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

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Abstract

A phenomena identification and ranking table (PIRT) was developed for a main steam line break (MSLB) event for the Advanced Power Reactor-1400 (APR-1400). The selected event was a double-ended steam line break at full power, with the reactor coolant pump running. The developmental panel selected the fuel performance as the primary safety criterion during the ranking process. The plant design data, the results of the APR-1400 safety analysis, and the results of an additional best-estimate analysis by the MARS computer code were used in the development of the PIRT. The period of the transient was composed of three phases: pre-trip, rapid cool-down, and safety injection. Based on the relative importance to the primary evaluation criterion, the ranking of each system, component, and phenomenon/process was performed for each time phase. Finally, the knowledge-level for each important process for certain components was ranked in terms of existing knowledge. The PIRT can be used as a guide for planning cost-effective experimental programs and for code development efforts, especially for the quantification of those processes and/or phenomena that are highly important, but not well understood.

Key Words : PIRT, main steam line break, APR-1400, MARS, rank, knowledge level

1. Introduction

Two units of the advanced light water reactor of APR-1400 (Advanced Power Reactor-1400) will be constructed in Korea by 2011[1]. The APR-1400 employs novel safety systems, such as a direct vessel injection (DVI), a fluidic device in the safety injection tank (SIT), and an in-containment refueling water storage tank (IRWST). Consequently, the APR-1400 response to design basis accidents (DBA) will be accompanied by new thermal-hydraulic behaviors, some of which are highly important but not well understood, thus far, due to limited experimental data and knowledge. The new thermal-hydraulic behaviors should be fully verified and understood, to ensure that enhanced safety is provided by the new design features of the APR-1400.

A phenomena identification and ranking table (PIRT) was proposed to define plant behavior in the context of identifying the relative importance of the systems, components, processes, and phenomena in driving the plants responses for new plant designs[2]. The PIRT also has the additional functions of providing guidance in establishing the requirements for separate and integral effects experimental programs, and code development and improvement, where the objective is to insure that the code is capable of modeling the plant behavior [3, 4].

A PIRT was developed during the initial design phase of SMART (System-integrated Modular Advanced ReacTor), an integral-type reactor whose design was radically different from that of the conventional PWR [5]. Within the same context discussed above PIRTs were developed for a large-break loss-of-coolant accident [6] and a small-break loss-of-coolant accident(SBLOCA) [7] for the APR-1400. This paper discusses the process of developing a PIRT for a main steam line break (MSLB) event for the APR-1400. A team of experts from research institutes, industries, and the regulatory body contributed to the development of the PIRT. These experts used the plant design data, the results of the APR-1400 safety analysis, and the additional best estimate analysis results by the MARS computer code to develop the PIRT.

2. A Main Steam Line Break Scenario for APR-1400

The licensing analysis for the APR-1400 was performed by the CESEC computer code [8], which has MSLB specific conservative models to maximize either the pre-trip fuel failure or the potential for the post-trip return to power. To maximize the offsite dose [1, 9], the event scenario presented in the APR-1400 SSAR was somewhat distorted. Therefore, a best-estimate analysis was necessary to make a balanced judgment on the fundamental physics. The best-estimate analysis was performed by the MARS computer code [10].

The preliminary input deck for the APR-1400 SBLOCA analysis [11] was modified to analyze MSLB. The reactor vessel has a split core and down-comer nodes to model an asymmetric cool-down. The mixing factors in the lower plenum and the 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 both the main steam isolation valve and the break. The nodal scheme is shown in Figure 1.

