Severe Accident Modeling Under Extended SBO for Apr1400

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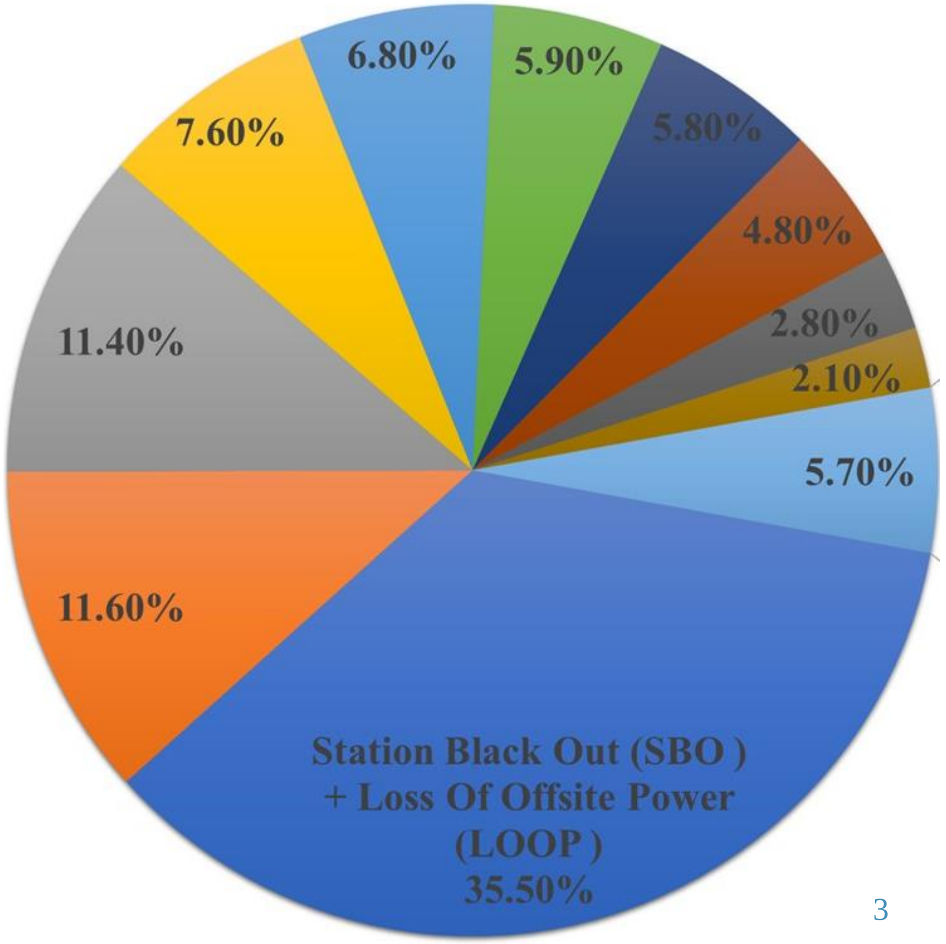
Introduction

- Fukushima accident revealed some vulnerabilities of existing nuclear power plants (NPPs under) an extended Station Black Out (SBO).
- This necessitates strengthening the plants' coping capability by developing appropriate Severe Accident Management (SAM) strategies.
- The In-Vessel Retention (IVR) Strategy stands as one of the key SAM strategies aiming to ensure the retention of the corium and fission products in the Reactor Pressure Vessel (RPV) by preventing the vessel failure.



Research Objective

- This thesis aims to understand the complex phenomena underlying a severe accident which jeopardize the integrity of the reactor pressure vessel.

- This is a basic step towards understanding the challenges of successful implementation the IVR strategy for APR1400 especially in consideration of both epistemic (phenomena-related) and aleatory (scenario-related) uncertainties.

- The goal is to identify the success window that guarantees the integrity of RPV is maintained in the event of a severe accident.

Research Plan

Milestone 1

Base Case

Unmitigated SBO

Milestone 2

Depressurization + Injection

High Level Candidate Actions for In-Vessel SAM Strategy

Milestone 3

Phenomenological Uncertainties

Scenario-Related Uncertainties

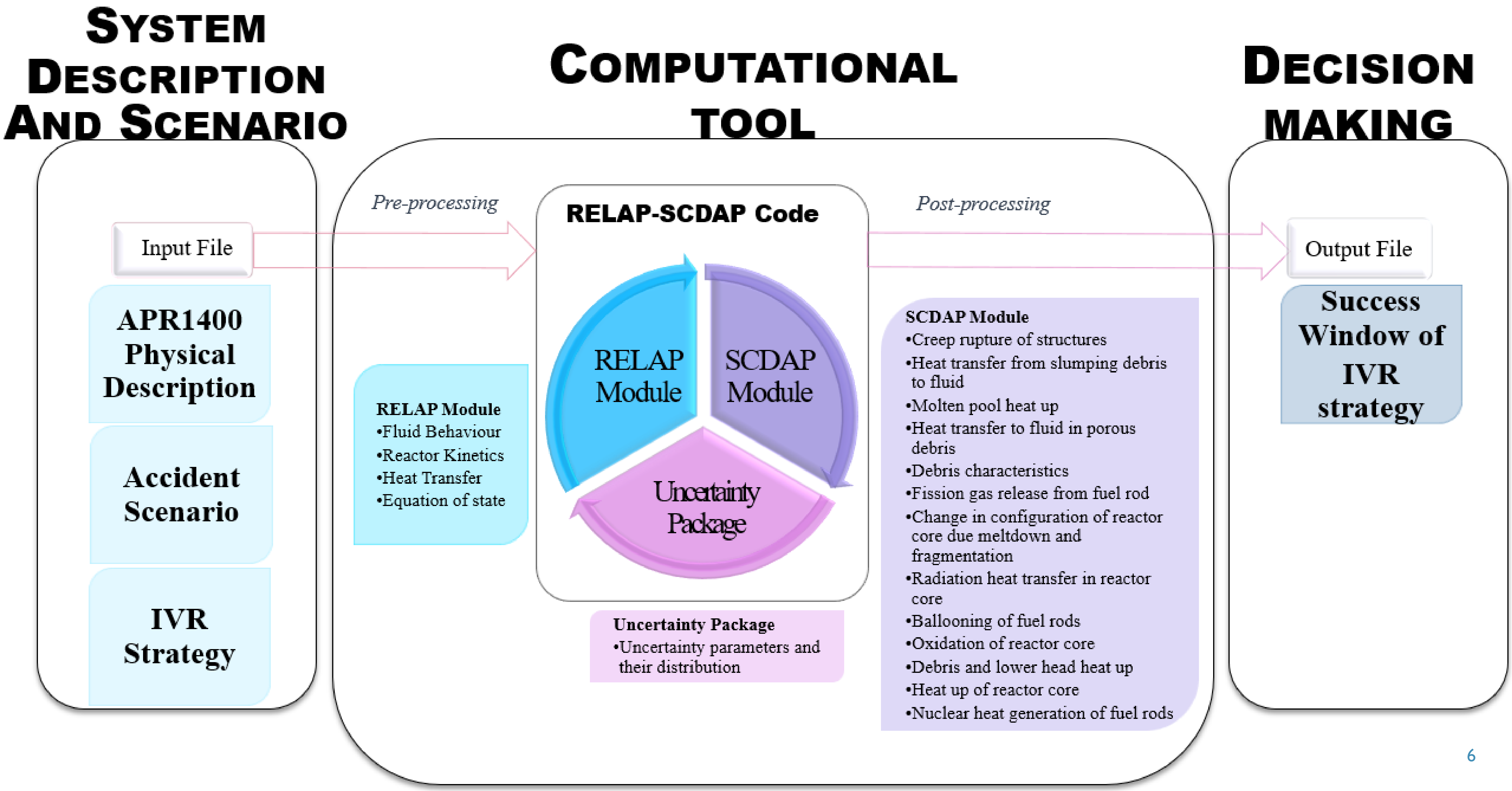
Uncertainty Quantification

Basic phenomena underling the sever accident initiated by unmitigated SBO

Impact of high-level candidate action implementation for in-vessel SAM

Uncertainty quantification in order to assess the IVR strategy and identify the success window

Methodology



SYSTEM DESCRIPTION AND SCENARIO

Input File

APR1400 Physical Description

Accident Scenario

IVR Strategy

COMPUTATIONAL TOOL

Pre-processing

RELAP-SCDAP Code

RELAP Module

SCDAP Module

Uncertainty Package

RELAP Module
- Fluid Behaviour
- Reactor Kinetics
- Heat Transfer
- Equation of state

