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TITLE: BEST-ESTIMATE MARK 22 POWER AND TEMPERATURE LIMITS DURING THE FLOW INSTABILITY PHASE OF K REACTOR LBLOCAS

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Best-Estimate Mark 22 Power and Temperature Limits During the Flow Instability Phase of K Reactor LBLOCAs

by

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I. INTRODUCTION

Los Alamos National Laboratory (LANL) has been providing independent analyses to the Department of Energy in its endeavor to enhance the safe operation of the K Reactor located at the Savannah River Laboratory (SRL). LANL has performed neutronic and thermal-hydraulic system simulations to assess the impact of hypothesized accidents in the K Reactor. In particular, the large-break loss-of-coolant accident (LBLOCA) was one of the major transients that was analyzed. The LBLOCA consists of two distinct thermal-hydraulic phases: the flow instability (FI) phase and the emergency coolant system (ECS) phase. Each phase results in reactor temperature and power limits that are determined using different criteria.

The FI phase occurs during the first 2 s or so of the LBLOCA simulation. During this time, the flow rate drops at a much faster rate than the channel power, resulting in a power to flow-rate mismatch (Fig. 1) that may lead to FI, also known as a Ledinegg flow instability. If FI occurs, it may lead to local heat-up and melting of the fuel. Therefore, the preaccident power must be low enough to prevent FI. The ECS phase is the portion of the LBLOCA where the ECS remains activated. During the ECS phase, the fuel must be protected from heat-up and melting. In addition, gamma heating is of great concern during the ECS phase because the non-fueled reactor core components heat up almost adiabatically as the tank level drops.

In addition to other calculations, LANL provided SRL with an independent check of Mark 22 power and temperature limits calculations during the FI and ECS phases of K Reactor LBLOCAs. The analyses at LANL were performed using TRAC, which is a best-estimate reactor-analyses code. This report will limit its coverage to the methodology used in the FI phase.

Before calculating the best-estimate effluent temperature and power limits that bound FI during a LBLOCA, it was demonstrated that 1) TRAC adequately benchmarked the Babcock & Wilcox (B&W) Mark 22 Tests, and 2) TRAC can calculate the Stanton number (St) to within data uncertainty. As will be discussed later, St was used as a criterion that FI does not occur. The first demonstration was necessary because it substantiated TRAC's ability to bound FI in Mark 22 assemblies. The second demonstration was needed because St is a measure of how close a surface is to the onset of significant voiding (OSV). OSV is a precursor to FI.

II. BEST-ESTIMATE THERMAL-HYDRAULIC ANALYSIS

Two TRAC models were applied to the calculation of power and temperature limits during the FI phase: a K Reactor system model and a single-assembly Mark 22 model. The analyses and benchmarking models are discussed next.

A. TRAC K REACTOR SYSTEM CALCULATIONS

The TRAC K Reactor system model has 152 one-dimensional hydrodynamic components consisting of 1152 cells. The reactor vessel is divided into two three-dimensional hydrodynamic components consisting of 432 cells (Fig. 2). The model consists of six primary system loops. Each loop has a primary system pump, heat exchanger, rotovalve, and connecting piping (Fig. 3). The single-phase pump homologous curves were obtained from manufacturer test data and are therefore best-estimate. The Mark 22 assemblies are modeled by 36 lumped-heat structure components. Four ECS loops provide dynamic injection into the primary system. Each ECS loop has tank-level-activated control valves. The ECS injection rate is a function of tank level, primary system pressure, and break location and size. The vent paths, gas blanket system, and septifoil system were also modeled.

The primary system pressure drops and flow rates were benchmarked against the 1985 and 1989 L-Area tests.[1] TRAC adequately calculated core flow as a function of moderator tank level in the L-Area tests. The pump model was benchmarked and flow reversal was benchmarked when only five out of six primary pumps were running. During an LBLOCA, the broken primary loop undergoes flow reversal. Furthermore, the model was benchmarked against the A-Tank Mark 22 assembly tests. These tests demonstrated the ability of TRAC to match the plenum liquid level as a function of liquid and air flow into the plenum. Air enters the break and the vents during an LBLOCA. The ECS model was benchmarked against the K Reactor ECS supply curves.[2]

