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DEVELOPMENT OF A PIRT (PHENOMENA IDENTIFICATION AND RANKING TABLE) FOR A POSTULATED DOUBLE-ENDED GUILLOTINE BREAK IN A PRODUCTION REACTOR*

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ABSTRACT

The U.S. Nuclear Regulatory Commission has developed a generic methodology to quantify the uncertainty in best estimate computer codes used to license commercial light water reactors. This same methodology is equally applicable to other reactor designs with regards to providing a technical basis which supports the establishment and demonstration of compliance with safe operating margins. One of the cornerstones of the method is the identification and ranking of phenomena that are important to the postulated scenario. This paper references descriptions of the total methodology, describes the first three steps (i.e., through the identification and ranking of phenomena), and summarizes the results of the application of the methodology to a double-ended guillotine break loss of coolant accident in a production reactor.

INTRODUCTION

In recent years, production reactors in the United States have come under increasing scrutiny with respect to safe operation. As a results increased attention is being directed toward demonstration of their safety margins. The use of BE (Best Estimate) computer codes, in safety analysis, is receiving increased favor throughout the industry[1]; however, the uncertainty in the code simulations must quantified. To support this need an uncertainty quantification process called the CSAU (Code Scaling, Applicability and Uncertainty)[2,3] evaluation methodology was developed. CSAU is a practical method for combining quantitative analysis and expert opinions to arrive at computed values of uncertainty. At the process level the method is generic to any application which relies on computer code simulations to determine safe operating margins, therefore, it may be applied to DOE production reactors. One of the cornerstones of the method is the identification and ranking of phenomena that are important to the postulated scenario. Descriptions of the steps in the methodology leading to PIRTs, and the application of the steps to a DEGB (Double-Ended Guillotine Break) LOCA (Loss of Coolant Accident) in a production reactor are provided in this paper.

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PIRT METHODOLOGY

The CSAU methodology consists of three basic elements containing fourteen steps as depicted in Figure 1. The complete methodology and an application to a large break LOCA in a commercial pressurized water reactor is fully described in References 2 and 3. In addition, an overview of the full CSAU is presented in a companion paper at this meeting[4], including potential applications to evaluations of advanced reactor designs.

The first three steps, which form a cornerstone of the methodology, are summarized in Table 1. These steps identify the plausible phenomena and processes which occur in the scenario of interest, and prioritize them with respect to their importance to the system response, in the context of the safety criteria.

Table 1. Prescriptive steps of CSAU through the identification and ranking of phenomena (Numbered to conform to Fig. 1)

1. Specify Scenario: Code applicability and uncertainty are transient dependent because processes and safety parameters of interest may change from one scenario to another. Consequently, it is necessary to specify the scenario to establish the parameters that need to be evaluated. In this process, it is advantageous to subdivide the scenario into phases. By doing so, the complexity of analyzing the components and phenomena is reduced. The subdivision allows reduction of the analysis to only those processes and components that are important during each phase. By carefully defining the scenario and its phases, the ground work for the identification and ranking is laid.
2. Select Nuclear Power Plant (NPP): The processes and safety parameters may also differ from one plant design to another. Consequently, the NPP to which the analysis applies is specified. The various U.S. production reactors have individual designs. Although generally similar, they differ significantly in the detail of their systems and subsystems. As examples, up or down flow vs. horizontal, number of loops, fuel design, etc. Thus, selection of a specific design is necessary to identification of the plausible and important phenomena.
3. Identify and Rank Processes: The CSAU focuses on phenomena/processes that are important (drive) to the particular scenario in the specified NPP. Plausible physical processes and their associated system components are identified first. These are then ranked with respect to their influence on the primary safety criteria to establish PIRTs. The identification and ranking are justified and documented. Each phase of the scenario is separately investigated. The processes and phenomena associated with each component are examined. Cause and effect are differentiated. The processes and phenomena are found by examination of experimental data and code simulations related to the plant and scenario. Independent techniques to accomplish the ranking include expert opinion, subjective decision making methods (such as the Analytical Hierarchical Process [AHP]) and selected calculations. Examples of the first two are found in Reference 2, and the last in Reference 5. Comparison of the results of these techniques provides assurance of the accuracy and sufficiency of the process.