Analyses were performed for both a main steam line break at full power with the reactor coolant pump running (SLBFP) and a main steam break at full power with a loss of offsite power (SLBFPLOP). It is a double-ended guillotine break. The conservative input data, including the set points and the capacity of the safety systems used

Table 1. Initial and Boundary Conditions for the CESEC and MARS Analysis

Parameter	Values used in MARS Analysis	Values used in CESEC Analysis
Core Power Level, MWt	3914	4062.66
Core Inlet Coolant Temperature, oC	295	295
Core Mass Flow Rate, 106 kg/hr	77.10	69.64
Pressurizer Pressure, kg/cm^2	155.17	163.46
Pressurizer Water Volume, m^3	29.89	39.63
ASI	0.3	0.3
CEA Worth for Trip,% $\Delta\rho$	-9.03	-9.03
Doppler Coefficient	Most Negative	Most Negative
Moderator Coefficient	Most Negative	Most Negative
Steam Generator Liquid Inventory per SG,kg	109,387	117,041
One SI Pump	Fail to start	Fail to start
Blowdown Area for Each Steam Line, m^2	0.119	0.119
Loss of offsite Power	Not Assumed	Not Assumed
Variable Overpower trip set point, %	103.5	103.5
Main Steam Isolation set point, kg/cm^2	52.73	52.73
Safety Injection Actuation set point, kg/cm^2	109.3	109.3

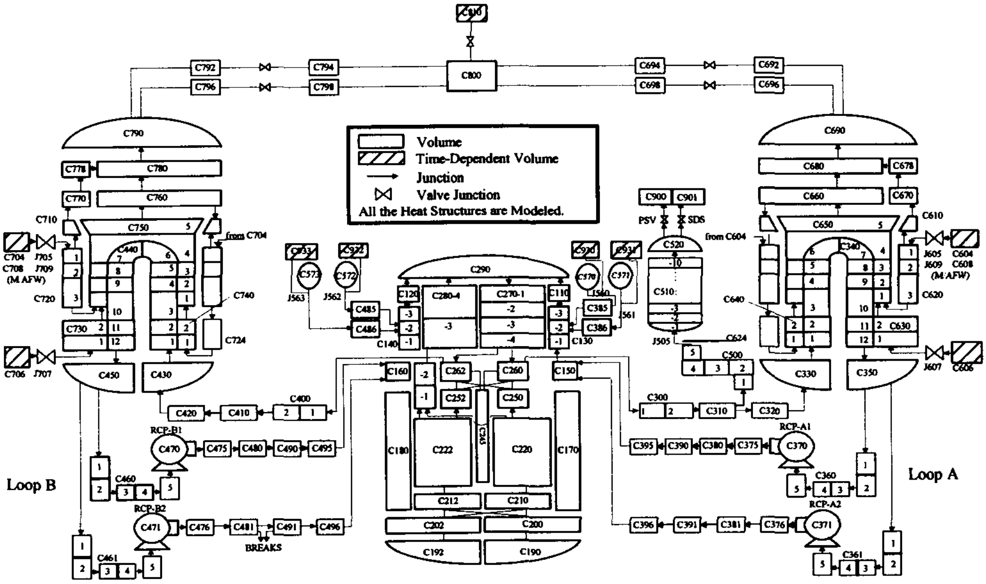

Fig. 1. Nodalization Diagram for APR1400 MSLB Analysis

in the SSAR analysis, were used in the MARS analysis to make a fair comparison of the thermal-hydraulic response of the system.

2.1. The Steam Line Break at Full Power

A comparative analysis was performed by the MARS computer code against that provided in the APR 1400 SAR, which was analyzed by the CESEC computer code. Major initial and boundary conditions are provided in Table 1. Table 1 shows that the major initial and boundary conditions for those two cases are almost identical, enabling a fair comparison with slight differences in the pressurizer pressure, steam generator inventory, and reactor coolant flow rate. The steam line break scenario provided in APR SAR was simulated by the MARS computer code.

