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RELAP5-3D SIMULATION OF THE EFFFECT FROM COMPLEX IN-VESSEL FLOW PATTERNS ON THE PERFORMANCE OF REACTOR COOLANT TEMPERATURE SENSORS LOCATED AT THE CORE OUTLET AND AT IN-CORE ELEVATIONS

BEL V

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CONTENTS

OBJECTIVES

1) Test the RELAP5-3D code's ability to simulate successfully free convection of coolant flows in a detailed 3D nodalization, both of the core and of the reactor vessel upper plenum;

2) Simulate the performance of coolant temperature sensors placed either above the core outlet (**CETC**), or at in-core elevations, inserted into the instrumentation thimbles (**IITA**)

3) Compare different Accident Management (**AM**) strategies and grade them, ie quantify the cost for their successful implementation, by using as a criterion the ***degree of core damage***, defined by parameters as:

- **PCT :** Peak Cladding Temperature
- **LMO :** thickness of the maximum Local clad Metal Oxidation layer
- **CWO :** mass of hydrogen produced in a Core Wide Oxidation, and
- ***Blockage of Flow :*** relative area of coolant flow through the bundles of fuel pins in the core

1) INTRODUCTION

1.1) The Concept of Accident Management in NPP

1.1.a) Accident Management (AM): Implement pre-defined strategies and measures in two domains:

- **AM PREVENTON domain**:

i. Loss of safety functions, eg. Loss of control over reactor power, or fuel cooling, and radioactivity confinement

ii. Primary objective: Restore critical safety functions (eg subcriticality, core cooling, heat sink, primary inventory) without exceeding NPP and site licensing limits

- **AM MITIGATION domain**:

i. Respond to the consequences from loss of fuel integrity,

ii. Primary objective: Prevent loss of last Defence-in-Depth barrier, ie containment integrity.

iii. Terminate further fuel degradation

1.1.b) AM Procedures and Guidelines

EOPs *(Emergency Operating Procedures)* - used ***prior to fuel damage***

EOPs = Event-Based «E» procedures (eg scram, SI) + Symptom-Oriented «F» procedures *(eg challenge to CSF)*

AM strategies in the ***AM PREVENTION*** domain include measures to ***prevent loss of fuel integrity***, ie the Defence-in-Depth first barrier, in excess of the respective fuel Safety Limits (usually given as fraction of fuel pins with failed cladding integrity)

SAMGs *(Severe Accident Management Guidelines) -* used ***when fuel damage has occurred***, the plant damage state poses significant challenges to containment integrity, and “early” and/or “large” radiation release is highly likely if containment integrity is lost.

AM strategies in the ***AM MITIGATION*** domain to implement measures to terminate further fuel damage, mitigate consequences from fuel damage, prevent loss of the last Defence-in-Depth barrier, ie the leak-tight Containment

1) INTRODUCTION

1.1.c) Inadequate Core Cooling condition:

- **Onset of fuel clad runaway overheating**, ie imminent fuel clad failure, clad balooning and burting resulting in flow blockage in-core, hydrogen generation

- **Suitable symptom to enter EOPs, eg the symptom-oriented FR-C.1 response to ICC condition**

- **Characterize ICC condition**: by using Fuel Cladding temperature, Local Maximum Clad Oxidation, Core Wide oxidation, fraction of core with coolant flow blocked by balooned/burst fuel cladding

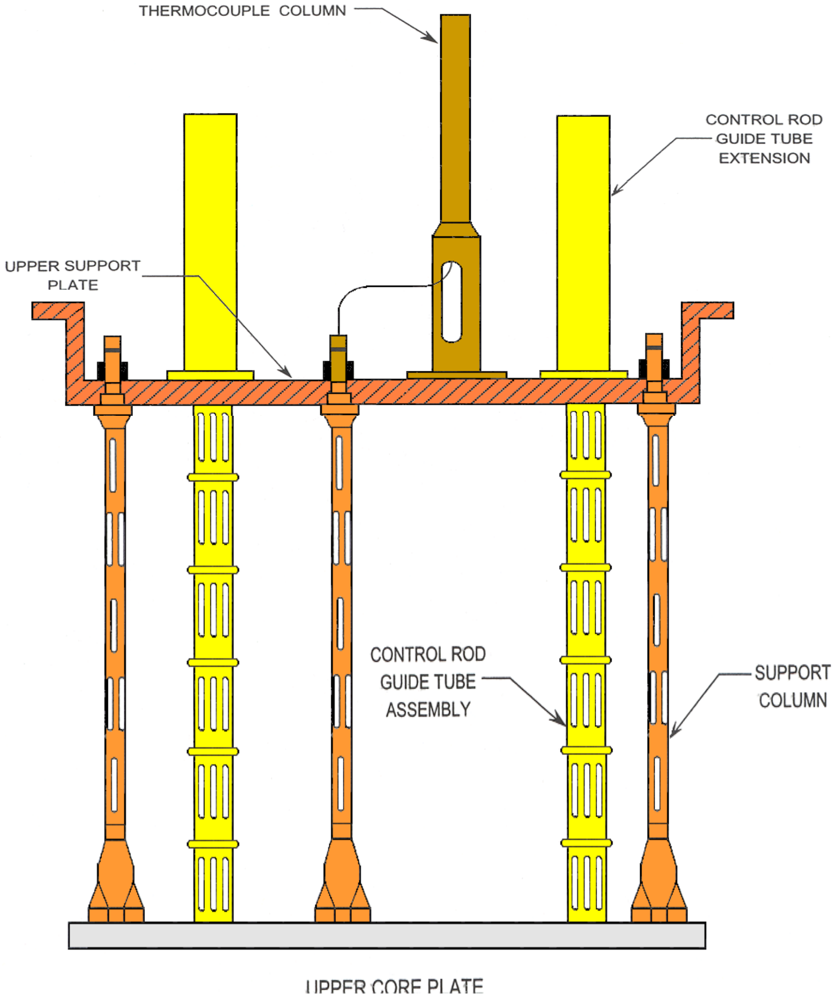
- **Indicate ICC to operators**: diagnoze ICC by using readings of coolant temperature sensors located in-core or at core outlet

Note: Some NPP vendors suggest the use of coolant temperature measurements, together with measurements of coolant liquid level in the core

1) INTRODUCTION

1.2) Limitations in the Use for AM of In-Vessel Coolant Temperature Measurements

a) CETC: Use thermocouples at core exit to measure temperature of superheated steam rising from the core into the upper internals plenum: **Fig. 5.A.1** and **Fig. 5.A.2**



Reference: [20]

Fig. 5A.1

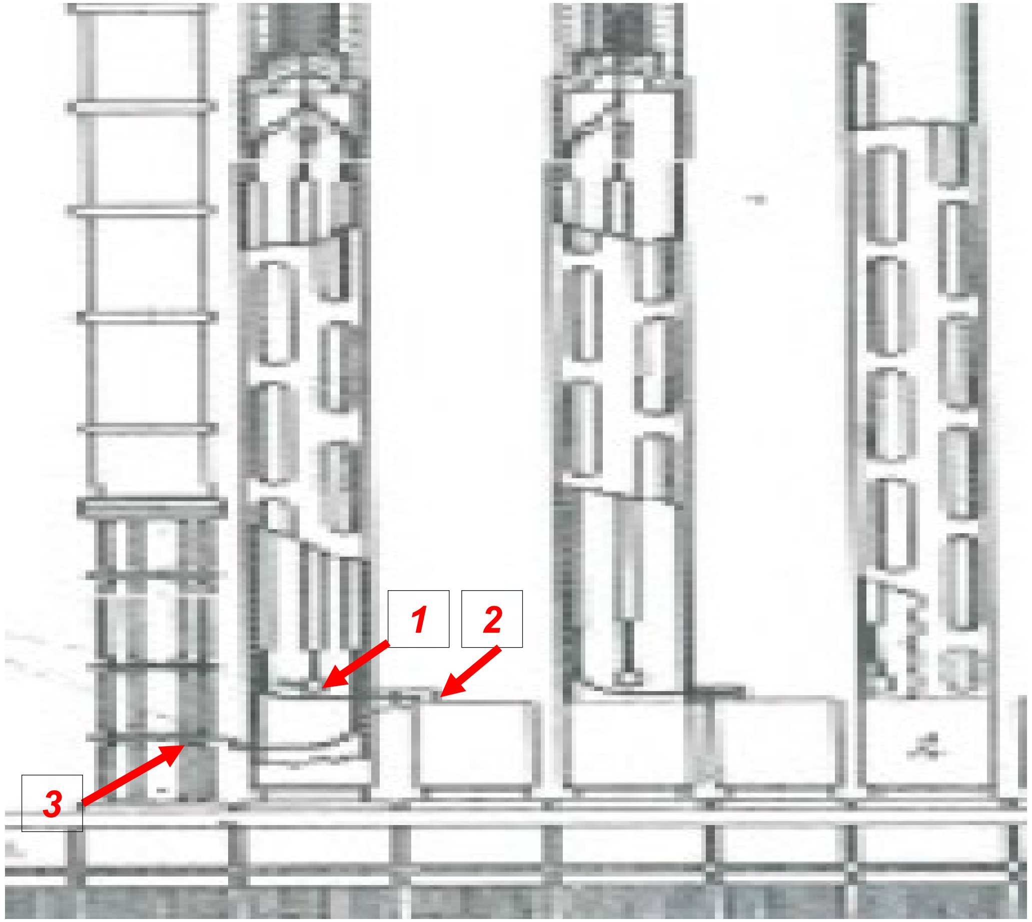


Fig. 5A.2 [12]

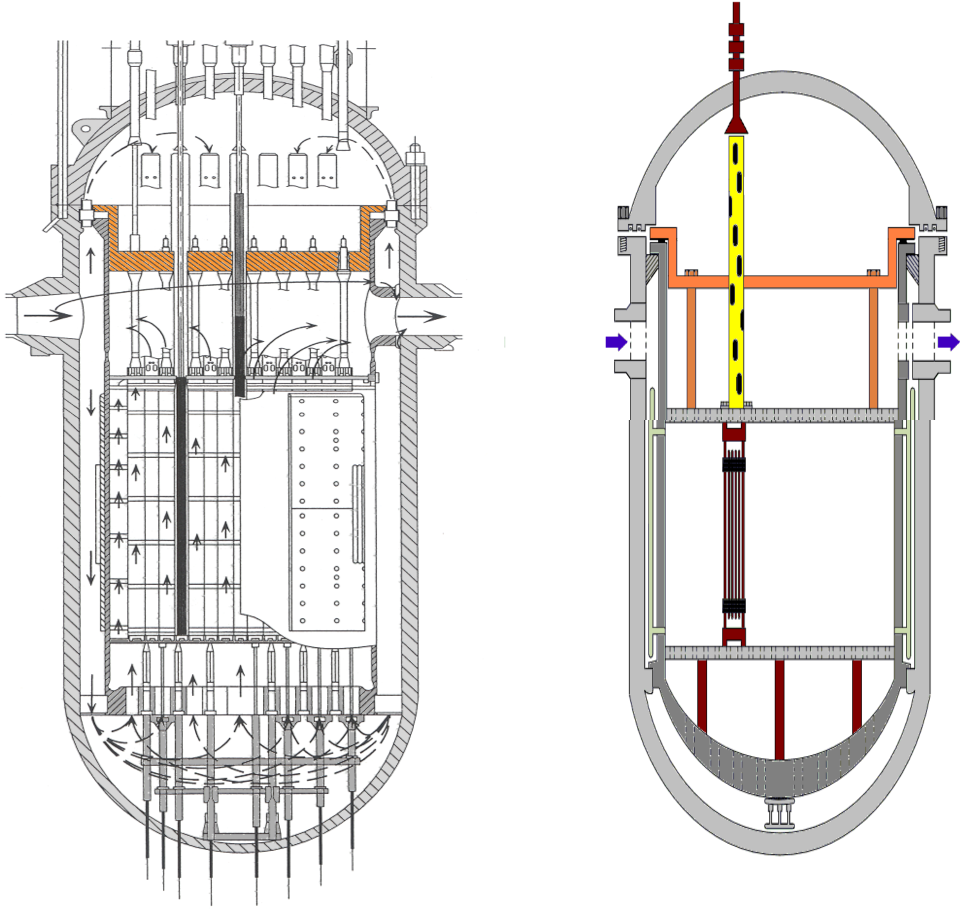
1: CETC in CRGT
2: CETC in mixer
3: CETC without mixer

1) INTRODUCTION

1.2) Limitations in the Use for AM of In-Vessel Coolant Temperature Measurements

b) **CETC Limitations** in indicating ICC condition with free coolant convection inside the reactor vessel (**RPV**)

- Significant time delay from the moment of core uncovery until the moment when CETC readings respond to it.
- CETC readings are much lower than the maximum fuel clad temperature
- CETC performance strongly depends on the accident scenario that has led to ICC and the flow conditions in the core and in the part of the upper plenum where the CETC are located



Reference: [20]

c) Causes for CETC Limitations in indicating ICC

i. Natural Circulation (Nat.Circ) cells in core:

Fluid temperatures ***along the core radius differ significantly*** during the approach to ICC, both at elevations ***below and above*** the upper core plate, where the CETC are located.

Need to represent core in 3D to capture in greater detail the spatial distribution of fluids with different temperature

ii. Cooling effect on the vapor from the unheated metal structures in the RPV upper internals: The massive metal structures in the RPV upper plenum produce a substantial cooling effect that can cause some of the saturated steam in the upper plenum to condense into liquid and then flow downwards along the CETC thimbles.

The liquid can envelop the CETC hot junction and block the contact between the CETC and the superheated vapor rising from the core top towards the CETC.

Need to represent upper internals (UI) in a greater detail to capture:

- ***the heat exchange between superheated vapor and the UI metal structures** and*
- ***the mixing of superheated vapor and saturated steam/liquid***

1) INTRODUCTION

c) **Causes** for **CETC** Limitations in indicating ICC

iii. The low rate of convection heat transfer from the clad surface to the low-velocity steam that flows past the fuel pins results in having a large temperature difference between the cladding and the fluid. Low steam velocity inside the fuel pins bundle and in the location of the CETC increase the significance of 3D flow patterns, e.g. superheated steam may flow sideways and thus miss the hot junction of the CETC located above the core upper support plate.

