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Analysis of the DVI-LOCA in the AP1000-like reactor with MELCOR2.1 code

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EMUG 2024-04

Agenda

- Introduction
- MELCOR Model
- Scenarios and assumptions
- Results and Discussion
- Conclusions

Introduction

- Deterministic safety study of the AP1000 based/like plant
- Develop MELCOR code model
  - ➢ Based on public data
- Study normal operation
  - ➢ Verify steady-state with public data
- Study Design Basis Accident (DBA)
  - ➢ Verify accident response with public data
  - ➢ Preliminary step for the future severe accident research
- Modelling approach / nodalization study
  - ➢ Study various modelling approaches
  - ➢ Plant characteristic phenomena
- Presentation based on publication:
  - ➢ *Włostowski, M., Darnowski, P. Study of the DVI-LOCA in the AP1000-like reactor with MELCOR code, Annals of Nuclear Energy 200 (2024) 110397, doi.org/10.1016/j.anucene.2024.110397*

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Study of the DVI-LOCA in the AP1000-like reactor with MELCOR code

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ABSTRACT

The paper presents the outcomes of the deterministic safety studies for a Pressurized Water Reactor based on the AP1000 design. The model was developed with MELCOR computer code using public references and qualified using data for nominal steady-state and double-ended Direct Vessel Injection line break accident. Emphasis was placed on thermal–hydraulic phenomena and modeling of the passive safety features. Different plant model variants were studied, including two models for the Automatic Depressurization System, two models for steam generators, and three models for hot-legs. Safety injections were investigated with a focus on the passive core cooling system, which is crucial during a Loss of Coolant Accident. Simulation results agree very well with available steady-state data. The model predicts expected plant behavior during a design basis accident, and results are not substantially different from predictions with system codes presented in the public reports. It shows that the developed model can be used in severe accident studies.

1. Introduction

1.1. Analysis with integral severe accident codes

Simulations with severe accident integral computer codes are part of the Deterministic Safety Analysis (DSA) but are also used in Probabilistic Safety Analysis (PSA) (IAEA, 2010b; IAEA, 2010a; IAEA, 2019). Severe accident analyses are usually performed with codes like MELCOR, ASTEC, or MAAP and allow for predicting the progression of accidents with reasonable accuracy (Haste et al., 2006; Sevón, 2015b,a). Results of deterministic calculations can be used to evaluate Design Extension Conditions (DEC) and verify their safety or acceptance criteria. They can be used in the development of Severe Accident Management Guidelines (SAMG) (Bal Raj Sehgal, 2012; Bentaib et al., 2015; IAEA, 2021; IAEA, 2019). In the framework of the PSA, these simulations allow verification of conditions for core damage, success, or failure criteria, as well as various hypotheses about the accident progression. Within the PSA framework, integral codes allow for studying fission product behavior, obtaining the source term estimation, assessing containment performance, predicting hydrogen behavior, and other relevant phenomena (Bal Raj Sehgal, 2012; Bentaib et al., 2015; IAEA, 2010b; IAEA, 2019).

In principle, severe accident integral tools can also be used as alternative tools to study Design Basis Accidents, other transients, and Anticipated Operational Occurrences (AOO). They allow the inclusion of a Reactor Coolant System (RCS) response and a containment response in an integrated approach. Integral codes like MELCOR allow predictions for the most important phenomena, especially thermal-hydraulics. Nevertheless, the thermal–hydraulic formulation in integral codes is usually simplified compared to system codes like RELAP or CATHARE, and they are considered less reliable and less precise for these applications. System codes are dedicated to detailed thermal hydraulic applications, specifically designed, qualified, extensively validated, and verified, and essential for licensing-type safety analysis. Integral codes for thermal-hydraulics are typically not accepted for licensing analysis. However, it is not the primary purpose of integral codes to predict thermal-hydraulics very precisely. The application of detailed models significantly increases computational time, and the current approach is a compromise between accuracy and resources. Nevertheless, during severe accidents, before initial core degradation, it is desirable to predict thermal hydraulics reasonably, basically to start the core degradation simulations with a reasonable initial state. After initial core degradation, for the late in-vessel phase or ex-vessel phase, it is more difficult to have detailed thermal–hydraulic simulations due to the increasing complexity, and new physical phenomena, increasing uncertainties, and modeling difficulties.

Thermal-hydraulics accuracy is a fundamental issue, especially for a short-term response during fast accidents – like LOCAs. Despite that, thermal-hydraulics predictions with integral codes can be comparable to system codes with uncertainties up to a dozen percent (Spirzewski et al., 2021). For other relevant severe accident phenomena, parameters are usually predicted with an uncertainty, typically up to an order of magnitude (Darnowski et al., 2020; Darnowski et al., 2021). For less essential phenomena, it is possible to have orders of magnitude differences due to gaps in knowledge (Bal Raj Sehgal, 2012; Bentaib et al.,

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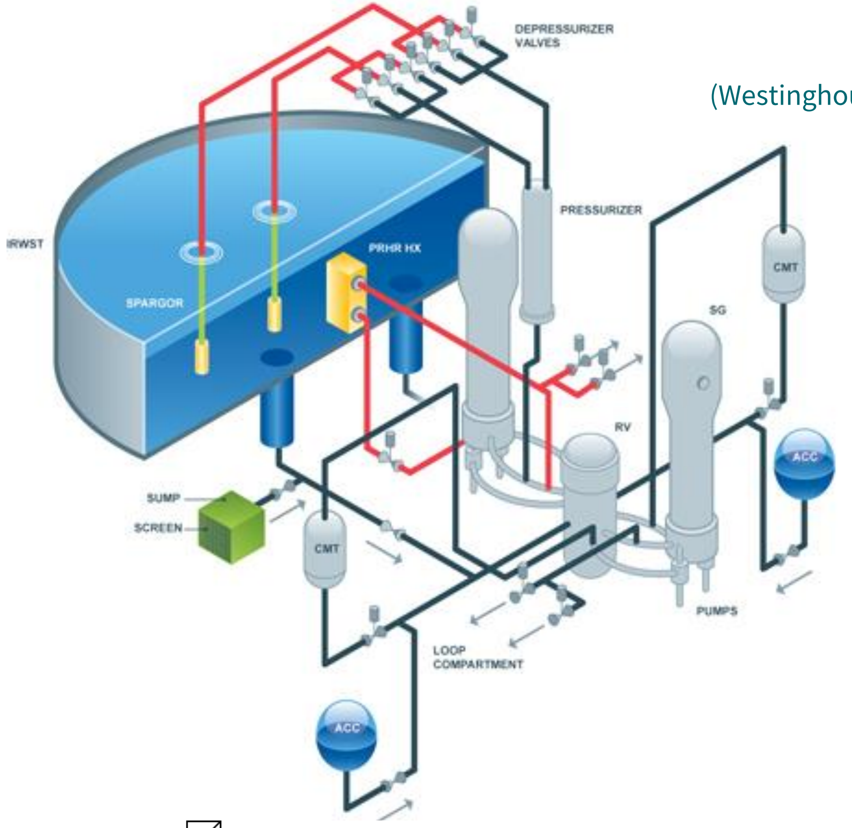
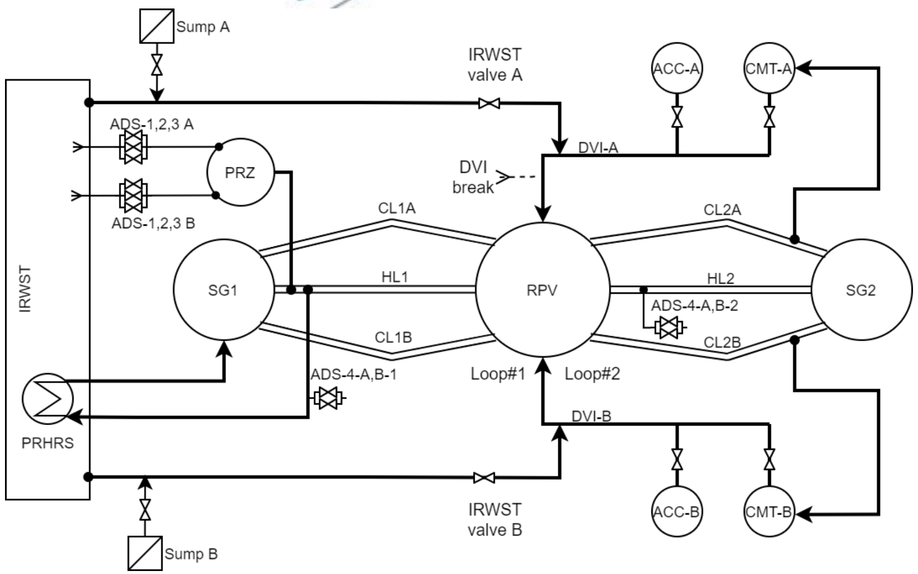
AP1000-like model