Figure 2 shows a comparison of the pressurizer pressure between the APR SAR analysis by CESEC and the analysis by MARS. The pressure behavior of the best estimate analysis by MARS is quite different from that of the CESEC. After the pressurizer is emptied, the RCS depressurization rate slowed down abruptly in the CESEC analysis. In contrast, the depressurization rate slowed down gradually in the MARS analysis. In addition, in the CESEC analysis, the RCSpressure decreases abruptly after 400 seconds, while the RCS pressures in the MARS analysis are recovered after steam generator dry-out. It is closely related to the specific modeling of the upper head in the CESEC. The CESEC explicitly models the steam void formation and collapse in the upper head region of the reactor vessel. Heat transfer from the metal structures to the reactor coolant system fluid is modeled, in addition to the flashing of the reactor coolant during a depressurization of the RCS. As an additional conservatism, a pressurizer volume is added to the upper head region to slow depressurization when the pressurizer is emptied. The later part is quite unphysical. Therefore, it could be the main reason for the difference in the behaviors of the pressurizer pressure shown by the MARS analysis and CESEC analysis.

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

As the upper head behavior is closely related to the RCS pressure, a sensitivity study was performed. The results are indicated as a dashed line with a single point in Figures 2 and 3. By increasing the k-factors at the junctions of the top head from the down-comer and the core to the

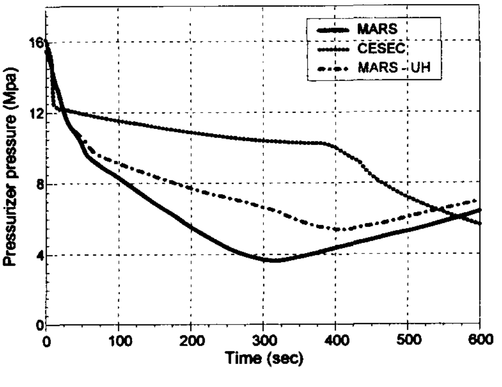

Fig. 2. Pressurizer Pressure for the SLBFP

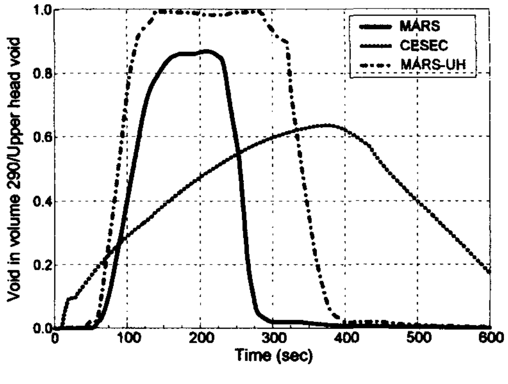

Fig. 3. Upper Head Void Fraction for the SLBFP

upper guide structure, the effect of the upper head modeling on the RCS pressurization was investigated. As expected, as the upper head was more isolated from the system, a greater void fraction in the upper-head resulted. It also resulted in a slower depressurization. The margin to return to power was substantial in the best estimate analysis, while the CESEC analysis resulted in a return to power. Therefore, the behavior of the upper-head void fraction is very important in terms of the primary safety criterion.

2.2. The Steam Line Break at Full Power with a Loss of Offsite Power

In the case of a steam line break at full power with a loss of offsite power (SLBFPLOP), the RCS pressure behaviors from CESEC and MARS are quite similar. The pressurizer pressure and upper head void fraction are shown in Figures 4 and 5. Figure 5 compares the void fraction of the highest volume of the MARS analysis, 290, and the upper head void fraction of CESEC. As the CESEC upper head is equivalent to the volume that consisted of volumes of 120, 110, 270, 280, and 290 of MARS, the comparison is rather qualitative. However, it clearly indicates that the upper head remained voided while the system cooled down. Then, the upper head is isolated from the remainder of the system, as there is little flow from the remainder of the RCS to the upper head. Therefore, the effect of the difference in the upper head modeling did not affect the results substantially.