The information obtained at the completion of Step 3 identifies the requirements which will be imposed on the analytical tools used to simulate the accident. In addition, those requirements are prioritized with respect to their contributions to the total uncertainty of the calculated reactor response, in the context of the safety criteria. Because it is not cost effective to assess and examine all the parameters and models in a best

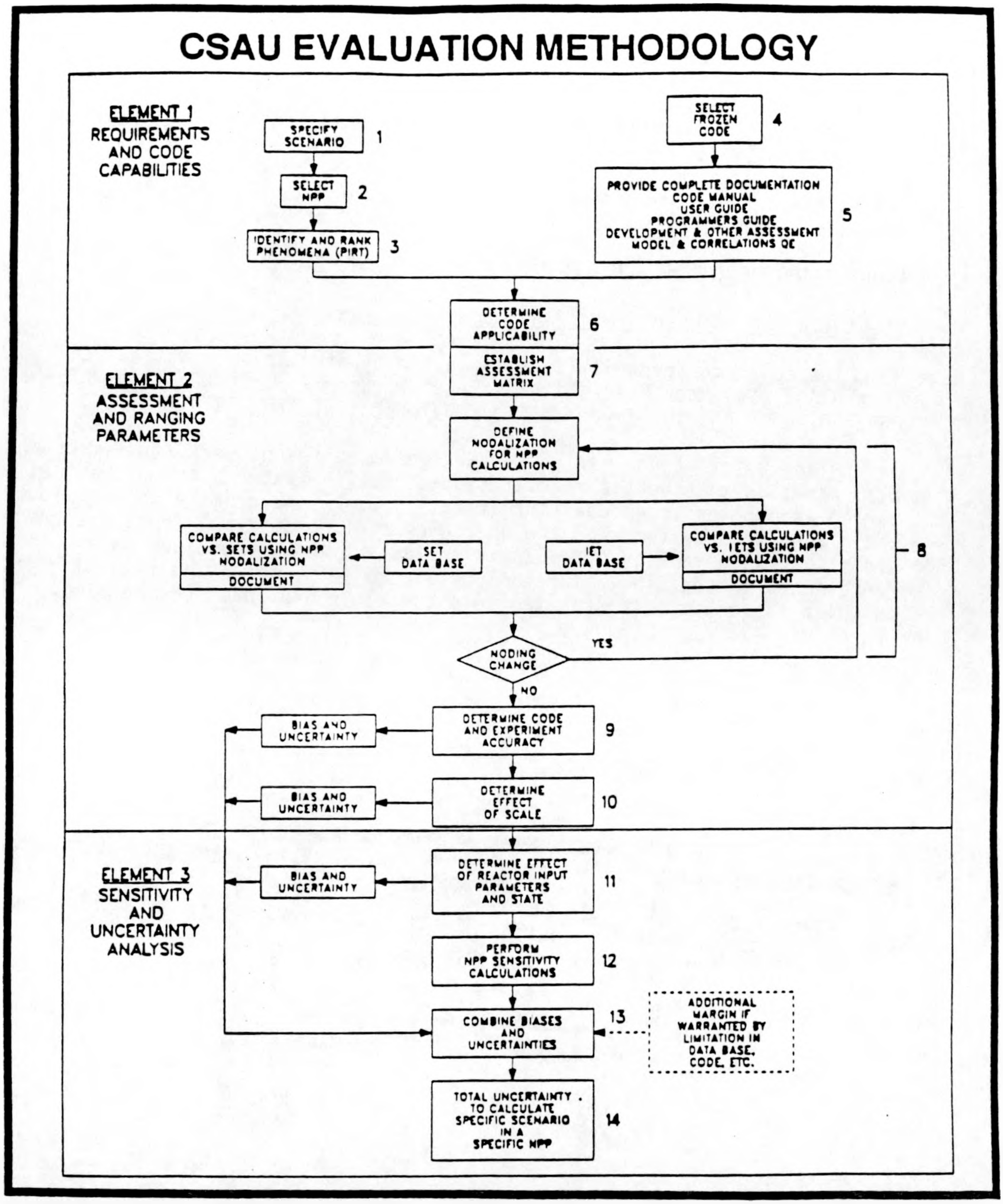


Figure 1. Code Scaling, Applicability and Uncertainty evaluation methodology

estimate code in a uniform fashion, the methodology focuses on those processes and phenomena which dominate the transient behavior, although all plausible effects are considered. This screening of plausible phenomena, to determine those which dominate the plant response, insures a sufficient, yet efficient analysis. The CSAU is not code-specific through the first three steps. That is, the PIRTs are applicable to the scenario and plant design regardless of which code may be chosen to perform the subsequent uncertainty analysis. This also adds to the efficiency and generality of the process.

APPLICATION OF THE METHODOLOGY TO A PRODUCTION REACTOR

Steps 1 and 2, Scenario and Plant Specification

The selected scenario (Step 1) is the hypothesized, limiting DEGB LOCA in the SRS (Savannah River Site) L-Reactor (Step 2). Descriptions of the reactor and scenario, important to development of the PIRTs, follow.