B. TRAC MARK 22 ASSEMBLY CALCULATIONS

The TRAC Mark 22 model is shown in Fig. 4. Numbers inside the ovals and rectangles refer to the TRAC input file hydrodynamic and heat-structure components, respectively. The tank bottom and upper-plenum pressure boundaries were modeled with time-dependent BREAK components, components 4 and 304, respectively. Boundary conditions from the full-plant calculations were used as input for these components. The assembly top end fitting was modeled with a two-cell PIPE component, component 802, and a PLENUM component, component 300. The PLENUM component was needed to distribute the coolant flow to the core section subchannels. The middle section modeled the core region. Five PIPE components, components 811, 812, 813, 814, and 815, were used to model this section. Components 811 and 815 were low-flow purge channels, and 812, 813, and 814 were the main coolant flow channels.

The core section in the TRAC model consisted of five heat structures, each having 15 cells. The heat structures were modeled as RODS and were labeled as components 911, 912, 913, 914, and 915, which modeled the universal sleeve housing (USH), outer target, outer fuel, inner fuel, and inner target, respectively. The USH was a nonpowered heat structure, while the other heat structures were powered and double-sided heat-conducting. The 15 cell noding was used in previous Mark 22 flow-instability work, where, as a check of the core noding sensitivity, a 40-heated-cell model was also made. Very small differences were noted in the results. The fine noding also allows TRAC to pinpoint the first occurrence of OSV. TRAC used the SRL critical heat flux (CHF) correlation instead of the built-in Biasi correlation. The SRL CHF correlation is a best-estimate CHF correlation suitable for the low-pressure, low-temperature Mark 22 assemblies.

The bottom end fitting of the model consisted of a PLENUM component, component 8, and a three-cell PIPE component, component 806. The cell lengths were adjusted to position the flow-restriction points at about the correct elevations. The flow areas and hydraulic diameters of the bottom end fitting were those needed to represent the K Reactor Mark 22 bottom end fitting for the inner rings of the reactor; they model a single pressure plate and 36 shell holes. For a 36-shell-hole assembly, half the assembly exit flow was diverted past the monitor pin. Because this path was not modeled in the TRAC assembly model, it was represented by increasing the number of shell holes to 72 so that the shell-hole velocity and pressure drop were correct.

The detailed Mark 22 model was benchmarked using Mark 22 single-phase hydraulics test data. The agreement between the data and those calculated by TRAC was excellent, usually within 0.5%, and well within typical experimental error. The only exceptions were the channel pressure drops and the pressure drops from top stem to fuel top cells; however, the sum of these two pressure drops (for each of channels 2, 3, and 4) agreed very well between TRAC and the data. The test data and TRAC-calculated temperatures were within 1%.

The extensive modeling and benchmarking of the reactor system and Mark 22 assembly provide us with confidence that TRAC and the K Reactor model provide a best-estimate evaluation of the complex phenomena that occurs during a LBLOCA in the K Reactor.

III. ASSEMBLY POWER AND TEMPERATURE LIMITS CRITERION

A. MODIFIED SAHA-ZUBER CORRELATION

A criterion was selected based on its ability to bound the possibility of fuel and/or target cladding failure in the Mark 22 assembly, and thus the release of fission products would be averted. The integrity of the fuel and target cladding can be assured if there is sufficient coolant flow rate in the Mark 22 assemblies such that FI will not occur. Because OSV is a precursor to FI, a correlation that predicts OSV was used in the analysis. The Saha-Zuber correlation for OSV uses St as an indicator of OSV. OSV was conservatively bounded by using a St criterion of 0.00455, which is 30% below the best-estimate value of the Saha-Zuber correlation, and bounds all the data used in the Saha-Zuber correlation and the SRL data for OSV. The St criterion that was used in the calculations is defined as:

$$St = 0.00455 \text{ for } Pe > 0 ,$$

where Pe is the Peclet number. St represents the ratio between local heat flux transferred from a heat structure and the thermal capacity of the fluid. If the assembly being modeled has ribs (and therefore has a nonuniform heat flux), the criterion is 0.00455/PF. PF is the peaking factor that accounts for local heat flux peaking.