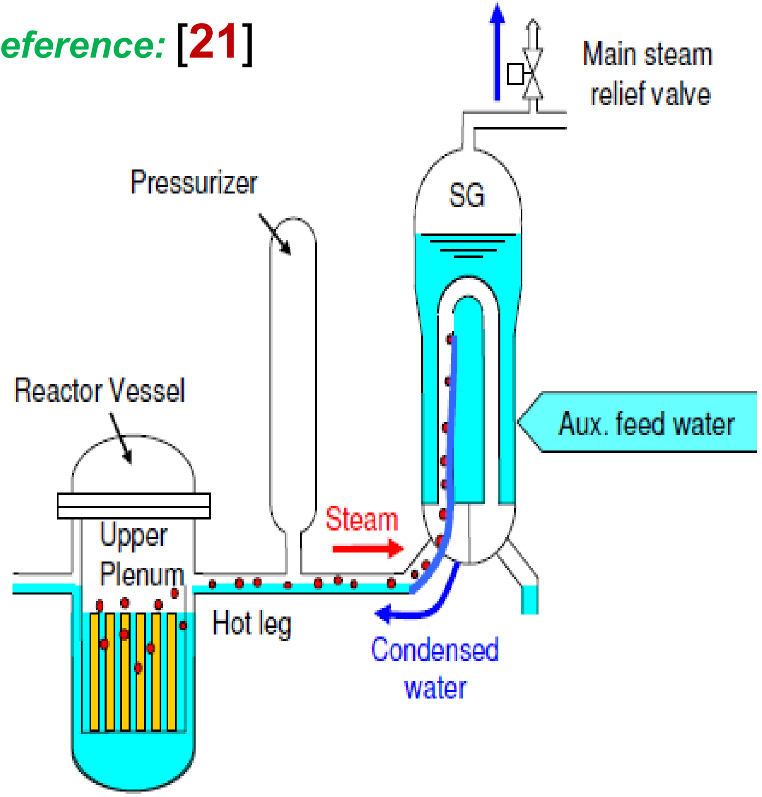
Need to represent the reactor core in 3D to capture in greater detail the spatial distribution the flow of superheated vapor and saturated steam/liquid mixtures

c) **Causes** for **CETC** Limitations in indicating ICC

iv. Reflux cooling in the SG produces some liquid that flows in reverse direction, (i.e. from SG towards RPV), along the bottom of the hot legs into the RPV upper ple-num. This liquid may provide some cooling effect that brings down the CETC mea-surements. This cooling effect on the CETC is stronger for PWR plants with safety injection of cold ECCS water (pumps or hydro-accumulators) into the hot leg.

Need to represent the hot leg pipes and the SG channel head and tubes' bundle in a greater detail to capture the counter-current flows of steam and liquid in the hot leg pipes.

Reference: [21]

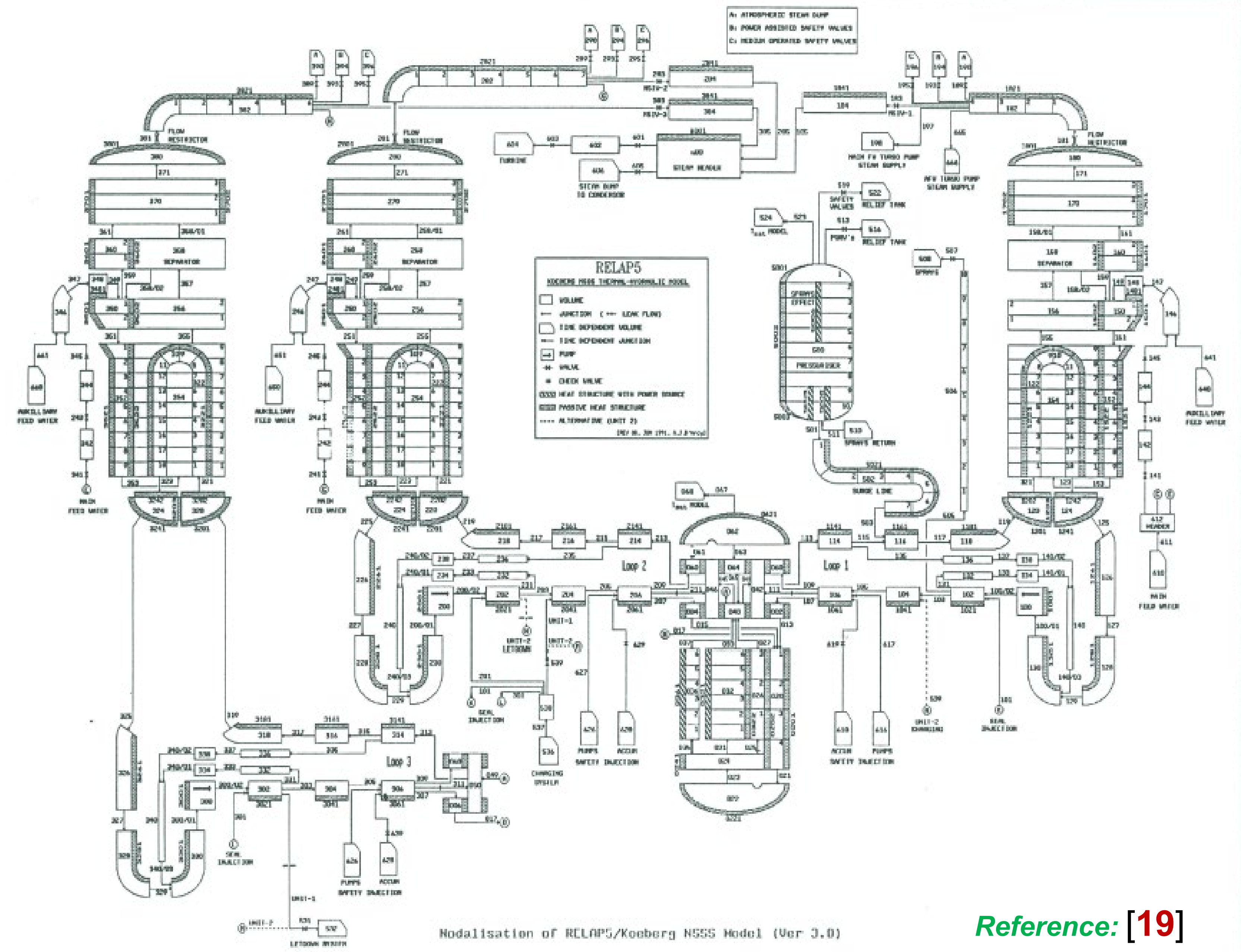


c) **Causes** for **CETC** Limitations in indicating ICC

v. The CETC indications may strongly **depend on the actual accident scenario**

In SBLOCA scenarios with a ***break located in RPV top head***, the control rods guide tubes (**CRGT**) serve as conduit that directs coolant towards the break, thus allowing it to bypass the CETC located nearby. This ***"chimney" effect*** may lead to having an advan-ced ICC condition, while at the same time the CETC readings indicate saturated fluid conditions in the upper plenum. Another example of the significant effect of the accident scenario on the CETCs readings is the ***downward fluid flow, away from the CETC***, in case of ***SBLOCA with break location in the lower RPV head***

2) Description of a Generic 3-Loop PWR System RELAP5-3D Model



Nodalisation of RELAP5/Koeberg NSSS Model (Ver 3.0)

Reference: [19]

Reference [19]

PWR 3-loop NPP, Q_{NOM}=**2775** MW

Core: **157** FA, **17x17**, height 12ft (**3.65**m)

ECCS: 2 HHSI, 2 LHSI: **280** kg/sec @ 0.9 MPa, cutoff @ P=1.17 MPa

3 Hydro-Accumul: (**29.7** m3 water, 4.1MPa nitrogen)

$\mathbf{T_{HOT}}$= 595 K, $\mathbf{T_{COLD}}$= 559 K; $\mathbf{P_{PRI}}$=15.5 MPa, Primary coolant flow: **14000** kg/s

Pressurizer PORVs discharge characteristics:

a) Saturated steam flow @ P=**16.2** MPa

F= 3x95 t/h= **79.17** kg/s

b) Superheated (773K) vapor flow @ P=**16.2** MPa:

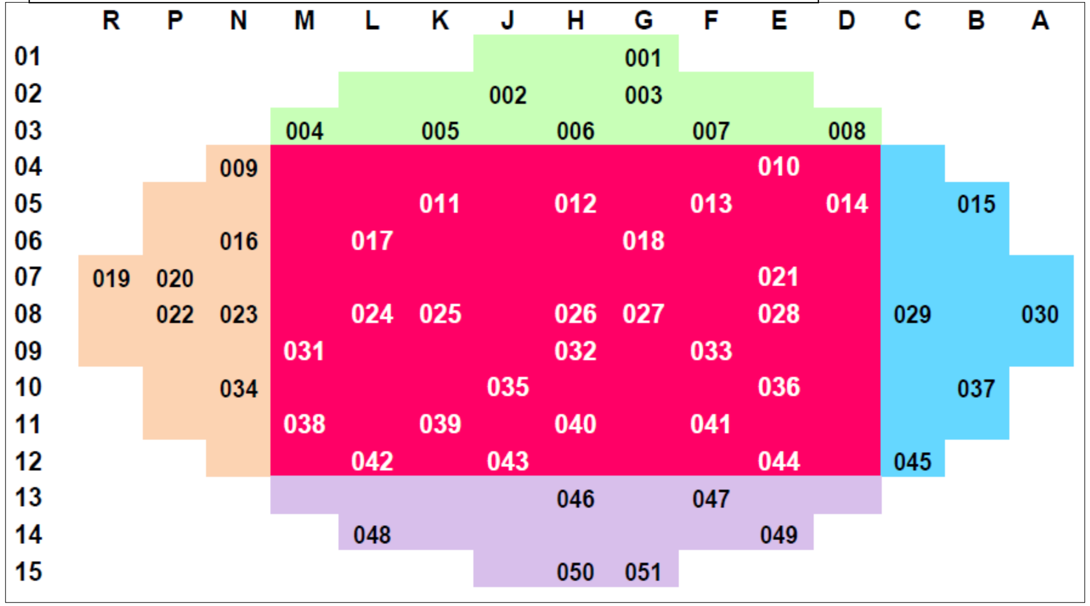
F=**40** kg/s

$\mathbf{P_{SEC}}$ =**5.7** MPa, Secondary steam flow: F_N=**3x500** kg/s

SG Relief valves: set P: **7.17** MPA, flow F=**83.3** kg/s

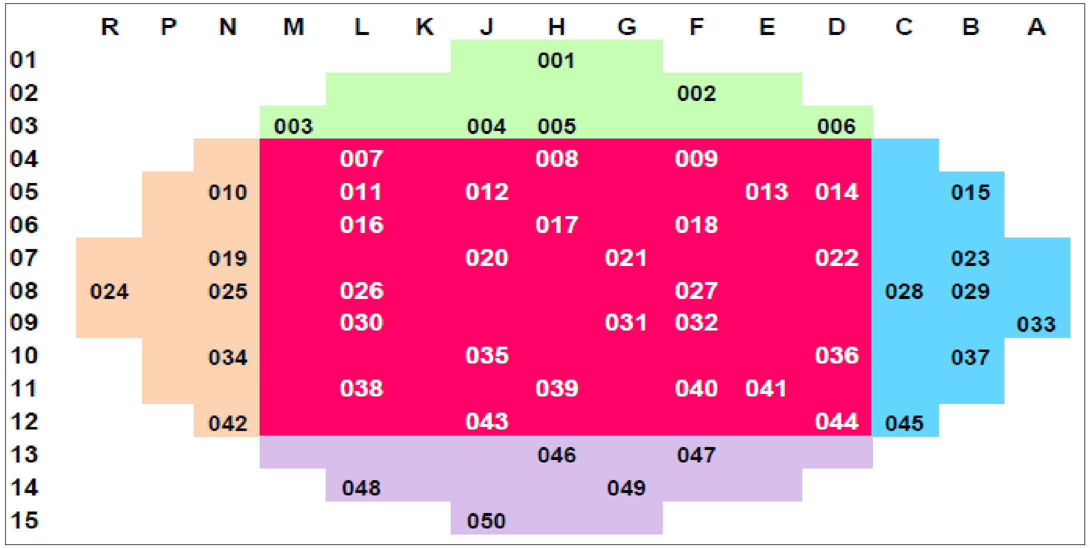
2) Description of a Generic 3-Loop PWR System RELAP5-3D Model

Core Exit Thermo-Couples (51 CETCs)



	R	P	N	M	L	K	J	H	G	F	E	D	C	B	A
01									001						
02							002		003						
03				004		005		006		007		008			
04			009								010				
05						011		012		013		014		015	
06			016		017				018						
07	019	020									021				
08		022	023		024	025		026	027		028		029		030
09				031				032		033					
10			034				035				036			037	
11				038		039		040		041					
12					042		043				044		045		
13								046		047					
14					048						049				
15								050	051						

In-core neutron flux and coolant temperature IITA (50 IITA sensors)



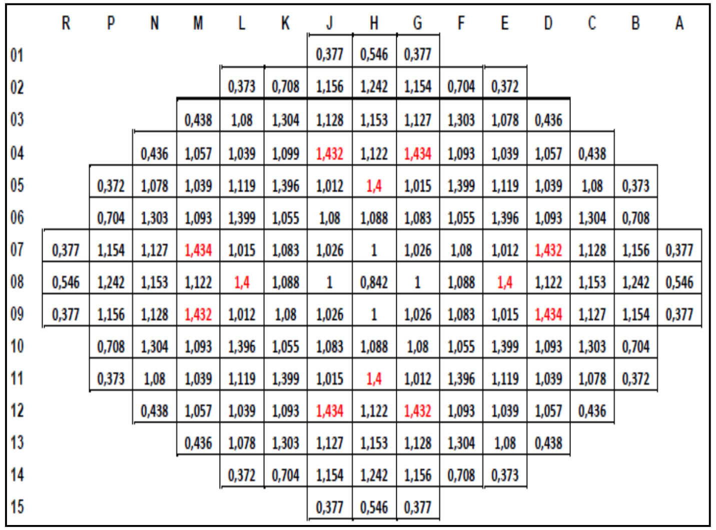
	R	P	N	M	L	K	J	H	G	F	E	D	C	B	A
01								001							
02										002					
03				003			004	005				006			
04					007			008		009					
05			010		011		012				013	014		015	
06					016			017		018					
07			019				020		021			022		023	
08	024		025		026					027			028	029	
09					030				031	032					033
10			034				035					036		037	
11					038			039		040	041				
12			042				043					044	045		
13								046		047					
14					048				049						
15							050								

Relative Fuel Assemblies Powers in Core

	R	P	N	M	L	K	J	H	G	F	E	D	C	B	A
01							0,377	0,546	0,377						
02					0,373	0,708	1,156	1,242	1,154	0,704	0,372				
03				0,438	1,08	1,304	1,128	1,153	1,127	1,303	1,078	0,436			
04			0,436	1,057	1,039	1,099	1,432	1,122	1,434	1,093	1,039	1,057	0,438		
05		0,372	1,078	1,039	1,119	1,396	1,012	1,4	1,015	1,399	1,119	1,039	1,08	0,373	
06		0,704	1,303	1,093	1,399	1,055	1,08	1,088	1,083	1,055	1,396	1,093	1,304	0,708	
07	0,377	1,154	1,127	1,434	1,015	1,083	1,026	1	1,026	1,08	1,012	1,432	1,128	1,156	0,377
08	0,546	1,242	1,153	1,122	1,4	1,088	1	0,842	1	1,088	1,4	1,122	1,153	1,242	0,546
09	0,377	1,156	1,128	1,432	1,012	1,08	1,026	1	1,026	1,083	1,015	1,434	1,127	1,154	0,377
10		0,708	1,304	1,093	1,396	1,055	1,083	1,088	1,08	1,055	1,399	1,093	1,303	0,704	
11		0,373	1,08	1,039	1,119	1,399	1,015	1,4	1,012	1,396	1,119	1,039	1,078	0,372	
12			0,438	1,057	1,039	1,093	1,434	1,122	1,432	1,093	1,039	1,057	0,436		
13				0,436	1,078	1,303	1,127	1,153	1,128	1,304	1,08	0,438			
14					0,372	0,704	1,154	1,242	1,156	0,708	0,373				
15							0,377	0,546	0,377						

