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The Phenomena Identification and Ranking Table for APR-1400 Main Steam Line Break

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Abstract

A Phenomena Identification and Ranking Table (PIRT) was developed for the Main Steam Line Break (MSLB) event of APR-1400 (Advanced Power Reactor-1400). A team of experts from research institute, industries, and regulatory body contributed to the development. The selected event was double-ended steam line break at full power with reactor coolant pump running. The panels selected the fuel performance as the primary safety criterion for ranking. The plant design data, the results of APR-1400 safety analysis, additional best estimate analysis results by MARS2.1 were utilized. Three phases of pre-trip, rapid cool-down, and safety injection phase are identified. Then, the ranking of a system, components, phenomenon/process based on the relative importance to the primary evaluation criterion are followed for each time phase. Finally, the knowledge-level for each important process in the component is ranked in terms of the existing knowledge.

The highly ranked phenomena identified for APR-1440 MSLB are the tube wall heat transfer at steam generator shell, void distribution at steam generator shell, liquid entrainment in the separators, mixture level in the separators, boron mixing in the upper down comer, boron transport and thermal mixing in the lower plenum, stored energy release in the upper head, and flow to and/from upper head. The PIRT developed in this study will be used as a guide to planning cost effective experimental programs and code development efforts, especially for the quantification of process and/or phenomena, which have high importance but low knowledge level.

1. Introduction

Two units of advance light water reactor of APR-1400 (Advanced Power reactor–1400) will be constructed in Korea by 2011[1]. As they have new advanced design features such as, Direct Vessel Injection (DVI), Fluidic device in the Safety Injection Tank (SIT), and In-containment Refueling Water Storage Tank (IRWST), it would accompany new thermal-hydraulic behaviors during the Design Basis Accidents (DBA), some of which have high importance but not understood well due to limited experimental data and knowledge. It should be fully understood and verified to ensure the enhanced safety provided by those design features.

The Phenomena Identification and Ranking Table (PIRT) was proposed to define the plant behavior in the context of identifying the relative importance of systems, components, processes and phenomena in driving the plant response for new plant designs. It was very effective and has adjunct functions of providing guidance in establishing the requirements in separate and integral effects experimental program, and the code development and improvement, where the objective is to help insure the code is capable of modeling the plant behavior [3,4].

The PIRT was developed during the initial design phase of the integral type reactor of SMART (System Integrated Modular rector), whose design was radically different from that of the conventional PWR [5]. Within the same contest discussed above, a PIRT was developed the Large Break Loss of Coolant Accident (LBLOCA) of APR-1400 [6]. This paper discusses the process of developing a PIRT for the Main Steam Line Break (MSLB) event of APR-1400. A team of experts from research institute, industries, and regulatory body contributed to the development. The plant design data, the results of APR-1400 safety analysis [1], additional best estimate analysis results by MARS2.1 were utilized.

2. A Best Estimate Analysis of the MSLB

The licensing analysis for APR-1400 was performed by the CESEC computer code [7]. It has MSLB specific conservative models to maximize either the pre-trip fuel failure or potential for the post-trip return to power, which would result in the conservative offsite dose [1,8]. So, the event scenario presented in APR-1400 SSAR is rather distorted. As it could bias the expert opinion during PIRT process, a best estimate analysis of the MSLB event for APR-1400 MSLB was performed by MARS[9].

The preliminary input deck for APR-1400 SBLOCA analysis [10] was modified to analyze MSLB. The reactor vessel has splitted core and down-comer nodes to model the asymmetric cool down. The mixing factors in the lower plenum and upper plenum employed in the CESEC analysis are modeled by adjusting the k-factors in the flow paths in the MARS analysis. Each steam line has four nodes to model main steam isolation valve and break. The nodal scheme is shown in Figure 1 below.