- AP1000 like plant MELCOR model
  - ➢ Based on public data US DCD/UK PCSR/Generic Westinghouse data
- Main relevant systems and components
  - ➢ Core & RPV
  - ➢ Reactor Coolant System – Pipework, Pumps, Pressurizer
  - ➢ All relevant safety systems
    - ❑ IRWST (In-Containment Reactors Water Storage Tank)
    - ❑ ADSs (Automatic Depressurization System)
    - ❑ ACC (Accumulators)
    - ❑ CMT (Core Make-up Tanks)
    - ❑ PRHRS (Passive Residual Heat Removal System)
  - ➢ Containment (no focus here)
  - ➢ Related control systems, setpoints, I&C

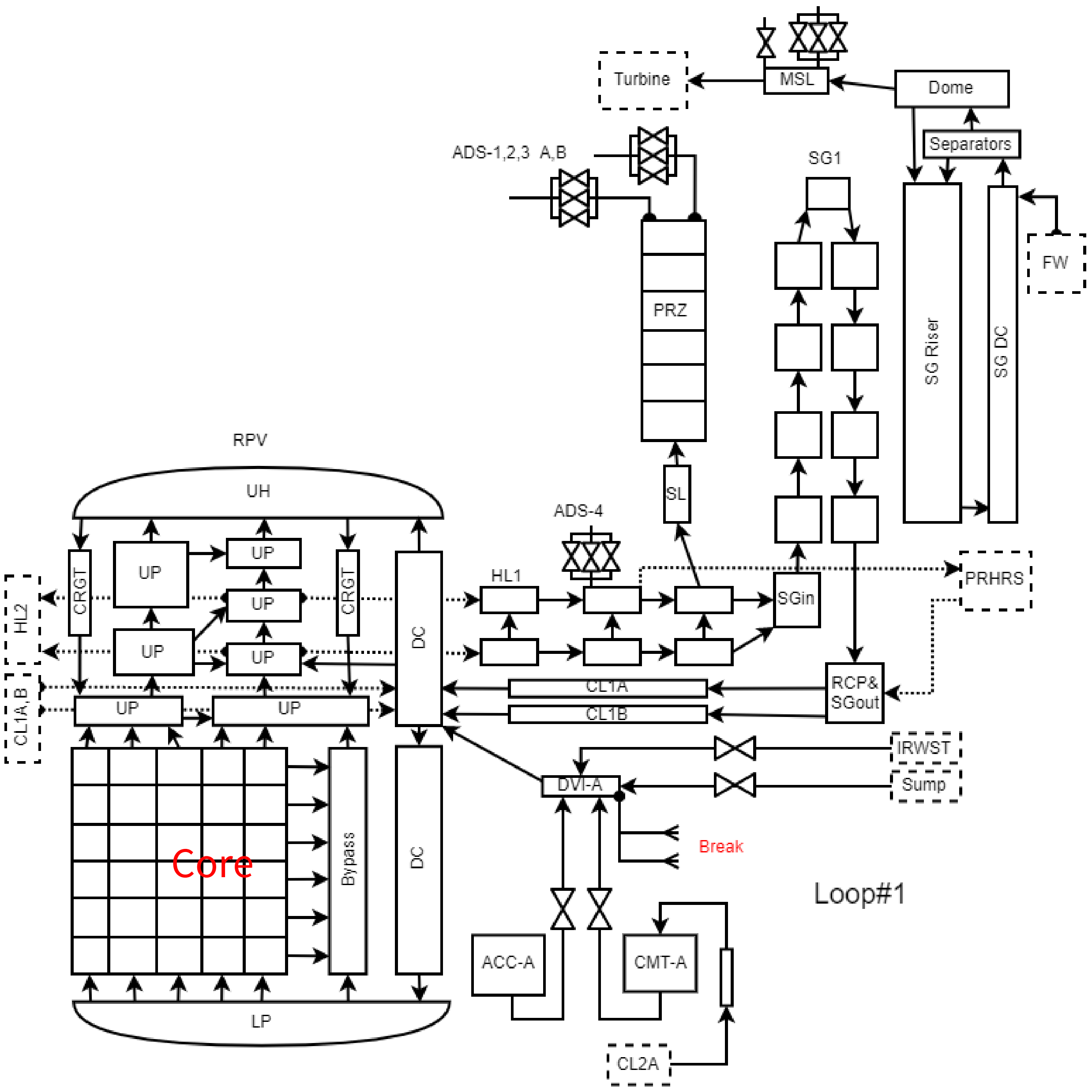


(Westinghouse, 2011)



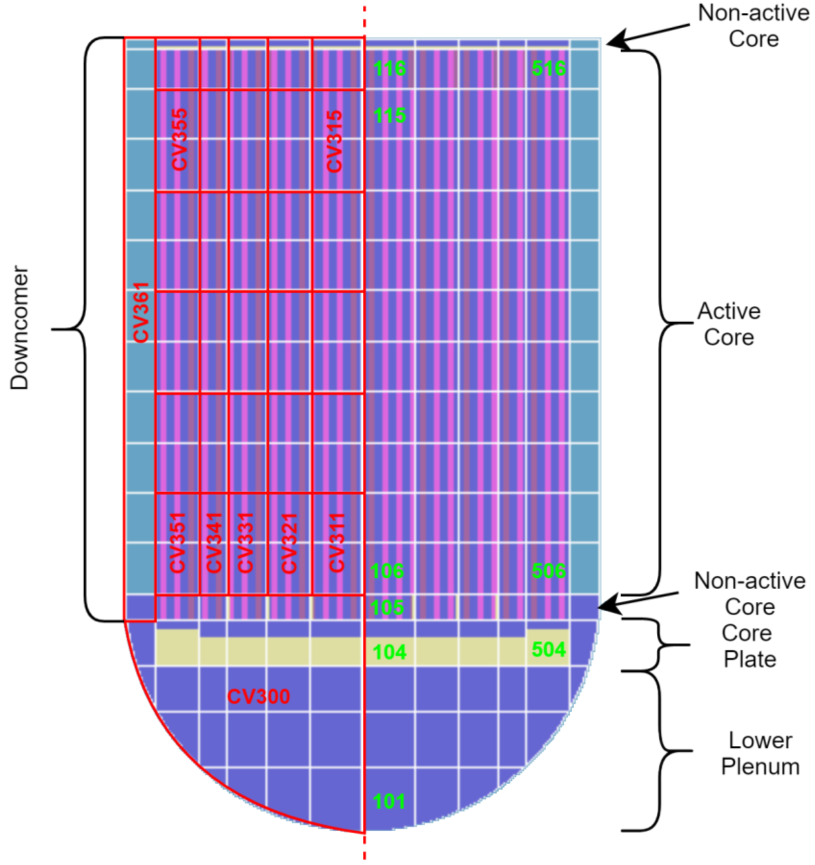
Reactor Coolant System model

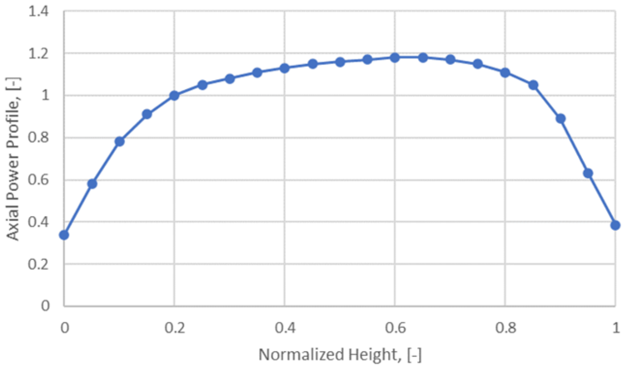
- Reactor Pressure Vessel
- Two main cooling circuits
  - Hot Legs x2
  - Cold Legs x4
  - Reactor Coolant Pump x4
- Steam Generators primary and secondary side
- Pressurizer with valves
- Main safety systems
- Valves, pumps etc.

