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REACTOR SCRAM EVENTS IN THE UPDATED PIUS 600 ADVANCED REACTOR DESIGN*

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ABSTRACT

The PIUS advanced reactor is a 640-MWe pressurized water reactor concept developed by Asea Brown Boveri. A unique feature of PIUS is the absence of mechanical control and shutdown rods. Reactivity is controlled by coolant boron concentration and the temperature of the moderator coolant. Los Alamos supported the US Nuclear Regulatory Commission's preapplication review of the PIUS reactor. Baseline calculations of the PIUS design were performed for active and passive reactor scrams using TRAC-PF1/MOD2. Additional sensitivity studies examined flow blockage and boron dilution events to explore the robustness of the PIUS concept for low-probability combination events following active-system scrams.

INTRODUCTION

The PIUS advanced reactor is a four-loop, Asea Brown Boveri (ABB) designed pressurized water reactor (PWR) with a nominal core rating of 2000 MWt and 640 MWe (Pederson 1993). A schematic of the basic PIUS reactor arrangement is shown in Fig. 1. The schematic is generally representative of the design except that the downcomer and riser are integrated rather than separated as shown in the schematic. Reactivity is controlled by coolant boron concentration and temperature; there are no mechanical control or shutdown rods. The core is submerged in a large pool of highly borated water, and is in continuous communication with the pool water through pipe openings called density locks. The density locks provide a continuously open flow path between the primary system and the reactor pool. The reactor coolant pumps (RCPs) are operated so that there is a hydraulic balance in the density locks between the primary coolant loop and the pool, keeping the pool water and primary coolant separated during normal operation. PIUS contains an active-scram system, but this system requires operation of the RCPs and is, therefore, not available following some initiators, e.g., a loss-of-offsite power (LOSP). PIUS also has a passive-scram system that functions should the RCPs be unable to maintain the balance between the primary coolant loop and the reactor pool. This can occur, for example, upon loss of motive power to one or more RCPs or if the primary coolant overheats beyond the point where the speed-limited RCPs can compensate. Highly borated water enters the primary system from the reactor pool via natural circulation and this process shuts the reactor down and cools the core. The heated coolant returns to the reactor pool, which can be cooled by either an active, nonsafety-class system or a fully passive, safety-class system.

As part of the preapplication and eventual design certification process, advanced reactor applicants are required to submit neutronic and thermal-hydraulic safety analyses over a sufficient range of normal operation, transient conditions, and specified accident sequences. ABB submitted a Preliminary Safety Information Document (PSID) (ABB Atom, 1989) to the US Nuclear Regulatory Commission (NRC) for preapplication safety review in 1990. Early in 1992, ABB submitted a Supplemental Information Package to the NRC to reflect recent design modifications (Brinkman, 1993). The ABB safety analyses are based on results from the RIGEL code (Babala et al., 1990), a one-dimensional (1D) thermal-hydraulic system analysis code developed at ABB Atom for PIUS reactor analysis. Los Alamos supported the

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NRC's preapplication review of the PIUS reactor. A baseline calculation of the PIUS Supplement design was performed for an active-system reactor scram. In addition, sensitivity studies examined flow blockage and boron dilution events to explore the robustness of the PIUS concept to severe off-normal conditions following an active-system reactor scram. Finally, a calculation of a passive-system scram following the loss of motive power to one RCP was performed.

TRAC ADEQUACY FOR THE PIUS APPLICATION

The TRAC-PF1/MOD2 code (Spore et al., 1993), version 5.3.05, was used for each calculation. The TRAC code series was developed at Los Alamos to provide advanced, best-estimate predictions for postulated accidents in PWRs. The code incorporates four-component (liquid water, water vapor, liquid solute, and noncondensible gas), two-fluid (liquid and gas), and nonequilibrium modeling of thermal-hydraulic behavior.

