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ABSTRACT

The Boiling Water Reactor (BWR) version of the Transient Reactor Analysis Code (TRAC) is being developed at the Idaho National Engineering Laboratory (INEL) to provide an advanced best-estimate predictive capability for the analysis of postulated accidents in BWRs. The TRAC-BD1 program provides the Loss of Coolant Accident (LOCA) analysis capability for BWRs and for many BWR related thermal hydraulic experimental facilities. This code features a three-dimensional treatment of the BWR pressure vessel; a detailed model of a BWR fuel bundle including multirod, multibundle, radiation heat transfer, leakage path modeling capability, flow-regime-dependent constitutive equation treatment, reflood tracking capability for both falling films and bottom flood quench fronts, and consistent treatment of the entire accident sequence. The BWR component models in TRAC-BD1 will be described and comparisons with data presented. Application of the code to a BWR6 LOCA will also be presented.

1. INTRODUCTION

The Transient Reactor Analysis Code for BWR systems is being developed at INEL with the objective of providing the Nuclear Regulatory Commission (NRC) and the nuclear industry with a best-estimate capability for the detailed analysis of LOCAs in BWR systems. Another objective is to provide analytical support to experimental BWR safety programs sponsored by NRC. TRAC-BD1 [1], the first released version of the TRAC-BWR code, is based on a developmental version of TRAC [2] supplied by the Los Alamos National Laboratory which uses a two-fluid hydrodynamics model for both the one- and three-dimensional flow components.

In this first year and half of TRAC-BWR development, a new approach to modeling BWR systems with TRAC has been designed and implemented. New models required for BWR systems analysis have been developed by the INEL code development group in cooperation with the General Electric Company code development group. A significant number of code improvements in terms of user convenience features and improved modeling capabilities have also been implemented into TRAC. This report will describe the BWR features of the code and present comparisons with available test data.

2. TRAC-BD1 COMPONENT MODELS

TRAC-BD1 provides distinct models for the hardware components that distinguish BWR systems: shrouded fuel bundles, jet pumps, and steam separator/dryers. The INEL approach to modeling of a BWR system is based on a new component called the CHAN, that simulates a fuel bundle and canister assembly. The CHAN is a TRAC one-dimensional flow component in which fuel rod and channel wall heat transfer models have been included. In modeling a BWR core region, CHAN components are connected across the core region of the VESSEL component, while the three-dimensional flow in the core bypass is calculated by the usual VESSEL hydrodynamics solution. This allows for the separation of the hydrodynamic solution in the bypass from the solution within the CHAN components. There are leakage flow paths [3] and channel wall heat transfer models that do allow for communication between the flow inside of the CHAN and the flow in the bypass. These models can be important for simulation of a BWR reflood transient since penetration of the Emergency Core Cooling System (ECCS) water from the upper plenum into the fuel bundle can be limited by the Counter Current Flow Limiting (CCFL) phenomenon that will occur at the fuel bundle upper tie plate [4]. The leakage flow paths from the bypass to the BWR fuel bundle provide another mechanism for allowing ECCS water to enter into the fuel bundle. The channel wall heat transfer model can also provide a heat transfer path for removing energy from the fuel bundle even if CCFL is occurring for a significant length of time during a BWR LOCA. In the case of the BWR6 ECC system, the low pressure core injection system is used to flood the core bypass which will improve heat transfer through this path as well as provide ECCS water to the leakage flow paths in the bottom of the BWR fuel bundles.

Application of the TRAC-BD1 CHAN to simulation of a BWR6 218 plant core region is illustrated in Figure 1. Six CHAN components were used to simulate the 624 fuel bundles contained in the actual plant core region. The simulation of three power rings or regions (high, average and low power densities) is an important modeling consideration for a BWR LOCA calculation, since the steam flow rate up from each of the CHAN components will be affected by the local bundle power being simulated. The steam flow rate up from the bundles determines the amount of ECCS water penetrating into the bundle due to CCFL at the top of the bundle. The steam flow rate up also affects the subcooling of the ECCS water in the upper plenum. Experimental observations indicate that the CCFL conditions at the top of the BWR fuel bundle will break down when subcooled liquid penetrates into the fuel bundle [4]. Therefore, in a BWR LOCA, CCFL breakdown would be expected to occur first in the lower power bundles around the periphery of core, since these bundles have the lowest upflow of steam and the largest subcooling in the ECCS water in the upper plenum. The largest subcooling would be around the periphery of the upper plenum because the ECCS water is entering the upper plenum via spray nozzles around the periphery of the upper plenum. Therefore, the modeling of power regions in the BWR core geometry is essential for determination of CCFL breakdown.

A jet pump component (JETP) was also developed for TRAC-BD1. The momentum equations for the TRAC TEE component were modified so that they accurately represented the momentum exchange that occurs in a jet pump. Comparison of the jet pump model with the INEL 1/6-scale jet pump data [5] and with the BWR6 full-scale jet pump data are given in Figures 2 and 3. These comparisons indicate that the jet pump model performs well over a wide range of operating conditions for the jet pump. The definition of the N and M ratios are illustrated in Figure 4. The INEL jet pump model assumes complete mixin in the throat section of the jet pump and represents irreversible pressure losses with appropriate loss coefficients for abrupt or smooth area changes. The user only has to supply a minimum of geometric input for the JETP component since an input processor has been developed for this component.

In the steam separator dryer model in TRAC-BD1, separation of steam and liquid is accomplished by appropriate choices for phasic loss coefficients in the separator/dryer region of the TRAC-BD1 VESSEL component. The user only has to identify the region in the VESSEL component that will contain the separator/dryer and the code will initialize the model automatically. The present model assumes 100% separation.

In addition to these BWR components, most of PWR TRAC components are available in TRAC-BD1. The component models available in TRAC-BD1 are: VESSEL, PIPE, PUMP, VALVE, FILL, BREAK, TEE, CHAN and JETP.