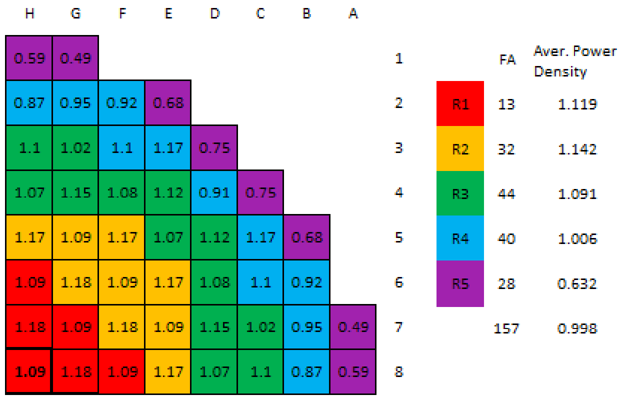


Core model

- Typical “detailed” MELCOR core model
- Core model for degradation
  - COR package
  - 5 radial rings, 16 axial levels
- Thermal-hydraulics model
  - CVH/FL Package
  - Superimposed on the COR package model
  - 30 CVs for core
  - 1 lower plenum
  - 1 downcomer

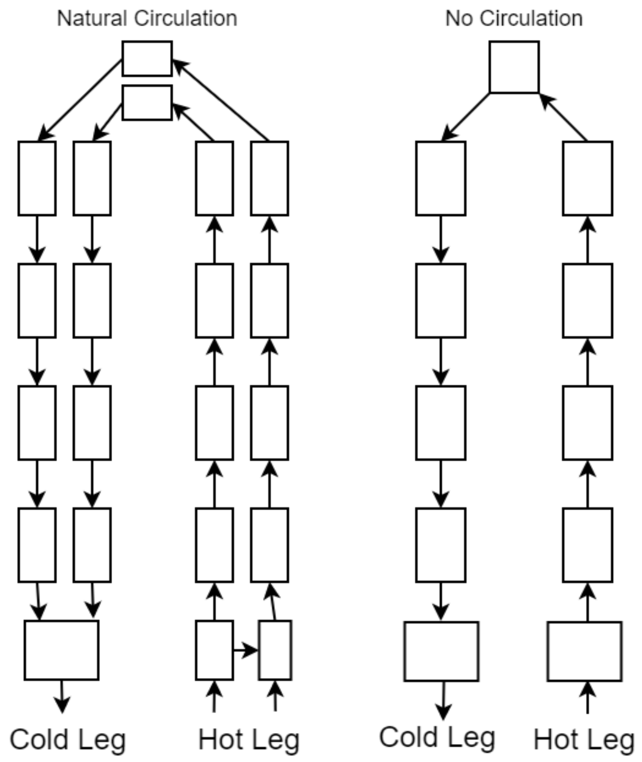


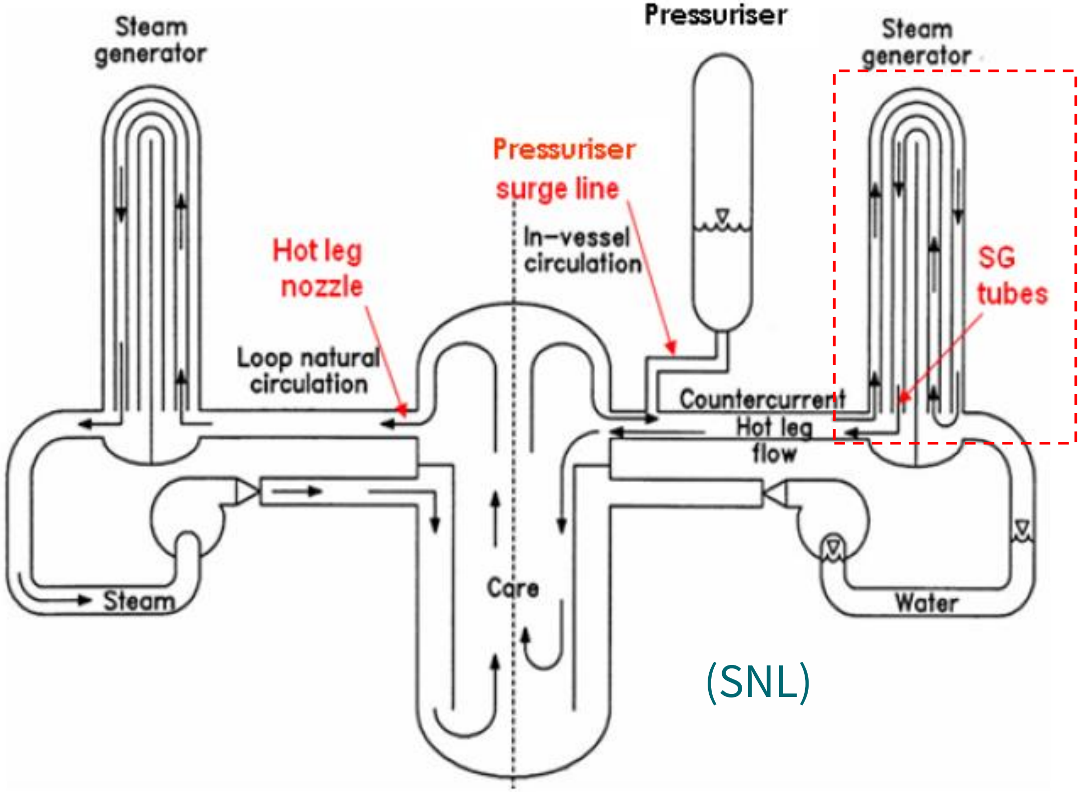




Steam Generator models

- Two nodalization variants
- Simple model not allowing two-way circulation of steam/liquid in tubes
- Complex model allowing two-way circulation



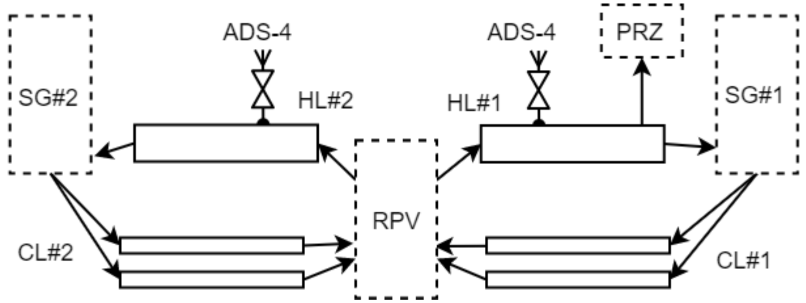


(SNL)

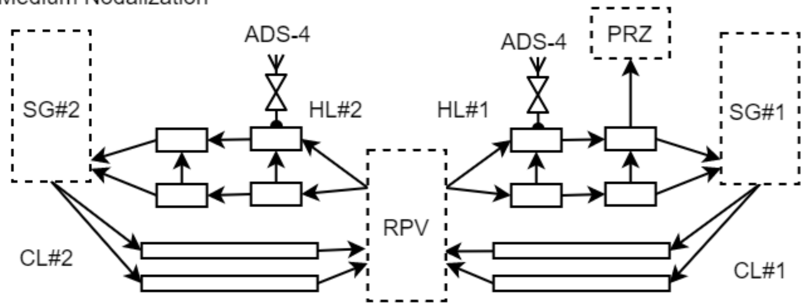
Hot Leg models

- HL nodalization study
- Three models Complex/Medium/Simple
- Complex with separate CVs connected to the ADS-4 and Pressurizer and RPV outlet
- Medium/Complex allowing counter-current flow
- Simple model – old style with 1 CV