The ability of TRAC to model key PIUS systems, components, processes and phenomena was demonstrated in an assessment activity using integral data from the ATLE facility (Babala et al., 1990). ATLE is a 1/308 volume scale integral test facility that simulates the PIUS reactor. TRAC correctly calculated all major trends and phenomena (Stumpf, 1993). However, the calculated results were frequently outside the data uncertainty. There were two major discrepancies. First, TRAC calculated a too-rapid diffusion of the solute (boron simulant). Second, in simulating a two-pump trip scram experiment similar to a LOSP event, the initial surge flow from the reactor pool through the lower density lock was underpredicted by about 25%. The underprediction would influence the early course, but not the final or end state of a similar transient in the PIUS reactor.

Benchmarking against another validated code is a second approach to demonstrating adequacy. ABB has published updated RIGEL-based analyses for both active- and passive-system scrams in the PSID supplement (Brinkman, 1993). Additional code-to-code comparisons have been prepared for both small-break and large-break loss-of-coolant accidents (LOCA) for which ABB calculations of the PSID Supplement design are available (Boyack et al., 1993 and Steiner et al., 1993). The RIGEL- and TRAC-calculated results display the same processes and phenomena and are in reasonable quantitative agreement.

The most important physical processes in PIUS are related to reactor shutdown because the PIUS reactor does not contain control and shutdown rods. Coupled core neutronic and thermal-hydraulic effects are possible, including multidimensional interactions arising from nonuniform introduction of boron across the core. At the present time, it is not known whether coupled core neutronic, thermal-hydraulic, and multidimensional effects are important.

The four-loop TRAC model consists of 74 1D hydrodynamic components (727 computational fluid cells) and one heat-structure component representing the fuel rods. The reactor power is calculated with a space-independent point-kinetics model. The TRAC-calculated and PSID Supplement steady-state values are in close agreement as shown below.

	TRAC	PSID Supplement
Core mass flow (kg/s)	12822	12880
Core bypass flow (kg/s)	200.2	200
Loop flow (kg/s)	3255	3266
Cold-leg temperature (K)	531.0	527.1
Hot-leg temperature (K)	560.7	557.3
Pressurizer pressure (MPa)	9.5	9.5
Steam exit pressure (MPa)	4.0	4.0
Steam exit temperature (K)	540.3	543
Steam flow superheat (°C)	15.3	20
Steam and feedwater mass flow (kg/s)	243	243

BASELINE ACTIVE-SCRAM EVENT

The active-scram system was incorporated in the PSID Supplement design with the intent that it function for most anticipated and accident transients. The baseline active-scram transient is initiated by opening a valve in each scram line connecting the reactor pool to the RCP inlet. Essentially all important phenomena arise from opening the scram valves and terminating feedwater flow to the steam generators. The total scram line flow, which varies between 700 and 800 kg/s, produces several effects. First, primary coolant is displaced from the primary system and enters the reactor pool, primarily through the upper density lock but also through the lower density lock (Fig. 2). Second, the highly-borated water injected by the active-scram system mixes with the primary coolant. The boron concentration increases rapidly while the scram valves are open, but the increase is terminated when the scram valves shut. The primary boron concentration stabilizes at about 860 ppm (Fig. 3). The increasing concentration of boron in the core inserts sufficient negative reactivity to reduce the core power to decay heat levels (Fig. 4). Following closure of the scram valves, the flows of highly borated pool water through the active-scram system into the primary system are terminated, and control of the lower density lock thermal interface is recovered by the RCP speed control system. Primary-to-secondary heat transfer in the steam generators terminates by 115 s, following the early trip of the main feedwater pumps. With the loss of the steam-generator heat sink and the RCPs maintaining a no-flow condition through the density locks, core decay heat is deposited in the primary coolant, and fuel and coolant temperatures begin a steady increase at 40 K/h (Fig. 5). If no action were taken, the primary would continue to heat, the RCPs would increase speed to maintain control of the lower density lock thermal interface until the RCP overspeed limit of 115% was reached, and the density locks would activate to initiate natural circulation between the primary system and the reactor pool. The pool would be cooled by either active (nonsafety grade) or passive (fully safety grade) pool cooling systems that reject core decay heat to the ultimate heat sink. Other analyses demonstrating activation of the density locks with the RCPs operating has been reported elsewhere (Harmony, 1993).

