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Thermal-Hydraulic Evaluation of Pressurized Water Reactor Transients during Steam Line and Feedwater Break Events with Induced Steam Generator Tube Leakage

TR-103671

Draft Report
June 1, 1993

NON-PROPRIETARY VERSION

Prepared by
Science Applications International Corporation
2109 Air Park Road S.E.
Albuquerque, NM 87106
and
Gabor, Kenton and Associates, Inc.
770 Pasquinelli Drive, Suite 426
Westmont, IL 60559

Prepared for
Electric Power Research Insitutute
3412 Hillview Avenue
Palo Alto, California 94304

EPRI Project Manager
E. L. Fuller
Nuclear Power Division

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Westmont, IL 60559

Principal Authors
N. Morris (SAIC)
K.C. Wagner (SAIC)
K. Ross (SAIC)
J.H. Holderness (SAIC)
K.A. Williams (SAIC)
B. Putney (SAIC)
M.A. Kenton (GKA)
D.E. Vanover (GKA)
E.L. Fuller (EPRI)

Prepared for
Electric Power Research Institute
Nuclear Safety Analysis and Response Center
3412 Hillview Avenue
Palo Alto, CA 94303

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ACRONYMS

ADV	Atmospheric Dump Valve
AFW	Auxiliary Feedwater
ARC	Alternate Repair Criteria
EOP	Emergency Operating Procedure
EPRI	Electric Power Research Institute
ERG	Emergency Response Guideline
LOCA	Loss-of-Coolant Accident
MAAP	Modular Accident Analysis Program
MFLB	Main Feed Line Break
MSIV	Main Steam Isolation Valve
MSLB	Main Steam Line Break
NRC	U. S. Nuclear Regulatory Commission
NSAR	Nuclear Safety Analysis and Response
PORV	Power-Operated Relief Valve
PWR	Pressurized Water Reactor
PZR	Pressurizer
RCP	Reactor Coolant Pump
RCS	Reactor Coolant System
RESAR	Reference Safety Analyses Report
RHR	Residual Heat Removal
RWST	Refueling Water Storage Tank
S/G	Steam Generator
SGTR	Steam Generator Tube Rupture
SI	Safety Injection
SNUPPS	Standardized Nuclear Unit Power Plant System
S/RV	Safety Relief Valve

EXECUTIVE SUMMARY AND CONCLUSIONS

In support of Electric Power Research Institute's (EPRI's) Nuclear Safety Analysis and Response (NSAR) program, comprehensive thermal-hydraulic computer analyses were performed to address issues pertinent to the utility industry's initiative on steam generator alternate repair criteria (ARC). The U.S. Nuclear Regulatory Commission (NRC) has raised concerns over pressurized water reactor (PWR) core coolability and operator actions in the hypothetical event of steam generator (S/G) tube leakage being induced concurrent with a secondary system loss-of-coolant accident (LOCA). Both the RELAP5/MOD3.1 and the Modular Accident Analysis Program (MAAP3.0B-PWR) computer codes were used to simulate plant transient behavior under secondary system LOCA events that are not isolatable, considering induced tube leakage and emergency operating procedures (EOPs). The RELAP5 model that was developed approximated a four-loop Westinghouse PWR plant represented by the Reference Safety Analyses Report (RESAR III), at a thermal power of 3411 MW. The MAAP plant model approximated a four-loop Westinghouse Standardized Nuclear Unit Power Plant System (SNUPPS) PWR at a thermal power of 3565 MW.

Objectives

- Characterization of PWR transient thermal-hydraulic behavior under hypothetical secondary LOCA events, addressing the following issues:
  - Effects of emergency operating procedures (EOPs)
  - Likelihood of induced steam generator (S/G) tube leakage
  - Effects of varying leak rates
  - Identification of controlling thermal-hydraulic phenomena with a best-estimate computer code
- Potential for stable, long-term residual core heat removal.

EOP Review

A review of the relevant EOPs was used to determine the operator actions that would be taken during secondary LOCA events that induce significant tube leakage. An iterative process was used with the operator actions and the thermal-hydraulic analysis to determine a final characterization of the accident scenario. The review concluded that procedures direct the operators in such a way that cold shutdown conditions will be achieved in a timely fashion.

Transients Evaluated with RELAP5

A total of eight main steam line break (MSLB) transients were simulated with the RELAP5/MOD3.1 code. Baseline calculations were made to investigate the timing of possible induced tube leakage. Sensitivity studies were then performed to assess the effects of tube leakage, tube leak rate, and operator actions. In addition, two transients were considered for a main feed line break (MFLB) with S/G tube leakage.

Transients Evaluated with MAAP

A total of forty-six transients were simulated with MAAP3.0B-PWR, Revision 19.0. These were made to investigate a wide range of uncertainties and boundary conditions and to guide the more detailed RELAP5 calculations. Sensitivities were performed to investigate the timing and choice of various operator actions and equipment availability, as well as the assumed steam line and tube leak areas. Key information summarizing the sensitivities is presented for various steam line break sizes without induced leakage, for MSLBs with and without operator actions, and finally, for the best estimate MSLBs with various tube leak areas initiated at psid between the primary and secondary.

Transients Overview/Controlling Phenomena

Initial calculations focused on determining if reactor coolant system (RCS) pressurization to high pressure (greater than psid) was likely. Transient results indicate that within approximately 20 minutes, the charging pumps bring the RCS to this value, with the safety/relief valves (S/RVs) or power-operated relief valves (PORVs) cycling to limit pressures. Subsequent calculations were performed with S/G tube leakage to quantify the sensitivity to assumptions on induced rupture timing, leak area, and operator actions (i.e., EOPs).

The analyses revealed that the dominant, or controlling, phenomenon is a significant and sustained cooldown of the primary system due to safety injection (SI) system flow through the primary and out the S/G tube leak. Core exit temperatures were below °F (the residual heat removal (RHR) system temperature entry point) within hours for all calculations. Indeed, increasing the assumed tube leak area only increased the SI flow and more quickly reduced the core temperature. The primary coolant is highly subcooled during the transient, with primary system pressure maintained only by the SI pumping head. Operator actions could easily reduce the pressure in several ways such as throttling the SI system, operating the pressurizer (PZR) sprays, and/or opening a PZR PORV. Within hours or less, depending on the size or existence of induced leakage, both the pressure and temperature conditions are such that entry into RHR could be initiated. The MAAP results were qualitatively consistent with those from RELAP5.

Induced S/G Leakage

- For a large MSLB that is not isolatable, the primary system pressurizes relatively quickly (minutes), reducing the likelihood that the operators will be able to limit the differential pressure across the S/G tubes by terminating or reducing the charging pump flow prior to repressurization.

- For an MFLB, the primary system pressurizes much more quickly than for the MSLB, causing tube leakage to be induced earlier.

- For a slower S/G depressurization, such as that due to a stuck-open atmospheric dump valve (ADV), the operators have much more time to respond. Termination of charging flow is likely prior to pressurizing the reactor coolant system (RCS) to pressures above the relief valve setpoint. This initiating event is also much more likely than a large MSLB outside containment.

- Water discharged through the S/G tube leak allows for two heat removal mechanisms not present in MSLB calculations without leakage. First, the mass and enthalpy of the fluid leaving the break removes energy from the primary system. Second, the water that did not flash when discharged into the S/G is subsequently boiled due to primary-to-faulted-secondary heat transfer. The cold SI and charging water replaces the water lost out the tube leak and cools the primary system water.

Depletion of Refueling Water Storage Tank (RWST) and Long-Term Heat Removal

- The operators have ample time (hours minimum) and measures to reduce the RCS pressure and temperature to enter the shutdown cooling mode. In the analyses performed, less than percent of the RWST water was injected before shutdown cooling entry conditions were achieved.

- The ability to achieve shutdown cooling in a timely manner is helped by the RCS cooldown induced by the initial MSLB. In cases including tube leakage, instead of beginning a cooldown at hot shutdown conditions (°F), the cooldown is effectively initiated at a much lower RCS temperature depending on the size of the break.

- Depletion of the RWST water is further inhibited by the reduction in the leakage rate as the RCS is depressurized. Based on the analyses performed here, the RCS depressurization could be successfully initiated less than hours after the S/G tube leak was induced. Larger leak rates allow earlier initiation.

Conclusions

In summary, these comprehensive thermal-hydraulic calculations, including the use of a best-estimate code, demonstrate that S/G tube leakage in combination with MSLB or MFLB events would result in a cooldown of the primary system due to SI inflow into the system. This cooldown would allow ample time for the operators to enter stable, long-term decay heat removal long before depletion of the RWST. Thus, tube leakage events that were postulated to occur from MSLB/MFLB transients with plants operating under the ARC would have no new core coolability issues and existing EOPs are appropriate.

1

INTRODUCTION

The NRC has expressed concerns regarding ultimate core coolability in the hypothetical event of secondary system LOCA that induces tube leakage [1, 2, 3]. It is postulated that in a secondary system LOCA scenario, stresses resulting from the S/G blowdown and the subsequent primary system pressurization could cause a significant increase in S/G tube leakage. These stresses result from the increase in the pressure difference across the tubes. For most LOCAs, water is injected into the primary system from the RWST and is collected in the containment sump. However, with the combination of tube leakage and a faulted main steam line outside containment, the water injected into the primary system leaks to the faulted S/G and is boiled away. The NRC is concerned that if this type of accident were to occur, the RWST could be drained before the shutdown cooling mode could be achieved, eventually causing core damage.

The EOPs that apply to cases in which a secondary system LOCA induces significant tube leakage were reviewed. The operator actions that would be taken in such a scenario were determined and were used as input for the thermal hydraulic analyses. The EOP review is discussed in Section 2.0. If it can be shown that the primary coolant system can be depressurized and cooled to conditions where the shutdown cooling system could be activated prior to depletion of the RWST water supply, a stable, safe shutdown could be achieved. The shutdown RHR system recirculates the primary system water in a closed loop through heat exchangers. Consequently, there is no concern for the depletion of the water supplies once this system is activated and/or the primary system has been brought down to atmospheric conditions. Furthermore, since the RHR is a closed loop system and the pump suction points are below the tubesheet, core cooling will be maintained even if the primary system liquid level drops below the leak elevation.

