Warsaw University of Technology

An overview of MELCOR activities at Warsaw University of Technology

Piotr Darnowski

EMUG-2022, 29.04.2022

Faculty of Power and Aeronautical Engineering
WARSAW UNIVERSITY OF TECHNOLOGY

ITC INSTITUTE OF HEAT ENGINEERING

Warsaw University of Technology

- The largest technical university (Politechnika) in Poland
- Located in Warsaw (capital city)
- Provides technical education since 1826
- University since 1915
- Top ranked in Poland among 18 universities of technology
- Students ~30 000
- Academic Staff ~2 500
- 20 faculties (almost all engineering)

WUT

Faculty of Power and Aeronautical Engineering

Faculty of Power and Aeronautical Engineering

INSTITUTE OF HEAT ENGINEERING

INSTITUTE OF AERONAUTICS AND APPLIED MECHANICS

EDUCATION AND RESEARCH

Undergraduate courses (B.Sc.)

- Power Engineering
- Aerospace Engineering
- Mechanical Engineering
- Robotics

Graduate courses (M.Sc.)

- Power Engineering
  - **also Nuclear Power Engineering**
- Aerospace Engineering
- Mechanical Engineering and Machine Design
- Robotics

Institute of Heat Engineering

INSTITUTE OF HEAT ENGINEERING

IHE (ITC)

- **Divided into 5 divisions**
  - **Division of Refrigeration and Energy in Buildings**
  - **Division of Aircraft Engines**
  - **Division of Thermodynamics**
  - **Division of Rational Use of Energy**
  - **Division of Power Engineering (ZMiUE)**
    - **Including Nuclear Power Group**

Nuclear Power Group

- Responsible for Nuclear Engineering Education and Research

Education:

- Nuclear (Power) Engineering 2-year Master Programme (MSc)
  - Started in 1959, ended 1992 when NPP Zarnowiec was cancelled (1990)
  - Educational programme restarted at WUT in 2006
- Postgraduate courses in Nuclear Energy
- BSc courses related to Nuclear Energy
- PhD programme
- Nuclear activities also at other faculties (e.g. Faculty of Physics)

https://ppej.pl/en/news/preferred-site-of-the-first-polish-nuclear-power-plant-indicated-by-investor

Nuclear Power Group

INSTITUTE OF HEAT ENGINEERING

ZAKŁAD MASZYN I URZĄDZEŃ ENERGETYCZNYCH
POWER ENGINEERING DIVISION

Research:

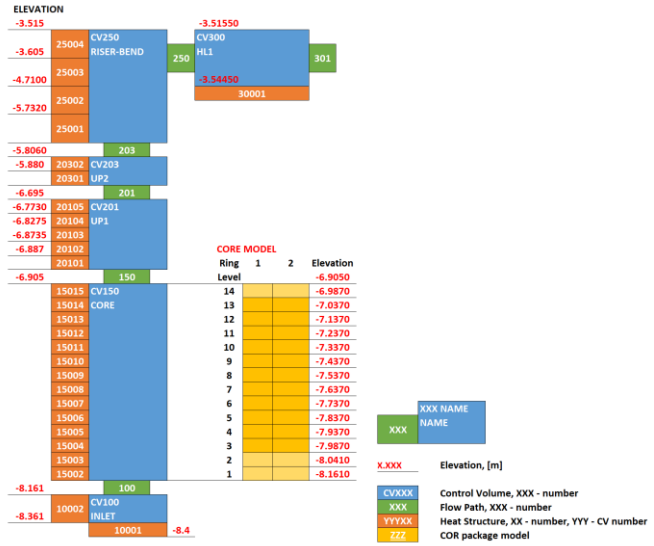
- Focus on Deterministic Safety Analysis
- TH, neutronics, SA
- Light Water Reactor technology
- Accredited by PAA
- Research and Training cooperation with PAA
- Cooperation with different organizations, e.g. PAA, NCBJ, Framatome and other

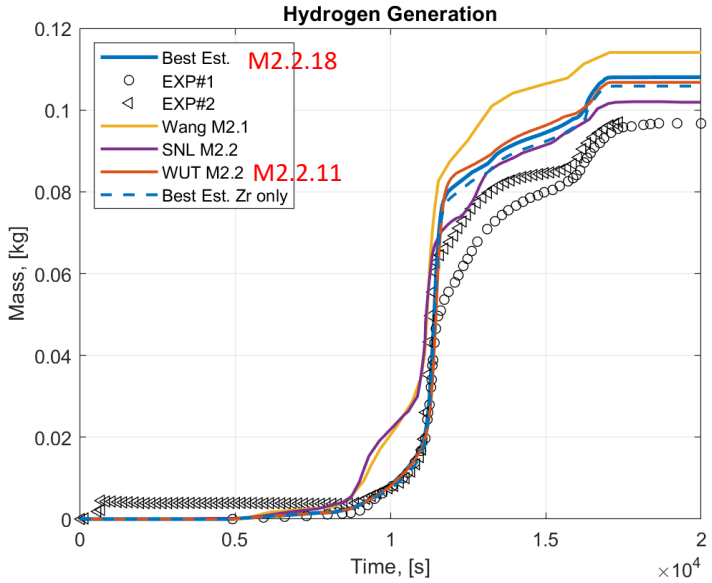
MELCOR:

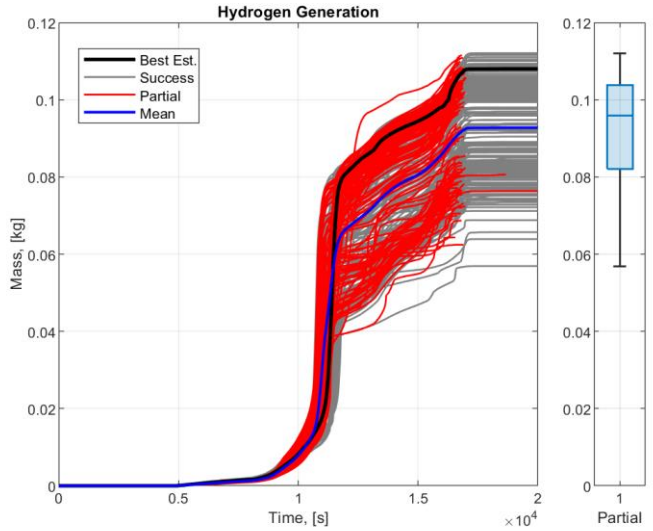
- Varying number of users – currently ~ 2
- MELCOR – main tool which we use in SA related research
- We started with MELCOR in 2013
- This presentation overviews selected MELCOR activities in last 3 years.

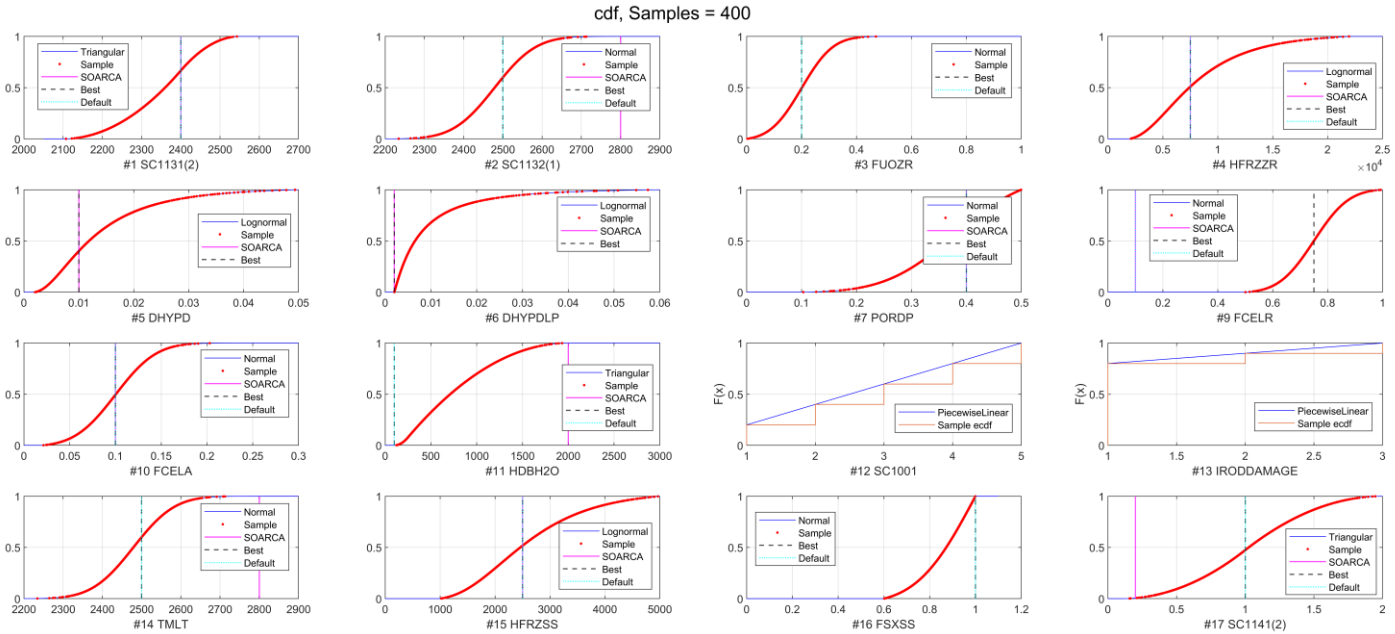
Phebus FPT-1

- Presented @ EMUG2021
- Cooperation with PAA
- Updated model with M2.2.18
- S&U study focused on hydrogen generation
- COR_EUT tested but large portion of inputs failed –we stayed with INT model
- Comparison with Gen-III PWR within NARSIS project





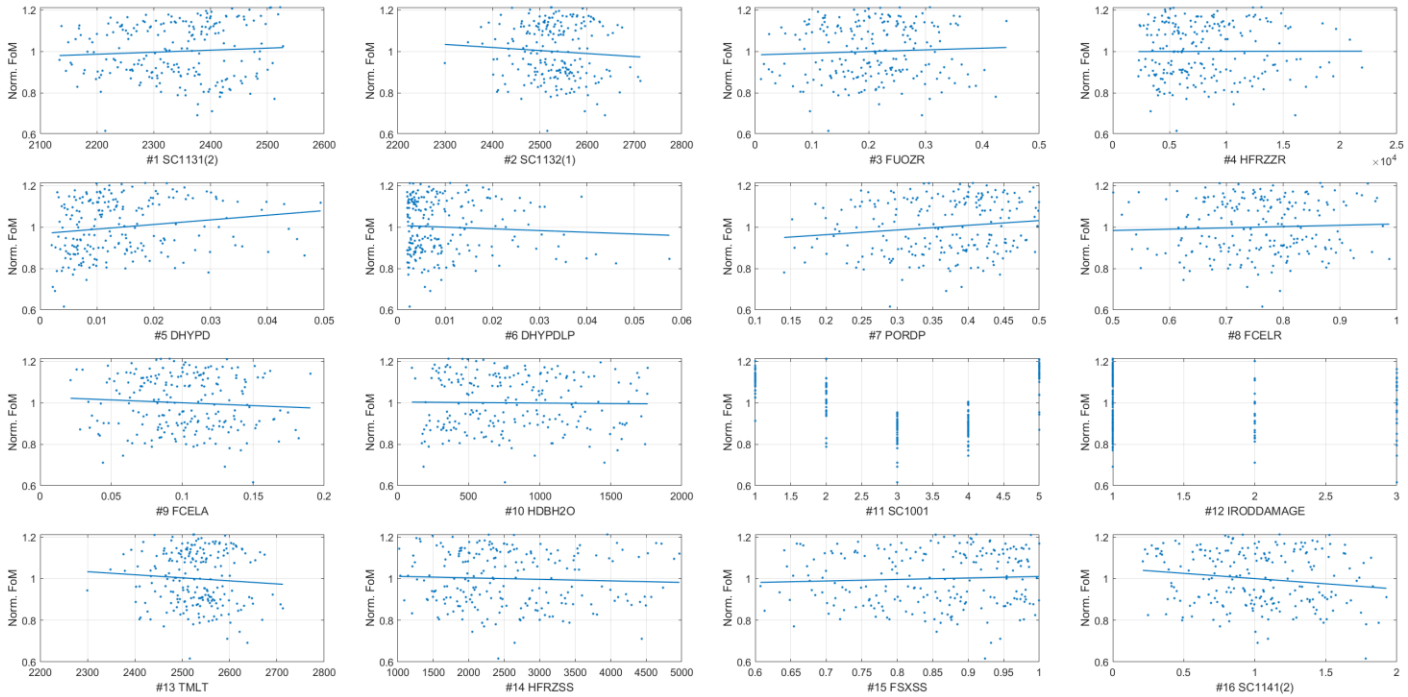


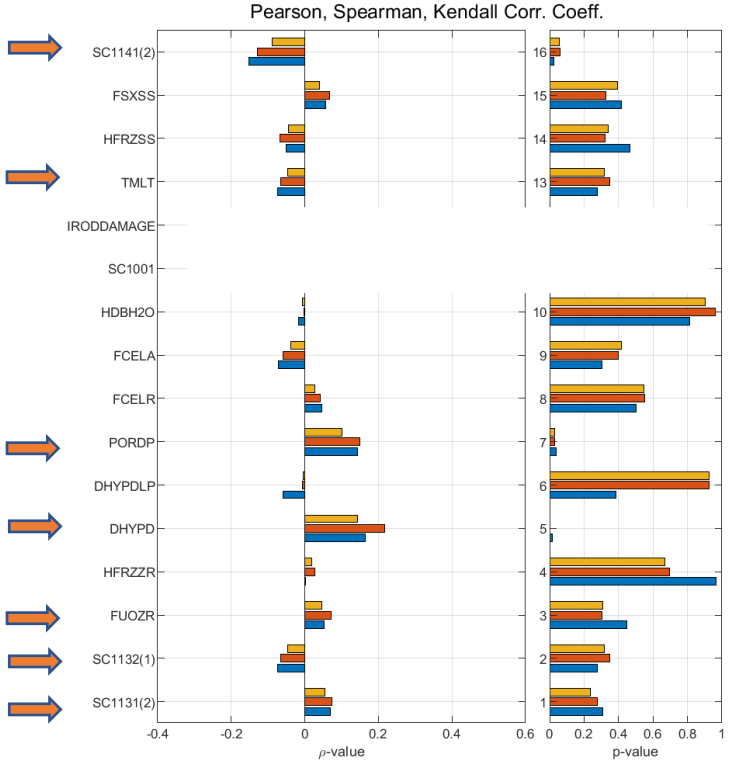


P. Darnowski, et. al., Uncertainty and sensitivity analysis of the in-vessel hydrogen generation for Gen-III PWR and Phebus FPT-1 with MELCOR 2.2. doi.org/10.3390/en14164884
P. Darnowski et. al., Study of the material release during Phébus FPT-1 bundle phase with MELCOR 2.2.11954, doi: 10.1016/j.anucene.2020.107700,

Phebus FPT-1

- Monte Carlo with N=400
- BE pdfs
- LHS (also SRS)



