Italian National Agency for New Technologies, Energy and Sustainable Economic Development

ENEA ACTIVITIES IN THE FIELD OF SEVERE ACCIDENTS BY USING MELCOR CODE

12th Meeting of the European MELCOR and MACCS User Group

Fulvio Mascari[1]

Contributions from: D. Dongiovanni[2], S. Ederli[3], M. Massone[1], F. Giannetti[4], A. Bersano[1], P. Maccari[5], G. Agnello[6] , M. Angelucci[7]

1 ENEA-Bologna; 2 ENEA- Frascati; 3 ENEA-CASACCIA, 4 UNIROMA1; 5 UNIBO; 6 UNIPA; 7 UNIPI; Italy

INTRODUCTION

- ENEA activities in the field of severe accidents by using MELCOR code is based on the analyses of current and advanced reactor designs in steady and transient conditions.

- The following activities are developped:
  - Simulation and evaluation of severe accident evolutions and source term for “safety assessment”, mainly focusing on the characteristics of NPPs located at the Italian border;
  - Code to code benchmark with other severe accident codes (e.g. ASTEC, MAAP, etc);
  - Analyses of MELCOR code capability against experimental data for current and advanced designs;
  - Coupling of MELCOR code with uncertainty tools (e.g. DAKOTA, RAVEN, etc).
  - Use of the MELCOR code for fusion technology applications.

- The activity is developped in International, European and Italian research projects:
  - European Union Research and Innovation Programme (e.g. MUSA,..);
  - NUGENIA project (e.g. ASCOM,..);
  - EUROFUSION activity;
  - Italian domestic project funded by the Ministry of Economic development;
  - Etc

- The activity is developped in collaboration with Italian Universities.

ENEA ACTIVITIES IN THE FIELD OF SEVERE ACCIDENTS BY USING MELCOR CODE

- MELCOR/DAKOTA COUPLING IN A SNAP ENVIRONMENT ARCHTECTURE
  - Considering that currently the International Nuclear Technical Community is exploring the possibility of using severe accident code in a BEPU framework (e.g. MUSA, IAEA CRP(I31033), etc) , the target of this activity is to show the main details and capability of the MELCOR/DAKOTA coupling in a SNAP environment/architecture, and the different steps necessary to set-up it.
    - *A NUREG-IA, in SANDIA REVIEW process, has been prepared to investigate the MELCOR/DAKOTA coupling in a SNAP environment/architecture*
    - *A MELCOR/DAKOTA COUPLING group has been established in the CSARP framework to be a platform of discussion and two meetings have been already organized.*
  - Activity are on going

- EU project MUSA (MANAGEMENT AND UNCERTAINTIES OF SEVERE ACCIDENTS):
  - ENEA is involved in the development of a PHEBUS FPT1 uncertainty analyses by using MELCOR/DAKOTA coupling in a SNAP environment architecture;
  - ENEA is involved in the development of PWR-900 uncertainty analyses by using MELCOR/DAKOTA coupling in a SNAP environment architecture;
  - ENEA is the leader of:
    - WP4: Application of UQ Methods against Integral Experiments (AUQMIE);
    - Sub-WP3.3: Feedback integration from application of uncertainty tools;
    - Sub-WP6.3: Assessment of potential radiological consequences reduction from innovative SAM measures and systems;
    - Has coordinate the DAKOTA review and is the leader of MELCOR for the elaboration of guidelines for the use of UaSA codes/methods (WP3.2).
  - The project is on going

ENEA ACTIVITIES USING MELCOR CODE

- ENEA INVOLVMENT IN EUROFUSION: Accident analyses within EUROFusion project:
  - DEMO Tokamak plant: Divertor system analyses
  - DONES neutron Irradiation facility
  - Activity are on going

- NUGENIA ASCOM (ASTEC COMMUNITY) Project:

ENEA is involved in the:

- WP4: ASTEC analyses at plant scale and associate crosswalk studies: here MELCOR code is used to benchmark ASTEC code:
  - A comparison for an unmitigated SBO has ben conducted in the 2019;
  - A comparison for an unmitigated 2-inch Cold Leg LOCA accident has ben conducted in the 2020

- ENEA ACTIVITIES IN THE FIELD OF SEVERE ACCIDENTS (FUSION REACTOR): activity developed in the EMUG framework:
  - Analyses of the physical models necessary to be implemented in MELCOR_2.2 for fusion reactor safety analyses and the current models already implemented in MELCOR fusion
  - The activity is finished but could start again

- Participation within Italian domestic project funded by the Ministry of Economic development.
  - In the framework of the ENEA-MSE agreement, ENEA activities related to the MELCOR code are mainly oriented to the evaluation of severe accident source term for "safety assessment activity", mainly focusing on the characteristics of NPPs located near the Italian border.
  - The project is finished.

ENEA ACTIVITIES IN THE FIELD OF SEVERE ACCIDENTS

- EU project IVMR (In-Vessel Melt Retention Severe Accident Management Strategy for Existing and Future NPPs):
  - ENEA has been involved in the development of a “PWR 900 like” input-deck with MELCOR code for benchmarking ASTEC code in relation to the In-Vessel Melt Retention issues during an unmitigated SBO.
  - A first calculation phase and a second phase for revised calculation have been performed.
  - The project is finished.

- EU-FASTNET project (FAST Nuclear Emergency Tools):
  - ENEA has been involved in the development of a source term database with MELCOR for selected transients.
  - The project is finished

- EU project JASMIN (Joint Advanced Severe Accidents Modelling and Integration for Sodium-Cooled Fast Neutron Reactors)
  - ENEA used the MELCOR code in order to benchmark the CPA module of ASTEC-NA.
  - The project is finished.
  - *A NUREG-IA based on the MELCOR calculation has been proposed; the proposal has been accepted and the NUREG-IA analyses should be based on the update code prediction obtained with the MELCOR release where the pool fire modeling have been implemented.*

- EU-CESAM project (Code for European Severe Accident Management):
  - ENEA has been involved in the development of a “PWR 900 like” input-deck with MELCOR code for benchmarking the ASTEC code.
  - The project is finished.
  - A NUREG-IA has been published: F. Mascari, J. C. De La Rosa Blul, M. Sangiorgi, G. Bandini, Analyses of an Unmitigated Station Blackout Transient in a Generic PWR–900 with ASTEC, MAAP and MELCOR Codes (NUREG/IA-0515), U.S. Nuclear Regulatory Commission Washington, DC 20555-0001

GRAZIE PER LA VOSTRA ATTENZIONE

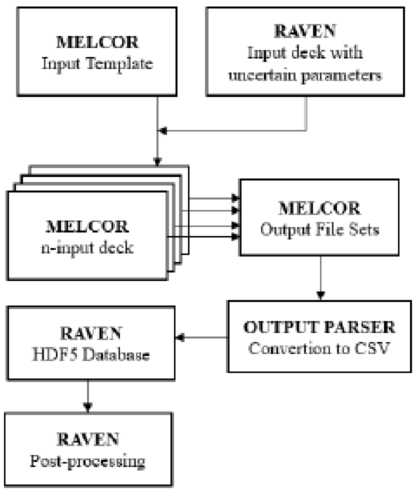
ENEA ACTIVITIES IN THE FIELD OF SEVERE ACCIDENTS – UNCERTAINTY ANALYSES

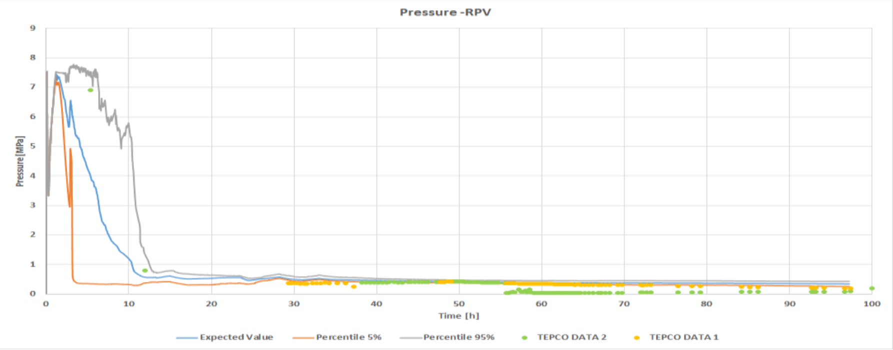
- In the evaluation of safety margins, the use of BEPU approach by coupling selected calculated parameters with the related uncertainty range is of great interest for the International Scientific Community.
- Considering the reached level of development and maturity of severe accident codes and their application on SAMG assessment, the discussion and application of severe accident progression analyses with uncertainty estimation is currently a key topic in BEPU applications.
- In the view of the research activity that are currently under development in domestic and in international framework *(e.g. MUSA project funded in the H2020 European Framework Programme, etc, IAEA CRP, etc),* ENEA have started different activities related to the uncertainty estimation:
  - Developing uncertainty analyses using the DAKOTA software tool coupled with MELCOR code in SNAP environment/architecture;
  - In collaboration with Sapienza University of Roma is developing uncertainty analyses using the RAVEN software tool coupled with MELCOR code;
  - In collaboration with the Politecnico di Torino and University of Palermo is developing uncertainty analyses using the DAKOTA software tool coupled with TRACE code in SNAP environment/architecture (TH activity):
    - Ingress of coolant event (in a fusion reactor) uncertainty analyses along a validation study
    - CL guillotine break in a generic PWR-900 uncertainty study
  - In collaboration with IRSN and University of Bologna is developing uncertainty analyses using RAVEN software tool coupled with ASTEC code :
    - Ingress of coolant event (in a fusion reactor) uncertainty analyses along a validation study
    - In collaboration with UNIPI is developing the Python Script Stream in SNAP to manage the MELCOR runs failure.

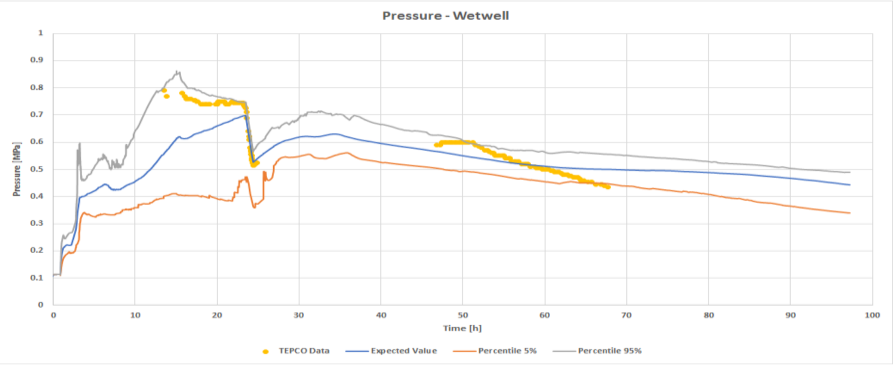
ENEA

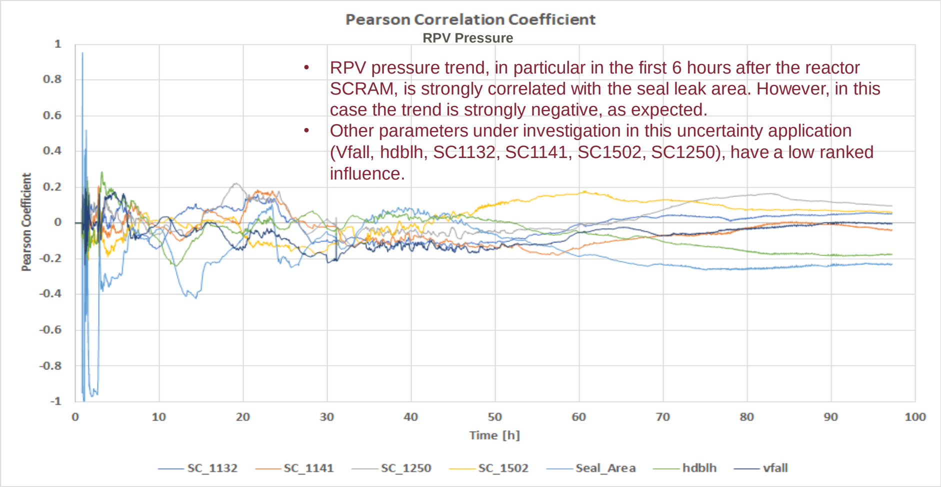
UNCERTAINTY ANALYSES

MELCOR/RAVEN:
Analysis of the BWR FUKUSHIMA DAIICHI UNIT 1 SEVERE ACCIDENT







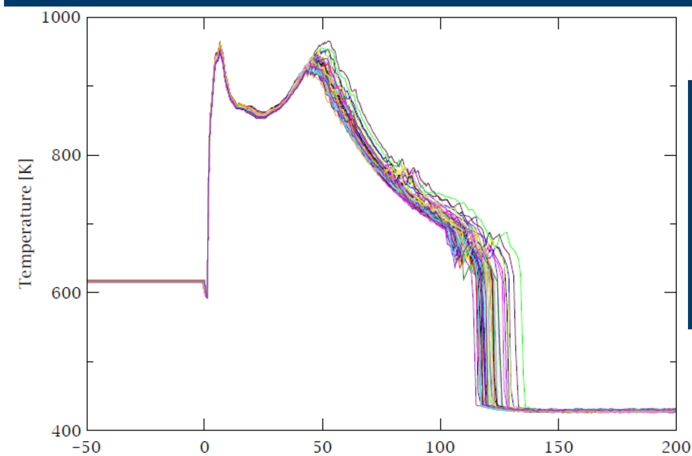


- RPV pressure trend, in particular in the first 6 hours after the reactor SCRAM, is strongly correlated with the seal leak area. However, in this case the trend is strongly negative, as expected.
- Other parameters under investigation in this uncertainty application (Vfall, hdblh, SC1132, SC1141, SC1502, SC1250), have a low ranked influence.

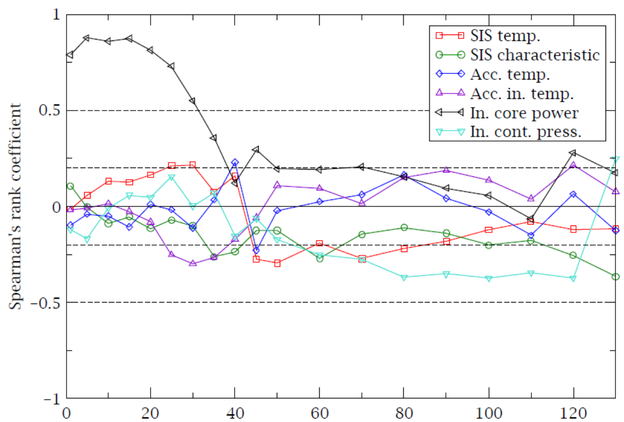
The activity has been done in collaboration with Sapienza University of Rome.