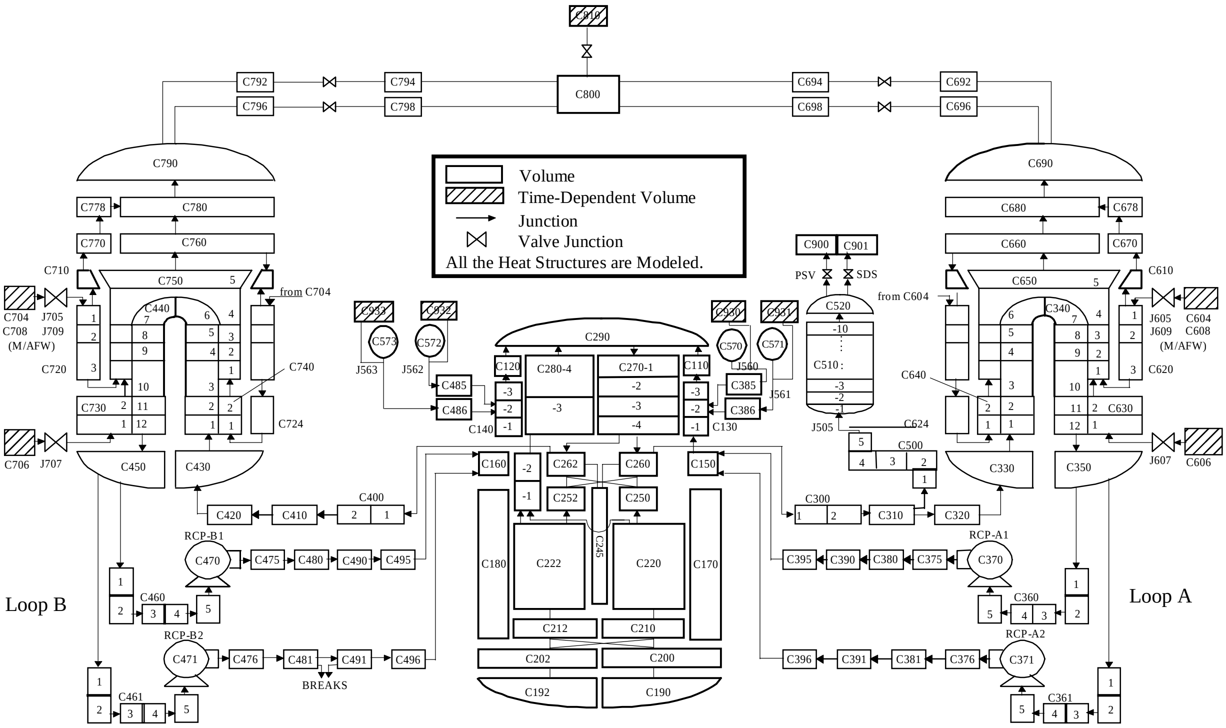

Fig. 1 Nodalization Diagram for APR1400 MSLB Analysis

The analysis were performed for the main Steam Line Break at Full Power with reactor coolant pump running (SLBFP) and the main steam break at full power with Loss of Offsite Power (SLBFPLOP). It is double-ended guillotine break. The conservative input data including the set points and capacity of the safety systems used in the SSAR analysis were used in the MARS analysis to make fair comparison of thermal-hydraulic response of the system.

2.1 The Analysis results for SLBFP

A comparison of pressurizer pressure is made between the APR SSAR analysis by CESEC (dotted line), and MARS analysis (solid line) in Figure 2. It is shown that the pressure behavior of best estimate analysis by MARS is quite different from that of CESEC. After pressurizer is being emptied the RCS depressurization slowed down abruptly in the CESEC analysis, while the depressurization rate slowed down just a little bit in the MARS analysis. Also, in the CESEC analysis, the RCS pressure decreases abruptly after 400 seconds, while the RCS pressures from the MARS analysis are recovered after the steam generator dry-out. It is closely related to the specific modeling of upper head in the CESEC. The CESEC behavior seems to be rather distorted.