B. PEAKING FACTOR CALCULATIONS

A series of calculations were performed to determine the effect of hot spots in the Mark 22 assemblies. The peaking factor is a best-estimate value that quantifies how much the heat flux is increased at the hot spots. The hot spots are created by the insulating effect of the gap between the rib tips and the fuel tube surface. The gaps are filled with stagnant coolant fluid, and very little heat is removed from the fuel tube surfaces by the coolant in the gaps. As a result, hot spots develop on the fuel tube circumference at the ends of the gaps. These hot spots are located at corners in the coolant channels formed by the ribs and the fuel tube surfaces. Sensitivity studies showed that the value of the peaking factor was highly dependent on the geometry and only slightly on the boundary conditions.

The hot-spot heat flux was calculated for the K Reactor core with the HERA/TRAC[3] code, which can calculate heat conduction and solid temperature distributions in two and three dimensions. The effect of the ribs was determined by calculating a uniform heat flux for the fuel tubes with no ribs present, and then calculating the actual heat flux distribution at the fuel tube surfaces with the ribs modeled. A heat flux peaking factor was then determined by dividing the heat flux calculated at the hot spots by the uniform heat flux calculated without ribs.

IV. BENCHMARK CALCULATIONS

A. B&W MARK 22 BENCHMARK TESTS

A TRAC one-dimensional model of the B&W Mark 22 test facility was verified using data from pressure drop characterization tests and thermal characterization tests. A rib-effect peaking factor value of 1.56 was calculated using a three-dimensional heat-structure component in TRAC. The peaking factor was used to account for heat flux peaking in the B&W test section. The test facility maximum power at flow stability was calculated for LBLOCA tests with TRAC using the B&W model. The maximum power without reaching FI was determined by varying the power until the criterion of St = 0.00455/1.56 = 0.00292 was met. The results indicated that the calculated power, using St = 0.00292, was approximately 17% below the measured power at FI (Fig. 5). In addition, TRAC correctly predicted the location of the temperature excursion in the B&W Mark 22 Tests when the St limit was used.

B. SRL DOWNFLOW RIG TESTS

A simulation of an SRL downflow assembly was performed using TRAC so that St from TRAC and data could be compared. The facility had no ribs, so PF = 1.0. A wide scope of St data ranging from 0.00212 to 0.0171 was compared.[4] Because OSV is predicted to occur at St $\geq$ 0.00455, the St region that was compared corresponds to the downflow assembly being below, at, and beyond OSV. In addition to using TRAC to calculate St, St was hand-calculated. The data, TRAC, and hand-calculated St were compared and were found to be within the data uncertainty, as shown in Table I. Therefore, TRAC can calculate St within data uncertainty over the range of St values where OSV is expected to occur.

V. POWER AND EFFLUENT TEMPERATURE CALCULATIONS

The FI limit calculations for the plant were based on a two-part simulation using TRAC. The first part of the simulation used the full-plant model to calculate the first 5.0 s of each LBLOCA examined. This calculation provided the boundary conditions that were used in the second part of the simulation. The second part used a detailed model of the Mark 22 fuel/target assembly. A rib effect peaking factor value of 1.13 was calculated for the inner inner surface of the inner fuel using a three-dimensional heat structure component in TRAC. The peaking factor of the B&W test is much larger than the peaking factor of the Mark 22 assembly because the ribs in the test had insulators, whereas the Mark 22 assembly had aluminum. Pump-discharge and pump-suction LBLOCAs are less limiting than the plenum-inlet LBLOCA, so only plenum-inlet LBLOCAs are discussed here.

The power in the Mark 22 model was then changed iteratively until the maximum St reached 0.00455/1.13 = 0.00403. The maximum power that does not reach St = 0.00403 on any heated surface is the best-estimate power required to bound FI in the assembly. Thus, the assembly power that bounds FI was calculated at 53% of historical power. This best-estimate power level determines the effluent temperature limit at steady state.

TRAC is a best-estimate code, so the boundary conditions (inlet pressure and temperature, and outlet pressure) used in the second part of the calculation are best-estimate. The Saha-Zuber correlation is also best-estimate. However, the St criterion used in this analysis is conservative because it is 30% below the Saha-Zuber correlation and bounds all the data used in the Saha Zuber correlation. As a result of the limited FI power data in the B&W tests, we feel that this extra conservatism is justified. Furthermore, studies have shown that the difference in power levels between an assembly at FI and one that is not experiencing FI can be on the order of 1% for Mark 22 assemblies.[5] Because the boundary conditions used in the analysis are best-estimate, the uncertainty analysis on the boundary conditions will result in a reduction of the best-estimate power. On the other hand, no further power reduction is required as a result of the St criterion that was used.