Uncertainty Package
- Uncertainty parameters and their distribution

Post-processing

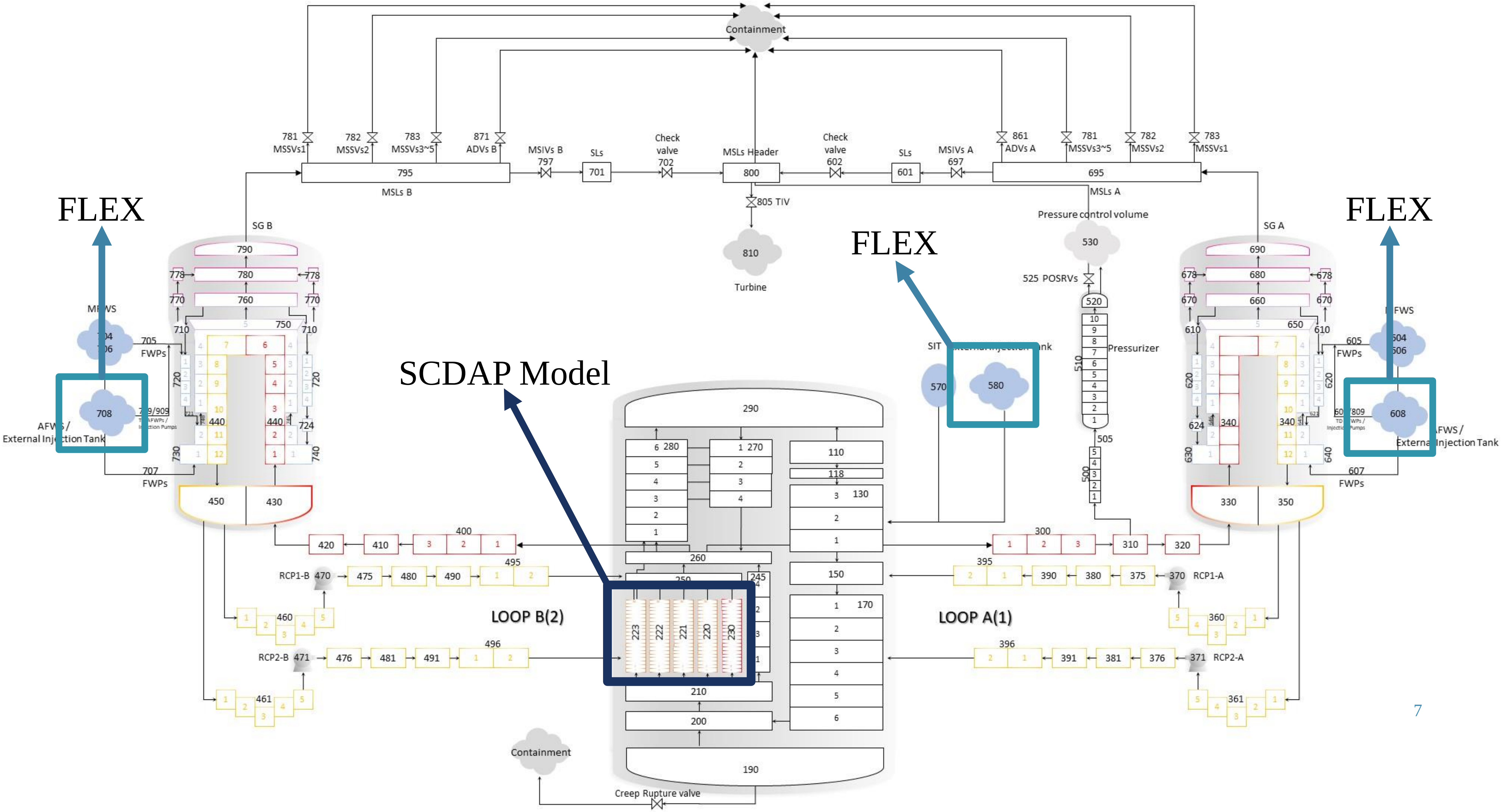
SCDAP Module
- Creep rupture of structures
- Heat transfer from slumping debris to fluid
- Molten pool heat up
- Heat transfer to fluid in porous debris
- Debris characteristics
- Fission gas release from fuel rod
- Change in configuration of reactor core due meltdown and fragmentation
- Radiation heat transfer in reactor core
- Ballooning of fuel rods
- Oxidation of reactor core
- Debris and lower head heat up
- Heat up of reactor core
- Nuclear heat generation of fuel rods