A RIGEL calculation of the active-system scram has been reported (Brinkman, 1993). Several results from the RIGEL calculations have been coplotted with the TRAC-calculated results for this transient. The RIGEL calculations were terminated at 300 s, while the TRAC calculations were terminated at 1200 s. The TRAC- and RIGEL-calculated core powers are shown in Fig. 4. The upper and lower density lock flows are compared in Fig. 2, and the primary loop boron concentrations are compared in Fig. 3. The TRAC- and RIGEL-calculated results are both qualitatively and quantitatively similar, and are, therefore, in reasonable agreement. Because the two codes were independently developed, this reasonable agreement provides an added assurance that the major trends and processes associated with the active scram are correctly represented to the extent they are well modeled by 1D thermal-hydraulics and point kinetics.

SENSITIVITY CASES

Sensitivity studies were performed to explore the robustness of the PIUS concept to severe off-normal conditions following active-system trips. The most severe of these conditions are very-low-probability events. Fractional and complete blockages of the lower density lock were analyzed. Given the small flows through the lower density lock for the baseline transient (Fig. 2), even a total blockage produces only a minimal impact on the course of the transient. As a further assessment of the robustness of the PIUS concept, total blockages of both the upper and lower density locks were assumed. A shutdown in core power is again achieved. However, with both density locks blocked, the amount of pool water injected through the scram lines is reduced compared with the baseline because primary inventory can only be displaced into the reactor pool through the small standpipes that connect the pressurizer steam space and the reactor pool (Fig. 1). With the reduced scram line flow, the primary boron concentration increased to only 480 ppm before the scram valves closed. For this transient, the core power decreases more slowly than in the baseline and the fuel and moderator temperatures remain higher. When the scram valves close, flow through the standpipes terminates. As with the baseline transient, the primary coolant begins to heat. Once the RCPs reach their overspeed limit of 115%, the density locks activate and the primary is cooled via the natural circulation flow between the primary and the pool through the lower and upper density locks.

Other sensitivity calculations were performed to examine the effect of reduced pool boron concentration. Active scrams with pool boron concentrations of 1800 and 1000 ppm were examined. The first corresponds to the level at which a reactor scram is initiated on low pool boron concentration (Brinkman, 1993). The second corresponds to the condition at which a critical core can be achieved at cold shutdown conditions and BOC. For the 1800 ppm case, core power decreases at a slightly slower rate than the baseline, but the power levels are indistinguishable by 200 s. The active-system scram with the pool boron concentration at 1000 ppm also culminates in a shutdown condition, although the phenomena are markedly different. After the scram valves have closed, the primary boron concentration stabilizes at about 550 ppm compared with 840 ppm in the baseline. As less boron is delivered to the core while the scram valves are open, the core power decreases at a slower rate than in the baseline and does not reach the same level as the baseline until 400 s. Consequently, the extra decay heat deposited in the primary causes the primary system to heat and pressurize. The pressure relief system safety valves open several times while the scram valves are open and periodically after the scram valves are closed. Once the scram valves are closed, the primary temperatures steadily increase. Eventually, the RCP overspeed limit is reached and flow from the pool enters the primary through the lower density lock and returns to the pool through the upper density lock. The pool is cooled by the available pool cooling systems. Additional actions are required to fully terminate this event, e.g., injection of additional boron into the primary.

PASSIVE-SCRAM EVENT

The initiating event selected to demonstrate the passive-scram system is the loss of a single RCP. The primary reason for selecting this transient is the availability of a RIGEL calculation for the same sequence (Brinkman, 1993) In addition, the trip of a single RCP was the planned scram operation in the original PSID design (ABB Atom, 1989). Essentially all important phenomena in this sequence result from tripping of a single RCP. By assumption, the active-scram system does not operate during the sequence. The RCPs in the remaining three loops continue to operate throughout the transient.