VI. CONCLUSION

A methodology was developed using TRAC to calculate best-estimate Mark 22 power and temperature limits that bound FI during LBLOCAS. The adequacy of TRAC to bound FI in Mark 22 assemblies was demonstrated by comparisons with data. Using a St limit, TRAC correctly predicted the location of the temperature excursion in the B&W Mark 22 tests. In addition, TRAC conservatively calculated power below the measured power at FI in the B&W tests. Next, it was shown that TRAC calculated St to within data uncertainty for St within the region where OSV is expected to occur. The results show that the criterion, St = 0.00455 for Pe > 0, is a conservative bound of FI in Mark 22 fuel/target assemblies during the FI phase of LBLOCAs, provided that if the assembly being modeled has ribs, the criterion is 0.00455/PF, and if no ribs are present, the criterion is 0.00455.

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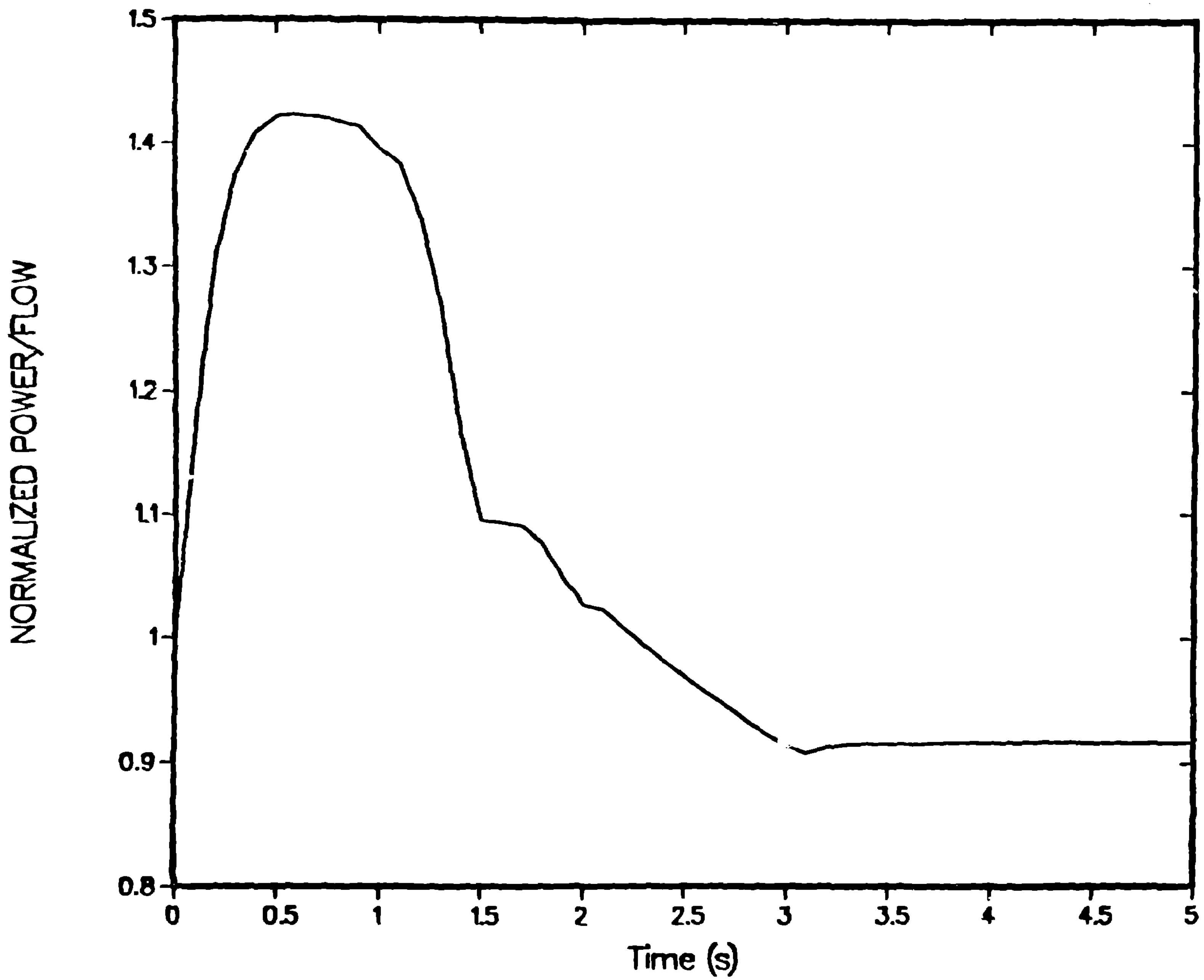

