senior Expert Symposium on Electricity and the Environment, 13-17 May 1991, Helsinki, Finland.

DeKay, M. and McClelland, G. H. (1993), Predicting Loss of Life in Cases of Dam Failure. Risk Analysis, **13** (1993) 193-205.

Dones, R., Gantner, U., Hirschberg, S., Doka, G. and Knoepfel, I. (1996), Environmental Inventories for Future Electricity Supply Systems for Switzerland. PSI Report Nr. 96-07, Paul Scherrer Institute, Wurenlingen and Villigen, Switzerland, February 1996.

EC/IAEA/WHO (1996), Summary of the Conference Results of the EC/IAEA/WHO International Conference: “One Decade after Chernobyl — Summing up the Consequences of the Accident”, 8-12 April 1996, Vienna, Austria. IAEA Proceedings Series, Vienna (1996) 3-17.

Encyclopaedia Britannica (1974-1997), Book of the Year. University of Chicago, 1974-1997.

ExternE (1996), Externalities of Energy, Vol. 5: Nuclear. Published by the European Commission Directorate General XII, L-2985 Luxemburg.

Frischknecht R. (Ed.) et al. (1996), Ökoinventare von Energiesystemen - Grundlagen für den ökologischen Vergleich von Energiesystemen und den Einbezug von Energiesystemen in Ökobilanzen für die Schweiz. 3rd Ed. (in German), Swiss Federal Institute of Technology Zurich (ETHZ) / Paul Scherrer Institute (PSI), Zurich, Switzerland, July 1996.

Fritzsche, A. F. (1988), Gesundheitsrisiken von Energieversorgungssystemen; Von der Kohle bis zu Energien der Zukunft und den Rohstoffen bis zu Entsorgung (in German). Köln: Verlag TÜV Rheinland.

Fritzsche, A. F. (1989), The Health Risks of Energy Production. Risk Analysis, **9** (1989) 565-577.

Haller M. and Maas, P. (1994), Bericht'94 (in German). Stiftung Risiko-Dialog, St. Gallen, Switzerland.

Hirschberg, S. (1992), Prospects for Probabilistic Safety Assessment. Nuclear Safety, **33** (1992) 365-380.

Hirschberg, S. (1996), Key Methodological Issues, 33 pp., March 1996. Contribution to the IAEA Guidelines for the Comparative Assessment of Health and Environmental Impacts of Electrical Energy Systems (to be published 1998).

Hirschberg, S. and Cazzoli, E. (1994), Contribution of Severe Accidents to External Costs of Nuclear Power. Proceedings of ENS Topical Meeting on PSA/PRA and Severe Accidents '94, 17-20 April 1994, Ljubljana, Slovenia.

IEA (1996), Energy Statistics and Balances, OECD (1960-1995), Non-OECD (1971-1995). International Energy Agency, Diskette Service, OECD, Paris.

Königswieser, R., Haller, M., Maas, P., Jarmai, H., ed. (1996), Risiko-Dialog, Zukunft ohne Harmonieformel (in German). Köln: Deutscher Instituts-Verlag GmbH.

Mohr, E. (1997), Severe Accidents in the Energy Sector: Comment. University of St. Gallen, Switzerland.

RfF (1993), Fatal Hazardous Materials Accidents Database. Resources for the Future, N. W., Washington D.C., USA.

Sandman, P., Covello, V. and Slovic, P. (1988), Risk Communication, Risk Statistics and Risk Comparisons: A Manual for Plant Managers. Chemical Manufacturers Associations, Washington D.C., USA.

SilverPlatter Directory (1998), A Directory of Electronic Information Products. SilverPlatter Information Ltd., Chiswick, London, UK.

Swiss Re (1970-1996), Naturkatastrophen und Grossschäden (in German). Nr. 1, January 1970, 1971,..., 1996), Swiss Reinsurance Company, Zurich, Switzerland.

UNSCEAR (1993), 1993 Report to the General Assembly, with Scientific Annexes. United Nations Scientific Committee on the Effects of Atomic Radiation, United Nations Sales Publication E.94.IX.2, New York, USA.

USDOE (1988), Energy Technologies & the Environment. Environmental Information Handbook, U.S. Department of Energy, Washington D.C., USA.

USNRC (1990), Severe Accident Risks: An Assessment for Five U.S. Nuclear Power Plants. Final Report. Report NUREG-1150, U.S. Nuclear Regulatory Commission, Washington D.C., USA.