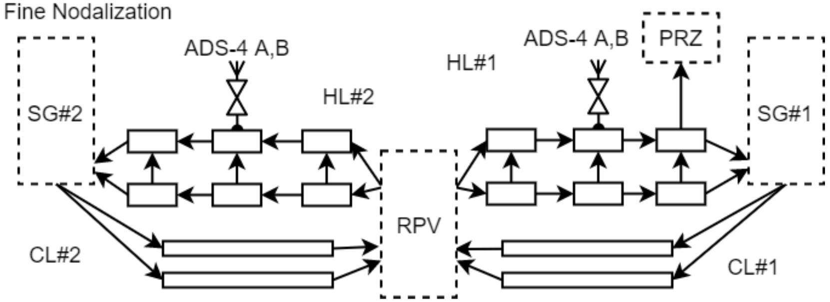
Coarse Nodalization

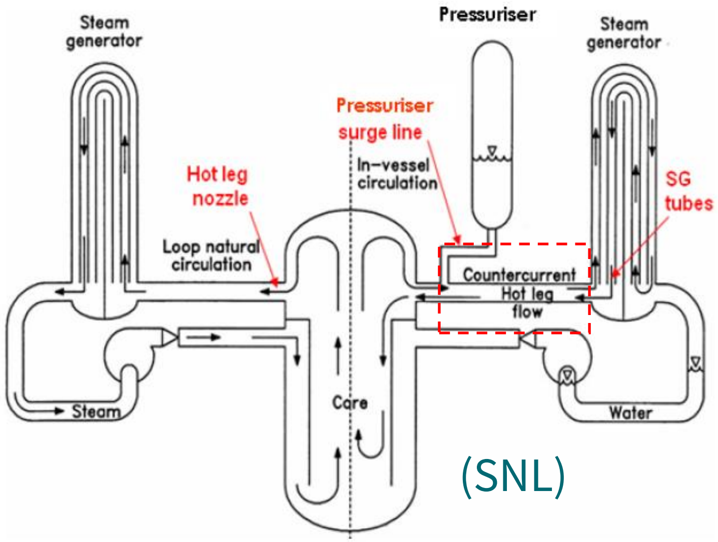


Medium Nodalization



Fine Nodalization





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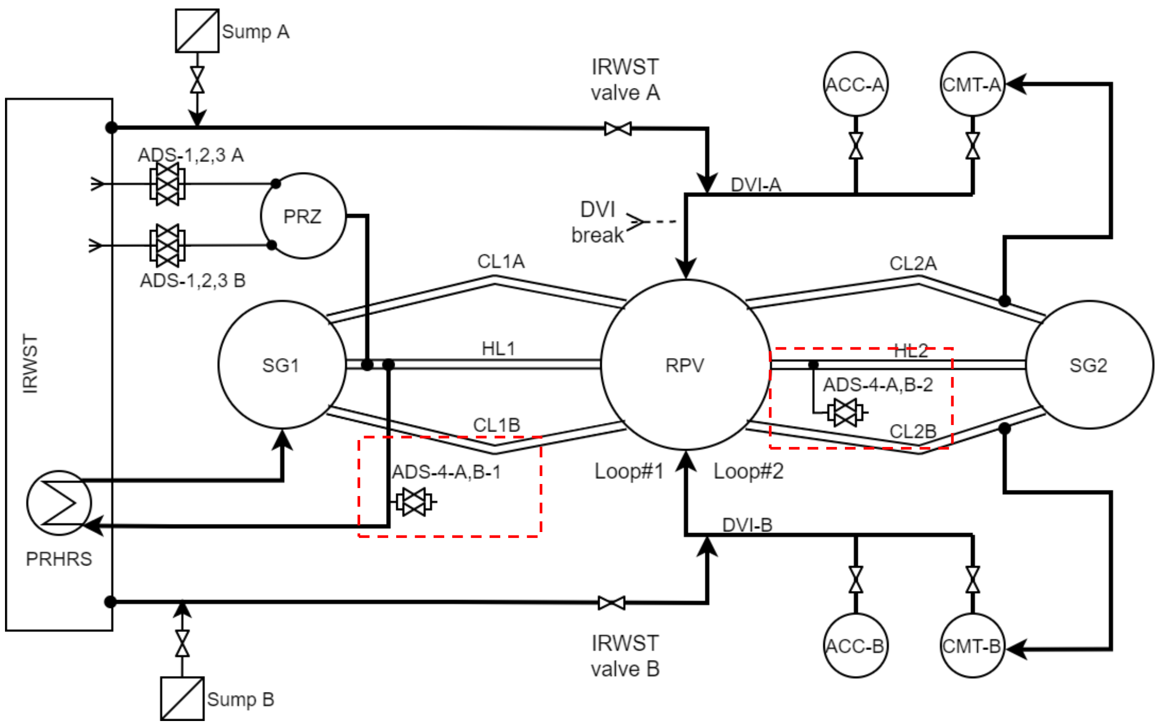
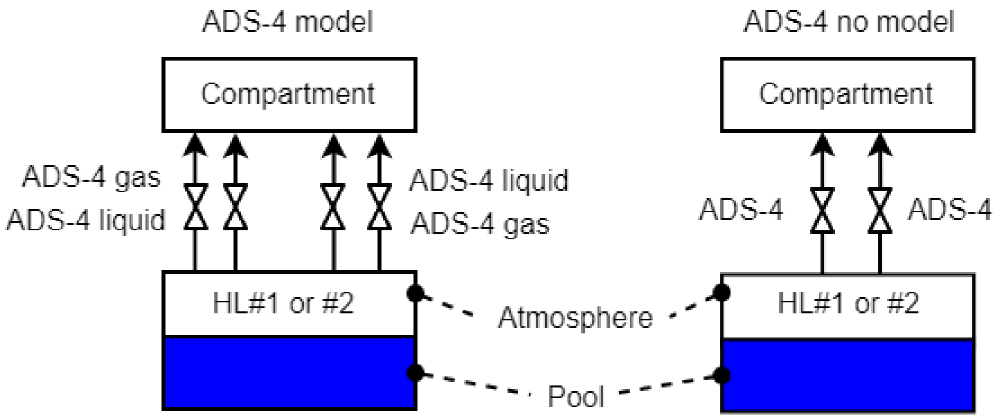
ADS-4 valves model

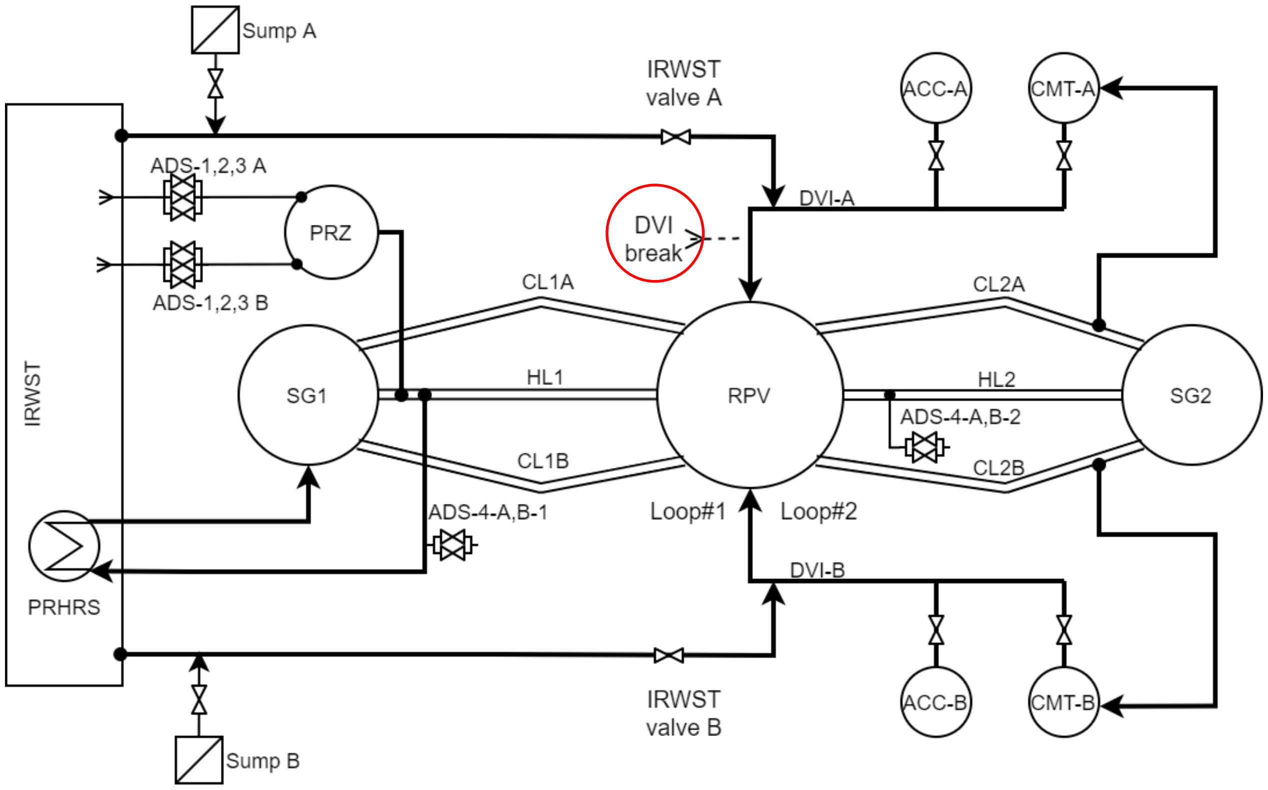
- Automatic Depressurization Valves Stage 4
  - Opens path to containment to assure low pressure in the RCS and operation of safety injection
- Two models
  - With separate liquid/steam flow paths
  - Without separate paths
  - Based on (Wang, 2020)