3. TRAC-BD1 HEAT TRANSFER MODELS

BWR application of the TRAC computer program requiresadditional heat transfer modeling capability beyond what was available in previous versions of the TRAC program. Heat transfer models developed for TRAC-BD1 are listed below:

a. Rod to rod, rod to coolant, and rod to channel wall radiation heat transfer model

b. Channel wall heat transfer model

c. BWR DNB model

d. Quench propagation model on the inside of the channel wall as well as on each of the rod groups, both bottom up as well as falling film

e. Improved heat slab modeling techniques

f. ANSI/ANS 5.1 decay heat model

g. TRAC-PD2 wall heat transfer improvements.

Radiation heat transfer can be a significant mode of heat transfer in a BWR fuel bundle, especially if the bundle is being steam cooled due to complete shut-off of ECCS water penetration and if the channel wall is being cooled on the outside by a supply of ECCS water. This situation can occur if CCFL at the upper tie plate continues for a long time and if water from the low pressure coolant injection system has flooded the core bypass regions. The TRAC-BD1 radiation model is described in Reference (7). A comparison of the TRAC-BD1 CHAN component predictions for a 8x8 bundle in the Göta test loop in which cooling of the bundle is predominately radiation heat transfer cooled is given in Figure 5. This comparison indicates that the TRAC-BD1 radiation heat transfer model agrees quite well with bundle radiation heat transfer data.

Departure from Nucleate Boiling (DNB) in a BWR system cannot be described by a local condition correlation[13] due to the nonuniform axial heat flux profile and the high steady state steam qualities that exist in a BWR fuel bundle. As a result, an integral correlation must be used. The integral correlation included in TRAC-BD1 is the CISE-GE boiling length correlation given in Reference (8). Comparisons with TLTA 4904 test results with and without the CISE-GE correlation is shown in Figure 6. From these comparisons, it can be seen that DNB will not be predicted well with a local condition correlation.

The quench front propagation model employed in TRAC-BD1 is described in Reference (10) and is applied to each rod group within a CHAN component and to the inside of the channel wall. The quenching of the channel wall can be an important phenomenon to model in a BWR fuel bundle, since the quenched channel wall results in a lower sink temperature for radiation heat transfer from the rods and also results in a higher effective emissivity for channel wall surface [3] (i.e, $\varepsilon_{zr02} \approx 0.67$ to $\varepsilon_{h20} \approx 0.96$). Comparisons of the TRAC-BD1 quench front model with bundle mid plane data for FLECHT Test 9077 is given in Figure 7. Results indicate that the quench front propagation is calculated quite well. However, the early cooling in the calculation is attributed to high entrainment and high interfacial heat transfer rate in the high void fraction flow region. Less entrainment and less interfacial heat transfer would have allowed the rods to heat up early in the test rather than cool off.

Improved heat slab modeling techniques were required in order to be able to accurately simulate the control rod guide tubes, vessel wall, and other heat structures in the lower plenum of a BWR vessel. Pipe and jet pump wall heat transfer models were modified so that a user could simulate the heat transfer between the fluid inside of the guide tubes and the fluid in the lower plenum as well as the heat transfer between the fluid inside of the jet pumps and the fluid in the downcomer. Previous versions of TRAC restricted the user to lumped parameter heat structure models in the vessel. This has been modified in TRAC-BD1 so that the user can specify as many nodes as desired to simulate the conduction heat transfer within a structure. This is a significant improvement for vessel wall heat transfer modeling.

In TRAC-PD2 the wall heat transfer correlation package was smoothed to eliminate discontinuities in the boiling curve that must result in instabilities in the TRAC calculation. These improvements were incorporated into TRAC-BD1.

4. TRAC-BD1 HYDRODYNAMICS

TRAC-BD1 solves the two-fluid hydrodynamic equations given below

Vapor Continuity

$$\frac{\partial(\rho_v \alpha_v)}{\alpha t} + \frac{1}{A} \nabla \cdot (\rho_v \alpha_v V_v A) = \Gamma_g \tag{1}$$

Liquid Continuity

$$\frac{\partial(\rho_\ell \alpha_\ell)}{\alpha t} + \frac{1}{A} \nabla \cdot (\rho_\ell \alpha_\ell V_\ell A) = - \Gamma_g \tag{2}$$

Vapor Energy

$$\frac{\partial(\rho_v \alpha_v e_v)}{\partial t} + \frac{1}{A} \nabla \cdot (\rho_\ell e_\ell \alpha_\ell V_\ell A) = - P \frac{\partial \alpha}{\partial t} - \frac{P}{A} \nabla \cdot (V_v \alpha A)$$

$$+ \Gamma_g h_{sg} - q_{vi} A_i + q_{wv} A \tag{3}$$

Mixture Energy

$$\frac{\partial[\rho_\ell \alpha_\ell e_\ell + \rho_v \alpha_v e_v]}{\partial t} + \frac{1}{A} \nabla \cdot [(\rho_v \alpha_v e_v V_v + \rho_\ell \alpha_\ell e_\ell V_\rho)A]$$

$$= \frac{P}{A} \nabla \cdot [V_v \partial_v A + V_\ell \alpha_\ell A] + A_t [q_{wv} + q_{w\ell}] \tag{4}$$

Liquid Momentum

$$\frac{\partial \vec{V}_\ell}{\partial t} + \vec{V}_\ell \cdot \nabla \vec{V}_\ell = \frac{C_i}{\rho_\ell \alpha_\ell} |\vec{V}_R| \vec{V}_R - \frac{1}{\rho_\ell} \nabla P - \frac{C_{w\ell}}{\rho_\ell \alpha_\ell} |\vec{V}_\ell| \vec{V}_\ell + \vec{g} \tag{5}$$

Vapor Momentum

$$\frac{\partial \vec{V}_2}{\partial t} + \vec{V}_v \cdot \nabla \vec{V}_v = - \frac{C_i}{\rho_v \alpha_v} |\vec{V}_R| \vec{V}_R - \frac{1}{\rho_v} \nabla P - \frac{C_{wv}}{\rho_v \alpha_v} |\vec{V}_v| \vec{V}_v + g \tag{6}$$

for both the one-dimensional flow components and for the three-dimensional flow components. The semi-implicit numerical scheme utilized in previous versions of TRAC is used in TRAC-BD1.