The RELAP5 computer code was used to characterize the best-estimate plant response following MSLB and MFLB scenarios with induced S/G tube leakage, and to quantify the potential for long-term, stable cooling. The analysis was completed assuming an S/G tube leak area equal to percent of the cross-sectional area of a single tube. Results from the RELAP5 analysis are presented in detail in Section 3.0.

Additional analyses were made with MAAP to investigate a wider range of uncertainties and boundary conditions. Insights from these analyses were used to guide the more detailed RELAP5 calculations. Sensitivities were performed to investigate the differences resulting from various steam line and tube leak areas. Additionally, the effects of variations on the timing and choice of various operator actions, and the availability of equipment were examined. These included the amount of auxiliary feedwater (AFW) flow, the number of SI and charging pumps, the operation of the main coolant pumps, and the choice of PZR PORVs or sprays to depressurize the primary system. Results from the MAAP calculations are discussed in Section 4.0.

2

REVIEW AND ANALYSIS OF OPERATOR ACTIONS

Relevant Westinghouse EOPs were reviewed to determine what operator actions would be taken in the event of a steam line break with induced S/G leakage. The operator actions were used as a basis for developing parameters for the thermal-hydraulic analysis. The results of the thermal-hydraulic analysis were then used to refine the operator actions and accident times to arrive at a final characterization of the accident scenario. Finally, the procedures were reviewed to determine their adequacy for response to the event.

The results of this task indicate that plant procedures based upon the Westinghouse Owner's Group Emergency Response Guidelines (ERGs) [4] have adequate provisions to ensure termination of the event (i.e., reaching cold shutdown conditions) long before there is a danger of draining the safety injection water source. There are specific steam generator tube rupture (SGTR) procedures for this scenario. There are numerous references in both fold-outs and continuing actions that provide guidance to identify S/G tube leakage and that would lead the operator to these procedures once S/G leakage is detected.

If primary leakage is not detected, the operator would follow plant LOCA procedures. These procedures call for actions similar to those for an SGTR and would result in an identical plant cooldown and depressurization to shutdown conditions long before SI inventory would be exhausted. Thermal-hydraulic analysis indicates that the time to reach cold shutdown is a function of leak rate, with higher leak rates resulting in achievement of cold shutdown in an accelerated fashion.

This analysis was based upon a review of the Westinghouse ERGs [4], recent EOPs from two Westinghouse PWRs with high pressure SI systems, and detailed discussions with plant training staff. The review of the EOPs indicates that current procedures closely follow the ERGs. The EOPs/ERGs reviewed include the following:

- E-0—Reactor Trip or Safety Injection
- EOP E-2—Faulted Generator Isolation
- EOP E-1—Loss of Reactor or Secondary Coolant
- EOP E-1.1—SI Termination Procedure
- EOP E-1.2—Post-LOCA Cooldown and Depressurization

- EOP E-3—Steam Generator Tube Rupture
- EOP ECA-3.1—SGTR with Loss of Coolant - Subcooled Recovery Required
- EOP ECA-3.2—SGTR with Loss of Coolant - Saturated Recovery Required

Figure 1 summarizes the operator actions early in the scenario, up until S/G leakage is identified. The initiating event is a large steam line break. This results in immediate AFW actuation, SI actuation and main steam isolation valve (MSIV) closure. The operator then enters procedure E-0 (Reactor Trip) and begins to check plant status. In ERG Step 19, the operator identifies that an S/G is depressurizing in an uncontrolled manner and transfer to Procedure E-2 (Faulted S/G Isolation). Procedure E-2 directs the operator to isolate AFW to the faulted S/G and transfer to EOP E-1 (Loss of Reactor or Secondary Coolant). This activity takes about minutes. After the S/G has blown down, SI flow pressurizes the RCS to the primary relief valve setpoints. According to the thermal-hydraulic analyses discussed in this report, this can occur in approximately minutes for an MSLB, and approximately minutes for an MFLB. Although it is reasonable to assume that the operator may throttle/secure SI and charging flow to prevent overpressurization, it is difficult to assume that this takes place in all cases. The primary system pressurization increases the differential pressure across the faulted S/G's tubes and is postulated to result in induced leakage.

In Procedure E-1, the operator monitors RCS pressure. If RCS pressure drops below psig, the reactor coolant pumps are stopped. The blowdown of the faulted S/G causes RCS pressure to be reduced to the vicinity of psig. Therefore, it is not absolutely certain whether the reactor coolant pumps (RCPs) would be stopped. The second step in this procedure is a continuing action that calls for the operator to check secondary systems for S/G tube leakage. This involves monitoring the following indications:

- Steam line radiation monitors—The delay in the occurrence of tube leakage after reactor trip may cause these monitors not to respond due to the decay of N-16 after the reactor trip. (Note that there is no dilution of primary inventory in the S/G since the S/G tube leakage is postulated to occur after all the secondary inventory has boiled off.)
- Steam Jet Air Ejector Radiation Monitor—These radiation detectors are isolated from the S/G by the MSIV closure.
- S/G Blowdown Radiation Monitor—These radiation detectors are isolated as part of the isolation of the steam line break, and lack of S/G inventory.
- Periodical sampling of all S/Gs for normal activity—This action results in detection of the S/G tube leakage. However, since the S/G is initially dry, this method of detection may be delayed until inventory is available.

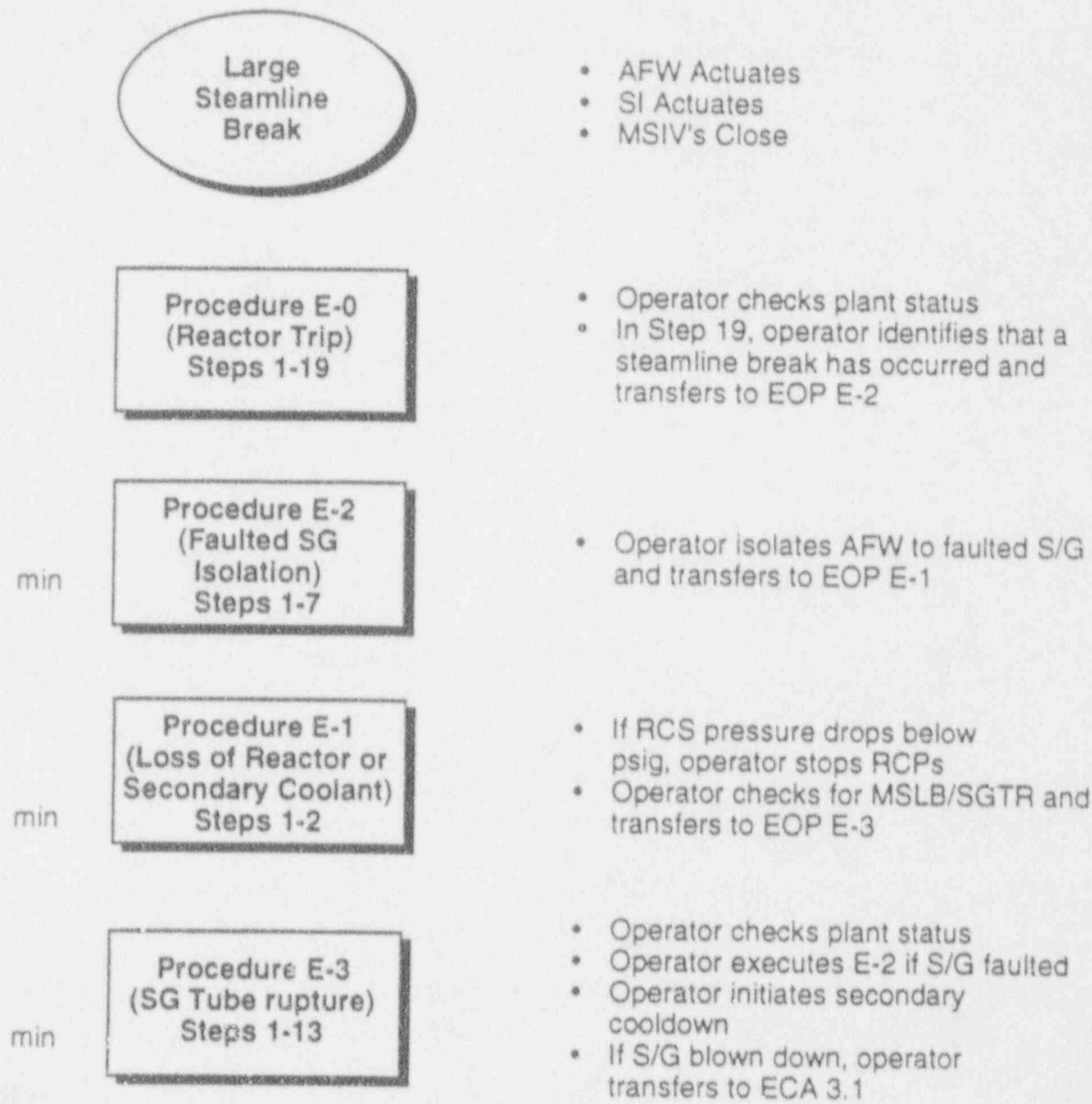

Figure 1
Initial Operator Actions

The procedure fold-out instructs the operator to transfer to E-3 if any S/G level increases in an uncontrolled manner, or if any abnormal S/G radiation is detected. For the case of S/G tube leakage in conjunction with a secondary side LOCA, such as uncontrolled level increase may not be immediately observable due to the initial depletion of the inventory and the subsequent boiloff of primary coolant which leaks to the secondary side. Eventually, however, primary coolant collects in the secondary side and the level increases in an uncontrolled manner.