2) Description of a Generic 3-Loop PWR System RELAP5-3D Model

2.1) Multi-Dimensional Model of Reactor Core and Upper Internals Plenum



	R	P	N	M	L	K	J	H	G	F	E	D	C	B	A
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02					0,373	0,708	1,156	1,242	1,154	0,704	0,372				
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07	0,377	1,154	1,127	1,434	1,015	1,083	1,026	1	1,026	1,08	1,012	1,432	1,128	1,156	0,377
08	0,546	1,242	1,153	1,122	1,4	1,088	1	0,842	1	1,088	1,4	1,122	1,153	1,242	0,546
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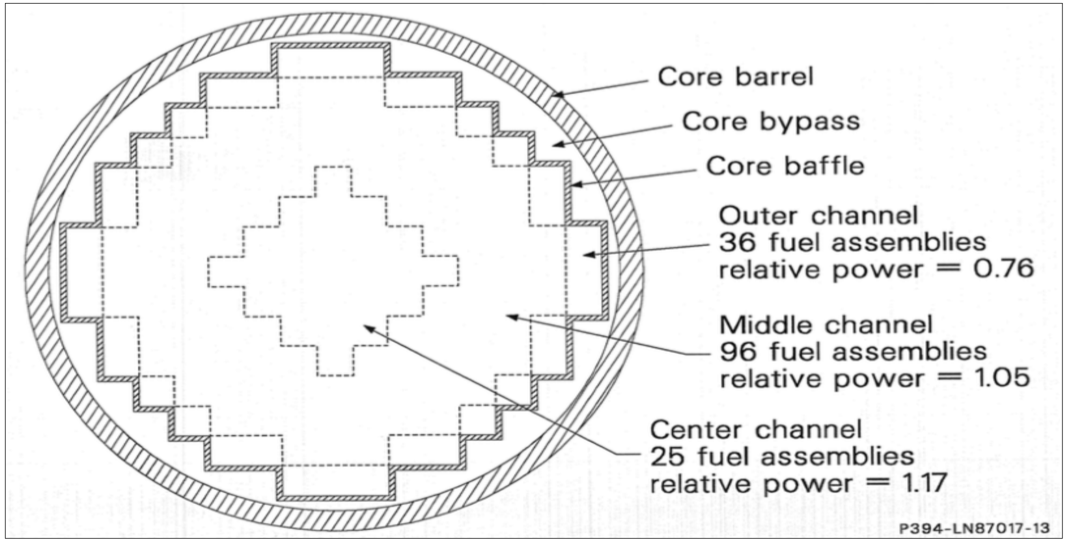
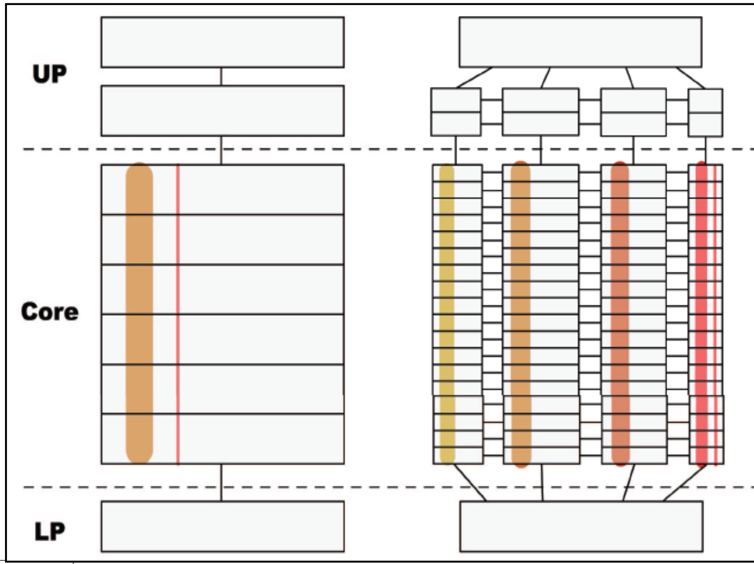
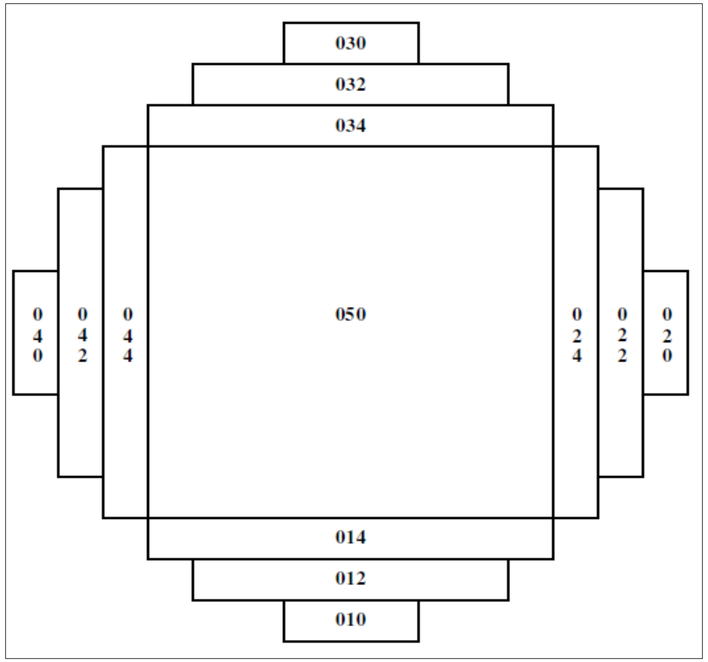
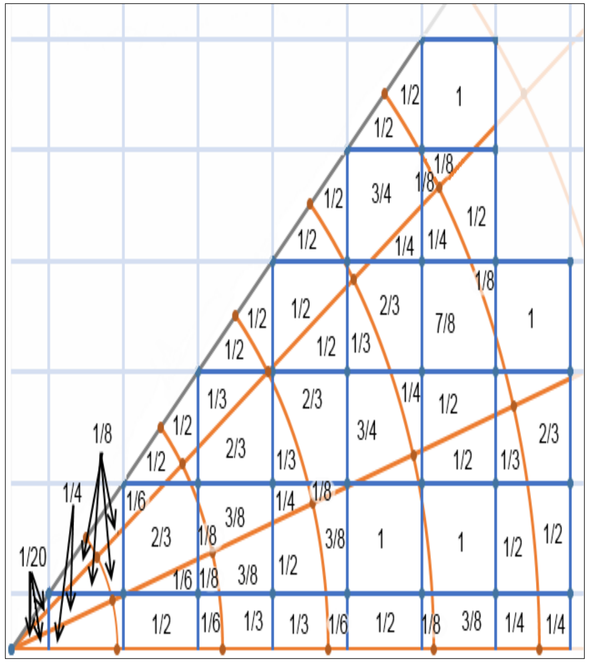
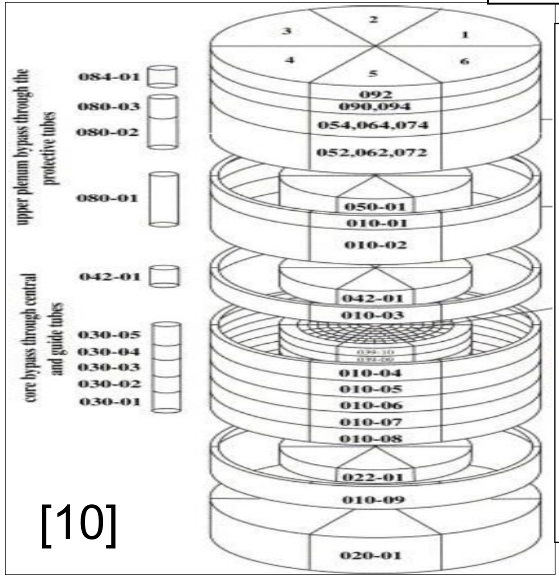










[10]

RELAP5-3D Multi-dimensional Component (MULTID)

The **MULTID** component defines a one, two, or three-dimensional array of volumes and the internal junctions connecting them.

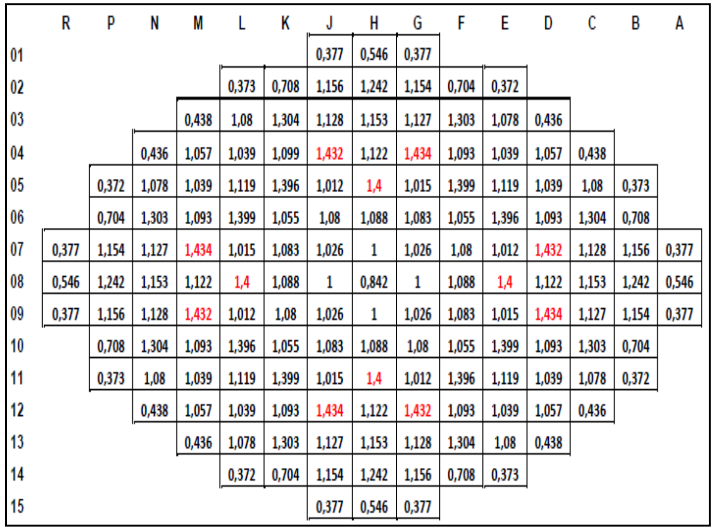
The geometry can be either:

a)Cylindrical (r, θ, z) or

b)Cartesian (x,y,z) ie an orthogonal, three-dimensional grid is defined by mesh interval input data in each of the three coordinate directions

2) Description of a Generic 3-Loop PWR System RELAP5-3D Model

2.1) Multi-Dimensional Model of Reactor Core and Upper Internals Plenum



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07	0,377	1,154	1,127	1,434	1,015	1,083	1,026	1	1,026	1,08	1,012	1,432	1,128	1,156	0,377
08	0,546	1,242	1,153	1,122	1,4	1,088	1	0,842	1	1,088	1,4	1,122	1,153	1,242	0,546
09	0,377	1,156	1,128	1,432	1,012	1,08	1,026	1	1,026	1,083	1,015	1,434	1,127	1,154	0,377
10		0,708	1,304	1,093	1,396	1,055	1,083	1,088	1,08	1,055	1,399	1,093	1,303	0,704	
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13				0,436	1,078	1,303	1,127	1,153	1,128	1,304	1,08	0,438			
14					0,372	0,704	1,154	1,242	1,156	0,708	0,373				
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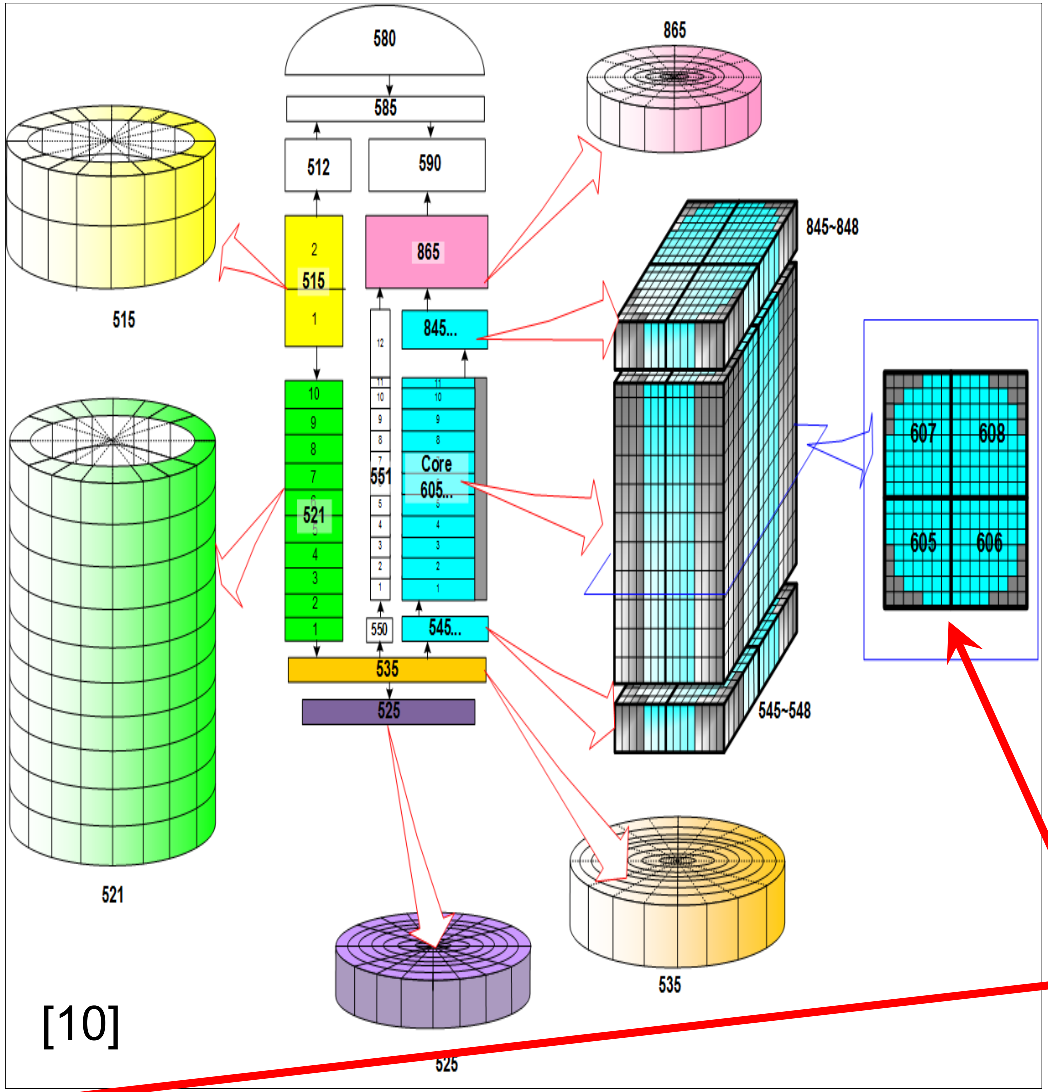
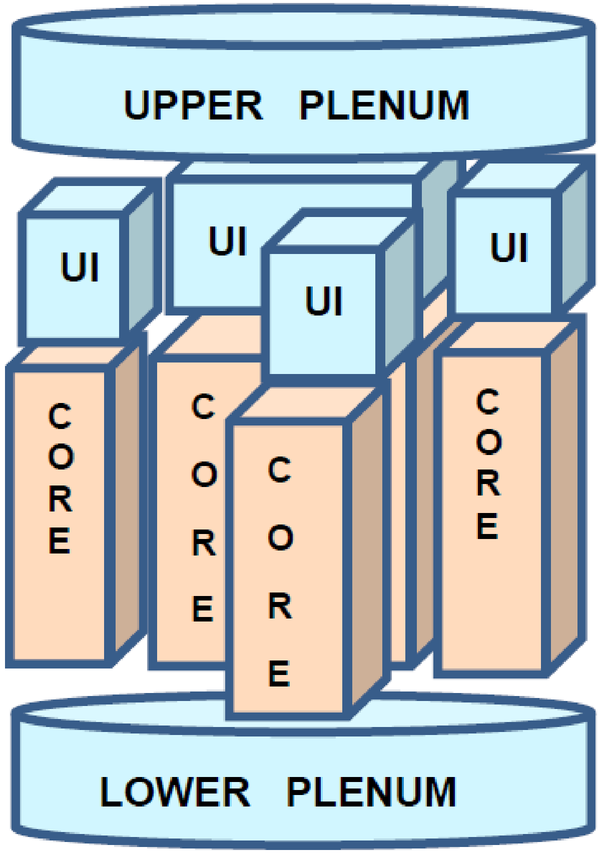
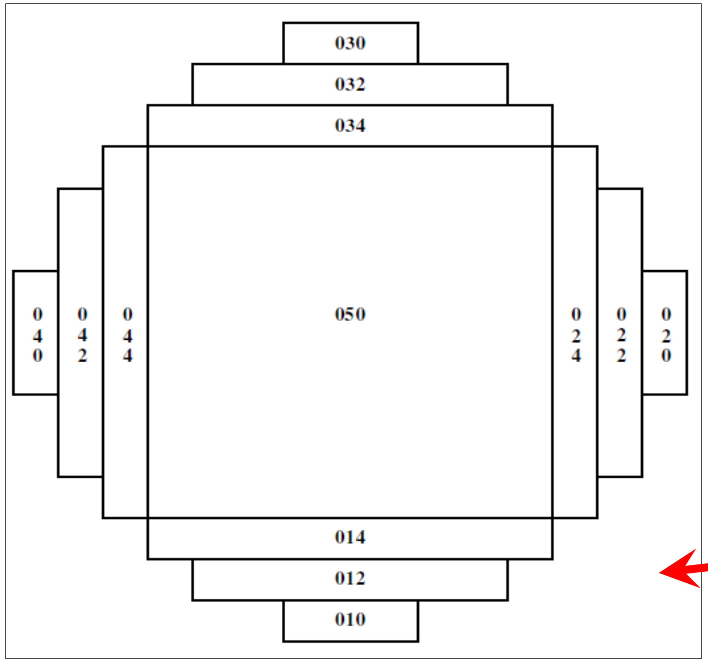