Plant Description - In the context of the present work, the important elements that make up the reactor system are: the water plenum, the fuel and target assemblies, the moderator (reactor) tank, the primary cooling loops, the blanket gas system, and the emergency cooling system. These elements are illustrated in Figure 2. In this figure five coolant loops are represented by the single lumped loop on the left, while the remaining loop, in which the break is postulated to occur, is represented on the right.

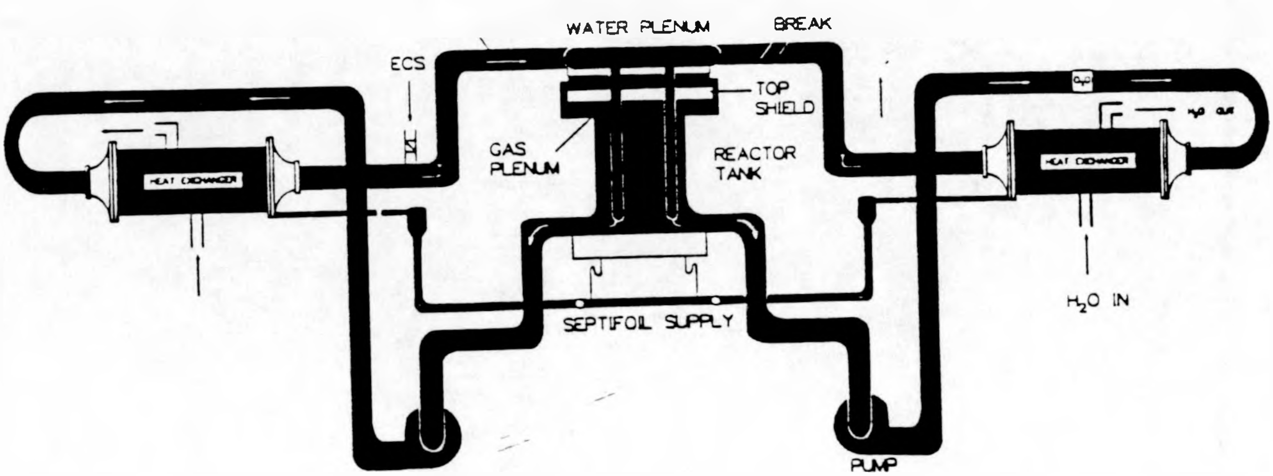


Figure 2. L-Reactor during normal operation just prior to initiation of a hypothesized DEGB.

The moderator tank is a cylindrical component 5 m (16.3 ft) in diameter and about 5.8 m (19 ft) high which accommodates the fuel assemblies during reactor operation. Above the tank is the gas plenum which, in conjunction with the blanket gas system, controls the system pressure. Above the gas plenum is the cylindrical water plenum, 5.3 m (17.45 ft) in diameter and 0.22 m (0.7 ft) high. Approximately 800 penetrations from the water plenum to the moderator tank facilitate insertion of the fuel assemblies into the tank from the top of the reactor. These penetrations also provide the path for coolant flow from the water plenum to the fuel assemblies.

The coolant water is circulated through the reactor by six loops. In each loop, about 95,000 kg/s (25,000 GPM) is pumped from one of the six outlet nozzles at the bottom of the moderator tank through two parallel heat exchangers into one of the six inlet nozzles to the water plenum. The coolant then flows into slotted sleeves and downward to the fuel and target assemblies.

The flow in each assembly is determined by the size of the orifices at the top of the assembly, the hydraulic resistance of the assembly itself, and by bottom fitting inserts at the base of the assembly. The coolant passes downward through each assembly, enters the surrounding moderator tank, and flows through the outlet nozzles to the coolant loops. Normally, a small portion of the flow is diverted from the heat exchangers to supply upflow headers for cooling the control rods.

The ECS (Emergency Cooling System) consists of four pumped loops that inject light water coolant into four of the six coolant loops, downstream of the heat exchangers. There is also an auxiliary process water system which provides for overflow, drainage, storage, pump seal supply, and leak collection.

<u>Scenario Description</u> - The limiting accident scenario assumes the broken loop is one of the four loops with an ECS injection point. Figure 2 shows the loop in which the break will occur on the right of the reactor. In addition, the limiting accident assumes one of the remaining three ECS injection points fails; thus leaving two ECS injection points operational. The loop on the left hand side of the reactor tank in Figure 2 is a representation of the five remaining loops, and two ECS lines.

The general progression of the transient is <u>illustrated</u> in Figures 3 through 7 and described below. The liquid fractions and times given in these figures conceptually portray the general trends in the reactor response used to help formulate the PIRTs.