In order to be able to model choking it was necessary to include a critical flow model into TRAC-BD1, since modeling of choking with a fine nodalization of the break plane with only semi-implicit numerics is impractical. The critical flow model included in BD1 is the RELAP5/MODO [10] nonhomogeneous equilibrium critical flow model. This model appears to be adequate for BWR applications since in BWR LOCA analysis, nonequilibrium effects on critical flow are negligible. The TRAC-BD1 comparisons with Edwards pipe blowdown data is given in Figures 8 and 9. From the comparisons it can be seen that the model performs quite well for both the short- and long-term behavior. The pressure does fall off too rapidly later in the blowdown which is attributed to low interfacial shear in the dispersed droplet flow regime, which results in high relative velocities late in the blowdown.

A CCFL model has also been implemented into TRAC-BD1. Based on the data of Jones [4], Tobin [11], and Naitok [12], a CCFL correlation in the form of a Wallis-Kutaledadze type correlation was developed for the BWR upper tie plate. The general form of this correlation was recommended by Sun [13] for BWR 7x7 bundle upper tie plates and also by Sun [14] for BWR 8x8 upper tie plates and is repeated below

$$K_g^{1/2} + m|K_f|^{1/2} = K^{1/2}. \tag{7}$$

The constants chosen for simulation of BWR upper tie plates are m = 1.0 and K = 3.2. For 8x8 bundles Sun recommends a higher K. However, due to the dependence of K on the injection method of steam into the channel, it was decided to use the lower K which appears to be able to correlate both 7x7 and 8x8 data satisfactorily. Comparisons of the correlation with m = 1.0 and K = 3.2 with 7x7 bundle data can be found in Reference (13). The TRAC-BD1 comparisons with Jones [4] data for an 8x8 bundle upper tie plate is given in Figure 10. This comparison indicates that K = 3.2 provides an adequate representation of the 8x8 bundle data.

CCFL has also been observed at the side entry orifices of a BWR fuel bundle [15]. Sun [14] recommends a correlation similar to equation (7) for the side-entry orifice except the m = 0.6 and the K is given as a function of the Bond number based on the wetted perimeter of the side entry orifice. This correlation for the side entry orifice is also available in TRAC-BD1.

Both the choking model and the CCFL model are implemented into the TRAC hydrodynamics solution as limit lines. For the choking model the limit is a critical mixture velocity defined by the critical flow model. For the CCFL model the limit is a critical liquid downflow rate defined by the CCFL correlation. In both cases, if the limit or critical velocity is exceeded by the normal TRAC hydrodynamics solution, then the linearized TRAC momentum equations are modified such that the hydrodynamics solution will follow the limit line defined by the appropriate correlation.

As part of the developmental assessment of TRAC-BD1, comparisons were made with experiments that would identify deficiencies in the TRAC-BD1 interfacial shear package. The TRAC-BD1 interfacial shear package was obtained from the TRAC-PD2 VESSEL component interfacial shear package. In Figure 11 TRAC-BD1 predictions of void fraction as a function of quality are compared with tube data obtained from Reference (16). TRAC-BD1 compares quite well indicating that the interfacial shear or relative velocity between the vapor and liquid velocities is consistent with measured data. In Figures 12 thru 15, TRAC-BD1 void fraction profiles are compared with measured void profile data for a General Electric level swell test [17]. Again, the comparisons indicate that interfacial shear predicted by TRAC results in void profile consistent with data.

5. USER CONVENIENCE FEATURES OF TRAC-BD1

A number of user convenience features or added modeling capabilities have been added to TRAC-BD1. These new features included in the program are listed below:

a. Increased input error checking

b. More readable output

c. Multiple pipe-to-vessel connection capability

d. Jet pump component input processor

e. Optional input for VESSEL hydraulic diameters

f. Optional input for surface roughness

g. Improved VALVE component which allows for modeling of banks of relief valves as well as motor controlled valves

h. Downcomer level trip

i. Improved heat transfer modeling capability discussed in Section 3

j. Slab or cylindrical VESSEL noding option.

These features are self explanatory except the multiple pipe-to-vessel connection capability. This code feature allows more than one pipe to be connected to a single vessel hydraulic cell. Previous versions of TRAC allowed only one pipe connection per vessel hydraulic cell. This multiple connection capability allows for coarser noding in the VESSEL component. The downcomer level trip is also an important BWR feature since many of the BWR safety systems are initiated by a low downcomer level.

6. TRAC-BD1 SYSTEM SIMULATION

TRAC-BD1 has been used to simulate the TLTA Test 6422-3. This TLTA simulation was with all ECCS on and with an 8x8 fuel bundle at average power (5.0 Mw). The steam dome pressure and core flow are predicted well by TRAC-BD1 as illustrated in Figures 16 and 17. The TRAC-BD1 predicted pressure does tend to fall off too rapidly. This can be attributed to high relative velocities predicted at the break plane for the dispersed droplet flow regime. Lower plenum flashing is predicted to occur at approximately 12 seconds as indicated by the core flow comparisons in Figure 17. TRAC-BD1 is underpredicting the core flow during lower plenum flashing; however, the trend is predicted quite well. Dryout was predicted and observed in the test to occur late in the blowdown as illustrated in Figure 18. The rods rewet soon after dryout from the ECCS water being injected into the system.

One explanation for the late dryout for the rods is the holdup of water in the bundle due to CCFL at the bundle inlet. This was also observed in the TRAC calculation. Overall the TRAC calculation performed quite well in predicting trends and observed phenomena.