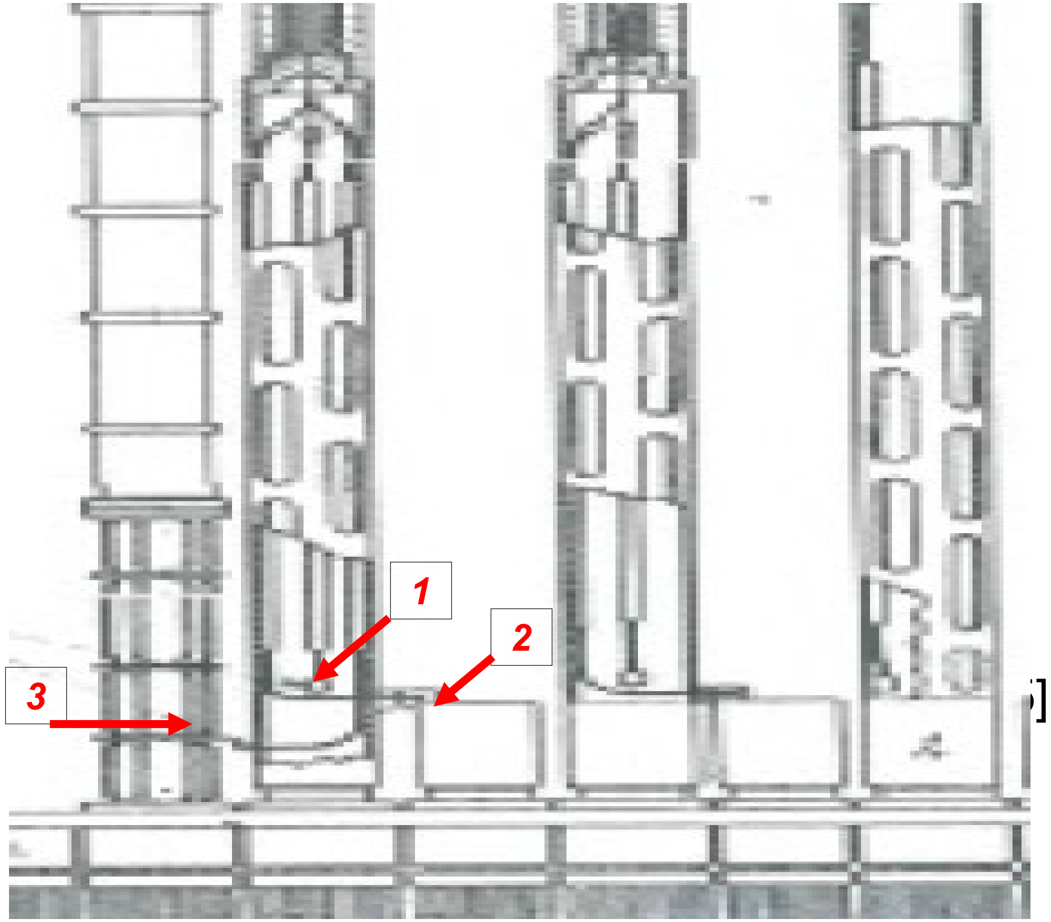
Alternative Cartesian nodalizations:
Each node represents a single fuel assembly

a) **MULTID: 8x8; 7x8; 7x7; 7x7**
b) **MULTID: 4(1x3), 4(1x7), 4 (1x9), 9x9**



2) Description of a Generic 3-Loop PWR System RELAP5-3D Model

2.2) Coolant Temperature Sensors Modeling - **C**ore **E**xit **T**hermo-**C**ouples (**CETC**)



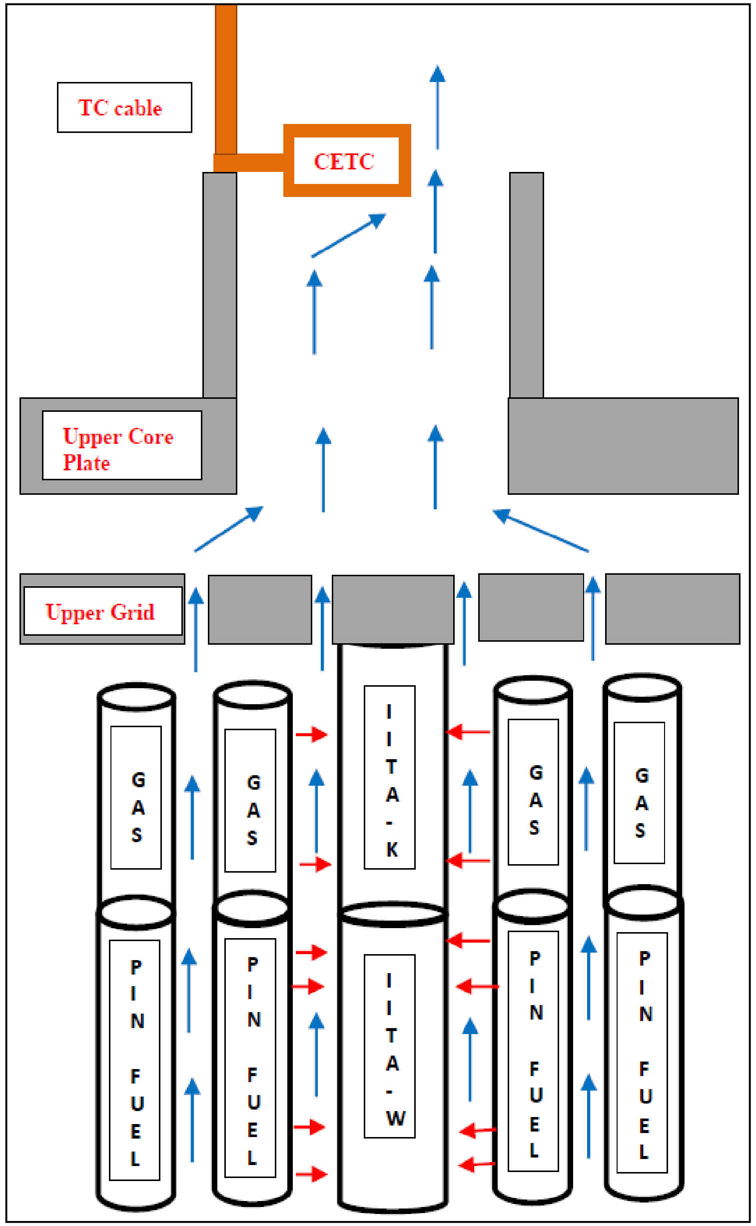
1: CETC in CRGT
2: CETC in mixer
3: CETC without mixer

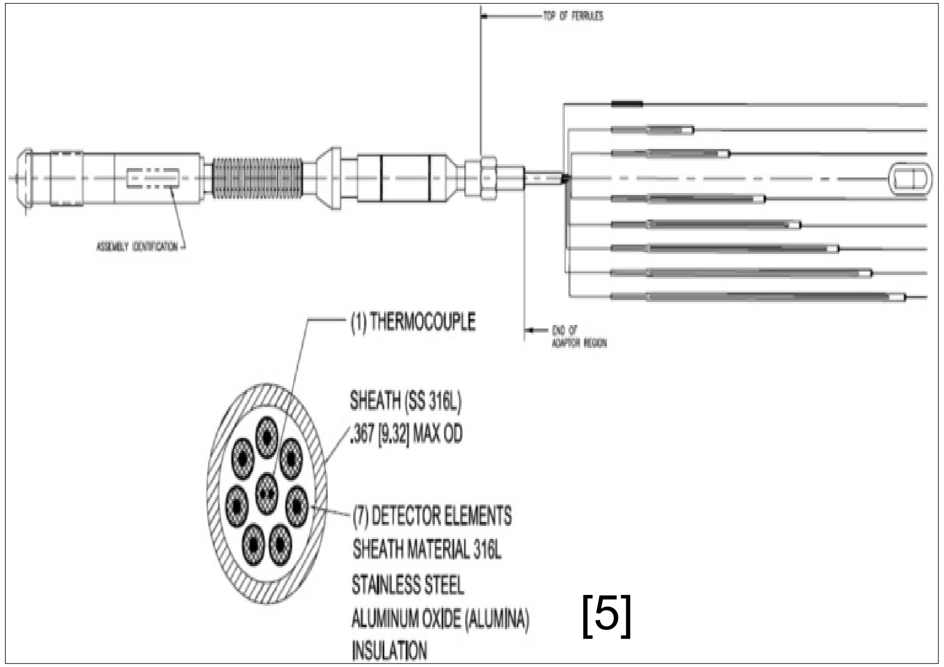
CETC= Core Exit Thermo-Couples

a) Each CETC is modeled as a cylindrical "heat structure": radial dimensions on Fig 5B
b) Each CETC exchanges heat via convection with coolant in node located above upper core plate

2) Description of a Generic 3-Loop PWR System RELAP5-3D Model

2.2) Coolant Temperature Sensors Modeling - **In**-core **I**nstrumentation **T**himble **A**ssembly (**IITA**)

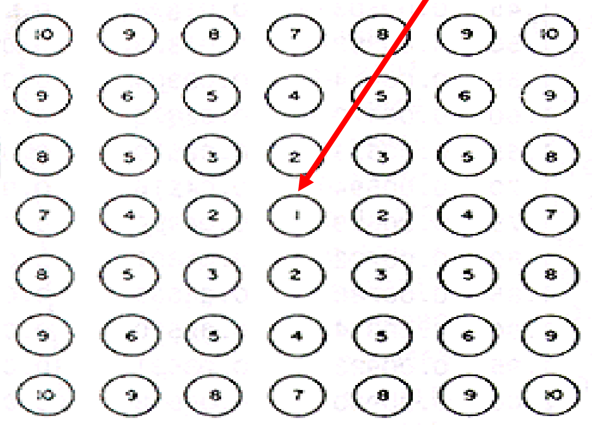




[5]

Actual arrangement of IITA (1) and fuel pins (2), (3), (4), …, (10)

[6]



In-core **I**nstrumentation **T**himble **A**ssembly (**IITA**)

a)Each **IITA** is modeled as a cylindrical "heat structure": Radial dimensions on Fig 5B

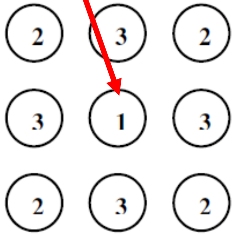
b)Each **IITA** exchanges heat via:

- ***Convection*** with coolant in adjacent node
- ***Thermal radiation*** with adjacent fuel pins:

IITA-K sensors exchange heat via ***thermal radiation*** with the ***fuel-free*** top part of adjacent fuel pins

IITA-W sensors exchange heat via thermal radiation with the topmost (height 0.365m) ***fueled part*** of adjacent fuel pins

Simplified RELAP-3D "radiation enclosure" model: IITA (1) and fuel pins (2), (3)