Figure 3 shows the behavior of void fraction in the upper head in case of CESEC and MARS. The void collapses early in MARS analysis. In the CESEC analysis, when the upper head void collapses, the RCS pressure decreases very fast and the RCS pressure increases as the upper head void is being collapsed.

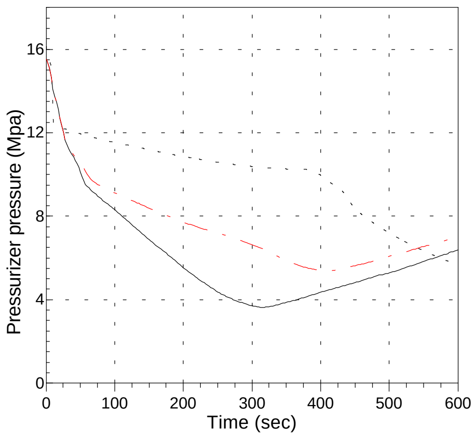

Figure 2 Pressurizer Pressure for SLBFP

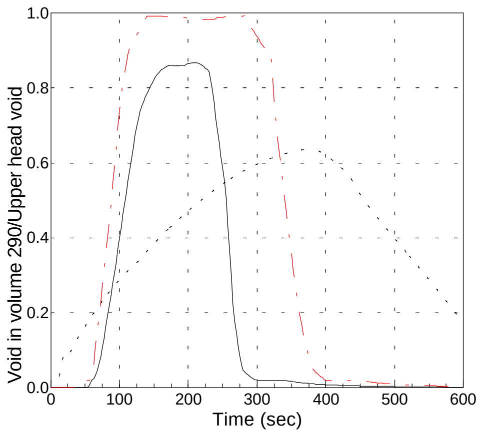

Figure 3 Upper head void fraction for SLBFP

As the upper head behavior is closely related to the RCS pressure, a sensitivity study was performed. The results are indicated as a dash line with single point in Figures 2 and 3. By increasing the K-factors at junctions to top head from down-comer, core to upper guide structure, the effect of upper head modeling on RCS pressurization was investigated. As expected, the upper head was more isolated from the system and it resulted in a more void in the upper head. It resulted in a slower depressurization.

It is to be noted that the margin to return to power was substantial in the best estimate analysis, while CESEC analysis resulted in a return to power. It is due to the difference in the RCS pressure behavior.

2.2 Analysis results for SLBFPLOP

In the case of Steam Line Break at Full Power with Loss of Offsite Power (SLBFPLOP), the RCS pressure behaviors from CESEC and MARS are quite similar. The pressurizer pressure and upper head void fraction is shown in Figures 4 and 5. As there is little flow from the remainder of the RCS, the upper head is isolated from the remainder of the system. So, the upper head remained voided while the system cooled down. So, the effect of difference in the upper head modeling did not affect the results much.

Figure 6 shows that the steam generator pressures for both cases. They are similar. Figure 7 indicates that the margin to return to power is smaller in this case than that of SLBFP, which is in the opposite direction to that of CESEC. So, the reason for this difference should be elaborated during the PIRT process.