TRAC-BD1 was also used to simulate a BWR6 218 plant 200% recirculation line break LOCA. The model noding is given in Figure 1. The average bundle behavior is similar to the TLTA test; however, rewet was delayed due to multidimensional effects in the upper plenum. CCFL breakdown in the low power bundles was predicted to occur at 75 seconds. The CCFL breakdown allows the lower plenum to fill and then the average and high power bundles begin to fill from the lower plenum. This calculation indicates that TRAC-BD1 is capable of modeling all of the important phenomenon that occurs during a BWR LOCA.

7. CONCLUSIONS

TRAC-BD1 has a best estimate capability for the detailed analysis of a BWR LOCA. Comparisons with data indicate that TRAC-BD1 does quite well in representing the important phenomenon that are anticipated to occur during a BWR LOCA.

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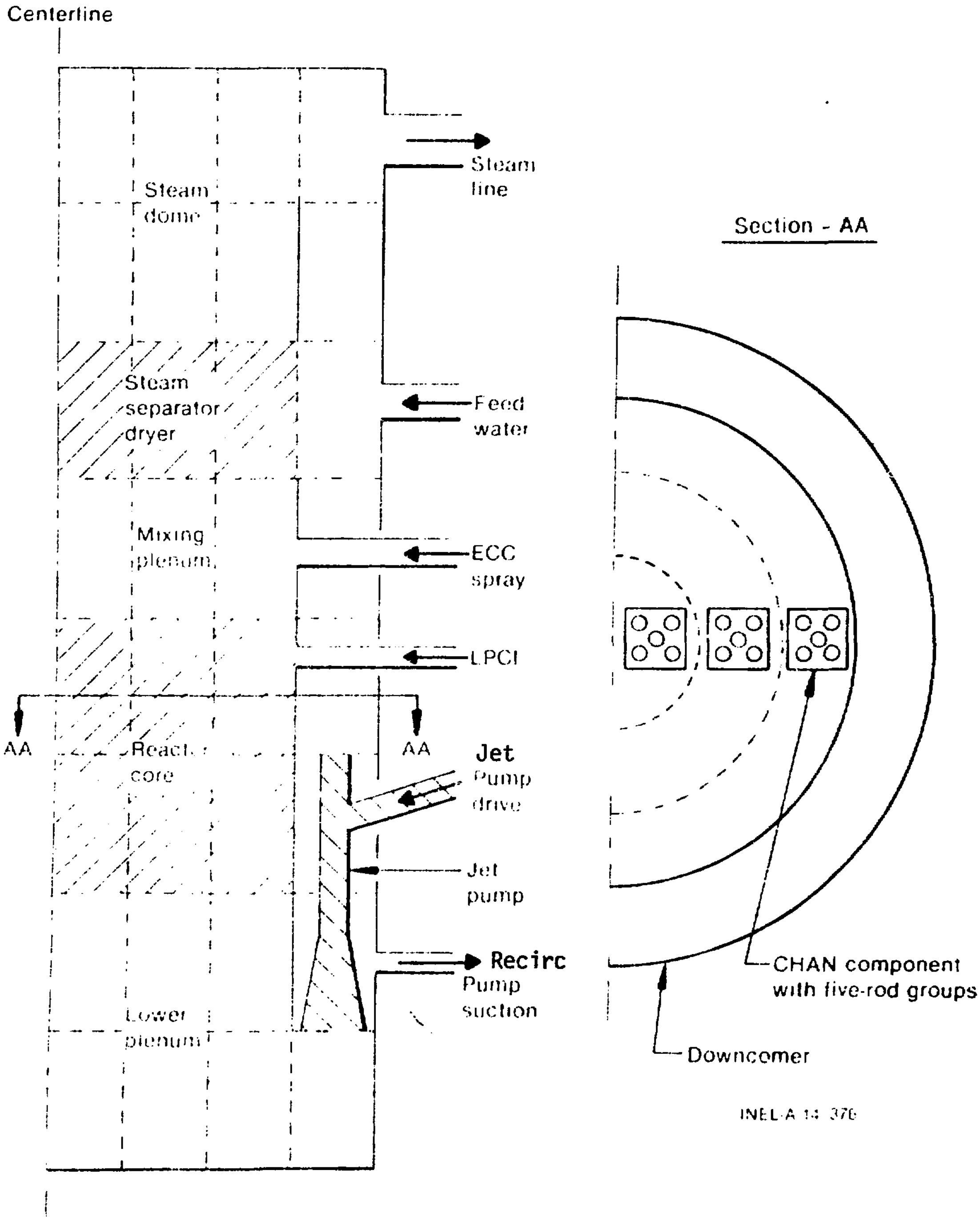


Figure 1. TRAC Boiling Water Reactor Nodalization (vessel half section)