UNCERTAINTY ANALYSES

TRACE/DAKOTA:
Evaluation of a Double-Ended Guillotine LBLOCA Transient in a Generic Three-Loops PWR-900 with TRACE Code Coupled with DAKOTA Uncertainty Analysis



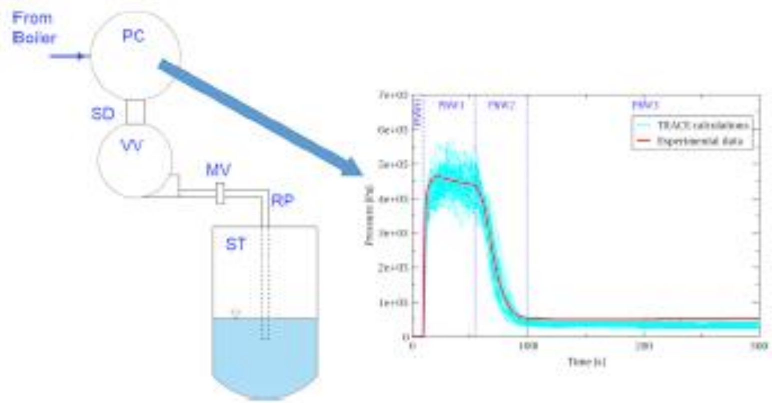
Cladding temperature of the hot rod predicted by TRACE code



Spearman rank correlation coefficient

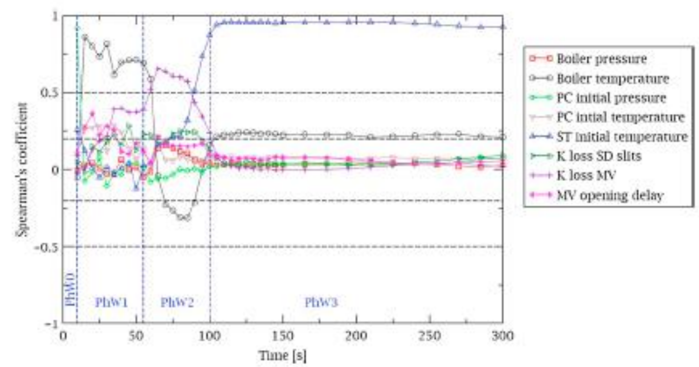
The activity has been done in collaboration with Politecnico di Torino.

TRACE/DAKOTA:
Ingress of Coolant Event simulation with TRACE code with accuracy evaluation and coupled DAKOTA Uncertainty Analysis



PC pressure predicted by TRACE code

Spearman rank correlation coefficient

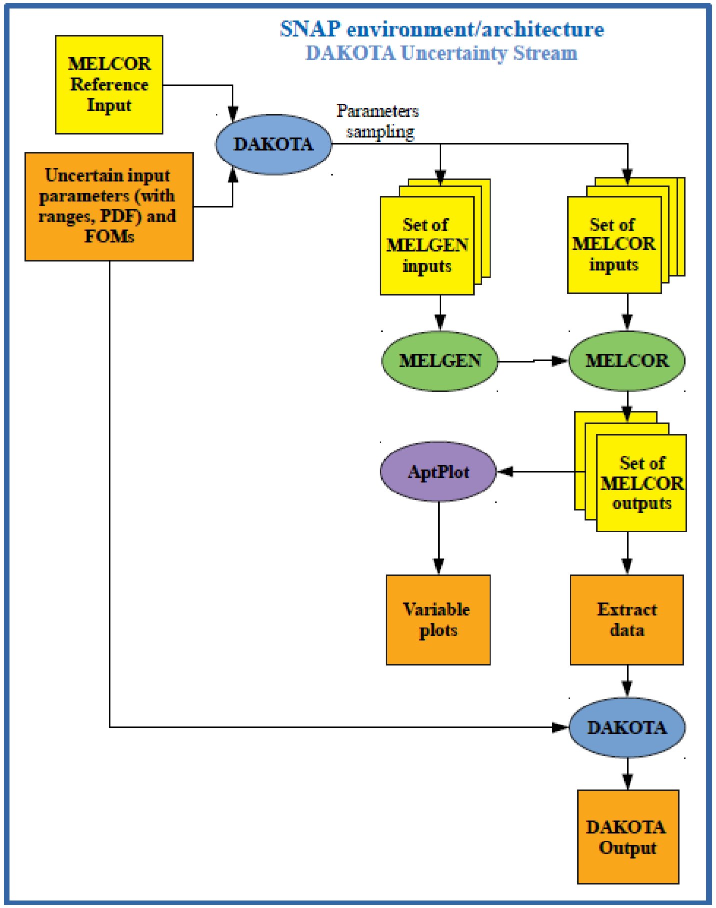


The activity has been done in collaboration with Politecnico di Torino and University of Bologna.

MELCOR – DAKOTA COUPLING FOR UNCERTAINTY ANALYSES, IN A SNAP ENVIRONMENT/ARCHITECTURE

- Considering that currently the International Community (e.g. MUSA, IAEA CRP (I31033), etc) is exploring the possibility of using SA code in a BEPU framework, the target of this activity is to test and show the main details and capability of the MELCOR/DAKOTA coupling in a SNAP environment/architecture and the different steps necessary to set-up it.

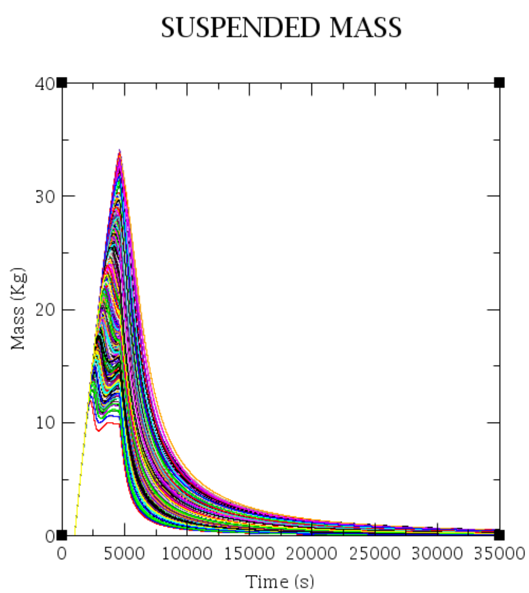
- A NUREG–IA, developed together with SANDIA and POLITO, is in review phase and has the main target of
  - Showing the main details of the MELCOR/DAKOTA coupling in a SNAP environment/architecture;
  - Showing the different steps necessary to set it up;
  - Describing two sample applications to show the feasibility and to analyze the capabilities of this coupling (*these first excercises aiming to show only the complete application of the coupling procedure of MELCOR and DAKOTA in a SNAP enviroment/architecture; they do not want to represent a complete and representative analyses of the MELCOR code uncertainty).*
  - Supporting MECOR users.

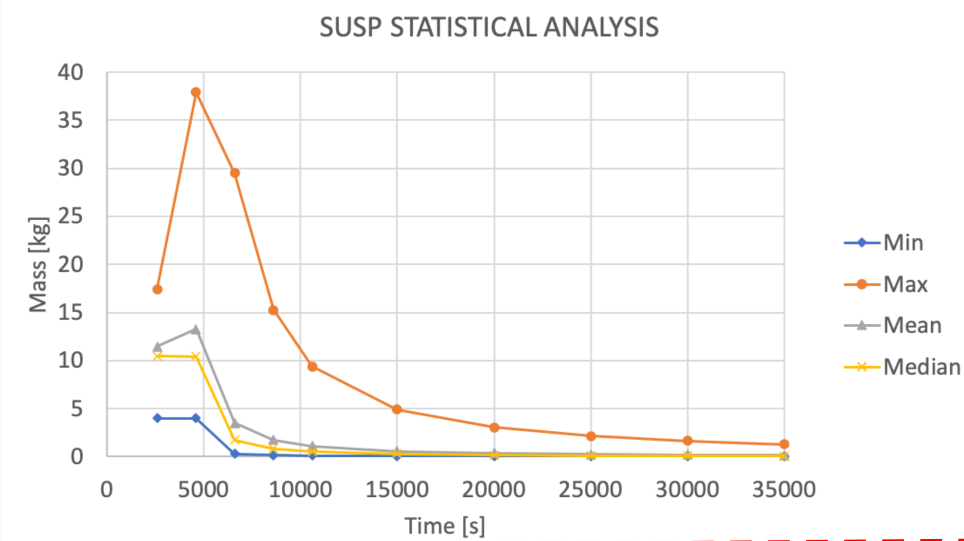


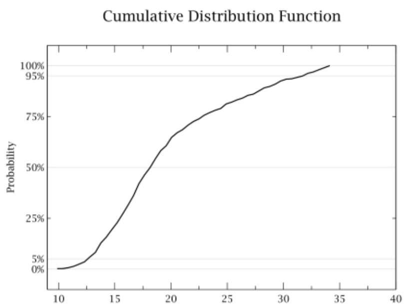
ENEA

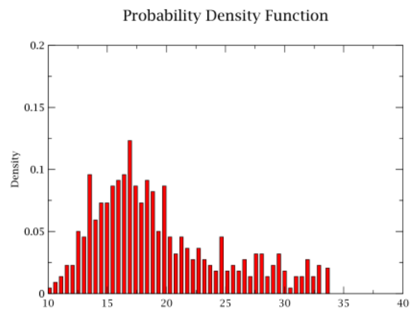
MELCOR – DAKOTA COUPLING FOR UNCERTAINTY ANALYSES, IN A SNAP ENVIRONMENT/ARCHITECTURE

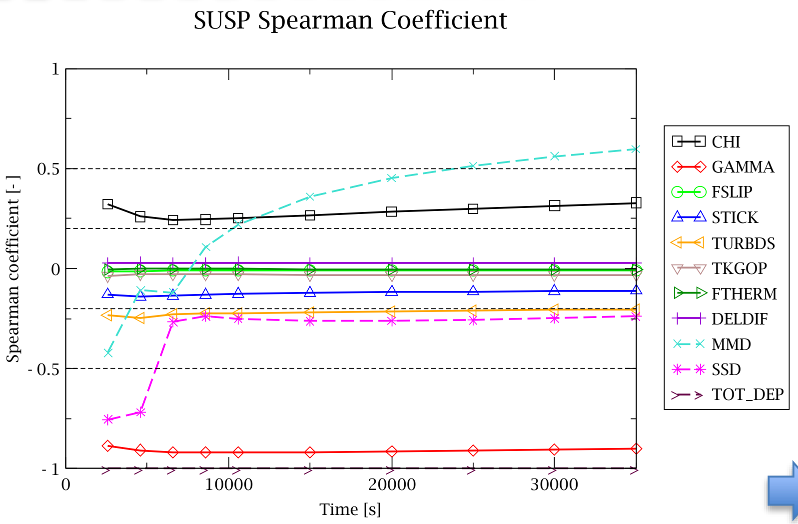
MELCOR/DAKOTA:
MELCOR/DAKOTA COUPLING AGAINST CSTF-AB1 test











A NUREG-IA, in SANDIA REVIEW process, has been prepared to investigate the MELCOR/DAKOTA coupling in a SNAP environment/architecture and to be an endorsed user-guide

NUREG/IA-

International Agreement Report

MELCOR – DAKOTA Coupling for Uncertainty Analyses, in a SNAP Environment/Architecture

Prepared by:
Fulvio Mascari*, Andrea Bersano**, Jesse Phillips***

*ENEA, Nuclear Safety, Security and Sustainability Division (FSN-SICNUC), Via Martiri di Monte Sole 4, Bologna, 40129, Italy

**Politecnico di Torino, Energy Department (DENERG), Corso Duca degli Abruzzi 24, Turin, 10129, Italy

***Sandia National Laboratories, 1515 Eubank SE Albuquerque, New Mexico 87123

H. Hossein, NRC Project Manager

Division full name spelled out
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UNDER SANDIA REVIEW

A NUREG-IA, in SANDIA REVIEW process, has been prepared to investigate the MELCOR/DAKOTA coupling in a SNAP environment/architecture and to be an endorsed user-guide

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The activity is done in collaboration with POLITO, SANDIA.

MELCOR/DAKOTA COUPLING GROUP

- The quantification of the uncertainty in a SA transient calculation is a currently relevant topic in the BEPU framework;
- Among the available methodologies, the probabilistic method to propagate input uncertainties is widely adopted in deterministic safety analyses;
- Several MELCOR users are currently applying this method with the DAKOTA Uncertainty Tool (UT), developed by SNL;
- The goal of this group is to create a platform for MELCOR users for sharing experience and discussing the coupling with DAKOTA, both through the Symbolic Nuclear Analysis Package (SNAP) and with other coupling methods (e.g. Python scripts);
- The activity is performed in the framework of the USNRC Cooperative Severe Accident Research Program (CSARP).
- A «MELCOR/DAKOTA coupling» Project has been set in Researchgate for sharing public material.
- Meetings:
  - *Two meetings have been already carried out;*
  - *A third meeting will be planned in the next months for discussing and consolidate the current approaches for coupling MELCOR and UT tools*
- The activity is done in collaboration with:
  - *CIEMAT, ENEA, JACOBS, KIT, POLITO, PSI, SANDIA, UNIPA, UNIPI, UNIROMA1, USNRC*

NEXT MELCOR/DAKOTA COUPLING GROUP MEETING

- Considering the feedback from the previous meetings we propose to have a further dedicated meeting open to:
  - MELCOR user community,
  - MELCOR developer,
  - DAKOTA developer,
  - SNAP developer

  to discuss in detail the MELCOR/DAKOTA coupling aspects.

- At the end of this meeting will be useful to prepare a document that could be a consolidate and endorsed reference to perform uncertainty analyses with MELCOR.

- Eventually this document could be a NUREG-IA that could be an endorsed reference that summarize the use of MELCOR with uncertainty tools as DAKOTA or RAVEN.

- The possible date could be in May but the date is open to discussion to optimize the interaction and effectiveness with MUSA and CRP activities where a lot of use of MELCOR/DAKOTA activity is in progress.

EU-MUSA PROJECT

- Management and Uncertainties Of Severe Accidents (MUSA) project was founded in HORIZON 2020 EURATOM NFRP-2018 call on “Safety assessments to improve accident management strategies for generation II and III reactor, and it is coordinated by CIEMAT (Spain).