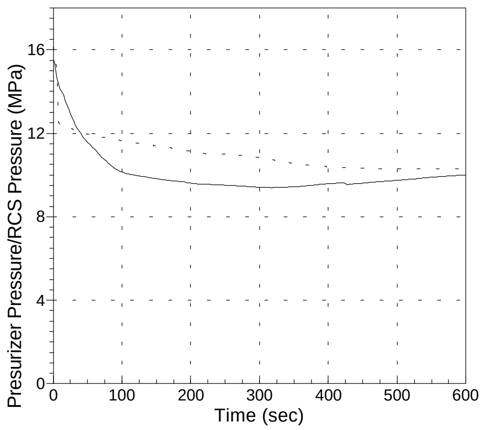

Figure 4 Pressurizer Pressure for SLBFPLOP

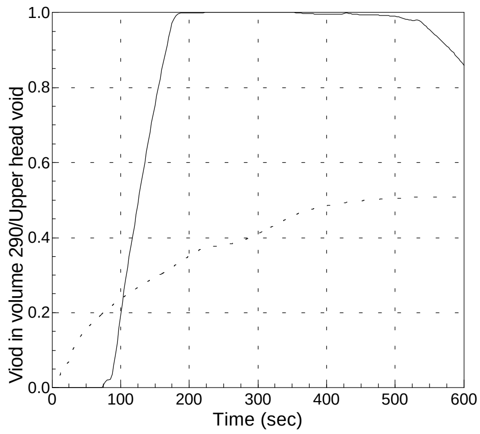

Figure 5 Upper head void fraction SLBFPLOP

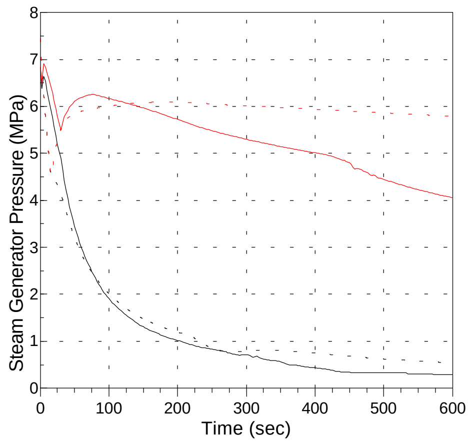

Figure 6 SG Pressure for SLBFPLOP

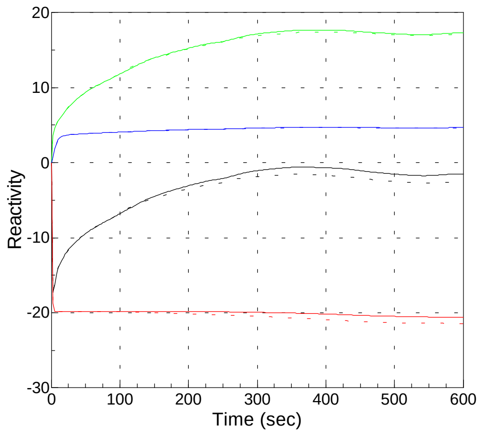

Figure 7 Reactivity change for SLBFPLOP

The effect of cold leg injection and direct vessel injection was investigated. The solid line is the direct vessel injection case and the dotted line represents the cold leg injection case in Figure 7. Direct vessel injection was worse in terms of margin to return to power. Part of the safety injection flow is mixed with stagnant liquid in the upper down comer in the direct vessel injection case, while safety injection flow is directly mixed with the cold leg water and supplied directly to the down-comer. So, the boron delivery to the core is delayed in the direct vessel injection case as shown in the above plot.

3. The PIRT process

The PIRT process consisted of 15 steps. The expert panels had intense and interactive discussions to reach common understanding and conclusion.

Step 1: Define problems: The selected event was the main steam line break at full power with double ended guillotine break. Major phenomena and results of conservative analysis in APR-1400 and best estimate analysis are provided by MARS analysis.

Step 2: Define PIRT objectives: The panels agreed that the PIRT process should not be biased for the application in designing the Integral Effect Test (IET). The panels will look at all the important aspect of the MSLB for both the experimental programs and code development efforts.

Step 3: Define plant designs: The panels were familiar with APR-1400, as the panels were actively involved in the design, research, and regulatory activities for APR-1400. Whenever, it was necessary, plant design data and P&ID were looked up.

Step 4: Define potential scenarios: The selected event is double-ended steam line break at full power with reactor coolant pump running, as this case was the limiting case in APR-1400 SAR. However, the effect of RCP, break size, and power was evaluated case by case.

Step 5: Define parameters of interest: The law 10CFR100 specifies that the offsite dose resulting from the MSLB should be within certain limit. In the next level of safety criteria of General Design Criteria (GDC) and Standard Review Plan (SRP), there are two primary safety criteria. The first one is the design limit on the containment pressure and temperature. The second is the limit on the fuel failure, which is determined by the pre-trip fuel failure and post-trip fuel failure. The panels decided to focus on the fuel performance as it is directly related to the off-site dose. It is assumed that Architect Engineer (AE) would provide enough safety-margin for the containment. Not only the pure thermal hydraulics but also phenomena related to the reactivity feedback should also be looked at.