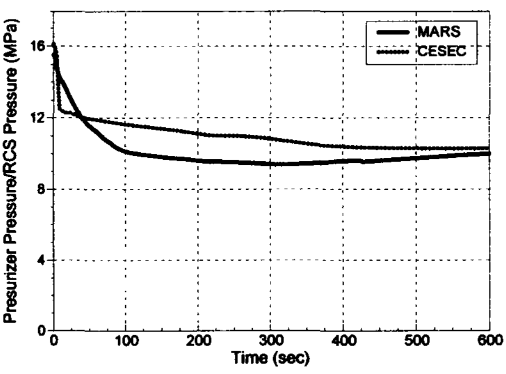

Fig. 4. Pressurizer Pressure for the SLBFPLOP

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

The effects of a cold leg injection and a direct vessel injection were investigated. In Figure 7, the

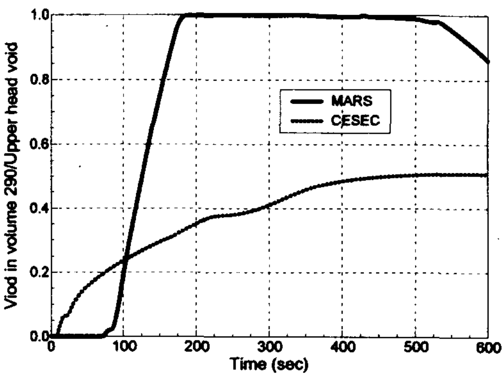

Fig. 5. Upper Head Void Fraction the SLBFPLOP

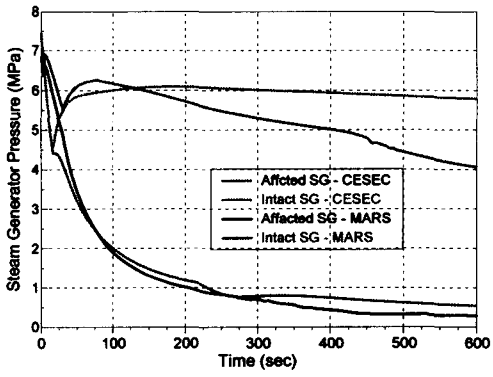

Fig. 6. SG Pressure for the SLBFPLOP

solid line represents the direct vessel injection case and the dotted line represents the cold leg injection (CLI) case. Direct vessel injection (DVI) was worse in terms of the margin to return to power. In the direct vessel injection case, part of the safety injection flow is mixed with the stagnant liquid in the upper down-comer, while the safety injection flow is directly mixed with the cold leg water and supplied directly to the down-comer. Therefore, the boron delivery to the core is delayed in the direct vessel injection case, as shown in the above plot. It was suggested that this difference in boron delivery between the DVI case and CLI case could be more severe in a case with a forced flow. The boron rich safety injection flow supplied in the DVI line, which is above the cold leg, could not be easily pushed to the down-comer by the forced flow in the cold leg. While the boron rich safety injection flow would be easily pushed to the down-comer in the case of CLI, as the safety injection is directly supplied to the cold leg.

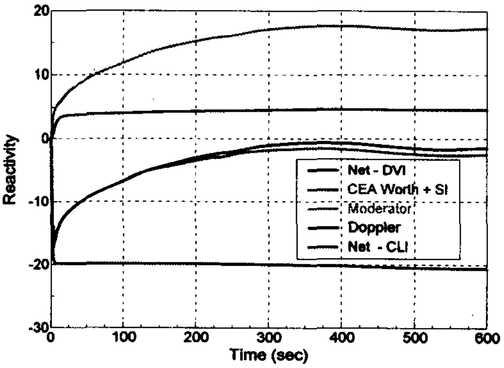

Fig. 7. Reactivity Change for the SLBFPLOP

3. The PIRT Process

The PIRT development process was composed of 15 steps; at each step, our research panel held a discussion to reach a common understanding and conclusion. For example, at step 13, each panel had a different rank for a specific phenomenon or a process and the rationale for the decision initially. A statistical decision-making process was not adopted, since such a process would filter strong but correct opinions and it might not be able to highlight the important phenomenon or process. In addition, there were too few panel members to use a statistical approach. Instead, it was suggested that an interactive discussion be held, until the panel reached a consensus on the rank for a specific phenomenon or process. This approach was quite effective, and it was applied in other steps.