There are two postulated limiting phases during the transient. The first, the FI (flow instability) phase, occurs during the first approximately 2 seconds of the transient. Immediately after the postulated DEGB the coolant flow delivered to the fuel assemblies in the most affected region will likely decrease. The flow degradation combined with an inherent delay in reactor scram may result in the onset of flow instability, above a limiting power level. The progression of FI in the affected fuel assemblies will result in reduced heat flux, fuel heat-up and ultimately localized fuel melting, if left unchecked. The progression of reactor hydraulics to FI is depicted in Figure 8. The relationship between the break and ECS flows, power, and the fluid level in the reactor tank is illustrated in the normalized plots of Figure 9, for the full transient.

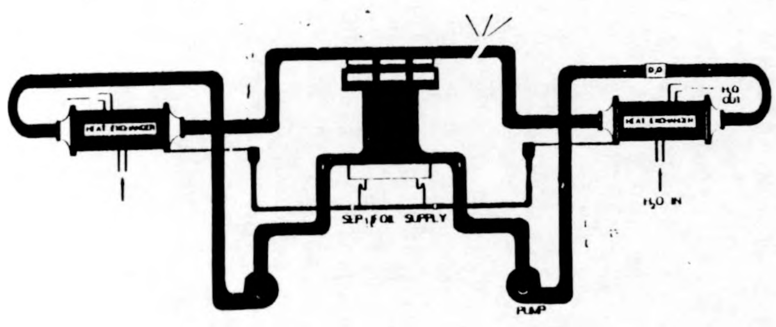


Figure 3. Reactor hydraulic condition at break initiation (t = 0 s).

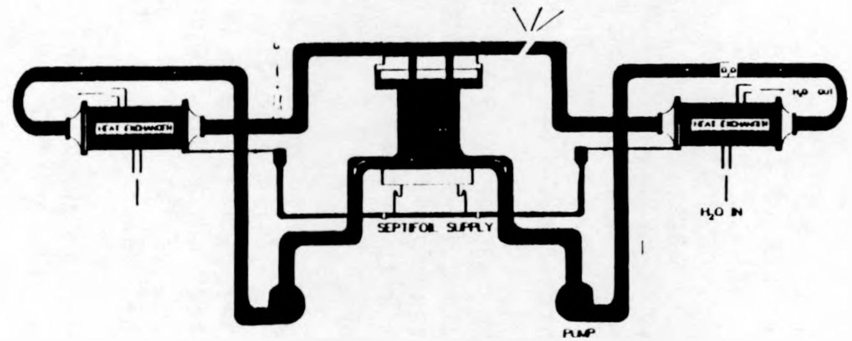
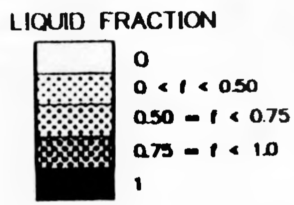


Figure 4. Reactor hydraulic condition at FI initiation (t ≈ 1.0 s).



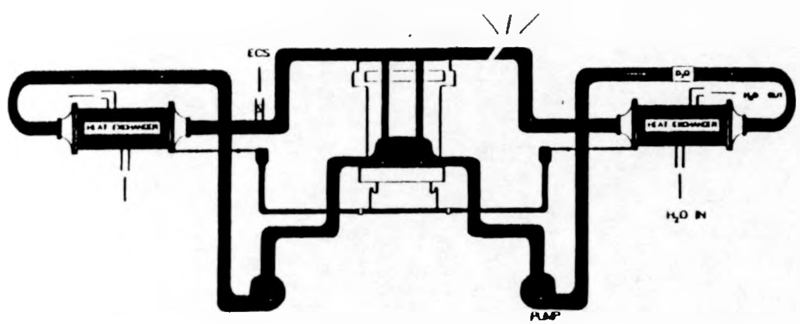


Figure 5. Reactor hydraulic condition at start of air aspiration (t ≈ 12 s).

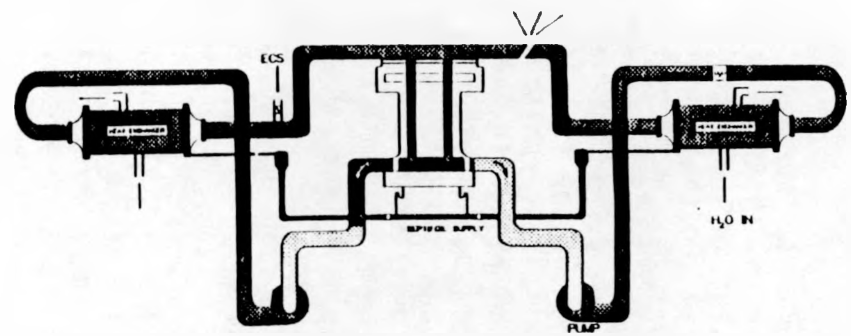


Figure 6. Reactor hydraulic condition shortly after ECS reaches peak flow (t ≈ 25 s).