Step 6: Identify, obtain and review all available experimental and analytical data: APR-1400 SAR, UCN 3&4 SAR, KNGR MSLB analysis by MARS, plant design data, and P&ID were used.

Step 7-8: Define high-level basic system process/Partition scenario into convenient time phase:

Three phases of pre-trip, rapid cool-down, and safety injection phase are identified. The pre-trip phase is the period before reactor trip. The rapid cool-down phase is the phase before the safety injection, during which the pressurizer empties, the void increases in the upper head, the reactivity continue to increase, the steam generator level drops or being empties, but the pressurizer pressure is still high for the boron delivery. As the steam generator dry-out is the outstanding event and it has big effect on the RCS behavior, the third phase could be named as the post steam generator dry-out phase. However, as the post-trip return to power is of more concern and the auxiliary feed water could be continuously supplied to the affected generator depending on the auxiliary feed water system design, the third phase was named as safety injection phase. Cartoons for each phase are shown below

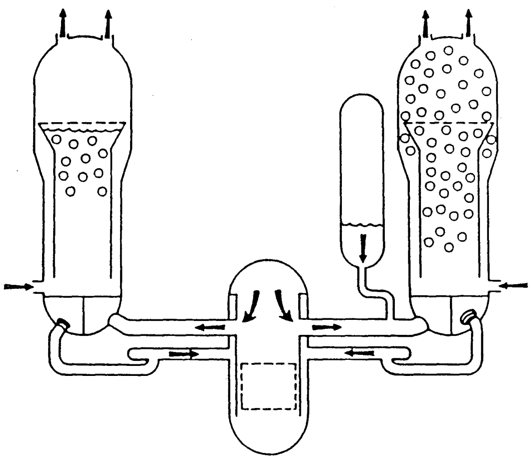

Figure 8 Pre-trip phase

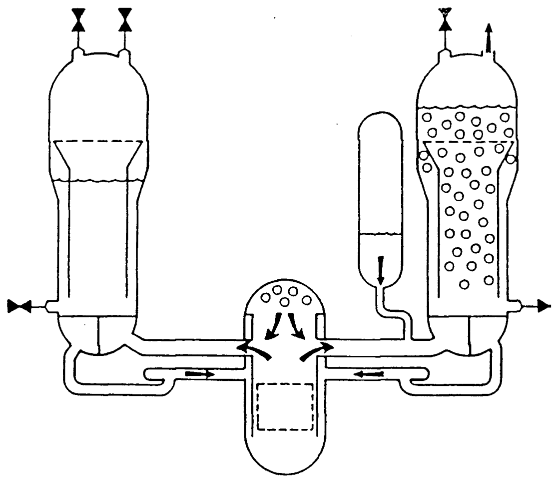

Figure 9 Cool down phase(Early)

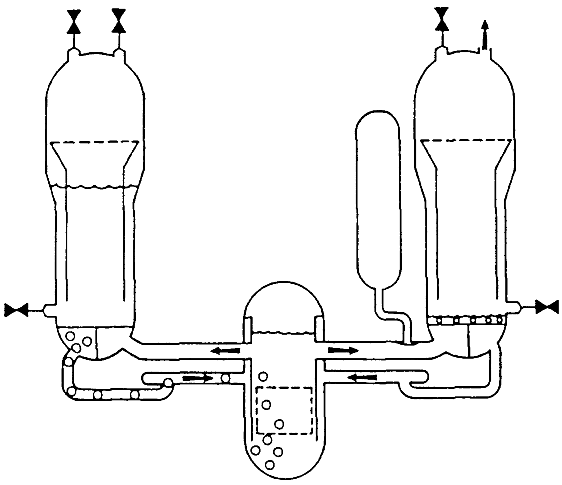

Figure 10 Cool down phase (Late)