The tripped RCP coasts down while the remaining three RCPs increase speed, rapidly reaching their overspeed limit of 115% while attempting to maintain control of the lower density lock interface. The imbalance caused by loss of one RCP is, by design, too large for the pump speed control causing the lower density locks to activate (Fig. 6). The flow through the lower density lock peaks at 550 kg/s on the first insurge after activation. Following two early oscillations, the lower density lock flow decreases smoothly. Boron enters the primary through the lower density lock and the primary boron concentration increases (Fig. 7). The boron concentration increases rapidly while the lower density lock flow is high and then continues to increase at a lower rate as a stable natural circulation flow is established between the primary system and the pool through the density locks. The core power decreases rapidly to shutdown conditions (Fig. 8). The RIGEL-calculated peak lower density lock flows are higher than those calculated by TRAC. This result is consistent with the results of the ATLE assessment. The RIGEL-calculated power decreases slightly faster than that calculated by TRAC. This trend is consistent with the faster introduction of boron associated with the higher RIGEL-calculated lower density lock flow. Overall, the calculated results of the two codes are in reasonable agreement early in the transient. The late time results are in excellent agreement.

SUMMARY OBSERVATIONS

1. Two systems exist for reactor shutdown—active and passive. Each system effectively scrams the reactor. The predicted key trends and processes for the active and passive scram transients can be expected to occur in PIUS to the extent that they are accurately represented with 1D thermal-hydraulic and point kinetics models.

2. The PIUS core, as presently conceived, has inherent, compensating neutronic shutdown mechanisms. PIUS also has multiple flow paths between the primary system and reactor pool. Alternate flow paths exist even if complete blockage of either density lock occurs. Neither operator nor active system actions are needed to accomplish reactor shutdown, even for scram initiators combined with these very low probability occurrences.

3. Our confidence in the baseline simulations is enhanced by the assessment activity performed using ATLE data. The ATLE processes and phenomena were correctly predicted by TRAC. However, there are quantitative discrepancies between key TRAC-calculated parameter values and the ATLE data. We would like to better understand the reasons for these differences.

4. Our confidence in the baseline active- and passive-scram system simulations is enhanced by the benchmark activities for these transients. Additional confidence is gained from the code-to-code benchmarks for non-LOSP transients (small- and large-break LOCAs). Both the RIGEL- and TRAC-calculated results display the same processes and phenomena and are in reasonable quantitative agreement. The sensitivity calculations are for conditions far removed from both the assessment conditions using ATLE data and the code-to-code benchmark conditions with RIGEL.

5. At the present time, it is not known whether coupled multidimensional core neutronic and thermal-hydraulic effects are important.

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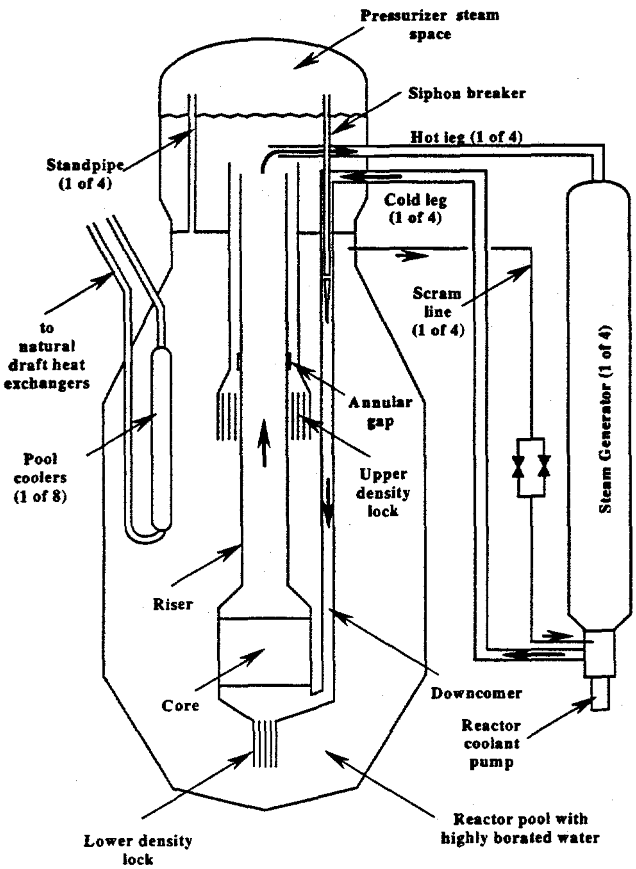

Fig.1. Schematic of the PIUS Reactor. Same as Nuclear Safety article, Fig. 1, LA-UR-94-3467.