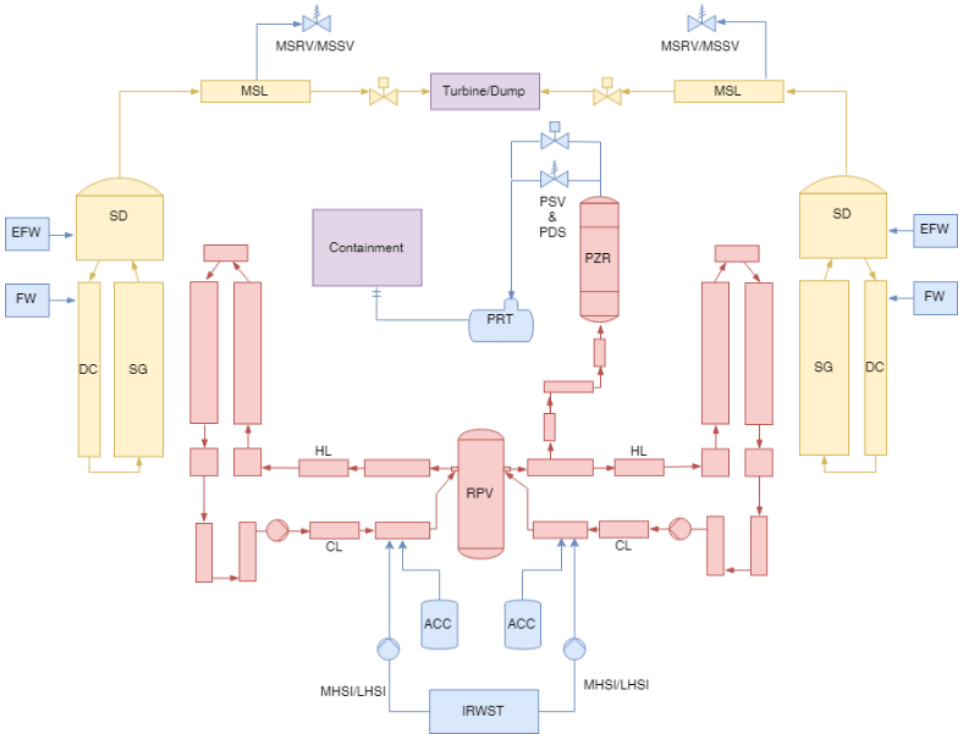


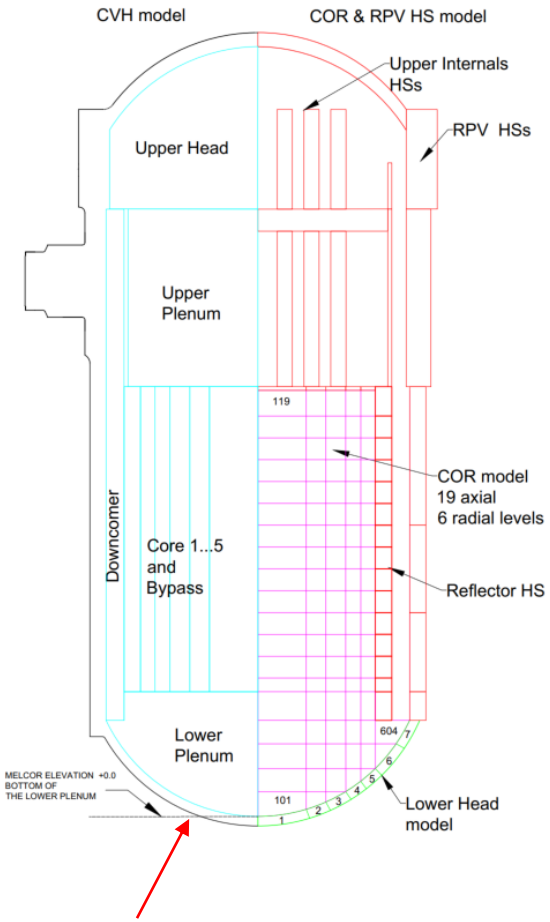
No	MELCOR Field Name	Description
1	SC1131(2)	Zircalloy Melt Breakout Temperature
2	SC1132(1)	Fuel Rod Collapse Temperature
3	FUOZR	Fractional Dissolution of Uranium in Molten Zirconium
4	HFRZZR	Candling/Refreezing HTC for Zirconium
5	DHYPD	Debris Diameter in Core Region
6	DHYPDLP	Debris Diameter in Lower Plenum
7	PORDP	Debris Porosity
8	FCELR	Radiation Exchange Factors – Radial
9	FCELA	Radiation Exchange Factors – Axial
10	HDBH2O	In-Vessel Falling Debris HTC
11	SC1001	Zircaloy–Steam Oxidation Correlation
12	IRODDAMAGE	Time-at-Temperature Model
13	TMLT	Interactive Model Melting/Eutectic Temperature
14	HFRZSS	Candling/Refreezing HTC for Steel
15	FSXSS	Fractional Dissolution of Steel Oxide in Molten Stainless Steel
16	SC1141(2)	Maximum Melt Flow Rate after Breakthrough

P. Darnowski, et. al., Uncertainty and sensitivity analysis of the in-vessel hydrogen generation for Gen-III PWR and Phebus FPT-1 with MELCOR 2.2. doi.org/10.3390/en14164884

Gen-III NPP H2 S&U

- Updated Gen-III NPP model
- Within NARSIS Horizon 2020 Project – generic referential EU large NPP with PWR
- Fast running simple RPV
- Study of H2 production S&UA + FPT-1
- LB-LOCA unmitigated
- No Ex-vessel



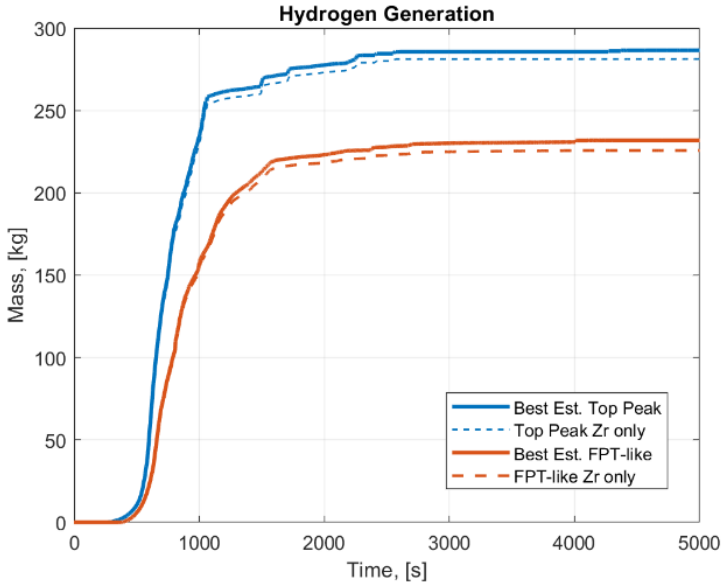


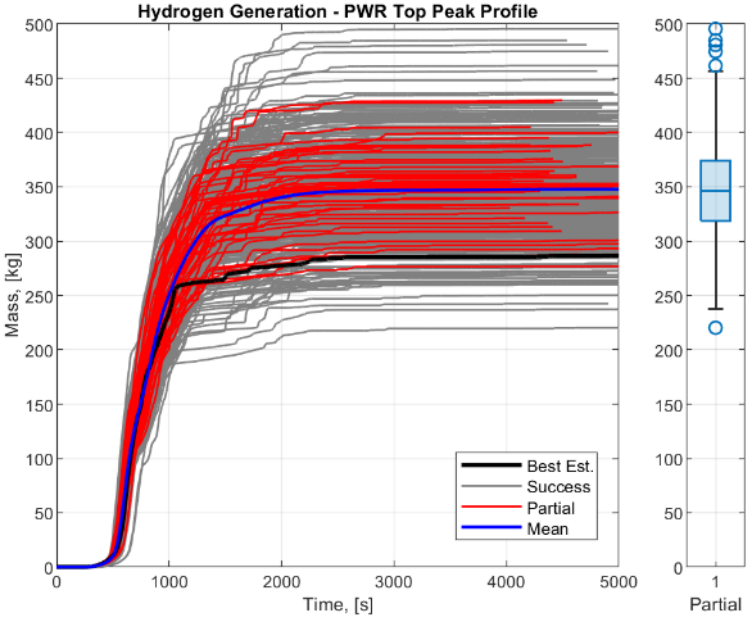
Interesting issue. First LP model was smaller with only 4 axail levels. It lead to very large temperatures, problems with convergence and large difference in H2 production due to blockages near core plate with H2 prod ~150 kg

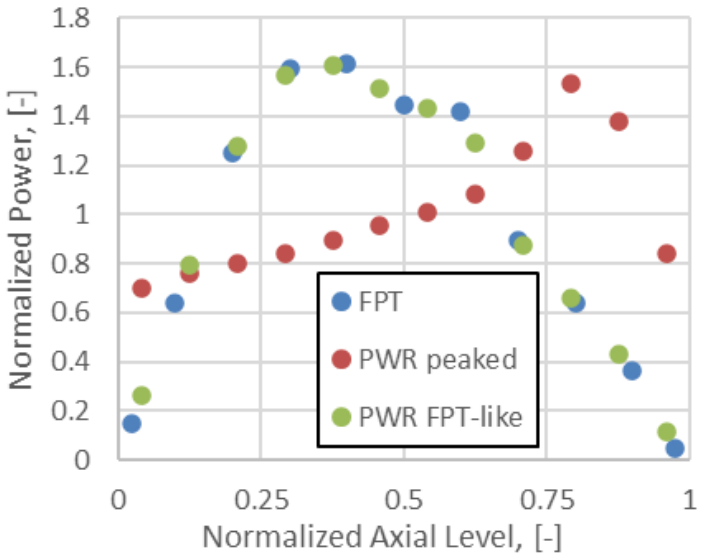
P. Darnowski, et. al., Uncertainty and sensitivity analysis of the in-vessel hydrogen generation for Gen-III PWR and Phebus FPT-1 with MELCOR 2.2. doi.org/10.3390/en14164884

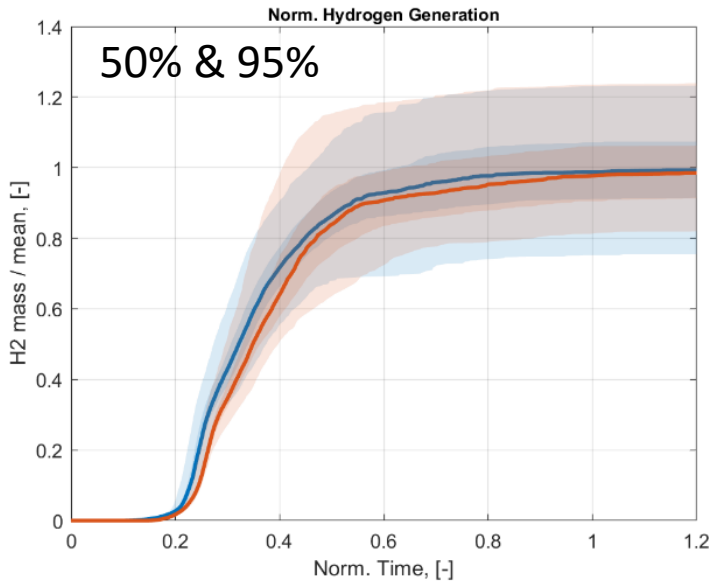
Gen-III NPP H2 S&U

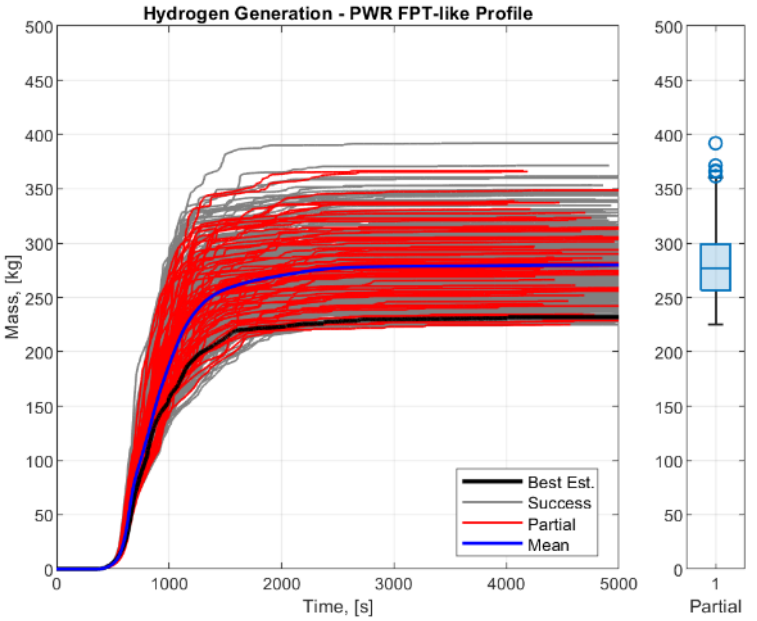
- Comparison of two different power profiles
- Top peaked and FPT-1 based
- S&UA with Monte Carlo N=400 + LHS
- also Global analysis by NCBJ for N=3000 but not reported today