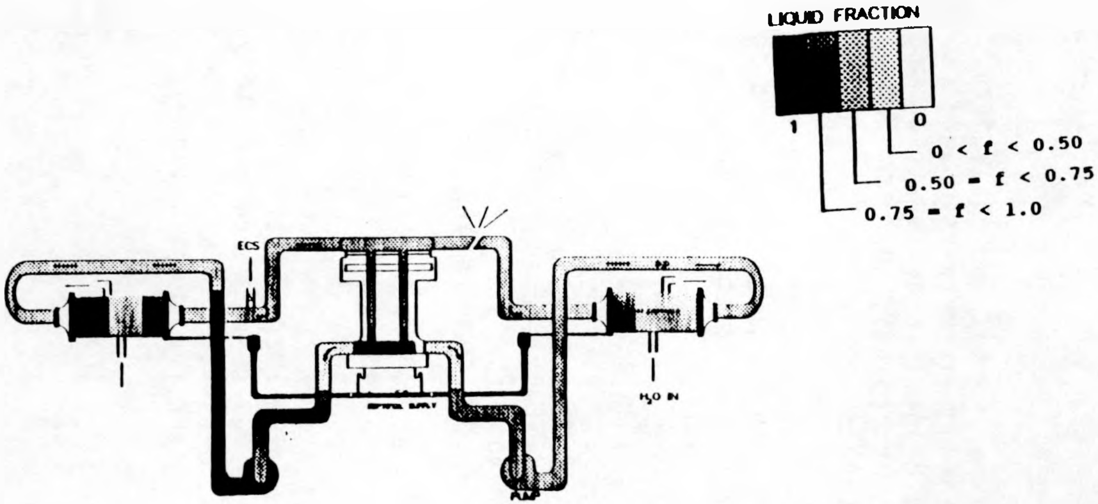


Figure 7. Reactor long term stable hydraulic condition (t $\geq$ 150 s).

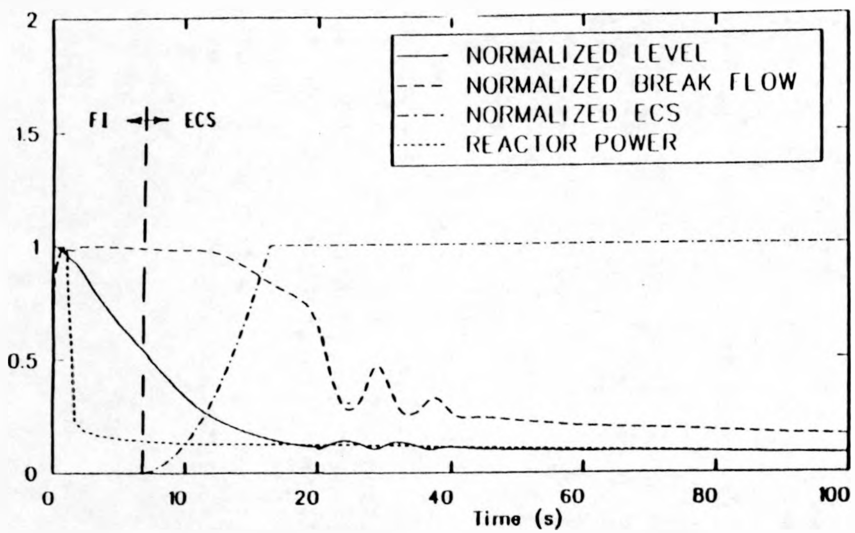


Figure 9. Normalized break and ECS flow, power and moderator tank level during a hypothesized DEGB LOCA.