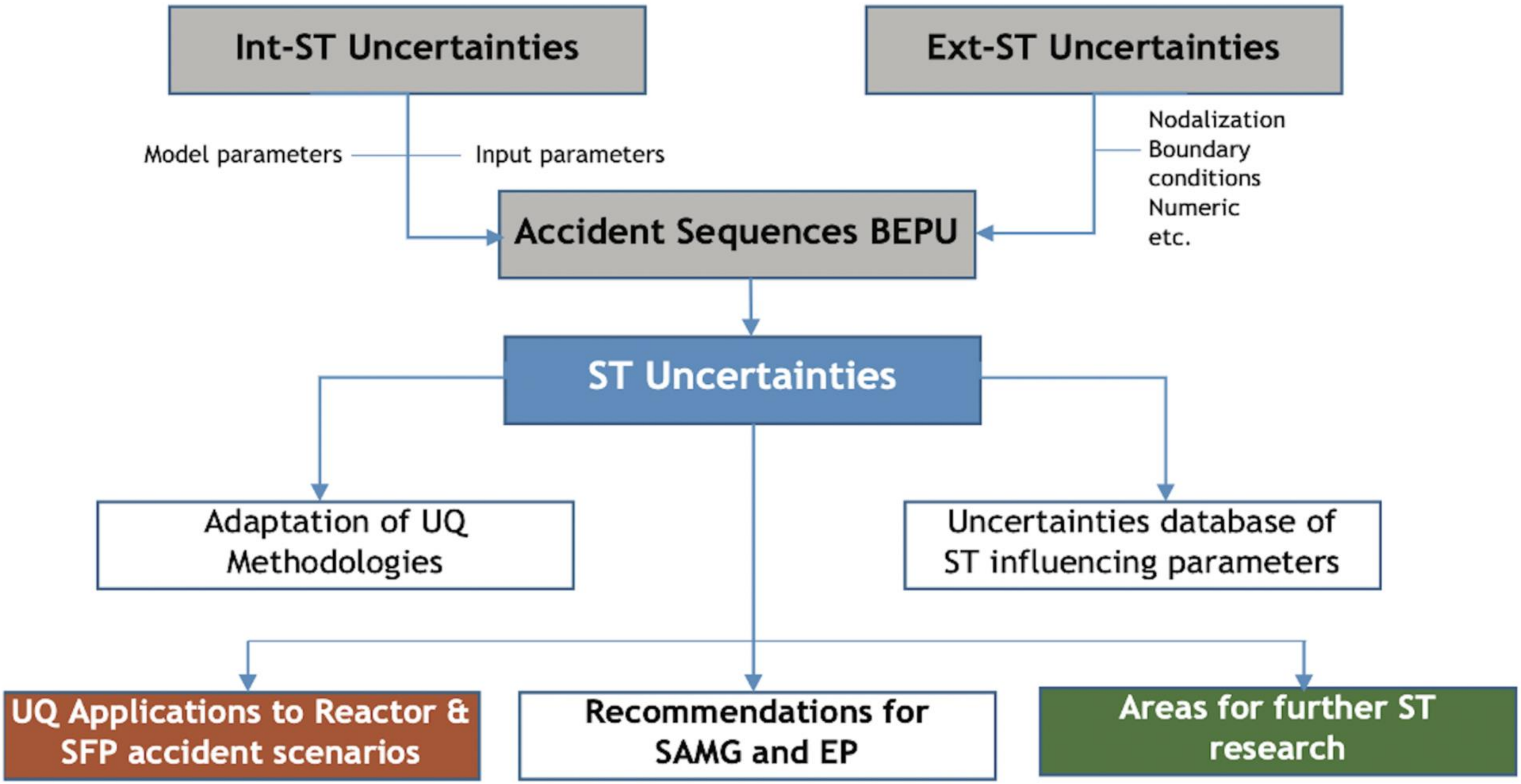
- The project started on the 1st June 2019 and the planned duration is 48 months; the overall cost is 5.768,452.50.

- 28 Organizations from 16 Countries are involved, and it has the NUGENIA label that recognizes the excellence of the project proposal (obtained on 7 July 2018).

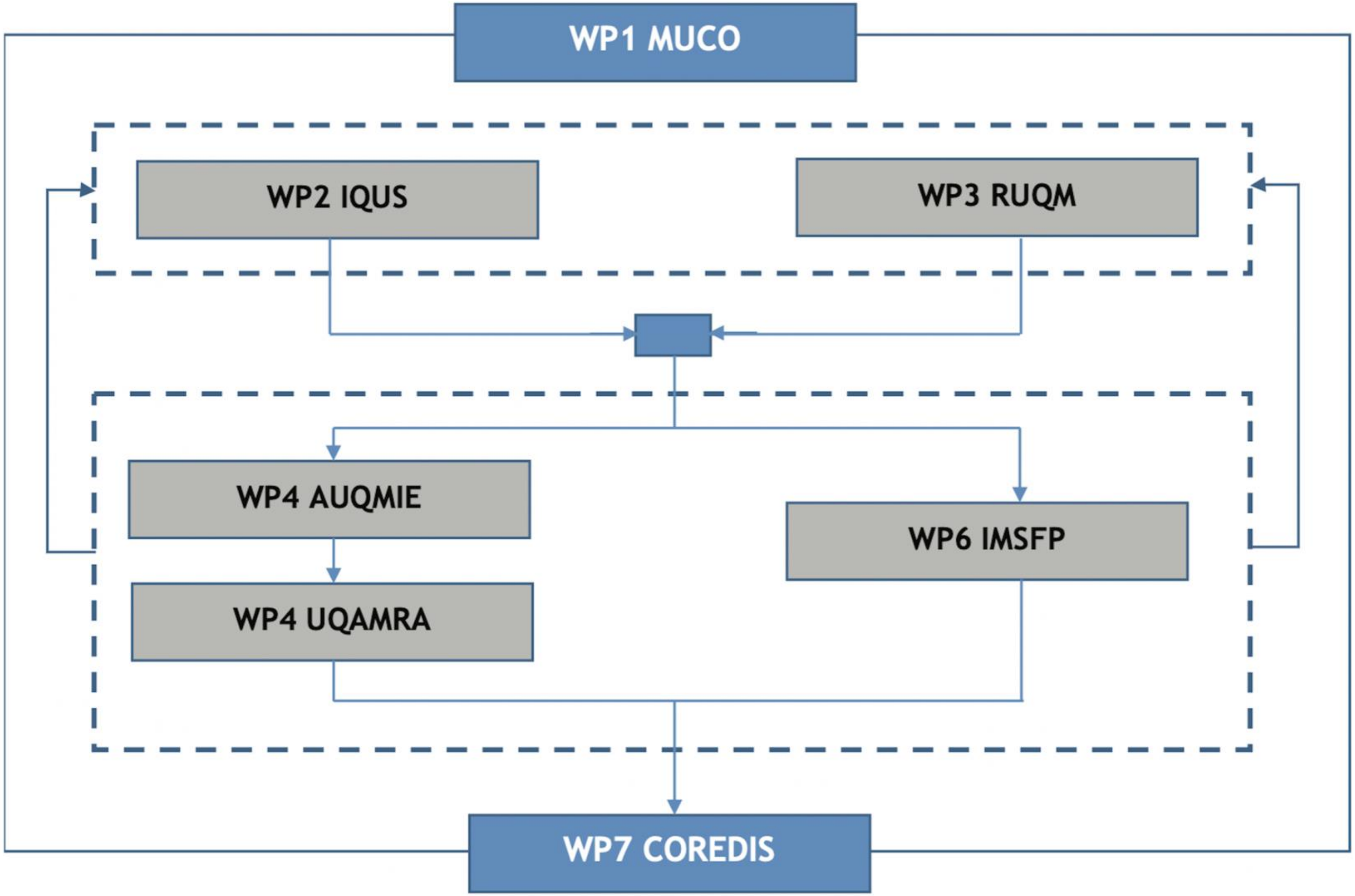
- MUSA project aims to establish a harmonized approach for the analysis of uncertainties and sensitivities associated with Severe Accident (SA) analysis among EU and non-EU entities.

- The main objective of the project is to assess the capability of SA codes when modelling Nuclear Power Plant (NPP)/ Spent Fuel Pool (SFP) accident scenarios of GEN II, GEN III designs through the:
  - Identification of Uncertainty Quantification (UQ) methodologies to be employed, with emphasis on the effect of both existing and innovative SA Management (SAM) measures on the accident progression, particularly those measures related to the Source Term (ST) mitigation;
  - Determination of the state-of-the-art prediction capability of SA codes regarding the ST that potentially may be released to the external environment, and to the quantification of the associated code’s uncertainties applied to SA sequences in NPPs and SFPs.

EU-MUSA PROJECT



EU-MUSA PROJECT



EU-MUSA PROJECT

- WP4, named AUQMIE (Application of UQ Methods against Integral Experiments), is aimed at applying and testing UQ methodologies, investigated in the WP3, lead by KIT, against the internationally recognized PHEBUS FPT1 test.

- The WP4, lead by ENEA, is divided in three main subWPs: the specification phase (WP4.1) lead by IRSN, the calculation phase (WP4.2) lead by GRS, and the analyses of the results (WP4.3), lead by UNIPI.

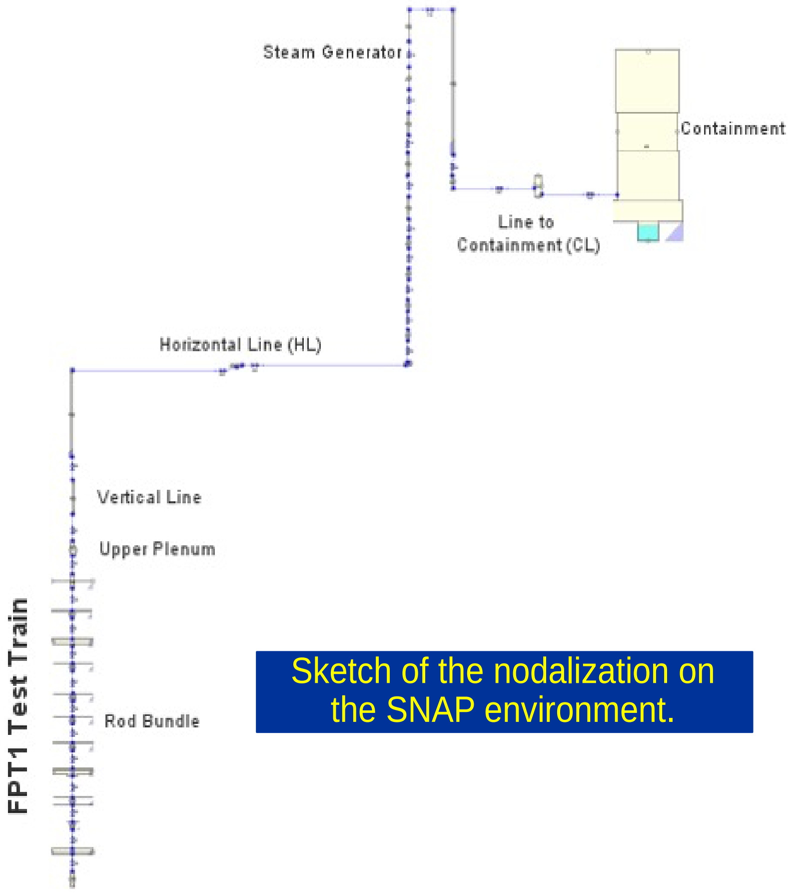
- Partners involved are CIEMAT, CEA, CNPRI, CNSC, CNPE, ENEA, LLC ENERGORISK, EPRI, GRS, INRNE, IRSN, KIT, LEI, NPIC, PSI, SNERDI, TRACTEBEL, SSTC NRS, TUS, UNIPI, UNIRM1, USNRC, VTT.

- This UQ application:
  - Will train the project Partners gaining experience in the Uncertainty and Sensitivity Analyses (UaSA);
  - Will also provide a platform of discussion for proposing solutions if some issues arise during the UaSA applications and
  - Will be used as a technical background for the full plant, WP5 lead by JRC, and SFP, WP6 lead by IRSN, UaSA application.

- The selection of the Figure of Merits (FOMs) of the uncertainty analyses (e.g., release of iodine from the test fuel bundle, amount of suspended iodine in the containment's atmosphere, etc) and of the main uncertainty sources have been done in WP2, lead by GRS.

ENEA APPLICATIONS IN EU-MUSA PROJECT

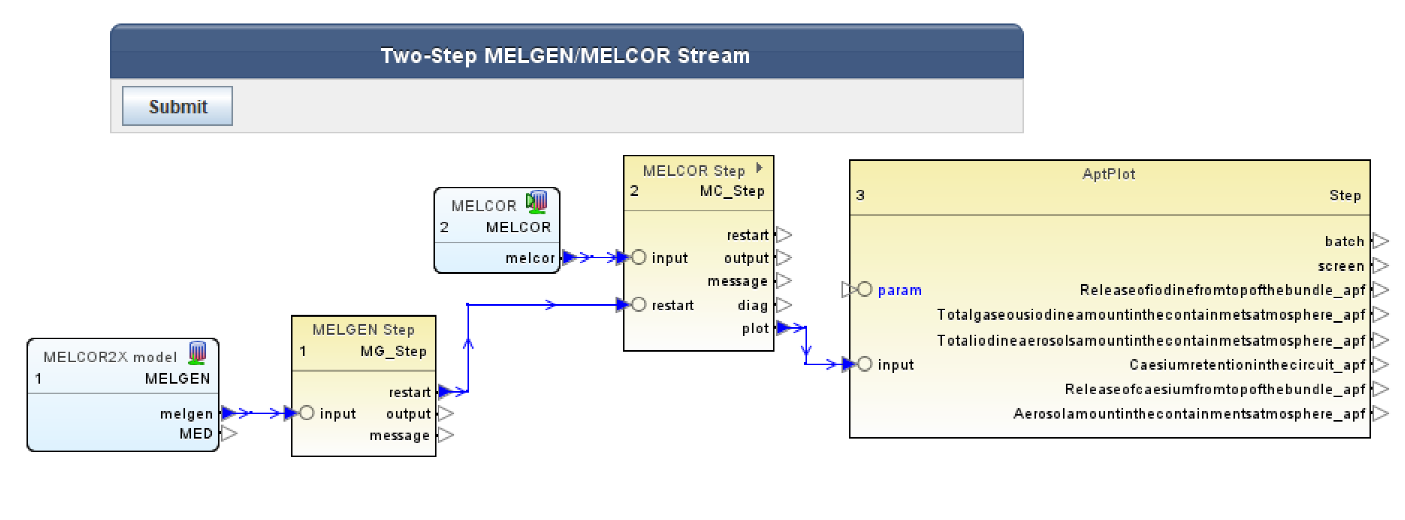
- Since Italy is a member of NRC's Cooperative Severe Accident Research Program (CSARP), ENEA has requested a PHEBUS FPT1 input-deck to USNRC. USNRC disclosed it and granted permission to ENEA to use it as a part of international collaboration on the MUSA project.
- Based on the USNRC input-deck, the SNAP model has been developed.
- The nodalization of the Phebus FPT1 used for the following study is composed of 31 control volumes, 29 Flow Paths and 68 Heat Structures.
- The fuel bundle is axially subdivided into eleven control volumes, modelled with the MELCOR CVH package. The vertical line above the bundle is subdivided into three regions corresponding to the Upper Plenum (UP), the lower vertical line and the upper vertical line.
- The horizontal line (HL) connecting vertical line above the bundle and inlet of the Steam Generator (SG) is modelled with two control volume. The SG is characterized by 9 control volumes in the ascending side and two control volumes in the descending side. There is one control volume connecting the outlet of the SG to the containment, which is modeled with one control volume.
- The bundle test section is modelled, in the COR package, by 31 axial regions and 2 radial regions.



Sketch of the nodalization on the SNAP environment.

ENEA APPLICATIONS IN EU-MUSA PROJECT

- At the present state of this research activity, the following preliminary FOMs, has been investigated:
  - Release of iodine from top of the bundle [% of initial inventory];
  - Release of Caesium from top of the bundle [% of initial inventory];
  - Caesium retention in the circuit [% of Cs released from the bundle];
  - Aerosol amount in the containment's atmosphere [g];
  - Total iodine aerosols amount in the containment's atmosphere [g];
  - Total gaseous iodine in the containment's atmosphere [g].
- The current calculation time is: 29500 s.

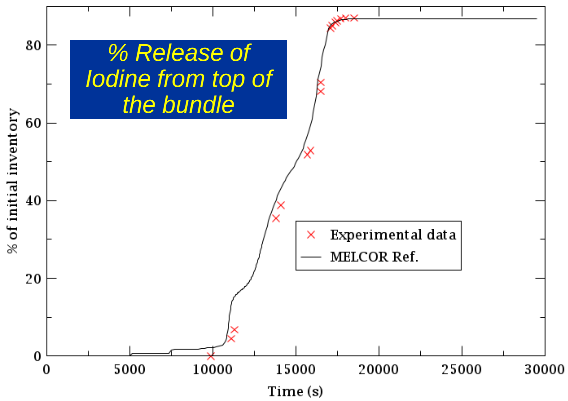


MELGEN/MELCOR stream flow for the reference case application.