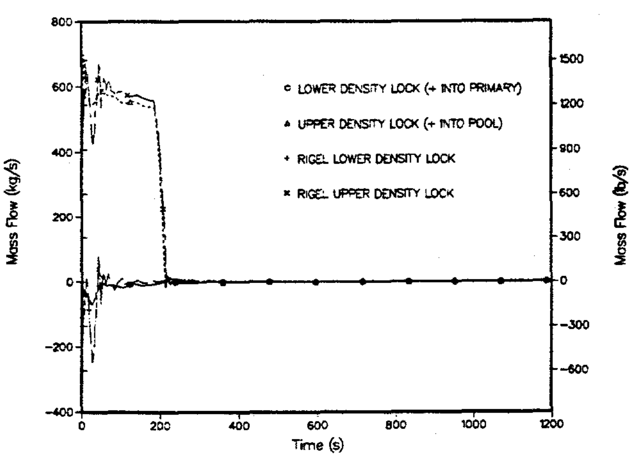

Fig. 2. Density lock flows for the active-scram system baseline case. Same as Nuclear Safety article, Fig. 2, LA-UR-94-3467.

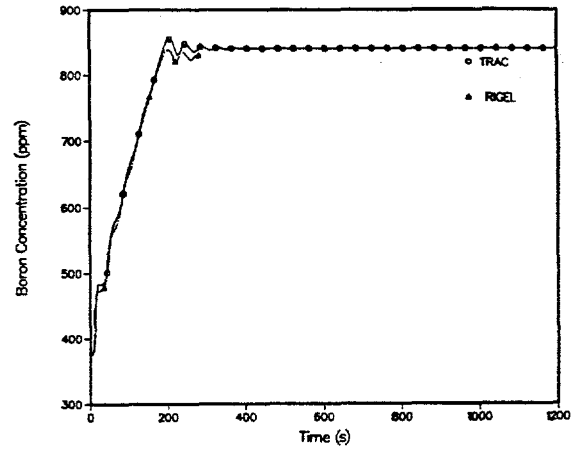

Fig. 3. Primary boron concentration for the active-scram system baseline case. Same as Nuclear Safety article, Fig. 3, LA-UR-94-3467.

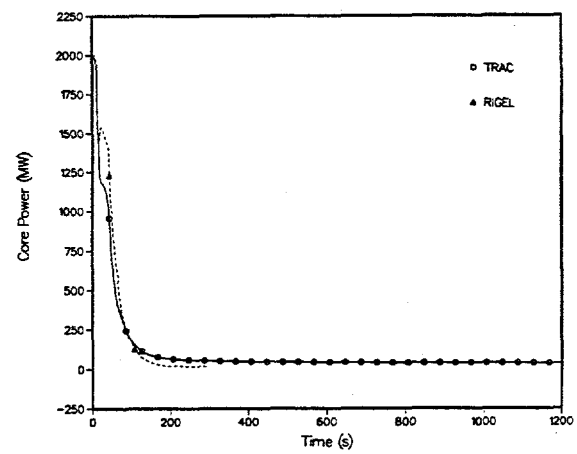

Fig. 4. Core power for active-scram system baseline case. Same as Nuclear Safety article, Fig. 4, LA-UR-94-3467.