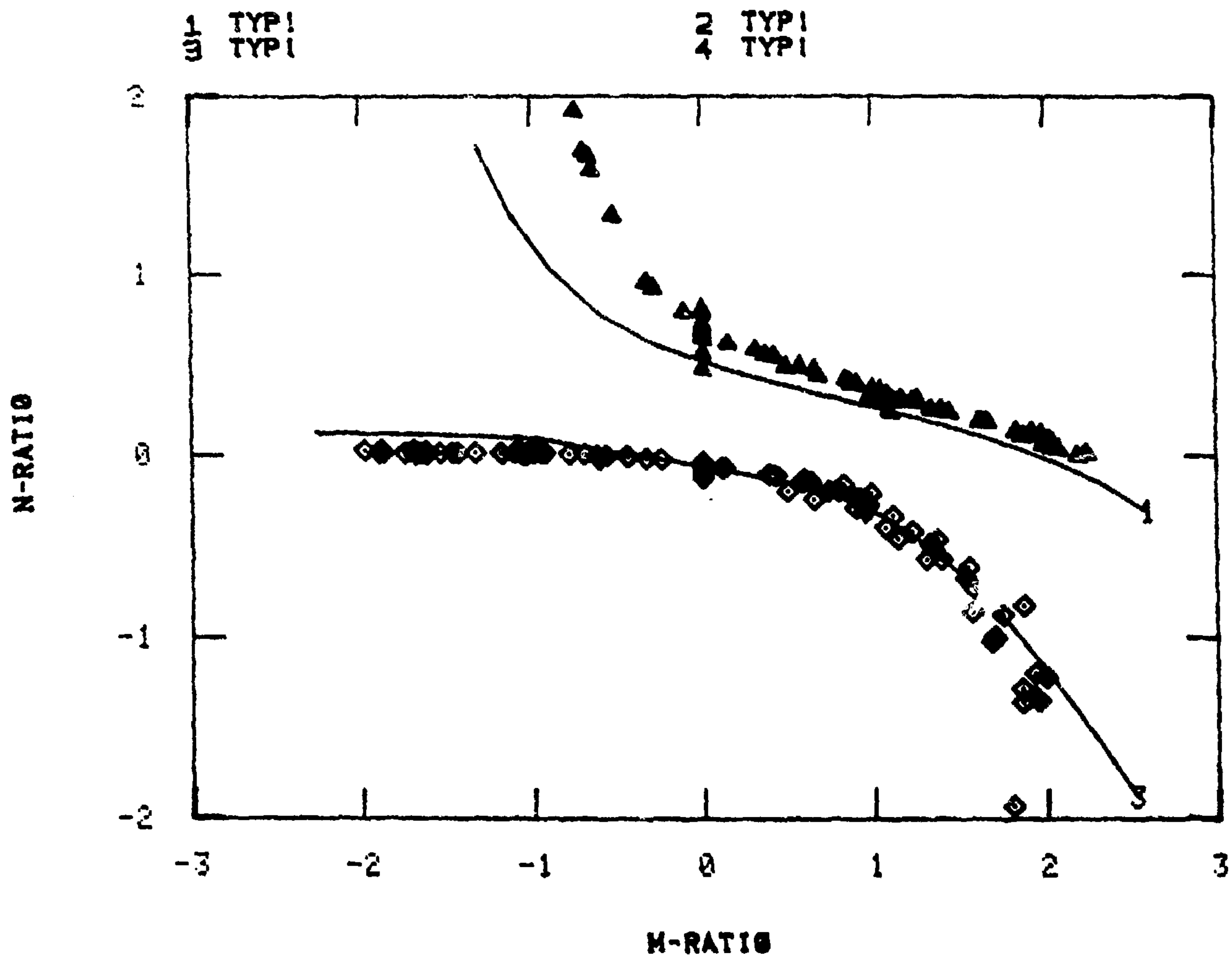


Figure 2. Comparison of TRAC-BD1 Predictions to INEL 1/6-Scale Jet Pump Data

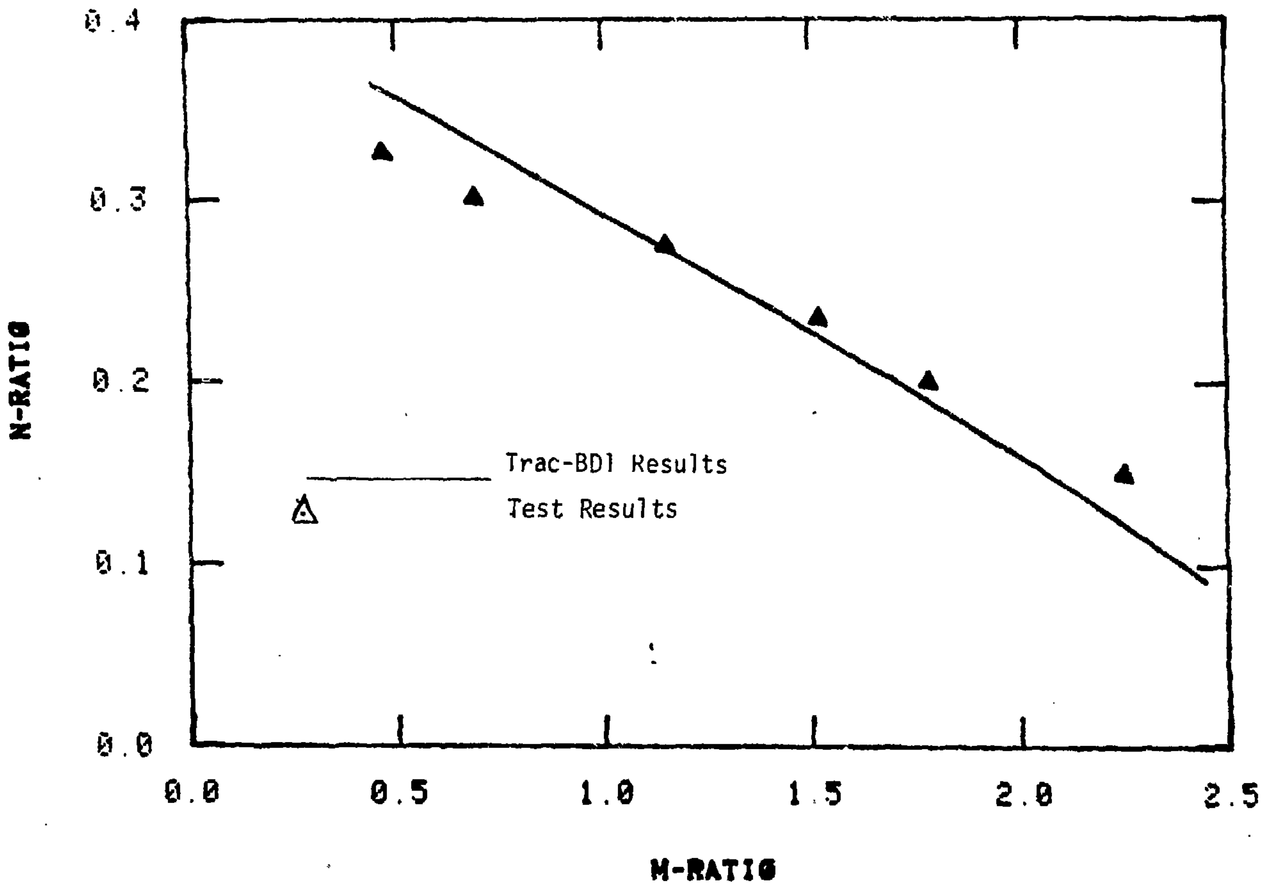
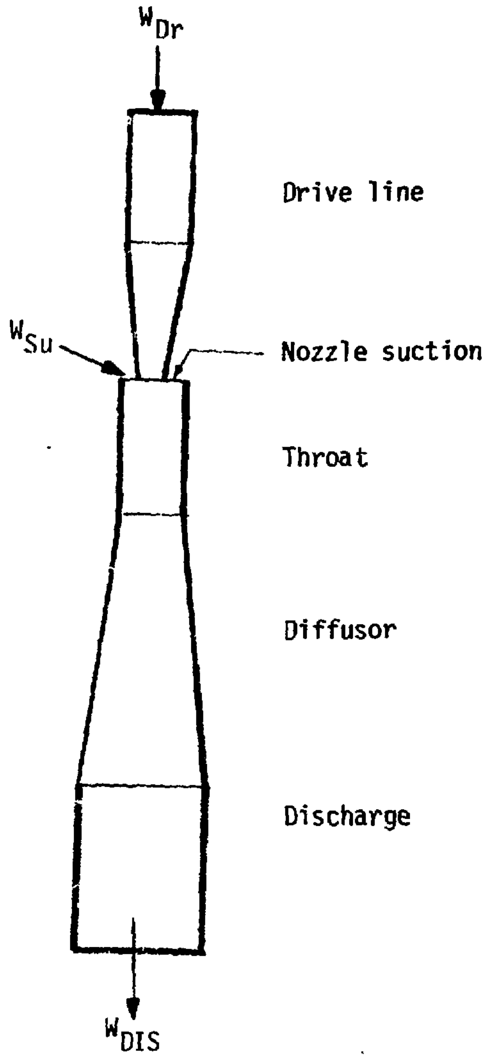