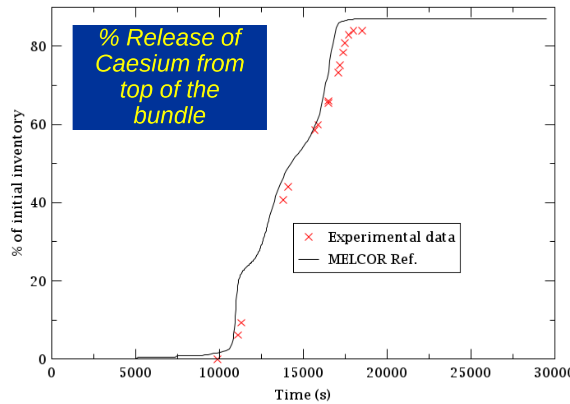
ENEA APPLICATIONS IN EU-MUSA PROJECT

Analyses of the code accuracy to predict the MUSA-WP4 FOM

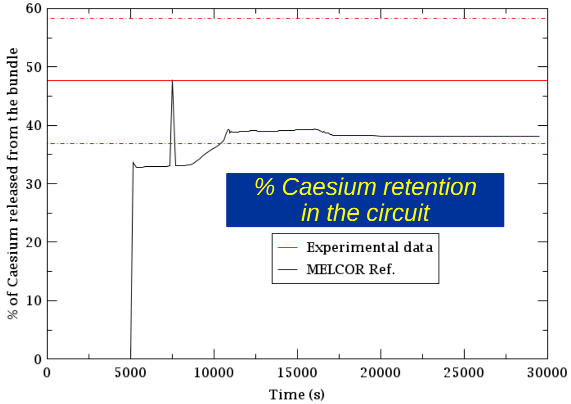
FOM 1 [1]

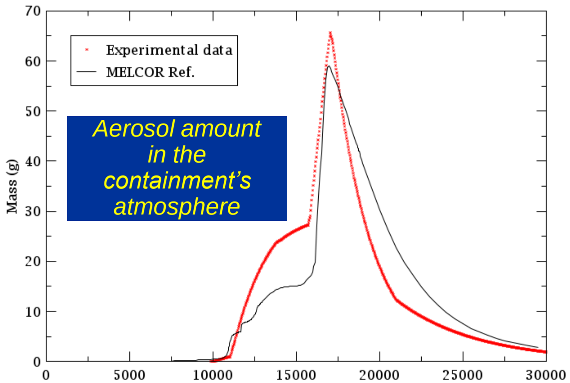


FOM 2 [2, 3]



FOM 3 [1]





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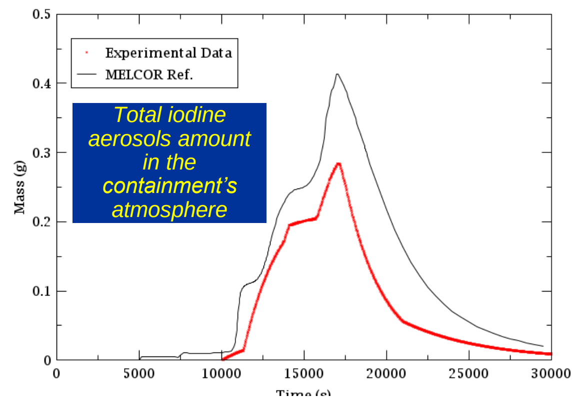
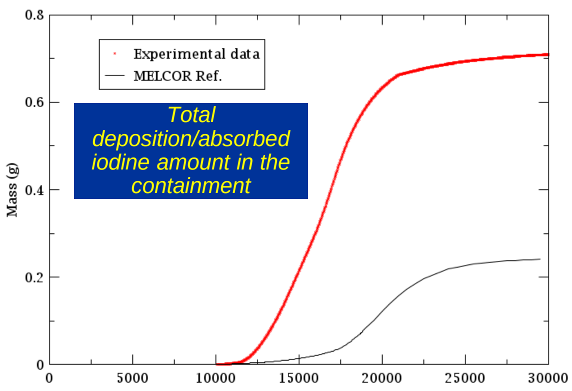


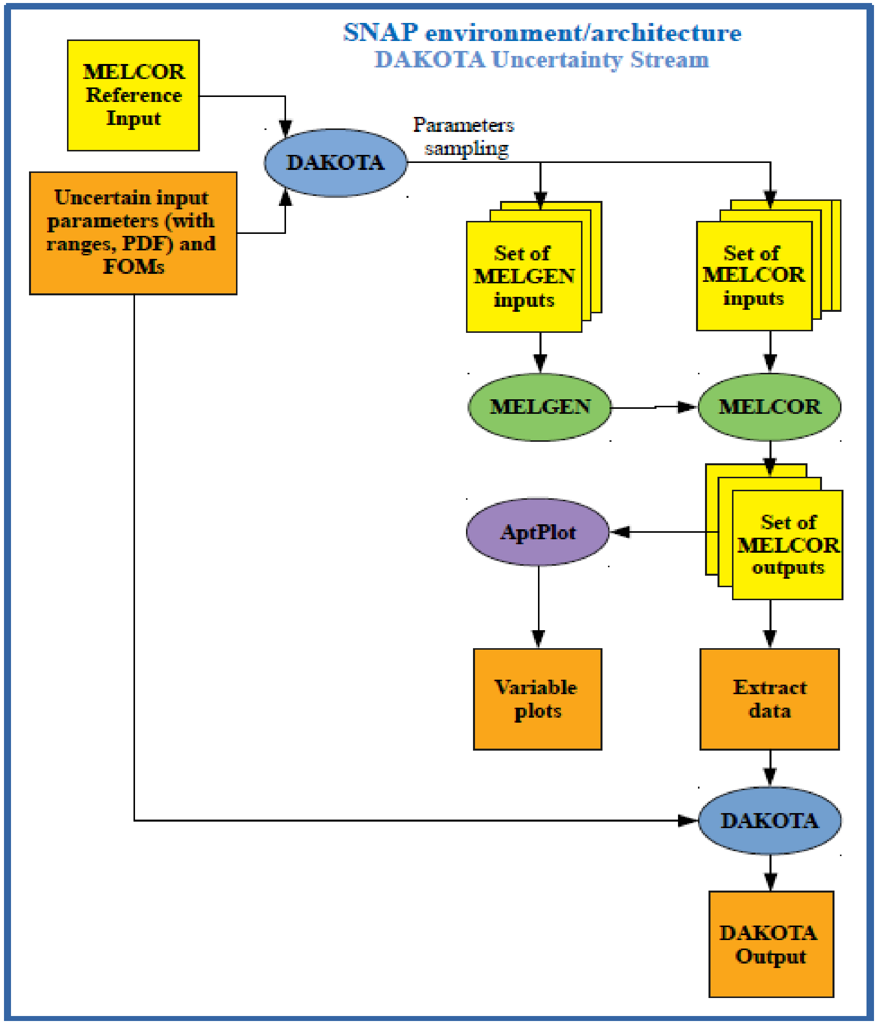
FOM 6 ≈[4]



FOM 7 ≈[4]

ENEA APPLICATIONS IN EU-MUSA PROJECT

- To develop the uncertainty analysis of this case, the coupling MELCOR/DAKOTA in SNAP environment/architecture will be used.
- DAKOTA toolkit, provide as a plug-in for SNAP, allows the following:
  - Enter the uncertain input parameters (with range and PDF);
  - Select the sampling method (Monte Carlo or Latin Hypercube);
  - Enter the desired FOMs for the analysis;
  - Set the final report.
- DAKOTA is used both at the beginning of the analysis to sample the uncertain input parameter values and to generate the set of code inputs.
- Then, after the solution of the set of code inputs and the extraction of the desired data, DAKOTA performs the uncertainty analysis and apply regression techniques to evaluate the correlation between input and output parameters selected as a FOM.
- At the present stage of the research activity, there are possible failure of the DAKOTA application in SNAP if one MELCOR calculation fails.



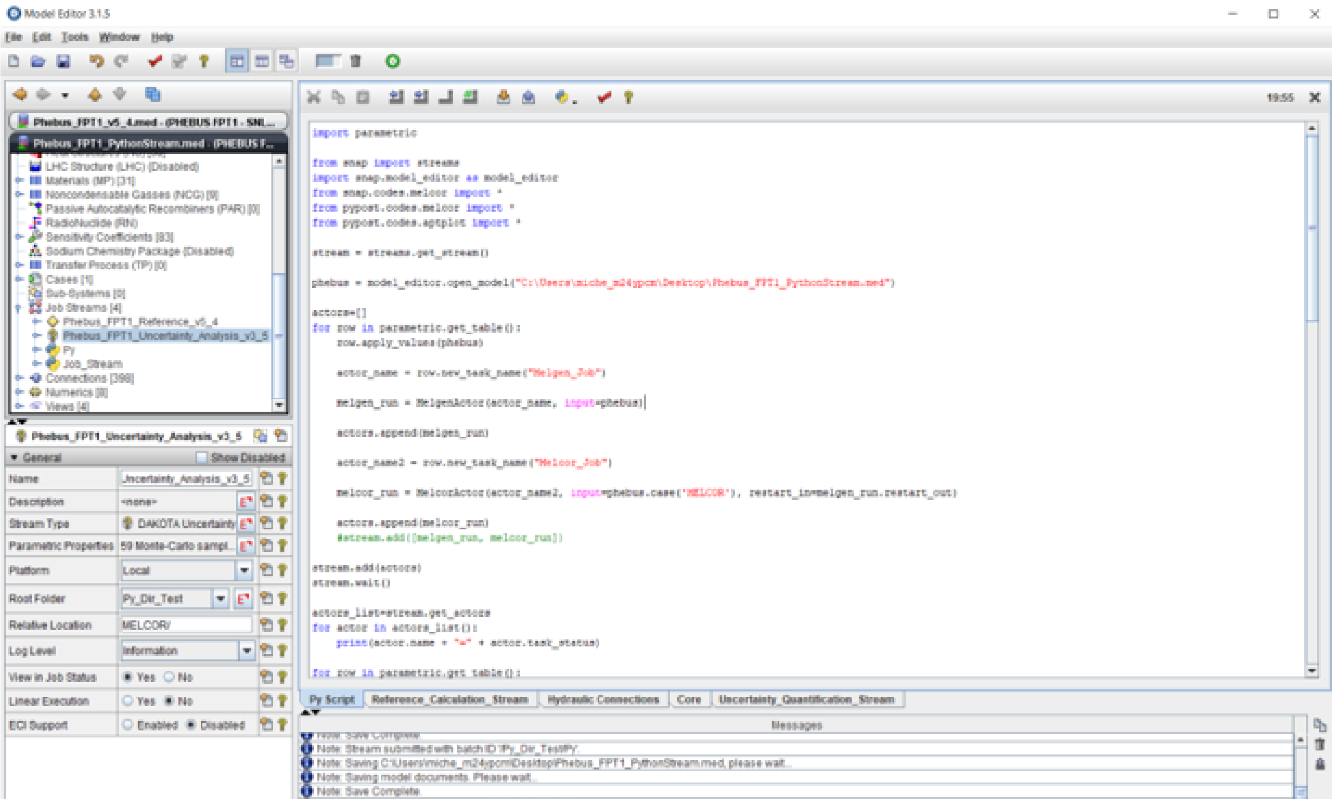
DAKOTA uncertainty analysis for MELCOR code in a SNAP environment/architecture.

ENEA APPLICATIONS IN EU-MUSA PROJECT

Currently if one calculation fails it prevents finalizing the UA application in SNAP:

o New Python directed job-stream capability in SNAP have been added;

o In the version 1.7 of the SNAP uncertainty plugin "the uncertainty quantification support in Python Directed streams was updated to support a specified number of "Replacement Samples" that are used to run additional tasks to replace those that fail to execute" (https://www.aptplot.com/snap/plugins/uncertainty/changes.jsp).



The Python directed stream job capability are under testing by UNIPI in collaboration with ENEA.

ENEA APPLICATIONS IN EU-MUSA PROJECT

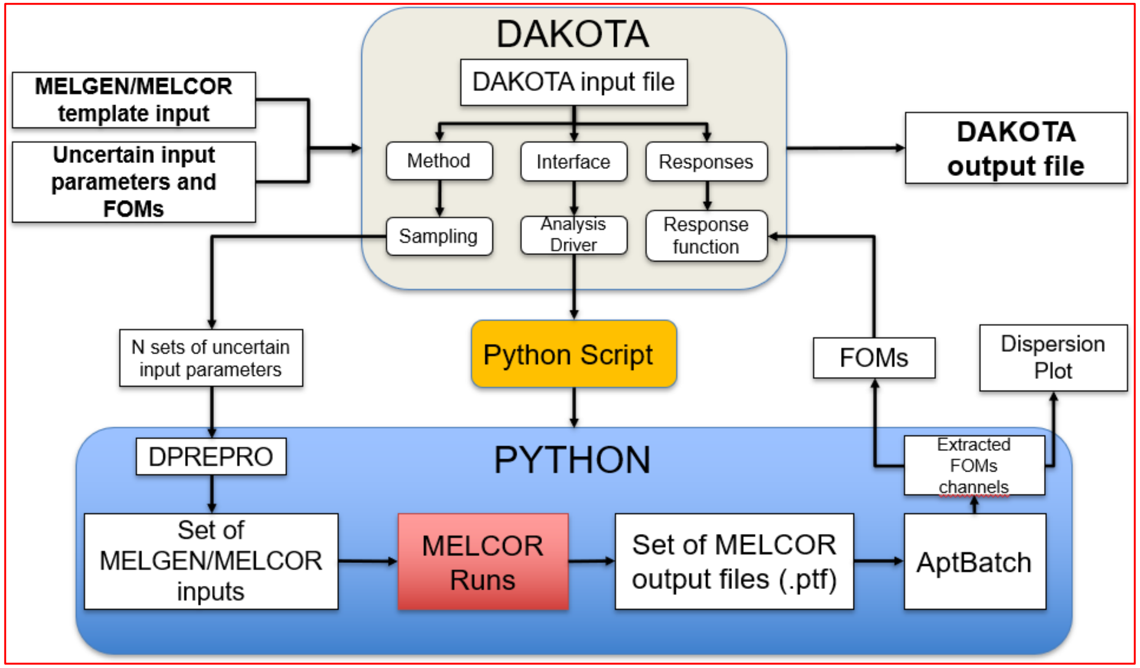
- The Python directed stream job capability are under testing together with UNIPI

- At the same time in ENEA the MELCOR/DAKOTA coupling has been investigated also outside from SNAP through python script

ENEA APPLICATIONS IN EU-MUSA PROJECT- Coupling MELCOR/DAKOTA with Python Script

- ❑Implementation of the coupling MELCOR/DAKOTA with Python Script.
- ❑Coupling based on using the user interface DAKOTA GUI implemented by DAKOTA.
- ❑Goal of this application is to resolve the issue of failed MELCOR runs, develop the uncertainty quantification report, and explore the full capability of DAKOTA stand alone.
- ❑This approach is based on the Python scripting:
  - to run the MELCOR cases;
  - extract the FOMs channels with AptBatch executable;
  - plot dispersion of FOMs channels.

DAKOTA uncertainty analysis for MELCOR code in a PYTHON environment/architecture.