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

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

Step 3: Define the plant designs. The panel members were quite familiar with APR-1400, as each panel member was actively involved in the design, research, and regulatory activities for the APR-1400. Whenever necessary, the panel referred to plant design data and P&ID.

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

Step 5: Define the parameters of interest. The law 10CFR100 specifies that the offsite dose resulting from an MSLB should be within certain limits. In the next tier of the safety criteria of the general design criteria (GDC) and the standard review plan (SRP), there are two primary safety criteria. The first criterion is the design limit on the containment pressure and temperature. The second criterion is the limit on the fuel failure, determined by a pre-trip fuel failure and a post-trip fuel failure. The panel decided to focus on fuel performance, as it is directly related to the off-site dose. It is assumed that Architect Engineer (AE) would provide a large enough safety-margin for the containment. In addition, both the pure thermal hydraulics and the phenomena related to a reactivity feedback should examined.

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

Steps 7-8: Define a high-level basic system process/Partition scenario into a convenient time phase. Three phases were identified: pre-trip, rapid cool-down, and safety injection. The pre-trip phase is the period before a reactor trip. The rapid cool-down phase is the phase before the safety injection. During this phase, the pressurizer empties, the void increases in the upper head, the reactivity continues to increase, and the steam generator level drops or empties; however, the pressurizer pressure is still high enough for a boron delivery. Because steam generator dry-out is an outstanding event that has a large effect on the RCS behavior, the third phase could have been termed "post steam generator dry-out phase." However, the panel chose the name "safety injection phase," since 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. Examples for each phase are shown in Figures 8-11.

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

Step 10: Identify and Define the Plausible Phenomena and Processes by a Phase and Component. The PIRT development employed the collective expertise of the panel members, as well as the results of the APR-1400 SSAR analysis, performed by a conservative CESECcomputer code, and the results by the MARS best-estimate analysis computer code. The question put to the panel was "How do the team members discover what they do not know?" with respect to expanding their state-of-the-art knowledge.

Step 11: Rank the High-Level Systems by Phase. The basis for ranking 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 in Table 2 is the same as the one used in reference 3.

Step 12: Rank the Components (Sub-Components) by Phase. Ranking of the components follows the ranking of the high-level