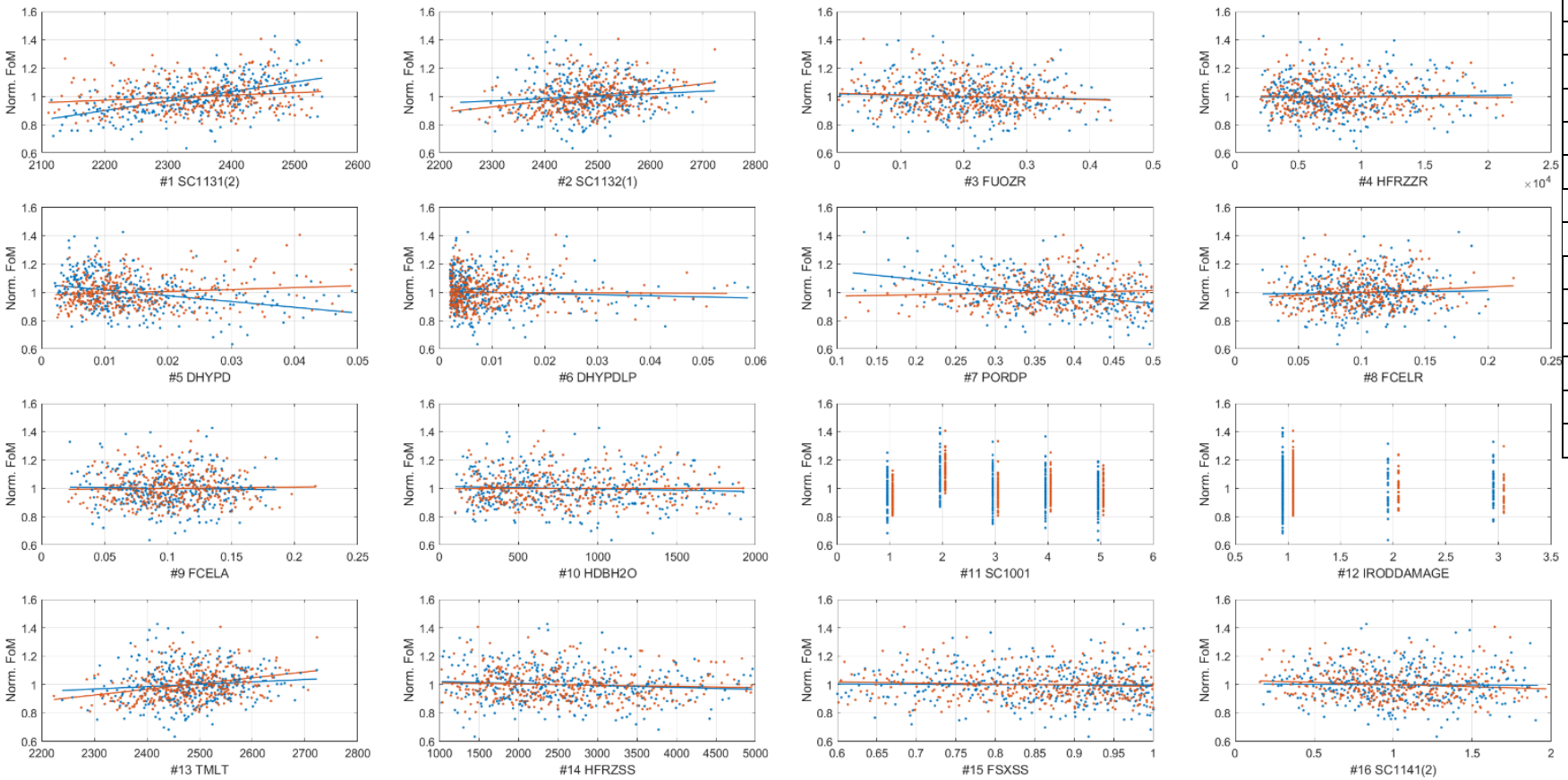




P. Darnowski, et. al., Uncertainty and sensitivity analysis of the in-vessel hydrogen generation for Gen-III PWR and Phebus FPT-1 with MELCOR 2.2. doi.org/10.3390/en14164884

Gen-III NPP H2 S&U

- Similar results for top-peak and FPT-like
- Similar to FPT-1 studies

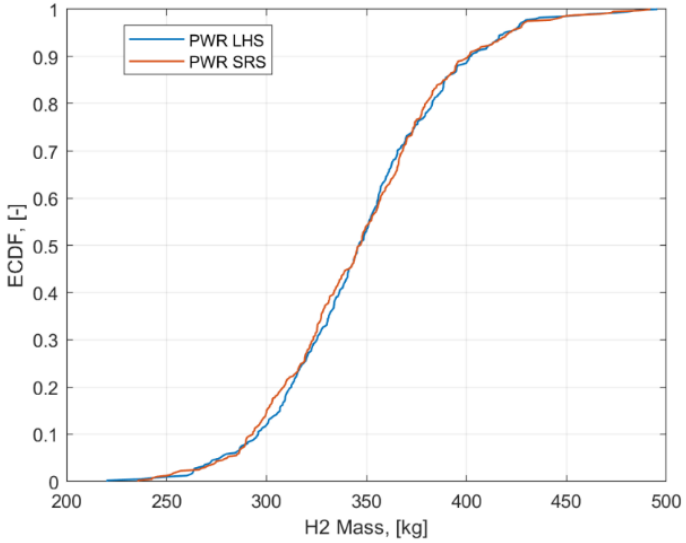


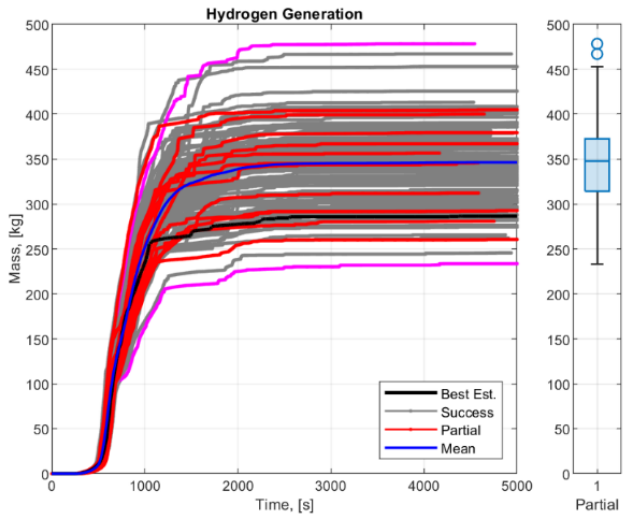
No	MELCOR Field Name	Description
1	SC1131(2)	Zircalloy Melt Breakout Temperature
2	SC1132(1)	Fuel Rod Collapse Temperature
3	FUOZR	Fractional Dissolution of Uranium in Molten Zirconium
4	HFRZZR	Candling/Refreezing HTC for Zirconium
5	DHYPD	Debris Diameter in Core Region
6	DHYPDLP	Debris Diameter in Lower Plenum
7	PORDP	Debris Porosity
8	FCELR	Radiation Exchange Factors – Radial
9	FCELA	Radiation Exchange Factors – Axial
10	HDBH2O	In-Vessel Falling Debris HTC
11	SC1001	Zircaloy–Steam Oxidation Correlation
12	IRODDAMAGE	Time-at-Temperature Model
13	TMLT	Interactive Model Melting/Eutectic Temperature
14	HFRZSS	Candling/Refreezing HTC for Steel
15	FSXSS	Fractional Dissolution of Steel Oxide in Molten Stainless Steel
16	SC1141(2)	Maximum Melt Flow Rate after Breakthrough

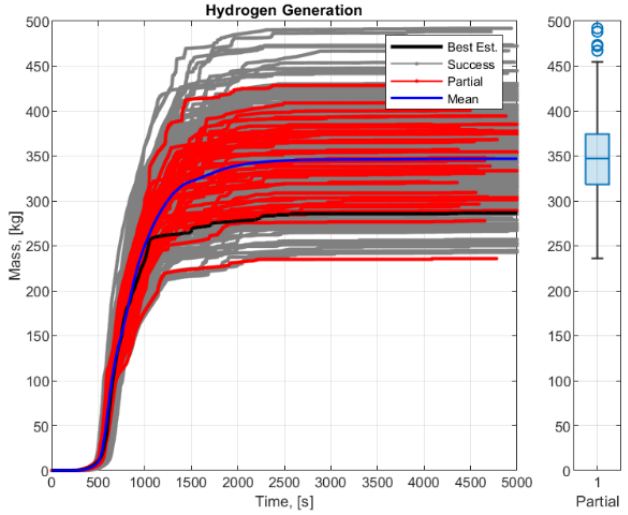
P. Darnowski, et. al., Uncertainty and sensitivity analysis of the in-vessel hydrogen generation for Gen-III PWR and Phebus FPT-1 with MELCOR 2.2. doi.org/10.3390/en14164884

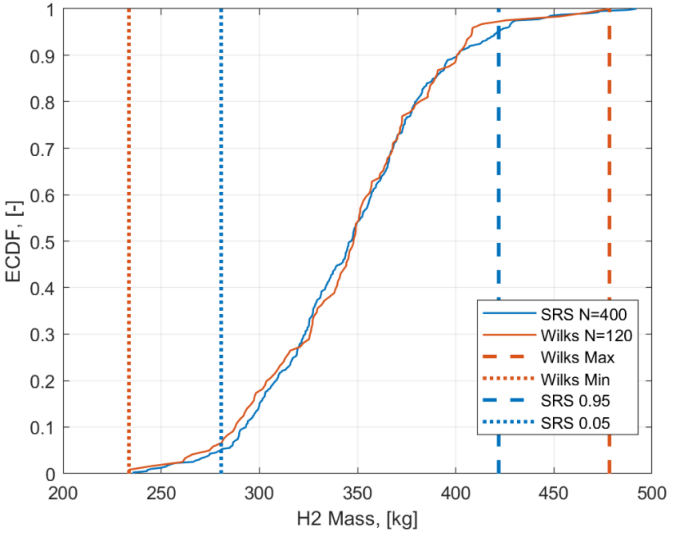
Gen-III NPP H2 S&U

- Comparison of LHS and SRS
  - With failed cases we should avoid LHS (see SOARCA reports).
  - We observed little difference between LHS/SRS for N=400
- Comparison of SRS Wilks (N~100) with SRS Monte Carlo (N=400)
  - BEPU people claim that using LHS with Wilks is wrong
  - Wilks 95/95 margins wider than Monte Carlo 95 bands as expected
  - Sensitivity more difficult, with Wilks for parameters with low p-value we can draw false conclusions





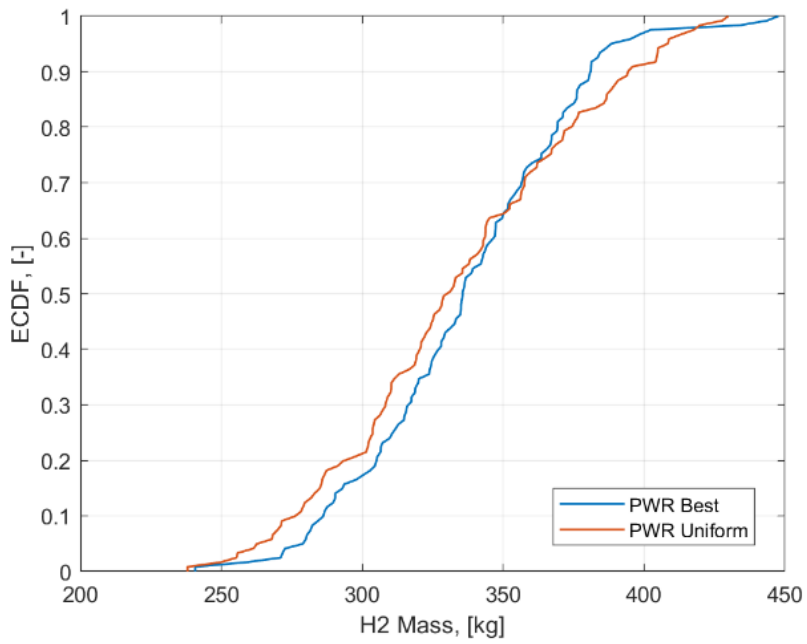


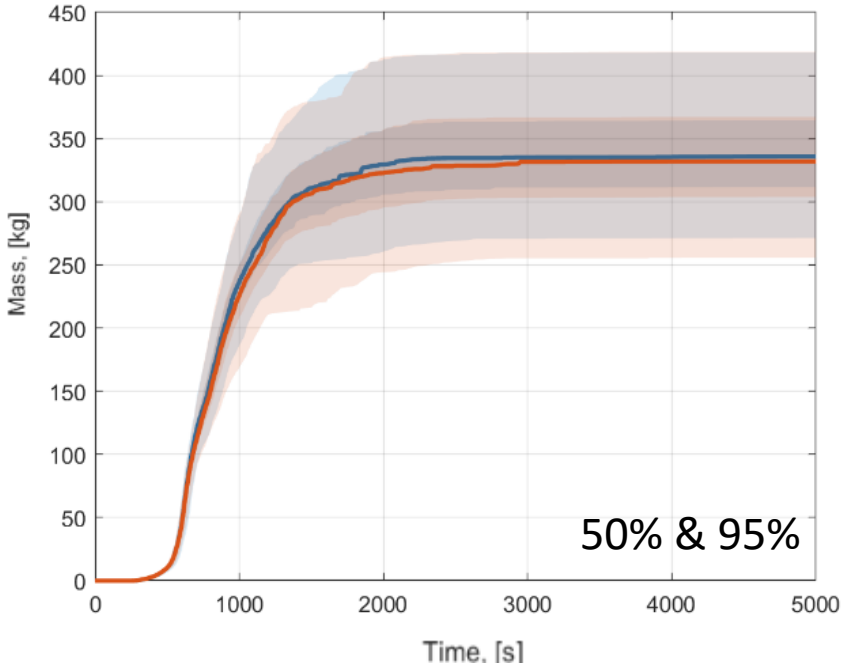


To be pubished: NARSIS report WP4.3

Gen-III NPP H2 S&U

- Comparison of BE pdfs and Uniform pdfs
- SRS, Wilks with N~ 100
- Results similar
- For BE more outliers – but small effect

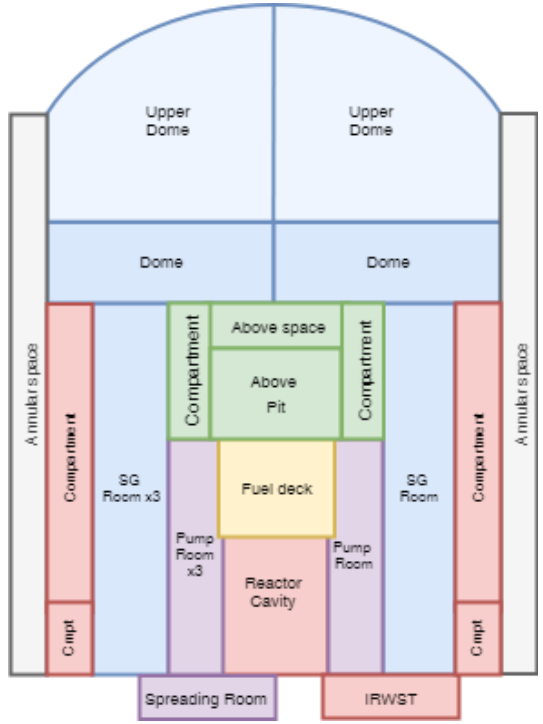


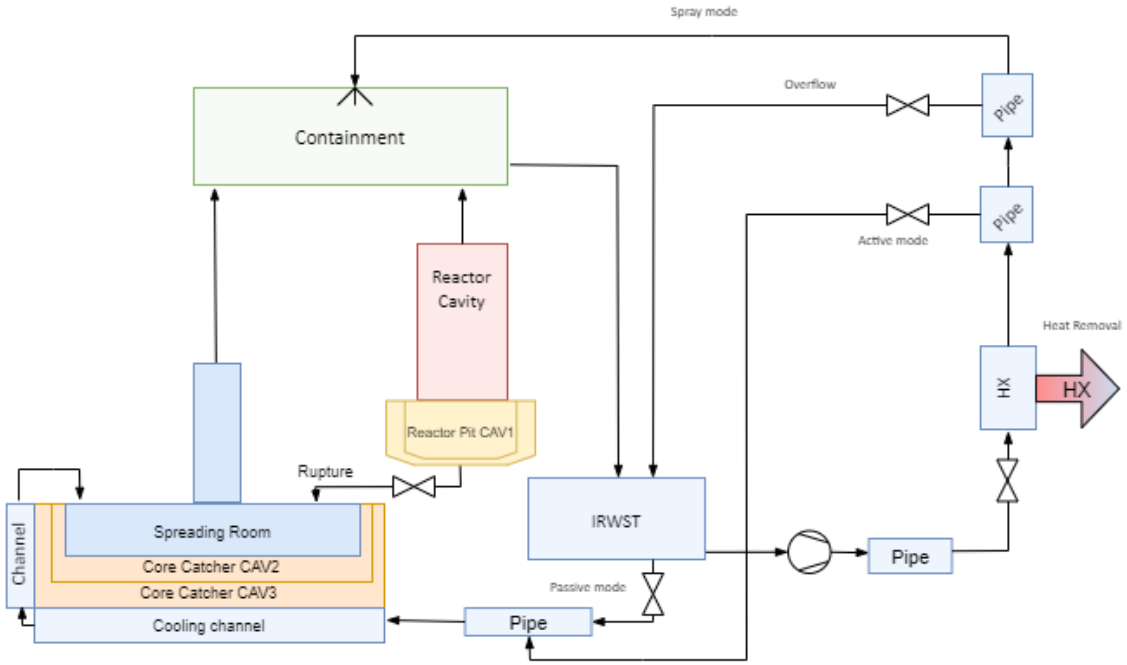


To be pubished: NARSIS report WP4.3

Gen-III NPP other activites

- Within NARSIS project other studies
- Gen-III NPP SBO – in-vessel + ex-vessel phases
- EVMR studies with CMSS
- Containment performance and Source Term studies