ENEA APPLICATIONS IN EU-MUSA PROJECT

- The uncertain input parameters selected from the WP2 database for the uncertainty analysis currently are:
  - CHI (Aerosol dynamic shape factor)
  - GAMMA (Aerosol agglomeration shape factor)
  - FSLIP (Particle slip coefficient)
  - STICK (Particle sticking coefficient)
  - TURBDS (Turbolence dissipation rate)
  - TKGOP (Ratio of the thermal conductivity of the gas over that for the particle)
  - FTHERM (Thermal accomodation coefficient)
  - DELDIF (Diffusion boundary layer thickness).

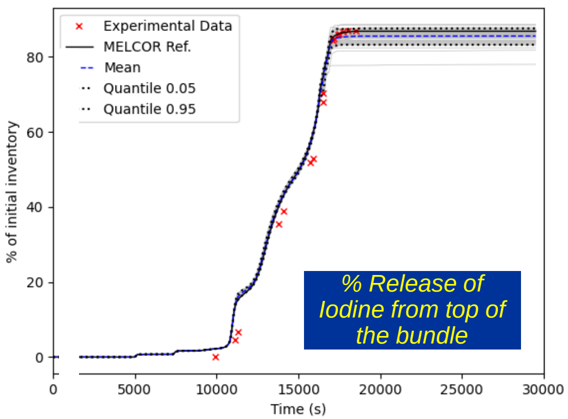
- At the current state of the activity, the preliminary FOM selected for the uncertainty analysis is the «Aerosol amount in the containment's atmosphere» and in particular the statistical analysis is conducted considering the maximum value of this one.

ENEA APPLICATIONS IN EU-MUSA PROJECT

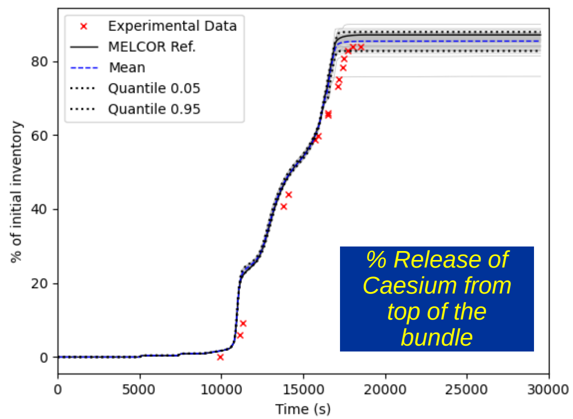
	Partner Choice
Uncertainty Methodology used	Probabilistic method to propagate input uncertainty
Methods used to define the required number of samples	Wilks Method
Sampling methods	Monte Carlo
Probability and confidence level selected	95%, 95%
Statistical analyses of the FOMs	Min value, max value, mean, median standard deviation, cumulative distribution function -CDF-, probability density function -PDF-.
Sensitivity analyses used to characterize the relation between the input uncertainty parameters and the FOM	Pearson and Spearman coefficients.

ENEA APPLICATIONS IN EU-MUSA PROJECT

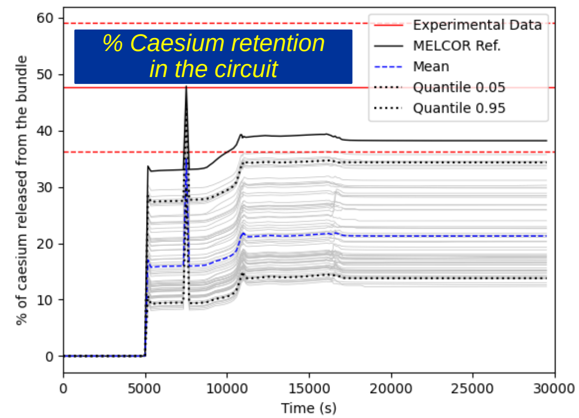
FOM 1 [1]

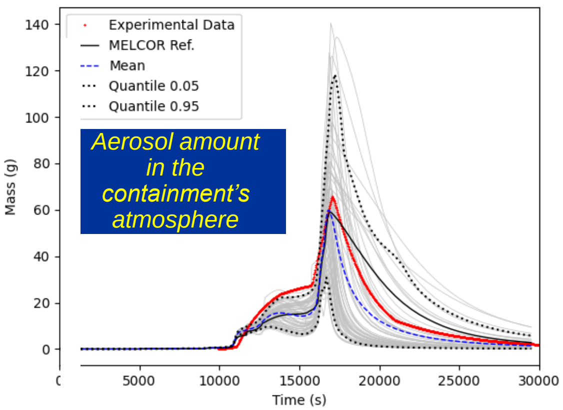


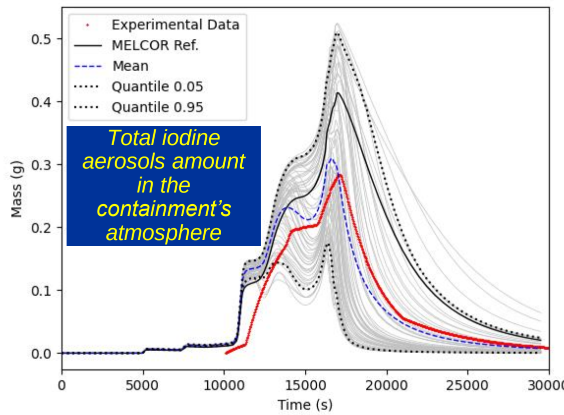
FOM 2 [2, 3]

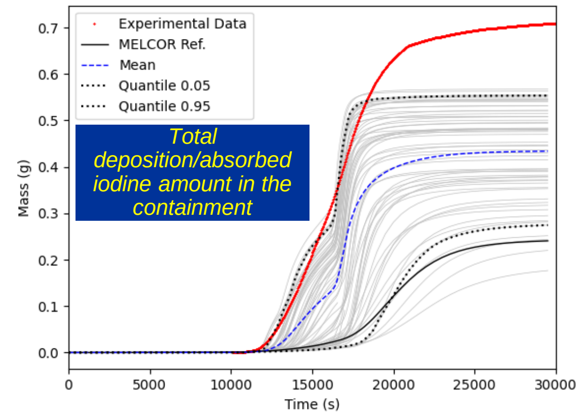


FOM 3 [1]









FOM 4 [1]

FOM 6 ≈[4]

FOM 7 ≈[4]

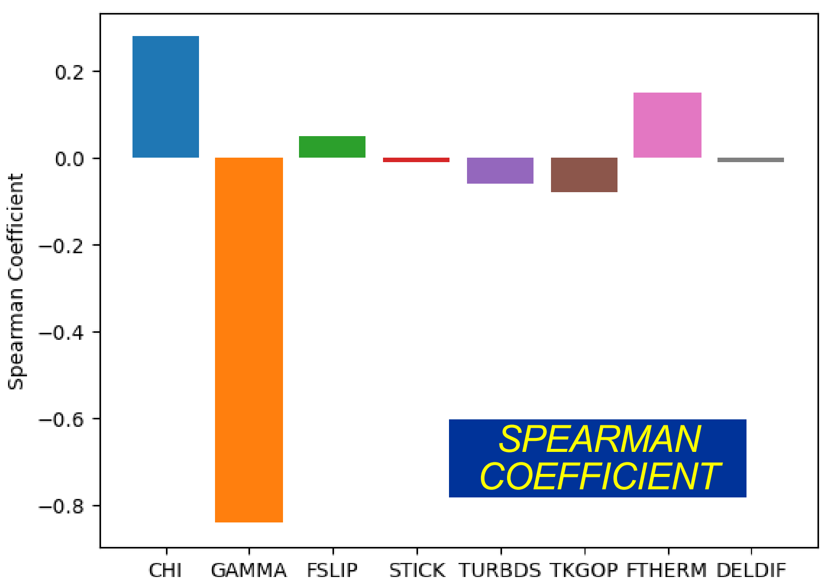
ENEA APPLICATIONS IN EU-MUSA PROJECT

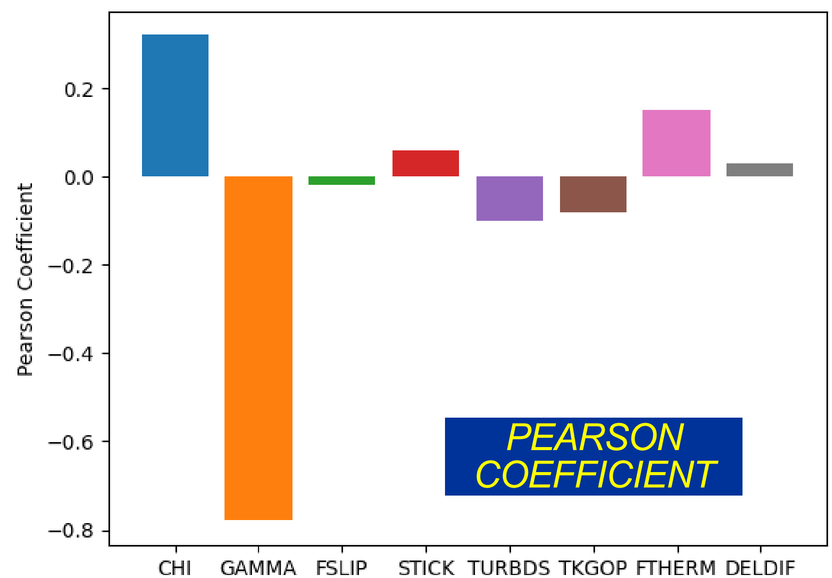
	Mean	Standard Deviation	LowerCI_Mean	UpperCI_Mean	LowerCI_StdDev	UpperCI_StdDev
FOM (max value of Aerosol amount in the containment's atmosphere) [g]	65.99	27.85	58.92	73.07	23.67	33.85

	CHI	GAMMA	FSLIP	STICK	TURBDS	TKGOP	FTHERM	DELDIF
Pearson Coefficient	0.32	-0.78	-0.02	0.06	-0.10	-0.08	0.15	0.03

	CHI	GAMMA	FSLIP	STICK	TURBDS	TKGOP	FTHERM	DELDIF
Spearman Coefficient	0.28	-0.84	0.05	-0.01	-0.06	-0.08	0.15	-0.01

The activity has been done in collaboration with University of Palermo.





ENEA INVOLVMENT IN EU-MUSA PROJECT

- At the present stage of the research activity, it has been possible develop a reference case for the Phebus FPT1.

- The preliminary FOMs currently investigated are "Release of iodine from top of the bundle", "Release of Caesium from top of the bundle", "Caesium retention in the circuit", "Aerosol amount in the containment's atmosphere" and "Total aerosols iodine in the containment's atmosphere".

- The probabilistic method to propagate input uncertainty by coupling MELCOR/DAKOTA in the SNAP environment/architecture has been chosen but some issues related to MELCOR runs failure do not allow the finalization of the uncertainty analysis.

- A MELCOR/DAKOTA coupling with Python has been developed. The uncertainty input parameters, selected from the WP2 have been added in the input model and a preliminary uncertainty application, assuming the maximum value of "Aerosol amount in the containment's atmosphere" as a FOM for the statistical analysis, has been developed only to test the methodology.

- Challenges:
  - Implementation of Python Stream in SNAP to resolve the issues related to possible MELCOR runs fail.
  - Further improvement of MELCOR/DAKOTA coupling with Python (outside form SNAP) to explore and testing the full capability of DAKOTA.
  - Implementation on the cluster of MELCOR/DAKOTA coupling.

ENEA APPLICATIONS IN EU-MUSA PROJECT

[1] Schwarz, M., Clement, B., Jones, A.V., 2001. Applicability of Phebus FP results to severe accident safety evaluations and management measures. Nucl. Eng. Des. 209, 173–181.

[2] Dubourg, R., Faure-Geors H., Nicaise, G., Barrachin, M., 2005. Fission product release in the first two PHEBUS tests FPT0 and FPT1. Nuclear Engineering and Design 235, 2183–2208

[3] Darnowski, P., Włostowski, M., Stępień, M., Niewiński, G., 2020. Study of the material release during PHÉBUS FPT-1 bundle phase with MELCOR 2.2, Annals of Nuclear Energy 148.

[4] Bosland, L., Weber, G., Klein-Hessling, W., Girault, N. & Clement, B., 2012. Modeling and Interpretation of Iodine Behavior in PHEBUS FPT-1 Containment with ASTEC and COCOSYS Codes, Nuclear Technology, 177:1, 36-62.

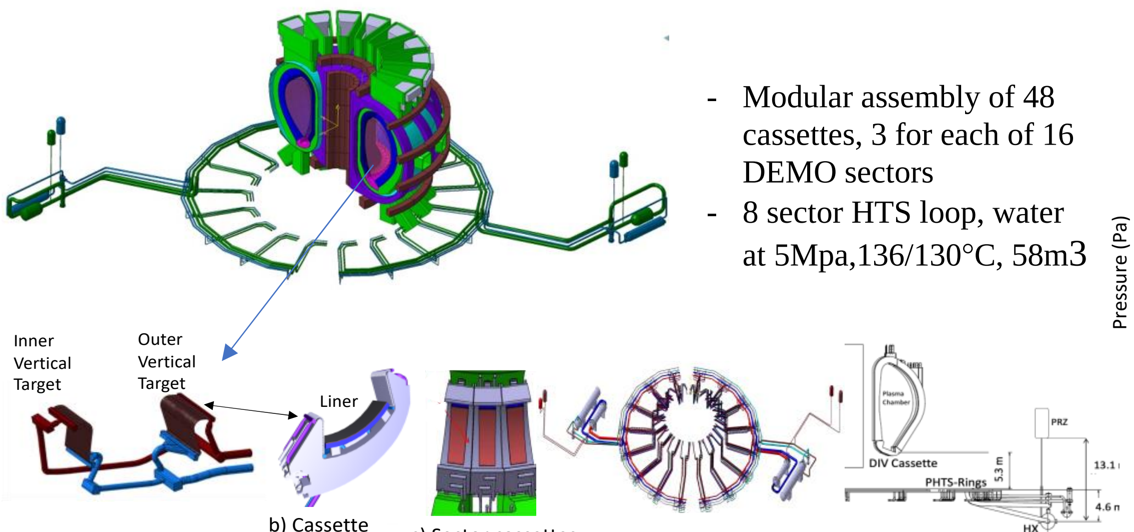
ENEA INVOLVMENT IN EU-MUSA PROJECT

This project has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 847441

ENEA INVOLVMENT IN EUROFUSION - Accident analyses within EUROFusion project:

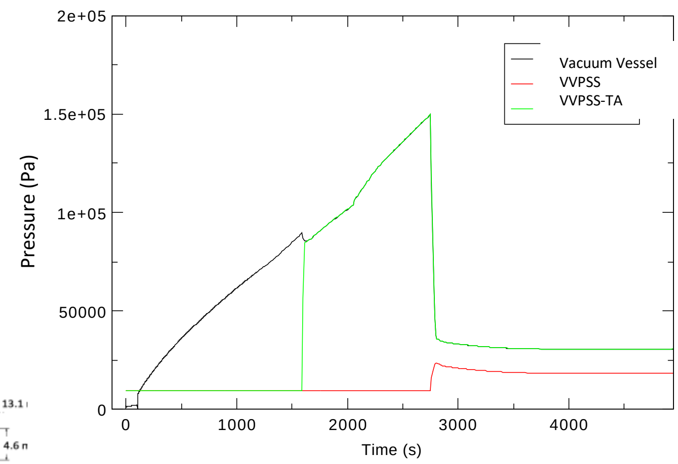
❑ DEMO Tokamak plant: Divertor system analyses

- Preliminary Safety Assessment of Conceptual design of European Nuclear Fusion DEMOnstrative Tokamak reactor plant
- Melcor v1.8.6 fusion, water coolant
- Design Basis Accident considered:
    - Postulated Initiating Event: a loss of coolant in the DV primary cooling circuit of the PFU inside the VacuumVessel (VV).
    - Demonstrate Vacuum Vessel pressurization within safety margins (<0.2 Mpa), considered safety provisions, e.g. Vacuum Vessel Pressure Suppression System (VVPSS).