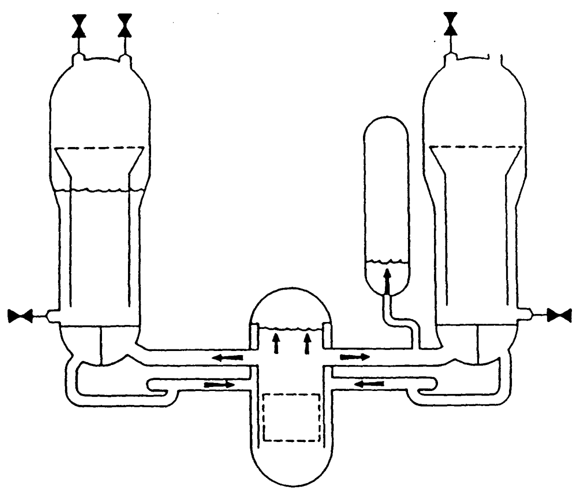

Figure 11 Safety Injection phase

Step 9. Partition plant designs into components: Though a typical PWR is a complicated system, it can be easily partitioned to subsystems and components by their functions. The components are selected in the aspect of their function during the main steam line break event are listed.

Step 10. Identify and Define Plausible Phenomena and Processes by Phase and Component: PIRT development was based on the collective expertise of broad experience. In addition, the analysis results of APR-1400 SSAR analysis, which were analyzed by conservative CESEC-III computer code, and a best estimate analysis results by MARS were provided. The question was "how do the team members discover what they do not know" with respect to expanding state-of-the-art knowledge.

Step. 11 Rank High-Level Systems by Phase: The basis for ranking of a phenomenon/process is in terms of its relative importance to the primary evaluation criterion, which is the fuel performance. Prior experience suggests a numerical ranking scheme of 1 to 5. The scale is the same one used in reference 3.

Step 12 Rank Components (Sub-Components) by Phase: Ranking of the components follows the ranking of the high-level systems. The same ranking scale is used as that of the high-level systems. As noted previously, a component cannot have a higher rank than the high-level system in which it is located.

Step 13 Rank Phenomena/Processes by Phase: Ranking of the phenomena/processes follows the ranking of the components. The same ranking scale is used as that of the components. As noted previously, a phenomenon/process cannot have a higher rank than the component in which it is located.

Step 14 Perform selected PIRT confirmation sensitivity studies: In large part, the initial ranking of high-level systems, components and phenomena are based on the collective knowledge of the expert panel, although the panel may be able to benefit from computer code simulations if they exist. During the PIRT meeting, following cases are suggested for further analyses to confirm the ranking assigned. (1) Comparison of cold leg injection and direct vessel injection case for MSLB at full power with reactor coolant pumps running to evaluate the boron transport phenomena, and (2) Evaluate the effect of upper head structure by performing a sensitivity study on heat structure.

Step 15 Evaluate Knowledge-Level of Ranks: The knowledge-level ranks the panel assigned to the phenomena/processes high importance ranks are summarized in PIRT in Table 1. The ranking scale is the same one used in the Reference 3.

4. Results of PIRT for APR-1400 MSLB

The PIRT for APR-1400 is provided in Table 1. The structure of the table follows the PIRT procedure described in the previous section. The high level systems, components and phenomena/process and their ranks for each of the three times phases are provided.

The PIRT can serve as a guide to planning cost effective experimental programs and code development efforts for APR-1400. Especially for the experimental programs, the process and/or phenomena, which have high importance but low knowledge level, are identified as below. Experimental verification of these phenomena will be very helpful to understand the APR-1440 MSLB in terms of primary safety criteria. Followings are discussions on each highly ranked phenomenon.