DECISION MAKING

Output File

Success Window of IVR strategy

RELAP System Nodalization



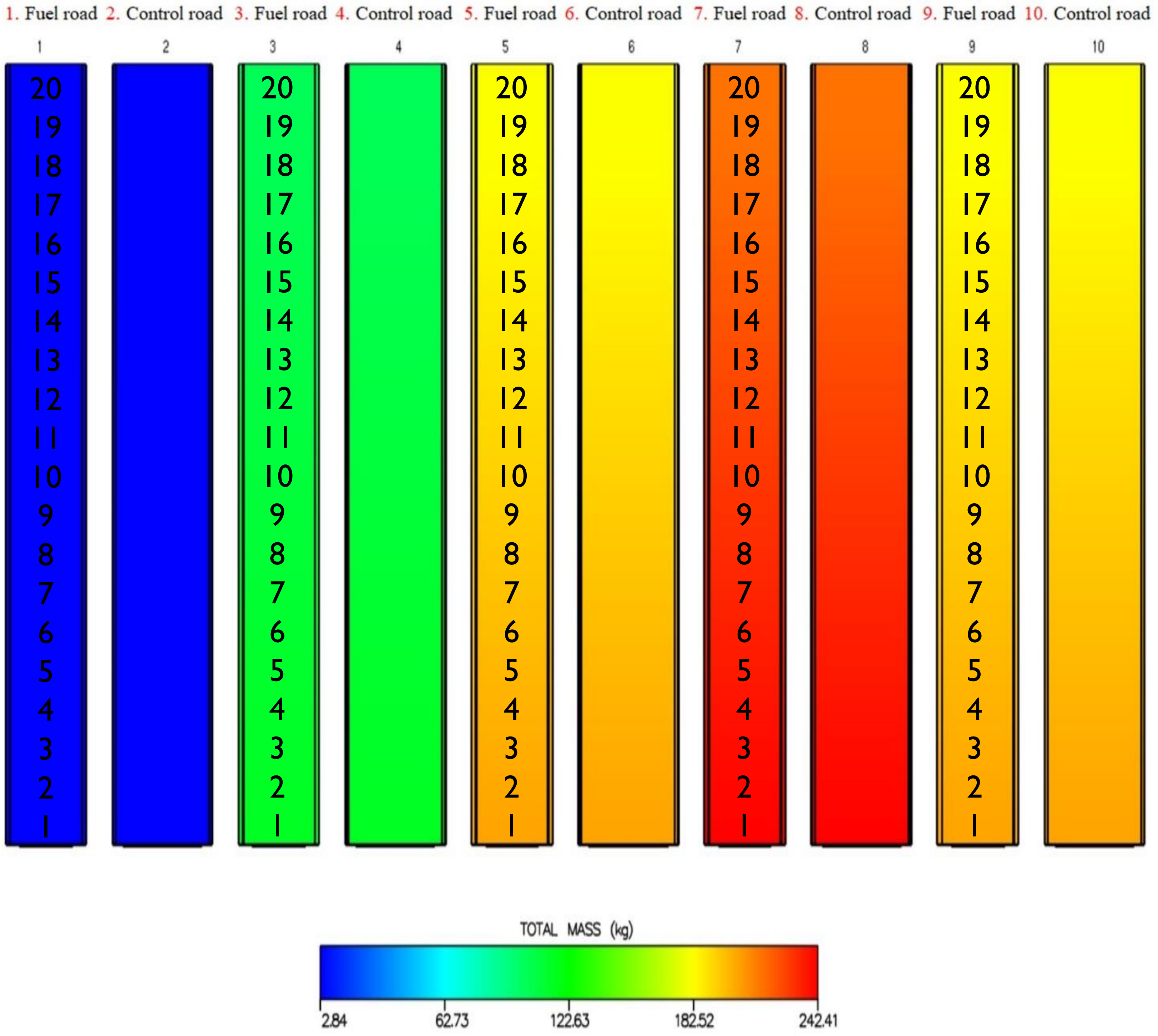
FLEX

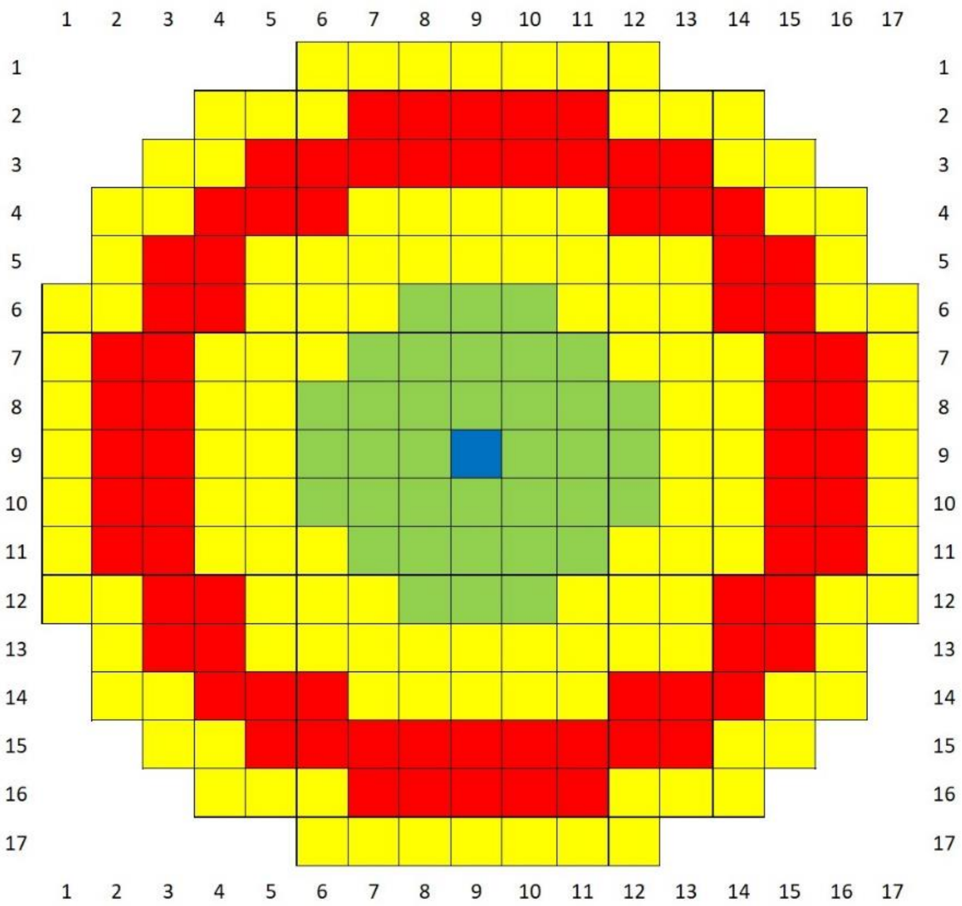
FLEX

FLEX

SCDAP Model

SCDAP Core Model





Chan ID	1	# FAs	1
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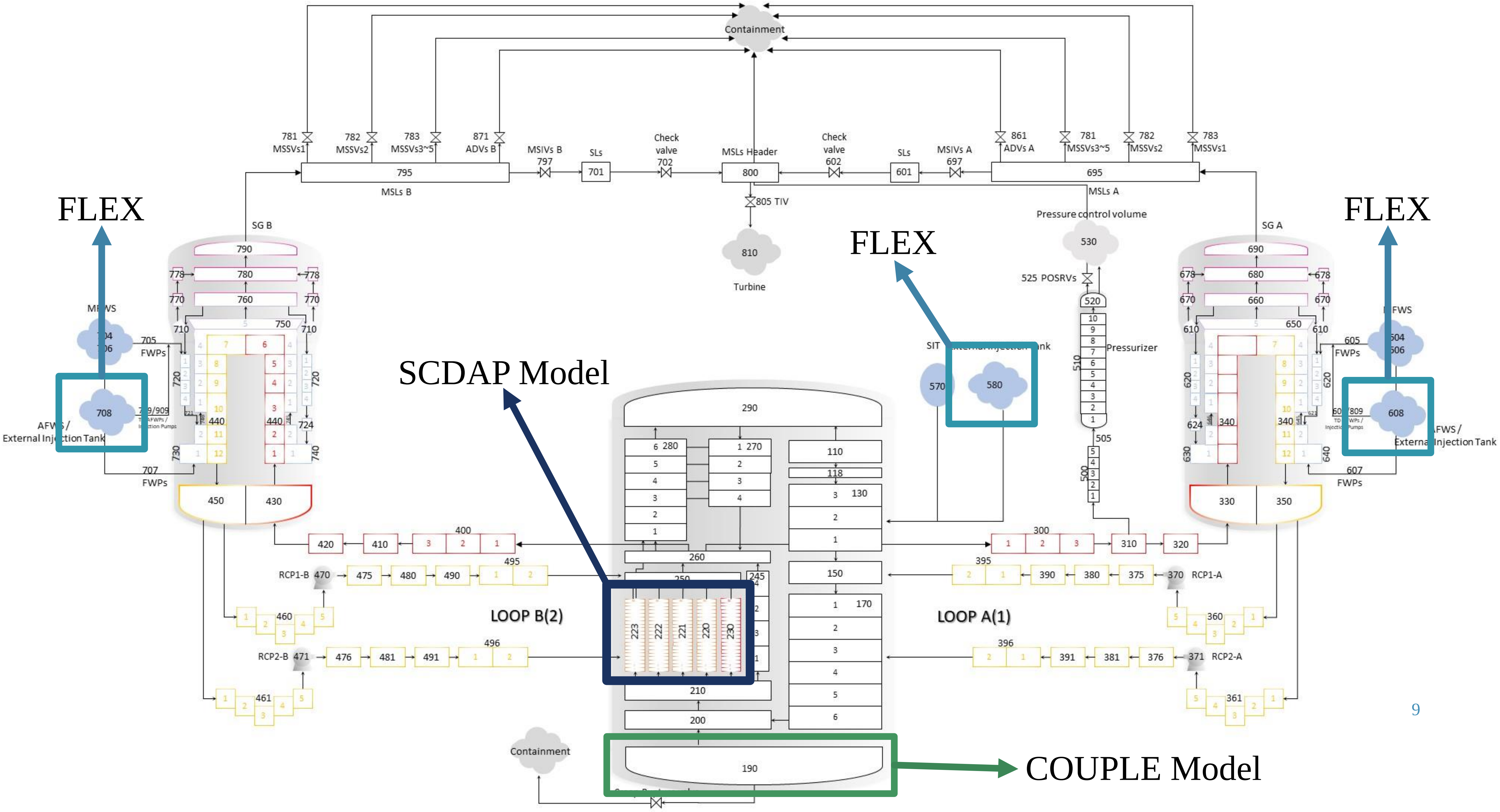
Chan ID	3	# FAs	64
Chan ID	4	# FAs	76
Chan ID	5	# FAs	64