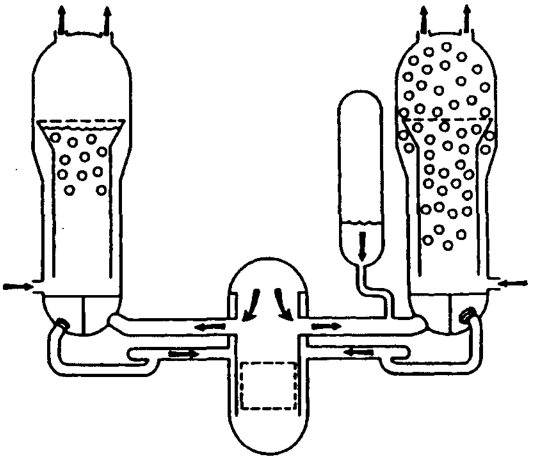

Fig. 8. Pre-Trip Phase

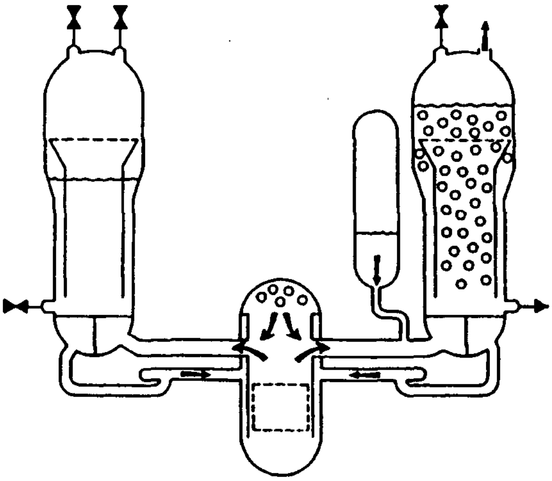

Fig. 9. Early Cool Down Phase

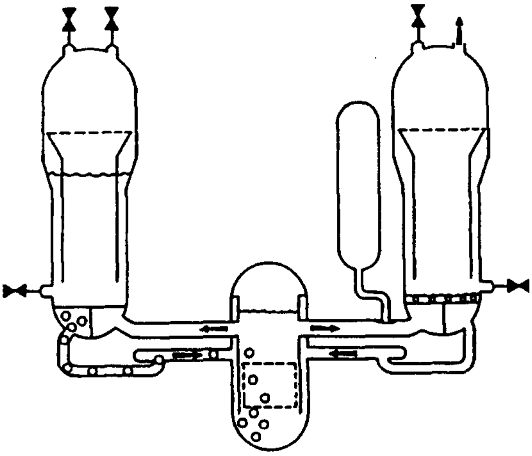

Fig. 10. Late Cool Down Phase

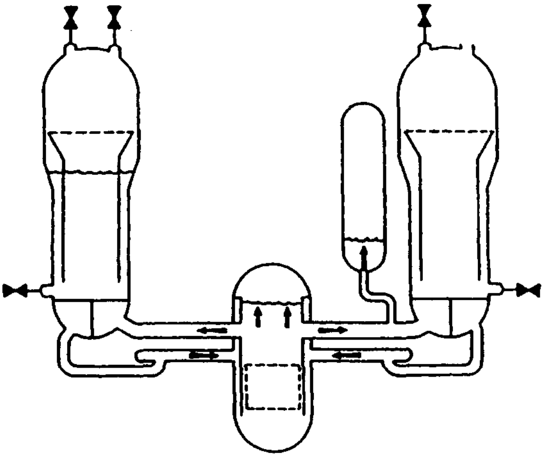

Fig. 11. Safety Injection Phase

systems. The same ranking scale was 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 the Phenomena/Processes by a Phase. Ranking of the phenomena/processes follows the ranking of the components. The same ranking scale used for the components was used for this step. 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, though the panel may also

Table 2. PIRT Ranking Scale for Relative Importance

Rank	General Descriptors
5	a. Highest of the high b. Experimental simulations and analytical modeling, with high degree of accuracy, is critical
4	a. High influence on FOM b. Needs to be experimentally present and/or analytically modeled with high degree of accuracy c. Approximately one -half the importance of rank 53
3	a. Moderate influence on FOM b. Needs to be experimentally present and/or analytically modeled with moderate degree of accuracy c. Approximately one -half the importance of rank 4
2	a. Low influence on (or importance to) FOM b. Needs to be experimental present and/or analytically modeled, but high uncertainty or inaccuracy is acceptable c. Approximately one -half the importance of rank 3
1	a. Lowest of the low in importance b. Very low influence on (or importance to) FOM c. Approximately one-half the importance of rank 2
IS	A system, component or process/phenomena may be active; however, its influence on the FOM is insignificant and may be ignored
NA	A system, component or process/phenomena is not active or present

Table 3. Knowledge-level Ranking Scale

Rank	Meaning
5	Fully Known. Small uncertainty.
4	Known. Moderate uncertainty.
3	Partially Known. Large uncertainty.
2	Very Limited Knowledge. Uncertainty cannot be characterized.
1	Totally Unknown.

utilize relevant information from computer code simulations, if available. During the PIRT meeting, further analyses to confirm the ranking assigned were suggested for the following cases: (1) the comparison of the cold leg injection and direct vessel injection case for MSLB at full power with the reactor coolant pumps running, to evaluate the boron transport phenomena; and (2) the evaluation of the effects of the upper head structure, by performing a sensitivity study on the heat structure.

Step 15: Evaluate the Knowledge-Level of Each Rank. The panel assigned knowledge-level ranks to those phenomena/processes that are of high importance. The ranking scale in Table 3 is the same as the one used in reference 3. The results for the PIRT are summarized in Table 4. Initially panel members had different knowledge levels for a specific phenomenon or a process and a different rationale for his or her decision. Panel discussions took place until a consensus for each rank was reached.