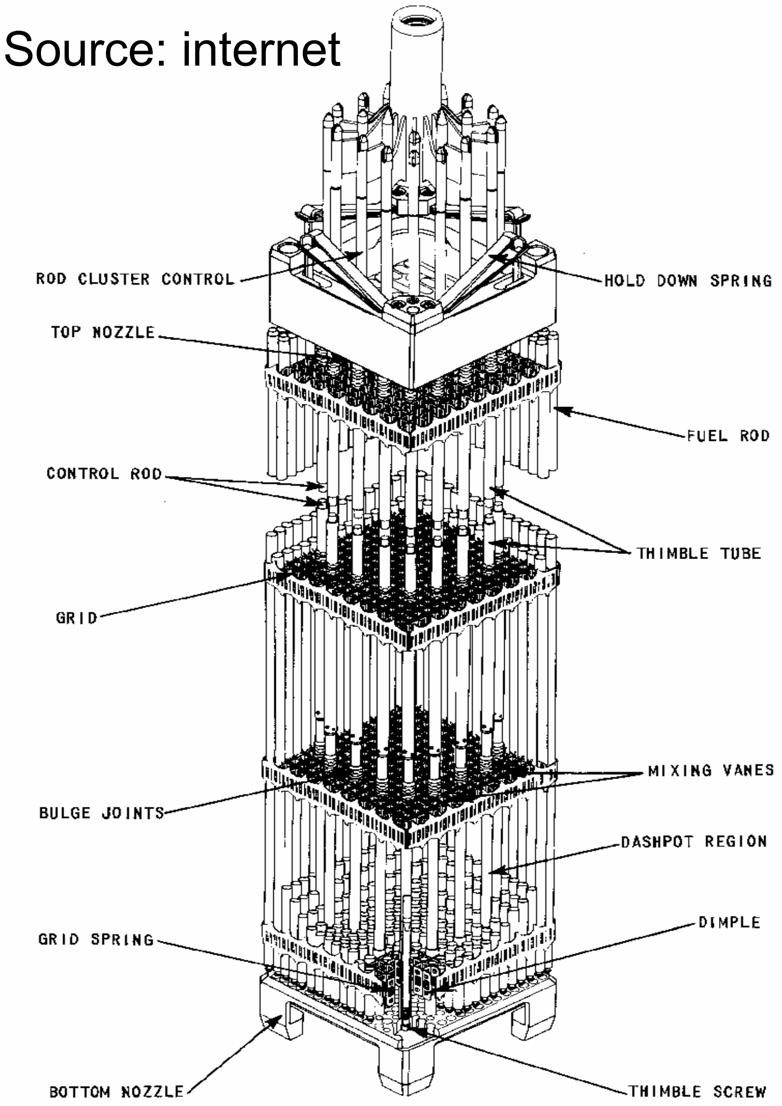


2) Description of a Generic 3-Loop PWR System RELAP5-3D Model

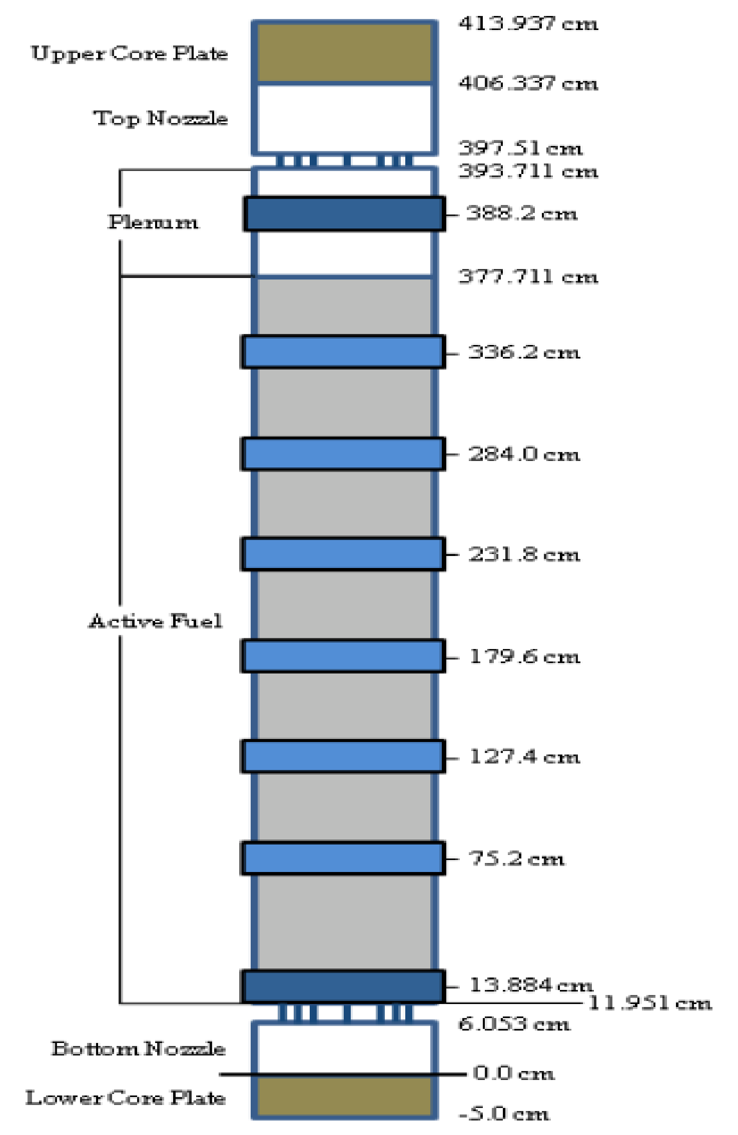
2.3) RELAP5-3D Fuel Performance Model

PWR Fuel assembly 17x17, height 12 ft

Source: internet



Fuel Assembly Axial Nodalization



RELAP5-3D Fuel pin model

Reflood calculaion begins when core voiding > 10%

Hydrogen + Heat generation:

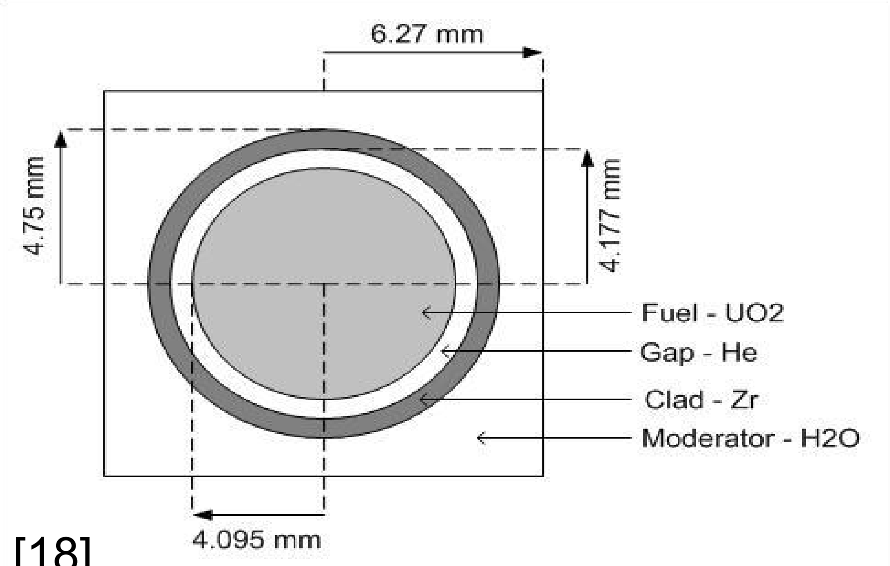
Fuel clad oxidation model: ON

Initial clad oxide layer 1.0e-6 (m)

Fuel pins swelling, rupture, core blockage:

Fuel clad deformation model: ON

Initial gas pressure in pin: 9.4 MPa



[18]

3) Transient Description and Simulation Results

3.1) Study Objectives

Definition of "**core damage**":

1) **PCT**: Peak cladding temperature, **Tclad**, becomes greater than 1475 (K);
2) **LMO**: The relative thickness of the oxide layer on the fuel cladding wall exceeds **LMO>17%** of the cladding thickness
3) **CWO**: The amount of hydrogen produced in the course of the accident exceeds **CWO>10** (kg)
4) **Core Blockage**: Blocked flow channels in the core as a fraction (eg perhaps 10% ?) of the total in-core flow channels

Study Objective: Compare the degrees of core damage of the plant response to ICC condition for two different entry symptoms to an emergency procedure that should restore core cooling and prevent core damage:

Case-1: *Core Outlet Temperature measured by the CETC sensors becoming greater than* ***923 (K)***

Case-2: *Core Outlet Temperature measured by the CETC sensors becoming greater than* ***643 (K)****, while the level of the saturated liquid-steam mixture in the core is less than* ***30%***

3.2) Transient description

1) SBLOCA in RPV Lower Head

The transient is initiated by the opening of a break with a throat area of $81*10^{-4}$ (m^2) in RPV lower head.

2) RCP tripped by operator.

Assume all reactor coolant pumps (RCPs) trip when voiding appears in the node representing the pump's volute.

3) Charging and Letdown isolated on reactor scram

4) HHSI and SG Emergency Feedwater unavailable

All "High-Head Safety Injection" (HHSI) pumps and the SG auxiliary feedwater pumps fail to start up.

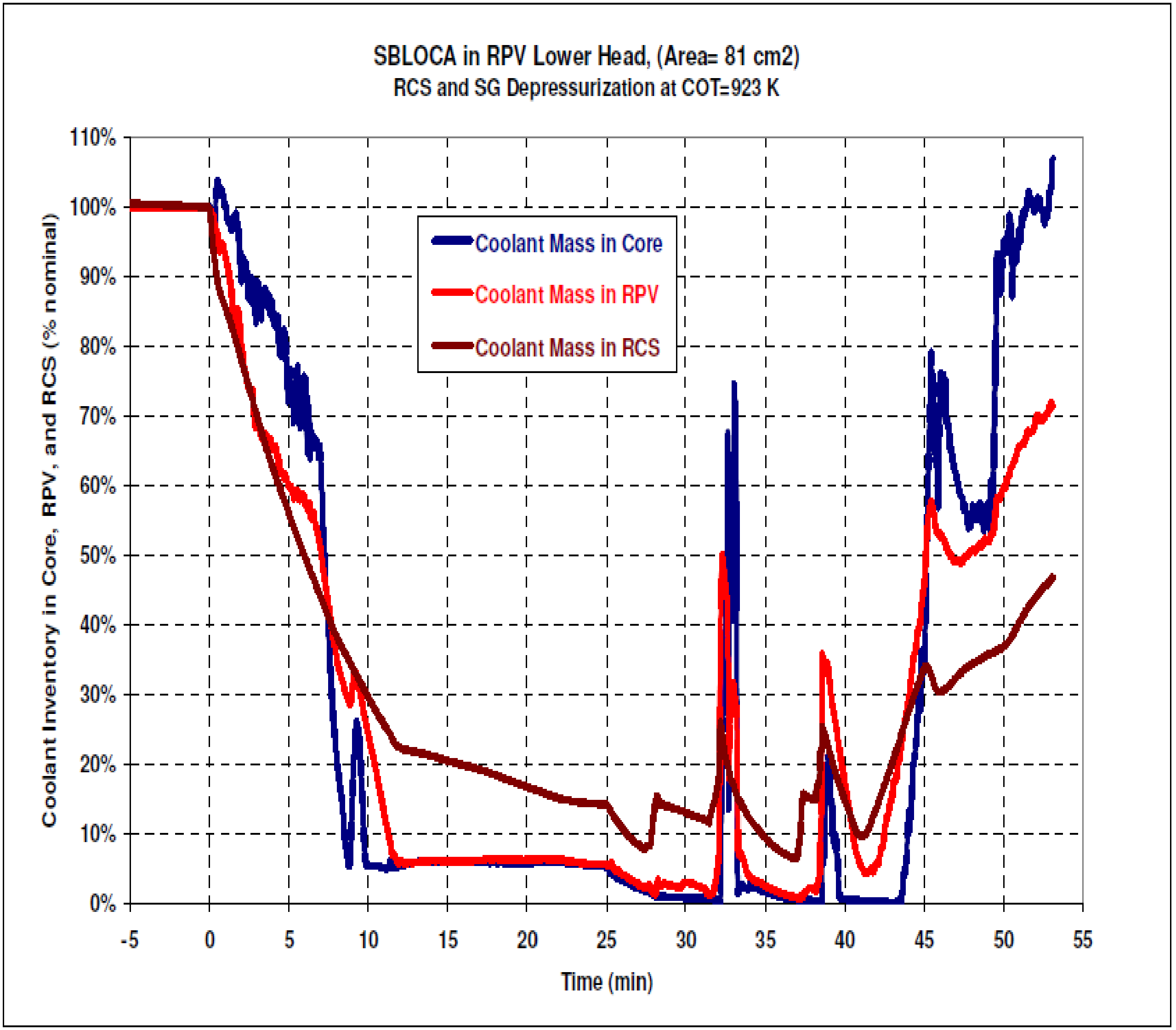
5) LHSI pumps available

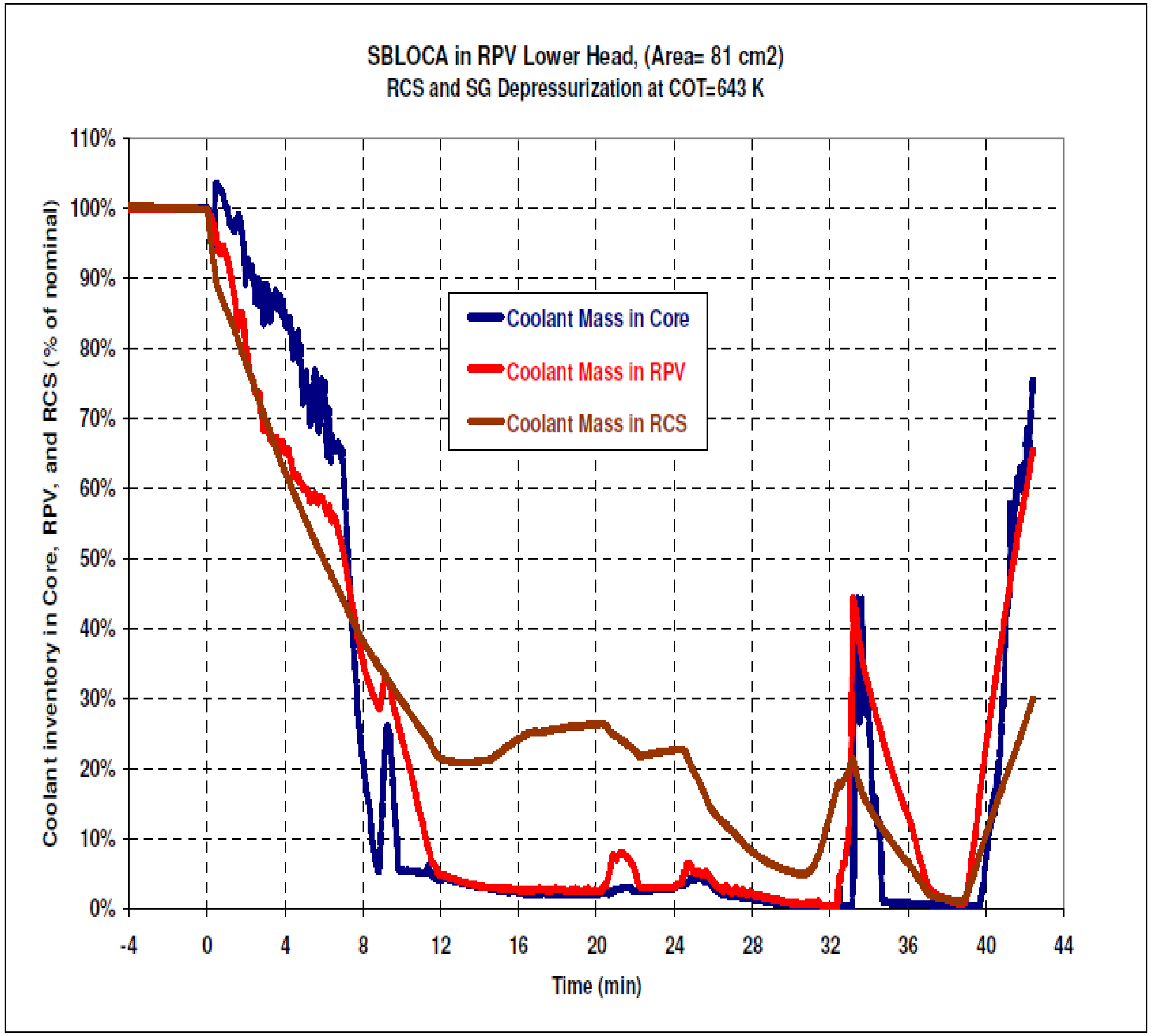
Two "Low-Head Safety Injection" (LHSI) pumps are assumed available and they are modeled to have a shut-off head of 1.17 (MPa) and both LHSI pumps deliver coolant at the rate of 280 kg/sec @ 0.9 MPa.

6) Depressurize RCS and all SGs

Once the COT measurements indicate the appearance of an ICC and assuming HHSI and Emergency Feedwater to SG are still unavailable, the operators respond by implementing an EOP: depressurize simultaneously both the primary and secondary sides by opening all PRZ PORVs and the relief valve on each SG to let Hydro-Accumulators reflood the core and enable LHSI to cool the core.