RELAP System Nodalization



FLEX

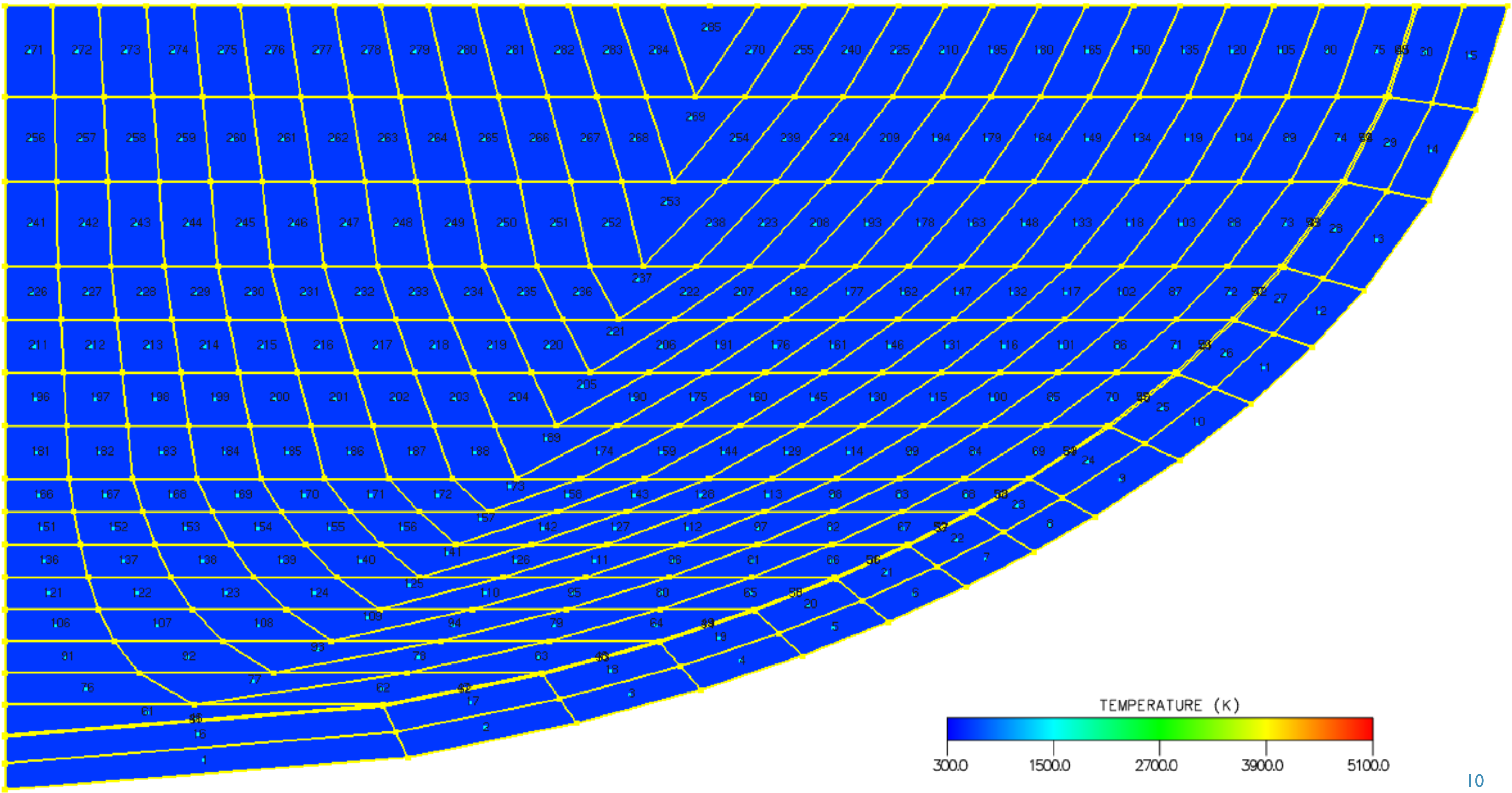
FLEX

FLEX

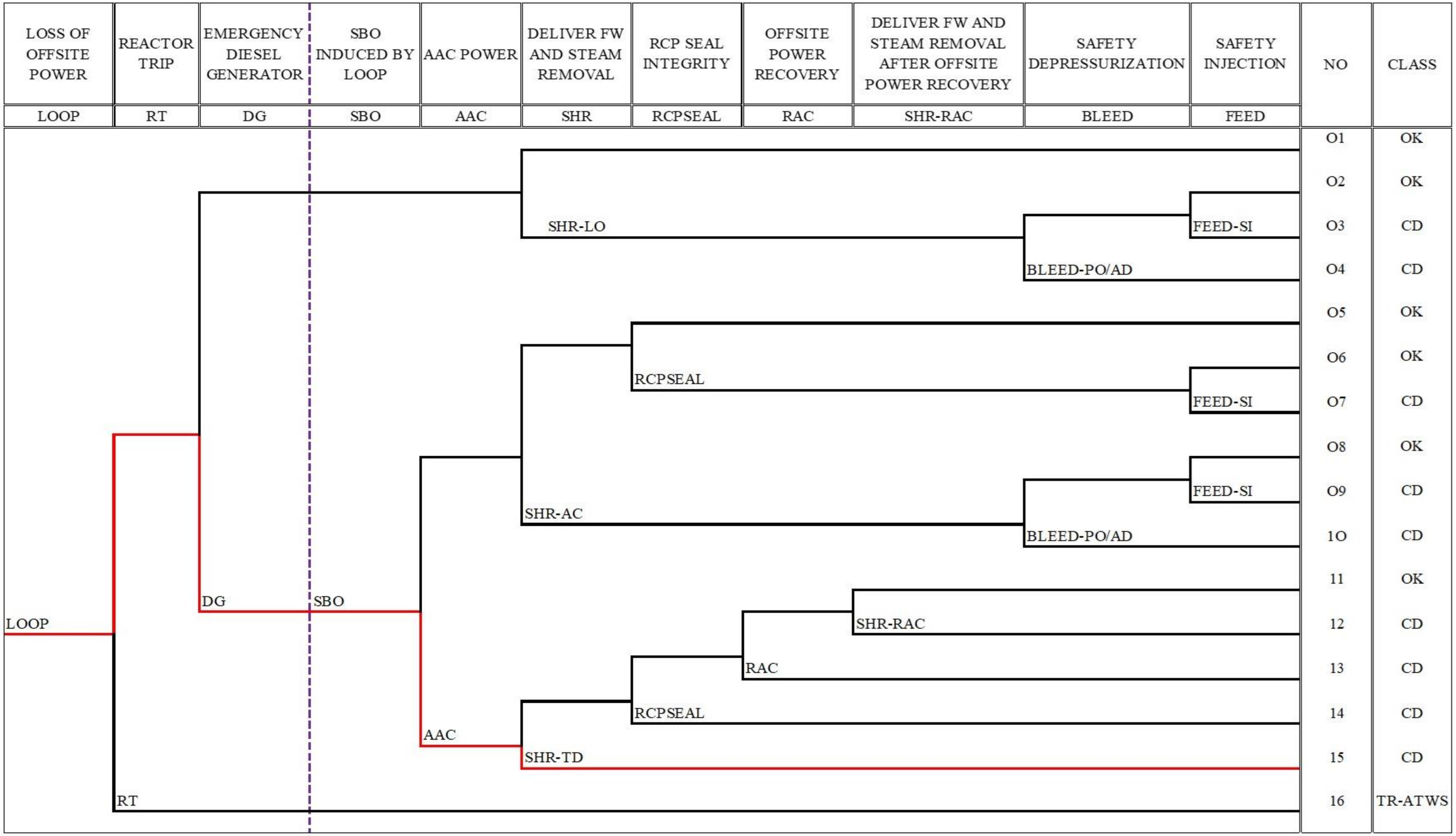
SCDAP Model

COUPLE Model

COUPLE Model



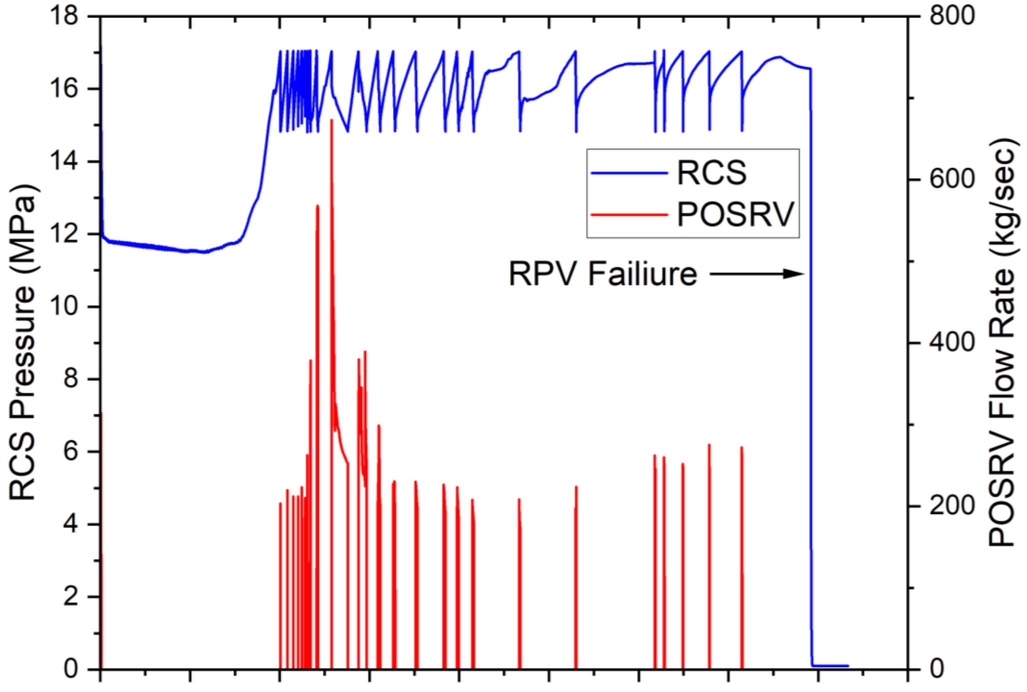
SBO Scenario



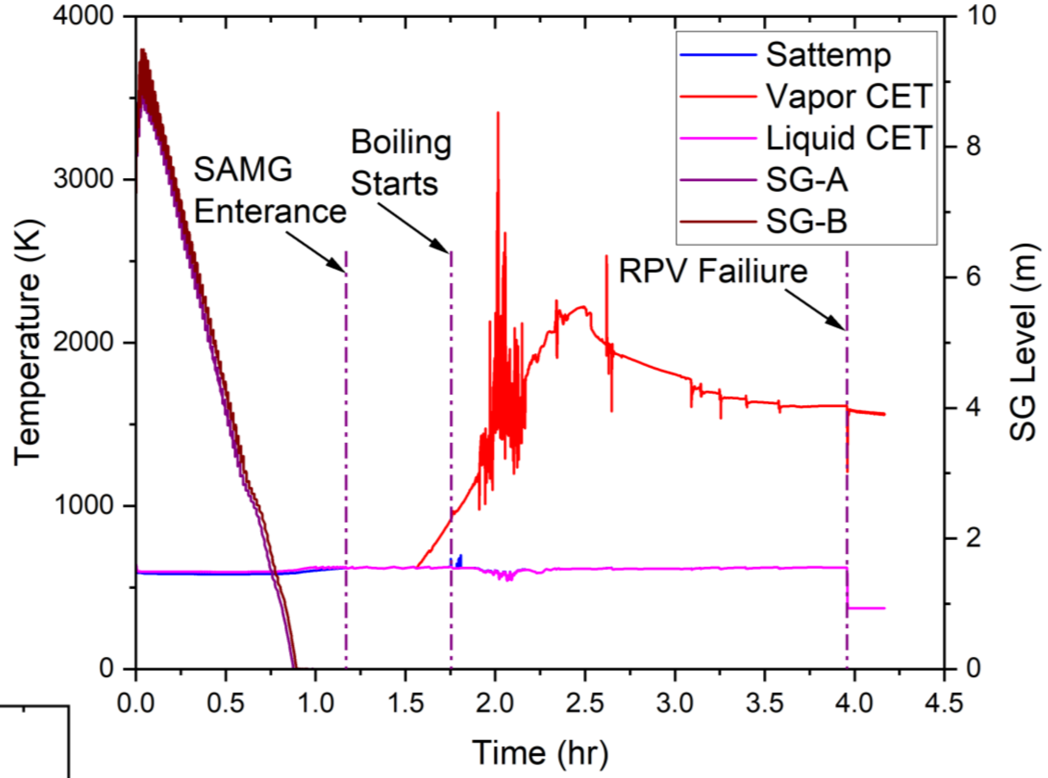
Model Assumptions

- All AC power and all equipment powered by AC power shall not be available.
- All AAC and emergency diesel generators shall not be available.
- The FLEX portable equipment should be aligned at 2 hours.
- The plant should provide feed and bleed to cope with severe accident conditions.
- Primary injection and secondary injection should be provided to cope with severe accident conditions.
- The operator action is expected within 30 minutes from SAM entrance.

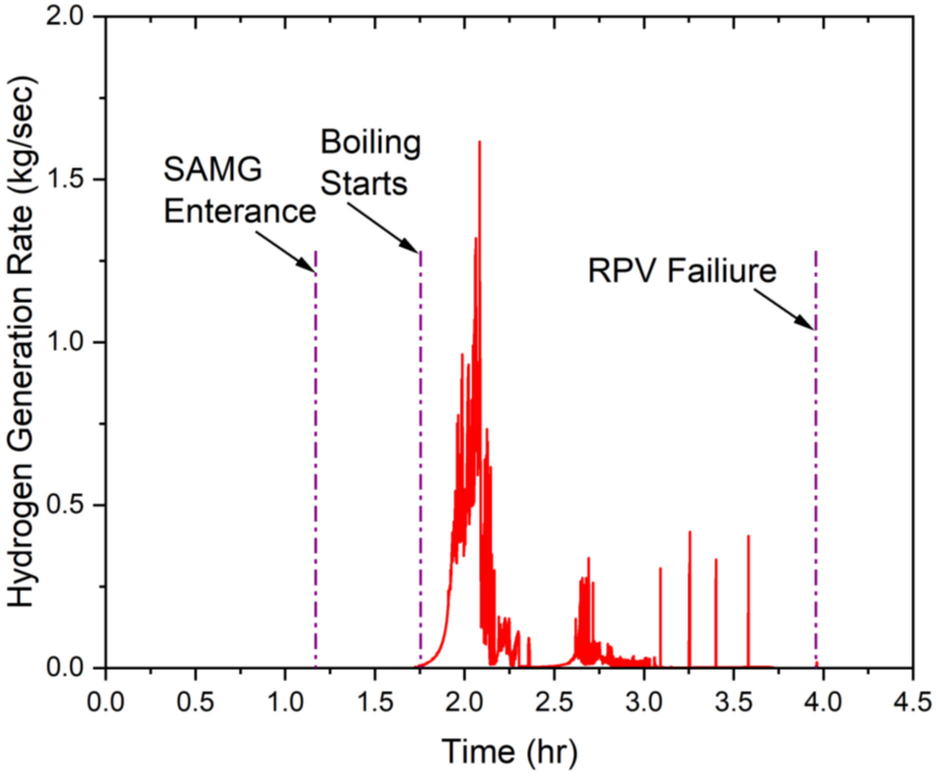
Base Case Results



POSRVs cycling vs. RCS pressure



SGs level and CET



Hydrogen production rate

CET

Base Case Results – Core Map

Fuel road component

SCDAP component	1	3	5	7	9
Axial node #					
20	I	I	I	I	I
19	I	I	I	I	I
18	I	I	I	I	I
17	I	I	I	I	I
16	I	I	I	I	I
15	I	I	I	I	I
14	I	I	I	I	I
13	I	I	I	I	I
12	I	I	I	I	I
11	I	I	I	I	I
10	I	I	I	I	I
9	I	I	I	I	I
8	I	I	I	I	I
7	I	I	I	I	I
6	I	I	I	I	I
5	I	I	I	I	I
4	I	I	I	I	I
3	I	I	I	I	I
2	I	I	I	I	I
1	I	I	I	I	I
RELAP volume	230000000	220000000	221000000	222000000	223000000

Intact core configuration

Fuel road component