Studied Scenario

- Direct Vessel Injection (DVI) line break
- Loss of Coolant Accident (LOCA)
  - Medium/Small break
- Design Basis Accident
- US DCD based conservative assumptions
  - DCD/PCSR NOTRUMP Westinghuse code for Small/Medium-LOCA
- Should end with safe controlled state
- Preceded with normal (steady-state) full-power operation
- It is not a severe accident. For severe accident we need additional failure.



Results – normal state

- Reference data from US DCD
- 1000 seconds steady-state
- Very good agreement
- Allowed error (Petruzzi, 2008)

Parameter	Unit	Design value	Source of information	MELCOR	Obtained error	Allowed error
Reactor core power	MW	3400.0	DCD Table 4.4-1 (1/2)	3400	0.00%	2%
Power of primary circuit	MW	3415.0	DCD Table 5.1-3	3415	0.00%	2%
Vessel flow rate	kg/s	15 170.1	DCD Table 5.1-3	15157.9	-0.08%	2%
Core flow rate	kg/s	14 275.6	DCD Table 5.1-3	14265.7	-0.07%	2%
Inlet RPV temperature	K	553.82	DCD Table 5.1-3	554.76	0.17%	0.50%
Outlet RPV temperature	K	594.26	DCD Table 5.1-3	595.1	0.14%	0.50%
Pressurizer steam pressure	MPa	15.41	DCD Table 5.1-1	15.41	0.00%	0.10%
Developed pump head	m	111.25	DCD Table 5.4-1	111.47	0.20%	1%
Pressure drop across the core	MPa	0.275	DCD Table 4.4-1 (1/2)	0.254	-7.64%	10%
Pressure drop across the vessel, including the nozzle	MPa	0.43	DCD Table 4.4-1 (1/2)	0.471	9.53%	10%
Water volume, including pressurizer	m^3	271.8	DCD Table 5.1-2	271.543	-0.09%	1%
Pressurizer water volume	m^3	28.3	DCD Table 5.1-2	28.25	-0.18%	1%
Exit steam pressure	MPa	5.76	DCD Table 5.1-2	5.764	0.00%	0.10%
Steam flow	kg/s	943.7	DCD Table 5.1-2	943.96	0.03%	2%
Feedwater temperature	K	499.82	DCD Table 5.1-2	499.82	0.00%	0.50%
Steam generator secondary side water volume	m	147.9	DCD Table 5.4-5	147.00	-0.61%	2%
Steam generator secondary side vapor volume	m^3	103.2	DCD Table 5.4-5	104.05	0.82%	2%

Sequence of events for base case model

- Example DVI-LOCA sequence
- Base case model with simple SG, no complex ADS, medium HL model
- Reference results with NOTRUMP code (US DCD / UK PCSR)
- Relatively good agreement

Event [s]	US AP1000 DCD – 20 psi containment pressure	UK AP1000 PCSR – 20 psia containment pressure	MELCOR base case model
Break opens	0.0	0.0	0.0
Reactor trip signal	13.1	13.4	14.0
Steam turbine stop valves close	19.1	13.4	20.0
"S" signal	18.6	19.8	17.8
Main feed isolation valves begin to close	20.6	26.8	19.8
Reactor coolant pumps start to coast down	24.6	26.8	23.8
ADS Stage 1	182.5	181.7	192.4
ADS Stage 2	252.5	229.7	262.4
Intact accumulator injection starts	254	244.2	219.4
ADS Stage 3	372.5	349.7	382.4
ADS Stage 4	492.5	477.7	502.4
Intact accumulator empties	600.0	573.6	557.7
Intact loop IRWST injection starts (continuous injection)	1470	1778.6	~1450
Intact loop core makeup tank empties	2123	1866.0	1794.2

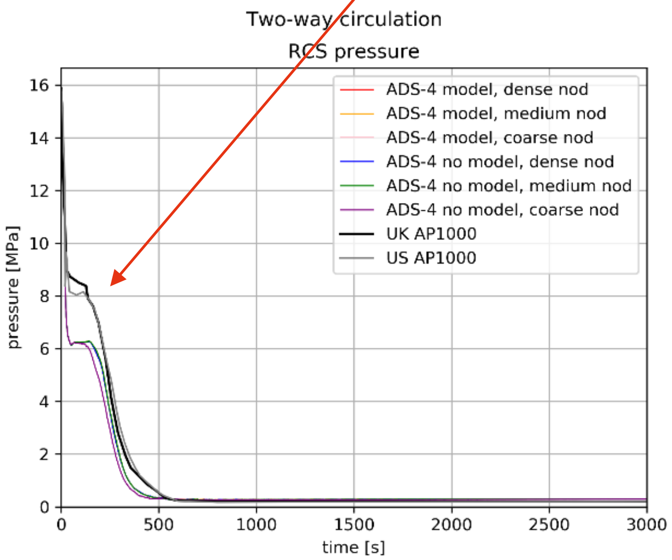
Results – list of studied cases

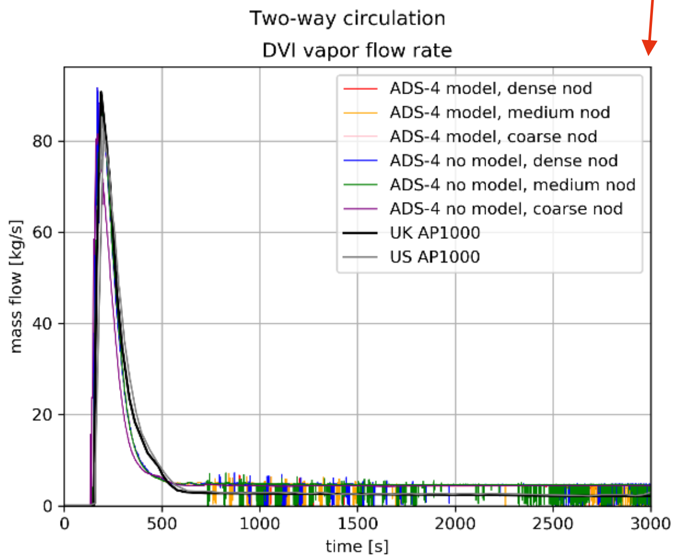
- In this work 12 sensitivity runs simulated
- Modified SG, HL and ADS models
- Only results for complex SG presented later

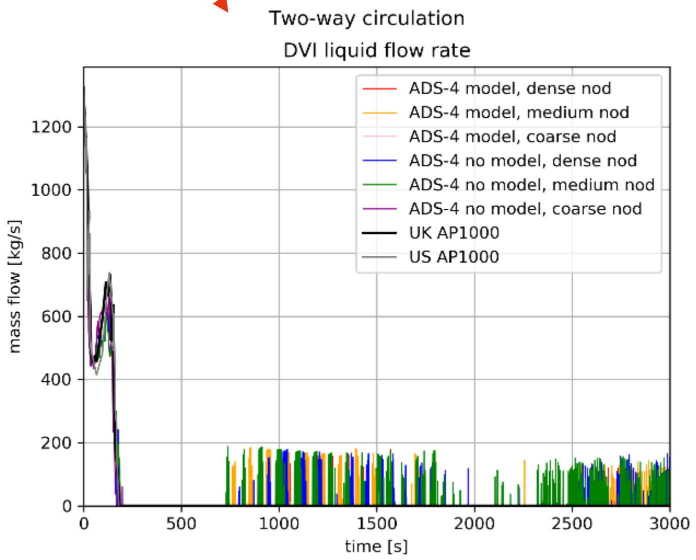
Case	SG modeling	ADS-4 modeling	HL modeling	Comment
1	simple	model	fine	sensitivity
2	simple	model	medium	sensitivity
3	simple	model	coarse	sensitivity
4	simple	no model	fine	sensitivity
5	simple	no model	medium	base model
6	simple	no model	coarse	sensitivity
7	**complex**	**model**	**fine**	**sensitivity**
8	**complex**	**model**	**medium**	**sensitivity**
9	**complex**	**model**	**coarse**	**sensitivity**
10	**complex**	**no model**	**fine**	**sensitivity**
11	**complex**	**no model**	**medium**	**sensitivity**
12	**complex**	**no model**	**coarse**	**sensitivity**