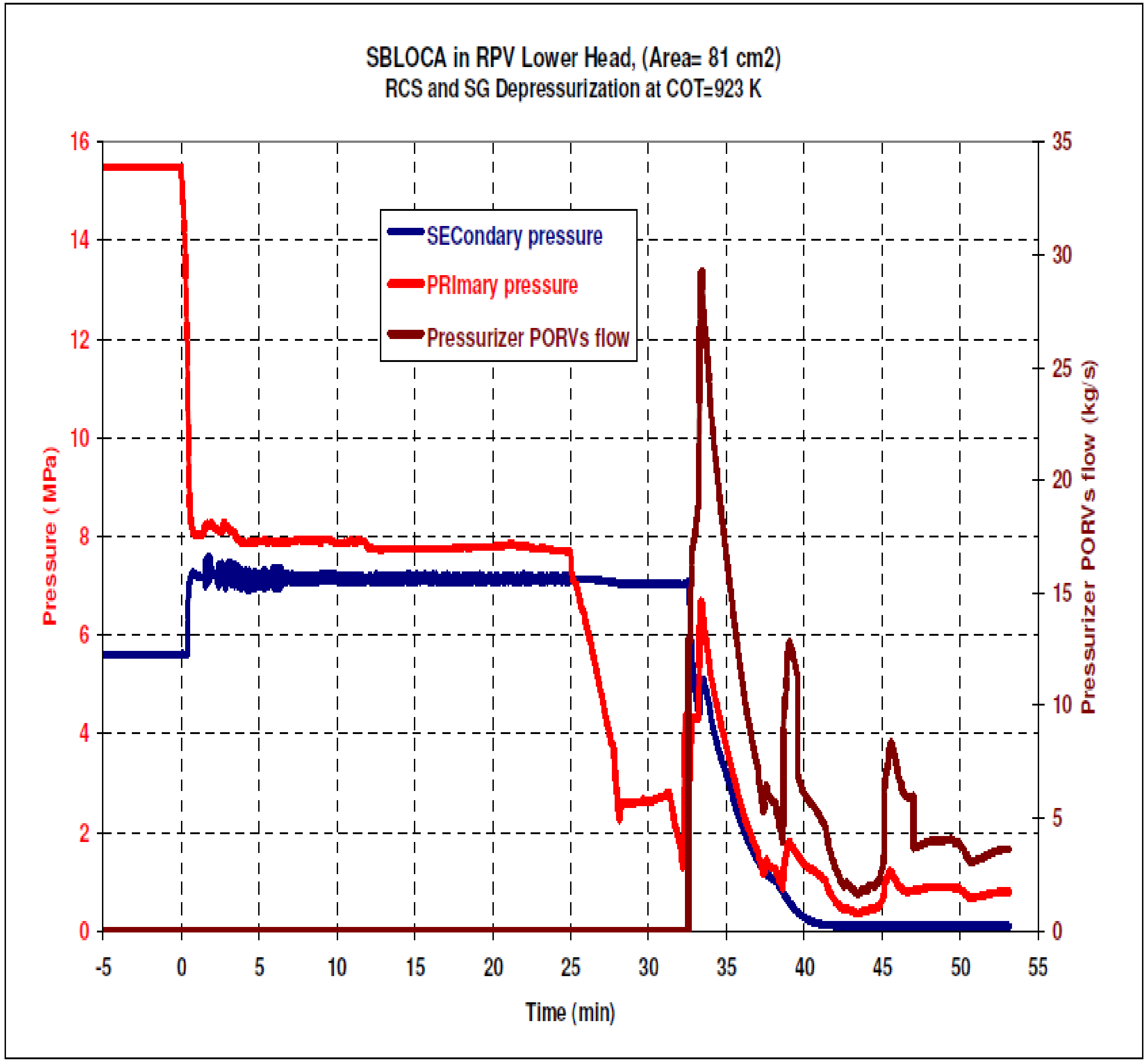
3) Transient Description and Simulation Results

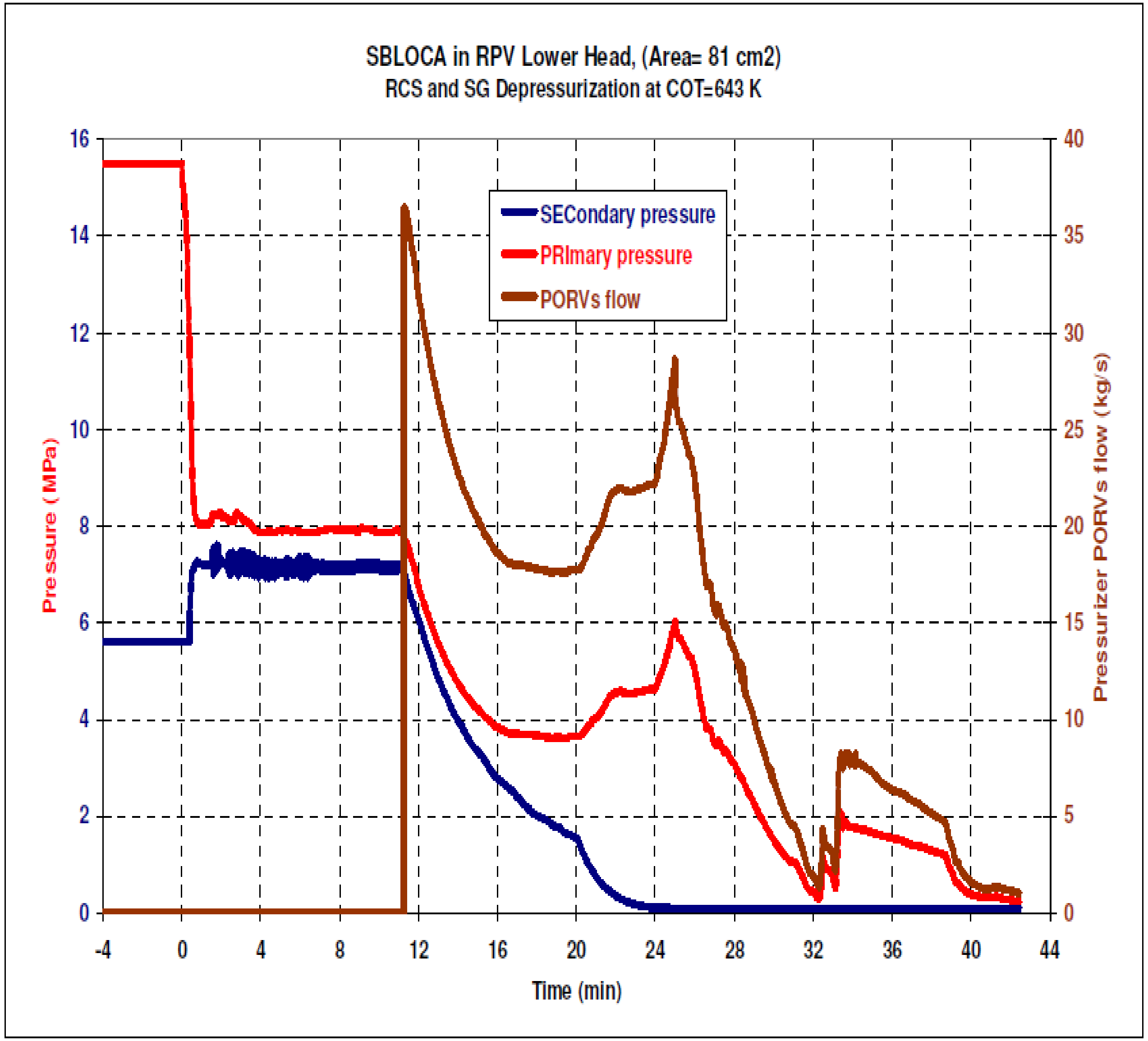




The coolant mass in the core begins to decrease and by time To+8 (min) the core is nearly fully voided. ECCS Hydro-Accumulators (ECCS H-A) begin to deliver in Case #2 (Fig.11-1) at time To+15(min), but are cut off when RCS repressurizes above the ECCS H-A nitrogen pressure

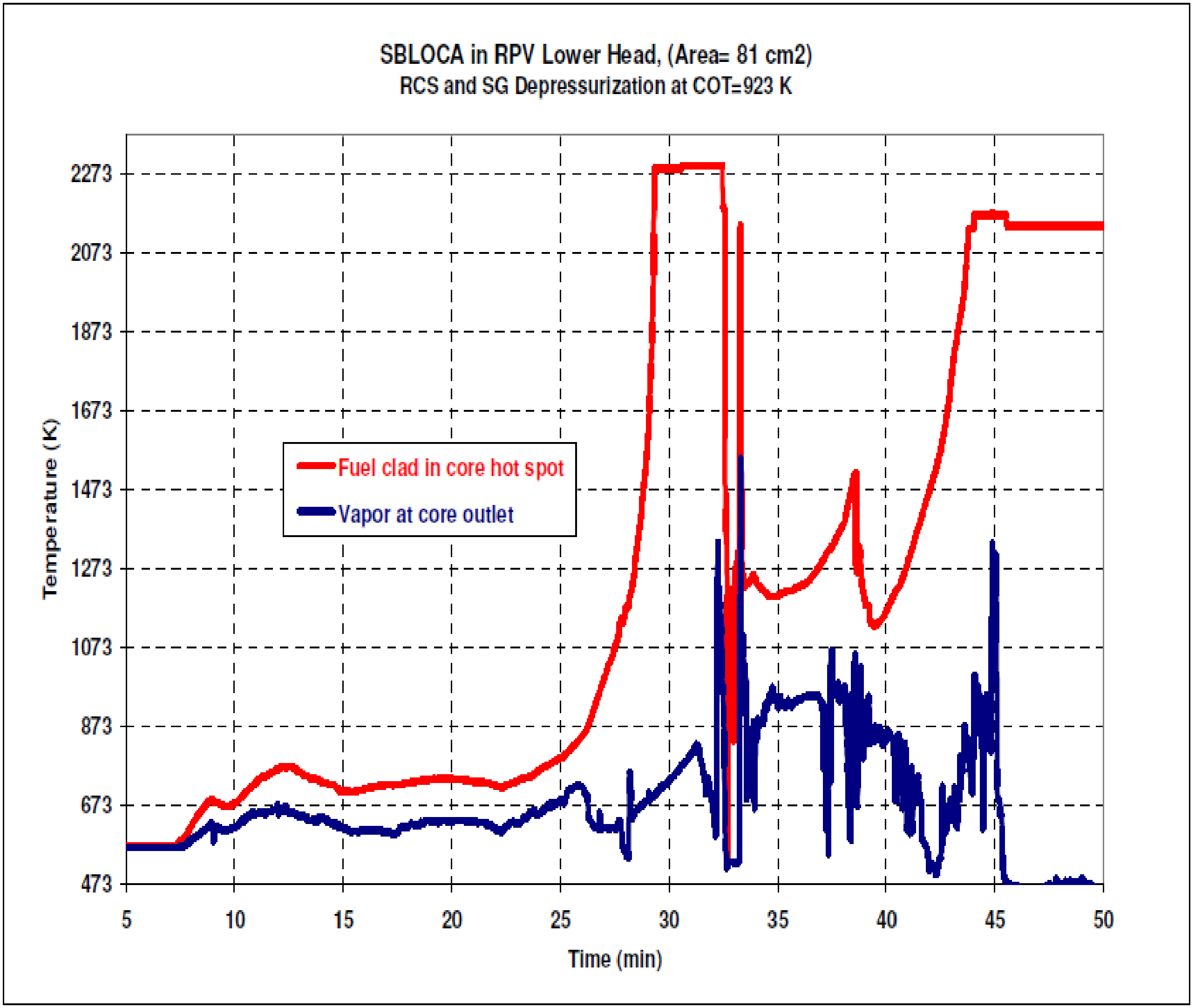
3) Transient Description and Simulation Results

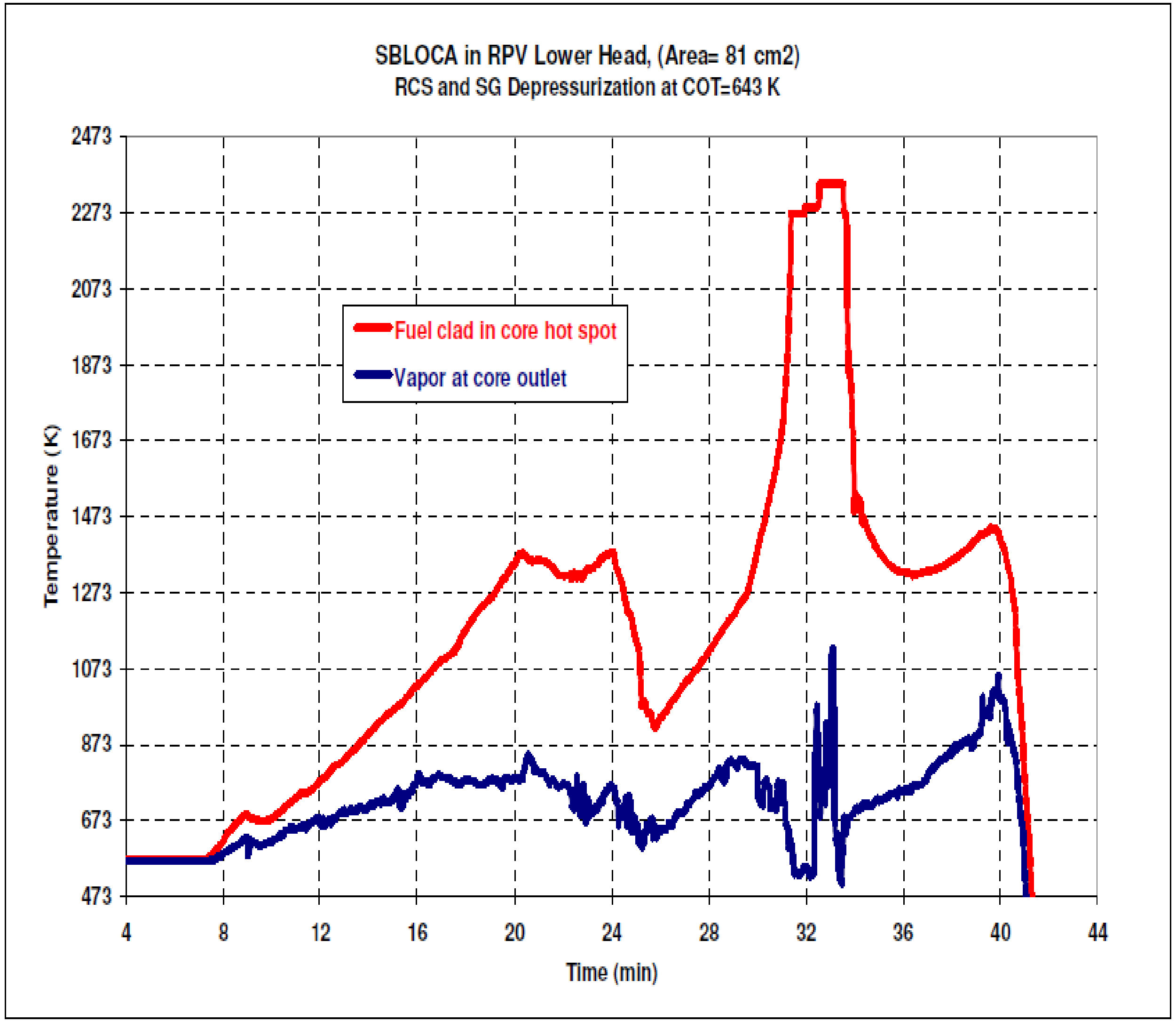




Depressurization of both the RCS and all SGs begins at To+33 (min) in Case #1 (ie COT>923 K) and at time To+11 (min) in Case #2 (ie COT> 643K)

