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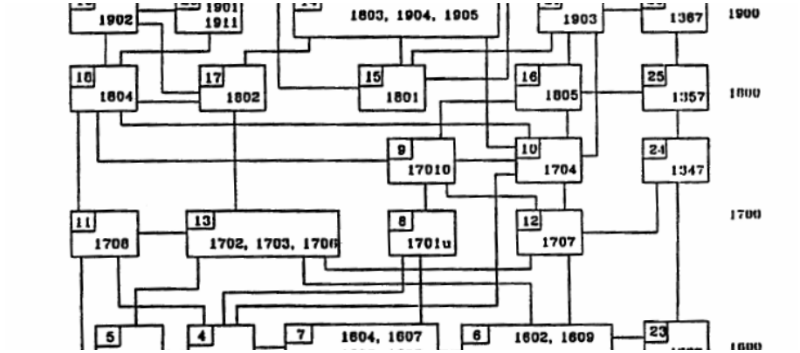
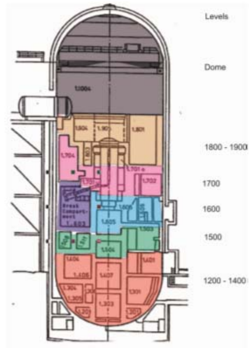
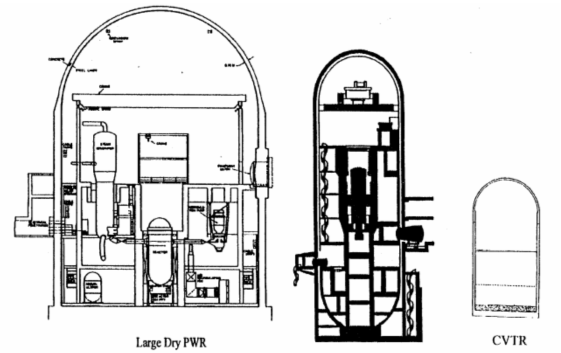






HDR Test Analyses with MELCOR

Presented by Jesse Phillips

SAND2017-3409 C

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

Overview

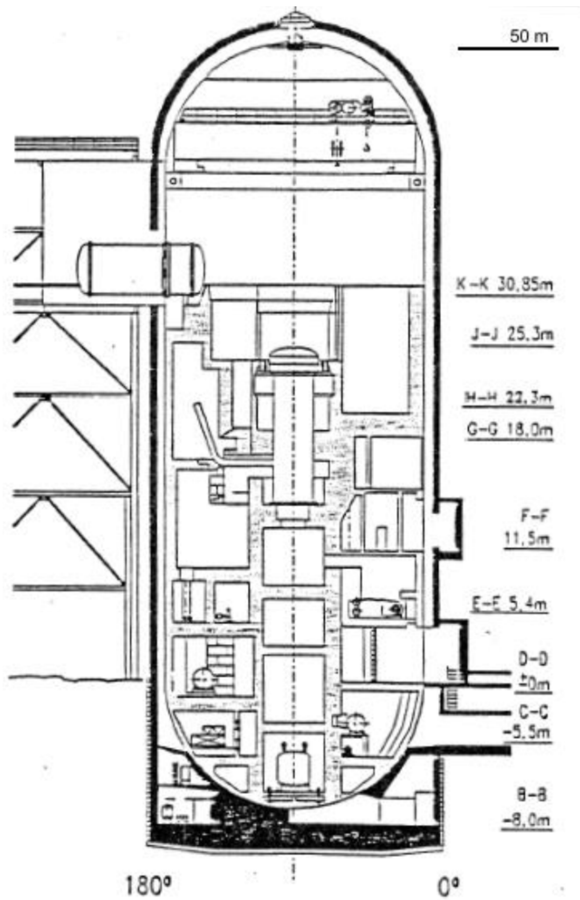
- Introduction
  - Purpose
  - Facility
  - Model development
- Present the results from International Standard Problems (ISPs) which the U.S.NRC/Sandia National Labs were participants
  - V44 : ISP-16
  - T31.5 : ISP-23
  - E11.2 : ISP-29 (Time permitting)
- Conclusions/Key Findings

Purpose of Experiment Evaluation

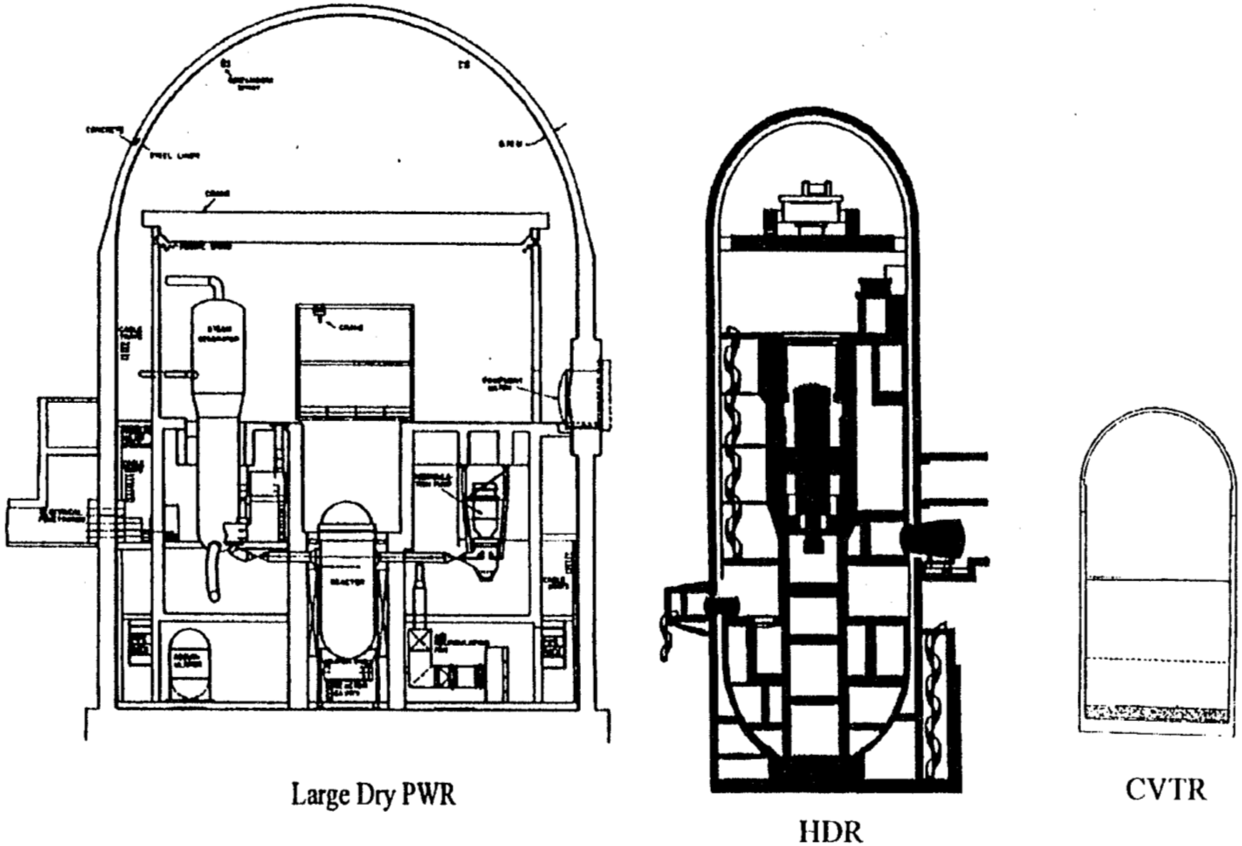
- Simulate and investigate key phenomena associated with containment licensing for loss of coolant accidents
  - Expansion and transport of high energy steam-water
  - Heat and mass transfer to structures
  - Containment gas mixing and stratification
    - Investigations of the above phenomena are performed across sensitivity studies, comparison between different models, and benchmarking
  - Validation of MELCOR results by comparison with the CONTAIN code
    - Key metrics are simply peak pressure and temperature for containment analysis.
    - Gas composition acts to indicate mixture and stratification modeling

Heissdampfreaktor (HDR) Facility

- Non-prototypic considerations in comparison to the commercial U.S. reactor fleet
  - Aspect ratio
  - Compartmentalization
  - Structure to free volume ratio
  - Break entrance height
  - Break room size
  - Flow area containment
  - Missing/degraded structures



HDR Facility – Scale/Comparts



Model Setup

- Original NRC/SNL participation in the ISPs was with the CONTAIN code
  - CONTAIN decks were converted to MELCOR input
    - Input discrepancies, due to differing input requirements, were addressed by hand as needed.
      - Example HS must exist within the bounds of a Control Volume (CV) in MELCOR but elevation is less relevant in CONTAIN since ATM/POOL are separately modeled.
  - Models are primarily HS/FL/CVH descriptions with mass/energy sources
  - Different experiments were modeled using different nodalizations and component model definitions
  - Higher fidelity models do may not directly equate to a more accurate representation.

Reference Analyses

- Temperature Flashing – DBA Guidance
- NOFOG – DBA Guidance
  - Settle out all suspended water droplets
- Natural/Forced Convection
  - Specified to use a similar method as CONTAIN
  - Max (Nu_{nat},Nu_{for})
  - Nu_{nat} adjusted to match CONTAIN correlation
    - Lead multiplier coeff set to 0.14 from default of 0.1
- Dynamic Film Flow
  - CONTAIN typically uses maximum film drainage
    - $Film_{depth} > Film_{limit}$; Drain to Limit
    - But has dynamic film flow available as well

Summary of Model Options

Test (ISP/HDR Proj)	Model/Input Option
V44 (ISP-16)	• 33 cell nodalization (33-CV) • HDR thermal properties for steel and concrete • No convective velocities • Default film thickness (film tracking) • No thermal radiation • Condensate drained to pools • Flow loss coefficients set to unity • Temperature flashing (default) • No fog
T31.5 (ISP-23)	• Same as V44 (ISP-16)
E11.2 (ISP-29)	• 15 cell nodalization (15-CV) includes secondary containment space • CONTAIN thermal properties for steel and concrete • No convective velocities • Default film thickness (dynamic film flow) • No thermal radiation • Blowdown & late-time external steam injection for pre-conditioning • Coolant energy extraction (Hydrogen sensors) • Condensate drained to pools • Overflow of pools to sump • Flow loss coefficient set to unity • Temperature flashing (default) • Fog model using aerosol physics • Exterior shell water flooding of dome • Secondary containment space modeled