In addition, to the above procedural instructions, the tube leakage may provide a number of other indications to the crew that would cause an SGTR to be diagnosed and transfer to E-3:

- Continued S/G steaming with no inventory level indicated in the S/G.
- Primary system depressurization and loss of PZR level with no compensating external containment effect (containment radiation, containment pressure, etc.).
- Significant SI flow into the RCS with no corresponding level indication in the containment sump.

Until there are indications of S/G tube leakage, Procedure E-1 continues the process of responding to a LOCA. The RCS will be highly subcooled (due to S/G blowdown, and SI flow into the RCS and out the tube leak). This allows the operator to transition to Procedure E-1.1 (SI Termination). Procedure E-1.1 instructs the operator to align charging flow, isolate charging injection, and begin to stop SI pumps. This causes RCS pressure to drop precipitously since the SI pump head is the cause of the RCS pressurization. For larger leaks this will result in a transfer to Procedure E-1.2 (Post-LOCA Cooldown and Depressurization). This procedure calls for the operator to begin RCS cooldown to cold shutdown at °F per hour, maintaining °F subcooling. The RCS depressurization to °F subcooled also greatly reduces RCS pressure and reduces leakage. The time required for cooldown to an RHR entry condition is a function of leak rate, with higher leak rates resulting in earlier entry to RHR. Thermal-hydraulic analysis indicates that for a leak area equal to the cross sectional area of a single tube, the RCS is cooled (by the S/G blowdown, SI flow into the RCS and flow out the break) to the necessary conditions within about hours (see Sections 3.0 and 4.0). Tube leakage and other factors could allow this to happen even earlier.

When the operator determines that S/G tube leakage is occurring, he will transfer to Procedure E-3 (S/G Tube Rupture). Procedure E-3 begins the actions for terminating leakage of reactor coolant into the secondary cooling system, as well as invoking Procedure E-2 if the faulted S/G has not been isolated. In this case, a faulted S/G prevents normal isolation of the leakage by elevating pressure on the faulted S/G and the operator is transferred to Procedure E-3.1 (SGTR with Loss of Coolant - Subcooled Recovery Required).

The cooldown to RHR entry conditions is illustrated in Figure 2. This procedure uses the same mitigation strategy as the post-LOCA cooldown and depressurization procedure previously described, and results in the alignment of the RHR system and cooldown to atmospheric pressure. In addition, this procedure calls for the operator to monitor the RWST level and if it reaches percent, the operator is transferred to Procedure ECA 3.2 (SGTR with Loss of Coolant - Saturated Recovery Required). This procedure calls for the operator to further depressurize the RCS to saturated conditions (which further reduces loss of coolant) and calls for the operator to begin make-up to the RWST. Due to the large volume of inventory available and the cooled-down status of the RCS, it is unlikely that this procedure would be reached.

This review indicates that, in the event of significant RCS leakage, the operator is directed to procedures that provide the necessary steps to depressurize the reactor and cooldown to cold shutdown conditions in a timely fashion. The thermal-hydraulic calculations indicate that the reactor tends toward these conditions as part of the natural course of events. Since the post-LOCA and SGTR procedures follow similar strategies, until RWST inventory is depleted (calculations indicate that cold shutdown is achieved by these procedures long before depletion of SI inventory), early diagnosis of S/G leakage is not critical. Later diagnosis, prior to depletion of SI inventory, is likely to occur since the faulted S/G level will rise, and activity samples of S/G activity will direct the operator to the SGTR procedures.

Tables 1 and 2 provide input to the thermal-hydraulic analysis for use in developing their special cases for evaluation.

Table 1
Operator Actions During MSLB with no S/G Leakage*

Event	Approximate Timing
MSLB	
Reactor trip	
Main feedwater trip	
SI pumps actuate	
AFW actuates	
Isolate AFW to faulted S/G	
Trip RCPs (if applicable)	
Trip all but one charging pump (if leakage rate allows)	
Trip SI pumps (if leakage rate allows)	

* S/G leakage, if any, is presumed to be too small to cause secondary side radiation alarms to be triggered.

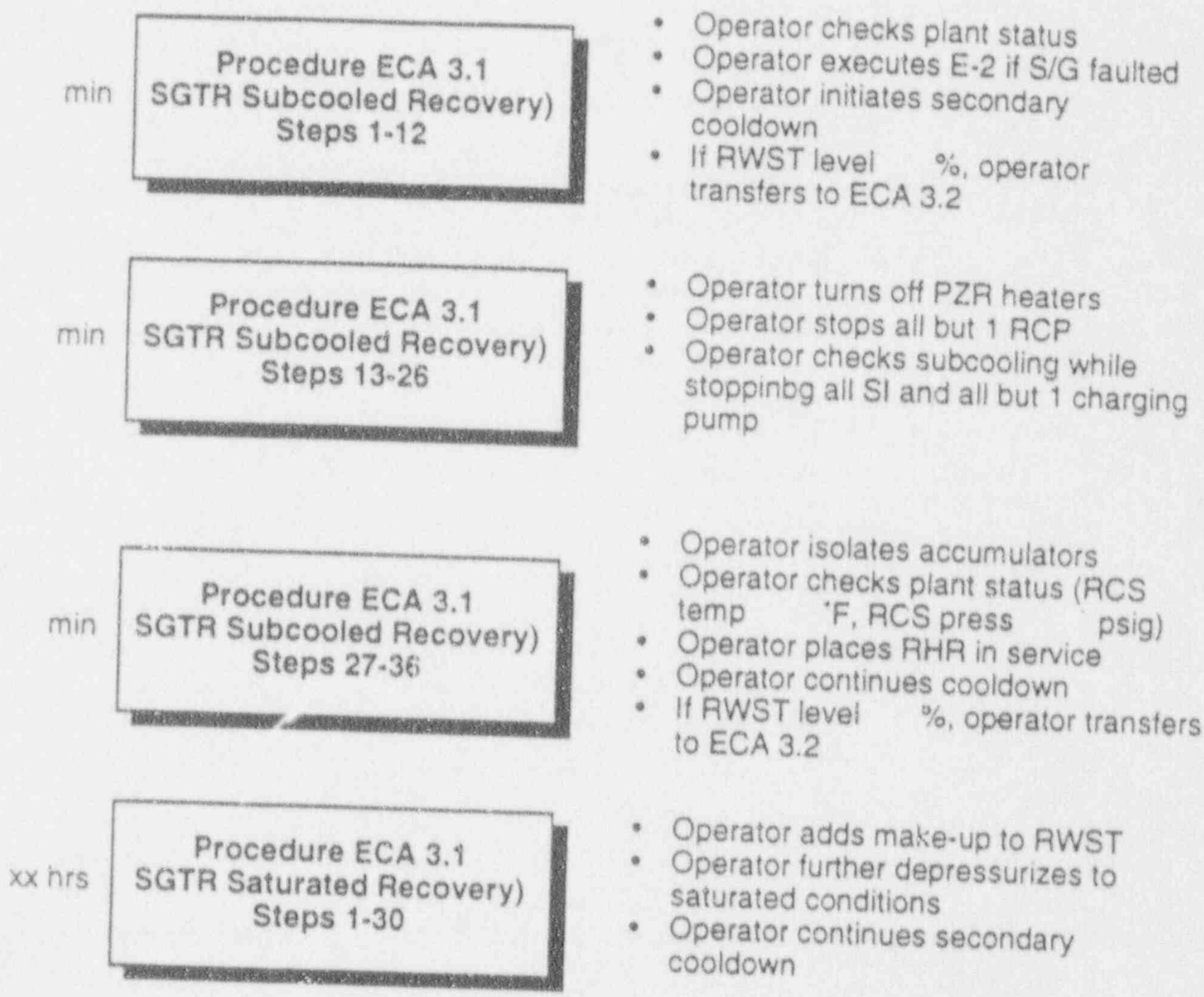

Figure 2
Operator Actions for Cooldown to RHR Entry Conditions

Table 2
Operator Actions During MSLB with S/G Leakage

Event	Approximate Timing
MSLB	
Reactor trip	
Main feedwater trip	
SI pumps actuate	
AFW actuates	
Isolate AFW to faulted S/G	
Trip RCPs (if applicable)	
Control intact S/Gs narrow range level between % and %	
Dump steam to condenser or atmosphere to maintain °F/hr cooldown	
Use PZR sprays or open one PZR PORV to depressurize RCS to shutdown cooling entry conditions	
Trip one charging pump (if leakage rate allows)	
Trip both SI pumps (if leakage rate allows)	
Maintain PZR level with charging pumps	

3

RELAP5 CALCULATIONS

A total of ten cases were analyzed with the RELAP5/MOD3.1 computer code [5]. The first two cases model the plant automatic response. In Case 1, the tube leakage was assumed to be too small to cause the secondary side radiation alarms to be triggered. Based on the differential pressure across the S/G tubes, this case was used to assess the likelihood and timing of induced S/G tube leakage. In Case 2, the MSLB induced tube leakage, causing the secondary radiation alarms to activate.

Cases 3 through 10 included operator actions, and were used to determine the effect of those actions on the transient. Case 3 simulated the MSLB with no S/G tube leakage. Cases 4 through 7 examined the plant response to leakage equivalent to an SGTR coincident with the MSLB. The effectiveness of the operator actions to achieve a safe, stable condition prior to exhausting the water supply in the RWST was also examined for these cases. Case 8 is the same as Case 6 except for a few refinements in the operator actions. In Cases 9 and 10, an MFLB (instead of an MSLB) induces an SGTR. Case 9 includes AFW to the intact S/G, while in Case 10 all AFW was assumed to fail.

3.1 RELAP5 Model Description

A four-loop Westinghouse RESAR III plant was modeled with RELAP5/MOD3. The nodalization diagram that was used is shown in Figure 3. The model consists of two loops; one representing the recirculation loop with the affected S/G and the other modeling the three intact loops. The S/RVs on the PZR and S/Gs were modeled as noted in the calculations, as were the AFW system, the charging system, and the SI system. The accumulators were assumed to be isolated during these transients. The PZR sprays and heaters were not modeled.