3) Transient Description and Simulation Results

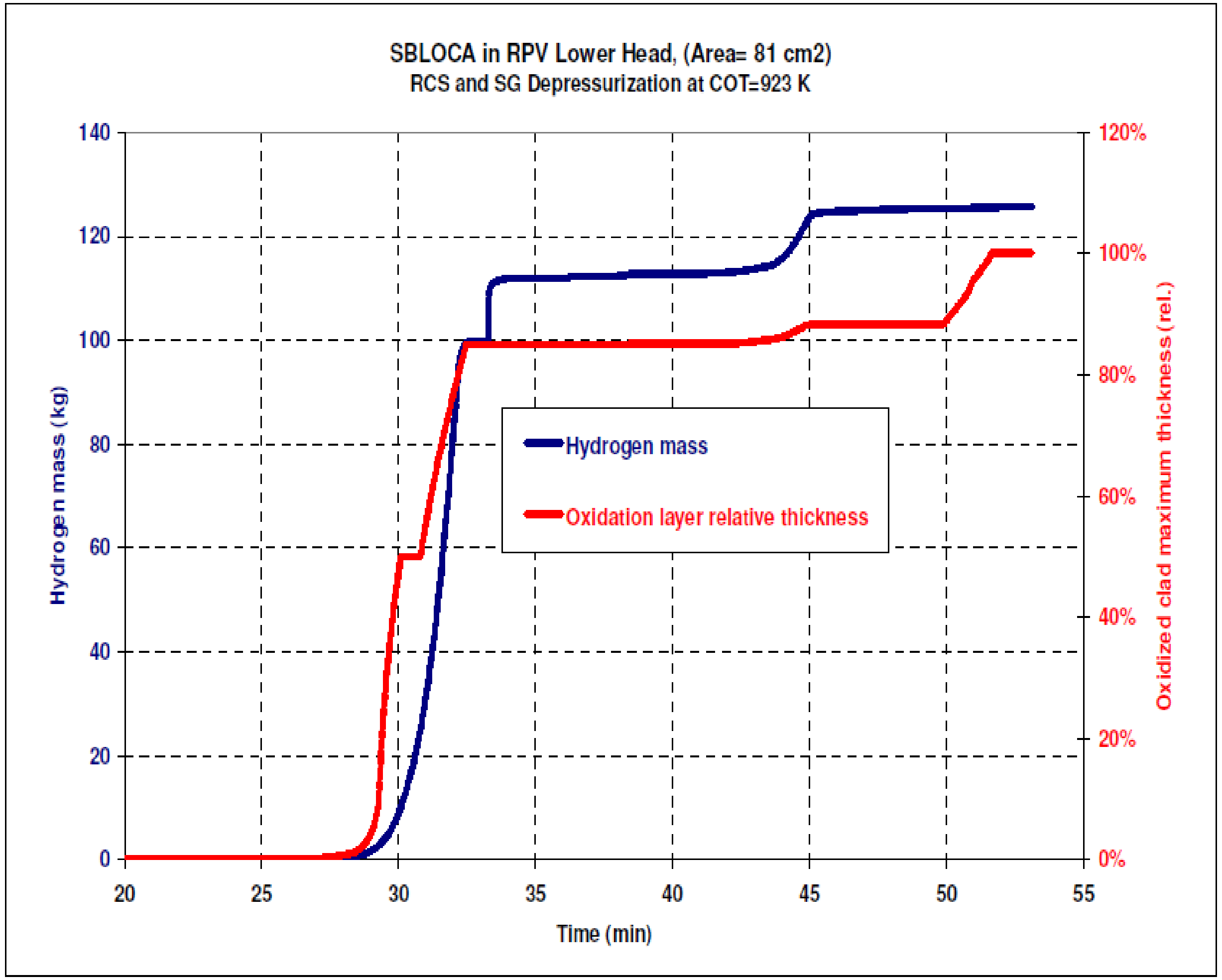

SBLOCA in RPV Lower Head, (Area= 81 cm2)
RCS and SG Depressurization at COT=923 K

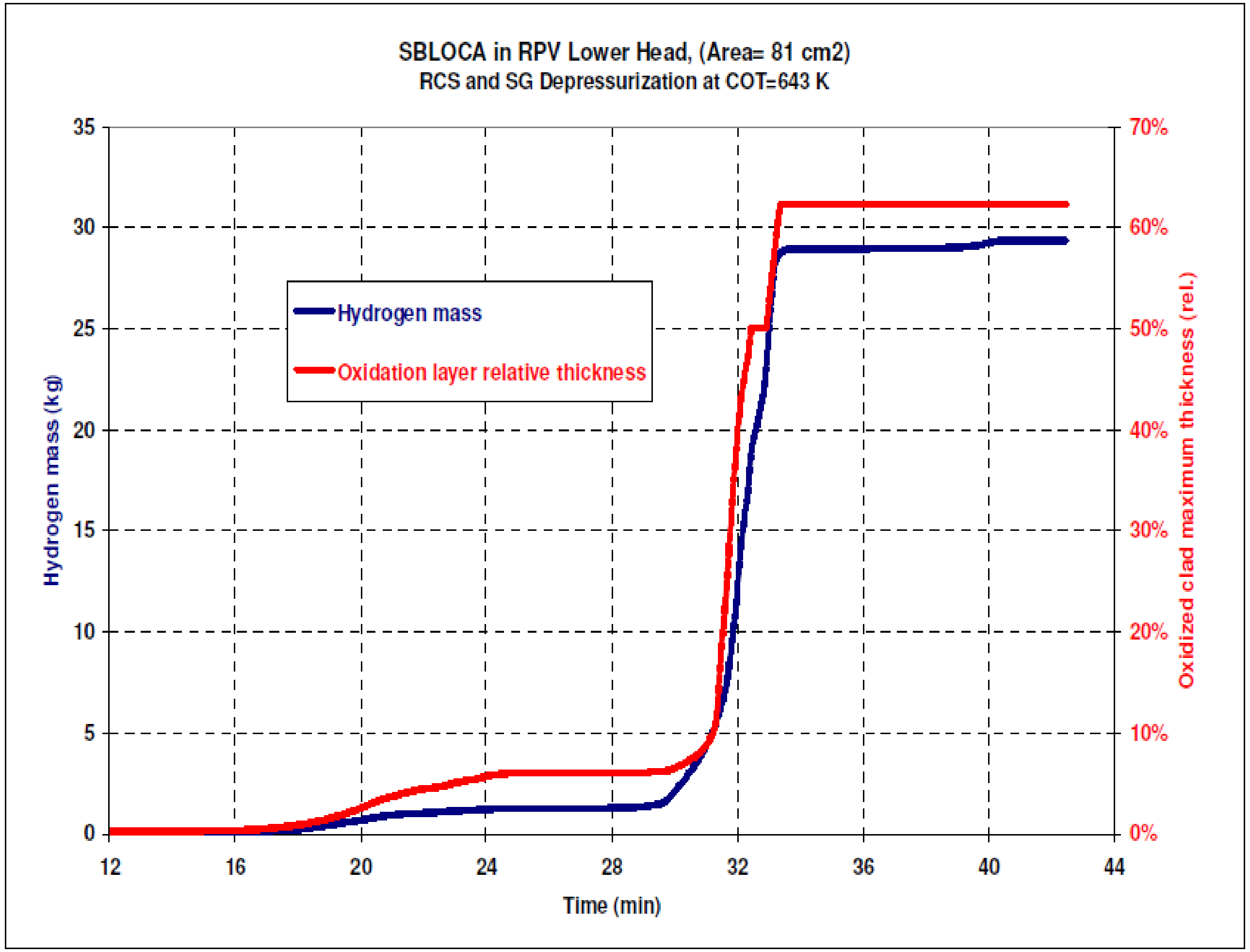

SBLOCA in RPV Lower Head, (Area= 81 cm2)
RCS and SG Depressurization at COT=643 K

Case #1 (COT=923K) Fuel clad peak temperature exceeds the **first fuel damage criterion** (ie PCT<1477) at **To+27** (min), ie prior to initiating AM:"Depressurization of both the RCS and all SGs"

Case #2 (COT=643) Fuel clad peak temperature exceeds the **first fuel damage criterion** (ie PCT<1477) at **To+31** (min), ie after initiating AM:"Depressurization of both the RCS and all SGs"

3) Transient Description and Simulation Results

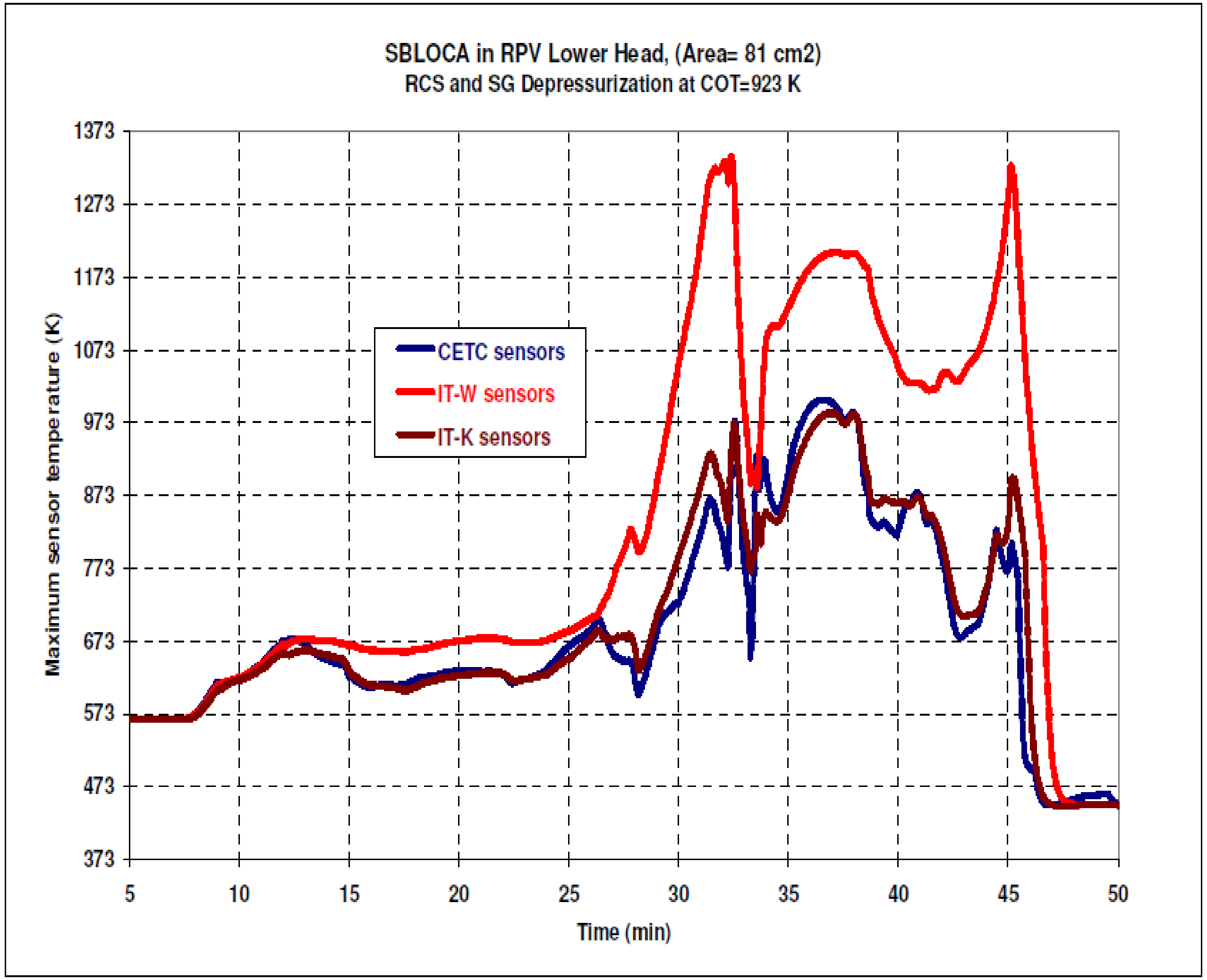


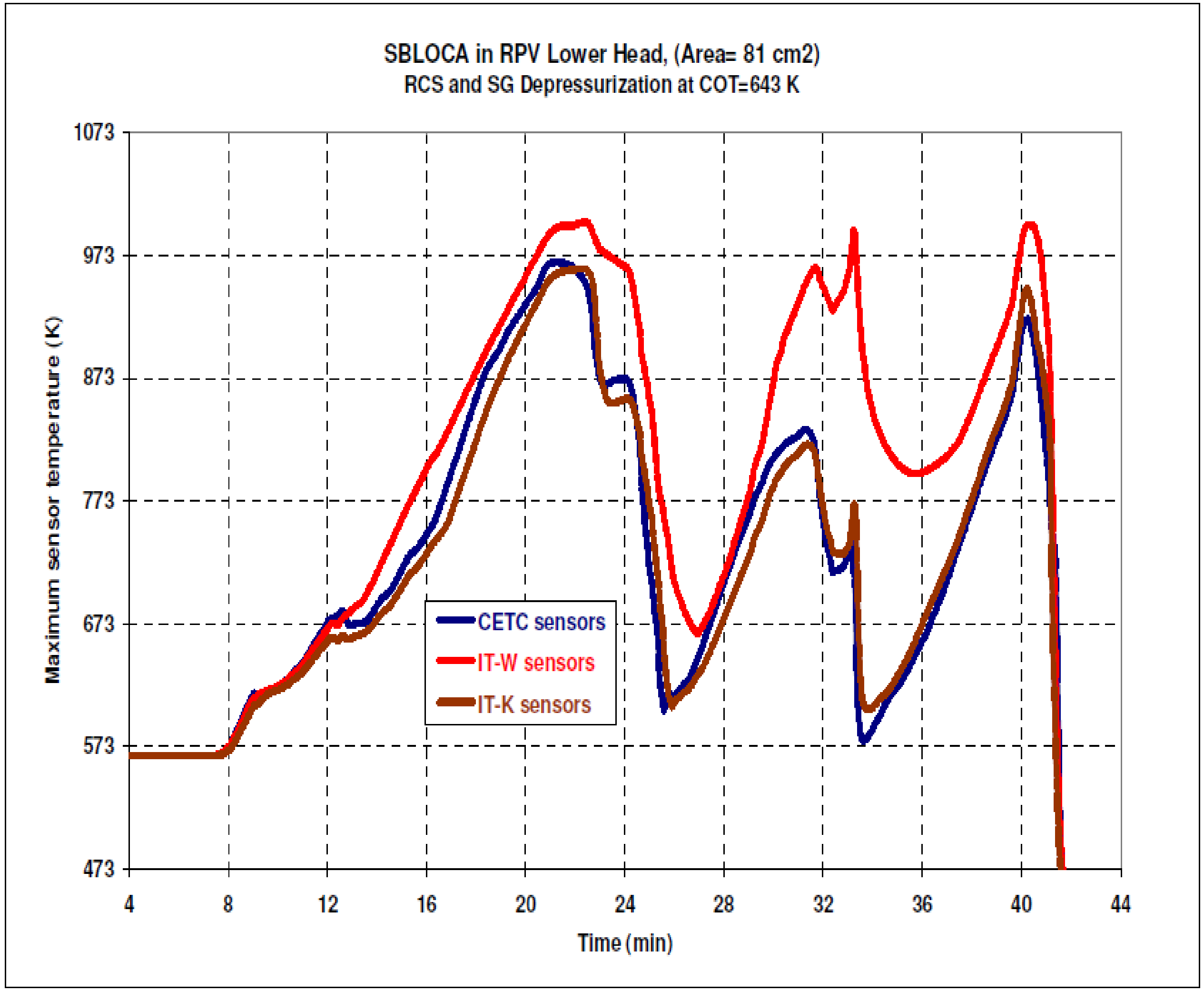


Case #1 (COT=923 K) The second fuel damage criterion (ie CWO <1%, defined as Mass of Hydrogen <10 kg) is exceeded at **To+27** (min), ie prior to initiating AM:"Depressurization of both the RCS and all SGs". By the time ICC was terminated, the total mass of hydrogen reached **124 kg**
The third fuel damage criterion, LMO<17%, oxidation layer on fuel clad wall, was exceeded at **To+28 (min)**