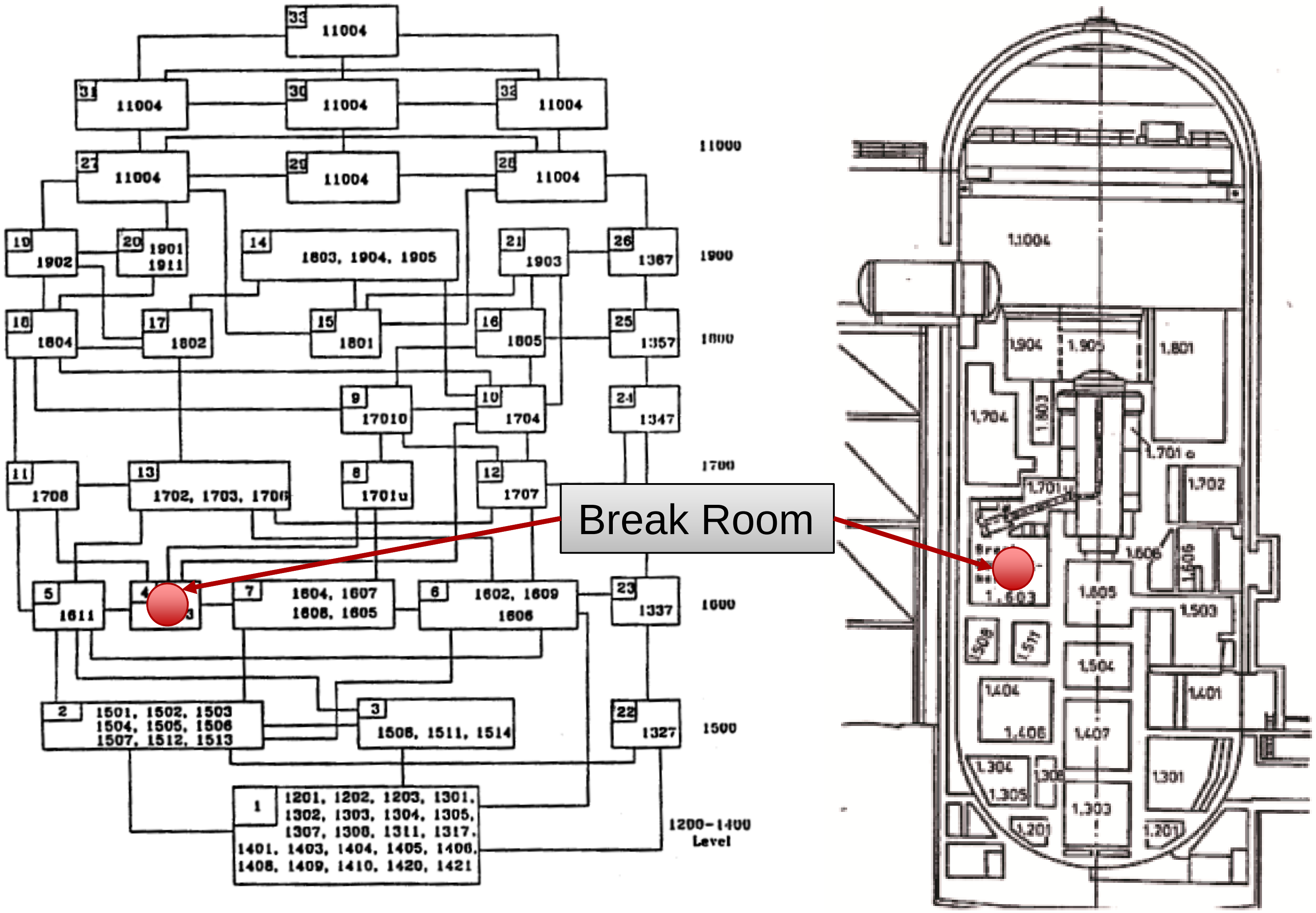
Test Suite

Experiment	Type	Test Conditions	General Observations
HDR V44 (ISP-16)	LOCA	55 sec 2-phase steam blowdown in a small (280 m^3) mid-elevation room.	Test provides an indication of the effect of force convective condensation during a blowdown event. Pressure differentials between blowdown and adjacent compartments are recorded.
HDR T31.5 (ISP-23)	LOCA	55 sec 2-phase steam blowdown in a large (793 m^3) mid-elevation room. ISP-23 exercise extends to 20 minutes.	Pressure response similar to V44.
HDR E11.2 (ISP-29)	SBLOCA	12 hr steam injection for pre-heating prior to 20 min hydrogen/helium injection (injections at mid-elevation). Followed by 3 hr steam injection in lower containment and 3 hr 45 min. outer vessel spray cooling.	Stable temperature and steam stratification developed near the injection location. Hydrogen stratification observed with enhancement in the upper containment due to low steam injection and later outer spray cooling.

V44 (ISP-16)

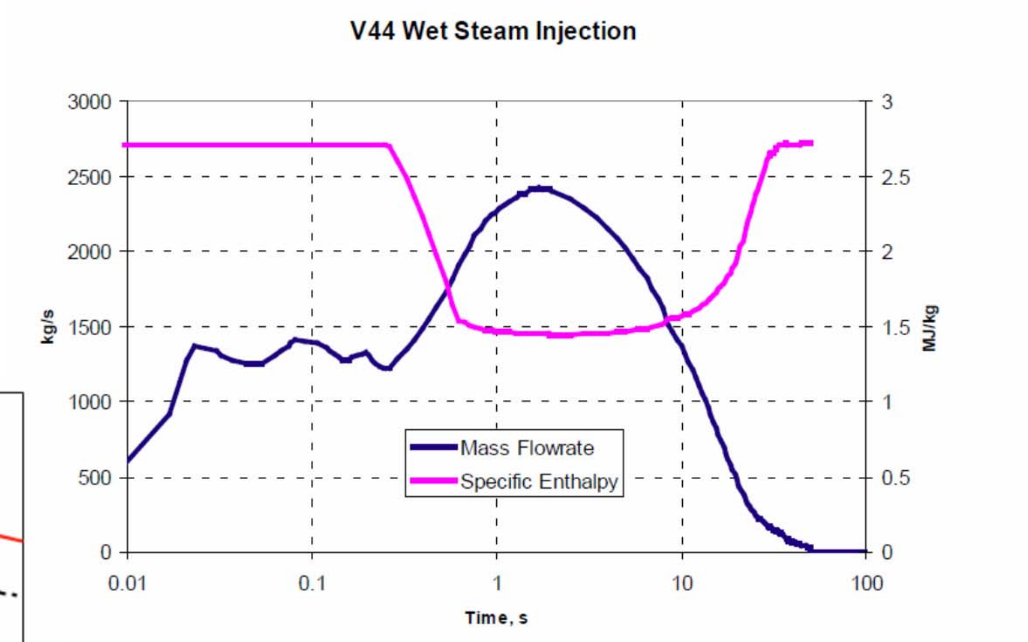
- Break room is notionally small
  - But very open to surrounding rooms
  - Forced/Natural convection results
- Sensitivities performed
  - Flashing treatment investigated
    - Temperature / Pressure Flashing
  - User specified velocities (Forced Convection)
  - Single control volume
  - Max film drainage (MAXENFORCE)
  - FOG active and/or RN enabled
- Original 5 CV model was discarded and instead represented with the T31.5 (ISP-23) model definition with 33CV

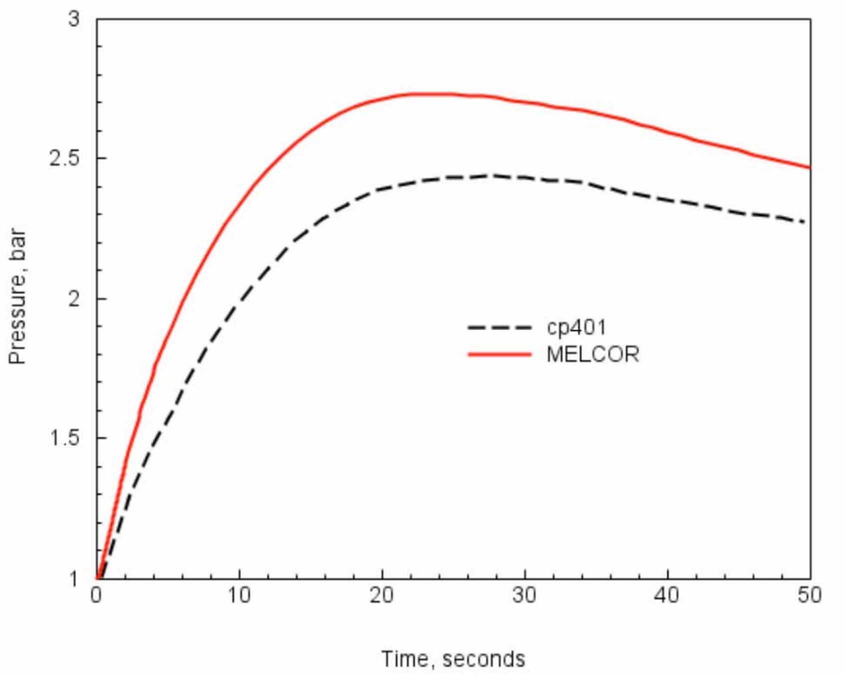
V44/T31.5 Nodalization
V44 Break Site



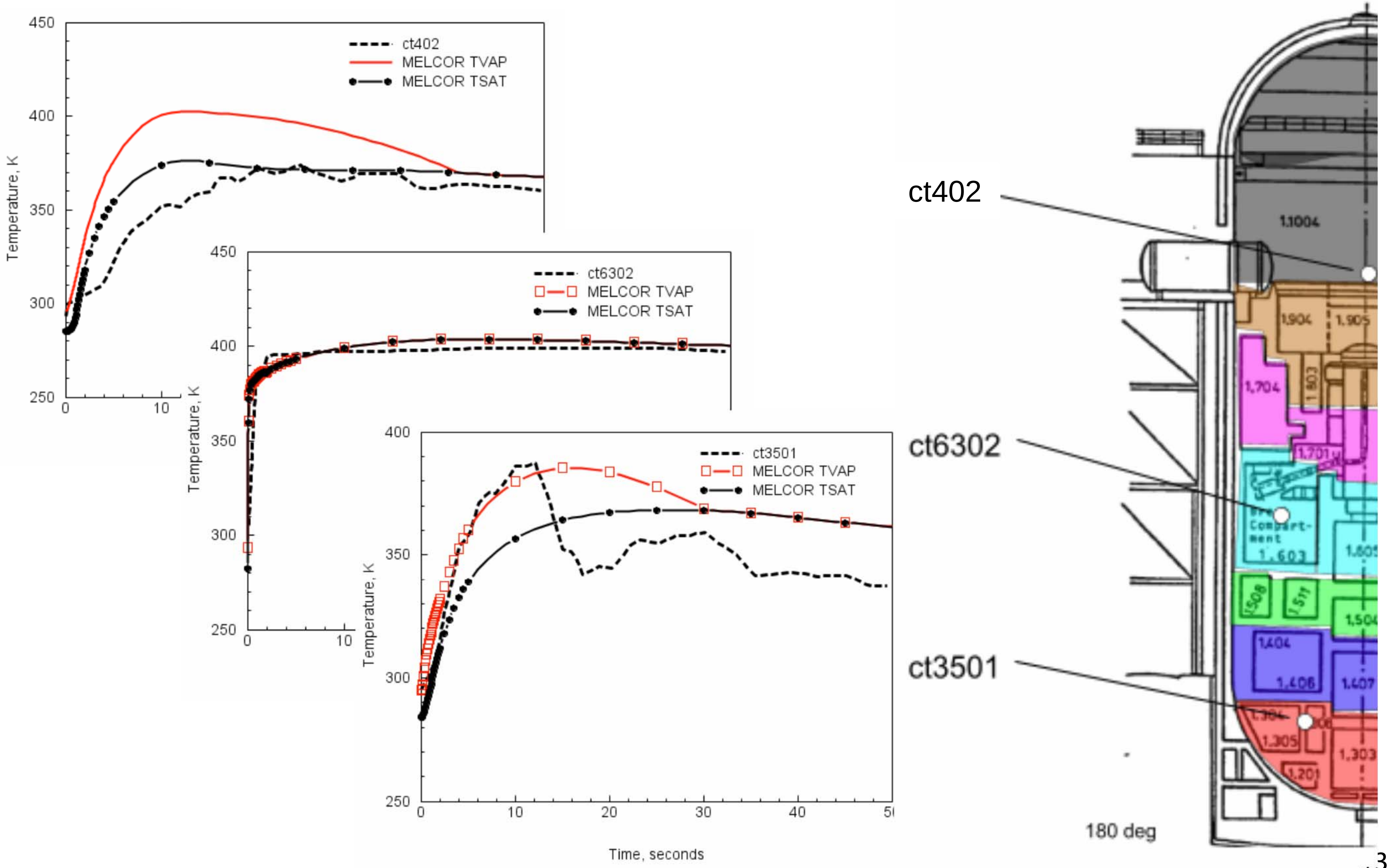
V44 – Injection Source Reference Analysis – Pressure