Zweifel, P. (1997), Kommentar zu "Severe Accidents in the Energy Sector" von S. Hirschberg, G. Spiekerman und R. Dones (in German). University of Zurich, Switzerland.

List of Abbreviations

ACNS	Advisory Committee on Nuclear Safety
AHE	Acute Hazardous Events
ARS	Acute Radiation Sickness
BLEVE	Boiling liquid expanding vapour explosion
CANDU	Canada Deuterium Uranium (a pressurised-heavy-water, natural-uranium power reactor designed first in the 1960's by a consortium of Canadian government and private industry)
Cb	Dam of type buttress
CDDFA	Catalogue of Dam Disasters, Failures and Accidents
CDF	Core Damage Frequency
CEPN	Centre d'Etude sur l'Evaluation et la protection dans le domaine Nucléaire
CO	Carbon monoxide
CRP	Co-ordinated Research Programme
CSNI	Committee on the Safety of Nuclear Installations
DECADES	Databases and Methodologies for Comparative Assessment of Different Energy Sources
DNV	Det Norske Veritas
DPE	Dynamic Positioning Equipment
EC	European Commission
EDF	Environmental Defence Fund
ENI	Ente Nazionale Idrocarburi
ENSAD	Energy-related Severe Accident Database
EOP	Emergency Procedures
EPA	Environmental Protection Agency
Er	Dam of type rockfill
ERG	Energy Research Group
ESCAP	Economic and Social Commission for Asia and the Pacific
ETDE	Energy Technology Data Exchange
ETHZ	Eidgenössische Technische Hochschule Zürich Swiss Federal Institute of Technology
FACTS	Failure and Accidents Technical Information System
GaBE	Ganzheitliche Betrachtung von Energiesystemen Comprehensive Assessment of Energy Systems
GHG	Green House Gas
GWe*a	Giga Watt electric year
HSK	Hauptabteilung für die Sicherheit von Kernanlagen
IAEA	International Atomic Energy Agency
IBRD	Institute for Biological Research and Development
ICOLD	International Commission On Large Dams
ICRP	International Commission on Radiological Protection
IEA	International Energy Agency

IIASA	Institute of Islamic and Arabic Sciences in America
INIS	International Nuclear Information Database
ISEI	Institute of Systems Engineering and Information, Ispra, Italy
LCA	Life Cycle Analysis
LPG	Liquid Petroleum Gas
LWR	Light Water Reactor
MACCS	MELCOR Accident Consequence Code System
MARS	Major Accident Research Reporting System
MHIDAS	Major Hazards Incidence Data Service
MMS	Mineral Management Services
Mv	Dam of type multi-arch
NEA	Nuclear Energy Agency
NMHSA	National Mine Health and Safety Academy
NOAA	National Oceanic and Atmospheric Administration
NPP	Nuclear Power Plant
NRC	National Response Center
NUREG/CR	Nuclear Regulatory Commission Report
OECD	Organisation for Economic Co-operation and Development
OFDA	Office of US Foreign Disaster Assistance
OPEC	Organisation of the Petroleum Exporting Countries
ORNL	Oak Ridge National Laboratory
PC	Personal Computer
PDS	Plant damage states
Pg	Dam of type gravity
PRA	Probabilistic Risk Assessment
PSA	Probabilistic Safety Assessment
PSI	Paul Scherrer Institute
PWR	Pressurised Water Reactor
QRA	Quantitative Risk Assessment
R&D	Risk and Development
RBMK	RBMK is the Russian acronym for graphite moderated, boiling water cooled channel type reactors designed in the former Soviet Union
RfF	Fatal Hazardous Material Accident Database / Resources for the Future
SIGMA	The „Sigma“ Publication, Schweizer Rück
SRD	Safety Reliability Directorate
Te	Dam of type earth
TMI	Three Mile Island
TNO	Institute of Environmental Sciences, energy Research and Process Innovation, Apeldorn, The Netherlands
UBA	Umweltbundesamt, Germany
UN	United Nations
UNIDO	United Nations Industrial Development Organisation

UNSCEAR	United Nations Scientific Committee of the Effects of Atomic Radiation
USAEC	U.S. Atomic Energy Commission
USDOE	U.S. Department of Energy
USNRC	U.S. Nuclear Regulatory Commission
USSR	Union of Soviet Socialist Republics
Va	Dam of type arch
WASH	Washington
WHO	World Health Organisation
WMO	World Meteorological Organisation
WOAD	World-wide Offshore Accident Databank