The design parameters and setpoints required for the RELAP5 input deck were chosen to approximate that of a large, four-loop Westinghouse reactor. The following assumptions were made in the calculations:

- Rated reactor thermal power MW_{th}.
- The MSLB area is ft^2, the area of the flow restrictor in the main steam line. The MFLB area is ft^2.
- The cross-sectional flow area of a single S/G tube is ft^2. Tube leakage was based on this critical flow area.

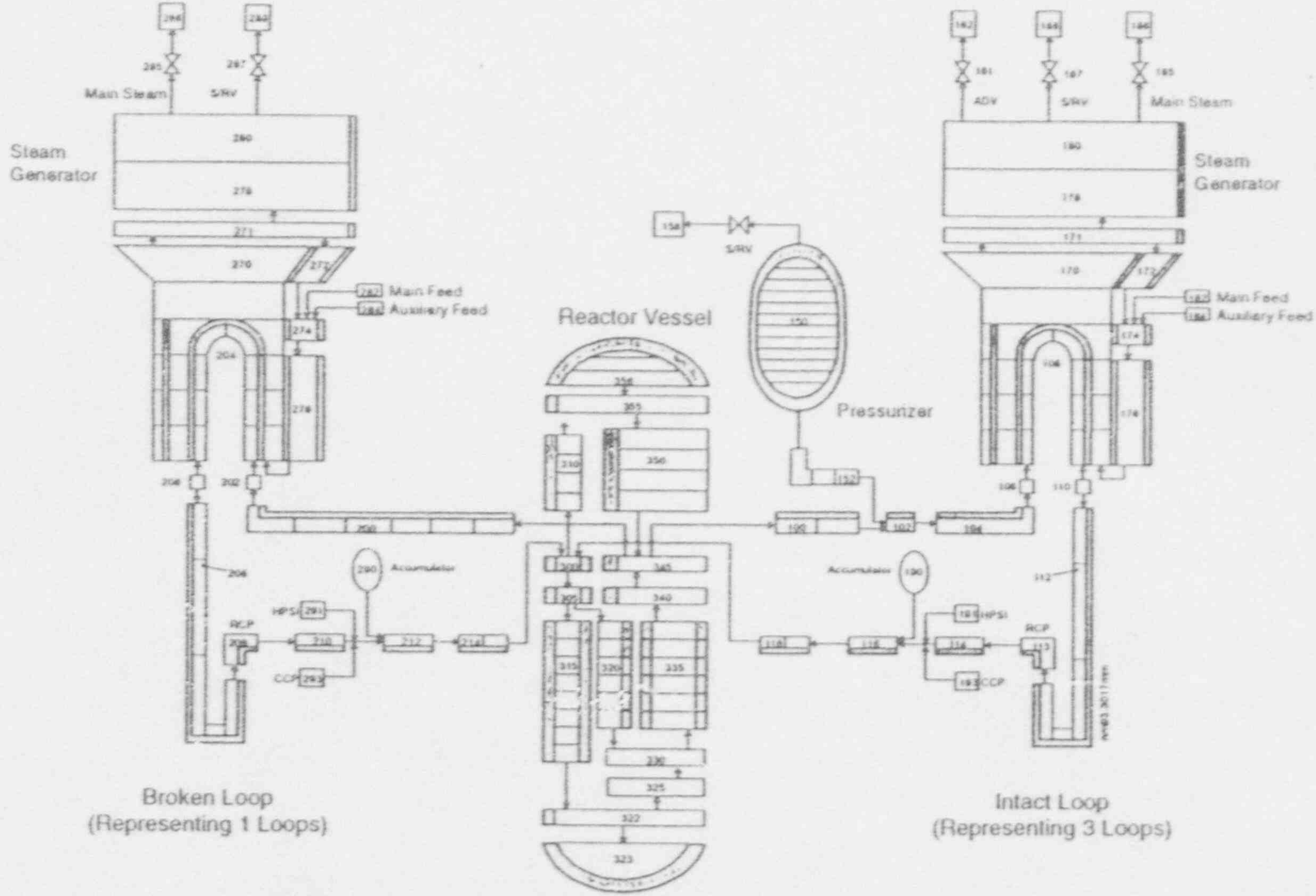

Figure 3
RELAP5 Nodalization Diagram for a Westinghouse Four-Loop Plant

- The reactor was set to trip on the following signals with a two second delay: (1) low PZR pressure of psig, (2) low-low S/G level of ft, and (3) high differential pressure between the S/Gs of psid.

- The main feedwater isolation was set to actuate on the PZR or differential pressure signals with a delay time of seconds. The flow was then ramped linearly to zero over the next seconds.

- SI is actuated on the PZR or differential pressure signals with a delay time of seconds. The two high-pressure pumps and the two charging pumps were enabled at this time until any operator actions disable them. Pump flow curves are presented in Figures 4 and 5.

- AFW is actuated on any of the reactor trip signals with a second delay. Two motor-driven pumps (gpm each) were modeled at full flow.

- Offsite power is available.

- The RWST capacity is gallons.

- The RHR system entry points are psia and °F.

Ten cases were run with the RELAP5 model and are discussed in this report:

Cases without operator actions

- Case 1—MSLB.

- Case 2—MSLB with an induced leakage equivalent to an SGTR. The tube leakage occurs at time zero, and the leakage area is equal to the area of one end of the tube (percent break).

Cases with operator actions

- Case 3—MSLB with the operator actions listed in Table 1.

- Case 4—MSLB and leakage equivalent to a percent break SGTR at t=0, with the operator actions listed in Table 2.

- Case 5—MSLB and leakage equivalent to a percent break SGTR at t=0, with the operator actions listed in Table 2.

- Case 6—MSLB and leakage equivalent to a percent break SGTR, with the operator actions listed in Table 2. The tube break occurs when the primary to secondary differential pressure reaches psid.

Figure 4
Charging Flow versus Head Curve

Figure 5
Combined High and Low Pressure SI Injection Flows versus Head Curve

- Case 7—MSLB and leakage equivalent a percent break SGTR, with the operator actions listed in Table 2. The tube break occurs when the primary to secondary differential pressure reaches psid.

- Case 8—MSLB and leakage equivalent a percent break SGTR, with the operator actions of Table 2 that do not include the initial RCP trip. These actions are listed in Table 3. The tube break occurs when the primary to secondary differential pressure reaches psid.

Alternate Accident Cases

- Case 9—MSLB and leakage equivalent a percent break SGTR, with operator actions listed in Table 3. AFW is assumed to be intact. The tube break occurs when the primary to secondary differential pressure reaches psid.

- Case 9—MSLB and leakage equivalent a percent break SGTR, with operator actions listed in Table 3. AFW is assumed to fail. The tube break occurs when the primary to secondary differential pressure reaches psid.

Table 3
Revised Operator Actions During MSLB with SGTR–Equivalent Leakage

Event	Approximate Timing
MSLB	
Reactor trip	
Main feedwater trip	
SI pumps actuate	
AFW actuates	
Isolate AFW to faulted S/G	
Control intact S/Gs narrow range level between 4% and 44%	
Dump steam to condenser or atmosphere to maintain < 100°F/hr cooldown	
Trip three RCPs (last RCP is tripped at 1275 psia)	
Trip one charging pump	
Trip both SI pumps	
Maintain PZR level with charging pumps	

3.2 Results

The results from the RELAP5 calculations are discussed in two parts. The first set of calculations include the plant automatic response and assume that no actions are taken by the plant operators. The second set of calculations include operator actions to conserve SI water supplies and to permit eventual actuation of the shutdown RHR systems. The calculations were terminated at a time when it was clear that the operator could initiate this system. The subsequent cooldown by the RHR system was not modeled in the RELAP5 calculations. A complete set of plots for each of the ten cases analyzed is provided in Appendix A.

3.2.1 Plant Automatic Response (No Operator Actions)

Two calculations were performed to benchmark the plant automatic response for comparison to the operator action calculations. Case 1 was an MSLB without S/G tube leakage, while Case 2 included an MSLB coincident with tube leakage. Both cases result in a reactor scram immediately following the MSLB, due to high differential pressure between the faulted and intact S/Gs. The reactor coolant pumps were assumed to run for the duration of the transient. All AFW flow was assumed to be discharged into the faulted S/G because of the low pressure[1] and low liquid level conditions. The charging flow and SI flow were given by the pump head characteristics shown in Figures 4 and 5. Since operator actions were not modeled for these cases, the SI and charging flows were not decreased on high PZR level indications. The results from the two cases are described below.

Case 1—MSLB. As shown in Figure 6, the faulted S/G pressure dropped rapidly in response to the tube leakage. Within minutes the pressure had dropped below psig and over percent of the initial S/G liquid inventory had flashed and vented out the faulted line. All the AFW flow was injected into the faulted S/G but was inadequate to restore the liquid level. However, as shown by the intact S/G and primary system fluid temperature response (Figure 7), the faulted S/G was effective at removing the heat from the primary system and the intact S/Gs. This led to a cooldown of the primary system and the intact S/Gs as the energy was rejected to the faulted S/G.[2] After seconds, all four S/Gs and the primary system continued to cool down, but the primary system began to pressurize.

While the initial primary system depressurization was due to an overall contraction of the system due to a decrease in the primary system liquid specific volume, the subsequent primary pressurization was due to the net inflow of water from the charging and SI systems. By approximately seconds, the primary system had pressurized to the S/RV setpoint. (The PZR PORV was conservatively disabled to maximize the potential differential pressure between the primary and faulted S/G.) S/RV cycling relieved vapor, and subsequently liquid, to maintain the system pressure at psi. As shown in Figure 8, it is at this time that the tube differential pressure reaches a maximum. The small increase in differential pressure immediately following the MSLB was quickly offset by the depressurization (i.e., contraction) of the primary system. Consequently, the most severe tube differential pressure does approach psid until seconds into the transient.