- Loss of Coolant Accident

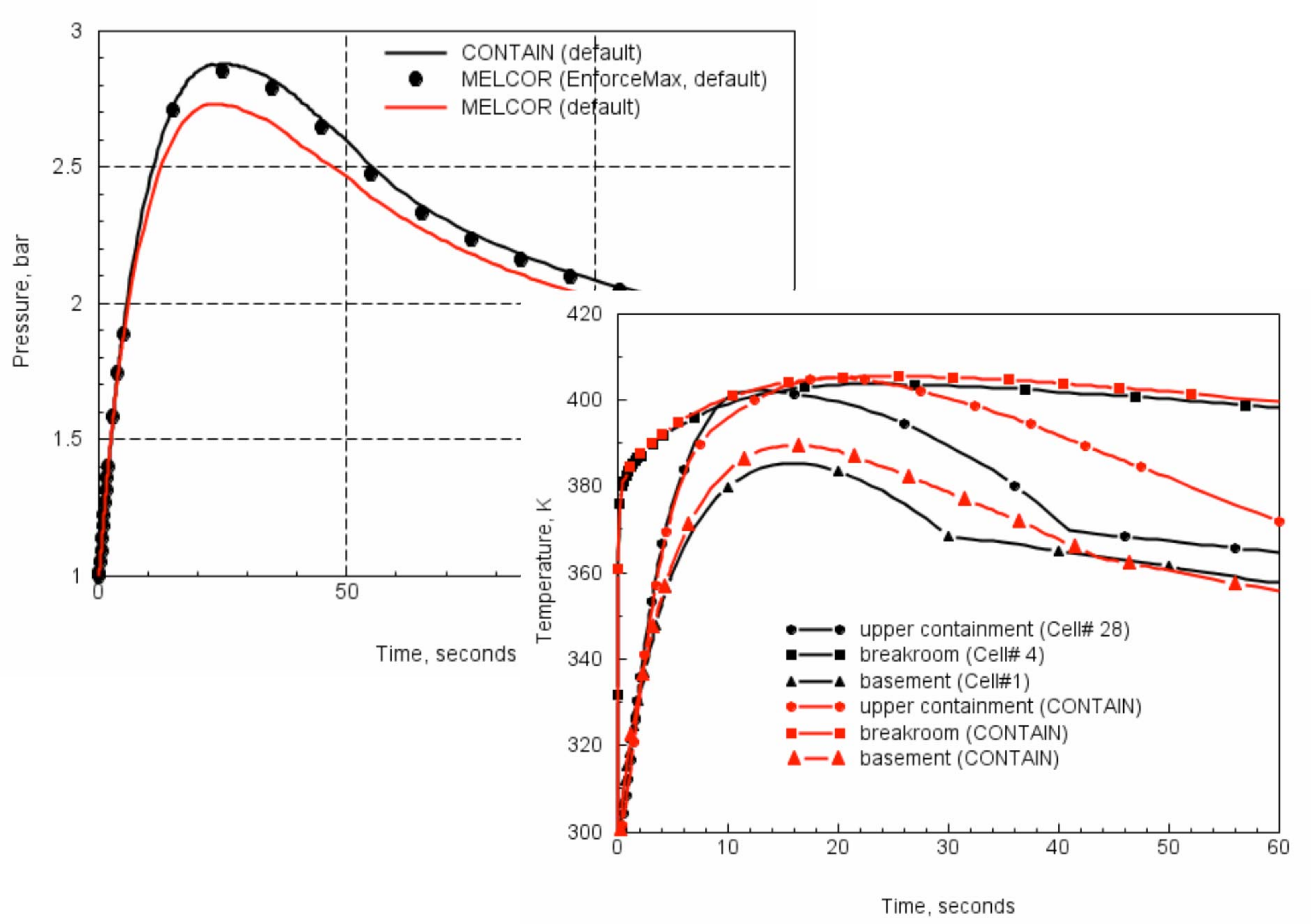




Reference Analysis - Temperature

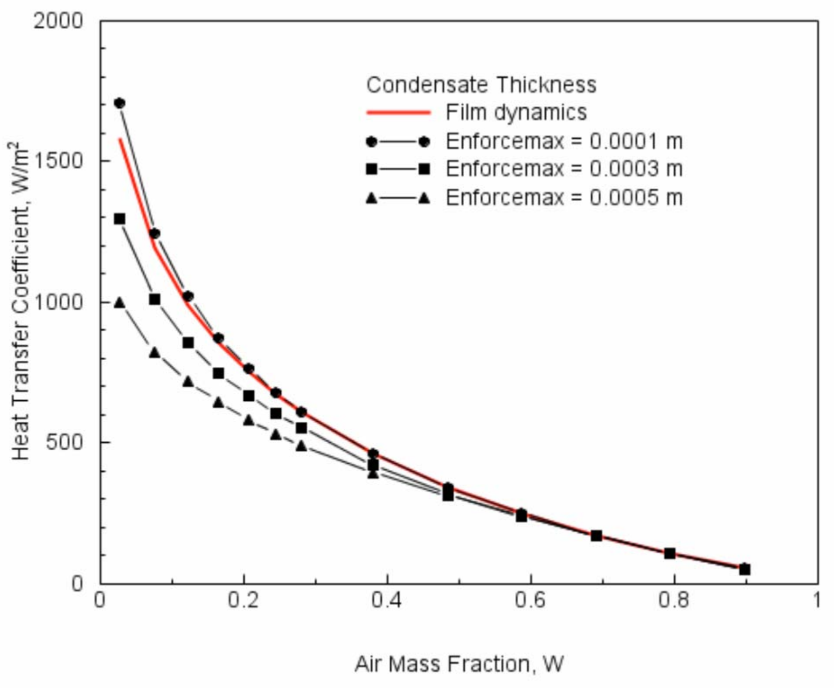


V44 CONTAIN/MELCOR Comparison



Results

- Significance of film modeling is observed.
  - This led to a code enhancement to permit a maximum film drainage model to be imposed.
  - New model permits investigation of the relevance of film depth, the corresponding heat transfer, and impact to peak pressure
  - Dehbi test geometry
    - Comparing dynamic modeling
    - With varying film depth



V44 Sensitivities – Peak Pressure

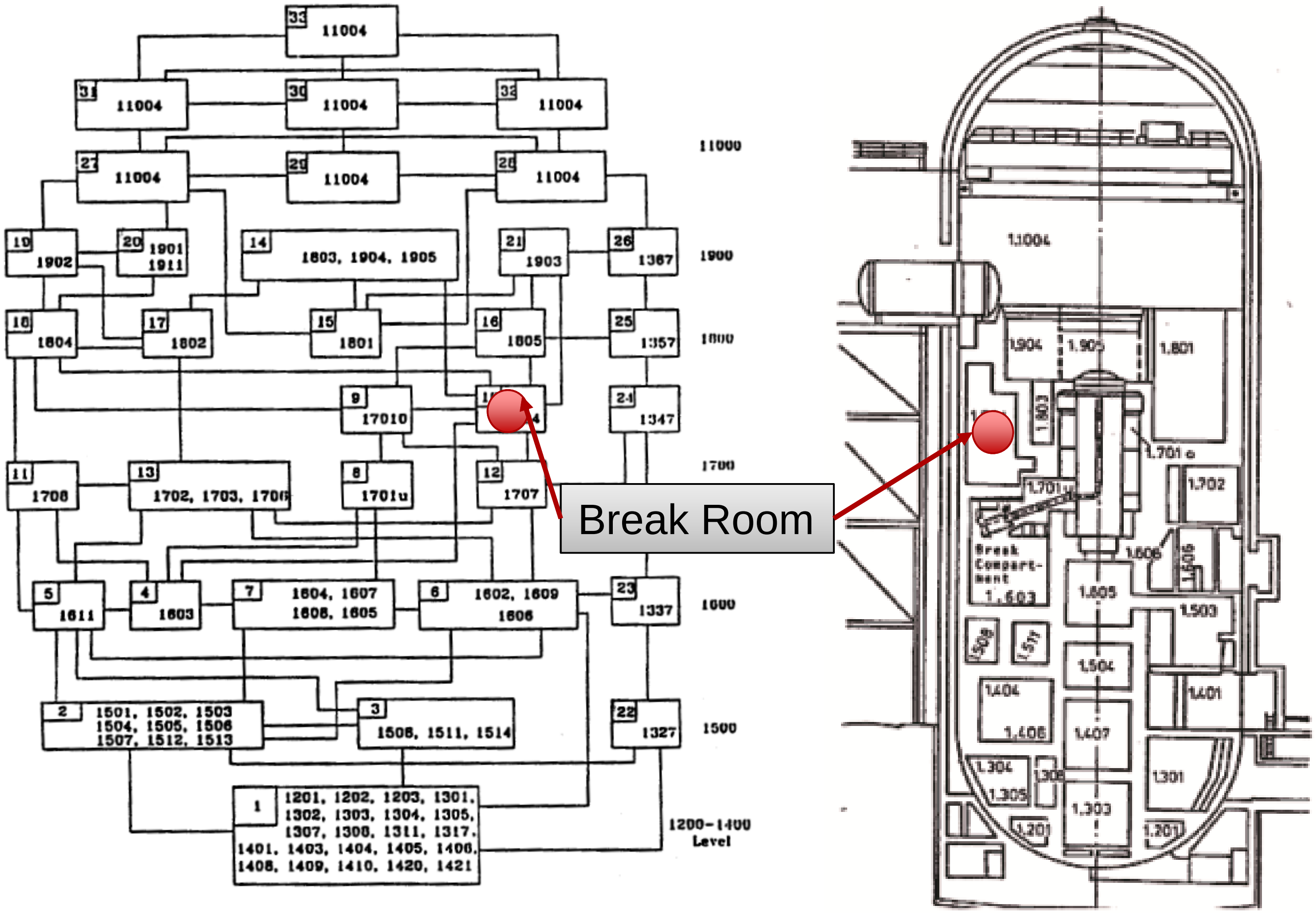
	Sensitivity	Peak Pressure (MPa) [%]*
Measured	---	0.244
Reference	33CV, Temperature Flash, NOFOG, Nat. Conv., dynamic film flow	0.273 [20.1]
Flash Model		
Case 1	Pressure Flash	0.273 [20.1]
Aerosol Physics		
Case 2	FOG active	0.270 [18.1]
Case 2a	FOG and RN1 active	0.267 [16.0]
Forced Convection		
Case 3	Forced Convective Vel. (20 m/s max) Levels 1600	0.267 [16.0]
Case 4	Levels 1600 and 1700	0.261 [11.8]
Case 5	Levels 1500, 1600, and 1700	0.256 [8.3]
Condensate Film Thickness Maximum, m		
Case 6	Enforcemax = 0.0005	0.285 [28.5]
Case 7	Enforcemax = 0.0001	0.272 [19.4]
Case 8	Enforcemax = 0.00005	0.267 [16.0]
Nodalization		
Case 9	Single Cell	0.336 [63.9]
Low-estimate		
Case 10	Cases 2, 5, 8	0.252 [5.6]

* Over-pressure error, % = $((P_{calc} - P_{data})/(P_{data} - 0.1MPa)) * 100$

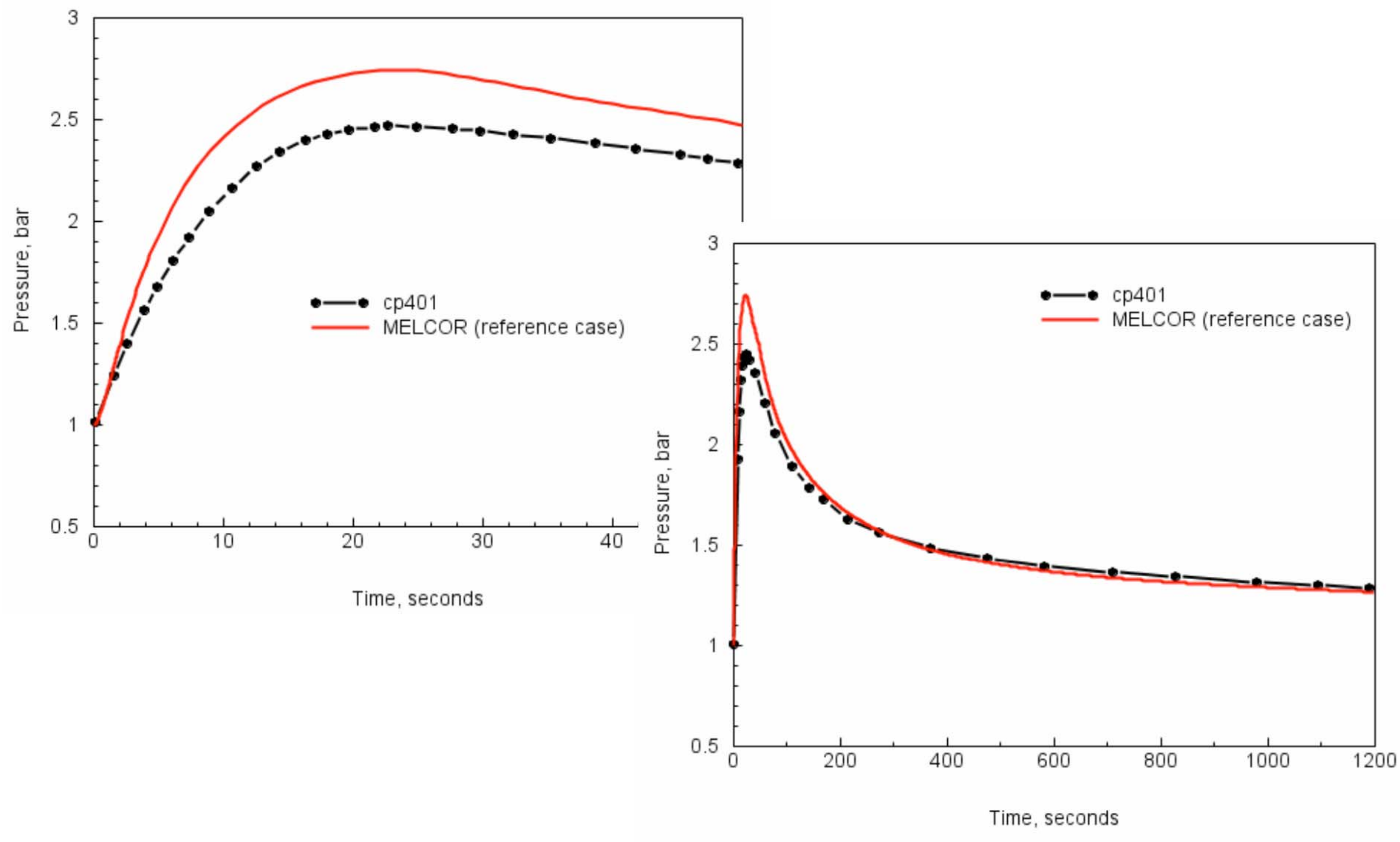
T31.5 (ISP-23)

- Uses a very similar break mass and energy source as the V44, but located in Room 1704
- Test duration extended to post-blowdown evaluation
  - 20 minute test duration
- The model used was developed specifically for this experiment, may provide better indication of local temperatures