Figure 1. Normalized Power-to-Flow Ratio during the FI Phase of a LBLOCA.

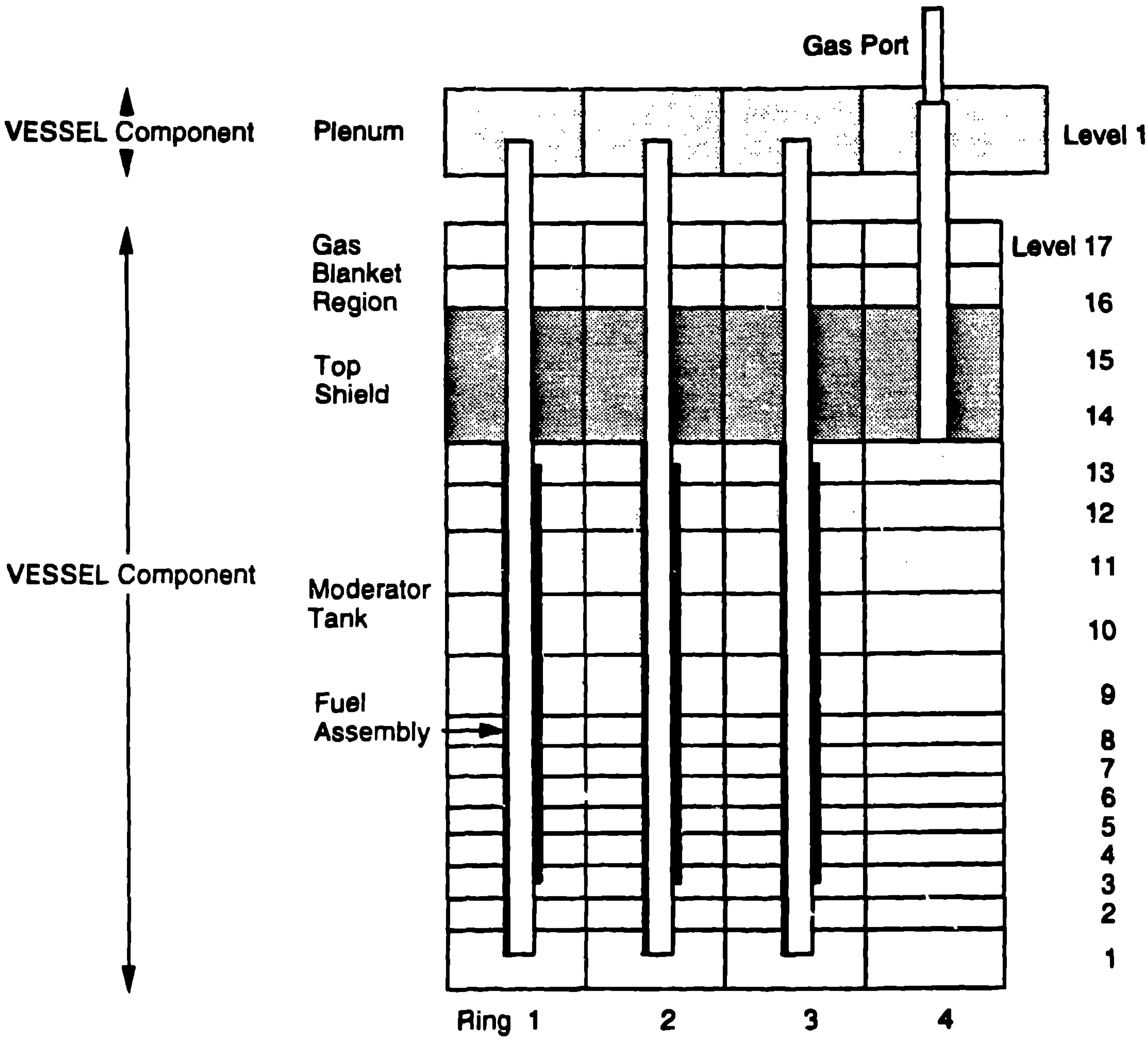

Figure 2. TRAC Vessel Model.