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1 The AFW lines for all four S/Gs have a common header. Therefore, most of the AFW flow would go to the low pressure, faulted S/G.

2 Some oscillations were present in the early S/G response as portions of the secondary side of the S/G (modeled with four heat structures and thermal-hydraulic cells) dried out and rewet.

Figure 6
Case 1–Primary and Secondary System Pressures

Figure 7
Case 1–Primary and Secondary Fluid Temperatures

Figure 8
Case 1–Faulted Steam Generator Tube Differential Pressure

Case 2—MSLB with a Percent SGTR at t= seconds. In Case 2, it was assumed that S/G tube leakage occurred with an effective leak area equivalent to the cross-sectional area of one tube. The early pressure response is very similar to Case 1 (see Figure 9). As expected, the primary system depressurized slightly more than Case 1 due to the SGTR leakage.[3] The tube leakage did not greatly affect the faulted S/G pressure response. However, due to the presence of a tube break, the primary system equilibrated at a pressure below the S/RV setpoint (see Figure 9). For the assumed tube break size and the pump head characteristics of the charging pumps used in this simulation, the net inflow and outflow balanced at approximately gpm (see Figure 10) and psi. Of course, with different S/G leak rates or different charging pump characteristics, the balance may occur at higher or lower primary system pressures.

The primary system and intact S/G fluid temperature response is comparable to Case 1, with heat transfer always toward the affected S/G. Similar to Case 1, the primary system has cooled down to less than seconds and could be rapidly depressurized to low pressure if the operator took actions to throttle or temporarily terminate all injection. Unlike Case 1, however, leakage through the S/G tube helps to depressurize the primary system after the operator throttles primary system injection.

3.2.2 Plant Response with Operator Actions

Six calculations were performed to examine the effectiveness of operator actions to bring the plant to a safe shutdown condition following an MSLB. Case 3 has initial conditions similar to Case 1, and does not include a coincident SGTR. Cases 4 and 5 include a coincident SGTR at the transient initiation, with a percent and percent tube break area, respectively. These two cases include the operator actions in response to the transient depicted in Case 2. The operator actions are those discussed in the previous section, and were specified to be identical to those used in the initial MAAP calculations [6].[4] Cases 5 and 6 assume the same operator actions as Cases 3 and 4, but do not include an SGTR until the primary system pressurizes to approximately psia. The specific results from the five operator action cases follow.

Case 3—MSLB with Operator Actions from Table 1. In Case 3, the operator was assumed to take actions to isolate the affected S/G and to control the primary injection systems. Since there was no SGTR for this scenario, no actions were taken immediately to depressurize the system. Figures 11 and 12 show the system pressure and

3 The sharp depressurization at seconds is a result of the nodalization used in the PZR and the absence of the PZR heaters. As the highly subcooled liquid level rises in to the PZR, the subcooled liquid-to-gas heat transfer in the PZR causes the depressurization. The problem does not persist and does not affect the conclusions from the calculation.

4 Further review of the Westinghouse EOPs suggests that the operator action of opening a PORV at 45 minutes would not be performed (see Case 8). The PORV would only be opened if the PZR liquid level was low. In the RELAP calculations, the system was water solid. Consequently, the PORV would not have been opened. This action only delays the timing until the operator successfully depressurizes the system to the RHR entry point (see Case 8). Eventually, throttling charging flow below the leak flow after minutes will allow the system to depressurize.

Figure 9
Case 2–Primary and Secondary System Pressures

Figure 10
Case 2–Comparison of the SI and Primary and Secondary System Leak Flow Rates

Figure 11
Case 3–Primary and Secondary System Pressures

Figure 12
Case 3–Primary and Secondary System Temperatures

temperature responses. As before, the faulted S/G pressure fell rapidly in response to the faulted steam line. At minutes, when the AFW was isolated in the affected S/G, the affected S/G boiled dry and the pressure fell to approximately atmospheric conditions. After this time, the heat generated in the primary system was rejected to the intact S/Gs. This caused the primary system and three intact S/Gs to gradually heat up for the duration of the transient. At the end of the transient, the intact S/G and the primary system temperatures were approaching °F. Once the intact S/Gs reach the S/RV setpoint, the intact S/Gs would not heat up or pressurize any further. This would also stop the primary system heat up as the heat transferred to the S/G would be discharged out the relief valve while AFW would make up the liquid inventory. The isolation of the faulted S/G also causes the RCS to pressurize sooner and at a faster rate than in the case with no operator actions (Case 1). The S/RV setpoint is reached at seconds.

Further actions were not modeled in this calculation since it was evident that even with early operator actions, the primary system could pressurize to the S/RV setpoint. Under these high differential pressure conditions across the S/G tubes, induced tube leakage may be a concern. It should be noted that with operator actions, the plant is at high pressure and temperature conditions, whereas the plant automatic response shows the S/Gs and the primary system to be at low temperature.

Case 4—MSLB with Percent SGTR at t= and Operator Action from Table 2. Figure 13 shows the primary and secondary pressure response to the MSLB and percent SGTR scenario. As in Case 3, termination of AFW at minutes to the affected S/G further reduced the faulted secondary pressure to near atmospheric conditions. However, water discharged through the S/G tube allowed for two heat removal mechanisms not present in Case 3. First, the mass and enthalpy of the fluid leaving the break removed energy from the primary system. Second, the water that did not flash when discharged into the S/G was subsequently boiled due to primary-to-faulted-secondary heat transfer. This led to a continued cooldown of both the primary and the intact S/Gs for the duration of the transient as the heat was removed through the faulted S/G.

Similar to Case 2, the primary system pressurized until the injection flow rate balanced the tube leak flow rate (see Figure 14). However, at minutes, actions were taken to depressurize the primary system (see Note 1). First, the atmospheric dump valves on the three intact S/Gs were controlled to perform a °F/hr cooldown of the primary system. Since heat removal through the faulted S/G was already cooling the primary system and intact S/Gs, this action did not contribute significantly to the primary system cooldown. However, at minutes the PORV was opened to depressurize the primary system. In response, there was a rapid depressurization of the primary system to under psi, until increased SI and charging injection flows slow the depressurization. If the SI, charging pumps, and accumulators had been isolated prior to this action, there is a potential for the primary to depressurize even further (see Figure 15 for primary system temperature). Eventually, the system stabilized at approximately psia, where the charging and SI flows balanced the tube leak and

Figure 13
Case 4–Primary and Secondary System Pressures

Figure 14
Case 4–Comparison of the SI and Primary and Secondary System Leak Flow Rates

Figure 15
Case 4–Primary and Secondary System Temperatures

PORV flows. At minutes, a charging pump and both SI pumps were isolated, respectively. This permitted the depressurization of the primary system to continue. After minutes, the last charging pump was throttled to control the liquid level in the PZR.

By the end of the calculation (seconds, or minutes), the system was below psia and °F. The RHR shutdown cooling procedures give the RHR entry point as psia and °F. Consequently, the operator could initiate low pressure RHR shutdown cooling and the plant would be safely shut down. Since the primary system had fallen below °F in less than minutes, the requirement is for the operator to control the injection systems and perform a controlled depressurization of the primary system. Since the water will not flash until it reaches saturation conditions, there is a potential for depressurization to psi (with no subcooling) after only minutes. At the end of the calculation, only gallons of SI and charging water had been injected into the primary system. Since the size of the RWST modeled was gallons [2], there is a large safety margin of injection water.

Case 5—MSLB with Percent SGTR at t= and Operator Actions from Table 2. The response of Case 5 was very similar to Case 4. The larger SGTR break area led to a larger initial drop in the primary pressure and a subsequently slower pressurization to psia. Both Case 4 (percent break) and Case 5 balanced out at approximately the same primary system pressure (psia). This is approximately the shut-off head of the SI pumps. Consequently, small variations in the system pressure around psia can double the total primary system injection flow rate. In general, the accident proceeded similar to Case 4 except a higher water injection rate into the faulted secondary actually enhanced the rate of the primary and intact S/G cooldown. By seconds, the primary system had cooled below °F. The higher leak rate contributed to a slightly higher integrated flow rate of water from the RWST: gallons, versus in Case 4. However, the primary system cooled below the RHR temperature entry conditions nearly minutes earlier than in Case 4, and at only seconds into the transient. Similar to Case 4, the primary challenge for the operators is to depressurize the primary system to the RHR entry point by throttling the injection flow.

Case 6—MSLB with Percent SGTR at ΔP= psid with Operator Actions from Table 2. A set of two sensitivity calculations were performed to assess how a delayed tube leakage would impact the accident progression. The timing of the operator actions was assumed identical to Cases 4 and 5. Therefore, it was assumed that there was enough leakage to activate the high radiation alarms early and the SGTR operator actions would be taken. When the primary-to-secondary differential pressure exceeded psid, it was assumed that leakage equivalent to either a percent or percent SGTR would be induced for Cases 6 and 7, respectively.

The early response of Case 6 is similar to Case 1 with the primary system pressure rising to psia by seconds. At this time, leakage equivalent to an SGTR occurred and depressurized the system to psia, where the tube leak flow balances the SI and charging injection flows. As in Case 4, the operator opened a PORV at minutes to depressurize the primary system. However, the SI and charging flows increased as the system pressure fell. This stopped a complete depressurization of the primary system to saturated conditions. However, the entire system continued to cool down. Both the °F/hr cooldown of the intact S/Gs and the energy flow out the S/G tube and the MSLB contributed to the system cooldown. As stated previously, the leakage was also contributing to the system cooldown. At the end of the transient, the primary system was below psia and °F. The total amount of water injected from the RWST was only gallons.

Case 7—MSLB with Percent SGTR at ΔP= psid with Operator Actions from Table 2. The next calculation was a variation of Case 6 with a percent SGTR when the tube differential pressure exceeded psid. The response was very similar to Case 6 with approximately the same end condition at the same time. Similar to the difference between Cases 4 and 5, the total injected SI and charging mass was slightly higher for the percent SGTR break. The total injected mass was gallons, versus gallons in Case 6. At the end of the transient, the primary system was below psia and F.