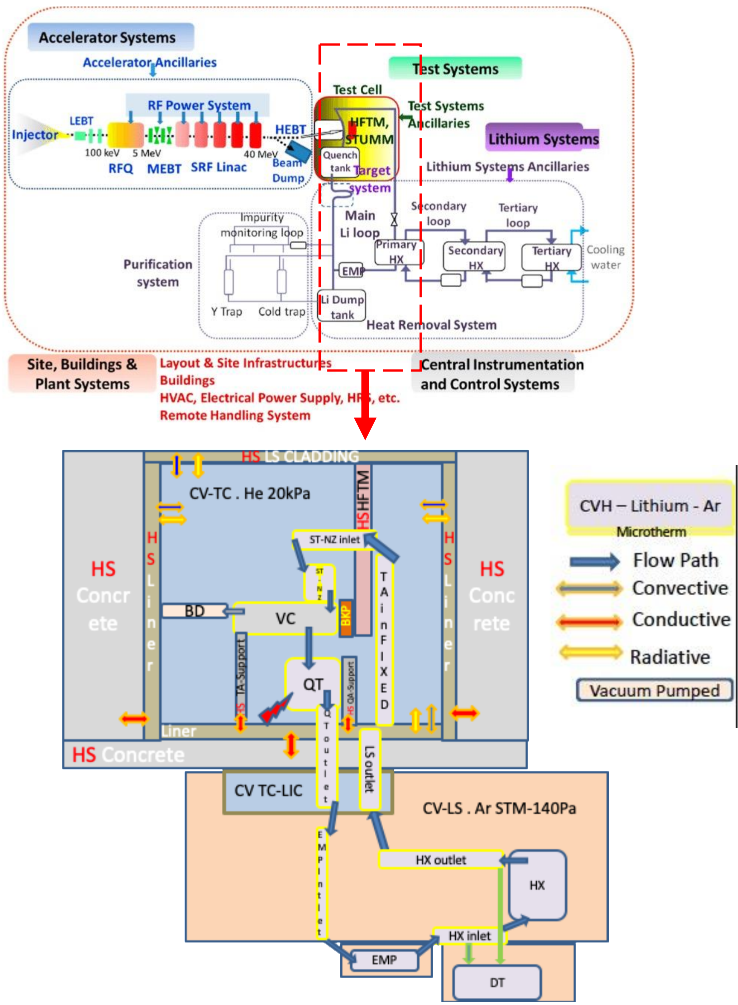
a) PFU module b) Cassette module c) Sector cassettes assembly d) Divertor HTS layout e) PFU/Cassette HTS elevations

- Modular assembly of 48 cassettes, 3 for each of 16 DEMO sectors
- 8 sector HTS loop, water at 5Mpa,136/130°C, 58m3

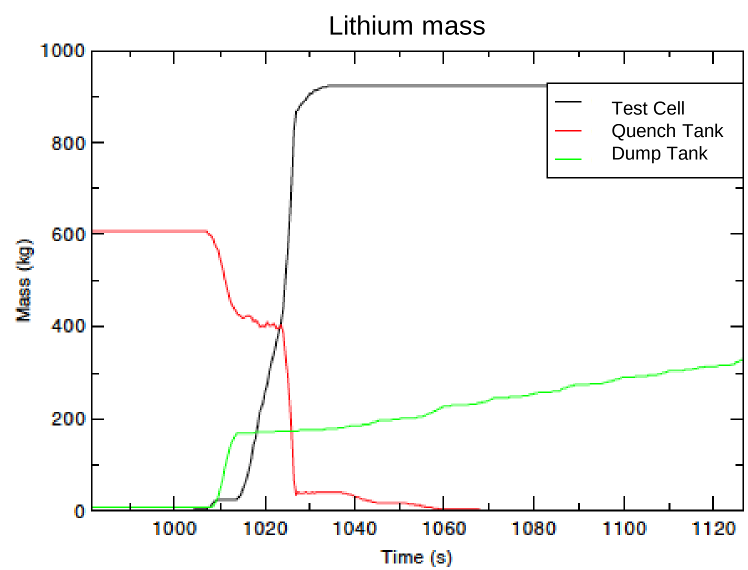


ENEA INVOLVMENT IN EUROFUSION - Accident analyses within EUROFusion project:

DONES neutron Irradiation facility

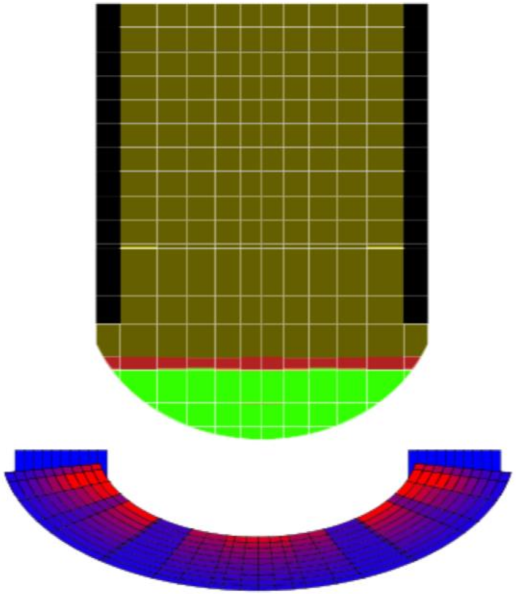


- DONES: Accelerated deuterons impacting a liquid lithium flowing film undergo striping reactions providing neutrons in fusion relevant energy spectrum for material testing purposes
- Melcor v1.8.6 fusion, lithium coolant
- Initiating Event: Loss of Lithium from primary loop due to large break in Quench Tank (QT) in Test Cell
- Purpose:
  - Assess released inventory of lithium
  - Impact on Test Cell containment atmosphere, water cooled floor liner

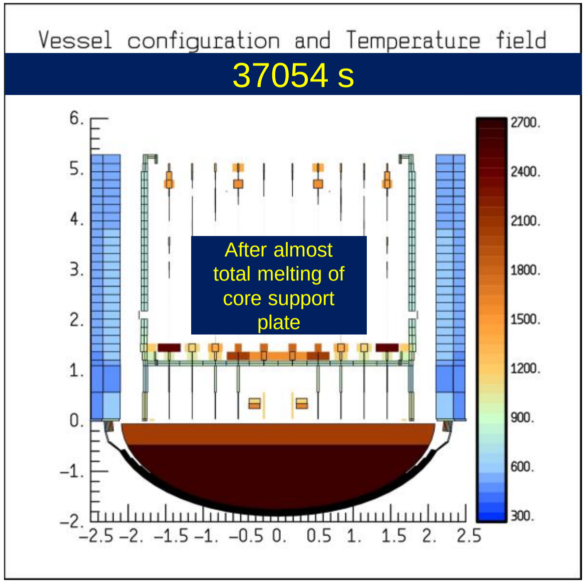


ENEA INVOLVMENT IN EU-IVMR PROJECT

- A first calculation by using 2800 K as the melting temperature for Uranium-dioxide and Zirconium-oxide has been performed;
- By a first comparison between ASTEC and MELCOR code results:
  - The sequence of main events is similar between ASTEC and MELCOR code;
  - The corium slumping into the LP take place at very similar times;
  - The time of the maximum heat flux in the LP take place at very similar times;
  - The maximum heat flux predicted by MELCOR is at *of the top of metallic pool as ASTEC;*
  - The maximum heat flux predicted by MELCOR is smaller in comparison with ASTEC (0.89 MW/m^2 VS 1.52 MW/m^2)
  - The corium physical characteristics in the LP are significantly different:
    - 2 layers molten pool in ASTEC (oxides at the bottom and metals at the top) with negligible particulate debris;
    - Bottom layer with particulate debris and top layer with metallic molten pool in MELCOR [small and intermittent quantity of oxidic molten pool].



In the last 3000 s of the transient the MELCOR calculation are characterized by bottom layer with particulate debris and top layer with metallic molten pool (small and intermittent quantity of oxidic molten pool at the top of the debris bed layer is observed)]. Debris bed mass is important during the whole transient before and after slumping (UO2 and ZrO2 are dominant).



In ASTEC code, corium pool composed of <u>oxides at the bottom and metals at the top</u>. Progressive increase of the top metals layer height due to melting of lower-head structures, ablation of vessel wall and almost total melting of core support plate (radiation from the top of molten corium).

ENEA

ENEA INVOLVMENT IN EU-IVMR PROJECT

- Following the completion of this first study and after consultation with MELCOR code development team, the 2800 K melting temperature for Uranium-dioxide and Zirconium-oxide suggested in the MELCOR best practice as applied in early SOARCA project [NUREG/CR-7008], does not represent the current understanding of material interaction.
  - Therefore this temperature was reduced to 2500 K in more recent studies (see for example the draft of the SOARCA SEQUOYAH, [https://www.nrc.gov/docs/ML1715/ML17156A270.pdf]).
  - This partially explains the difference between the corium behavior in the lower plenum between MELCOR and ASTEC code.
- A second calculation by using 2500 K as the melting temperature for Uranium-dioxide and Zirconium-oxide has been performed (in this calculation the lower head failure is not modeled);
  - By a first comparison between ASTEC and MELCOR code results:
    - The sequence of main events is similar between ASTEC and MELCOR code;
    - The corium slumping into the LP take place at very similar times;
    - The time of the maximum heat flux in the LP take place at very similar times;
    - The maximum heat Flux predicted by MELCOR is at *of the top of metallic pool as ASTEC;*
    - The maximum heat flux predicted by MELCOR is bigger in comparison with ASTEC (1.71 MW/m^2 VS 1.52 MW/m^2). In MELCOR calculation a first peak of about 2.18 MW/m2 has been observed at about 21600 due to the slumping phenomenology.

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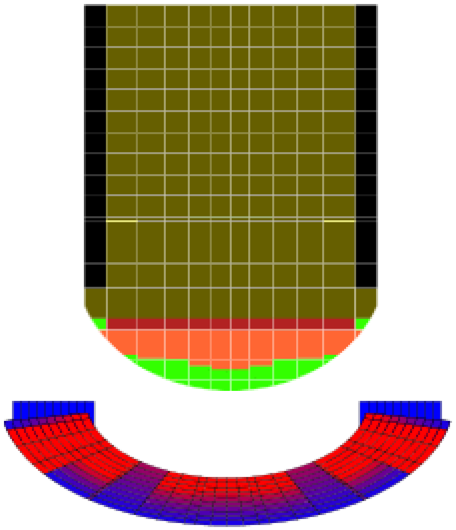
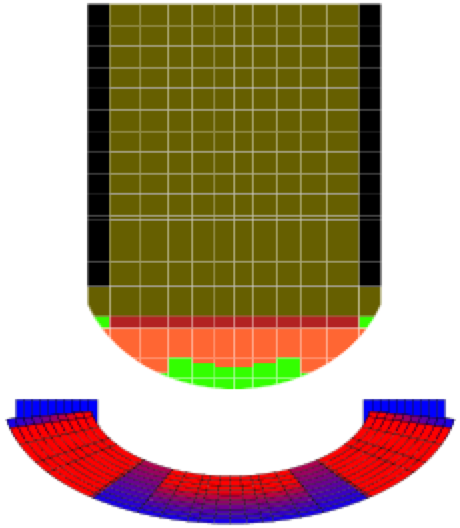
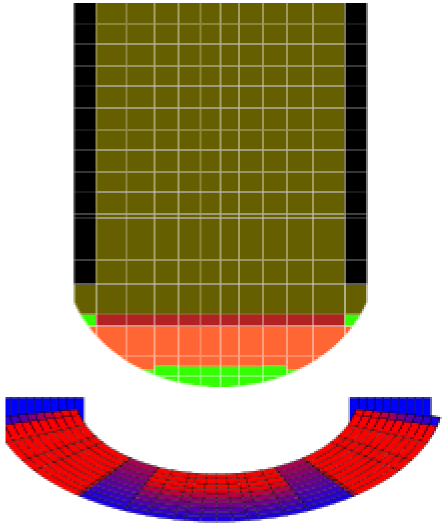
ENEA INVOLVMENT IN EU-IVMR PROJECT

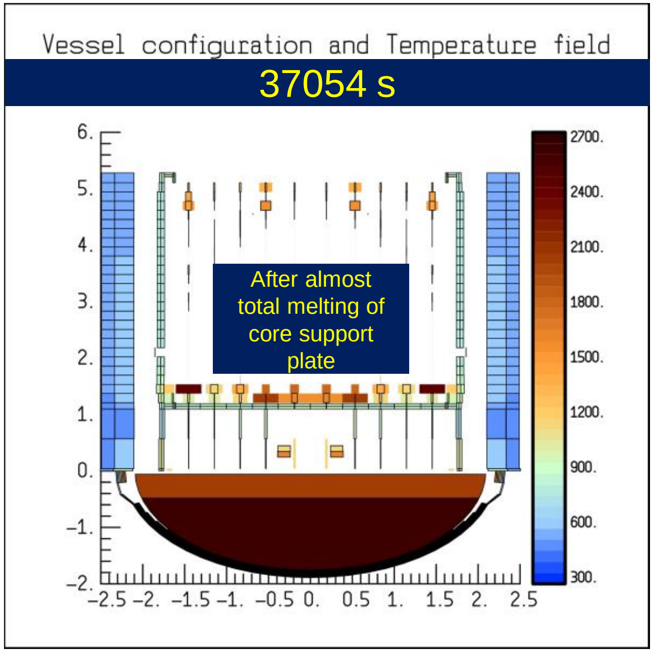






Corium pool composed of <u>oxides at the bottom and metals at the top</u>.
Progressive increase of the top oxide layer and the contemporary decrease of debris is observed.
The molten structural material of the LH cannot be part of the core package modeling; therefore the ablated LH material will not mix with the debris bed, molten metallic pool or oxide molten pool.

ASTEC



ANALYSES OF THE PHYSICAL MODELS NECESSARY TO BE IMPLEMENTED IN MELCOR_2.2 FOR FUSION REACTOR SAFETY ANALYSES AND THE CURRENT MODEL ALREADY IMPLEMENTED IN MELCOR FUSION

- During the last well organized EMUG meeting in Zagreb (25-27 April 2018), there was a very interesting discussion about the physical models necessary to be implemented in MELCOR_2.2 for fusion reactor safety analyses and the current model already implemented in MELCOR fusion.
- Since the session4 ("GEN IV and Fusion Applications") was chaired by ENEA, ENEA proposed an action that was agreed by all the Colleagues attending the meeting: ENEA will contact all the EMUG Partners to collect the information about physical models necessary to be implemented in MELCOR_2.2 for fusion reactor safety analyses and the current model already implemented in MELCOR fusion.
- ENEA has already contacted all the EMUG Partners to collect the information about physical models necessary to be implemented in MELCOR_2.2 for fusion reactor safety analyses and the current models already implemented in MELCOR fusion.
- These are the information requested:
    - Description of phenomenon of interest;
    - Safety relevance of the phenomenon for fusion reactor;
    - Rank of importance (1: low; 2: medium; 3: High) ==> priority for code development;
    - If models to characterize the phenomenon have been already implemented in MELCOR fusion and the related version.
- The final report related to this activity is in a draft form for comments and will be soon finalized and distributed.
- The activity has been developed in collaboration with BELV, CCFE, CIEMAT, KIT, CVR, Jacbsen Analytics, JSI, POLITO, UNIROMA1, UNIPI.