Blowdown phase

- Depressurization in 500s
- Pressure during two-phase choked flow lower – due to different choked flow models and containment pressure modelling
- Break flows in agreement
- Black lines – US DCD
- Grey lines – UK PCSR

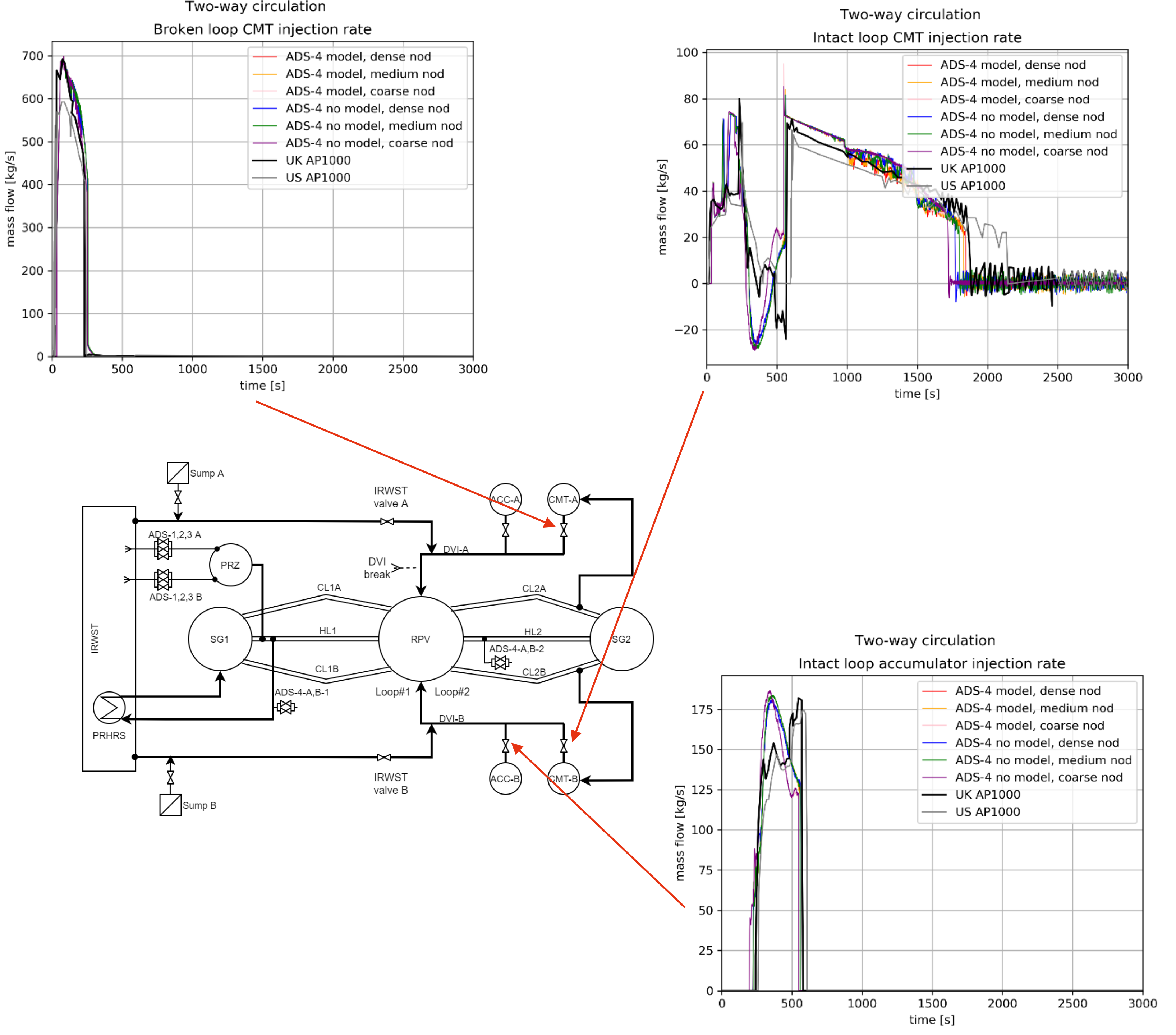






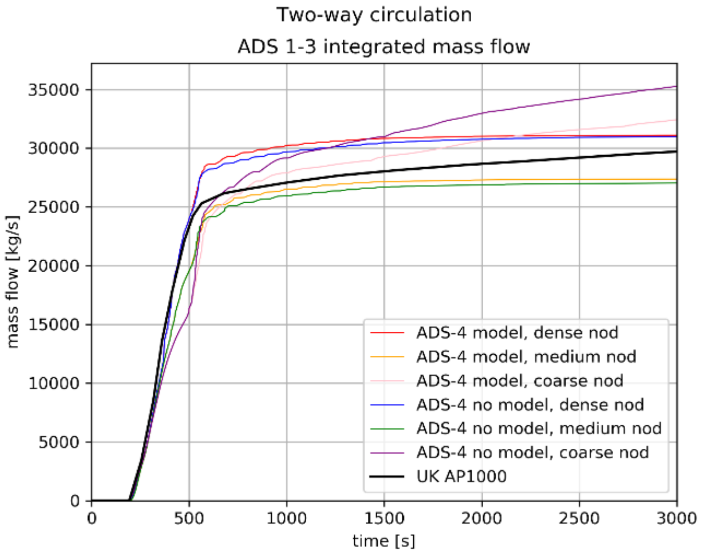
CMTs and ACCs

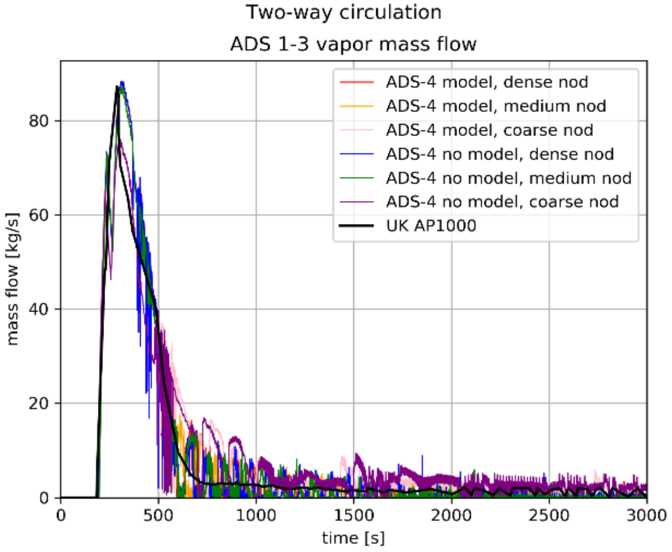
- CMT starts immediately – works as high-pressure injection
- Accumulators start at medium pressure
- Relatively good predictions