As before, the larger tube rupture area actually enhanced the timing for the primary system to drop below °F: minutes in Case 6, versus minutes in Case 7. However, both of these times are slower than in Cases 4 and 5, for two reasons. First, the integrated mass flow rate of cold injection into the primary system was greater earlier in Cases 4 and 5 versus Case 6 and 7 because of the leakage through the S/G tube. In Cases 4 and 5 the tube rupture occurs at the initiation of the transient, allowing leakage for a longer time period than in Cases 6 and 7. Since the SI and charging flow was very cold, the greater flow rate also contributed to the cooldown of the primary system. Second, the tube leakage enhanced heat transfer and energy removal from the primary system, as discussed in Case 4. Table 4 summarizes key timings for Cases 4 through 7.

Table 4
Summary of RELAP5 Calculations with Operator Actions

Case Number	Time to Tube Rupture [sec]	Equivalent Number of SGTRs	Time to RHR Entry [sec]	Volume of RWST Injected at RHR Entry [gal]	[%]
4					
5					
6					
7					

Case 8–MSLB with Percent SGTR at ΔP= psid and Revised Operator Actions from Table 3. A final MSLB simulation was performed which refined the likely operator actions (see Table 3). Examination of the emergency operator

procedures and the RELAP5 transient results in response to those actions suggested some modifications. In particular, four changes were made:

- Three of the main RCPs were tripped at   minutes and the last pump was tripped when the primary system depressurized below   psia
- The PZR PORV was not used to depressurize the primary system
- Two charging pumps were used to maintain the liquid level in the PZR
- The intact S/G AFW level setpoint was lowered to the top of the U-tubes

The first two modifications were made to better reflect the best-estimate operator actions for the calculated plant response. The first operator response modification was to delay tripping the RCPs. Cases 4 through 7 assumed all four RCPs would trip at   minutes. Review of the results of Cases 4 through 7 suggested that the operator would not trip the pumps until approximately   minutes. One RCP would be left running to support the PZR spray system (not simulated the in RELAP5 model). Once the primary system pressure dropped below   psia, the last RCP would be tripped. For the second operator action change, it was determined that the operator would be directed to use the PZR sprays to control the primary system pressure instead of the PZR PORV. Since the PZR sprays are not included in the RELAP5 model, no active primary system depressurization actions could be taken. However, the calculation was performed to assess the plant thermal response.

In addition, a review of the results of Cases 4 through 7 showed that one charging pump could not restore the PZR liquid level. Consequently, the third change was to use two charging pumps to maintain the liquid level for this transient. While one charging pump was sufficient to control the liquid level near the bottom of the PZR or in the surge line, there was insufficient flow to restore the normal liquid level in the PZR. Thus, it was assumed that the operator would add a charging pump and/or SI pumps to restore the PZR level. The results showed that the addition of the second charging pump was adequate to restore the PZR liquid level.

Finally, it was observed that the intact AFW flow was very effective in reducing the intact S/G pressure and fluid temperature. In the previous MSLB calculations with operator actions (e.g., Cases 4 through 7), boiling stopped at the beginning of the transient in the intact S/Gs as the heat flow reversed (e.g., the heat transfer was from the intact S/Gs to the primary system). This caused the voids in the boiler section to collapse and a corresponding drop in the collapsed downcomer level. The AFW was activated to restore the intact S/G downcomer level. The condensation and mixing caused by the AFW injection led to the depressurization of the intact S/Gs. While this effect was believed to be real, it was postulated that the RELAP5 model might have predicted an excessive amount of condensation. Consequently, the intact AFW level setpoint was conservatively lowered to approximately the top of the U-tubes for Case 8. If the level dropped below the top of the U-tubes due to ADV operation, AFW injection would be initiated to maintain the intact S/G inventories. Since the intact AFW was not actuated until after seconds, Case 8 effectively simulated no intact AFW and only minutes of AFW to the faulted S/G.

The system pressure results are shown in Figure 16. The primary system pressurization to psia occurred more quickly than the previous cases (e.g., seconds for Case 8, versus seconds for Cases 6 and 7). The more rapid pressurization was primarily attributed to the change in the AFW level setpoint of the intact S/Gs. The lower level setpoint meant that intact AFW was not initiated after the faulted S/G was isolated. In contrast to the previous results, the intact S/Gs remained at high pressure and did not contribute to the energy removal from the primary system. As shown in Figure 17, the intact S/Gs and the primary system temperatures were nearly in equilibrium. The heat transfer was generally from the intact S/Gs to the primary system. As noted above, the operator left the RCPs running for minutes. The key effect of the RCPs was to maintain the system flow. While increased flow through the faulted S/G U-tubes provided more uniform cooling, the influence of the intact S/Gs was to stabilize the primary system fluid temperature at the intact S/G temperature. The net effect was to minimize the primary system contraction and cause an earlier pressurization to psia.

Following the equivalent of a percent SGTR, the primary system depressurized to below psia. As in Cases 4 through 7, the subsequent primary and the faulted S/G system pressure oscillations were caused by heat transfer effects as the S/G tube walls alternately dried out and rewet. The oscillatory heat transfer behavior persisted through approximately seconds as the primary system pressure gradually dropped to below psia. After seconds, the primary system had cooled to a point where nucleate boiling heat transfer was sustained.

Between seconds, both charging pumps operated to restore the primary system inventory, causing a slow increase in the primary system pressure. After seconds, the charging pumps were cycled to maintain the PZR level for the duration of the transient. The primary system pressure remained at approximately psia for the remainder of the transient. By seconds, the primary system had cooled below °F. The total RWST injection was gallons. As discussed previously, the operator would have been directed to use the PZR sprays (not included in the RELAP5 model) to depressurize the primary system to the RHR entry point. Due to the relatively cool temperatures in the primary system and the large amount of injection water, it was expected that this operation could be readily achieved.

In comparison to the previous MSLB results (Cases 4 through 7), Case 8 resulted in a slower cooldown to the RHR entry point. Furthermore, Case 8 did not achieve the RHR pressure entry condition because the PZR sprays were not modeled (Case 4 through 7 used the PZR PORV to depressurize the primary system). However, the temperature entry condition was achieved with ample RWST water remaining. Based on the review of the operator actions, the PZR sprays would have been actuated at approximately minutes. The most significant differences between Case 4 through 7 and Case 8 was the

Figure 16
Case 8–Primary and Secondary System Pressures

Figure 17
Case 8–Primary and Secondary System Temperatures

conservative modeling of the intact AFW, the use of two charging pumps to maintain the PZR level, and no PORV actuation. All three changes slowed down the depressurization or cooldown of the primary system. However, only percent of the RWST was used when the primary system had achieved the temperature entry condition for RHR operation during Case 8. Therefore, it was expected that there was ample time for the operators to depressurize the system to the RHR entry condition.

Plant Response with Operator Actions for MFLB Scenarios. Two calculations were performed to examine the plant response to transients initiated with a break of the main feed line instead of the main steam line. It was assumed that the operator performed the same actions as were specified in the Case 8 analysis. It was also assumed that the MFLB caused immediate termination of normal feedwater flow to the faulted S/G and prevented any AFW injection. Similar to Case 8, the tube leakage was specified to occur when the differential pressure across the faulted S/G tubes exceeded psia. The equivalent of a percent SGTR was assumed to occur for both Cases 9 and 10. Case 9 included AFW flow to the intact S/Gs while Case 10 did not.

As in Case 8, the intact AFW level setpoint was conservatively lowered to approximately the top of the U-tubes for Case 9 (Case 10 did not include any AFW flow). If the level dropped below the top of the U-tubes due to ADV operation, AFW injection would be initiated to maintain the intact S/G inventories. Since the intact AFW was not actuated until after seconds, Cases 9 and 10 had identical response for the key portions of the transient. Due to the similarity in the system response for Cases 9 and 10, only the results from Case 9 are presented here.

Figure 18 shows the system pressure response. The primary system pressure rises for the first seconds until the reactor scrams and then drops with the primary system cooldown. SI stops the primary system depressurization and causes the system to pressurize to psia. At approximately seconds, the differential pressure across the faulted S/G tubes exceeds psid and the equivalent of a percent SGTR break was assumed to occur. In contrast, the induced SGTR in Cases 6 and 7 did not occur until seconds.

There are two key differences in the MFLB transients which affected the plant response; the break size and the break location. The break area was assumed to be ft^2, versus ft^2 for the steam line break. The smaller break size had an observable effect on the blowdown characteristics of the faulted S/G and subsequent behavior. In particular, the reactor scram occurred for the same reason as the MSLB transients but was delayed to approximately seconds. The break location also contributed to the delayed scram.

Figure 18
Case 9–Primary and Secondary System Pressures

Unlike the large steam line break which only removes high energy steam, the MFLB included a subcooled liquid and then saturated two-phase blowdown. The lower energy removal rate through the break contributed to the delay in reactor scram. Following the MFLB and subsequent S/G tube leakage, the faulted S/G pressure remained higher than during the MSLB transients. Both the smaller break size and the higher system resistance between the break location and the SGTR contributed to a higher secondary side pressure following scram. For example, the faulted S/G pressure was as high as psia following the tube rupture and generally higher than psia. In contrast, the faulted S/G pressure was always nearly at atmospheric conditions during the MSLB transients.

Following the start of the S/G tube leakage, the primary system pressure decreased while the faulted generator pressure increased. The faulted S/G began to fill in response to the S/G tube leak because the leak flow exceeded the faulted S/G break flow. The pressure response at seconds is again due to alternate dryout and rewetting of the S/G tubes. The primary system pressure balanced between and psia for the duration of the transient as the tube leak flow balanced the injection flow.