SCDAP component	1	3	5	7	9
Axial node #					
20	L	I	I	I	I
19	I	I	I	I	I
18	I	I	I	I	I
17	I	I	I	I	I
16	I	I	I	I	I
15	I	I	I	I	I
14	I	I	I	I	I
13	I	I	I	I	I
12	I	I	I	I	I
11	I	I	I	I	I
10	I	I	I	I	I
9	I	I	I	I	I
8	I	I	I	I	I
7	I	I	I	I	I
6	I	I	I	I	I
5	I	I	I	I	I
4	I	I	I	I	I
3	I	I	I	I	I
2	I	I	I	I	I
1	I	I	I	I	I
RELAP volume	230000000	220000000	221000000	222000000	223000000

First degradation of the core configuration

Fuel road component

SCDAP component	1	3	5	7	9
Axial node #					
20	L	I	I	I	I
19	L	L	I	I	I
18	L	I	I	I	I
17	L	L	I	I	I
16	L	I	I	L	I
15	L	L	V	P	L
14	L	L	xxMxx	L	I
13	L	L	P	I	L
12	L	L	L	I	L
11	L	I	I	I	I
10	I	I	I	I	I
9	I	L	I	L	I
8	I	I	I	I	I
7	I	I	I	I	I
6	I	I	I	I	I
5	I	I	I	I	I
4	I	I	I	I	I
3	I	I	I	I	I
2	I	I	I	I	I
1	I	I	I	I	I
RELAP volume	230000000	220000000	221000000	222000000	223000000

First in-core molten pool relocation and metalic blockage configuration

Fuel road component

SCDAP component	1	3	5	7	9
Axial node #					
20	V	P	L	P	L
19	V	V	P	P	P
18	V	V	L	P	L
17	V	V	P	P	P
16	V	V	P	V	P
15	V	V	V	V	P
14	V	V	V	V	P
13	V	V	V	V	V
12	V	V	V	V	V
11	V	V	V	V	V
10	V	V	V	V	V
9	V	V	V	V	V
8	V	V	V	V	V
7	xxMxx	xxMxx	xxMxx	xxMxx	xxMxx
6	xxMxx	xxMxx	xxMxx	xxMxx	xxMxx
5	xxMxx	xxMxx	xxMxx	xxMxx	xxMxx
4	xxMxx	xxMxx	xxMxx	xxMxx	xxMxx
3	xxMxx	xxMxx	xxMxx	xxMxx	xxMxx
2	xxMxx	xxMxx	xxMxx	xxMxx	xxMxx
1	P	P	P	P	P
RELAP volume	230000000	220000000	221000000	222000000	223000000