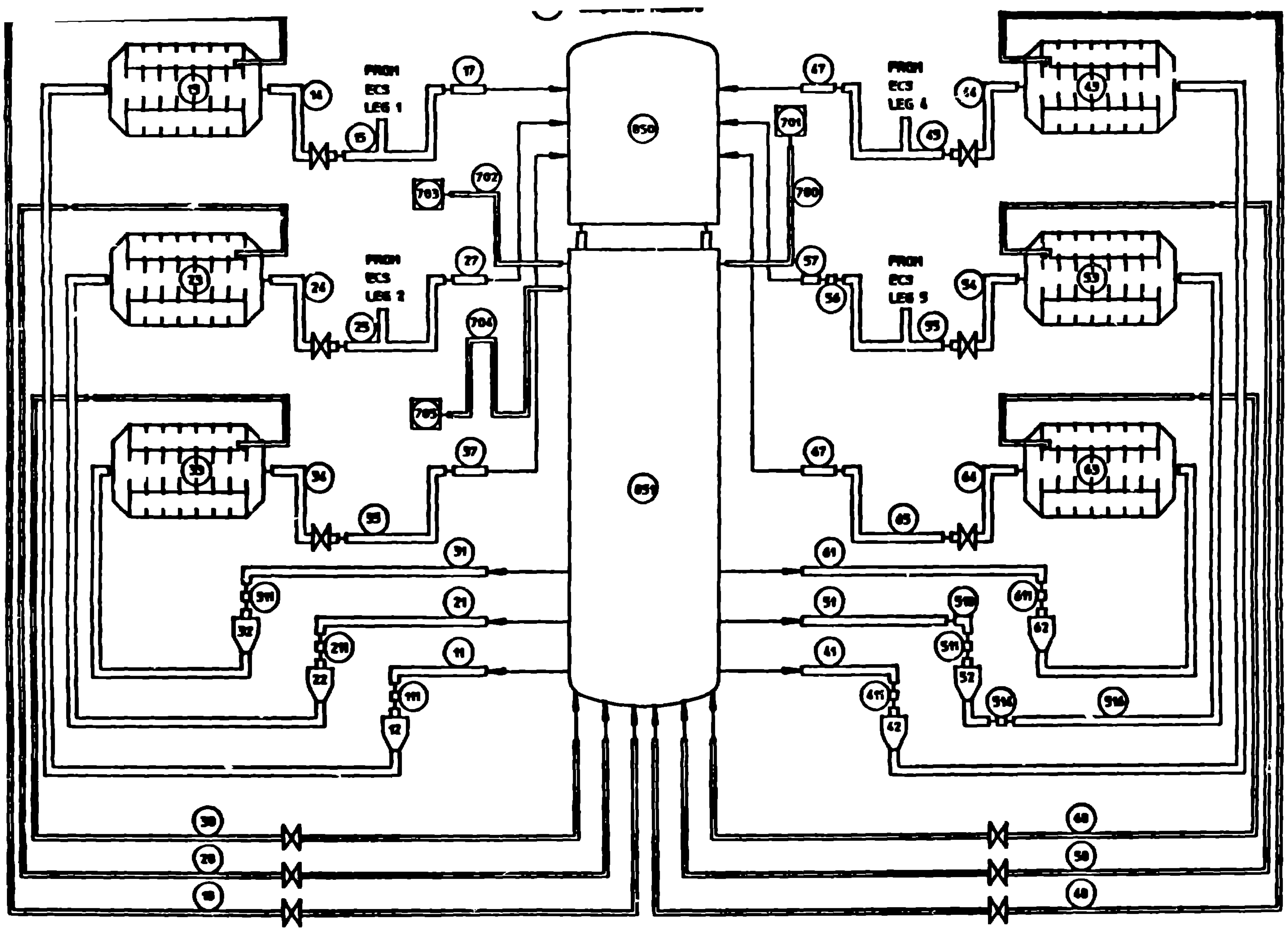

Figure 3. Schematic of TRAC K Reactor Model.