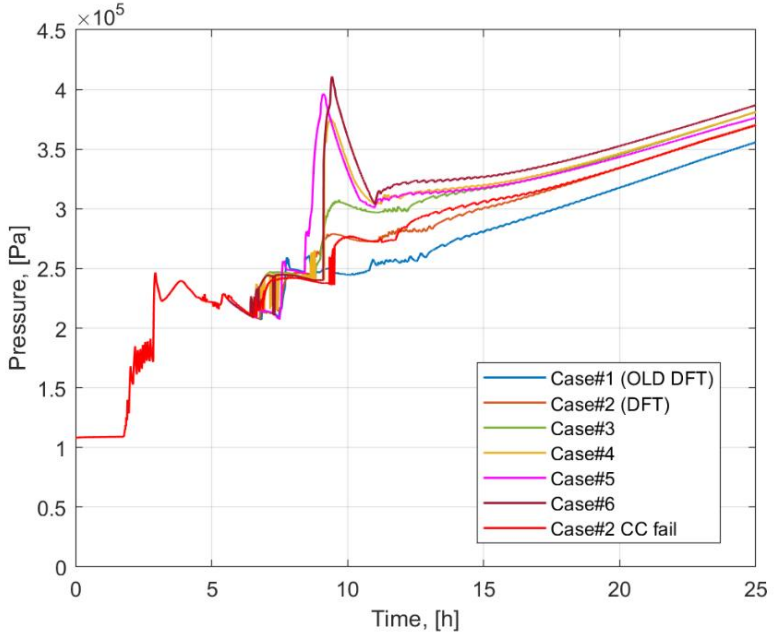


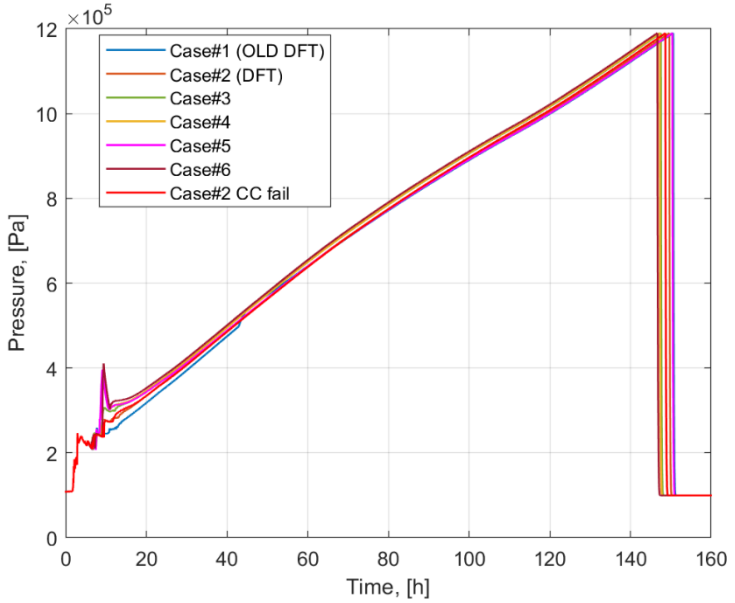
Newer results to be pubished, also in NARSIS report WP4.3
Older: Darnowski, P., et. al, MELCOR Simulations of the SBO in Gen III PWR with EVMR, in: NENE-2019, 28th Int. Conf. Nucl. Energy for New Europe.

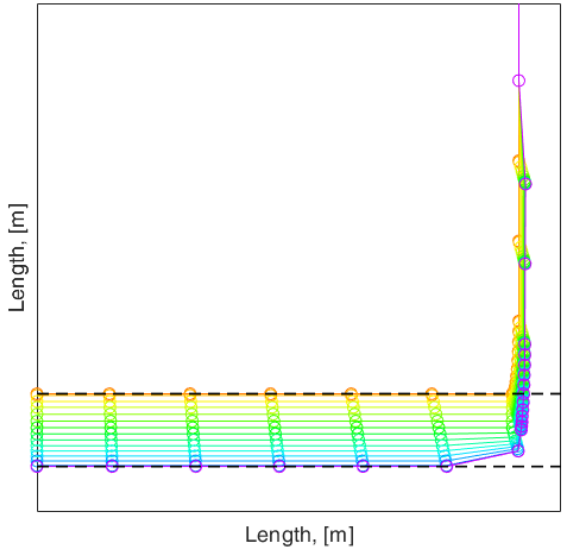
Gen-III NPP other activites

- NARSIS
- EXMR studies
- Parametric analysis for CMSS and MCCI options

Parameter	Variable	Base Case#1 Old Defaults	Case#2 New Defaults	Case#3	Case#4	Case#5	Case#6
CAV package emissivity of oxide/metallic/ surrounding	EMISS.OX EMISS.MET EMISS.SUR	0.6/0.6/0.6	0.9/0.9/0.9				
Multipliers for surface boiling heat transfer and oxide/metallic thermal conductivity	BOILING COND.OX COND.MET	1.0 1.0 1.0	10.0 5.0 5.0	10.0 10.0 10.0	10.0 50.0 50.0	10.0 100.0 100.0	10.0 200.0 200.0
Mixing between metallic & oxidic components of the debris	MIXING	ENFOR, enforce mixing (all debris forms a single mixed layer)					



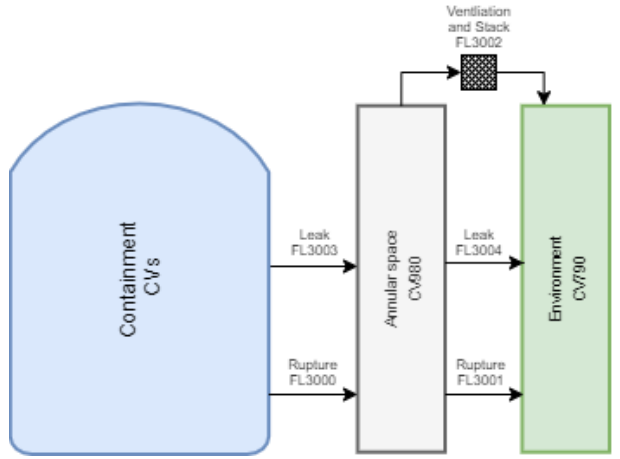


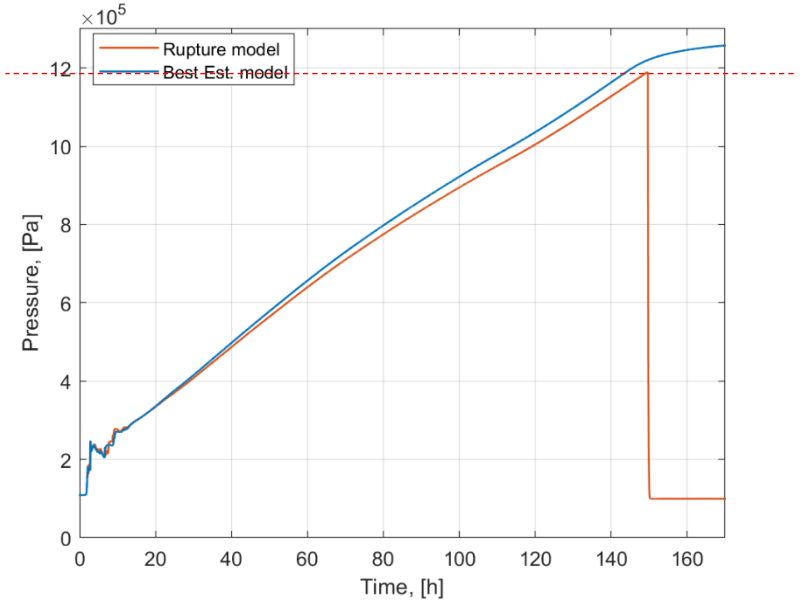


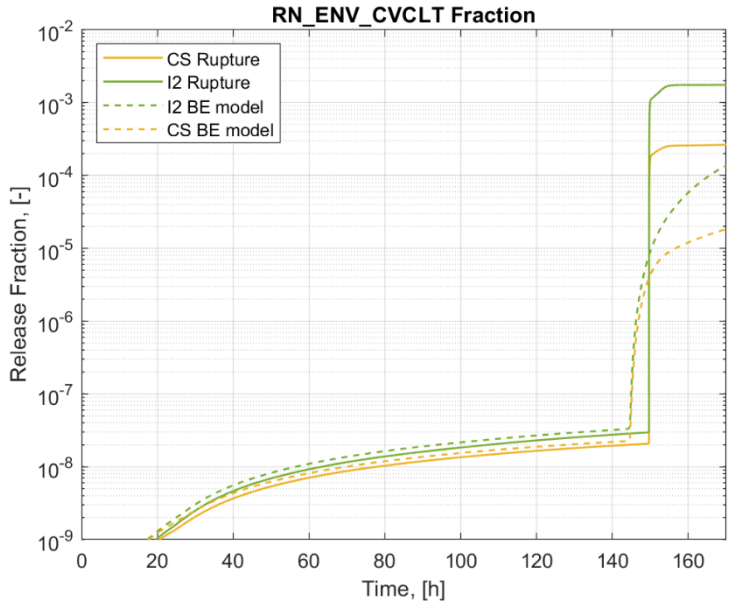
To be pubished: NARSIS report WP4.3

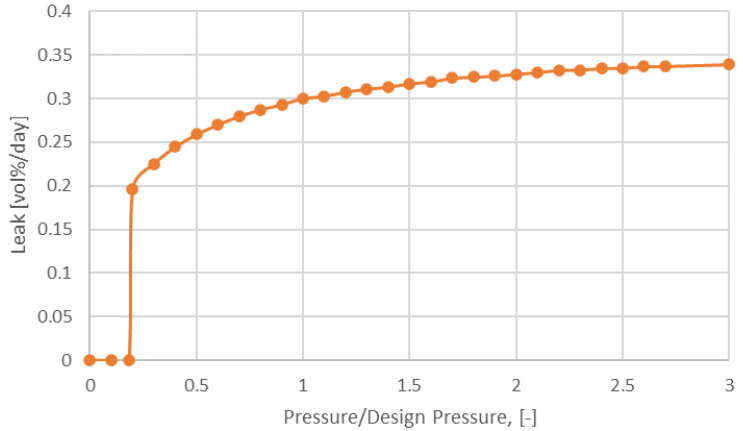
Gen-III NPP other activites

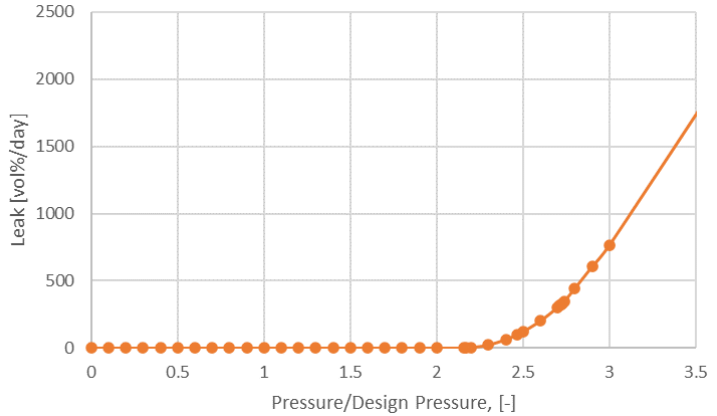
- NARSIS
- Containment performance and ST
- Comparison of rapid containment rupture and slow non-rupture leak (like in SOARCA Surry report)
- I2 and CS ~1 order of magnitude difference 24h after failure