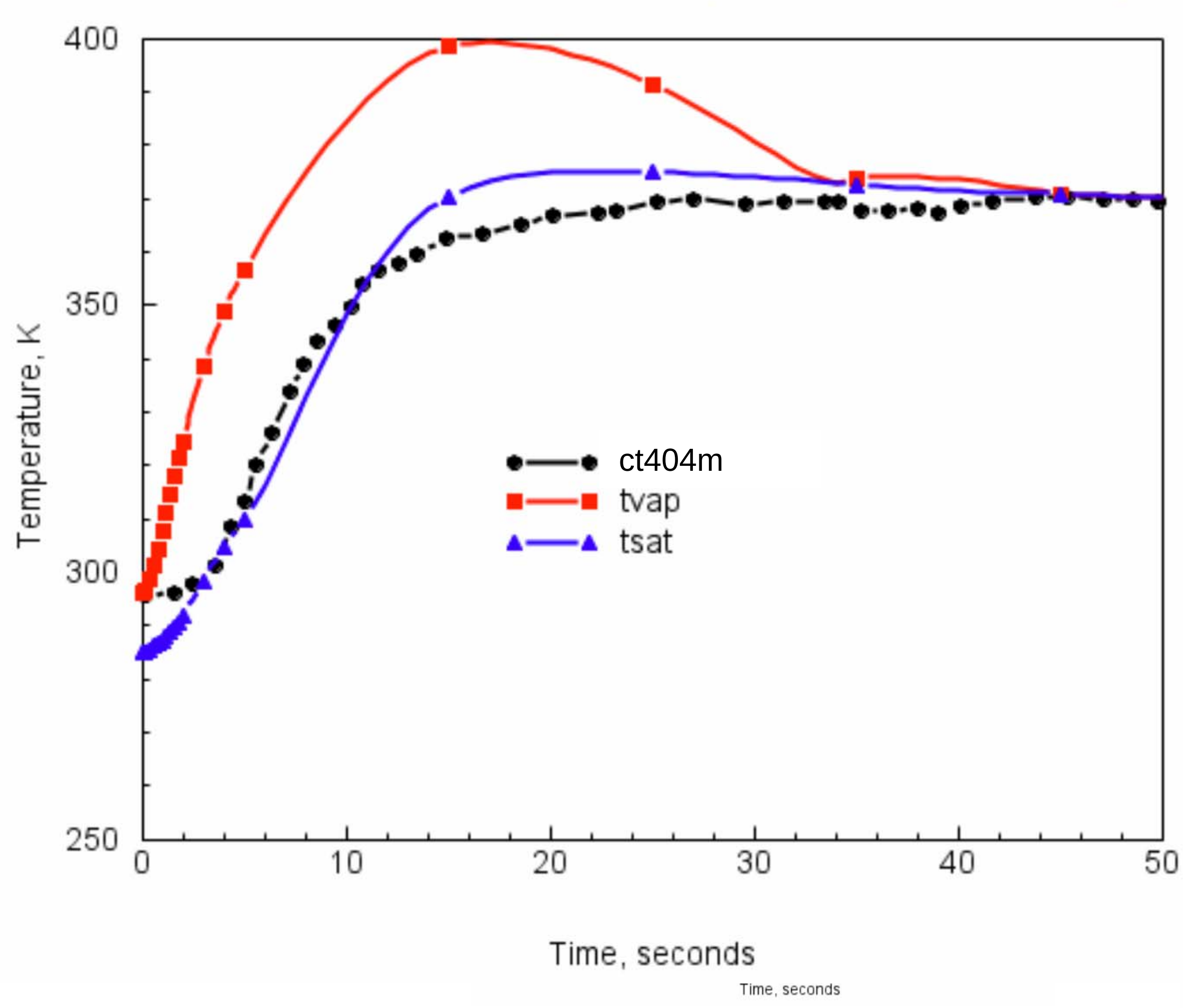
V44/T31.5 Nodalization
T31.5 Break Site

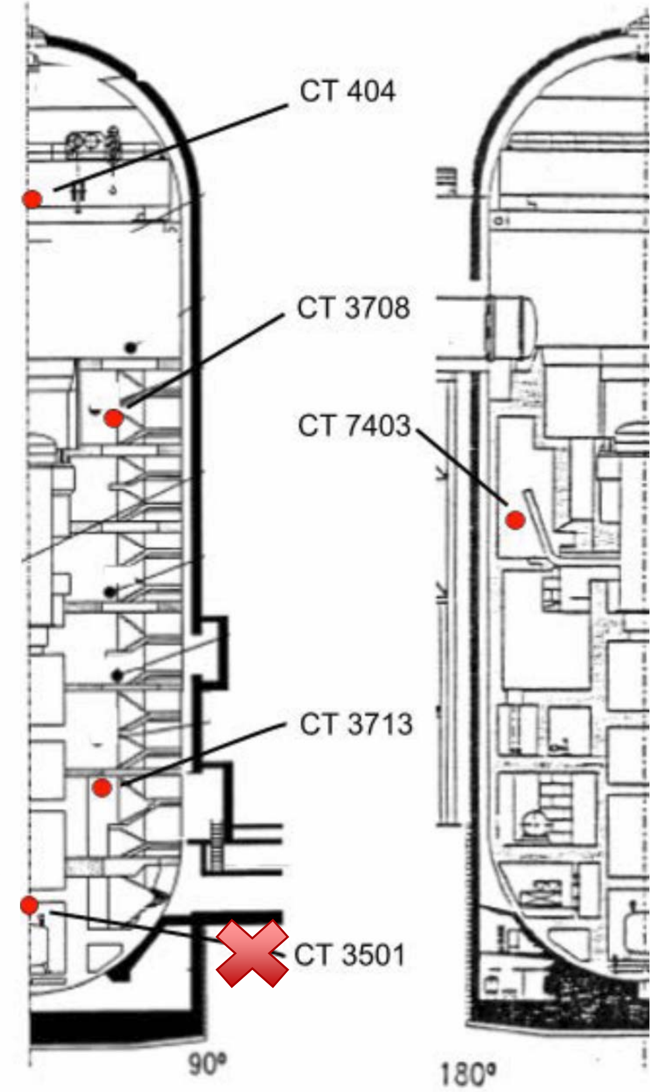


T31.5
Reference Analysis – Pressure

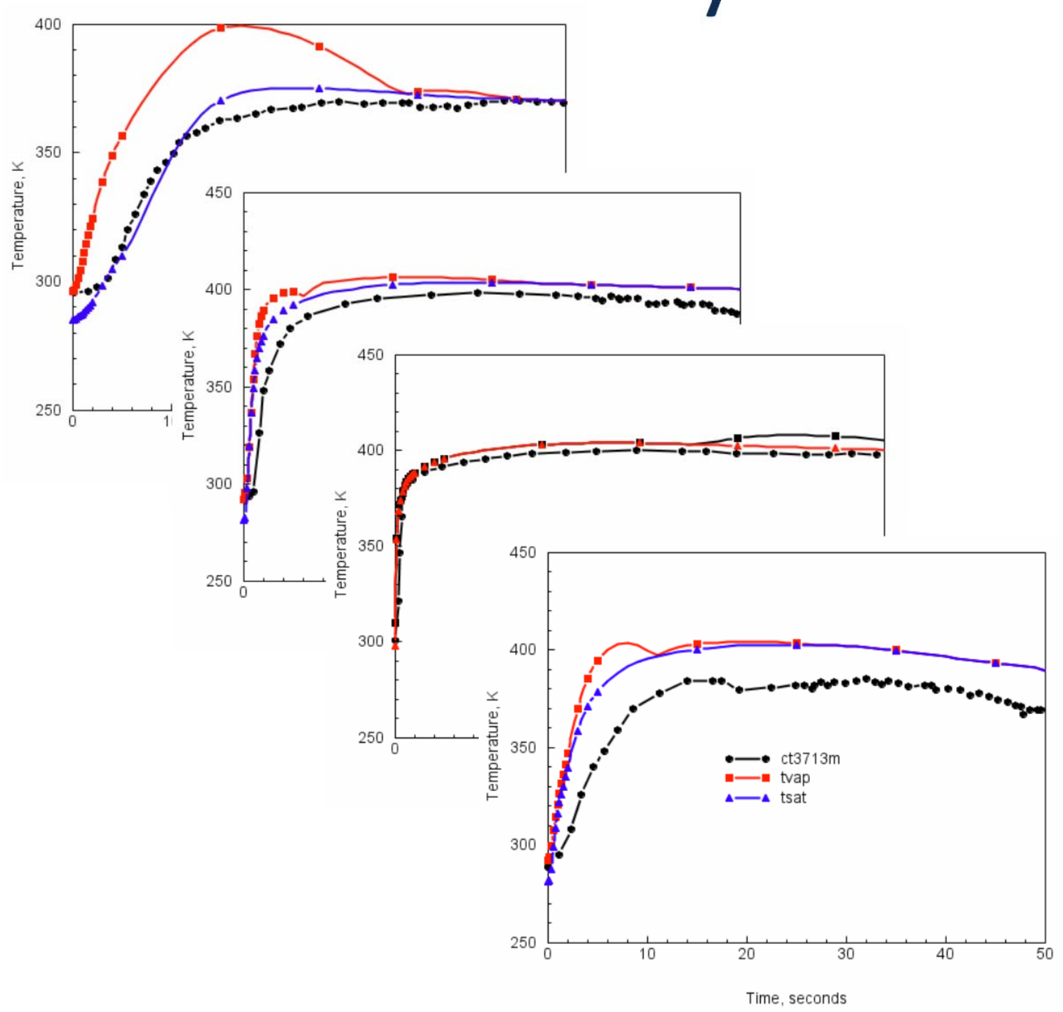


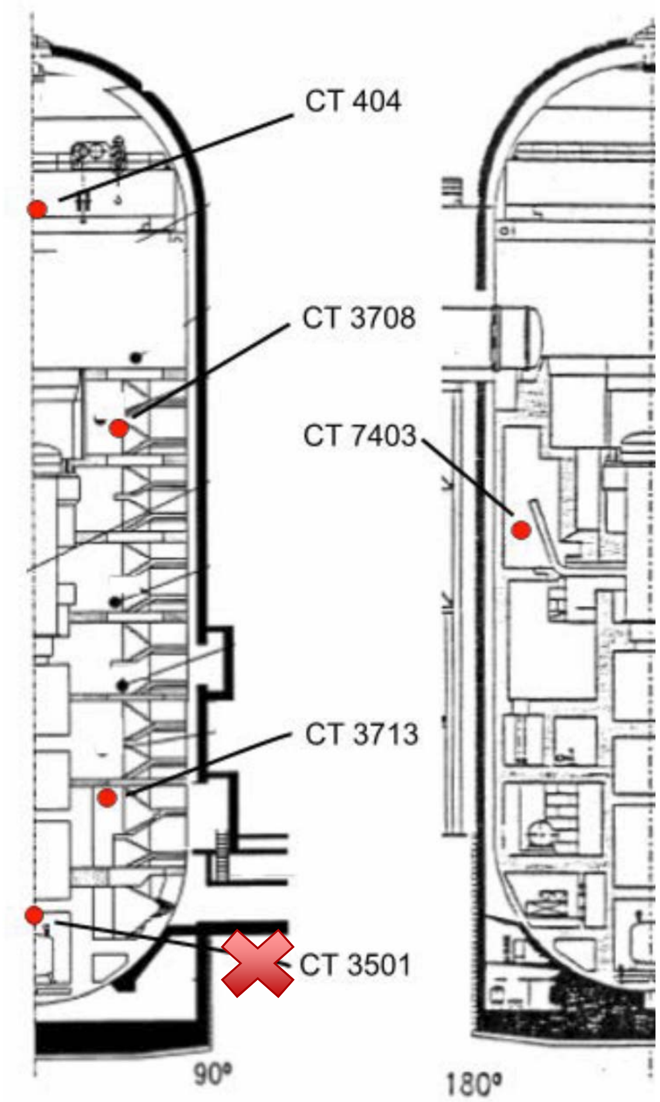
T31.5
Reference Analysis - Temperatures





T31.5