ANALYSES OF THE PHYSICAL MODELS NECESSARY TO BE IMPLEMENTED IN MELCOR_2.2 FOR FUSION REACTOR SAFETY ANALYSES AND THE CURRENT MODEL ALREADY IMPLEMENTED IN MELCOR FUSION

ISSUE N	ISSUE DESCRIPTION	Priority	Complexity of implementation	MELCOR_FUSION REFERENCES
1	Introduce additional working fluids with multiphase capabilities	3		[2][3]
2	Implementation of the possibility to use different fluids in different circuits at the same time during the calculation	3		-
3	Introduce models for chemical reactions in the case of different working fluids	2		[6][7][13]
4	Model steam oxidation of the Plasma-Facing-Component (PFC)	2		[2][4]
5	Model air oxidation of the Plasma-Facing-Component (PFC)	2		[4]
6	Introduce models for aerosols turbolent and inertial deposition	2		[2]
7	Introduce models for aerosols deposition with different carrying gas and mixtures	2		[2]
8	Introduce aerosol resuspension model	2		[9]
9	Extend the deposition and resuspension modelling to take into account remnant magnetization effects	1		
10	Introduce models for aerosols transport in multifluid (multi-working fluid) simulation.	2		-
11	Implementation of specific heat transfer correlations for simulating He as working fluid in the geometry of interest.	2		-
12	Standard Scrubber model in FL Package for Helium.	1		-
13	Introduce dissolved NCG species within working fluids	2		-
14	Implement magnetic pump modelling (for design) and features (e.g. coast-down, etc)	1		-
15	Include MHD effects on heat transfer correlation and pressure drop evaluation (for design)	1		-
16	Extend the water properties below triple point temperature	2		[2]
17	Air condensation onto cryogenic structures	2		[4][14]
18	Helium condensation onto cryogenic structures	2		[2]
19	Allow low temperature operations (>3K) and cryogen working fluids	2		
20	Extend material physical properties to cryogenic range	3		
21	Enclosure radiant heat transfer	2		[2]
22	A common release MELCOR 2.x incl. fusion features	1		
23	Hydrogen tritium oxide transport			
24	Tritium transport			
25	Dust and Hydrogen explosion			

ANALYSES OF THE PHYSICAL MODELS NECESSARY TO BE IMPLEMENTED IN MELCOR_2.2 FOR FUSION REACTOR SAFETY ANALYSES AND THE CURRENT MODEL ALREADY IMPLEMENTED IN MELCOR FUSION

- Considering the great feedback that the activity has received between colleagues and along the socials dissemination/communication could be of interest to prepare a journal paper or a journal technical note about it, in order to have an endorsed official reference.

ENEA INVOLVMENT IN ITALIAN SAFETY ASSESSMENT ACTIVITY

- The ENEA activities related to the MELCOR code are oriented to the simulation and evaluation of severe accident evolutions and source term for “safety assessment”, mainly focusing on the characteristics of NPPs located at the Italian border.

- The activity is the basis for the development of a source term database to be used as an input for the MACCS code available in ENEA .

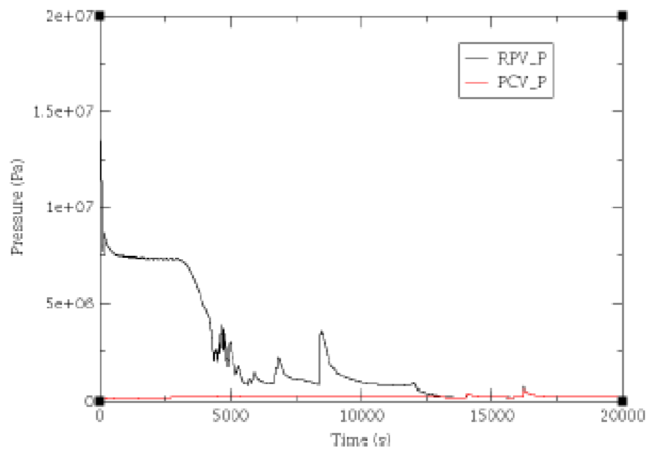
  - In-vessel analysis with the MELCOR 2.1 of three unmitigated LBLOCA severe accidents in a generic PWR of 900 MWe, caused by three distinct initiator events: a) Double-ended rupture of the cold leg of Loop 1; b) Double-ended rupture of the hot leg of Loop 1; c) Double-ended rupture of the surge line. The activity has been conducted in ENEA in the framework of a Master Degree thesis with the University of Bologna.

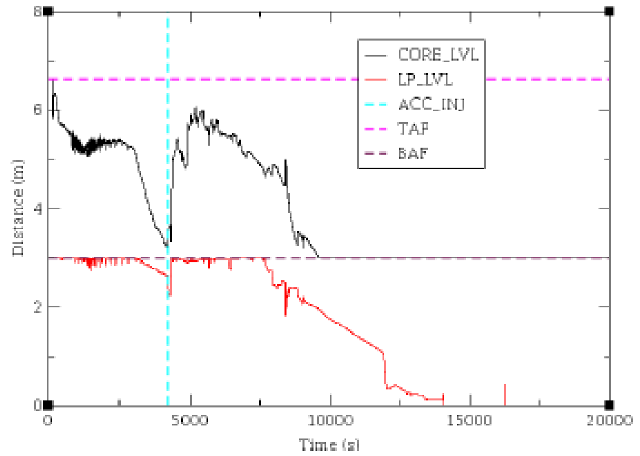
  - A short term Station Blackout (SBO) accident leading to a loss of the ultimate heat sink, and the possible thermal induced SGTR, with consequent evaluation of the source term has been calculated by MELCOR code.

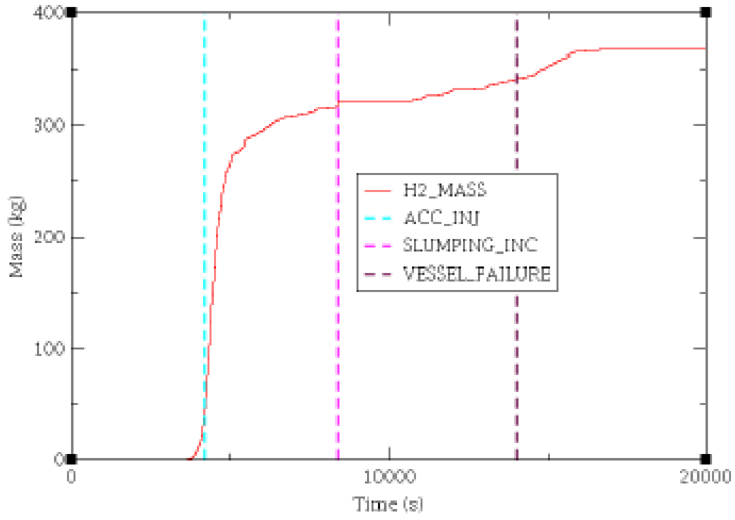
  - A 2 inch unmitigated SBLOCA has been calculated by MELCOR code:
    - The effect of the discharge coefficient at the break in the calculated results will be investigated.
    - The results could be compared with analogous ASTEC and MAAP results (independent user cross walk activity) done by JRC.

  - LFW and LBLOCA transient with MELCOR code have been performed by Sapienza University of Rome.

ITALIAN SAFETY ASSESSMENT ACTIVITY - 2 INCH UNMITIGATED SBLOCA







RELEVANT PHENOMENOLOGYCAL ASPECTS	MELCOR
SGs (1,2,3) Cycling Inception (s)	48, 50,50
Two Phase Inception in the HL 1,2,3 (s)	70,88,88
H2 Start (s)	2000
TCL 1300K (s)	3570*
TCL 1855K (s)	3870*
Start of Accumulators 1,2,3 Discharge (s)	4200
Upper Core Part Failure Inception (s)	4930
Massive Slumping Inception (s)	8390
Vessel Failure (s)	14000

* Radial ring 1 and axial level 16

ENEA INVOLVMENT IN ASCOM PROJECT

- The aim of this activity is to study the main phenomena during a postulate unmitigated 2-inch Cold Leg LOCA accident in a generic PWR 900 MWe three loops, especially as regards the thermal-hydraulic phases of the transient core degradation phenomena, the oxidation and hydrogen production processes.
- This transient is evaluated by the SA code ASTEC and compared with the results obtained with the SA code MELCOR.
- The transient selected for this analysis is initiated by a 2-inch break in the Cold Leg (CL) of the loop 1, where the Pressurizer (PRZ) is located. It is assumed that among the safety systems only the passive accumulators are in operation.
- The break event is coupled with:
  - Loss of offsite Alternating Current (AC) power;
  - Failure of all the diesel generators.

  This determines:
  - Primary pressure control systems (heaters and PRZ spry),
  - Chemical and Volume Control System (CVCS),
  - Reactor Coolant Pump (RCP) seal injection,
  - Active safety injection systems (High Pressure Injection System, HPIS, and Low Pressure Injecion System, LPIS),
  - Motor-driven Auxiliary Feedwater (MDAFW) system,

  are unavailable.

ENEA INVOLVMENT IN ASCOM PROJECT

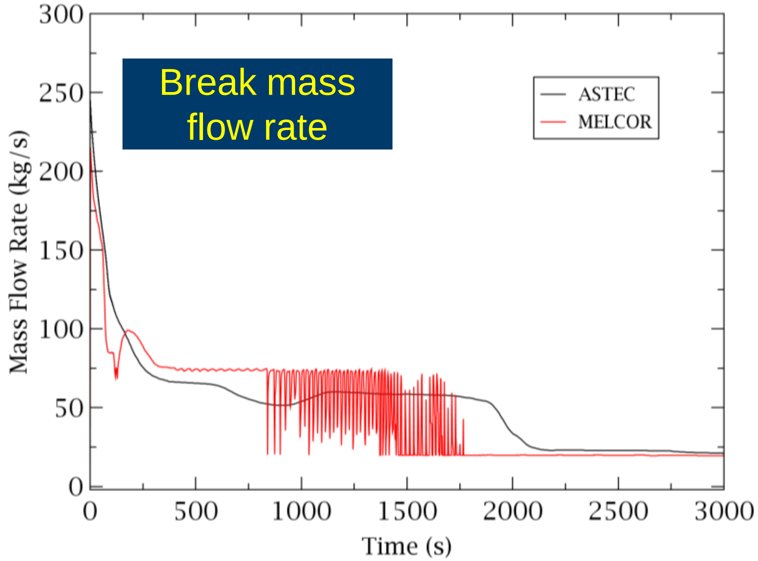
- The following hypotheses are also considered:
  - Reactor SCRAM and Steam Generators (SGs) isolation at the Start Of the Transient (SOT);
  - Indipendent failure of the Turbine Driven Auxiliary Feedwater (TDAFW) pump (no AFW available);
  - No primary boundary structures thermal induced degradation phenomena
  - Primary and secondary Steam Relief Valves (SRVs) availability throughout the accident evolution.
  - Safety Valves of Pressure Compensator (SEBIM) manually stuck open when the core exit temperature reaches 650 °C.

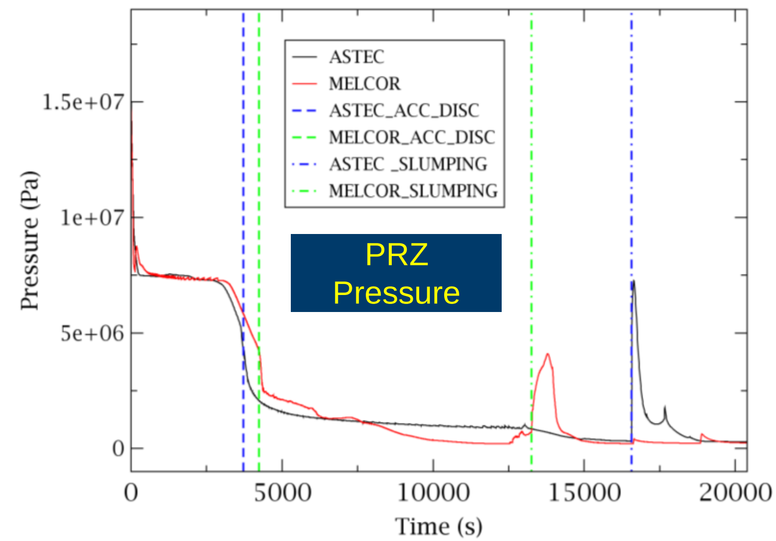
- The transient has been analyzed until the Lower Head (LH) failure.

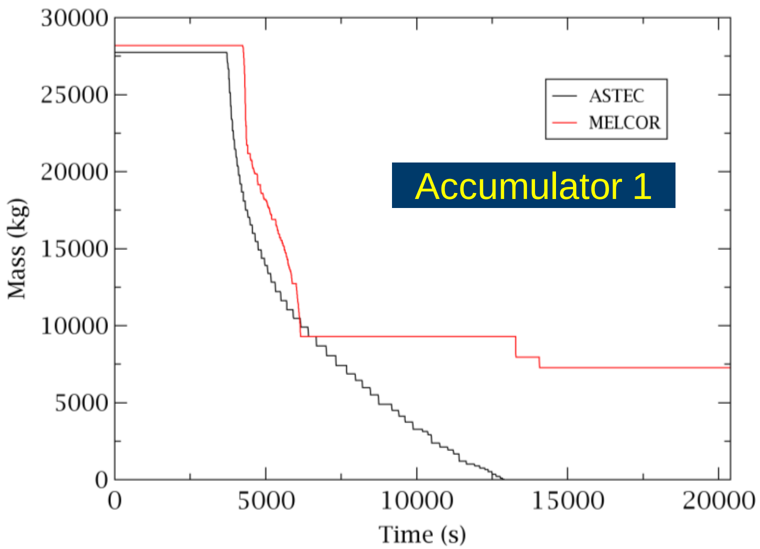
ENEA INVOLVMENT IN ASCOM PROJECT

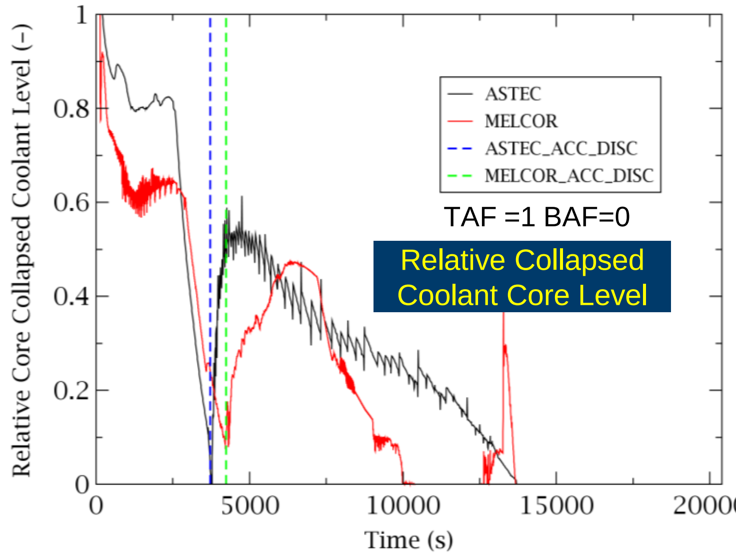
Relevant Phenomenological Aspects [s]	ASTEC	MELCOR	DISCR [%]
SOT, SCRAM, SGs isolation	0	0	0
SG 1,2,3 cycling inception	38,30,30	30,25,25	21.05,16.67,16.67
Core TAF uncovered	204	126	38.24
H_2 generation start	2923	3336	14.13
T > 1300 K (before accumulators injection)	-	3505	-
T > 1855 K (before accumulators injection)	-	3798	
Start of accumulators 1,2,3 discharge	3713,3713,3713	4236,4238,4238	14.09,14.14,14.14
Core BAF uncover	3773	-	-
T > 1300 K (after accumulators injection)	7208	8086	12.18
T > 1855 K (after accumulators injection)	7528	8707	15.66
Core BAF uncover	13702	10006	26.97
Slumping	16564	13253	19.99
LH failure	20394	20160	1.15