Case #2 (COT=643 K) The second fuel damage criterion (ie CWO <1%, defined as Mass of Hydrogen <10 kg) is exceeded at **To+32** (min), ie after initiating AM: "Depressurization of both the RCS and all SGs". By the time ICC was terminated, the total mass of hydrogen reached **28 kg**
The third fuel damage criterion, LMO<17%, oxidation layer on fuel clad wall, was exceeded at **To+32 (min)**

3) Transient Description and Simulation Results

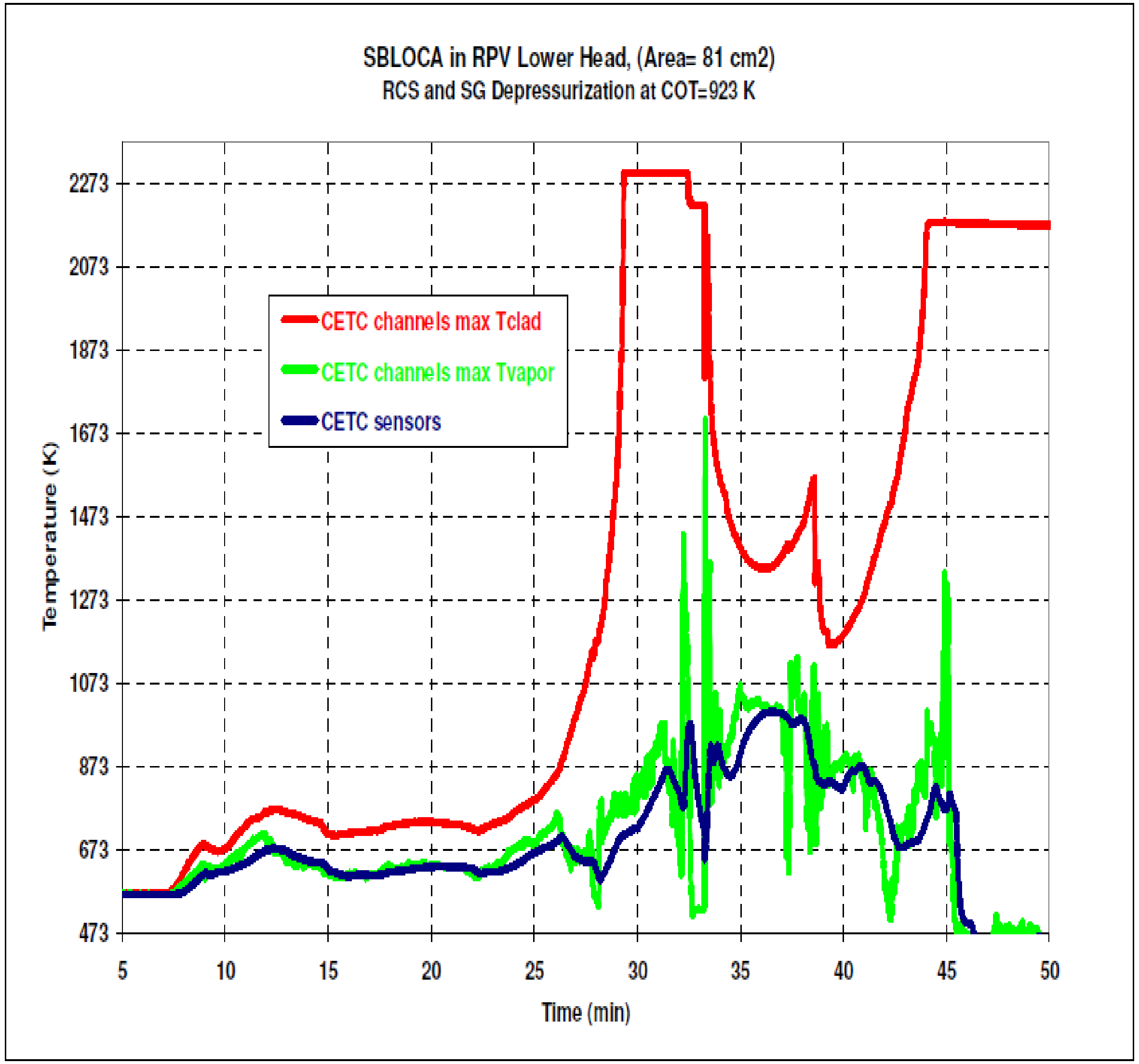

SBLOCA in RPV Lower Head, (Area= 81 cm2)
RCS and SG Depressurization at COT=923 K

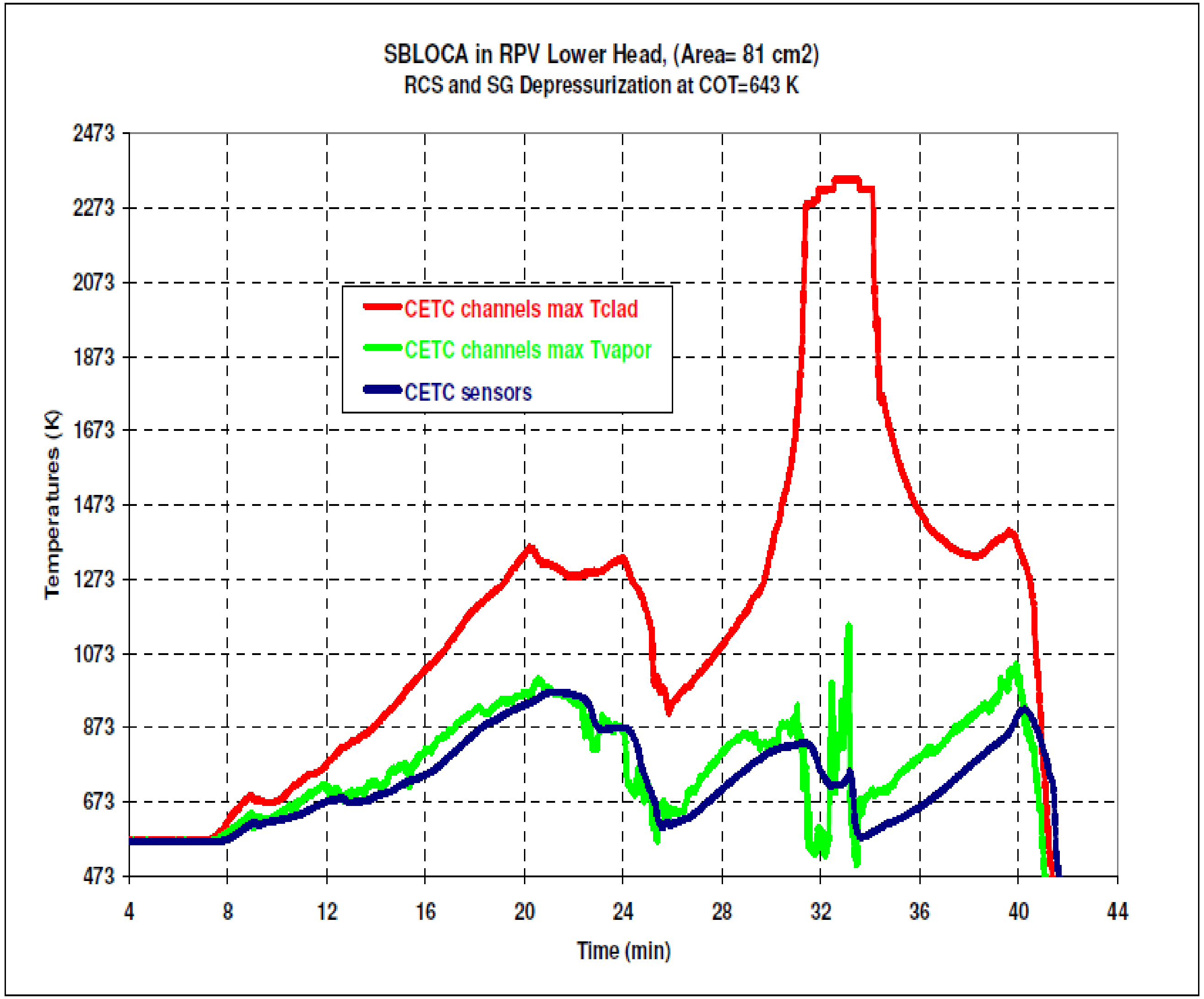

SBLOCA in RPV Lower Head, (Area= 81 cm2)
RCS and SG Depressurization at COT=643 K

Case #1 (COT=923 K) Both the CETC and the IITA-K fail to capture the rapid escalation of the fuel clad temperature (see Fig 10-3) at **To+27** (min), IITA-W appears better suited to track trends in the fuel clad temperature

Case #2 (COT=643 K) All sensors (CETC and IITA-K, IITA-W) track the first escalation at **To+20** min of the fuel clad temperature, but their readings are **300 K lower**. Only the IITA-W sensors respond to the second rise of the fuel clad temperature at **To+32** min.

3) Transient Description and Simulation Results





3) Transient Description and Simulation Results

	R	P	N	M	L	K	J	H	G	F	E	D	C	B	A
01							0,377	0,546	0,377						
02					0,373	0,708	1,156	1,242	1,154	0,704	0,372				
03				0,438	1,08	1,304	1,128	1,153	1,127	1,303	1,078	0,436			
04			0,436	1,057	1,039	1,099	1,432	1,122	1,434	1,093	1,039	1,057	0,438		
05		0,372	1,078	1,039	1,119	1,396	1,012	1,4	1,015	1,399	1,119	1,039	1,08	0,373	
06		0,704	1,303	1,093	1,399	1,055	1,08	1,088	1,083	1,055	1,396	1,093	1,304	0,708	
07	0,377	1,154	1,127	1,434	1,015	1,083	1,026	1	1,026	1,08	1,012	1,432	1,128	1,156	0,377
08	0,546	1,242	1,153	1,122	1,4	1,088	1	0,842	1	1,088	1,4	1,122	1,153	1,242	0,546
09	0,377	1,156	1,128	1,432	1,012	1,08	1,026	1	1,026	1,083	1,015	1,434	1,127	1,154	0,377
10		0,708	1,304	1,093	1,396	1,055	1,083	1,088	1,08	1,055	1,399	1,093	1,303	0,704	
11		0,373	1,08	1,039	1,119	1,399	1,015	1,4	1,012	1,396	1,119	1,039	1,078	0,372	
12			0,438	1,057	1,039	1,093	1,434	1,122	1,432	1,093	1,039	1,057	0,436		
13				0,436	1,078	1,303	1,127	1,153	1,128	1,304	1,08	0,438			
14					0,372	0,704	1,154	1,242	1,156	0,708	0,373				
15							0,377	0,546	0,377						

						100	81.3	81.3						
				100	100	100	29.3	100	36.6	100				
			100	100	28.9	100	29.4	100	100	100	100			
		100	100	100	100	100	28.9	28.8	100	100	100	100		
	100	100	100	28.9	28.7	100	100	100	100	100	100	100	100	
	100	100	28.7	28.7	100	100	100	100	100	100	100	100	100	
40.5	100	100	28.9	100	100	100	100	100	100	100	28.8	100	100	100
41	29	28.9	28.8	28.8	100	100	100	100	100	100	100	100	100	32.6
100	28.5	100	29.5	28.7	100	100	100	100	100	100	100	100	28.9	80.5
	100	28.9	28.9	28.5	100	29.2	100	100	100	100	100	28.9	100	
	100	100	100	28.8	28.8	100	100	100	100	100	100	100	100	
		100	100	100	28.7	28.8	100	100	100	100	100	100		
			29	100	28.7	100	100	100	100	100	100			
				100	100	100	30.4	28.9	100	100				
						82.1	60	100						

Fig 10-8

SBLOCA in RPV Lower Head, (Area= 81 cm2)
RCS and SG Depressurization at COT=923 K

Fig. 10-8. Relative Fuel Assembly Coolant Flow Area at time To+45.1 (min)
Fuel pins' clad rupture begins at To+34.2 (min) and ends at To+45.1 min
Average flow area per Fuel Assembly at time To+45.1 min: 83.2%

Fig 11-8

SBLOCA in RPV Lower Head, (Area= 81 cm2)
RCS and SG Depressurization at COT=643 K

						100	38.6	65.1						
				100	100	100	100	100	54.9	100				
			100	100	100	100	62	100	53.8	100	100			
		100	100	100	100	45.6	47.4	43.3	100	100	100	100		
	100	100	100	31.4	34	100	100	100	100	100	100	100	100	
	100	100	100	28.8	100	100	100	100	100	100	100	29.1	100	
100	100	100	29	100	100	100	100	100	100	100	31.1	100	100	100
69.8	38.6	33.6	32.1	30	100	100	100	100	100	100	100	32.1	33.9	78
74.9	39.5	38.7	33.2	29.1	100	100	100	100	100	100	100	100	32.1	100
	100	100	100	29	100	30.6	100	100	100	100	100	100	100	
	100	100	100	100	28.9	100	30.2	100	100	100	100	100	100	
		100	100	100	100	28.6	100	29.9	31.3	100	100	100		
			100	100	28.8	100	100	100	30.6	100	100			
				100	100	100	31.9	29.8	100	100				
						100	100	100						

Fig. 11-8. Relative Fuel Assembly Coolant Flow Area at time To+41 (min)
Fuel pins' clad rupture begins at To+21.4 (min) and ends at To+41 (min)
Average flow area per Fuel Assembly at time To+41 min: 84.8%

4) Conclusions

CONCLUSIONS

1) The RELAP5-3D code is capable of implementing a multi-dimensional approach to modeling complex flow patterns inside the core and in the upper internals plenum. This allows to simulate individual CETC and IITA sensors and to evaluate the impact on operator actions from sensors' failure;

2) The proposed modeling approach allows to tracking for the entire duration of the accident, how phenomena such as: in-core power radial and axial distribution, appearance of coolant circulation loops inside the core and the upper internals, and inflows of ECCS coolant into the RCS, influence the readings of individual CETC and IITA sensors.

3) In addition to the fuel's peak cladding temperature, (PCT), one may also consider the use of other RELAP5-3D calculated parameters, e.g. LMO, CWO, and the fraction of blocked in-core flow channels to evaluate the efficiency of a given accident management strategy and/or a particular operator action, eg depressurization of RCS and SG.

4) RELAP5-3D code is able to simulate the performance of in-core coolant temperature sensors of type IITA-W, i.e. those having heat exchange with neighboring fuel pins via thermal radiation in addition to convection with adjacent fluid. The comprehensive comparison of the performance of the IITA-W and CETC sensors requires a detailed description of the sensors design and characteristics and a consideration of wider set of accident scenarios.

5) Future activities, related to the topics investigated in this study, may include the validation of the developed modeling multi-dimensional approach by using experimental data, obtained in the framework of international research projects in which Bel V participates.

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