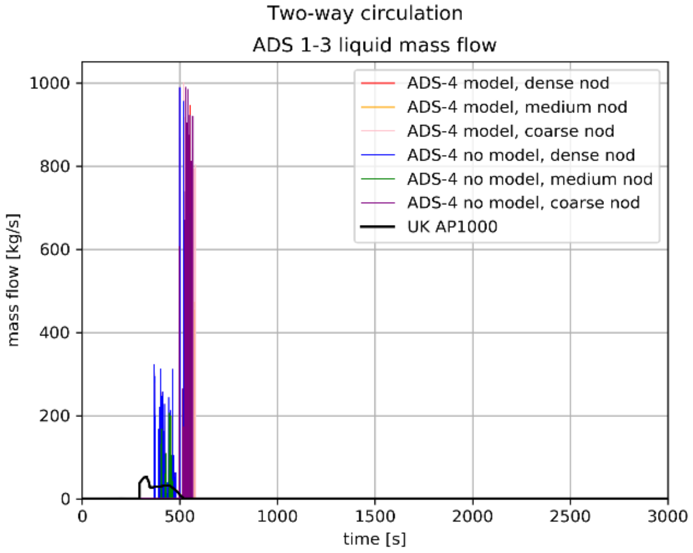


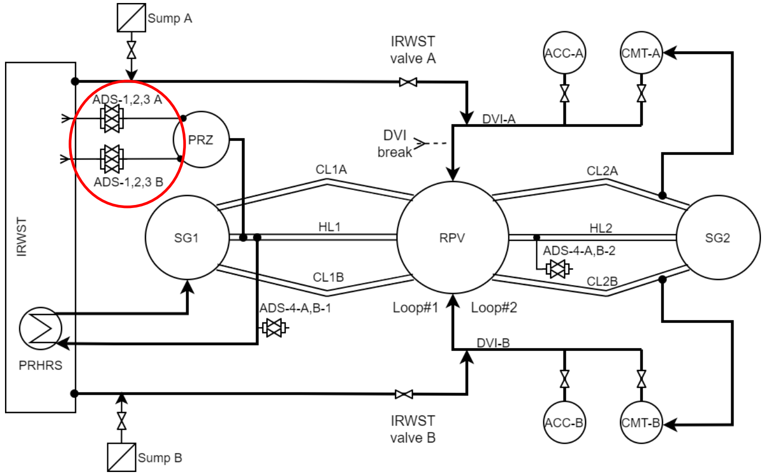
ADS #1-3 operation

- ADS works in series with delays
- Less violent reduction in pressure and activation of subsequent injections – CMT, ACCU and IRWST
- Vapor flow predicted accurately / liquid less
- Integrated flow reasonable



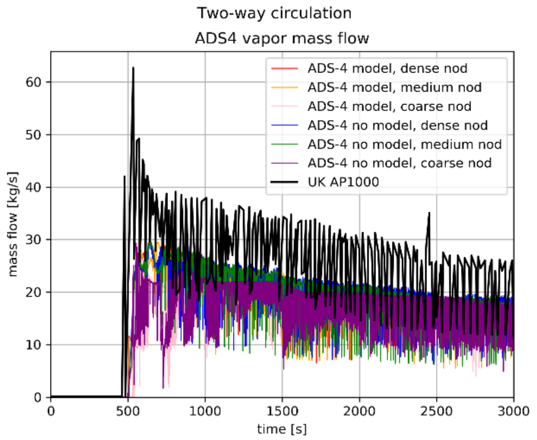


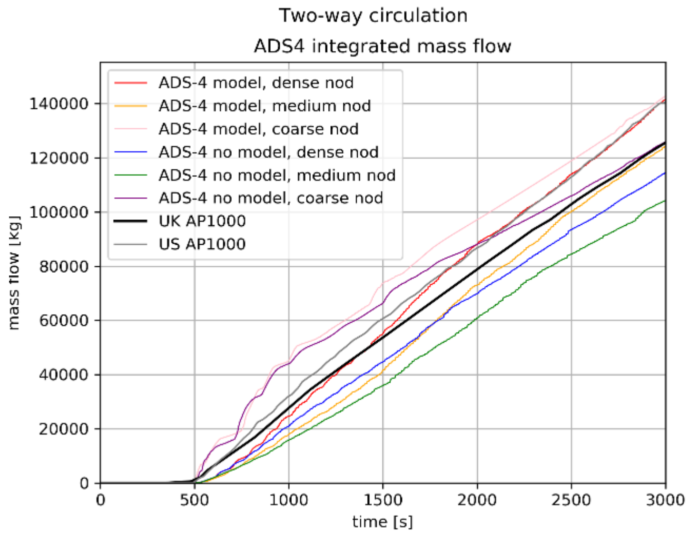


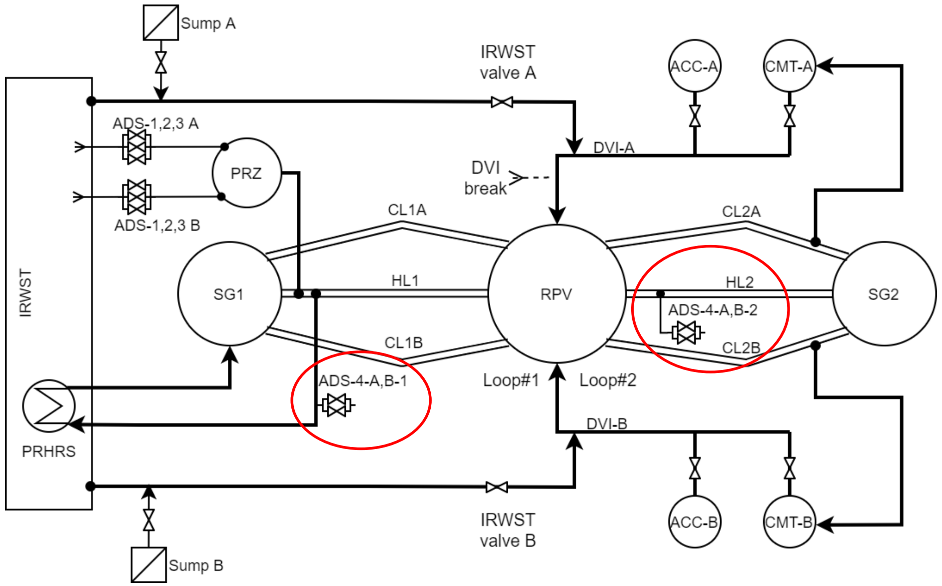


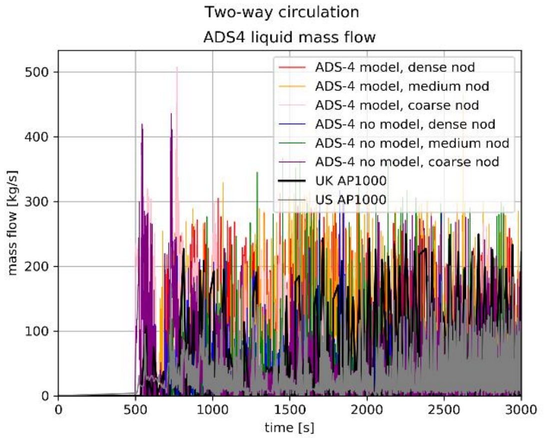
ADS #4 operation

- Final depressurization
- Vapor flow reasonable
- Liquid flow less accurate
- Integral flow relatively well predicted