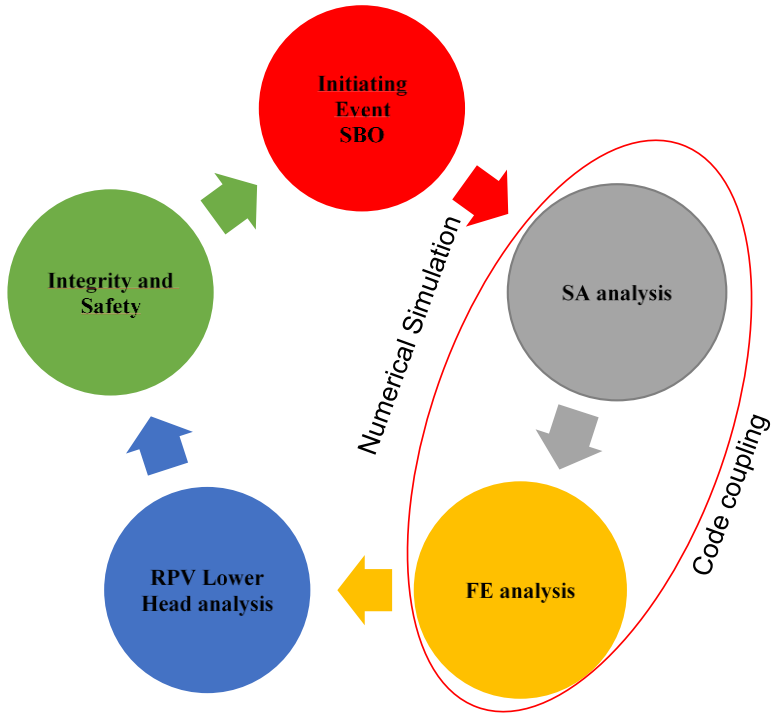


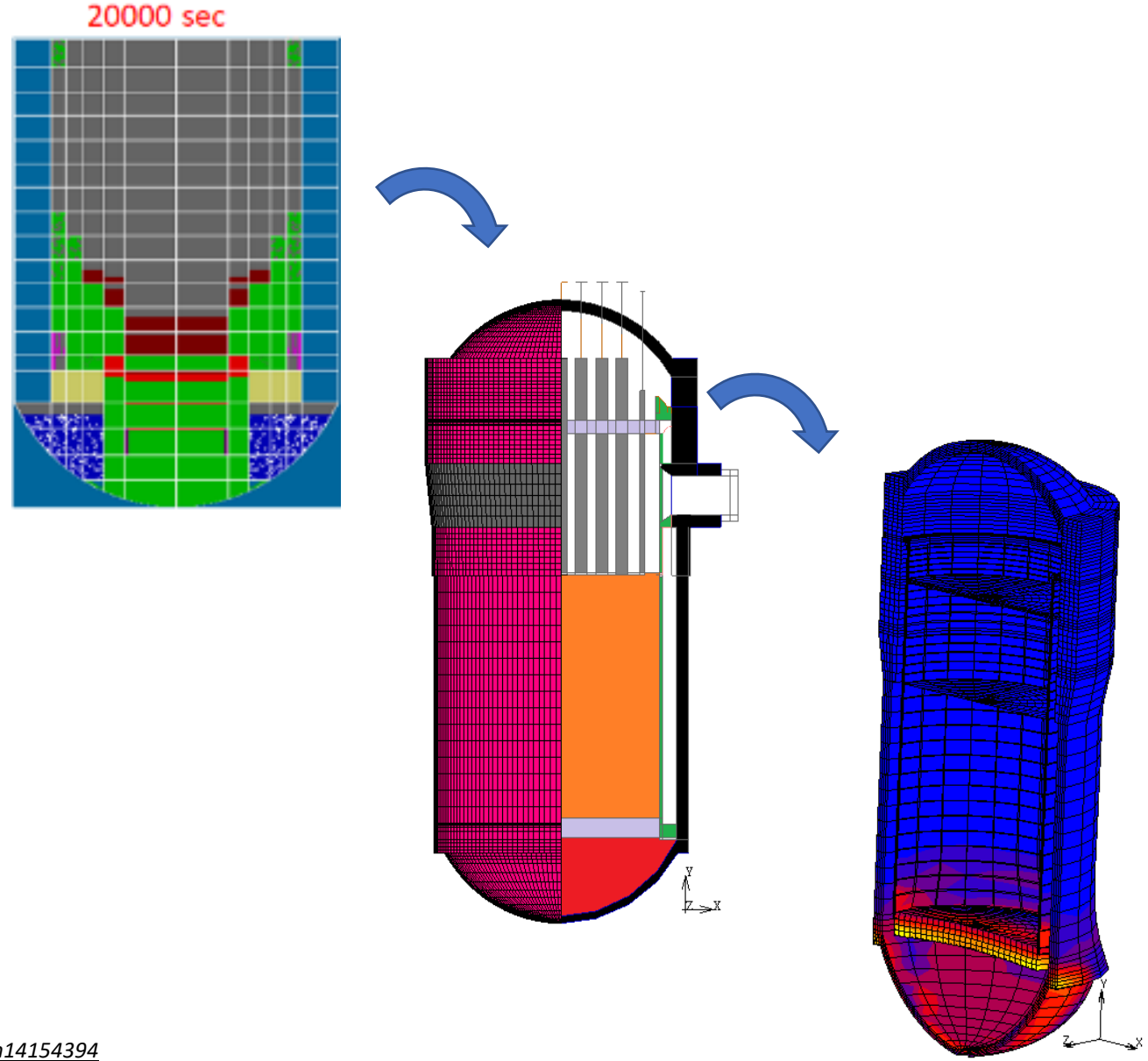


To be pubished: NARSIS report WP4.3

Gen-III coupling with FEM

- NARSIS
- University of Pisa FEM (MSC©MARC)
- WUT MELCOR
- UniPi Aging RPV ageing studies

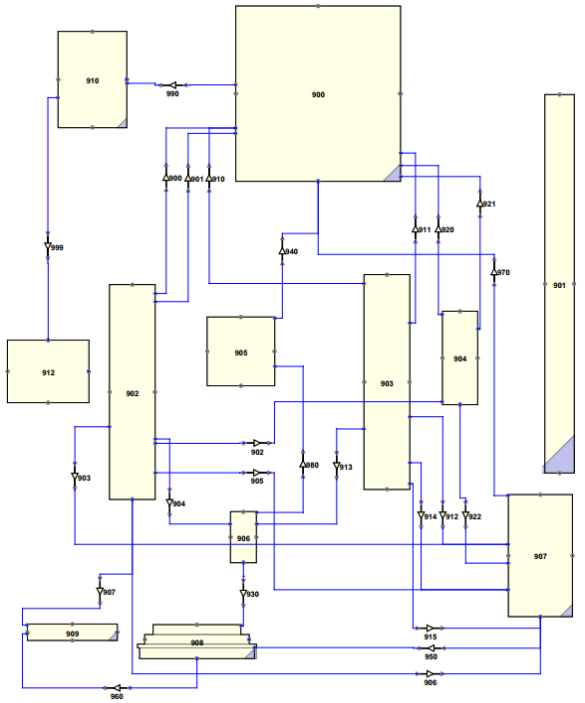


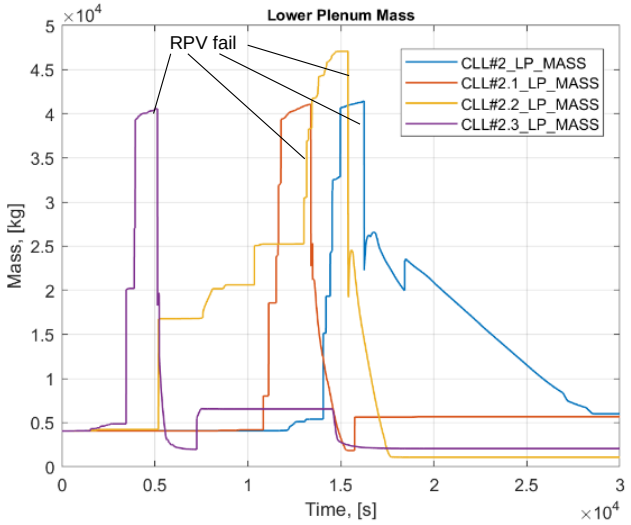


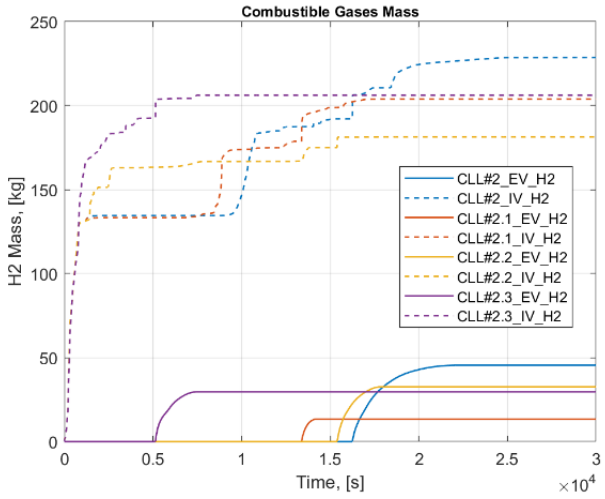
Lo Frano, R., et. al. Preliminary Analysis of an Aged RPV Subjected to Station Blackout, doi.org/10.3390/en14154394

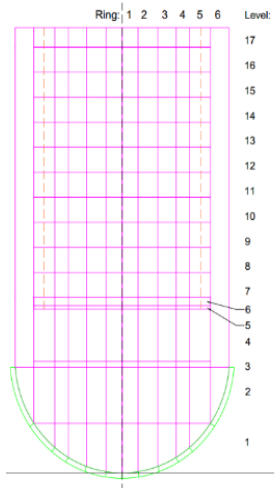
Gen-II studies for SAMG DM Tool

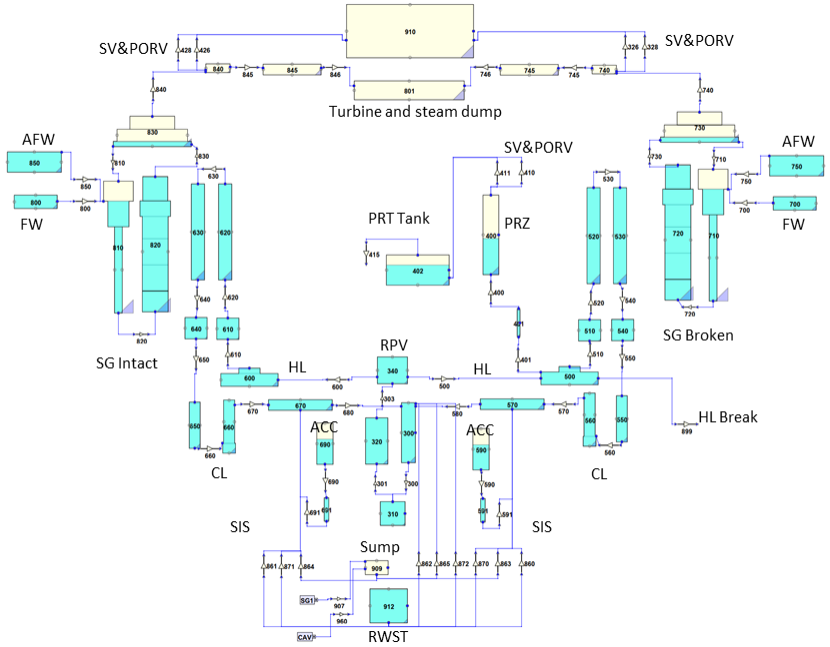
- NARSIS project
- NPP state database for testing SAMG DM tool (SEVERA) developed by JSI, Gen Energija, APOSS
- WUT – responsible for MELCOR + NCBJ, VTT
- Gen-II PWR reactor inputdeck with MELCOR 2.2
- Comparison of ~30 different sequences selected by PSA people
- Mainly LB-LOCAs for LP and SBOs for HP variants with different SAMGs









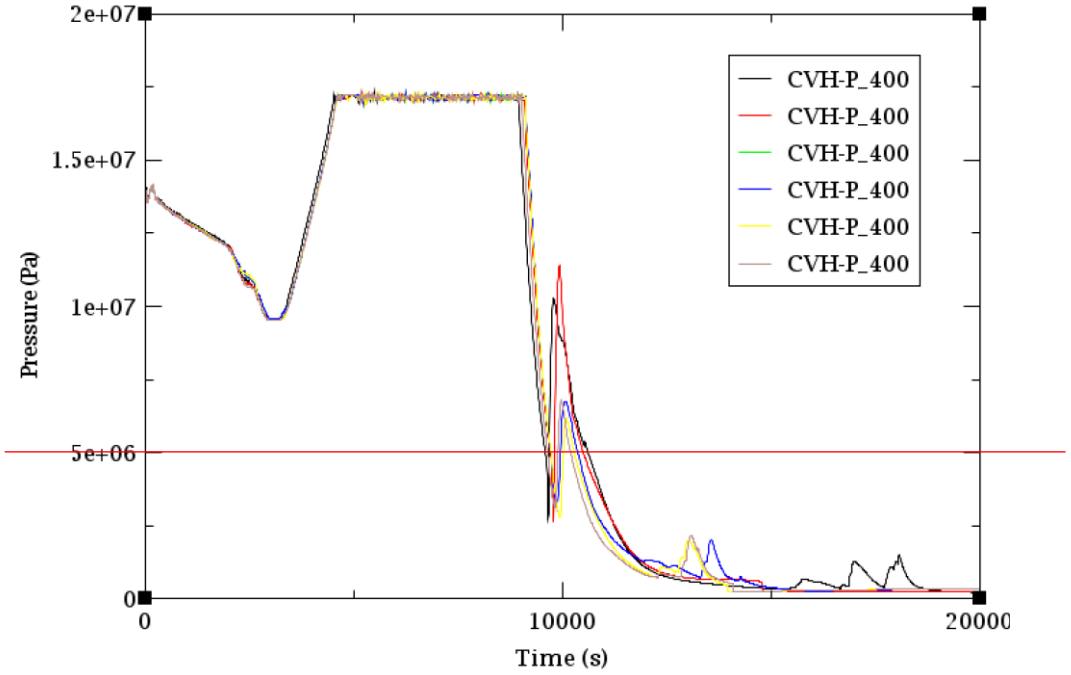


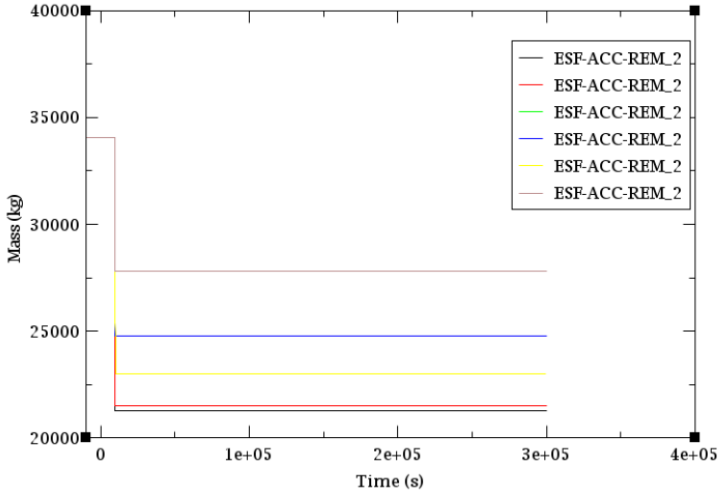
Bohanec, M., el. al. A decision-support approach to severe accident management in nuclear power plants. doi.org/10.1080/12460125.2020.1854426
Darnowski, P., et. al, Severe Accident Simulations Dedicated to the SAMG Decision- Making Tool Demonstration, in: NENE-2020 29th Int. Conf. Nucl. Energy f New Europe

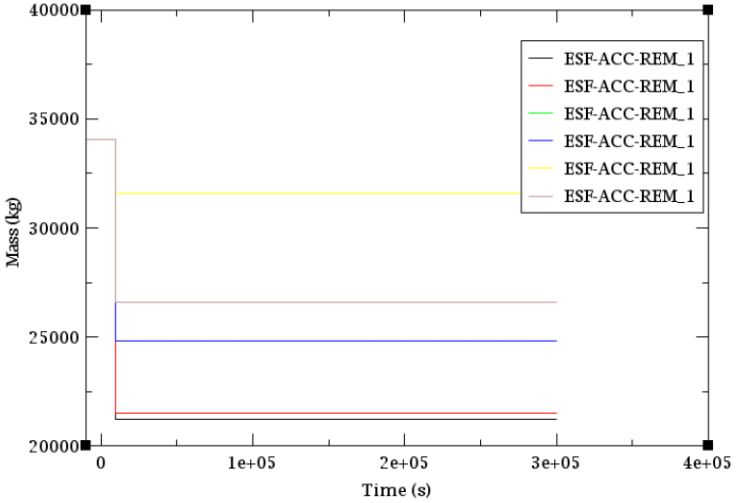
Possible MELCOR issue

M2.2.9
M2.2.11
M2.2.14
M2.2.15
M2.2.18
M2.2.21

- Also presented @EMUG2021
- M2.2.9-2.2.21 with PWR plant model and ACC model
- Recalculated for M2.2.21 – no change
- SBO + some LOCA; ACC activate, but in short time pressure increase again above setpoint.
- Later pressure drops again but ACC does not re-activate
- ESF-ACC-PRS and ESF-ACC-REM indicate water presence and proper pressure. P_activate ~ 4.9 Mpa, water ~70 m3