In-core molten pool configuration right before the slumping

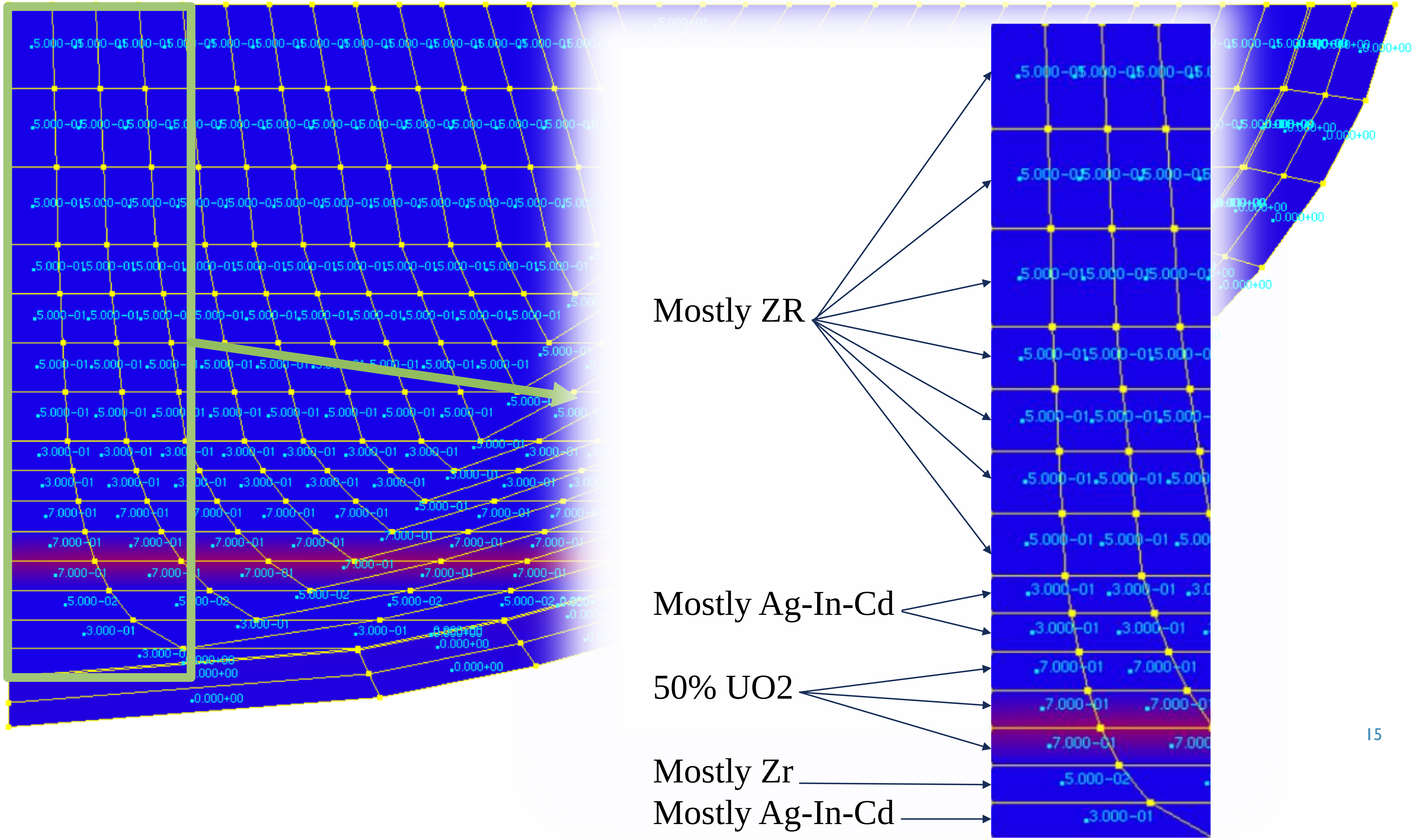
Fuel road component

SCDAP component	1	3	5	7	9
Axial node #					
20	V	P	P	P	L
19	V	V	V	P	P
18	V	V	V	P	L
17	V	V	V	P	P
16	V	V	V	V	P
15	V	V	V	V	P
14	V	V	V	V	V
13	V	V	V	V	V
12	V	V	V	V	V
11	V	V	V	V	V
10	V	V	V	V	V
9	V	V	V	V	V
8	V	V	V	V	V
7	V	V	V	V	V
6	V	V	V	V	V
5	V	V	V	V	V
4	V	V	V	V	V
3	V	V	V	V	V
2	V	V	V	V	V
1	P	P	P	P	P
RELAP volume	230000000	220000000	221000000	222000000	223000000

Core configuration right after the molten pool relocation to lower head

I	Intact fuel road
P	Porous debris
L	Liquified prous debris
xxMxx	Molten blockage
V	Empty node

Base Case Results – Molten Pool Configuration



Mostly ZR

Mostly Ag-In-Cd

50% UO2

Mostly Zr

Mostly Ag-In-Cd

Base Case Results - Summary

Accident progression

Time (hh:mm)	Sequence
00:00	Reactor TRIP Turbine TRIP RCPs TRIP FWPs TRIP MSIVs TRIP TIV TRIP
00:01	MSSVs START CYCLING
00:50	MSSVs STOP CYCLING SGs DRYOUT
01:03	POSRVs START CYCLING
01:05	Boiling START
01:11	Core UNCOVERY
01:46	Severe accident ENTRANCE
02:03	Core DAMAGE
02:18	Core DRYOUT
02:23	First Molten Pool FORMATION
03:05	Molten Pool Final Configuration
03:06	Molten Pool SLUMPED
03:49	Molten Pool Crust FAILURE
03:58	RPV FAILURE

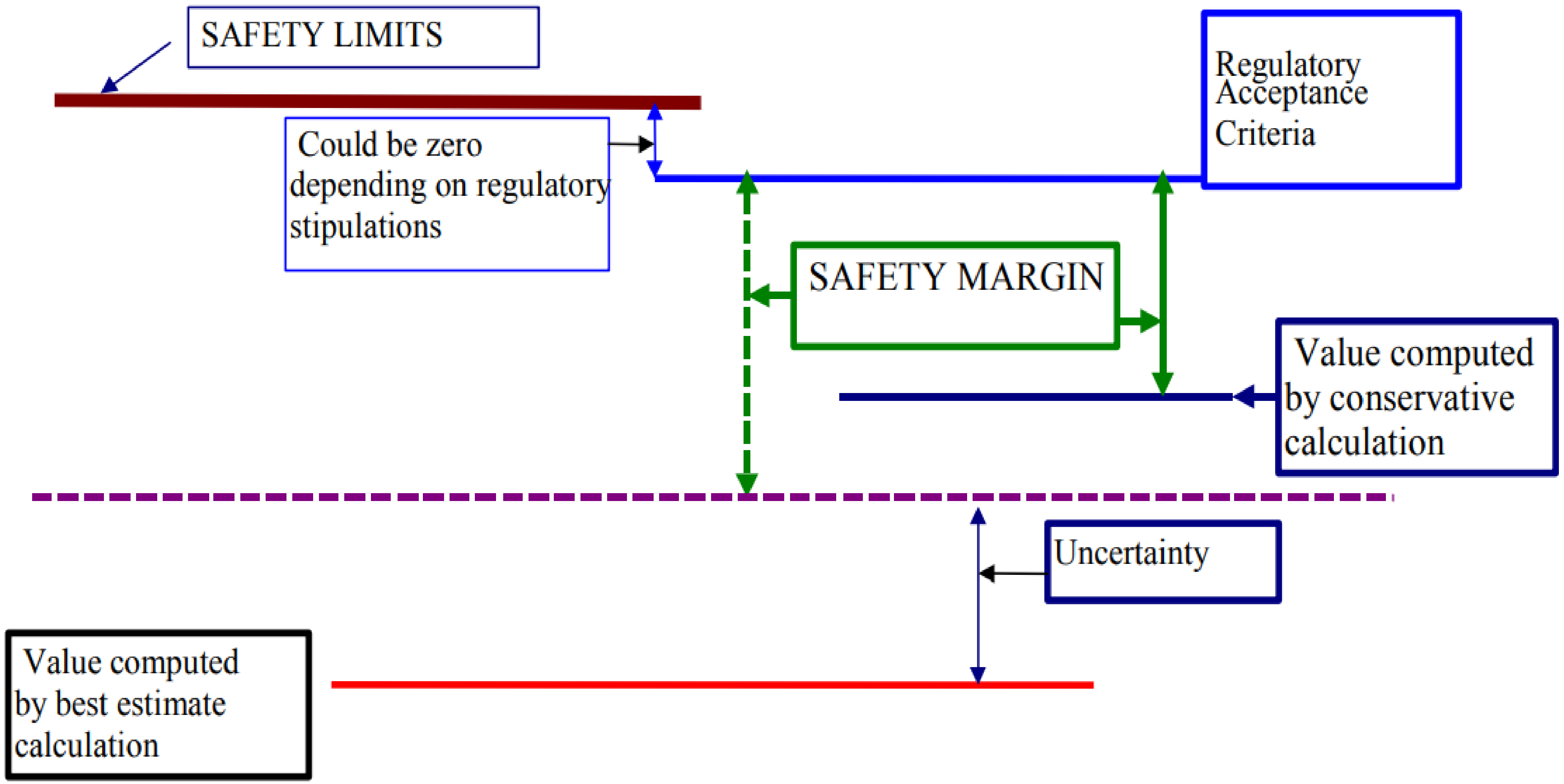
In-core molten pool parameters

Parameter	Value
Effective radius of pool, m	1.9399
Volume of molten pool, m^3	15.289
Temperature of molten pool, K	3156.56
Total heat generated in pool, MW	68.282
Total mass of UO2 in pool, kg	106670
Total mass of oxidic Zr, kg	11330.6
Total mass of metallic Zr, kg	3084.6
Mass of liquefied material in partially liquefied porous debris, kg	775.22
Liquidus temp of material, K	2873