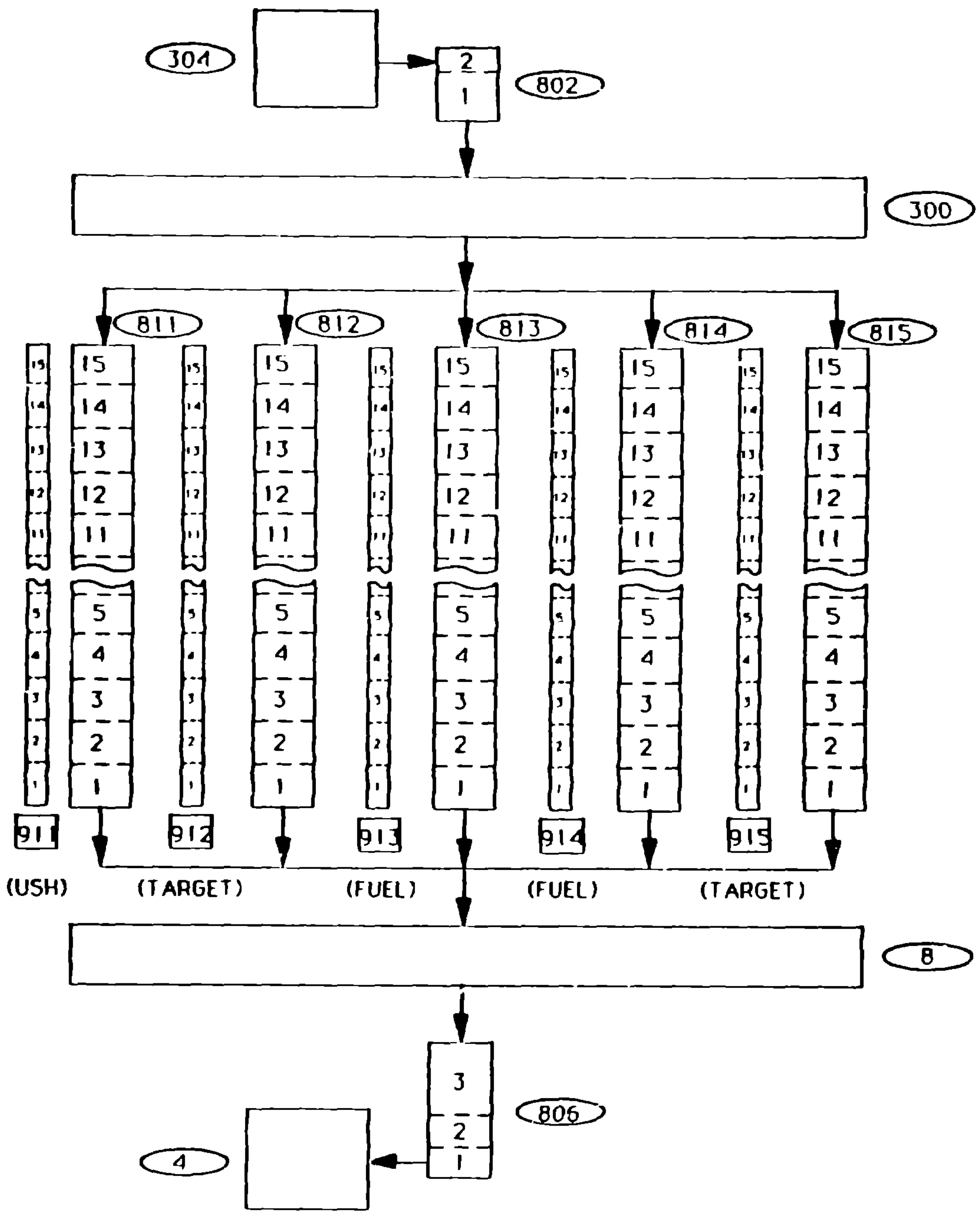

Figure 4. TRAC Mark 22 Fuel/Target Assembly Model.