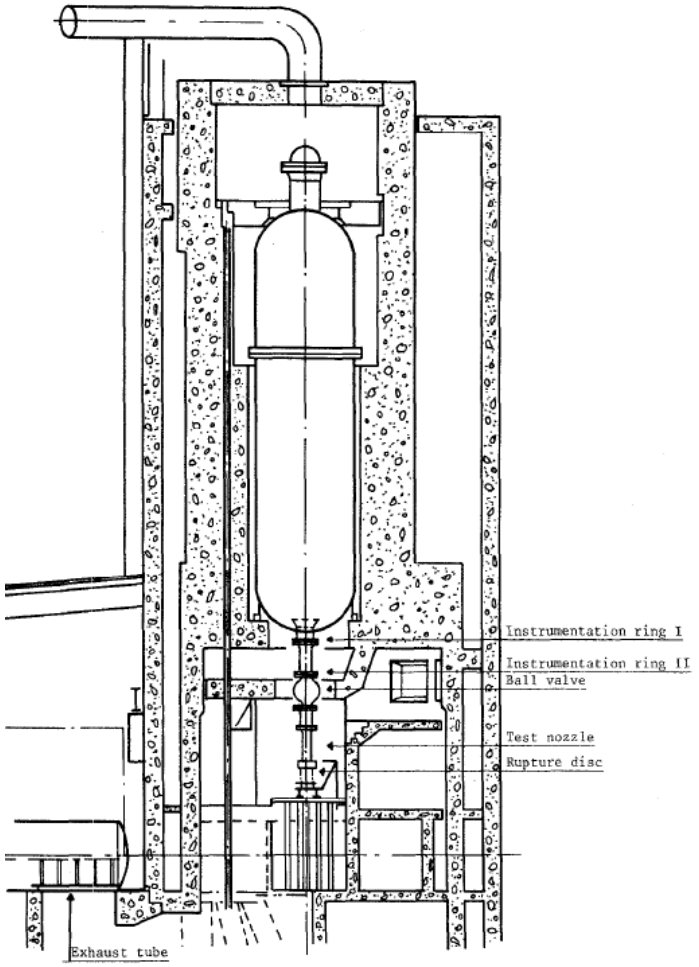
Marviken activites

- 3 small projects
- Critical Flow for TRACE and MELCOR

MARVIKEN:

- Vessel volume: 425 m^3
- Vessel length: 24.55 m
- Discharge pipe length: 6.308 m
- Drywell volume: 1934 m^3

Nozzle type no	D mm	L mm	L/D	L1 mm	L2 mm	L3 mm	L4 mm	R mm	Used in tests no
1	200	590	3,0	0	100	100	100	100	13, 14
2	300	290	1,0	55	150	150	150	150	6, 7
3	300	511	1.7	0	150	150	150	150	25, 26
4	300	895	3,0	55	150	150	150	150	1, 2, 12
5	300	1116	3.7	0	150	150	150	150	17, 18, 19
6	500	166	0.3	0	225	225	250	250	23, 24
7	500	730	1.5	0	225	225	250	250	20, 21, 22, 27
8	500	1809	3.6	0	181	156	241	250	15, 16
9	509	1589	3.1	55	156	225	241	250	3, 4, 5, 8, 9, 10, 11

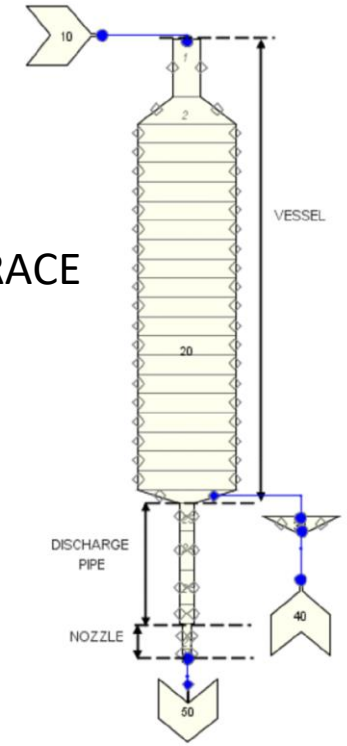


Marviken – MELCOR vs TRACE

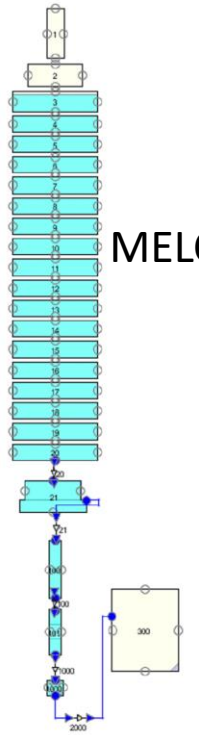
- Cooperation: PAA, NCBJ, WUT
- Comparison with TRACE assesment, MELCOR 2.1. assessment (SAND2015-6693R), NUREG/IA-0401, Mosunova @EMUG2013 (same Cd)
- MELCOR 2.2.11932

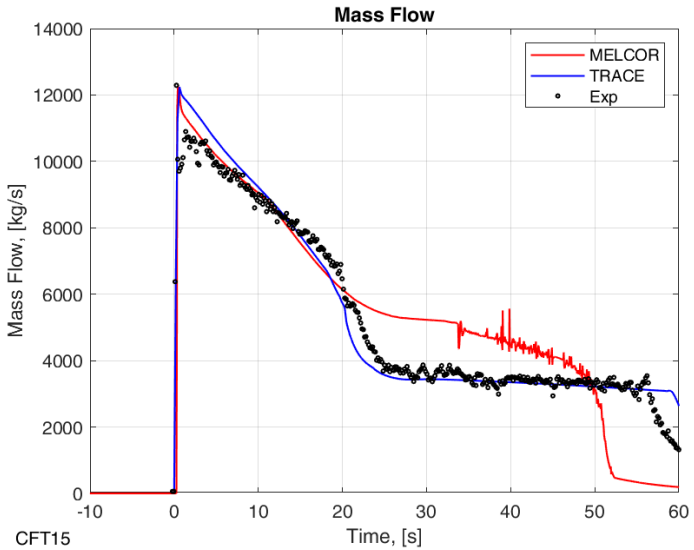
CFT	Pressure [MPa]	Subcooling [K]	Vessel Water Level [m]	Nozzle Diameter [m]	Nozzle Length [m]	Nozzle length to Diameter Ratio L/D [-]
4	4.97	38.31	17.59	0.509 - 0.609	1.976	3.882
15	5.04	30.42	19.93	0.509 – 0.5	1.966	3.862
21	4.94	33.57	19.95	0.509 - 0.5	0.956	1.878
24	4.96	32.53	19.88	0.5	0.391	0.782

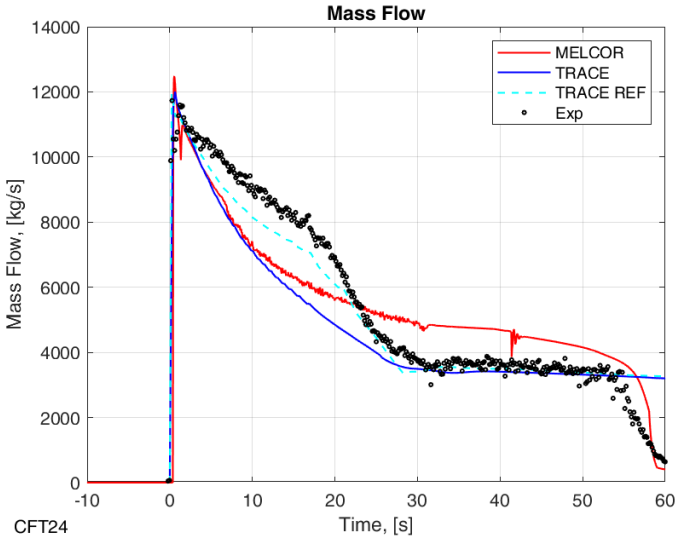
TRACE

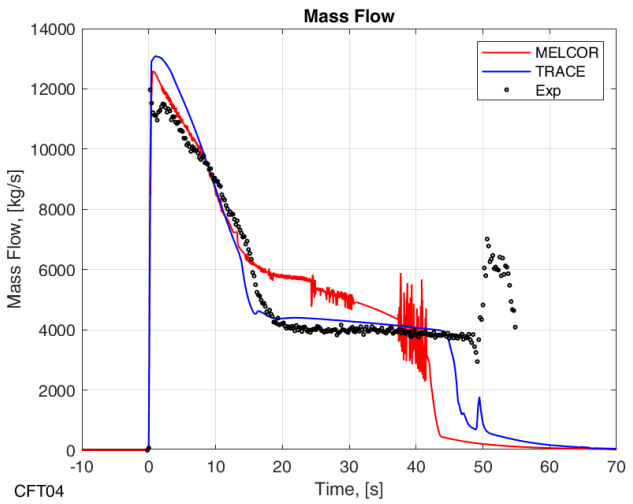


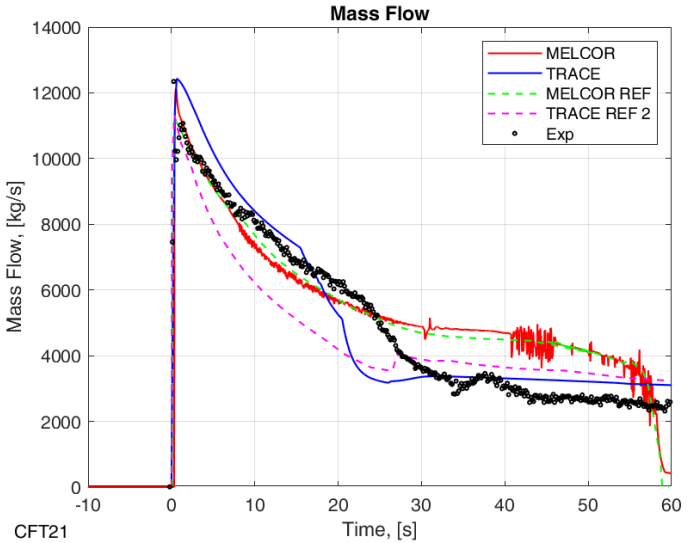
MELCOR











P. Domitr, et. al, The Assessment of the MELCOR2.2 Critical Flow Models Against MARVIKEN Critical Flow Tests and TRACE v5.0 patch 5 Calculations, NURETH-2019

Marviken – Global S&UA

- Cont. of previous work.
- Application of NCBJ's global S&U methodology - BIGUSA
- Use of Sobol indicies.
- Allows to identify sources of uncertainty
- Only for a few parameters: p, Cd, T
- Main motivation to test BIGUSA capabilities.
- Tens of thousands code runs with Python framework developed by NCBJ.
- Comparison of TRACE vs MELCOR for all Marviken tests

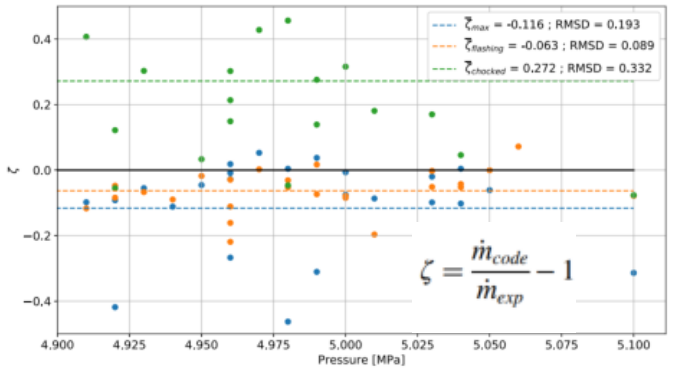
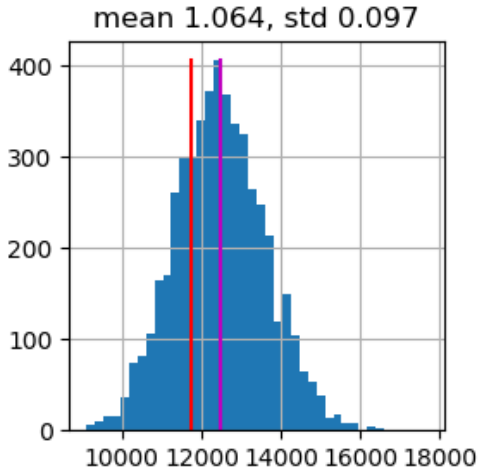
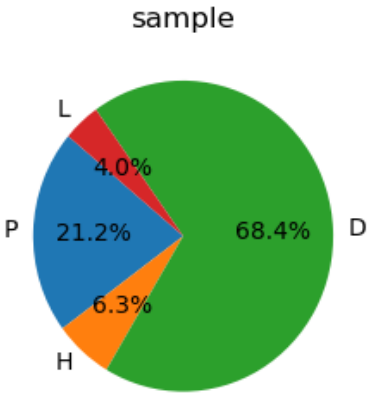


Fig. 4.3. Prediction errors for MELCOR code plotted with respect to pressure.





Reference case

Mean value from distribution

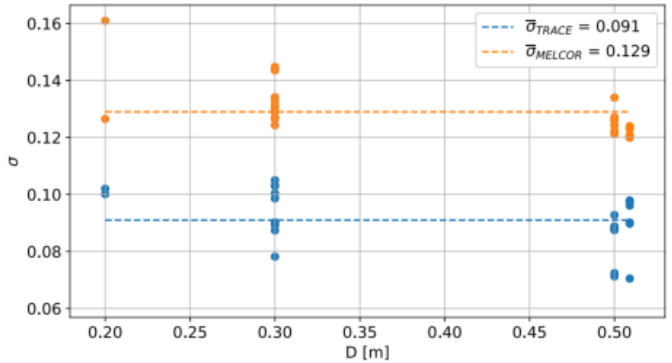
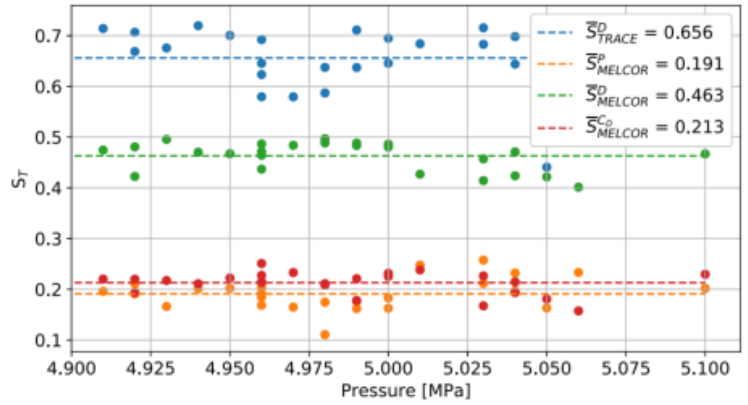


Fig. 4.4. Normalised standard deviation (Eq. 4.5) of all calculations results for maximal mass flow plotted with respect to hydraulic diameter for TRACE and MELCOR codes.