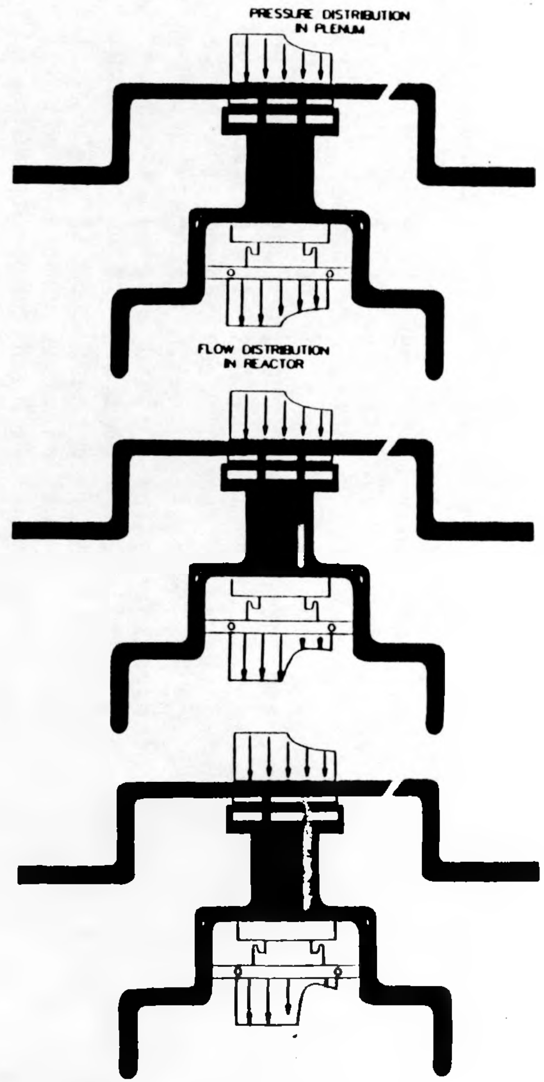


Figure 8. Progression to postulated FI in the limiting assembly.

The second segment of the transient, the ECS phase, is dominated by the injection of ECS flow into the reactor. Emergency coolant is injected into selected primary coolant loops to mitigate the LOCA induced inventory depletion. Since the coolant is injected into the loops at points close to the plenum inlet nozzle, the plenum inventory immediately benefits from the increased influx of coolant, which improves the availability of coolant to selected fuel assemblies. However, the potential exists for localized boiling to occur, which may impede the delivery of coolant to other fuel assemblies. In addition, air entrainment to the fuel assemblies (if present) has the double effect of reducing the net flow of coolant through the assemblies and reducing the heat transfer coefficient at the fuel surface. Ultimately the ECS inflow equalizes with the break outflow to achieve a stable, but not necessarily full, fluid level in the moderator tank surrounding the fuel assemblies. Prior to, or coincident with this stable system state, the flow of fluid from the plenum through the fuel assemblies to the moderator tank, is sufficient to remove the fuel fission power decay. This stable state is long term in nature, depending only on the ECS reservoir inventory, and terminated with isolation of the break.

Step 3, Identification and Ranking of Phenomena

General Procedure - Although based in experimental and analytical evidence, the identification and ranking of phenomena retains a subjective nature. Consequently, it is necessary to take specific action to insure the results are both complete and accurate. Accordingly this work was structured to use three independent expert panels to formulate three sets of PIRTs. Although there was limited discourse between some members of the panels, such contact was limited to sharing of plant design information, computer simulation and experimental data, and the general objectives and format for the PIRTs. As will be subsequently demonstrated by the differences in the three original PIRTs, the desired independence was achieved.

The three independent panels were constituted as follows:

a. The TPG (Technical Program Group), set up to advise, direct and support the Limits and Uncertainty Program. This group included knowledgeable and experienced members from academia, the national laboratories (excluding SRL), and industry.
b. INEL senior analysts experienced in both commercial power and production reactor safety analysis.
c. SRL personnel from various disciplines (i.e., experiments, analysis, operations, etc.) within the laboratory.

Subsequent to the formulation of the three independent sets of PIRTs the results were compared by the TPG. Significant differences were resolved primarily on the basis of technical arguments and reconciliation of criteria differences in the approach. In the few cases where a consensus was not reached with the preceding criteria, disputed plausible phenomena were retained, and disputed ranks were set at their highest value.

In accordance with the scenario previously described, PIRTs were separately formulated for the FI and ECS phases based on an evaluation of the appropriate criteria by which safe operation could be judged. The system was partitioned into logical components and each ranked according to its importance to the reactor response in the context of the safety criteria. This was followed by identification of the plausible phenomena in each component, and the ranking of the phenomena based on its importance in the component ("Within Component Ranking"), again in the context of the safety criteria.

Once the three independent lists of phenomena and ranks were prepared, the consistency and completeness of the rankings were evaluated with a systematic technique, commonly referred to as the Analytic Hierarchy Process (AHP)[6]. Any inconsistency or incompleteness indicated by the AHP was addressed by individual phenomenon, until closure was reached. The AHP results also provided the mechanics by which the within component phenomena ranking is weighted by the component ranking to produce phenomena ranking in terms of their importance to the system response ("Within System Ranking"). These ranks are normalized to a desired scale; 1 to 9 in the present case with: 1 - 3 = Low Importance, 4 - 6 = Medium Importance, and 7 - 9 = High Importance.

Armed with the three independent, within system ranking PIRTs for each phase, the TPG developed the final PIRTs through the process of comparison and resolution already described.

Results of the Phenomena Identification and Ranking

Based on experimental and analytical evidence and the objectives of the work, four candidate safety criteria were considered for the FI phase as shown in Table 2.

Table 2. Candidate safety criteria for the FI phase.