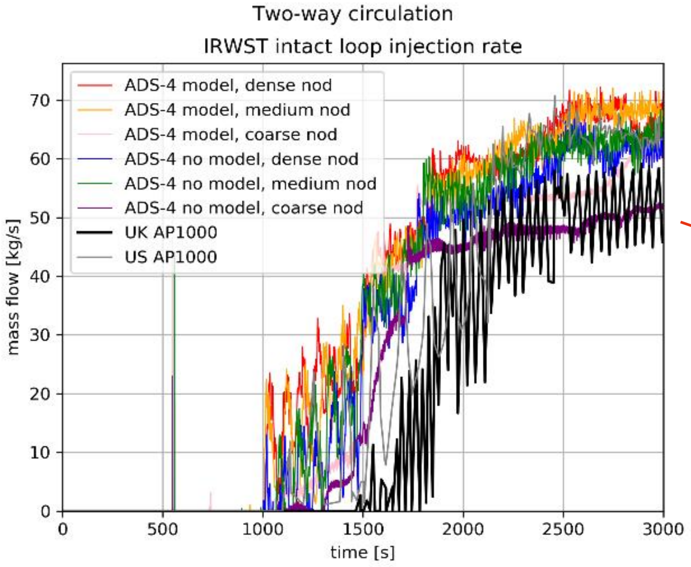


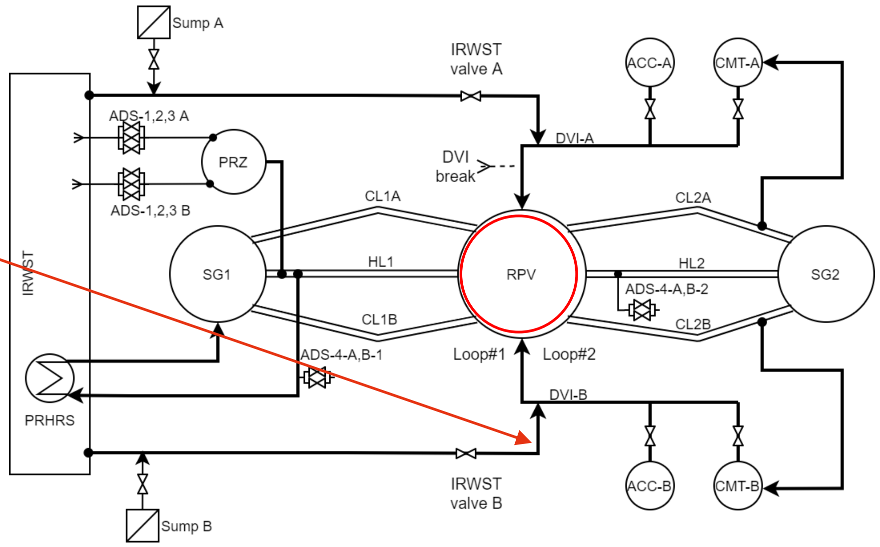


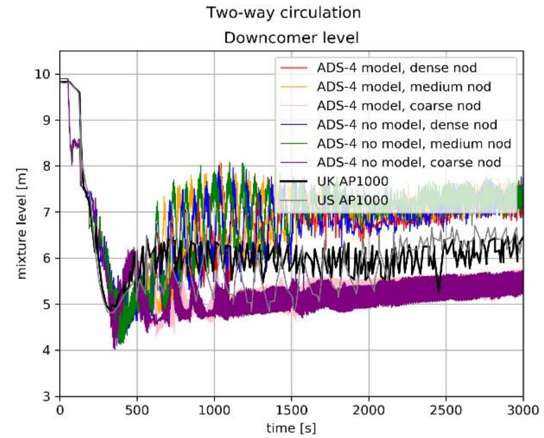


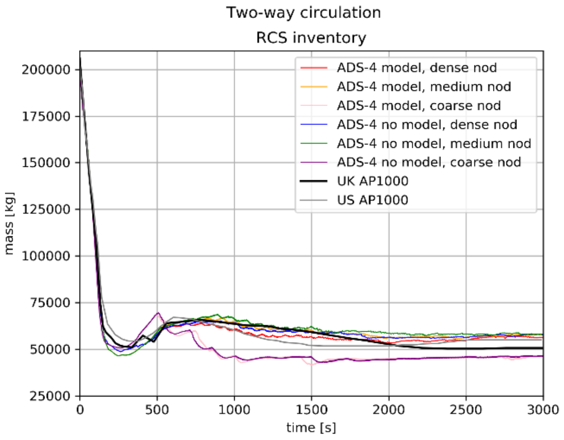
Safety injection

- IRWST low-pressure safety injection – acceptable
- Water level in downcomer reasonable
- Water inventory predicted by more complex models
- No temperature escalation – agreement with DCD/PCSR
- Core is properly covered with water









Conclusions and summary

- AP1000-like MELCOR model developed
- Model verified with normal operation state
- Model verified with design basis accident
- Various modelling options explored
  - ➢ HL, SG – significant effects
  - ➢ ADS-4 – small or no effect
  - ➢ The most detailed model provides the best results
  - ➢ Using simpler models also provide relatively good results
- Model can be used in further severe accident simulations
  - ➢ MELCOR is not typical system thermal-hydraulic code.
  - ➢ MELCOR can be used to alternative DB related research.
  - ➢ MELCOR predicts quite well but not perfectly (at least for our model).
  - ➢ Code (NOTRUMP) used in DCD/PCSR is dedicated for small/medium LOCAs – MELCOR is more general.

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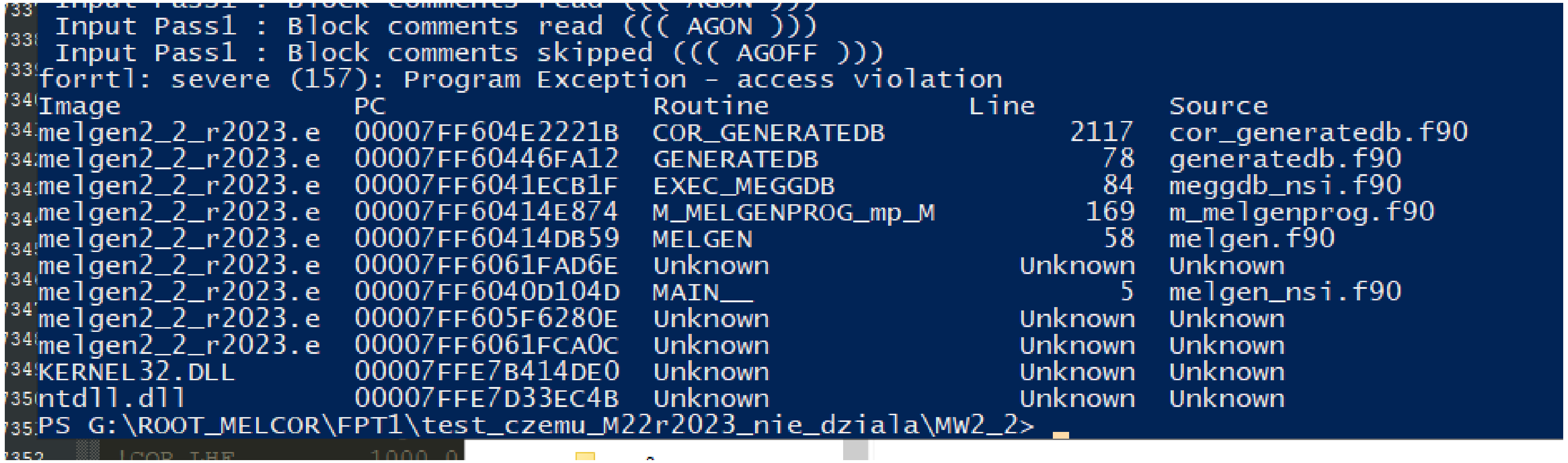
Possible bug – during UQ study for FPT-1

- COR_LP – debris fall velocity
- When given by number
  - COR_LP 1 1320.0 2.0E7 1.0 1 ! WORKS
  - works for M2.2.18, M2.2.21, M2.2r2023
- When given as parameter in DefineVariablesFile Variables.dat
  - COR_LP 1 1320.0 2.0E7 {{{VFALL=1.0}}} 1 ! DOES NOT WORK !!!
  - works for M2.2.18, M2.2.21 but DOES NOT WORK for M2.2r2023



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 Input Pass1 : Block comments read ((( AGON )))
 Input Pass1 : Block comments skipped ((( AGOFF )))
forrtl: severe (157): Program Exception - access violation
Image              PC                Routine            Line        Source
melgen2_2_r2023.e  00007FF604E2221B  COR_GENERATEDB          2117  cor_generatedb.f90
melgen2_2_r2023.e  00007FF60446FA12  GENERATEDB                78  generatedb.f90
melgen2_2_r2023.e  00007FF6041ECB1F  EXEC_MEGGDB               84  meggdb_nsi.f90
melgen2_2_r2023.e  00007FF60414E874  M_MELGENPROG_mp_M        169  m_melgenprog.f90
melgen2_2_r2023.e  00007FF60414DB59  MELGEN                    58  melgen.f90
melgen2_2_r2023.e  00007FF6061FAD6E  Unknown              Unknown  Unknown
melgen2_2_r2023.e  00007FF6040D104D  MAIN__                     5  melgen_nsi.f90
melgen2_2_r2023.e  00007FF605F6280E  Unknown              Unknown  Unknown
melgen2_2_r2023.e  00007FF6061FCA0C  Unknown              Unknown  Unknown
KERNEL32.DLL       00007FFE7B414DE0  Unknown              Unknown  Unknown
ntdll.dll          00007FFE7D33EC4B  Unknown              Unknown  Unknown
PS G:\ROOT_MELCOR\FPT1\test_czemu_M22r2023_nie_dziala\MW2_2>
```

Thank you!

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Addional slides