M. Spirzewski, et. al., Global uncertainty and sensitivity analysis of MELCOR and TRACE critical flow models against MARVIKEN tests, doi.org/10.1016/j.nucengdes.2021.111150
P. Domitr, et. al, The Assessment of the MELCOR2.2 Critical Flow Models Against MARVIKEN Critical Flow Tests and TRACE v5.0 patch 5 Calculations, NURETH-2019

Marviken – all tests

- MELCOR and TRACE models generated automatically
- with defaults – not perfect

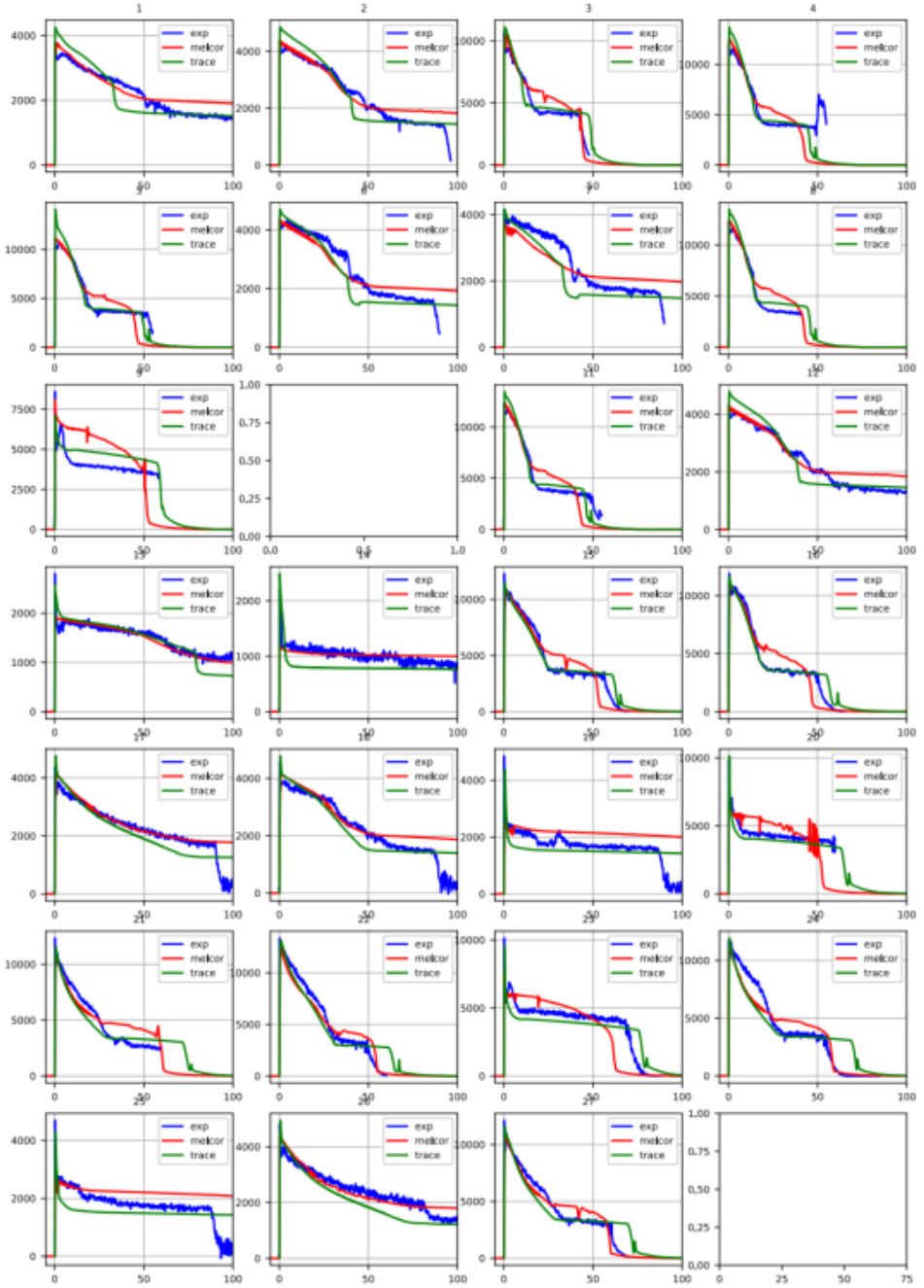
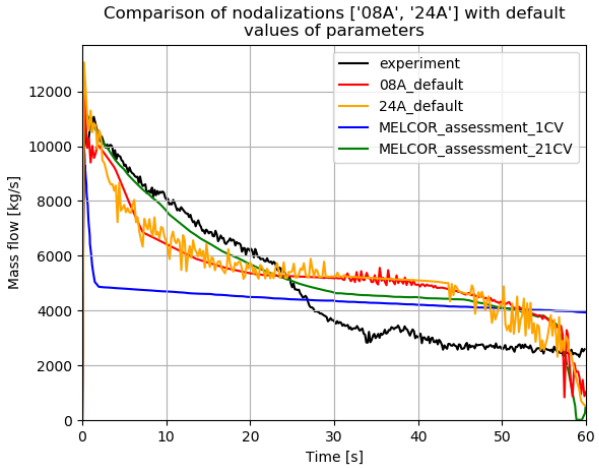


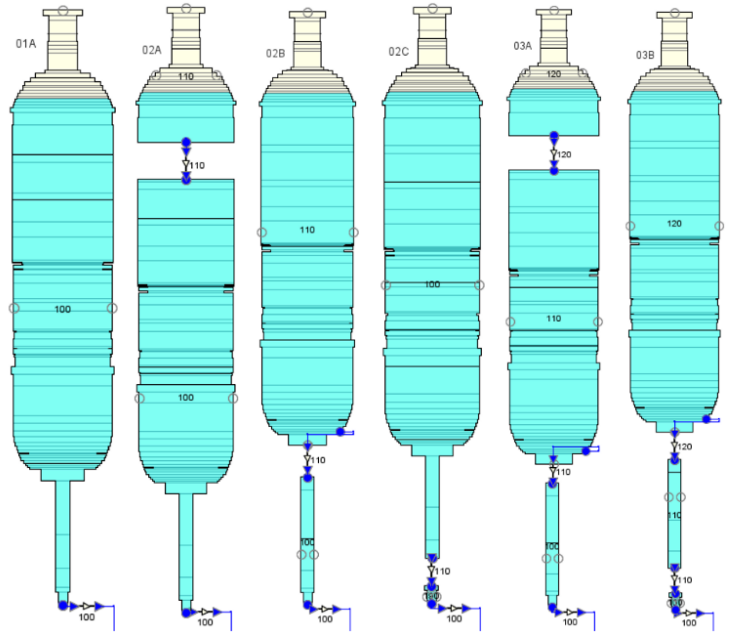
Fig. 5.1. Mass flow time trend of TRACE and MELCOR codes against the experimental measurement.

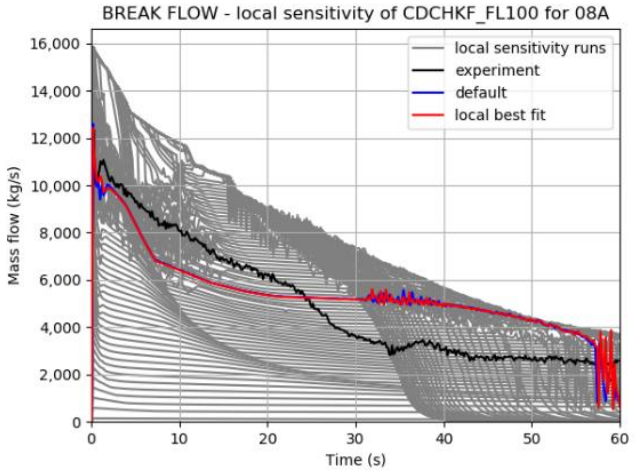
M. Spirzewski, et. al., Global uncertainty and sensitivity analysis of MELCOR and TRACE critical flow models against MARVIKEN tests, doi.org/10.1016/j.nucengdes.2021.111150

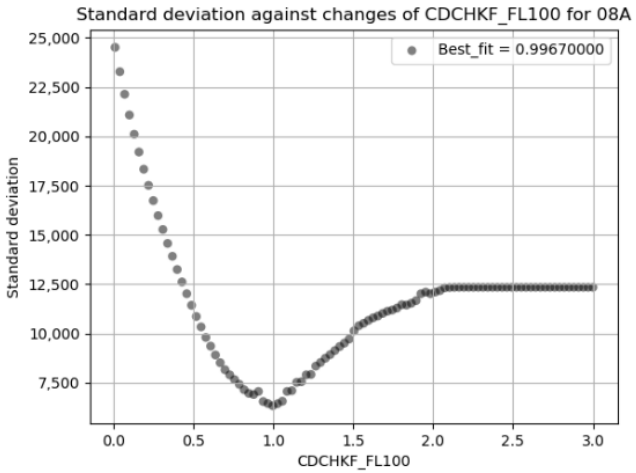
Marviken – nodalization and SC senstivity study

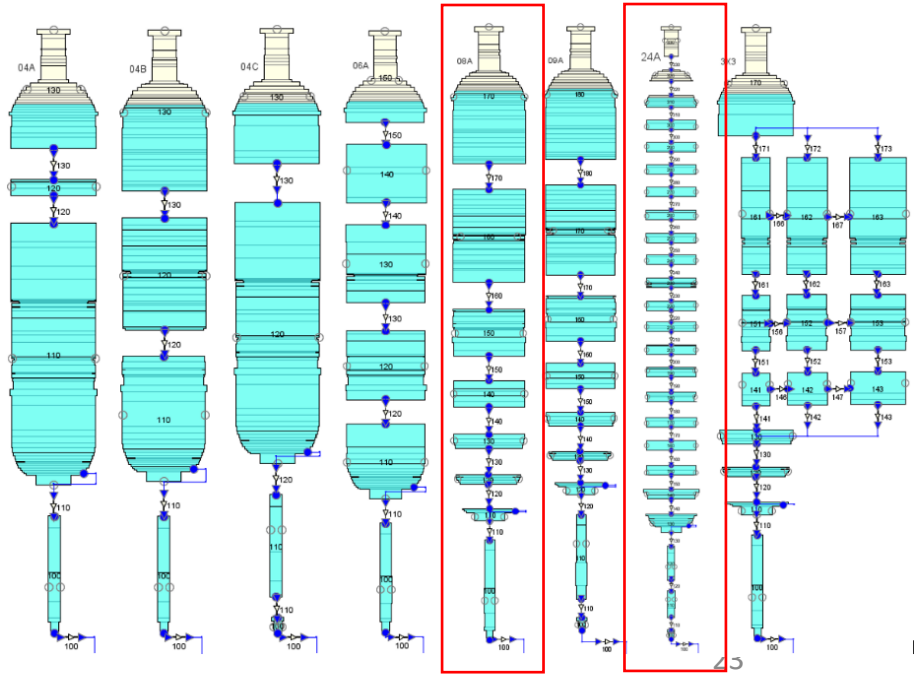
- Cooperation PAA and WUT
- Models prepared from scratch by different user separately from previous acitvites
- Parametric type senstivity of various S.C. and nodalization
- Most relevant for critical flow: CDCHKF, SC4407(1), SC4407(11), SC4402(1), SC4402(2)
- Results with 8CV similar to 24CVs









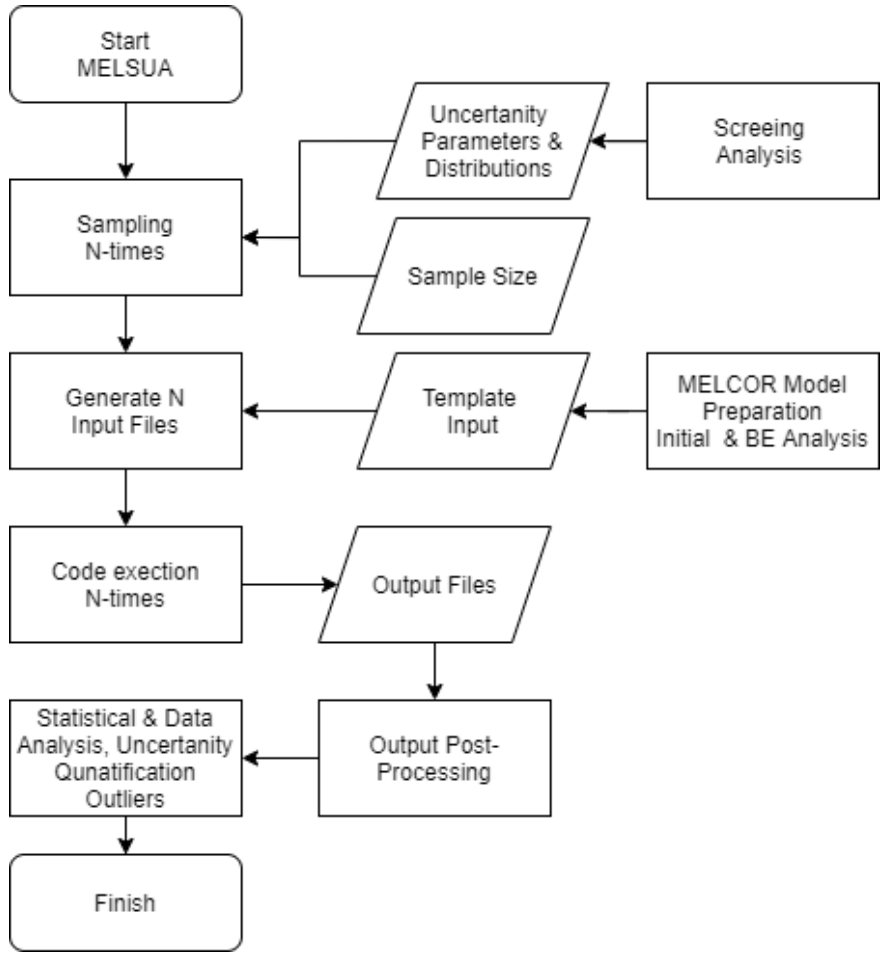


M. Włostowski, et. al., A Sensitivity Study of Critical Flow Modeling with MELCOR 2.2 Code Based on the MARVIKEN CFT-21 Experiment. doi.org/10.3390/en14164985