ENEA INVOLVMENT IN ASCOM PROJECT

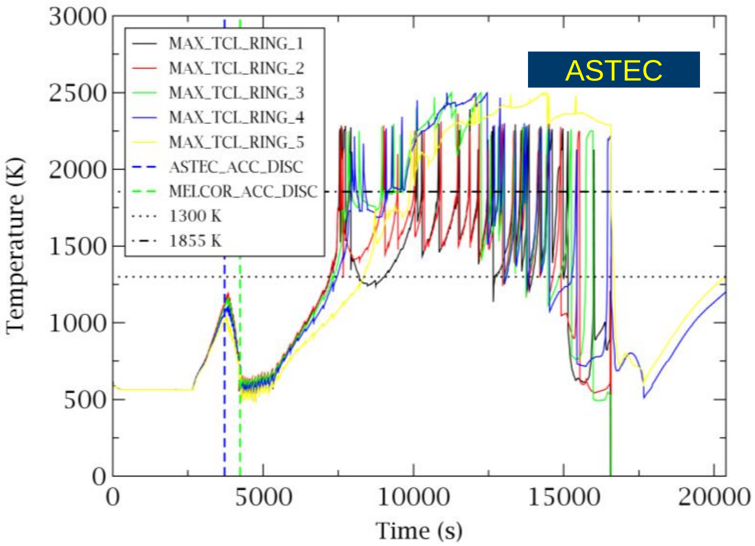


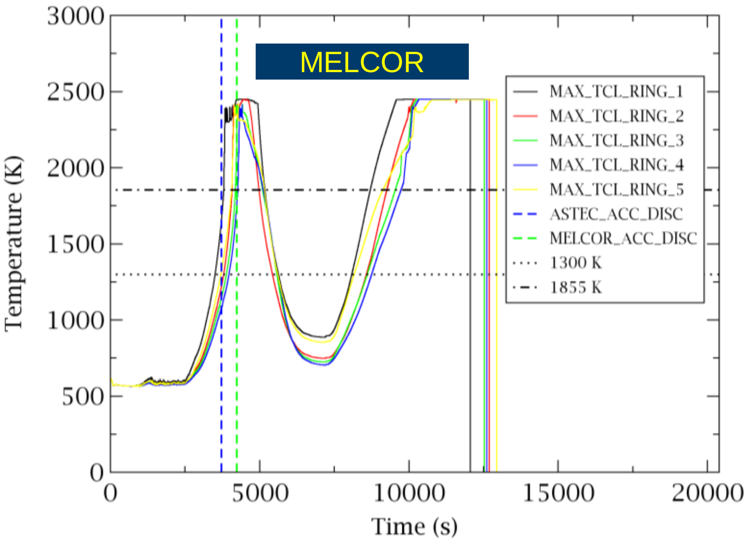


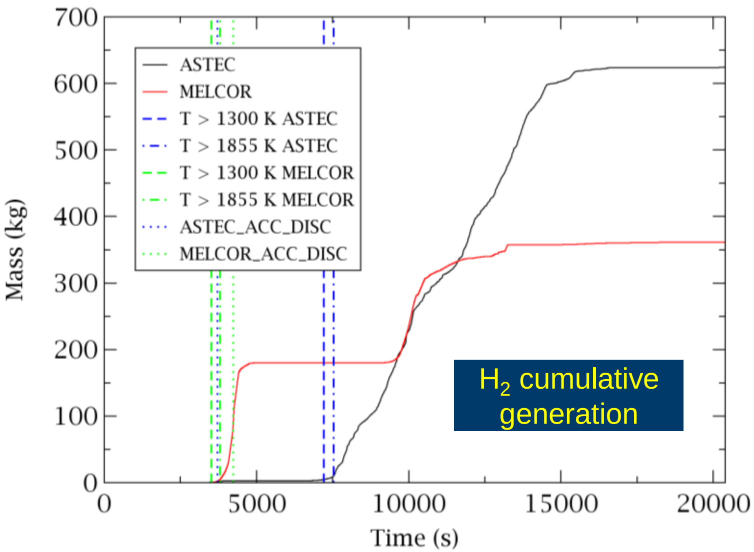


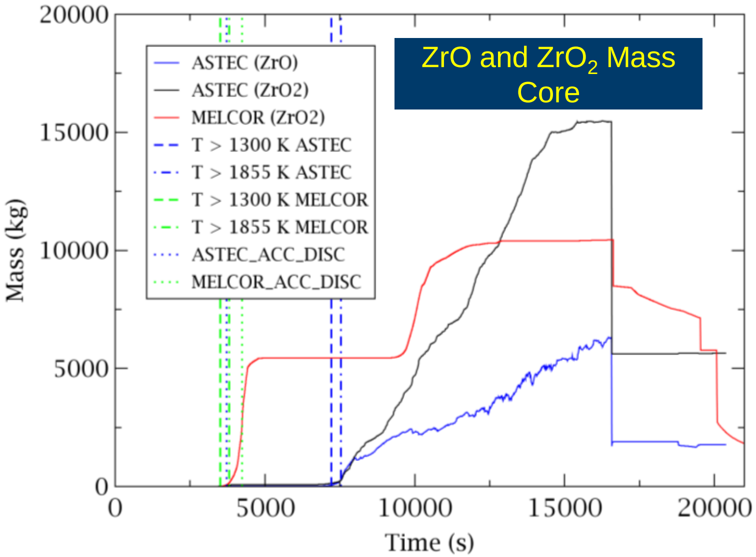


ENEA INVOLVMENT IN ASCOM PROJECT

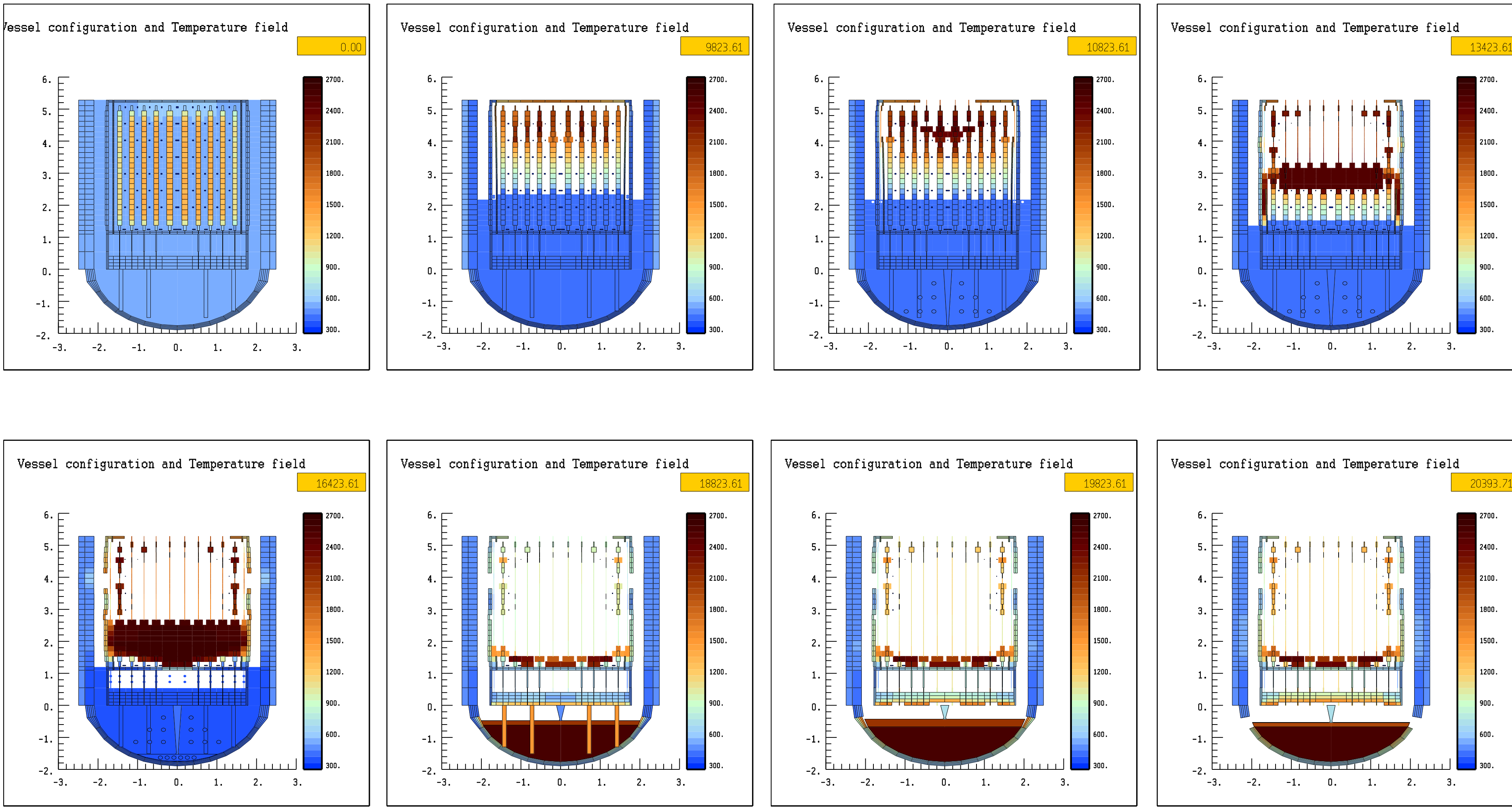




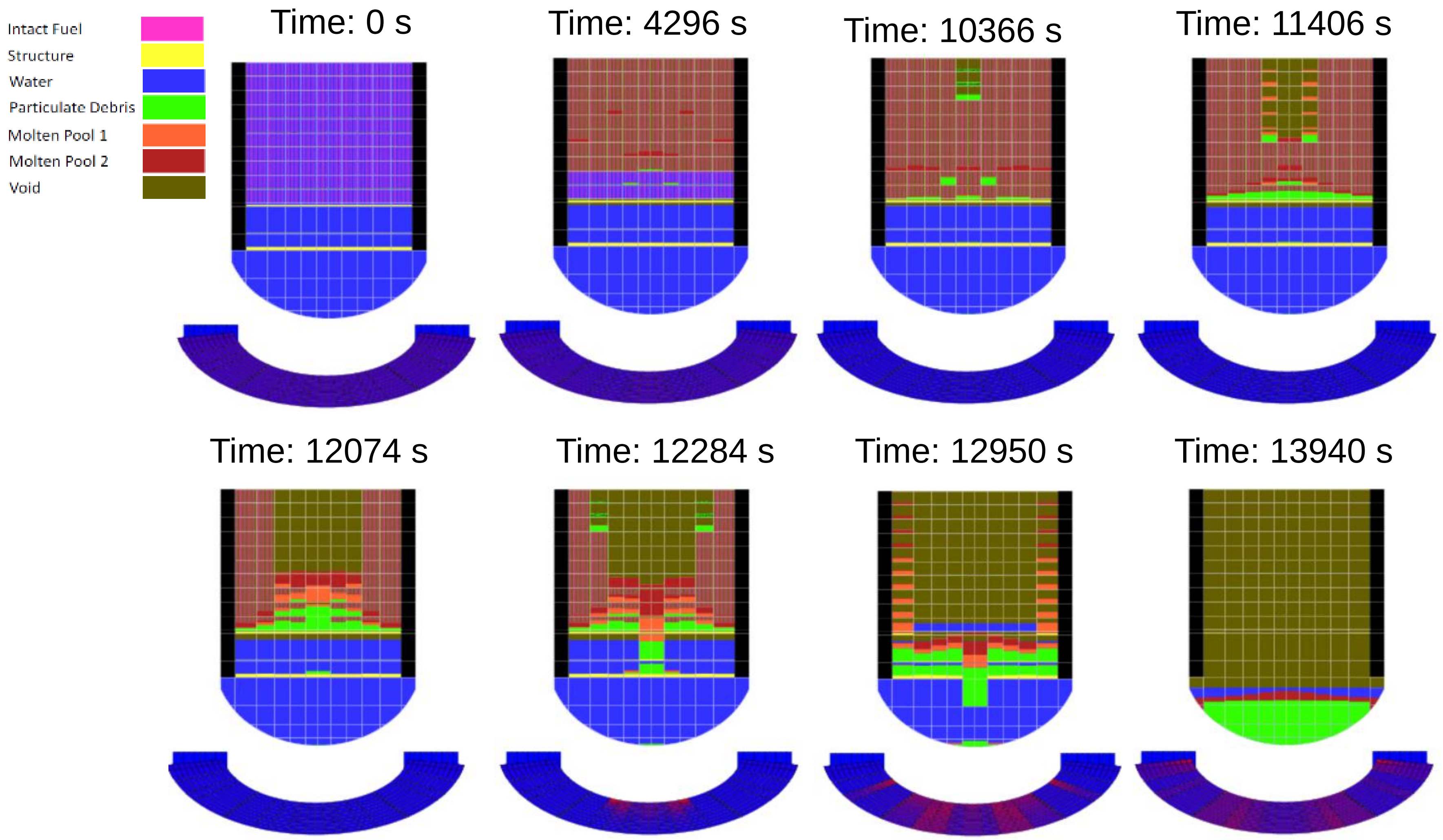




TRANSIENT ANALYSES: ASTEC CORE DEGRADATION ANIMATIONS



TRANSIENT ANALYSES: MELCOR CORE DEGRADATION ANIMATIONS



ENEA INVOLVMENT IN ASCOM PROJECT

- Similar thermal-hydraulic behaviour from the qualitative point of view between the two calculations even some quantitative differences are related to the break flow rate and the accumulator behaviour.
- Difference in terms of cladding temperature and the consequent H_2 generation before and after the accumulator injection.
- Even though MELCOR predict a faster degradation than ASTEC (also related to the different accumulator behaviour) and a consequent earlier corium relocation to the LP, the different retention time of the corium in the LP allow to have a discrepancy of about 1% for the LH failure, which occurs first in MELCOR than in ASTEC.
- The observed discrepancies underline some modelling differences between the two codes and details studies are in progress to characterize them and the user effect in view of uncertainty estimation.
- In relation to the user effect, in the case of MELCOR code the effect of the accumulator modelling is under investigation.

- *A paper is under preparation:*

  G. Agnello, S. Ederli, P. maccari, F. Mascari, ANALYSIS OF AN UNMITIGATED 2-INCH COLD LEG LOCA TRANSIENT WITH ASTEC AND MELCOR CODES, 38th International Conference on Heat and Mass Transfer (UIT), June 21-23, 2021, Gaeta, Italy

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Fulvio Mascari:
fulvio.mascari@enea.it