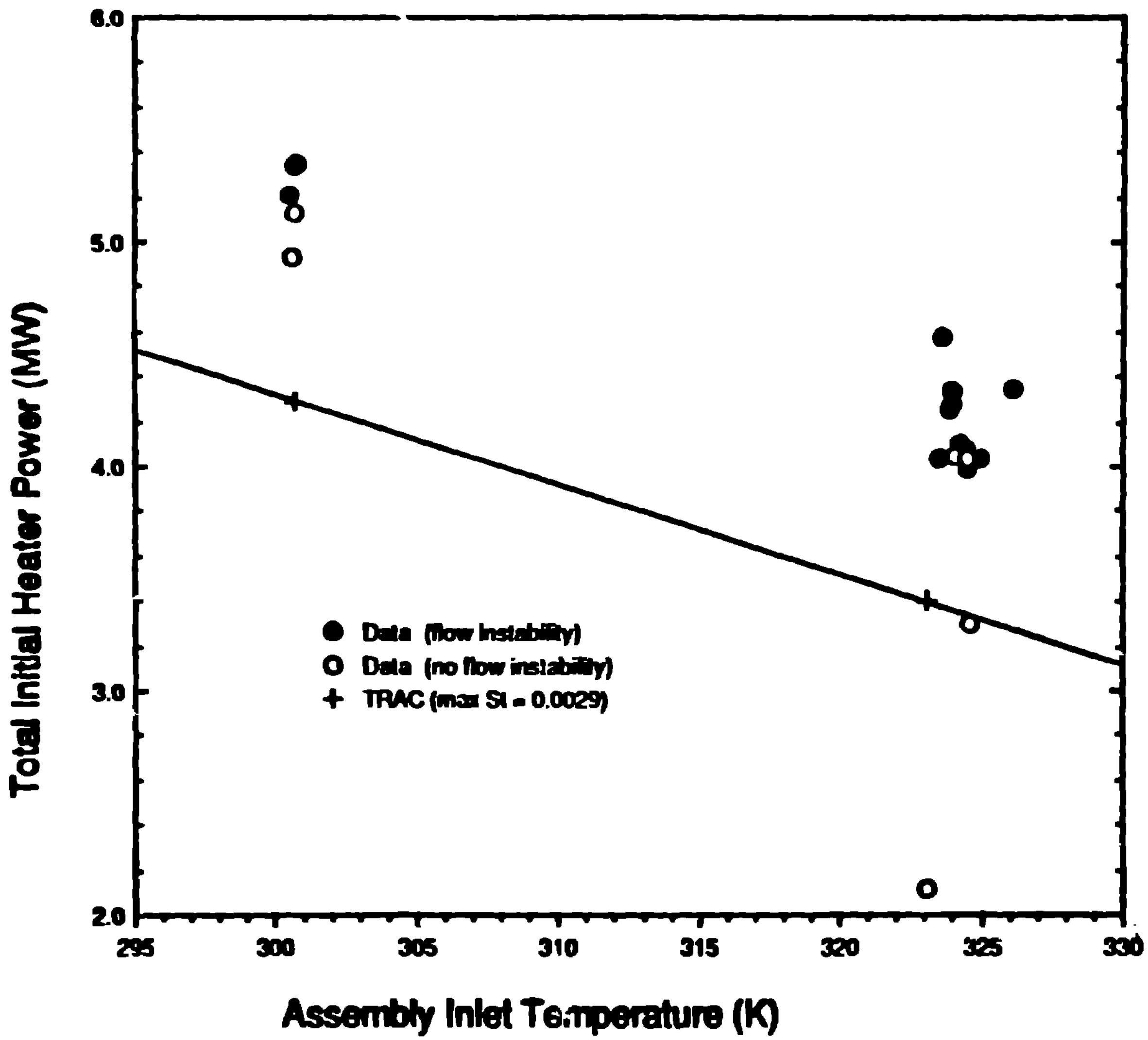

Figure 5. B&W Mark 22 Assembly Mockup: Normal Power Decay LOCA Results.

TABLE I

A COMPARISON OF DATA, TRAC, AND HAND-CALCULATED STANTON NUMBERS

Test Data Source	St_{Data}	St_{TRAC}	$St_{Calculation}$
SNBR-2T	0.00212 ± 0.00011	0.00202	0.00200
SNBR-2T	0.00255 ± 0.00014	0.00253	0.00251
SNBR-2T	0.00989 ± 0.00093	0.00865	0.00861
SNBR-2T	0.01710 ± 0.00209	0.01600	0.01590