MelSUA Matlab tool for S&UA

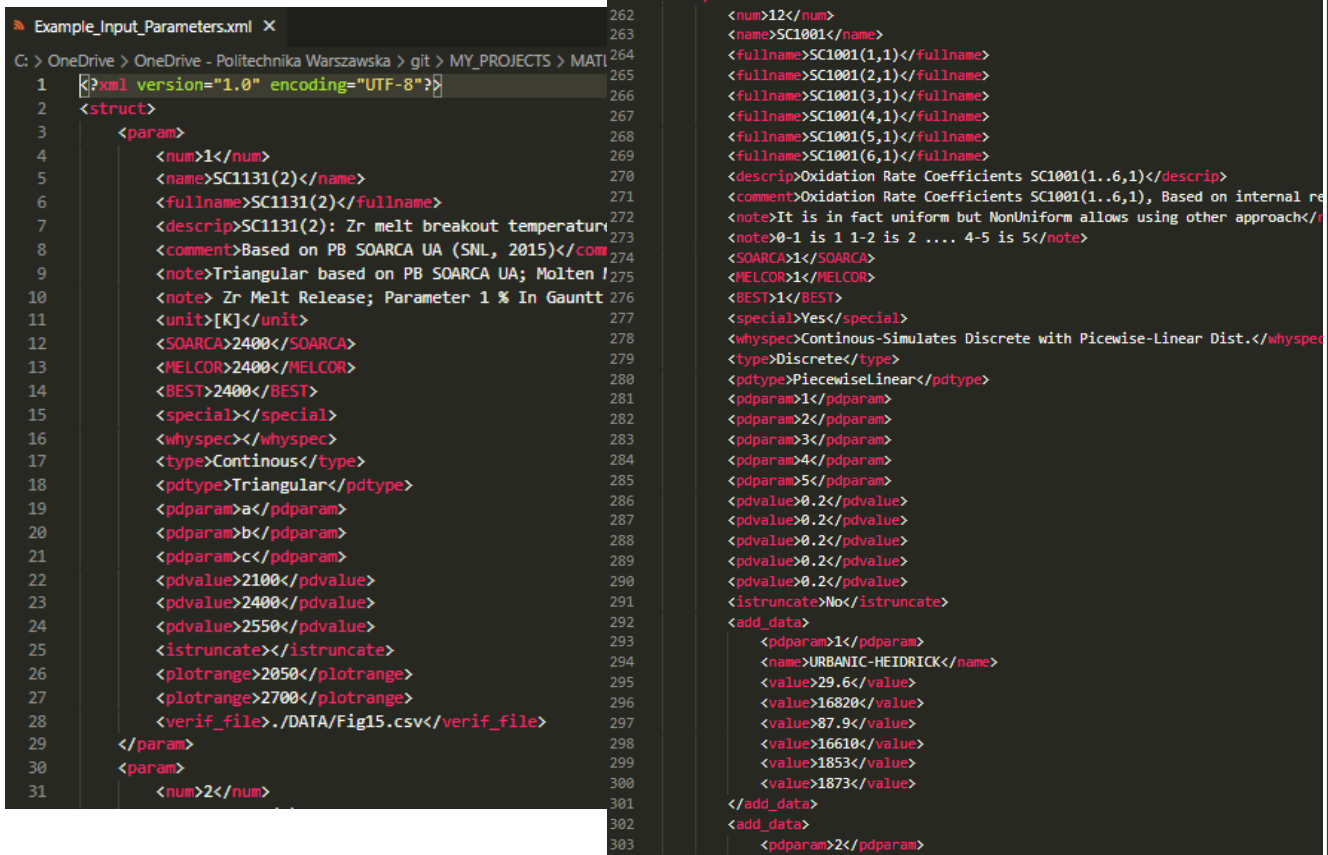
- Matlab open tool to perform uncertanity/senstivity
- Wilks type or Monte Carlo analysis
- Input as XML file stylized as MELCOR Unc. Tool or M-file.
- Uses MATLAB prob. toolboxes and allows e.g. truncated distributions, SRS or LHS ,etc.
- post-processing with EDF files scripts/files processing
- Currently it is internal tool with no manual, but if there will be any interest I can prepare it rapidly.
- BETA version available, GitLab repository:

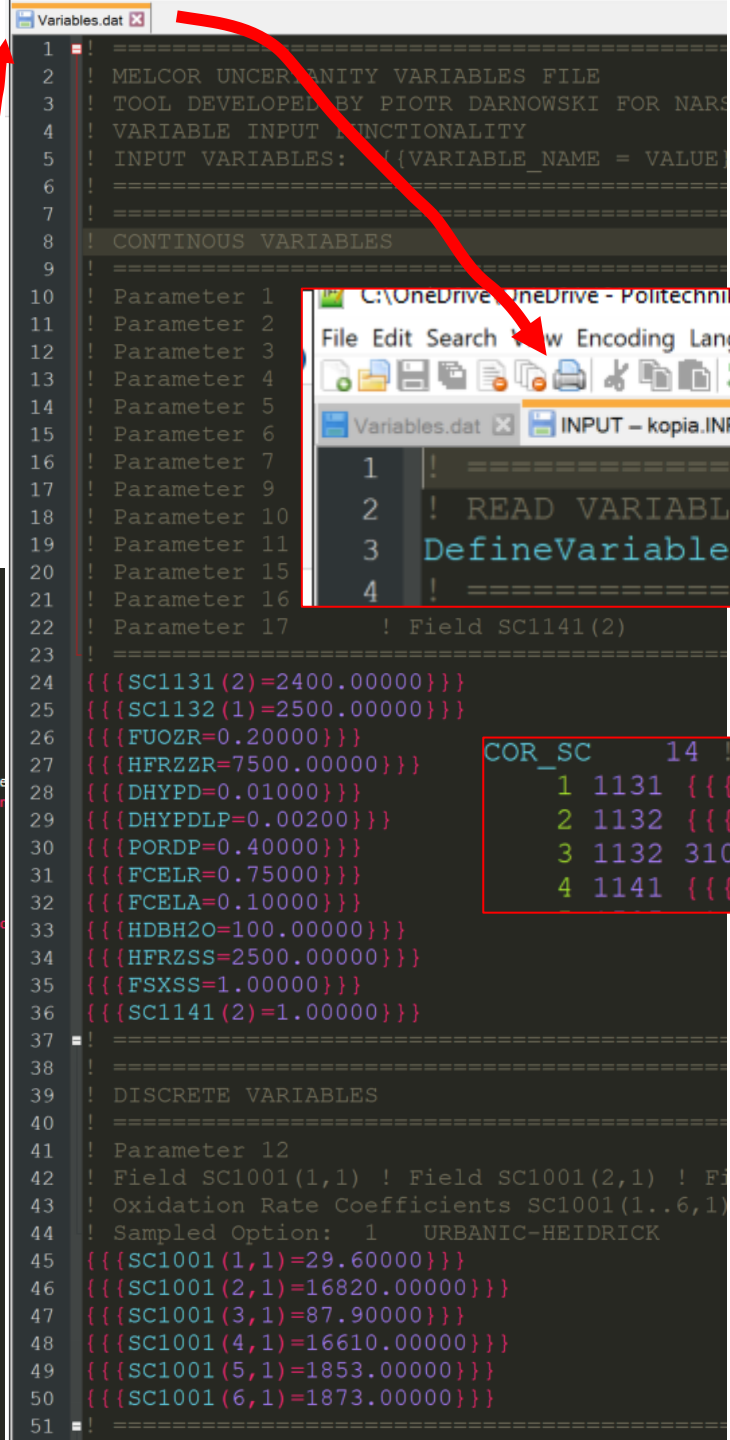
https://gitlab.com/darczu/x-core/-/tree/master/Modules/MLC_package/SenstivityUncertanityAnalysis

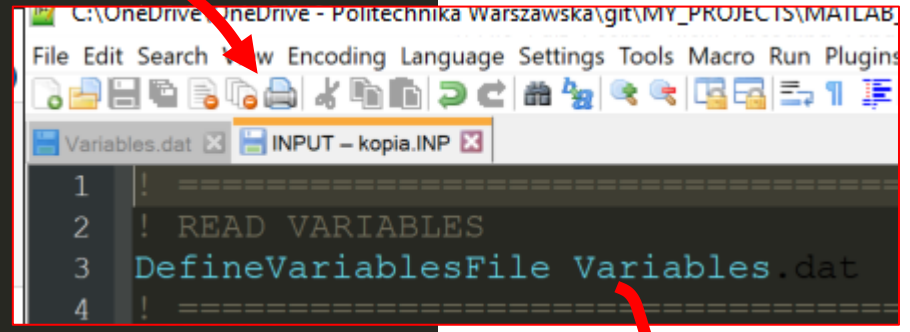


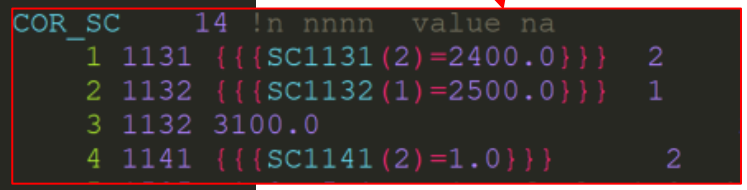
MelSUA Matlab tool for S&UA

- Example input
- Continous and Discrete variables
- MELCOR Input Variable Functionality
- Issue: Failed to use VariableValue record
- Issue: Failed to use CommentBlock and {{{Vars}}} at the same time







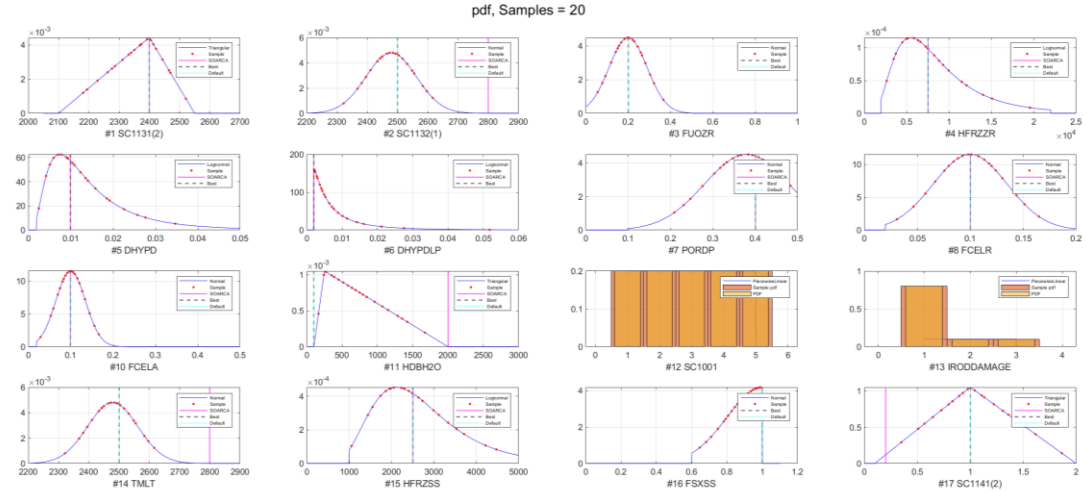


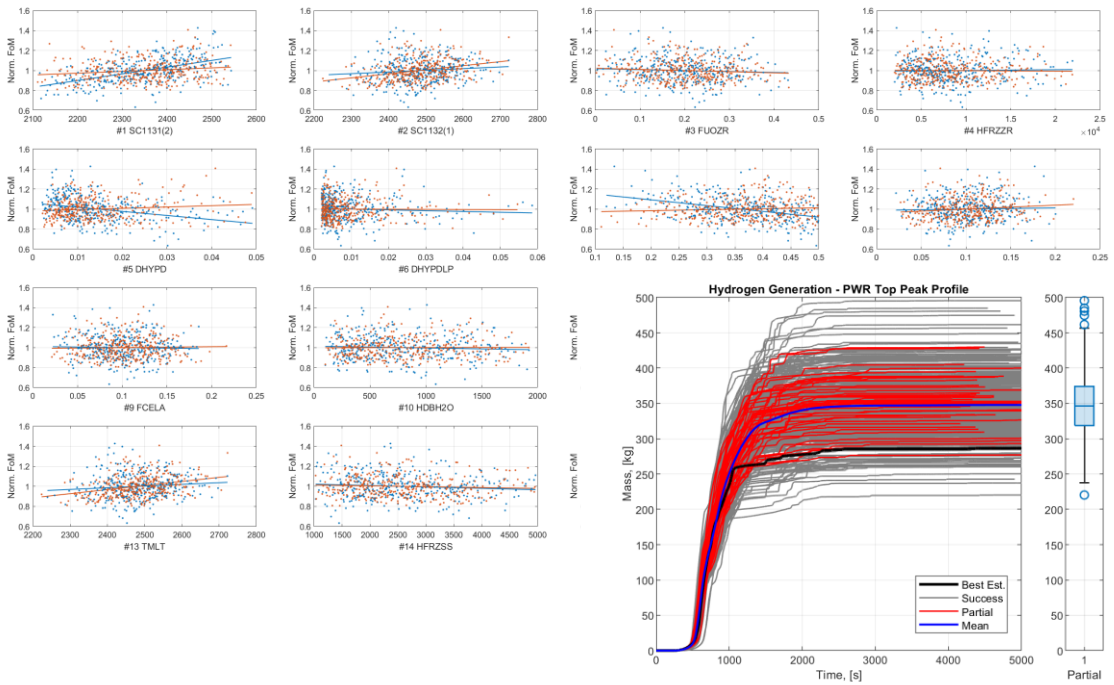
MelSUA Matlab tool for S&UA

- It generates PowerShell scripts and folders setup ready for running multiple terminals with batches of calcs.
- Generates MATLAB plots with desired output

Variables.dat | melcor_execute_NARSIS_UNC_PWR_014_SRS_INT_cases_1to120.ps1 | melcor_scripts_NARSIS_UNC_PWR_014_SRS_I

```
# ============================================================
# MELCOR EXECUTION FILE FOR POWER SHELL
# ============================================================
$scripts = @(
"melcor_unc 1; melcor_unc 2; melcor_unc 3; melcor_unc 4; melcor
"melcor_unc 11; melcor_unc 12; melcor_unc 13; melcor_unc 14; me
"melcor_unc 21; melcor_unc 22; melcor_unc 23; melcor_unc 24; me
"melcor_unc 31; melcor_unc 32; melcor_unc 33; melcor_unc 34; me
"melcor_unc 41; melcor_unc 42; melcor_unc 43; melcor_unc 44; me
"melcor_unc 51; melcor_unc 52; melcor_unc 53; melcor_unc 54; me
"melcor_unc 61; melcor_unc 62; melcor_unc 63; melcor_unc 64; me
"melcor_unc 71; melcor_unc 72; melcor_unc 73; melcor_unc 74; me
"melcor_unc 81; melcor_unc 82; melcor_unc 83; melcor_unc 84; me
"melcor_unc 91; melcor_unc 92; melcor_unc 93; melcor_unc 94; me
"melcor_unc 101; melcor_unc 102; melcor_unc 103; melcor_unc 104
"melcor_unc 111; melcor_unc 112; melcor_unc 113; melcor_unc 114
"melcor_unc 0;  "
)
# ============================================================
foreach($script in $scripts) {
    Start-Process powershell.exe "-NoExit .\melcor_scripts_NARS
  }
# ============================================================
 Pause
 'Finished Calculations...'
# ============================================================
```





Warsaw University of Technology

Thank you for your attention!

piotr.darnowski@pw.edu.pl

INSTITUTE OF HEAT ENGINEERING

Faculty of Power and Aeronautical Engineering
WARSAW UNIVERSITY OF TECHNOLOGY

Selected Nuclear Energy related papers

WUT publications search engine **http://repo.bg.pw.edu.pl/index.php/en/repository**

Faculty of Power and Aeronautical Engineering

Faculty of Physics

Faculty of Materials Science and Engineering

Faculty of Chemical and Process Engineering

Faculty of Civil Engineering

Faculty of Electronics and Information Technology

Faculty of Electrical Engineering

Faculty of Building Services, Hydro and Environmental Engineering

WUT