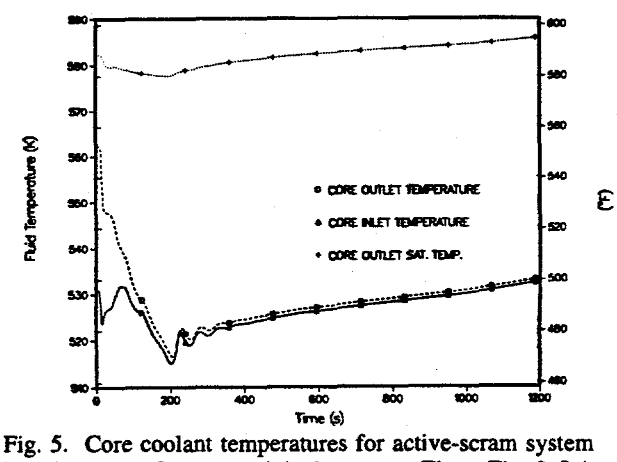

Fig. 5. Core coolant temperatures for active-scram system baseline case. Same as original report to Ebert, Fig. 8, LA-UR-93-4456.

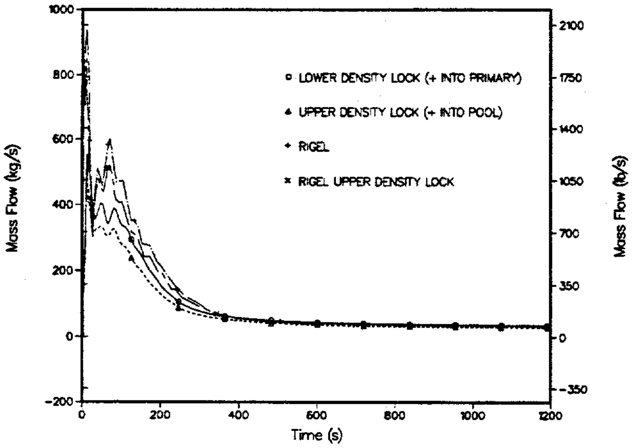

Fig. 6. Density lock flows for a passive scram following the loss of a single RCP. Same as Nuclear Safety article, Fig. 12, LA-UR-94-3467.

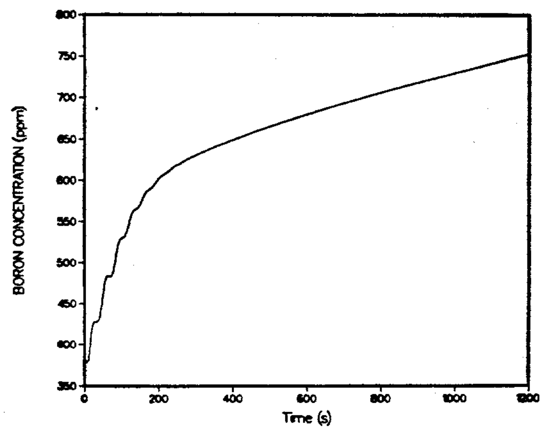

Fig. 7. Primary boron concentration for a passive-scram following the loss of a single RCP. Same as original report to Ebert, Fig. 15, LA-UR-93-4456.

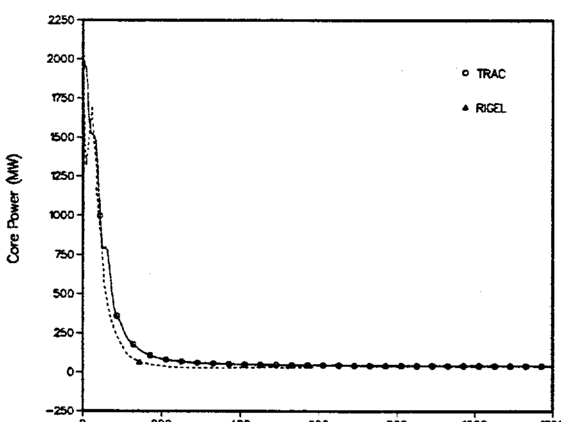

Fig. 8. Reactor power for a passive scram following the loss of a single RCP. Same as Nuclear Safety article, Fig. 13, LA-UR-94-3467.