Figure 3. Full-Scale BWR Jet Pump-Positive Drive Flow



$$M = \frac{W_{Su}}{W_{Dr}}$$

$$N = \frac{\left(\frac{P_a}{\rho_\ell}\right)_{Su} - \left(\frac{P_a}{\rho_\ell}\right)_{DIS}}{\left(\frac{P_a}{\rho_\ell}\right)_{DR} - \left(\frac{P_a}{\rho_\ell}\right)_{DIS}}$$

where

$$P_a = P + 1/2\ \rho_\ell V^2 + g\ z$$

Figure 4. Diagram for Jet Pump

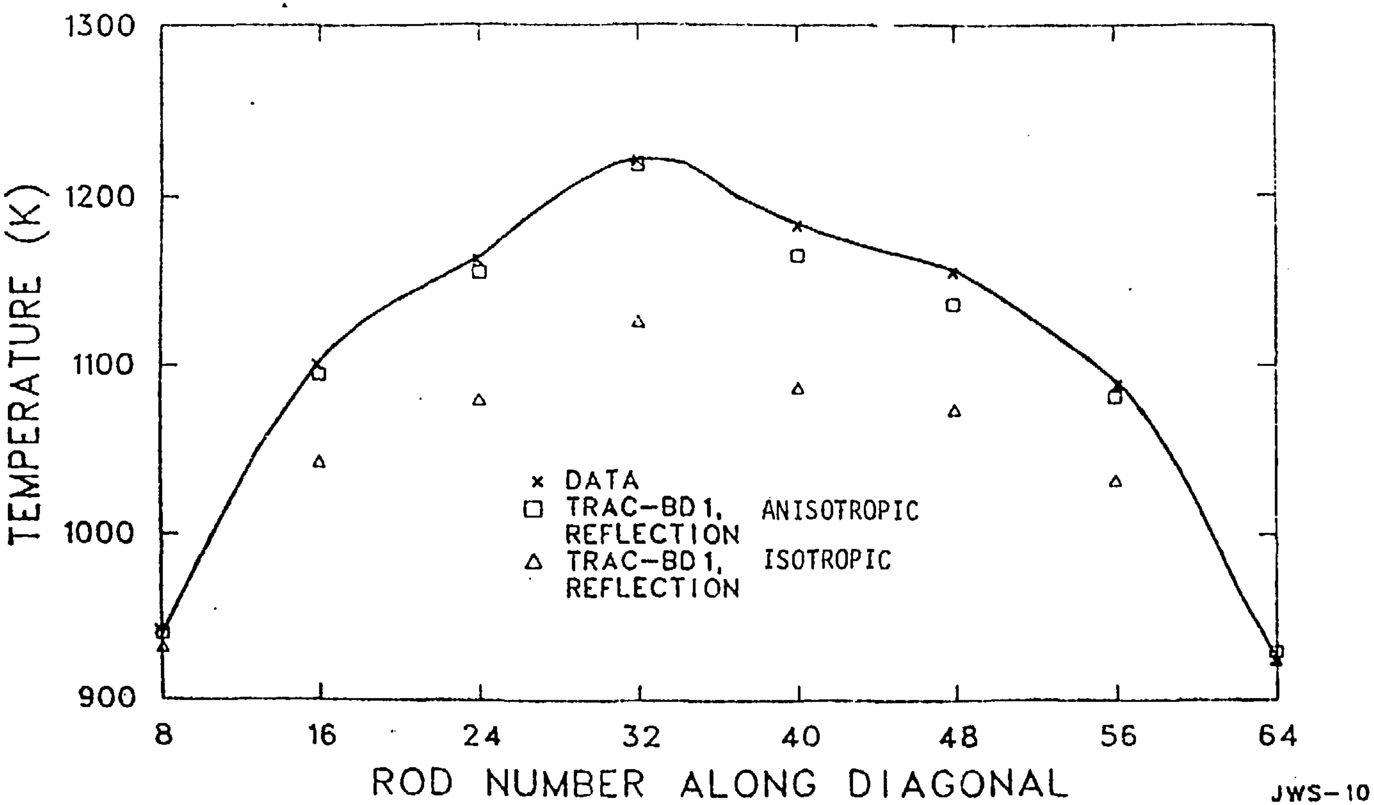


Figure 5. Comparison of TRAC-BD1 Predictions with Göta Radiation Heat Transfer Data