Between seconds, the faulted S/G pressure remained at psia and the primary and intact S/Gs slowly cooled. During this time, any water discharged through the SGTR was subsequently boiled and forced through the feed line break. At approximately seconds, the faulted S/G began to slowly fill with water and depressurize. The faulted S/G depressurization and increase in liquid inventory was primarily attributed to two factors: (1) a smaller flashing potential as the primary system liquid temperature approached the saturated liquid temperature of the faulted S/G, and (2) a change in the heat flow from the primary system to the intact S/Gs. After seconds, the primary system and the four S/Gs slowly cooled together until the end of the transient. By approximately seconds, the primary system had decreased below °F. The temperature response is shown in Figure 19.

The transient was terminated at seconds. The primary system had cooled below °F and was continuing to cool slowly. The primary system pressure was at approximately psia and holding steady. Both charging pumps were required to maintain the liquid level in the PZR. As shown in Figure 20, the primary system injection approximately equaled the S/G tube leakage and approximately gallons had been injected into the vessel. As discussed previously, the operator will have been instructed to use the PZR sprays to depressurize the primary system to the RHR entry point. Due to the relatively cool temperatures in the primary system and the large amount of water available for injection, it was expected that this operation could be readily achieved.

Figure 19
Case 9–Primary and Secondary System Temperatures

Figure 20
Case 9–Comparison of the SI and Primary and Secondary System Leak Flow Rates

3.3 Conclusion of RELAP5 Results

The five MSLB with SGTR-equivalent leakage transient calculations with RELAP5 show that a significant and sustained cooldown of the primary system due to SI system flow through the primary system and out the break is the dominant phenomenon. Within minutes, core exit temperatures were below the RHR system temperature entry point of °F. An increase in the tube rupture area caused an increase in the SI flow and a more rapid cooldown.

An additional analysis of the MFLB with SGTR-equivalent leakage scenario revealed that the small feed line break size and the different break location significantly affected the blowdown of the faulted S/G. In particular, the MFLB included a saturated two-phase blowdown and a delayed scram. The faulted S/G pressure remained higher for the duration of the calculation than during the MSLB cases. However, the core exit temperature was below °F by minutes as was the case in the MSLB scenarios.

4

MAAP CALCULATIONS

A total of forty-six transients were simulated with the MAAP computer code. Sensitivities were performed to investigate the timing and choice of various operator actions and equipment availability, as well as the assumed steam line and tube leakage areas. Rather than discussing every case, key information summarizing the sensitivities is presented for various steam line break sized without induced tube leakage, for MSLBs with and without operator actions and, finally, for the best estimate MSLBs with various tube leakage areas initiated at psid between the primary and secondary.

4.1 MAAP Model Description

MAAP3.0B-PWR, Revision 19.0 was used for the analysis [7]. A minor modification was made to the PZR spray control logic to ensure that it did not terminate prematurely. The plant model was a Westinghouse four-loop SNUPPS PWR. Similar to the RELAP5 representation, the MAAP model consists of two loops: one for the side with the affected S/G, and the other for the three intact loops. Representations for relief and safety valves of the S/Gs the AFW system, the main coolant pumps, the charging pumps, the SI pumps, the PZR sprays and heaters, and the accumulators were all as specified for the SNUPPS plant.

In addition to the standard inputs required to represent the SNUPPS plant with MAAP, the following assumptions were made in the calculations where appropriate:

- Initial percent full power conditions of MW_{th}, psia, and °F.
- The effective main steam line break area was ft^2 (this is the actual flow area of approximately ft^2 with nominal losses accounted for). Cases with smaller break areas were also investigated.
- The effective flow area of a double-ended break for a single S/G tube is ft^2. The total leakage area was, for convenience, characterized as being some multiple of this area.
- Reactor trips occurred on low PZR pressure of psig or low S/G water level of ft with a second time delay. If these signals were not reached within seconds, reactor trip was forced on assumed high differential S/G pressure.

- MSIV closure was initiated five seconds after reactor trip with a linear ramp down to full closed position occurring over the next five seconds.
- Main feedwater isolation was delayed seconds after reactor trip. The flow was then linearly ramped to zero over the next seconds.
- AFW was initiated seconds after a reactor trip signal. Two motor driven pumps were assumed to be available with a maximum flow of gpm. The turbine driven AFW pump was not modeled.
- SI was initiated on the low pressurizer pressure signal. Two high head charging pumps and two SI pumps were assumed to operate until operator actions were made to trip one or both pumps for each system. One and two pump operation flow curves are given in Figures 21 and 22.
- The PZR PORVs were initially assumed to be unavailable unless manually opened. This was done simply to examine the time required to reach the safety valve setpoint (in case the PORVs were unavailable).
- If sufficient level existed in the PZR and the pressure was below psia, then the PZR heaters automatically supplied MW of additional power.
- If main coolant pumps were on, the PZR sprays automatically initiated on high primary pressure of psia.
- The RWST capacity was gallons.
- The RHR entry conditions for shutdown cooling are RCS pressure less than psig and RCS average temperature below °F.
- Operation with one reactor coolant pump was simulated simply by reducing the flow rate and pump heat associated with each pump by a factor of four, since MAAP does not allow one to model such an evolution in any greater detail.

4.2 Background Analyses Without Induced Leakage Using MAAP

No Operator Actions

Several cases were run with no operator actions to investigate the early plant response, and to examine the effects of the assumed AFW flow, and the availability and operation of the SI and charging pumps. All of the cases resulted in reactor scram shortly after MSLB initiation. The reactor coolant pumps were assumed to run for the duration of the transient. All of the AFW flow from one pump was discharged into the faulted S/G. S/G level control was automatically maintained in the unfaulted units.

Figure 21
One and Two Pump Operation of SNUPPS Charging Pumps

Figure 22
One and Two Pump Operation of SNUPPS SI Pumps

The results from these cases were qualitatively similar to the results obtained by the NRC for a RESAR plant [1]. Variations of the assumed AFW flow and the capacity and availability of the injection systems influenced some of the details of the results, but the overall behavior was mostly unaffected. That is, the MSLB leads to a rapid S/G pressure and level drop. Figure 23, from a representative MAAP case with no operator actions, indicates that this also leads to a drop in primary system pressure sufficient to initiate SI systems. The actuation of the injection systems will eventually lead to the primary system repressurizing even though a rapid cooldown is underway caused by continuous operation of AFW to the faulted S/G. The time period associated with the repressurization is about a half-hour or more depending on the injection system capacities and the amount of AFW that is allowed to go to the faulted unit.

MSLB Operator Actions

As described in Section 2.0, there were two sets of operator actions considered. The first set assumes that the timing of the actions is based on entry into MSLB conditions only. That is, S/G leakage is presumed to be too small to cause secondary side radiation alarms to be triggered or any other indications of tube leakage such as increasing levels to occur. The timing of actions for these scenarios is shown in Table 5.

Table 5
Assumed Operator Actions for MAAP Calculations During MSLB without Entry into SGTR EOPs

Event	Timing
MSLB	
Reactor trip, main feedwater trip, SI pumps and AFW actuate	
SI Pumps and AFW actuate	
Isolate AFW to faulted S/G	
Trip all but one charging pump	
Initiate PZR level control	
Trip SI pumps	

From the MSLB operator action cases, the results of calculations with variations in the assumed MSLB area will be discussed. In all cases AFW to the faulted S/G is terminated at 5 minutes. Figure 24 demonstrates that similar behavior was obtained for a wide range of break areas. Only when the break area approaches something as small as one ADV with reduced AFW flow as shown in Figure 25 is there a substantial change in the results. The ADV-sized MSLB with reduced AFW flow to the intact loops was the only case that did not sufficiently depressurize the primary to initiate SI or the charging pumps. In the nominal stuck-ADV case, the increase in S/G inventory after the scram results in a gradual shrinkage of the RCS coolant volume, depressurization of the RCS, and activation of SI. If the S/G level is maintained constant after scram, this does not

Figure 23
Primary and Secondary System Pressures for MSLB without Operator Actions

Figure 24
Primary System Pressure for Various MSLB Areas

occur as is shown in the reduced AFW case in Figure 25. In reality, it is believed that normal make-up (not modeled in MAAP) would compensate for the shrinkage in the nominal stuck-ADV case and prevent SI activation.

In cases with SI activation, however, repressurization resulting from the injection systems is fairly similar in all cases regardless of the assumed steam line break area. The primary system pressure "bottoms out" between seconds as injection flow causes PZR level to begin to increase. Termination of AFW to the faulted unit at five minutes results in a more rapid pressurization rate than was seen in the no operator action cases. In any event, automatic actuation of the PZR sprays maintains the pressure below the PORV and safety valve setpoints until the PZR is full of water. Figure 26 indicates that this occurs between minutes in all cases in which safety injection was initiated (i.e., all but the ADV with reduced AFW case). Therefore, the assumed actions to control PZR level occur after the maximum primary to secondary pressure differential is reached. This increases the likelihood of enhanced leakage in the faulted S/G.

MSLB and SGTR Operator Actions

In the next case, it was assumed that the S/G leakage was sufficiently high to result in use of the SGTR EOPs, i.e., the operator actions shown in Table 6. To conservatively calculate the rate of pressurization, however, no leakage was actually modeled. The sequence of events is similar to the MSLB operator action case up to the time the SGTR procedures are entered. A °F/hr cooldown is initiated at minutes, and level control in the PZR commences at minutes. Once PZR level control is established, the primary system is depressurized with intermittent actuation of the PZR sprays in such a way as to maintain a minimum subcooling margin. Sensitivity cases also indicated that this could have been done by cycling the PZR PORVs if sprays were unavailable with little change in results.[5] Figure 27 shows that RHR entry conditions are reached by hours in this case and only percent of the RWST inventory (the mass required to make up for shrinkage) had been depleted by that time. The initiation of primary-to-secondary leakage will decrease the time to reach RHR entry conditions at the expense of increasing the amount of RWST inventory used. These cases are discussed in the next section.