Reference Analysis - Temperatures





T31.5
Reference Analysis - Temperatures

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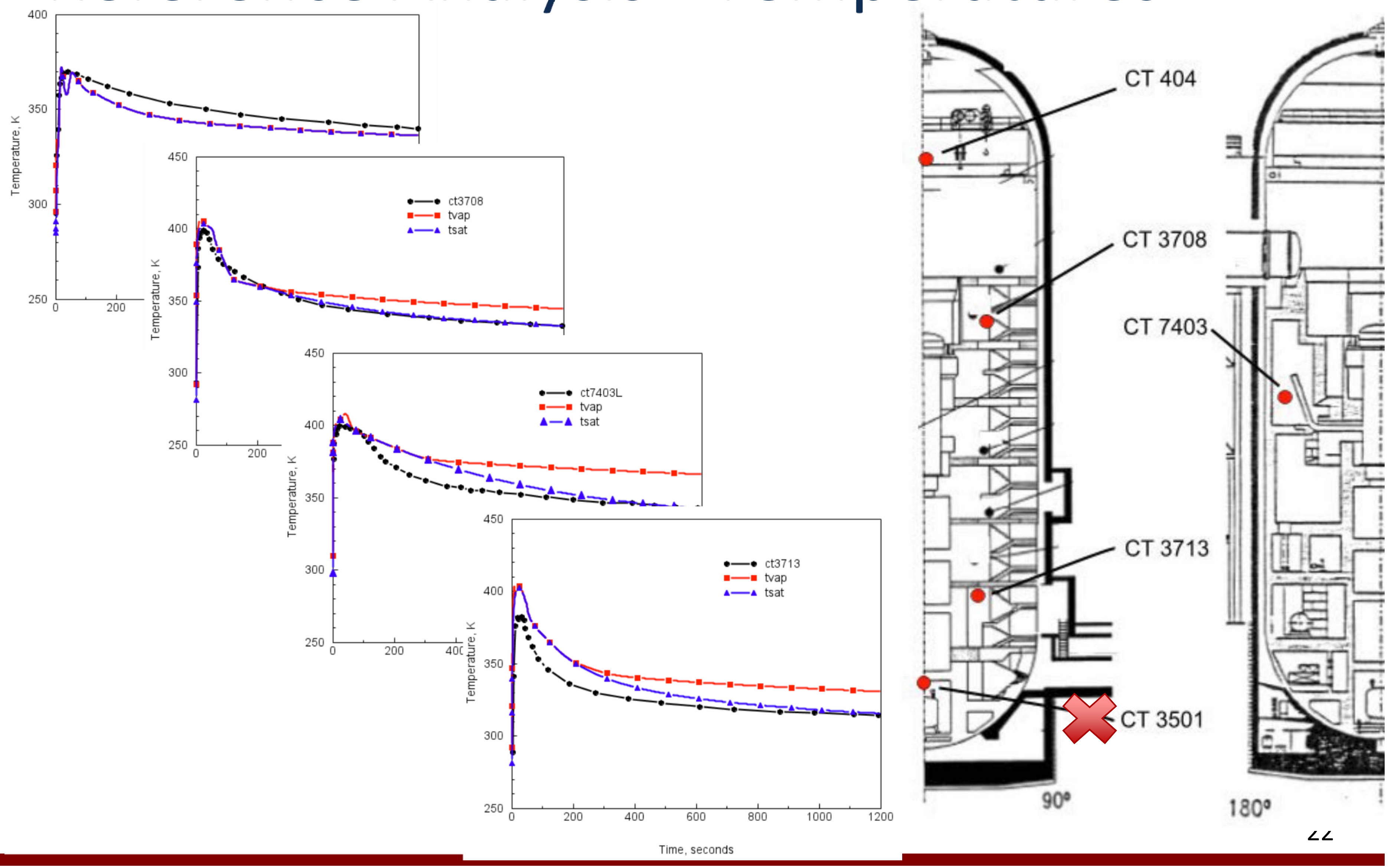
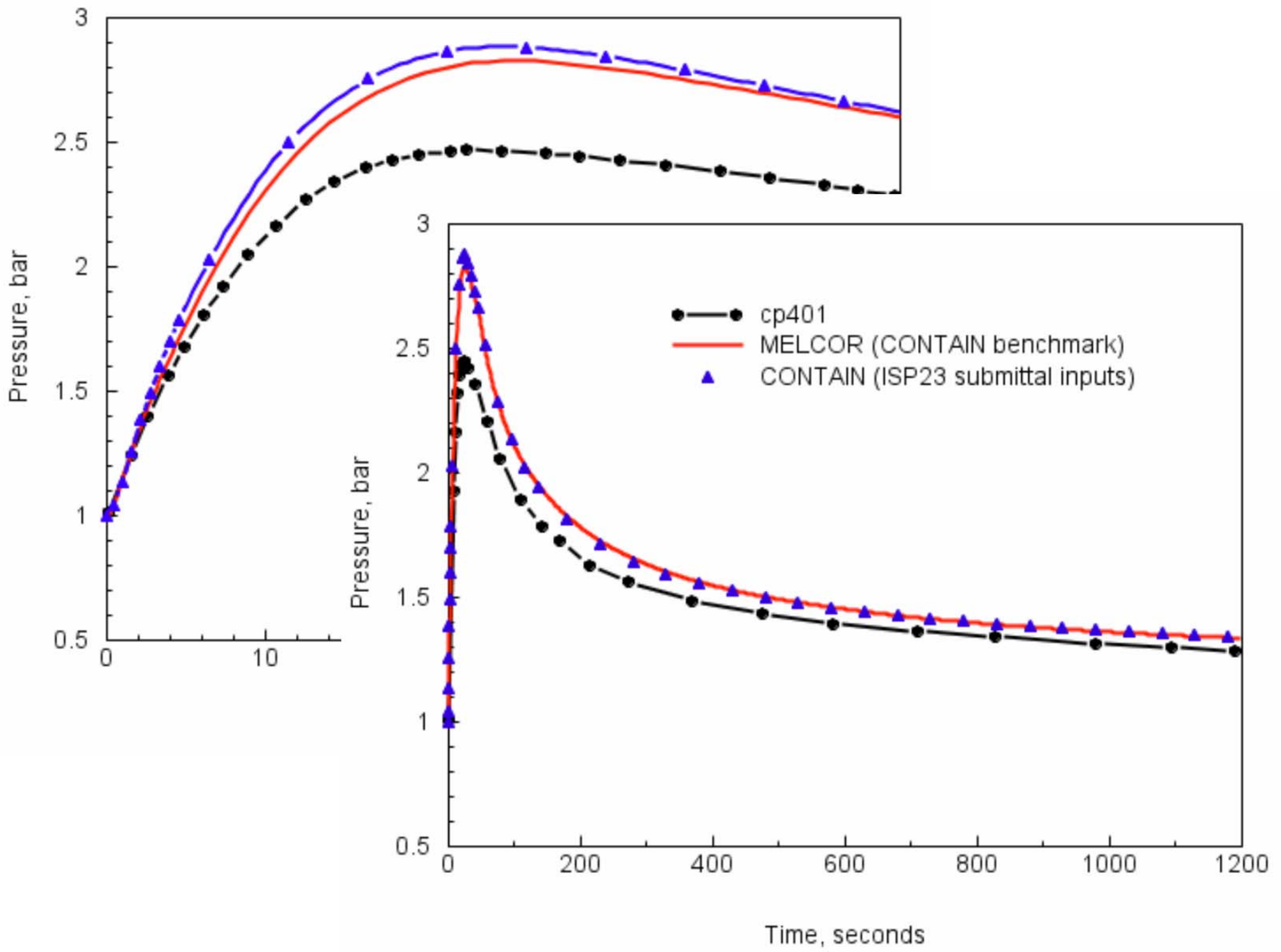
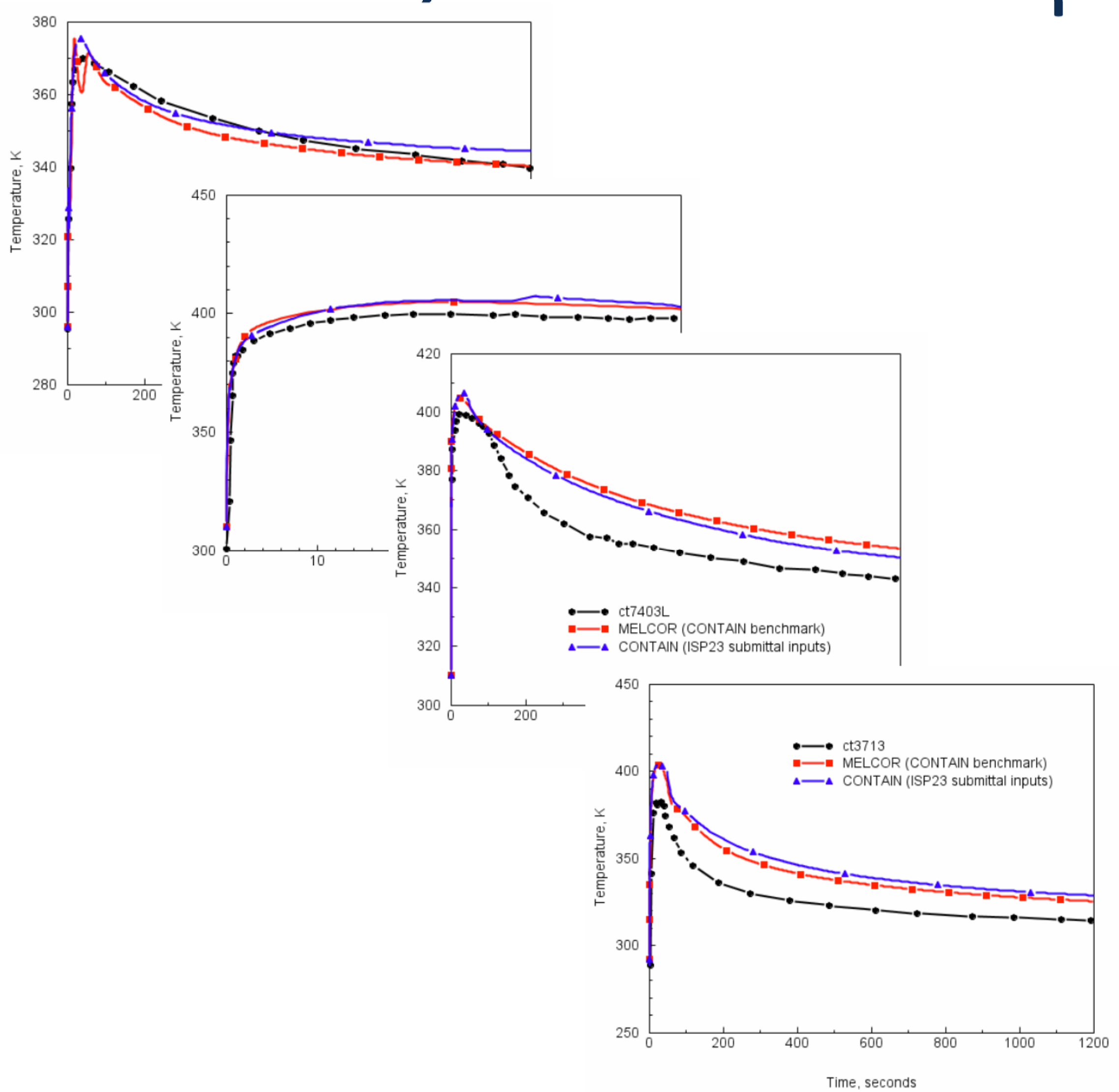
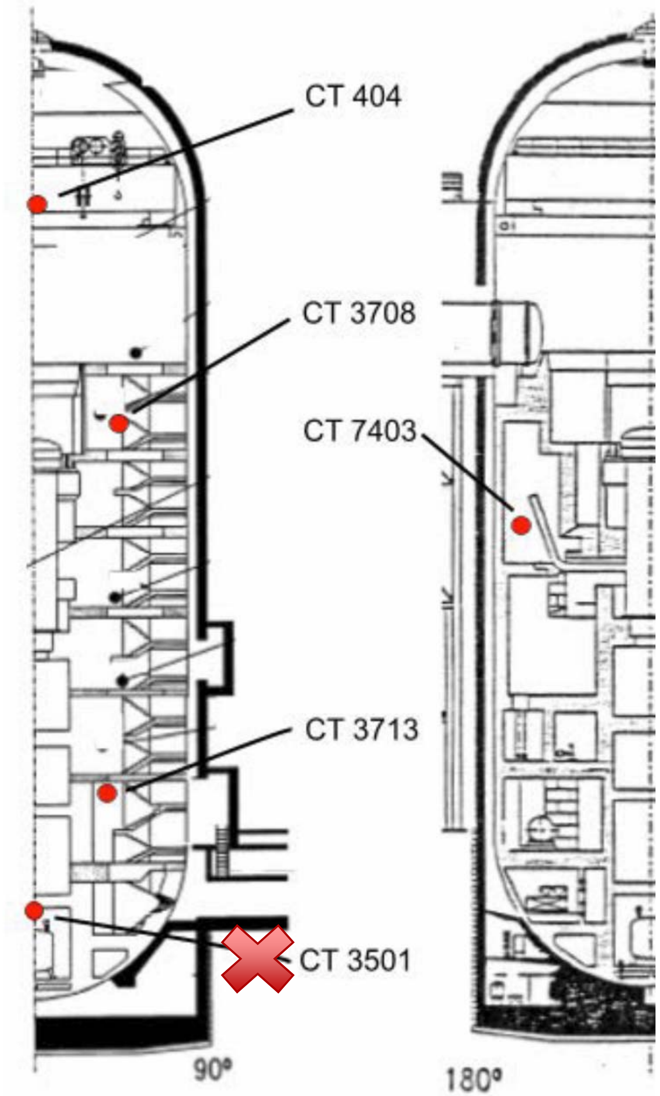