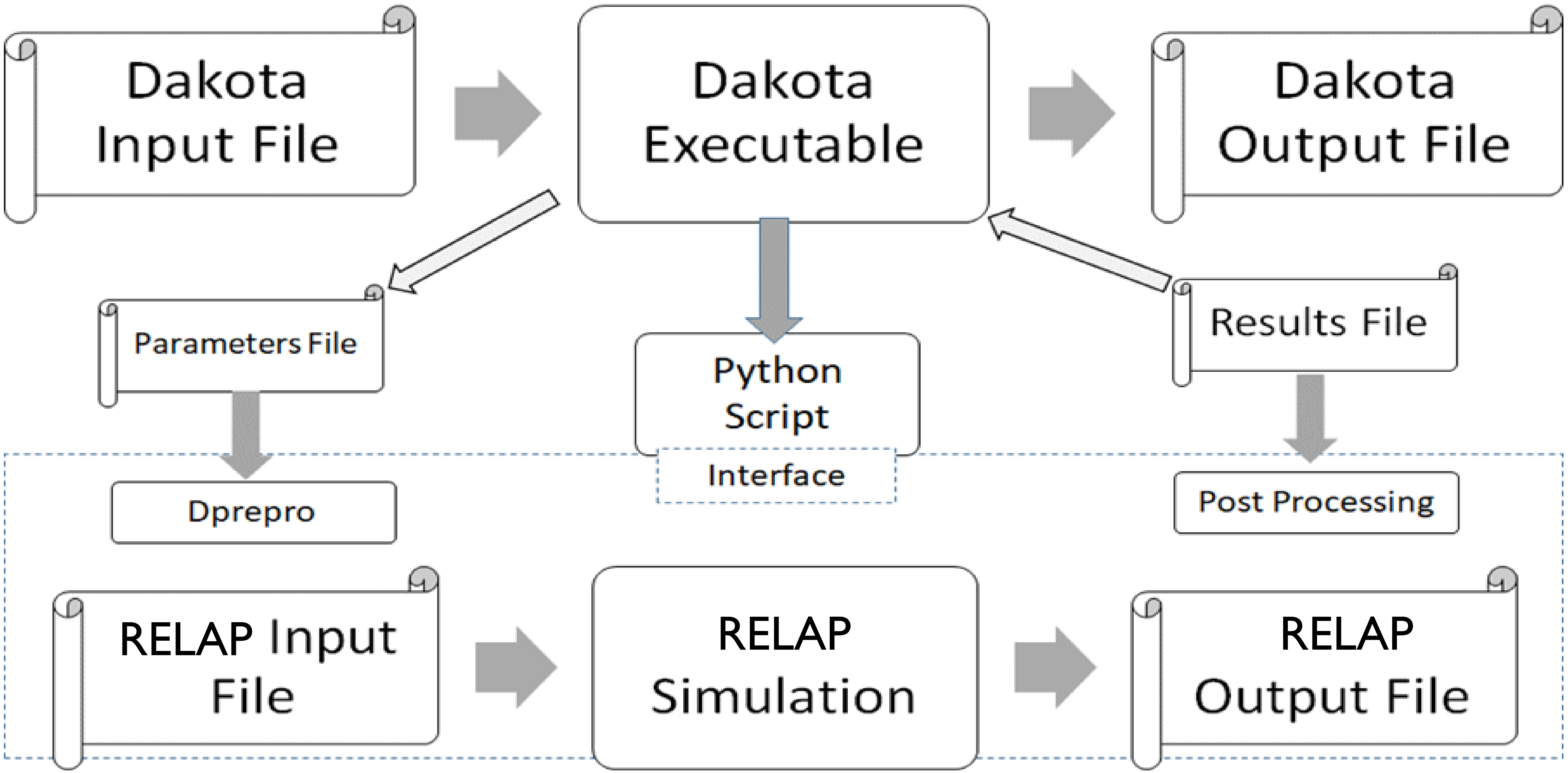
Molten pool configuration in lower head

Constituent	Slumped mass, kg	Atomic fraction	Mass in liquefied debris, kg
Zircaloy	1245.57	0.130693	24.564
Silver	3865.93	0.338654	158.80
Uranium dioxide	12168.6	0.430335	672.59
Zirconium dioxide	1292.28	0.100318	71.537

Safety Margin Evaluation



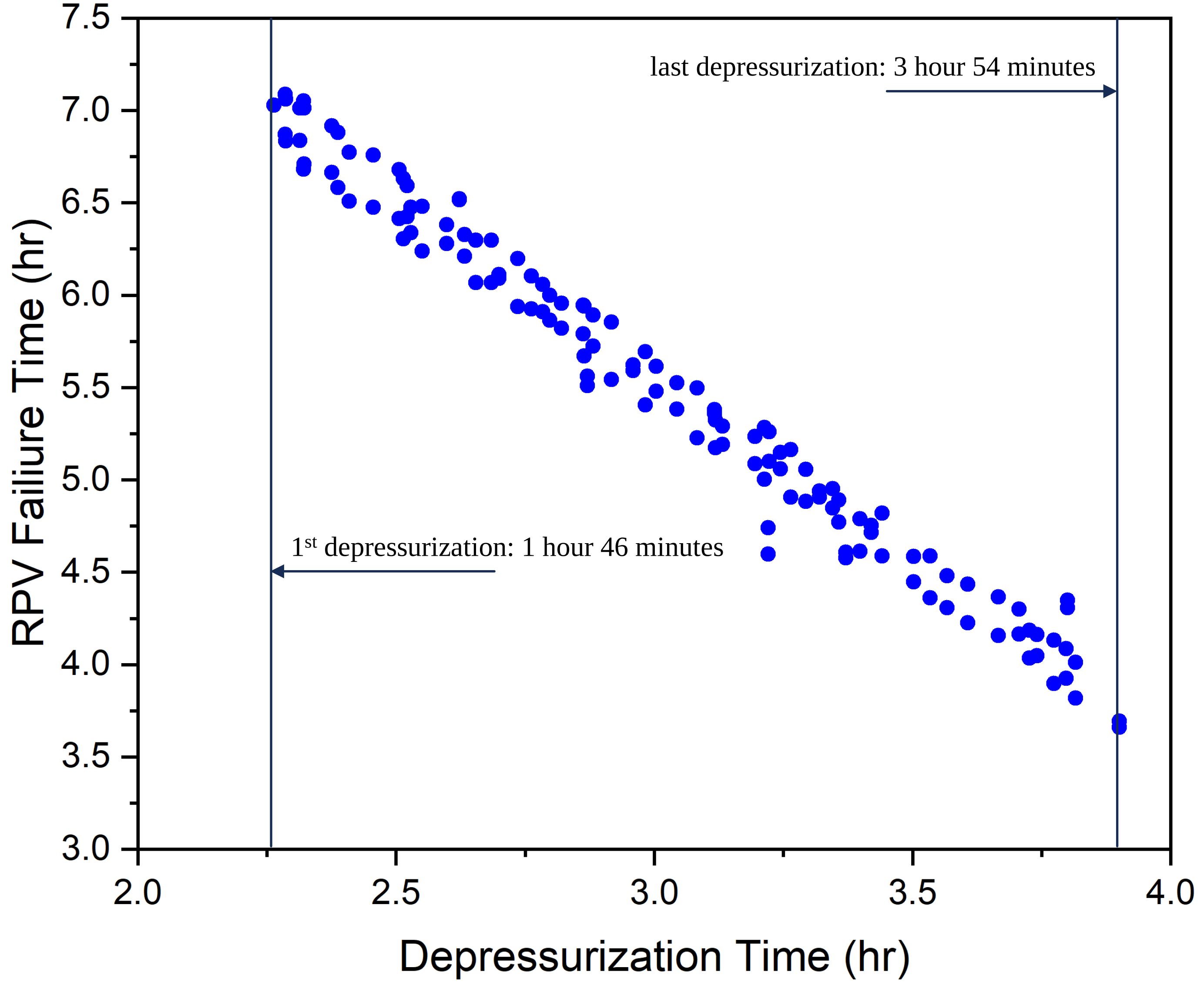
Uncertainty Quantification Framework



Depressurization Timing

- 131 cases have been simulated to identify the impact of the depressurization timing on the accident progression and the vessel failure.