4.3 Analyses With S/G Leakage

All cases discussed in this section are initiated with a main steam line break at time zero with an effective break area of ft^2. Reactor scram occurs at seconds on low S/G level. Main feedwater linearly coasts down over the next ten seconds, and the time delay on AFW allows it to initiate seconds after that. The MSIVs start to close

[5] The MSLB30, MSLB31, and MSLB32 results in Appendix B indicate similar behavior compared to the MSLB40, MSLB41, and MSLB42 results with slightly earlier times to RHR entry conditions if the PZR PORVs are used instead of sprays.

Figure 25
Primary System Pressure and Pressurizer Level for Stuck ADV Cases

Figure 26
Pressurizer Level for Various MSLB Areas

Figure 27
Progression to Shutdown Cooling for MSLB Without Induced Rupture

Table 6
Assumed Operator Actions for MAAP Calculations with Entry into Both MSLB and SGTR EOPs

Event	Timing
MSLB	
Reactor trip, main feedwater trip, SI pumps and AFW actuate	
Isolate AFW to faulted S/G	
Tube leakage occurs on high differential pressure	
Initiate °F/hr cooldown by dumping steam from unfaulted S/Gs	
Trip all but one main coolant pump, initiate PZR level control with one charging pump only, and disable PZR heaters	
After PZR level is controlled, isolate accumulators and use PZR sprays or PORVs to depressurize RCS while maintaining °F subcooling margin until shutdown cooling entry conditions are met	

seconds after scram and are fully closed by seconds after scram. It is assumed that feedwater flow to the faulted S/G is terminated at minutes. The SI and charging pump systems had both automatically initiated by that time on low PZR pressure. As the injection systems cause PZR level to recover, the PZR heaters or sprays automatically initiate. The PZR goes solid with water at about minutes. Shortly thereafter, a PZR safety valve first lifts, and the cases which are discussed below differ only in the amount of tube leakage that is assumed to initiate at that time.

GPM Equivalent Leak[6]

Since the tube leak rate is small compared to the injection flow rate, the PZR is still full when the °F/hr cooldown is initiated at minutes by depressurizing the intact S/Gs. Figure 28 shows that the primary pressure remains at the safety valve setpoint over this time period and Figure 29 indicates the successful implementation of the °F/hr cooldown. The PZR level only begins to drop after SI and the PZR heaters are tripped and one charging pump is used to control level starting at minutes. Figure 30 shows the PZR level drop to about percent by hours. At this time, the accumulators are isolated and the PZR sprays are cycled to maintain °F primary subcooling margin while depressurizing the RCS as is shown in Figure 31. By

[6] The tube leak area (ft^2) was chosen as that which would give exactly gpm for a code-side tube leak initiated at time zero from nominal full power conditions. In the case presented, however, the tube leak is not assumed to occur until the PZR safety valve first lifts (about minutes after sequence initiation). Due to the differences in subcooling and pressure at that time compared to full power conditions, the initial volumetric flow rate through the leak is slightly less than gpm, or about gpm.

Figure 28
Primary and Secondary System Pressures for MSLB with GPM Tube Leak @ psid

Figure 29
Average RCS Temperature for MSLB with GPM Tube Leak @ psid

Figure 30
Pressurizer Water Level for MSLB with GPM Tube Leak @ psid

Figure 31
RCS Subcooling Margin for MSLB with , GPM Tube Leak @ psid

hours (just slightly before the case without any induced leakage), the primary system conditions are suitable for activation of shutdown cooling (less than psig and less than °F), and only percent of the RWST inventory had been used by that time.

Tube Rupture-Equivalent Leak Cases

Similar sequences of events were investigated for leakage rates equivalent to and double-ended tube breaks. The only significant differences are in the time to RHR entry conditions and the amount of RWST inventory used. These results are summarized in Table 7. For the smallest (gpm), or non-existent (0 gpm) primary-to-secondary leakage, entry to shutdown cooling occurs prior to hours, and only a small portion of the RWST inventory had been depleted. The single tube rupture case results in entry to shutdown cooling conditions in hours. This is longer than that predicted by RELAP5 for the single tube rupture case, but this can be attributed to differences in the timing of the assumed rupture, and differences in the actual plant being modeled (RESAR versus SNUPPS). As with the RELAP5 results, however, the larger the assumed induced rupture, the earlier the time to reach entry into shutdown cooling conditions because the cooldown rate is accelerated by the flashing of leaked water in the faulted S/G. In all cases, less than percent of the RWST was used by the time this occurred.

Table 7
Summary of MAAP Results for Various Sizes of Tube Ruptures

Leakage Rate (No. of Tubes)	Entry to Shutdown Cooling (minutes)	RWST Used* (%)	Integrated Tube Leakage** ($lb_m \times 10^5$)

4.4 Summary and Conclusions from MAAP Results

MAAP calculations have been used to complement the RELAP5 results. Forty-six cases were run with variations in several parameters. These variations included the size of the steam line break area, the amount of assumed S/G leakage (gpm at nominal conditions), cases with and without RCPs, PZR spray, and PZR heater operation, and with the use of PORVs rather than sprays to accomplish RCS depressurization.

The MAAP results generally indicate that a somewhat longer time period is necessary to reach shutdown cooling entry conditions than was seen in the RELAP results. This difference is considered to be primarily due to differences in the plants being modeled. In any event, the MAAP results also clearly demonstrate that under a wide variety of assumed conditions, there is more than ample time available to cool down and depressurize the RCS.

Plotted output from 18 of the key MAAP calculations are provided in Appendix B.

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APPENDIX A

SELECTED OUTPUT FROM RELAP5 ANALYSES

Case 1
MSLB

Case 2
MSLB and SGTR

Case 3
MSLB with Operator Actions

Case 4
MSLB with SGTR and Operator Actions

Case 5
MSLB with SGTR and Operator Actions

Case 6
MSLB with Delayed SGTR and Operator Actions

Case 7
MSLB with Delayed SGTR and Operator Actions

Case 8
MSLB with Delayed SGTR and Revised Operator Actions

Case 9
MFLB with Delayed SGTR, Revised Operator Actions and AFW

Case 10
MFLB with Delayed SGTR, Revised Operator Actions and no AFW

APPENDIX B

SELECTED OUTPUT FROM MAAP ANALYSES

Output xfrom selected cases from the MAAP analyses are included here. The following variable description list is included as an aid in interpreting the plots that are attached.

PPS - Primary System Pressure
ZWPZ - PZR Water Level
TWPS - Primary System Average Water Temperature
PBS - Broken Loop S/G Pressure
PUS - Unbroken Loops S/G Pressure
WWSB - Primary to Secondary Mass Flow Rate
VOLLEAK - Primary to Secondary Volumetric Flow Rate

Results are presented for the following cases:

MSLB00 - ft^2 MSLB; No tube leak; No operator actions
MSLB10 - ft^2 MSLB; No tube leak; MSLB operator actions
MSLB11 - ft^2 MSLB; No tube leak; MSLB operator actions
MSLB12 - ft^2 MSLB; No tube leak; MSLB operator actions
MSLB13 - ft^2 MSLB; No tube leak; MSLB operator actions
MSLB15 - Stuck ADV; No tube leak; MSLB operator actions
MSLB16 - Stuck ADV, Reduced AFW; No tube leak; MSLB operator actions
MSLB18 - ft^2 MSLB, Reduced AFW; No tube leak; MSLB operator actions
MSLB30 - ft^2 MSLB; No tube leak; SGTR operator actions; PZR PORV used for cooldown
MSLB31 - ft^2 MSLB; tube leak; SGTR operator actions; PZR PORV used for cooldown
MSLB32 - ft^2 MSLB; tube leak; SGTR operator actions; PZR PORV used for cooldown
MSLB40 - ft^2 MSLB; No tube leak; SGTR operator actions; PZR sprays used for cooldown
MSLB41 - ft^2 MSLB; tube leak; SGTR operator actions; PZR sprays used for cooldown
MSLB42 - ft^2 MSLB; tube leak; SGTR operator actions; PZR sprays used for cooldown
MSLB43 - ft^2 MSLB; tube leak; SGTR operator actions; PZR sprays used for cooldown
MSLB44 - ft^2 MSLB; tube leak; SGTR operator actions; PZR sprays used for cooldown
MSLB45 - ft^2 MSLB; tube leak; SGTR operator actions; PZR sprays used for cooldown
MSLB46 - ft^2 MSLB; GPM tube leak; SGTR operator actions;PZR sprays used for cooldown

MSLB00
ft[2] MSLB; No tube leak; No operator actions

MSLB10
ft^2 MSLB; No tube leak; MSLB operator actions

MSLB11

ft^2 MSLB; No tube leak; MSLB operator actions

MSLB12

ft^2 MSLB; No tube leak; MSLB operator actions

MSLB13
ft^2 MSLB; No tube leak; MSLB operator actions

MSLB15
Stuck ADV; No tube leak; MSLB operator actions

MSLB16
Stuck ADV, Reduced AFW; No tube leak; MSLB operator actions

MSLB18
ft^2 MSLB, Reduced AFW; No tube leak; MSLB operator actions

MSLB30

ft^2 MSLB; No tube leak; SGTR operator actions; PZR PORV used for cooldown

MSLB';1

ft^2 MSLB; 1 tube leak; SGTR operator actions; PZR PORV used for cooldown

MSLB32
ft² MSLB tube leak; SGTR operator actions; PZR PORV used for cooldown

MSLB40
ft^2 MSLB; No tube leak; SGTR operator actions; PZR sprays used for cooldown

MSLB41

ft² MSLB; tube leak; SGTR operator actions; PZR sprays used for cooldown

MSLB42
ft^2 MSLB; tube leak; SGTR operator actions; PZR sprays used for cooldown

MSLB43

ft^2 MSLB; No tube leak; SGTR operator actions; PZR sprays used for cooldown

MSLB46

ft² MSLB; GPM tube leak; SGTR operator actions; PZR sprays used for cooldown