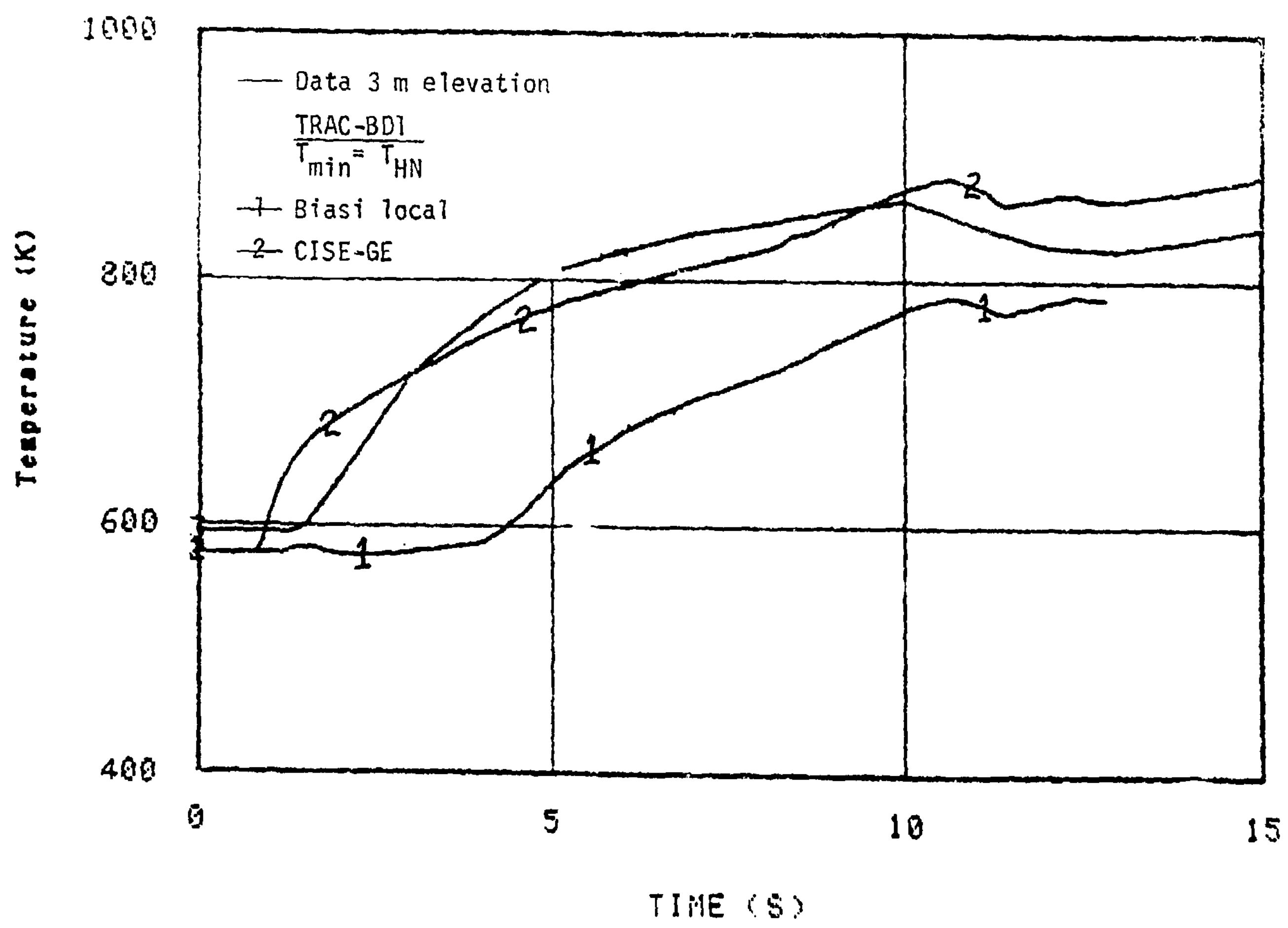


Figure 6. TLTA data, CISE-GE and Biasi local

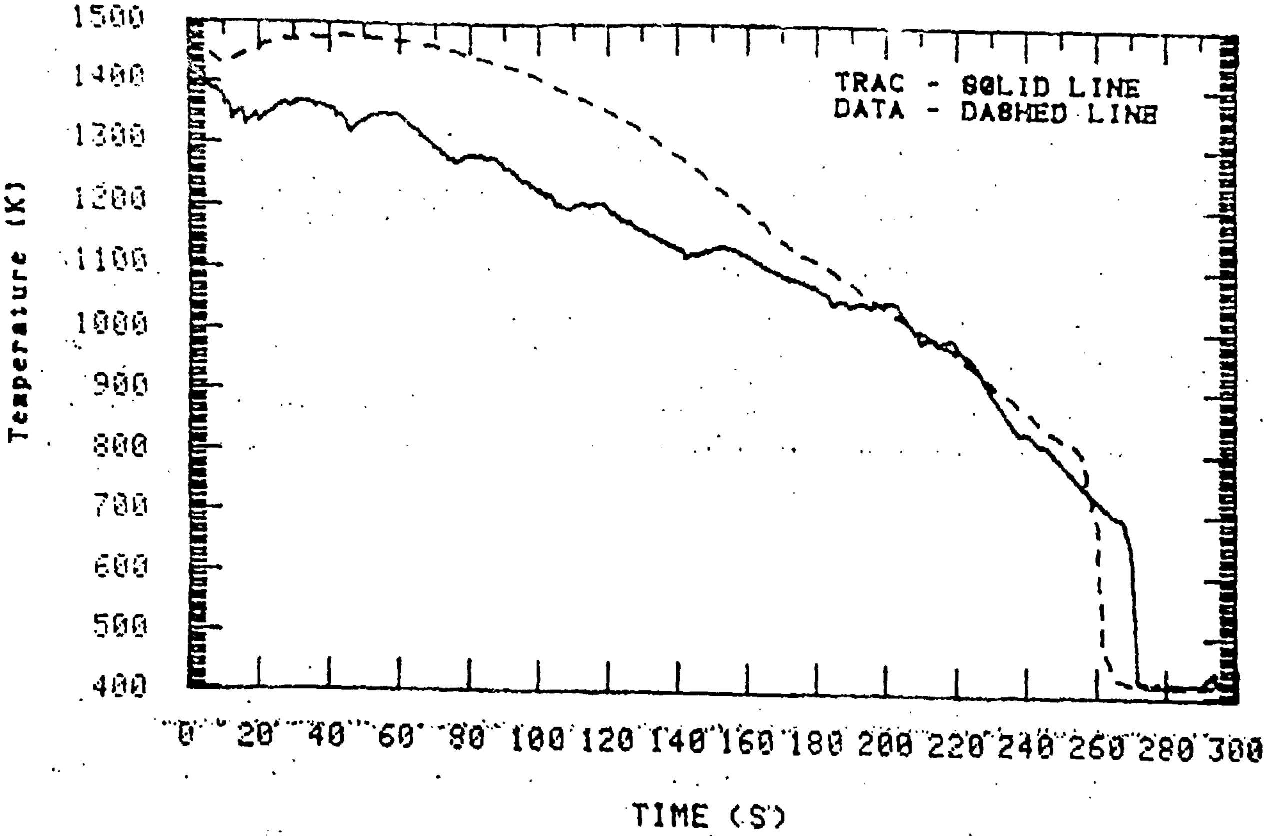


FIGURE 7. FLECHT TEST 9077
ROD TEMPERATURES