Table 4. PIRT for the 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 generator (secondary side)	5	5	4	**Main feed water line**	2	2	NA							
				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

4. PIRT for the APR-1400 MSLB

The PIRT for the APR-1400 is provided in Table 4. The structure of the table follows the PIRT procedure described in the previous section. The table shows the high-level systems, components, and phenomena/process, and their ranks for each of the three time phases.

The highly ranked phenomena can be categorized into three groups. The first group categorizes those phenomena that can only be quantified in the experimental program. The panel members recommended that a separator in full scale be installed in the integral effect test facility of ATLAS [12] to investigate these phenomena.

Liquid entrainment in the separators (Knowledge level 2, Importance 5): The liquid entrainment determines the blow-down rate from the steam generator. The superficial velocity of the steam is expected to be higher than that at a full power until the middle of the 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 for off-design conditions.

Mixture level in the separators (Knowledge level 2, Importance 5): It has the same degree of uncertainty and importance as the liquid entrainment.

The second group categorizes those phenomena that are important and for which the knowledge level is relatively high. Therefore, either an experimental or an analytical investigation of these phenomena would not be very difficult to perform and would be very effective in quantifying the safety margin against the primary safety criteria.

Stored energy release in the upper head (Knowledge level 4, Importance 5): The stored energy in the upper head has a large influence on the system's depressurization, as the volume of the upper head and the amount of the heat structure is large, relative to the other system components. The release of the stored energy in the upper head plays a major role in determining the amount of the void formed in the upper head: it governs the pressure during the depressurization. The stored energy release phenomenon itself is not uncertain; however, the complex geometry in the upper head causes moderate uncertainty.

Flow to and from the upper head (Knowledge level 4, Importance 5): The multi-dimensional flow pattern and the complicated flow path in the upper head determine the pressurization behavior. Therefore, they should be properly preserved in the experimental facility. The sensitivity analysis result by the MARS computer code in section 2 for the effect of the k-factor demonstrated the importance of this process.

The third group categorizes phenomena that require relatively complicated experimental or analytical investigations to quantify the fundamental physics behind them, as the knowledge level for these phenomena is relatively low. Therefore, careful investigations are necessary for these phenomena.

Tube wall heat transfer at the 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 the reactor coolant system. As a 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 a 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 codes for safety analyses entails large uncertainty. Some of the design codes for the performance of the steam generator are only tested for the full power condition. However, the thermal hydraulic condition during the blow down of the steam generator is far from the design condition. Therefore, the heat-transfer in the U-tube bank, having a complex geometry for the off-design conditions, needs to be investigated further.

Void distribution at the steam generator shell (Knowledge level 3, Importance 5): During the initial blow-down, the steam generator is filled with two-phases. After the main steam isolation, a 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 a complex geometry is not well known.

Boron mixing in the upper down-comer (Knowledge level 3, Importance 4): The sensitivity analysis results by the MARS computer code in section 2 indicate that the negative reactivity insertion by the borated water is quite different between the cold leg injection and the direct vessel injection. As the negative reactivity insertion by the borated water is the dominant factor for determining the potential of a return to power, the panel assigned an importance rank of 4 for this process. When the RCP runs, the safety injection flow with a high boron injection may flow into the upper head due to the bypass flow. If the amount of the safety injection flow 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 the safety injection flow that is 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 the lower plenum is complicated and there is little experimental data to benchmark the capability of the computation fluid dynamic (CFD) code for the mixing analysis, this phenomenon is highly uncertain.

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

5. Conclusions

An expert panel developed a PIRT for an MSLB event in the APR 1400. This PIRT can be utilized as a guide for planning cost-effective experimental programs and code development efforts for the APR-1400. To aid future experimental programs, the panel identified those process and/or phenomena that have a high level of importance but are not well understood. Experimental verification of these phenomena using ATLAS [12] will be very helpful in understanding the APR-1400 MSLB in terms of the primary safety criteria.

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