T31.5
CONTAIN/MELCOR Comparison



T31.5
CONTAIN/MELCOR Comparison





T31.5 Sensitivities

	Sensitivity	Pressure (MPa)	
		Peak	Long-term**
Measured		0.250	0.128
Reference model	---	0.274 [19.2]***	0.126 [-7.1]
Aerosol Physics			
Case 1	FOG and RN1 active	0.268 [15.1]	0.128 [0.0]
Forced convection			
Case 2	Forced convection*	0.258 [8.2]	0.127 [-3.6]
Film maximum thickness			
Case 3	Enforcemax = 0.00005m	0.268 [15.1]	0.127 [-3.6]
Case 4	Enforcemax = 0.0005m	0.290 [30.1]	0.130 [7.1]
Combination from above			
Case 5	Cases 1, 2, and 3	0.254 [5.5]	0.129 [3.6]
Nodalization			
Case 6	Single Cell	0.320 [50.7]	0.128 [0.0]

* forced velocity profile as V44 calculation, for levels 1600, 1700 and 1800

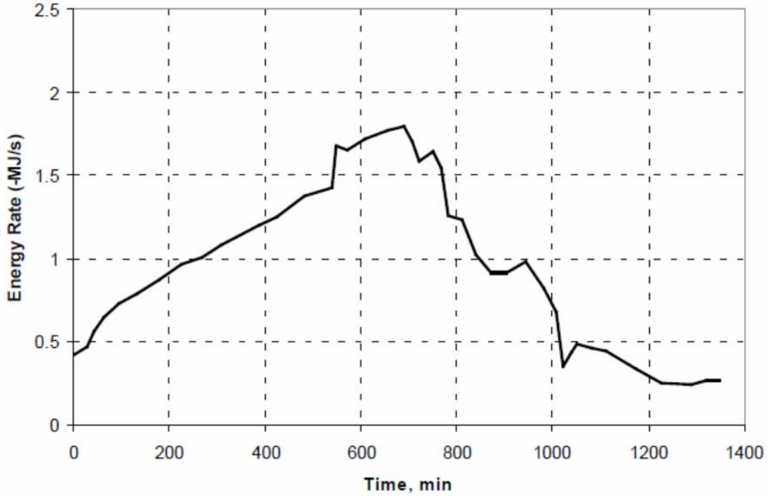
** measured and calculated at 1200 seconds

*** over-pressure error, % = $((P_{calc} - P_{data})/(P_{data} - 0.1MPa)) * 100$

E11.2 (ISP-29)

- Small LOCA with some severe accident consideration
  - Original analyses had a few issues
    - Nozzle was mischaracterized in the experiment, therefore, the blind test results compared poorly
    - Instrumentation cooling lines impacted results and needed to be directly modeled, weighted by number of sensors and partial pressure of vapor for a given CV

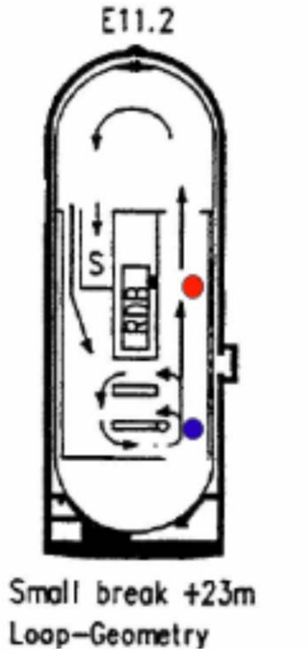
$$f_n = \frac{P_{v,n} cf_n}{\sum_{i}^{n} P_{v,i} cf_i}$$



- 2 separate steam injections with an intermediate Helium injection
- An outer dome spray was used for containment cooling

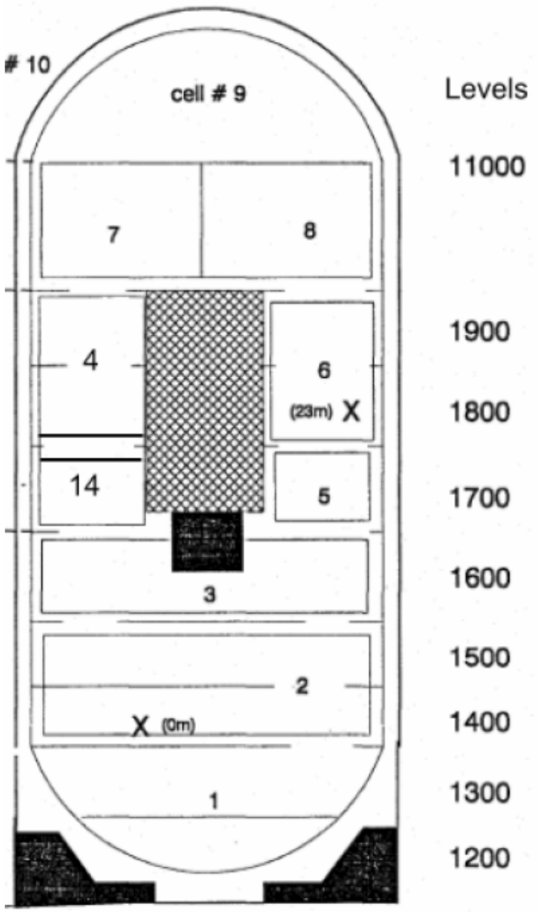
E11.2 Chronology

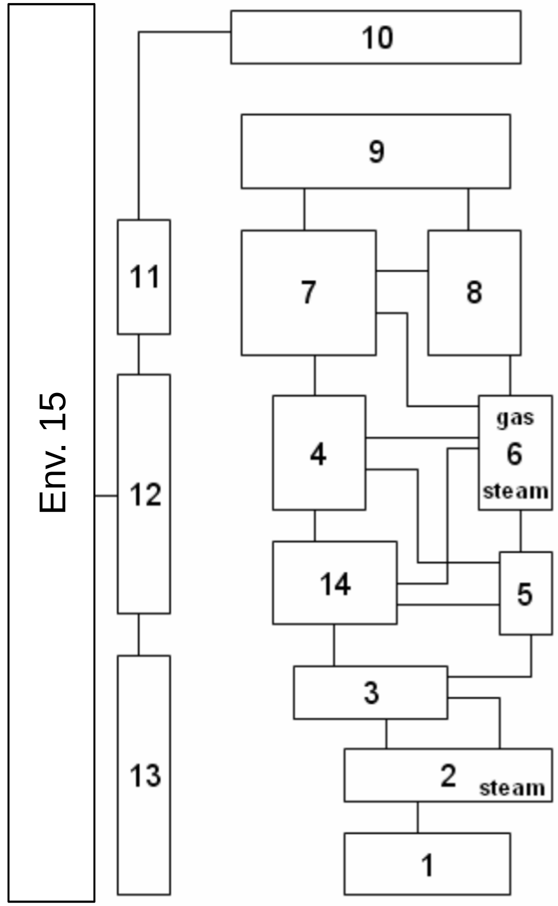
Period	Time, minutes	Description
1 (heat-up)	0.0 693.82 (41629 s)	Start small LOCA and external steam (upper) End LOCA and reduce external steam
2 (gas injection)	739.4 (44364) 749.98 (44999) 772.3 (46338)	Start of gas mixture injection End of external steam injection (upper) End of gas injection R1805
3 (lower steam)	772.93 (46376) 958.77 (57526)	Start of external steam release in R1405 End of external steam release
4 (outer spray)	975.0 (58500) 1095.0 (65700) 1155.0 (69300) 1185.0 (71100) 1203.0 (72180)	Start of outer spray period, mass flow rate = 5.83 kg/s Increase mass flow rate, 7.36 kg/s Increase mass flow rate, 9.17 kg/s Increase mass flow rate, 10.69 kg/s End of spray period and start of natural cooldown
5 (cooldown)	1445.0 (86700)	End of natural cooldown period



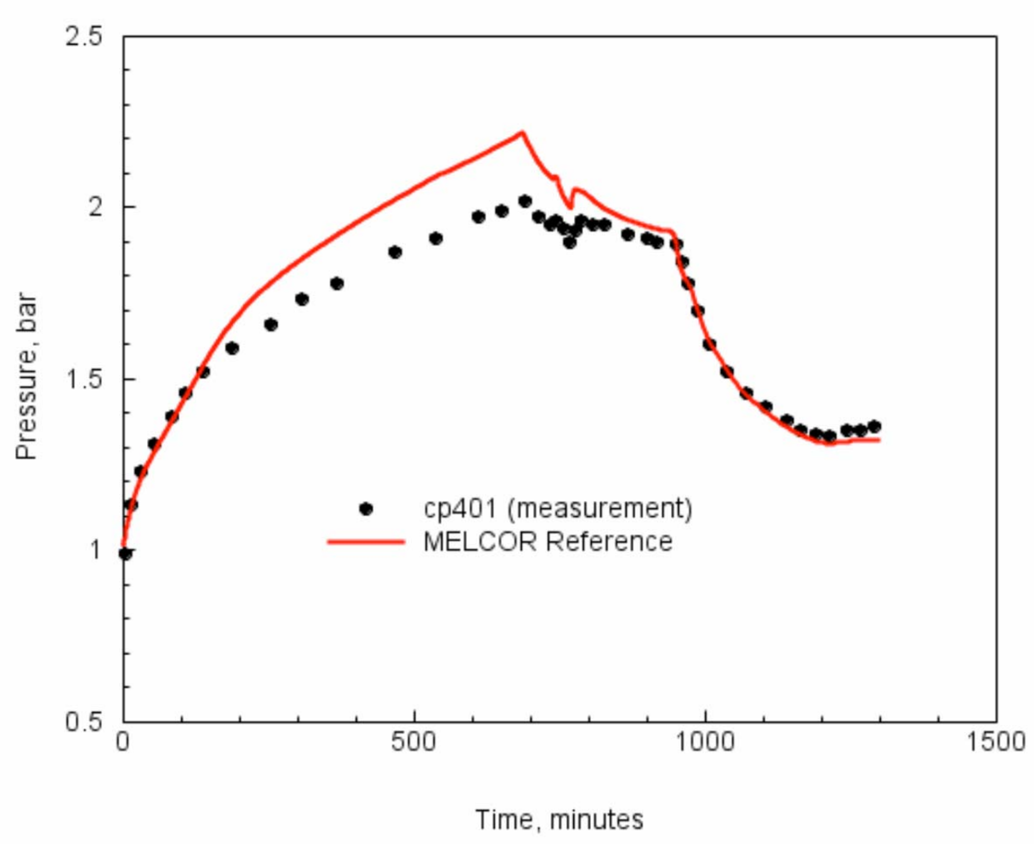
E11.2
15 CV Nodalization

- 1-9,14
  - Main body of facility
- 10-13
  - Volume external to shell
- 15
  - Environment