- The depressurization timing varied between 30 minutes from the SAM entrance, considering operator's action margins, and almost 4 hours correspondent to the time of vessel failure for the base case.



Depressurization Time vs. RPV Failure Time

Uncertainty Quantification

- To ensure the success of the intended IVR strategy, it is essential to quantify the underlying uncertainties given that the plant behavior is not equally influenced by all processes and phenomena that occur during the accident progression.

- The number of uncertainties considered for this particular problem had been limited by identifying and ranking the phenomena with respect to their influence on figures of merit. In other words, the top-down approach is adopted using PIRT.

Uncertainty Parameters

Phenomena related uncertainty parameters

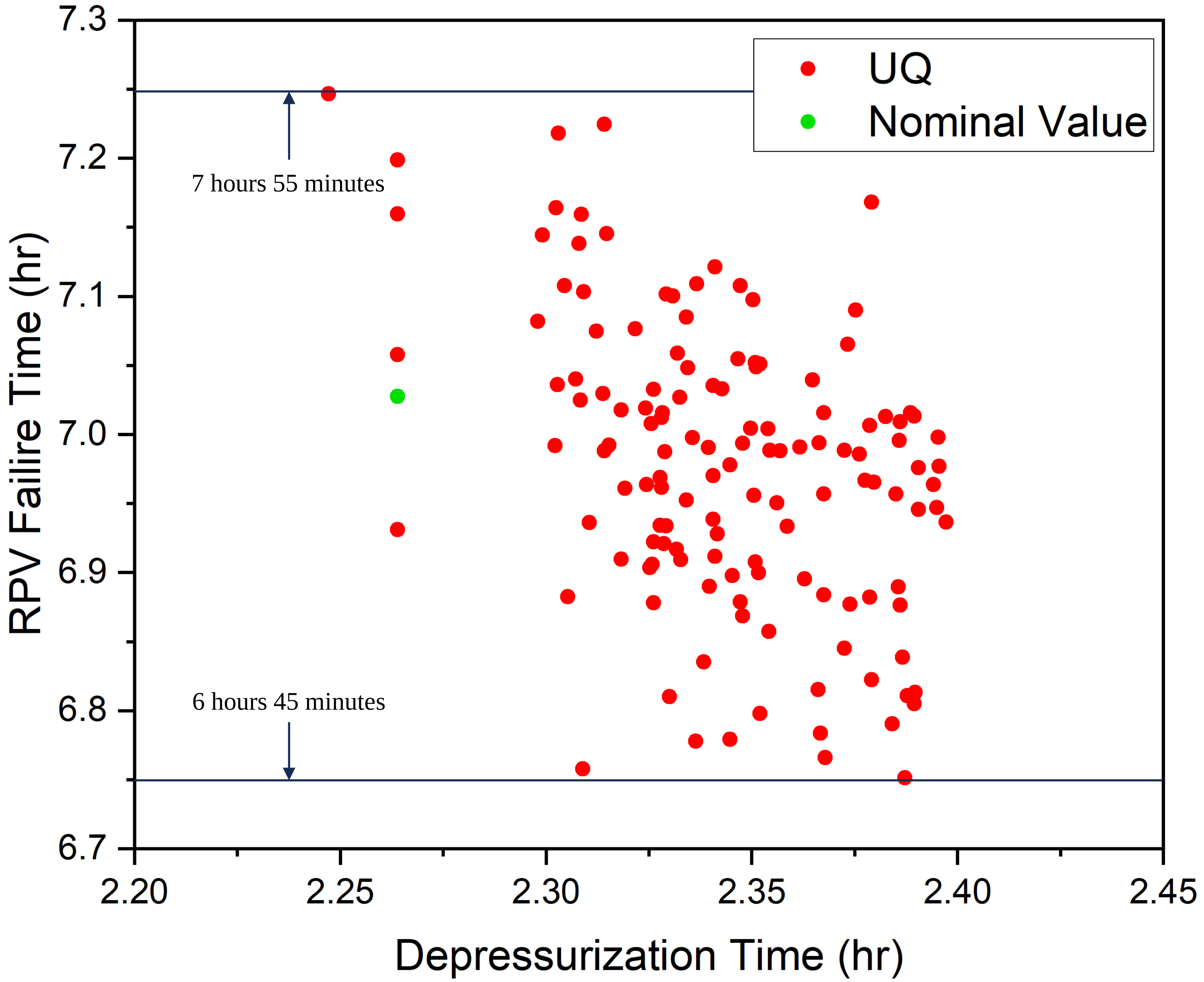
No.	Parameter	Lower Boundary	Mean	Upper boundary	PDF
1	Failure temperature of oxide shell (K)	2300	2475	2650	Uniform
2	Fraction of oxidation of fuel rod cladding for stable oxide shell	0.2	0.4	0.6	Uniform
3	Hoop strain threshold for double sided oxidation	0.02	0.045	0.07	Uniform
4	Fraction of surface area covered with drops that results in blockage that stops local oxidation	0.2	0.3	0.4	Uniform
5	Velocity of drops of cladding material slumping down outside surface of fuel rod (m/s).	0.5	0.75	1	Uniform
6	Hoop Strain at which Rupture of Fuel Cladding Occurs	0.15	0.165	0.18	Uniform
7	Transition Strain	0.182	0.192	0.202	Uniform

Aleatory uncertainty parameters

No.	Parameter	Lower Boundary	Mean	Upper boundary	PDF
8	Primary depressurization time (s)	8650	11350	15850	Uniform
9	Discharge coefficients for POSRVs	0.95	0.975	1	Uniform
10	SITs accumulator temperature (K)	335.7	373	410.3	Uniform
11	SITs accumulator loss coefficient	15.93	17.7	19.47	Uniform
12	SITs accumulator junction area (m)	0.18702	0.2078	0.22858	Uniform
13	FLEX accumulator temperature (K)	311	342.1	373.2	Uniform
14	FLEX accumulator loss coefficient	15.93	17.7	19.47	Uniform
15	FLEX accumulator junction area (m)	0.0072	0.008	0.0088	Uniform

Uncertainty Quantification Results

- A number of 800 cases were simulated to quantify the uncertainties.
- Only for 17% of the cases the vessel failure occurred.
- The margin of vessel failure time ranges from 6 hours 45 and 7 hours 15 minutes, approximatively ± 15 minutes from the vessel failure time of the nominal case (7 hours 2 minutes).



UQ for Depressurization Time performed at 30 minutes from SAM entrance vs. RPV Failure Time

Depressurization Timing and UQ for Depressurization performed at 30 minutes from SAM entrance vs. RPV Failure Time

Uncertainty Quantification Results

- For 35.875% of cases, no vessel failure was observed. The high-level candidate actions provided enough cooling the molten pool material which re-solidified and did not impose enough stress on the RPV to produce a vessel failure.

- For the last 47.127% of the cases, no vessel failure was observed. For 63.925% of these cases, the relocation was prevented, all the material re-solidified in the core region and no slumping to the lower head occurred. And for the remaining 36.075% of the cases, only a very small amount of core material slumped to the lower head.

Conclusion

- Proper implementation of the SAMG high-level candidate actions related to the in-vessel phase can maintain the vessel structural integrity and therefore the risk associated with the vessel failure can be minimized.

Conclusion - 1

- To increase the efficiency of the IVR strategy it is recommended for the operator to depressurize within 30 minutes from the SAM entrance. The early opening of the POSRVs help decelerate the progression of the severe accident by reducing the rate of in-core molten pool formation and consequently delaying the relocation of the molten corium.

Conclusion - 2

- The external injection flow rate should be much more than the discharged flow rate of the POSRVs to have any positive impact on the accident progression. For the investigated cases, whenever the difference between the two flow rates was not considerable, the vessel failure was observed more often. Another point that needs to be highlighted is that a large depressurization rate accelerates the core degradation especially for cases when the injection was not capable to replenish the released inventory.

Conclusion - 3

- For the investigated cases, when the depressurization was applied as early as half an hour from SAMG entrance, the vessel failure can be delayed to 7 hours 2 minutes with a margin of ±15 minutes given the key phenomenological uncertainties investigated. With implementation of enough external water injection, it is perceived that the vessel failure can be further delayed. However, this was not investigated in this thesis.

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