Tube wall heat transfer at steam generator shell (Knowledge level 3, Importance 5): The heat transfer at the steam generator U-tube shell plays a primary role in determining the cool down rate of reactor coolant system. As the negative moderator temperature feedback affects the reactivity in the core, the cool down rate directly determines the pre-trip core power and the possibility of post trip return to power. The heat transfer on the U-tube secondary side is either pool boiling or condensation. As the geometry of the U-tube bundle is very complicated, the heat transfer model employed in state of the art computer code for safety analysis has a big uncertainty. Some of the design code for the performance of steam generator is only tested for the full power condition. However, the thermal hydraulic condition during the blow down of steam generator is far from the design condition. So, the heat-transfer in the U-tube bank having complex geometry at off design condition needs to be investigated further.

Void distribution at steam generator shell (Knowledge level 3, Importance 5): During the initial blow-down, the steam generator is filled with two-phase. After the main steam isolation, the two-phase mixture level may form due to phase separation. As the amount of water inventory determines the steam generator dry out time, the void distribution is important. The void distribution in complex geometry is not well known.

Liquid entrainment in the separators (Knowledge level 2, Importance 5): The superficial velocity of steam is expected to be bigger than that at full power until the middle of second phase. During this period, the performance of the separator and the amount of water entrainment in the steam flow is uncertain, since the separator has never been tested at off design condition.

Mixture level in the separators (Knowledge level 3, Importance 5): It has same degree of uncertainty and importance as the liquid entrainment.

Boron mixing in the upper down comer (Knowledge level 3, Importance 4): When the RCP runs, the safety injection flow with high boron injection may flow into the upper head due to the bypass flow. If the amount of the safety injection flow being bypassed to the upper head is significant, the boron delivery to the core could be heavily affected. However, as the flow geometry is complicated, the amount of safety injection flow being bypassed is highly uncertain.

Boron transport in the lower plenum (Knowledge level 3, Importance 4): The boron injected into the down comer is mixed with unborated water in the lower plenum. As the geometry of lower plenum is complicated and there are few experimental data to bench mark the capability of CFD code for mixing analysis, the phenomena is highly uncertain.

Thermal mixing in the lower plenum (Knowledge level 3, Importance 4): It has same degree of uncertainty and importance as that in item above..

Stored energy release in the upper head (Knowledge level 4, Importance 5): The stored energy in the upper head has a big influence on the system depressurization, as the volume of the upper head and the amount of heat structure is big compared to other system components. The release of the stored energy in the upper head plays a major role in determining the amount of void formed in the upper head. As it governs the pressure during the depressriation, it is very important. The stored energy release phenomena itself is not uncertain, however, the complex geometry in the upper head make it have moderate uncertainty.

Flow to and/from upper head (Knowledge level 4, Importance 5): The multi-dimensional flow pattern and complicated flow path in the upper head determines the pressurization behavior. So, it should be properly preserved in the experimental facility.

Acknowledgement

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5. References

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Table 1 PIRT for APR-1400 MSLB

System	Rank by time phase			Component	Rank by time phase			Process/Phenomena	Rank by time phase			Knowledge Level		
	1	2	3		1	2	3		1	2	3	1	2	3
SIS	NA	NA	4	**HPSI**	NA	NA	4							
				Flow path				Delivery f(p)	NA	NA	4	NA	NA	5
				SI Piping										
				Fluid volume	NA	NA	4	Time delay due to unborated volume	NA	NA	4	NA	NA	5
RCS	3	4	3	**Pressurizer/surge-line**	3	4	3							
				Structure (wall, heater)				Heat loss, heating	1	2	2			
				Fluid volume				Depressurization (flashing)	3	4	3		5	
				Flow path				Pressure drop	2	4	3		4	
				Steam gen. (Pri. Side)	3	3	3							
				Structure				Stored energy release	<3	<3	<3			
				Fluid volume				Primary-secondary heat transfer	<3	<3	<3			
								Secondary-primary heat transfer	<3	<3	<3			
				Flow paths				Pressure drop	<3	<3	<3			
				RCP (Reactor coolant pump)	2	2	2							
				Fluid volume				Dissipation power	<2	<2	<2			
				Flow paths				Homologous curve	<2	<2	<2			
				Cold legs	1	1	1							
				Structure				Stored energy release	<1	<1	<1			
				Fluid volume				Flashing	<1	<1	<1			
				Flow paths				Delta-p	<1	<1	<1			
				Hot legs	2	2	2							
				Structure				Stored energy release	<2	<2	<2			
				Fluid volume				Flashing	<2	<2	<2			
				Flow paths				Delta-P (1-phase, 2-phase)	<2	<2	<2			
Steam	5	5	4	**Main feed water line**	2	2	NA							