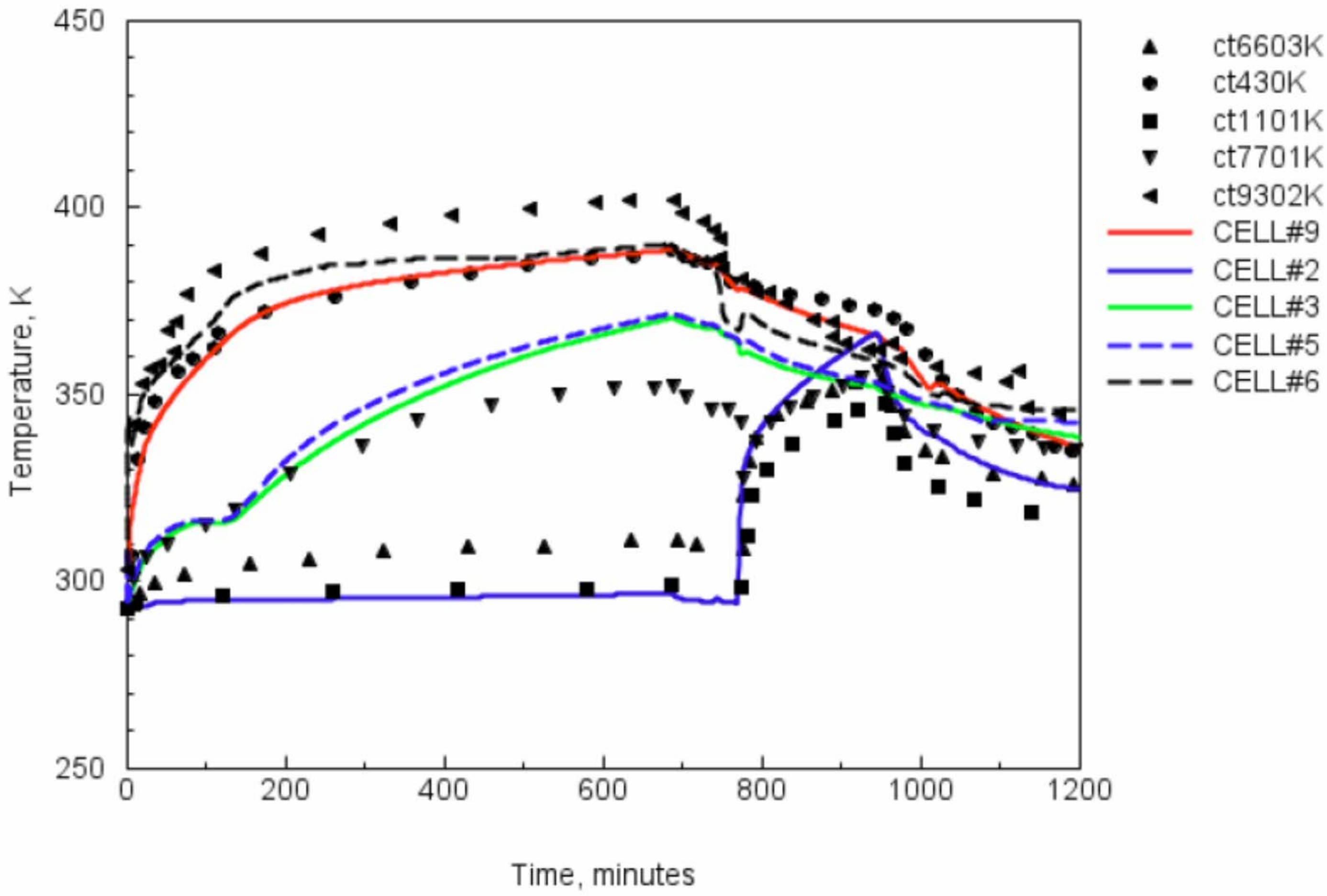


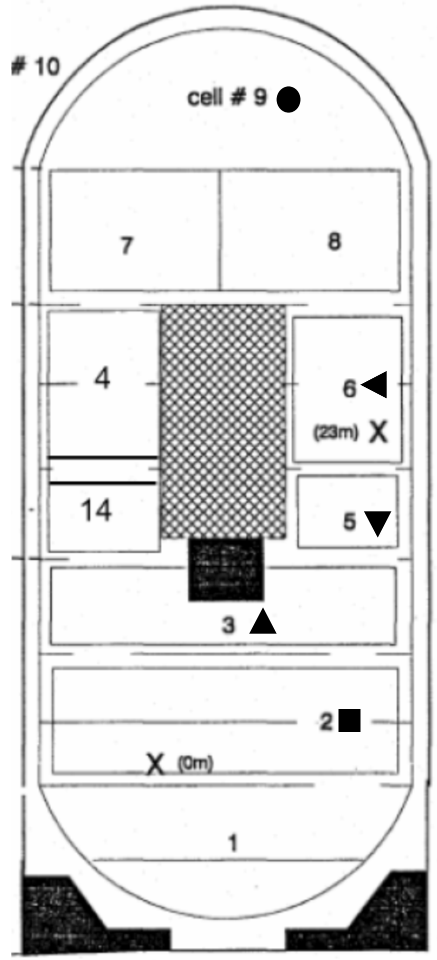
E11.2
Reference Analysis – Pressure



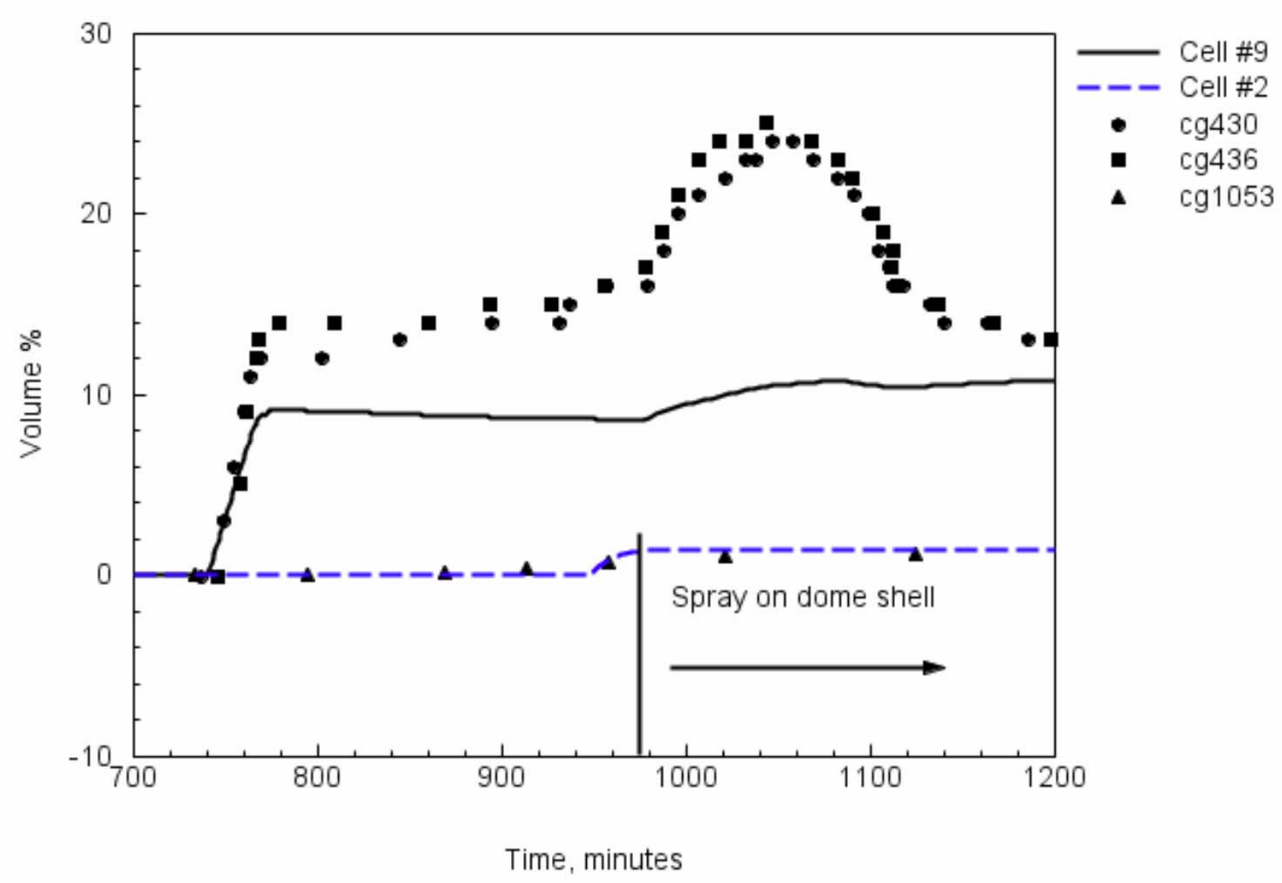
Period	Time, minutes
1 (heat-up)	0.0 693.82 (41629 s)
2 (gas injection)	739.4 (44364) 749.98 (44999) 772.3 (46338)
3 (lower steam)	772.93 (46376) 958.77 (57526)
4 (outer spray)	975.0 (58500) 1095.0 (65700) 1155.0 (69300) 1185.0 (71100) 1203.0 (72180)
5 (cooldown)	1445.0 (86700)