CRITERION	ADVANTAGE	DISADVANTAGE
Maintain coolable geometry	Least restrictive relative to power level	Low probability sufficient experimental data to evaluate uncertainty
Maximum surface temperature	Next least restrictive	See above
Onset of significant voids	High probability sufficient experimental data exists (or will soon exist) to evaluate uncertainty	May be more restrictive than eventually desired
Onset of nucleate boiling	Sufficient experimental data exists	Overly restrictive

There was concurrence that the onset of significant voids was the most appropriate safety criteria for the FI phase.

It was recognized that excursions past the local dry-out might be proven to be acceptably safe in the ECS phase. However, there exists some doubt that the necessary experimental evidence for this postulation would be readily available. Therefore, at least for the initial application, the safety criteria for this phase was defined as the onset of dry-out, conservatively defined as wall temperature equal to saturation temperature plus 10 C.

Tables 3 and 4 respectively summarize the FI and ECS phase final PIRTs in the context of the importance of each phenomena to the uncertainty in primary safety criteria. Table 5 illustrates how the independent panel evaluations were compared phenomena by phenomena, and significant differences resolved to produce Tables 3 and 4.

SUMMARY AND CONCLUSIONS

The generality, sufficiency and efficiency of the CSAU evaluation methodology PIRTs, developed in the commercial power arena, have been demonstrated in an application to a different design, a production reactor. The plausible phenomena have been identified and ranked with respect to the primary safety criteria by which the safety of the reactor may be judged. The dominant phenomena (rank 5 through 9) which can be expected to drive the reactor response constitute approximately 27% of the plausible items. This knowledge provides a <u>sufficient</u>, but <u>efficient</u> focus for subsequent analyses to determine individual uncertainties arising from variabilities in experimental data, code performance, scaling effects and the assumed reactor state at accident initiation. The important effects to be simulated will also provide the basis for a sufficient, but efficient reactor noding rationale. Combination of the individual uncertainties into a statement of total uncertainty, at a selected probability level, can be used to determine and judge acceptable safety margins as a function of operating power.

The PIRTs given here are doubly useful. They also provide an initial technical basis for new or continuing experimental work, to better understand the various phenomena. Completion of the total CSAU evaluation will provide the relative uncertainty for the individual important contributors. This information can be used to judge the cost effectiveness of additional experimental research, and to prioritize that work in the context of reaching an uncertainty level which is acceptably safe.

Table 3. Phenomena identification and ranking table for the flow instability phase of a L-reactor DEGB LOCA.

The component order (top down) is on the arbitrary basis of the single highest ranked phenomenon occurring in the component. The phenomena ranks (shown in parenthesis) are on a system wide basis with respect to influence on the primary safety criteria (onset of significant voids). The correlation between individual rank and importance range is: 1 - 3 = low importance, 4 - 6 = medium importance, 7 - 9 = high importance).

	PHENOMENA IMPORTANCE WITH RESPECT TO SAFETY CRITERIA		
COMPONENTS	HIGH	MEDIUM	LOW
Fuel assembly	Flashing (9) Subcooled nucleate boiling (9) Subchannel flow distribution (7)	Single phase heat transfer (6) Azimuthal heat tran. (5) Channel gap geometry (4)	Heated wall effects (3) Dissolved gas effects (3) Radial heat tran. (3) Fuel surface condition (3) Wall voidage effects (3) Assembly to moderator heat trans. (2) Cross-rib flow (2)
Fuel parameters	Safety rod delay (8) Power peaking (7) Thermal properties (7)		Rib effect (2)
Break	Flow rate (7)		
Water plenum		Pressure distribution (6) Primary flow pattern (6)	Nozzle stall (2) Swirl flow (2) Sonic wave propagation (2)
Pump and hot leg		Pump performance (5)	Sonic wave propagation (2) Pump work (2) Vapor lock (1) Friction pressure drop (1)
Moderator tank		Flashing (4)	Flow distribution (2) Sonic wave propagation (2) Vacuum (1)
Gas ports			Relative phase velocity (3) Flow resistance (1)
Heat exchanger and cold leg			Friction pressure drop (2) Heat transfer (2) Sonic wave propagation (2)
Vacuum breaker			Relative phase velocity (2) Flow resistance (1)
Gas plenum			Level tracking (2) Flow resistance (1)

Table 4. Phenomena identification and ranking table for the emergency coolant system phase of a L-reactor DEGB LOCA.

The component order (top down) is on the arbitrary basis of the single highest ranked phenomenon occurring in the component. The phenomena ranks (shown in parenthesis) are on a system wide basis with respect to influence on the primary safety criteria (dry out). The correlation between individual rank and importance range is: 1 - 3 = low importance, 4 - 6 = medium importance, 7 - 9 = high importance).