generator (secondary side)				Flow paths				Flow rate	<2	<2	<2			
				Fluid volume				Volume before MFIV	<2	<2	<2			
								Flashing	<2	<2	<2			
				Main steam line	1	1	1							
				Flow paths				Flow path to break	<1	<1	<1			
								Pressure drop	<1	<1	<1			
				Fluid volume				Total volume	<1	<1	<1			
				Break (flow restrictor)	5	5	4							
				Flow paths				Two-phase critical flow	5	5	4	4	4	5
				Main steam isolation valve	NA	2	NA	Time to close	NA	2	NA			
				Feed line isolation valves	NA	2	NA	Time to close	NA	2	NA			
				SG shell side volume	5	5	4							
				Fluid volume				Tube wall heat transfer	5	5	4	4	3	3
								Flashing	5	4	3	5	5	5
								Mixture Level/Void distribution	5	5	3	3	3	3
				SG separator /dryer	5	5	3							
				Fluid volume				Mixture level	5	4	3	3	3	5
								Liquid entrainment	5	5	3	2	3	5
				Steam generator Economizer	1	1	2							
				Fluid volume				Water hammer/FIV	<1	<1	<2			
				Heat structure				Stored energy release	<1	<1	<2			
				Steam generator Down-comer	2	2	2							
				Fluid volume				Water hammer/FIV	<2	<2	<2			
				Heat structure				Stored energy release	<2	<2	<2			
				AFWS	NA	3	4							
				Flow paths				Flow rate		3	4			5
Reactor Vessel	5	5	5	**Upper head**	2	5	3							
				Structures				Stored energy release	2	5	3		4	
				Fluid volume				Flashing	2	5	3		5	
								Condensation	NA	NA	3			
				Flow paths				Upper head to upper plenum	2	5	3		4	
								Upper down comer to upper head	2	5	3		5	

								Core to upper head	2	5	3		4	
								Multi-dimensional flow pattern	1	1	1			
				Upper down comer (DVI)	1	1	4							
				Fluid volume				Boron mixing	<1	<1	4			3
				Upper plenum	1	3	3							
				Structures				Stored energy release	<1	<3	<3			
				Fluid volume				Flashing	<1	<3	<3			
				Flow paths				Core to upper plenum flow	<1	<3	<3			
								Upper plenum to upper head	<1	<3	<3			
				Core region	5	5	5							
				Fuel rods				Rod heat transfer	5	5	5	4	5	4
								Scram reactivity	NA	5	5	NA	5	5
								Asymmetric 3D power distribution	5	5	5	4	4	4
								Fluid mixing in the 3D core	2	2	2	4	4	4
								Moderator feed back	5	5	5	5	5	5
								Doppler feedback	4	4	4	5	5	5
								Boron transport	NA	NA	5	NA	NA	4
								Decay power	NA	3	4	NA		5
				Barrel/Baffle region	1	1	1							
				Structures core barrel/baffle				Stored energy release	<1	<1	<1			
				Fluid volume				Flashing	<1	<1	<1			
				Flow path				LP - barrel baffle region flow	<1	<1	<1			
								Barrel baffle - UP flow						
				Lower plenum	3	4	4							
				Fluid volume				Boron transport	NA	NA	4			3
								Asymmetric mixing	3	4	4		3	3
				Down comer	3	4	4							
				Fluid volume				Boron transport	NA	NA	4			4
								Asymmetric Mixing	3	4	4		4	4