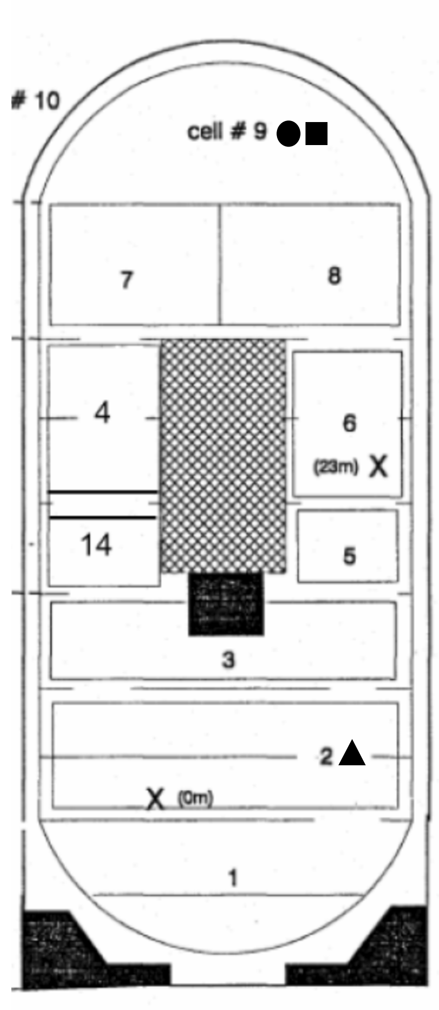
E11.2
Reference Analysis – Temperatures



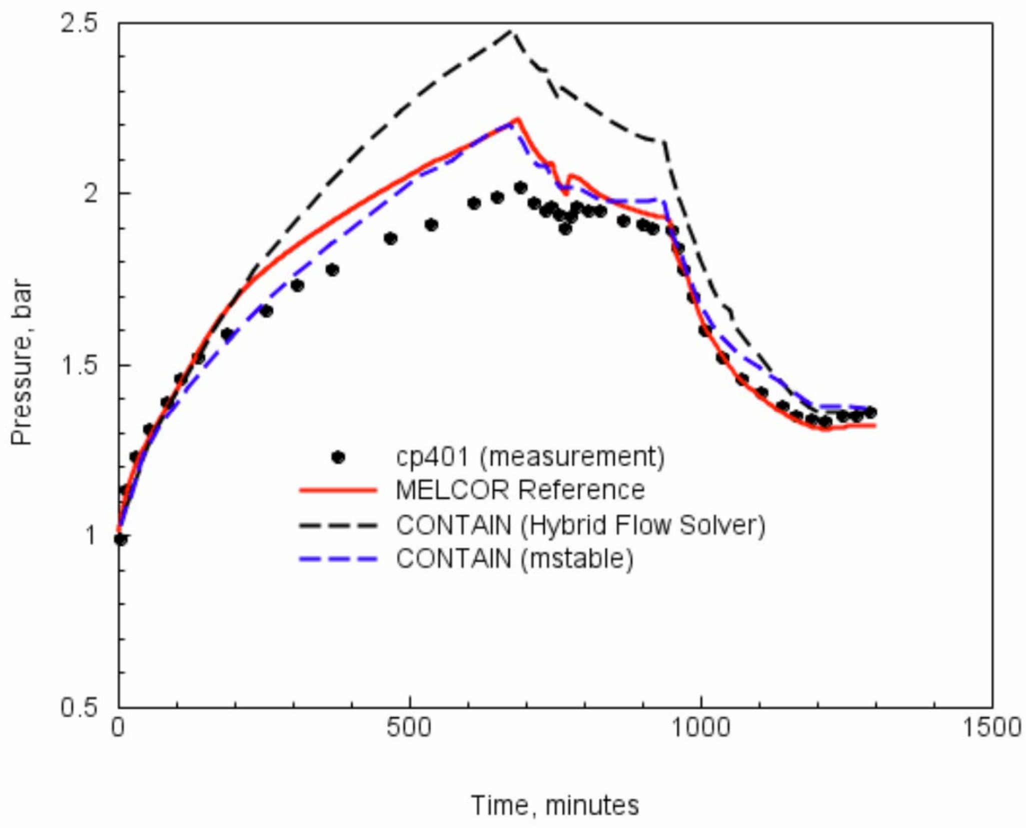


E11.2
Reference Analysis – Gas Composition



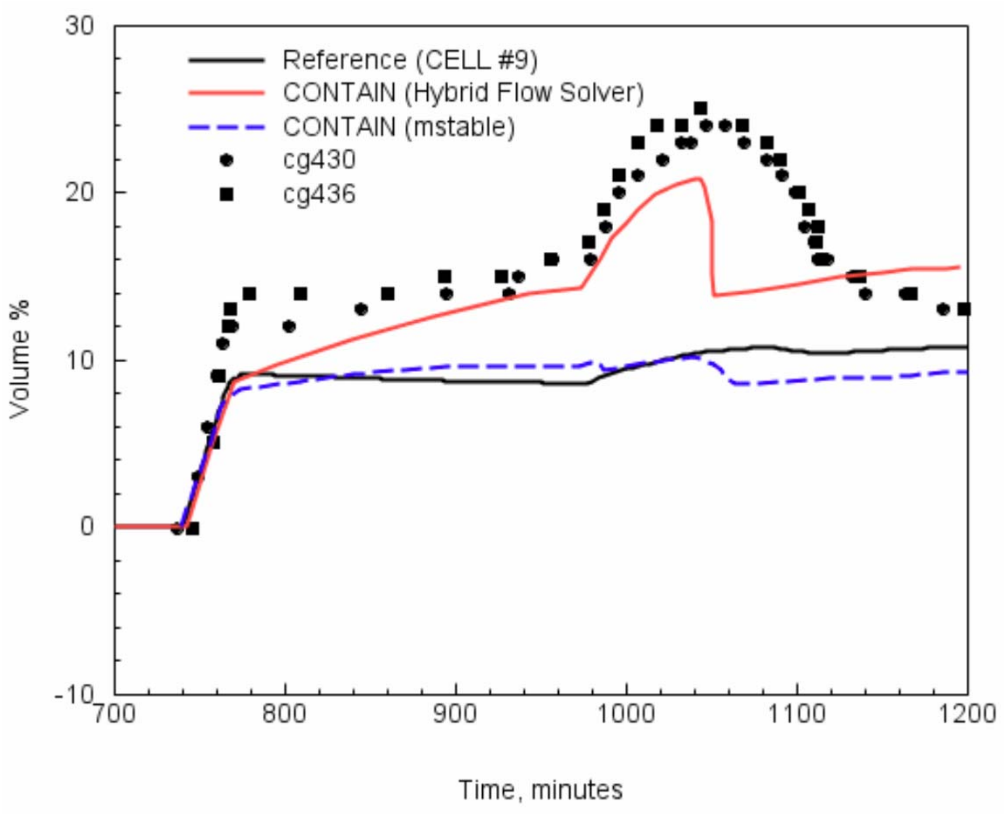


E11.2 CONTAIN/MELCOR Comparison



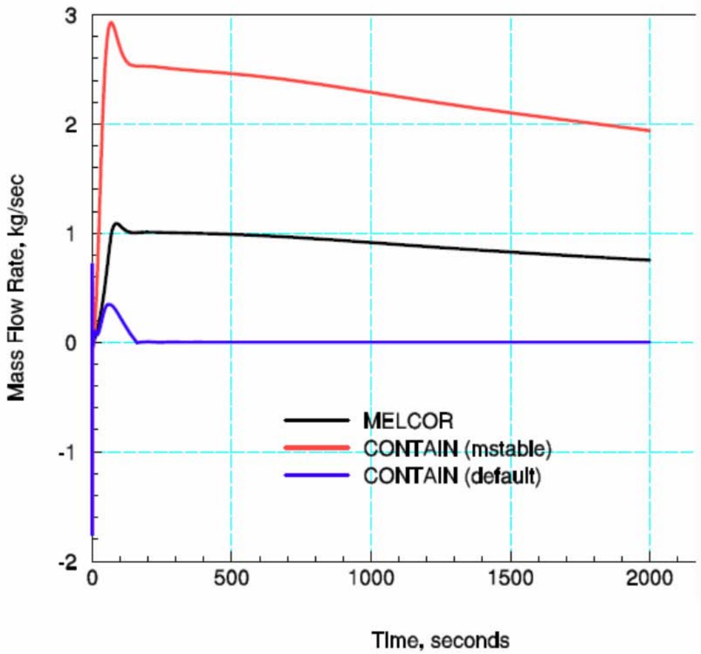
E11.2 CONTAIN/MELCOR Comparison

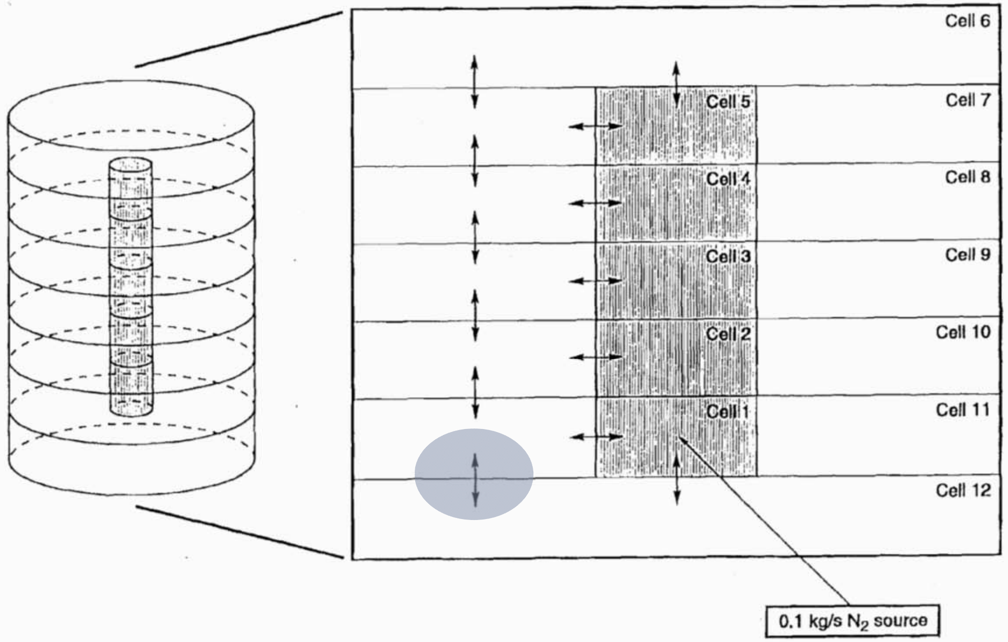
- mstable
  - Original CONTAIN model
  - Average density used in FL head determination
- Hybrid Flow Solver
  - Default CONTAIN 2.0 model
  - Modifies FL density based on stable/unstable density gradient
    - Still based on lumped parameter treatment of the control volume properties
    - Overmixes similar to mstable or MELCOR when becoming unstable



Simple Plume Model

- Used to demonstrate overmixing
- Figure-of-merit is the nonzero flow produced below the injection entrance





Conclusions/Findings

- Peak pressure and temperatures compare well
  - Pressure results compared well with experiments and benchmark with CONTAIN
  - Conservative input, used in DBA analyses, prescribed from CONTAIN applications shows an overestimation of pressure in all cases
  - Pressure trends are very similar between CONTAIN and MELCOR
    - With the exception of the E11.2
      - mstable/MELCOR showed good agreement – Overmixing is the likely reason
        - Elevated steam releases and energy extraction from lower containment cause E11.2 to deviate
        - Conventionally US fleet would produce lower containment releases and more thorough mixing of the containment could be anticipated
  - Deviation in local temperatures occur and is a product of containment mixing
  - Temperature disparities are moderate in comparison to pressure and gas composition comparisons

Conclusions/Findings

- Deviation in gas composition is more direct indicator of differences in transport not readily noted in local temperatures
- Over-mixing into lower elevations was observed

References

Firnhaber, M., “ISP16: Rupture of a Steam Line within the HDR-Containment leading to an Early Two-Phase Flow – Results of the Post-Test Analyses,” CSNI REPORT No. 112, June 1985.

Green, J. and Almenas, K., "Modeling of the HDR E 11.4 Experiment Using CONTAIN 1.12," Report to USNRC from College of Engineering, Nuclear Engineering Program, Materials and Nuclear Engineering, University of Maryland, College Park, Maryland, March 1992.

Holzbauer, H., Wolf, L., and Cron, T., “Investigations on Long-Term Behavior of the Atmosphereand on Hydrogen Distribution in a Reactor Containment after a Large LOCA, Final Evaluation Report, Test Group CON, Experiment T31.5,” (in German), Technical Report PHDR 95-91, Karlsruhe, FRG, December 1991.

Humphries. L. L., et al., “MELCOR Computer Code Manuals – Vol.1: Primer and User’s Guide, Version 2.1.6840,” SAND2015-6691 R, Sandia National Laboratories, Albuquerque, New Mexico, August 2015.

Humphries. L. L., et al., “MELCOR Computer Code Manuals – Vol.2: Reference Manuals, Version 2.1.6840,” SAND2015-6692 R, Sandia National Laboratories, Albuquerque, New Mexico, August 2015.

Karwat, H., "ISP23: Rupture of a Large-Diameter Pipe within the HDR-Containment," Vol. 1 and 2, CSNI Report No. 160, Committee on the Safety of Nuclear Installations - OECD Nuclear Energy Agency, Paris, France, 1989.

Karwat, H., Letter to ISP-29 Participants, dated 12 February, Technishche Universitat Munchen, 1991.

Karwat, H., Letter to ISP-29 Participants, dated 4 July, Technishche Universitat Munchen, 1991.

Karwat, H., "OECD-CSNI-ISP29, Distribution of Hydrogen within the HDR Containment under Severe Accident Conditions -Final Comparison Report," Organization for Economic Cooperation and Development -Committee on the Safety of Nuclear Installations, August 1992.

Lee, S. J., et al., “Benchmark of the Heiss Dampf Reaktor E11.2 Containment Hydrogen-Mixing Experiment Using the MAAP4 Code,” Nuclear Technology, Vol. 125, pp. 182-195, February 1999.

Murata, K. K., and Stamps, D. W., “Development and Assessment of the CONTAIN Hybrid Flow Solver,” SAND96-2792, Sandia National Laboratories, Albuquerque, NM, 1996. 6-2

Mur97 Murata, K. K., et al., “Code Manual for CONTAIN 2.0: A Computer Code for Nuclear Reactor Containment Analysis,” NUREG/CR-6533, SAND97-1735, Sandia National Laboratories, Albuquerque, New Mexico, December 1997.

OECD99 Prepared by an OECD/NEA Group of Experts, “SOAR on Containment Thermal Hydraulics and Hydrogen Distribution,” June 1999.

Royl, P., et al., “Validation of GASFLOW for Analysis of the Steam/Hydrogen Transport and Combustion Processes in Nuclear Reactor Containments,” Proceedings of the 13th Conference on Structural Mechanics in Reactor Technology, Porto Alegre, RS, Brazil, August 13-18, 1995.

References

Tills, J., "Analysis of the HDR Test E 11.2," Letter Report to USNRC from Department 6421, Sandia National Laboratories, Albuquerque, NM, May 1992.

Tills, J., Notafrancesco, A., and Murata, K., “An Assessment of CONTAIN 2.0: A Focus on Containment Thermal Hydraulics (Including Hydrogen Distributions),” SMSAB-02-02, USNRC ADAMS Accession Number ML022140438, July 2002.

Tills, J., Notafrancesco, A., and Murata, K., “CONTAIN Code Qualification Report/User Guide for Auditing Design Basis PWR Calculations,” SMSAB-02-03, USNRC ADAMS Accession Number ML022490381, August 2002.

Tills, J., Notafrancesco, A., and Longmire, P., “An Assessment of MELCOR 1.8.6: Design Basis Accident Tests of the Carolinas Virginia Tube Reactor (CVTR) Containment (Including Selected Separate Effects Tests), SAND2008-1224, Sandia National Laboratories, Albuquerque, NM, February 2008.

Tills, J., Notafrancesco, A., and Phillips, J., “Application of the MELCOR Code to Design Basis PWR Large Dry Containment Analysis,” SAND2009-2858, Sandia National Laboratories, Albuquerque, NM, May 2009.

Valencia, L., and Kanzleiter, T.F., “Blowdown Investigation in a Reactor Containment – Rupture of a Steam Pipe – Quick Look Report for Tests V42, V43, and V44,” Technical Report PHDR 38-83, Kernforschungszentrum, Karlsruhe, Germany, May 1983.

Valencia, L., Wolf, L., “Preliminary Design Report – Hydrogen Distribution Experiments E11.1 – E11.5,” Project HDR Safety Program, Karlsruhe, PHDR Work-Report Nr. 10.003/89, March 1989.

Valencia, L., “Input Data Set for E11.2 (Blind Calculations),” Project HDR Safety Program, Kernforschungszentrum, Karlsruhe, November 1989.

Valencia, L., et al., "Design Report - Hydrogen Distribution Experiments, E 11.1 - E 11.5," PHDR-Working Report No. 10.004/89, Kernforschungszentrum, Karlsruhe, Germany, August 1992. 6-3

Wenzel, H. H., et al., "Blowdown- und Wasserstoffvertieilungsversuche Versuchsgruppe CON Versuch T31.5," PHDR 3.520/88, Kernforschungszentrum, Karlsruhe, Germany, December 1987 (in German).

Wenzel, H., et al., “Quality Considerations of Major Direct and Indirect Measured Quantities During the Experiments of Test-Group E11,” PHDR Safety Program, Kernforschungszentrum, Karlsruhe, PHDR-Working Report No. 10.002/91, June 1991.

References

Wolf, L., Valencia, L., and Kanzleiter, T., “Overview of the HDR-containment tests,” NUREG/CP-0048, Vol. 3, Proceedings of the U.S. Nuclear Regulatory Commission Eleventh Water Reactor Safety Research Information Meeting, Gaithersburg, Maryland, October 24-28, 1983.

Wolf, L. and Valencia, L, "Experimental Results of the Preliminary HDR Hydrogen Distribution Test T31.5, Proceedings of the 4th International Topical Meeting on Nuclear Reactor Thermal Hydraulics, Karlsruhe, Germany, Vol. 2, p. 967, October 10-.13, 1989.

Wolf., L. and Valencia, L., "Hydrogen Mixing Experiments in the HDR-facility," NUREG/CP-0 *105, Proceedings of the U.S. Nuclear Regulatory Commission Seventeenth Water Reactor Safety Research Information Meeting,* Rockville, MD October 1989.