	PHENOMENA IMPORTANCE WITH RESPECT TO SAFETY CRITERIA		
COMPONENTS	HIGH	MEDIUM	LOW
Fuel assembly	Subchannel flow distribution (9) Solid heat tran. (8) Fission decay heat and local power density (7)	Rib effect (cross flow blockage and flow down rib) (6) Interfacial effects and void distribution (6)	Surface properties (3) Subchannel geometry (2) Tank heat transfer (2)
Water plenum	Level distribution (8)	Mixing (6) Pressure distribution (5)	Air ingestion (2) Air through piston rings and sparjets (2)
Pump and hot leg	Pump performance and degradation (7)	Liquid and air flow rate (4) Phase slip and relative velocity (4)	Pump and flywheel inertia (coastdown) (2) Two-phase pressure drop (1)
Moderator tank	Level tracking and distribution (6)	Air entrainment (at muff) (4)	3-D flow (2) Mixing, septifoil and sparger (2) Void distribution (1)
Break		Flow regime (5)	Water flow rate (3) Location (2) Air flow rate (2) Two-phase effects (1) Confinement pressure (1)
Heat exchanger and cold leg		Phase slip and relative velocity (4)	Gas inventory (3) Friction pressure drop (2) ECS mixing (2) Pluggage (2) Heat transfer (1) Pressure at ECS injection point (1)
Emergency cooling system		Flow vs pressure (4)	Fluid properties (3) Pluggage (screen bypass) (3) Fluid Temperature (2)
Gas port, Vacuum breaker and Top shield gas path			Gas flow (2) (all 3 components)

Table 5. Illustration of the comparison and resolution of rankings in the FI phase

The absence of a numerical value indicates the phenomenon was not considered, or was lumped within some other classification by the group performing the ranking. The basis for resolution of differences is provided immediately following the entry showing a significant variation. Differences not considered significant are those in which the three independent ranks all fall within the same relative importance range (1 - 3 = low importance, 4 - 6 = medium importance, 7 - 9 = high importance), or if the ranks are within ± 1 even though they might fall in two different ranges. Nonsignificant differences, as just defined, do not require resolution.

COMPONENT: Phenomena	FINAL RANK	TPG RANK	INEL RANK	SRL RANK
FUEL ASSEMBLY:				
Flashing	9	8	9	3
RESOLUTION: Low SRL rank based on belief effect not likely in FI phase. SRL panel agreed to high rank pending conformation.				
Azimuthal heat transfer	5		5	
Solid heat conduction				6
Boiling heat transfer				3
Critical heat flux			4	
Subcooled nucleate boiling	9	9	8	
RESOLUTION: The four phenomena above were combined into subcooled nucleate boiling and uprated to 9.				
Dissolved gas effects	3	2	2	4
Single phase heat transfer	6		6	5
Subaxial flow				6
Subchannel flow distribution	7	5	3	
RESOLUTION: Subaxial flow was combined with subchannel flow distribution, which was uprated to 7.				
Radial heat transfer	3	3		
Channel gap geometry	4	4		
Assembly to moderator heat transfer	2			1
Cross-rib flow	2			2
Heated wall effects	3			3
Sonic wave propagation	2			3
Fuel surface conditions	3			2
Wall voidage effects	3			3
SPARGER:				
Mixing			2	
RESOLUTION: INEL concluded mixing was included below.				
Flow magnitude and distribution	2	2		

COMPONENT: Phenomena	FINAL RANK	TPG RANK	INEL RANK	SRL RANK
WATER PLENUM:				
Pressure distribution	6	5	9	6
RESOLUTION: Upon reevaluation the INEL panel concluded its original ranking had been unduly influenced by code problems at the time of ranking, in another task. A key feature in PIRT is to consciously reject such code influence; doing so the INEL panel agreed with the the other panels.				
Secondary flow				3
RESOLUTION: Upon reconsideration the SRL staff concluded this effect was captured in the other items listed; secondary flow was deleted.				
Nozzle stall	2	2	2	
Swirl flow	2			2
Primary flow pattern	6			6
Sonic wave propagation	2			2
SEPTIFOIL:				
Flow resistance			2	
RESOLUTION: INEL concluded the desired effect was included below.				
Flow magnitude and distribution	2	2		9
RESOLUTION: SRL concluded that in the initial ranking they tended to uprate phenomenon that was common in numerous components (i.e., system type rank) and apply that rank in all components. This procedure is undesirable in the overall methodology because system wide ranks are determined later, and automatically, in the AHP analysis tool. Thus the rank was downrated by SRL.				
VENT PATHS: Free surface behavior, choking, blanket gas response, and pressure control were originally ranked, respectively 1, 1, 2 and 3. On further evaluation it was determined that a momentary vacuum in the moderator tank during FI phase was of little importance, thus this component was deleted from the matrix.				

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