6 FT ELEVATION (MID-PLANE)

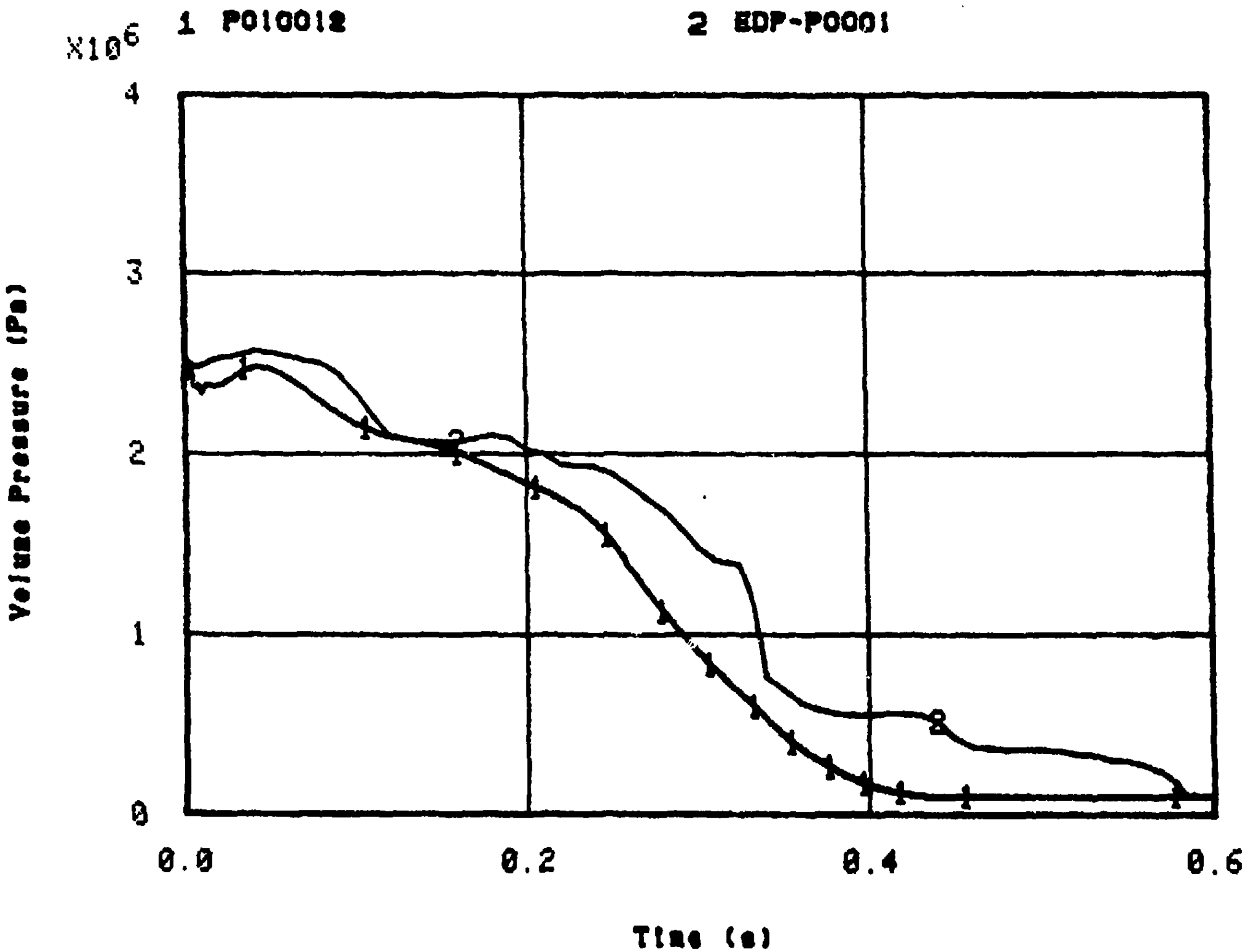


Figure 8. Comparison of TRAC-BD1 Predictions with Edwards Pipe Blowdown Pressure Data at Gauge Station 1

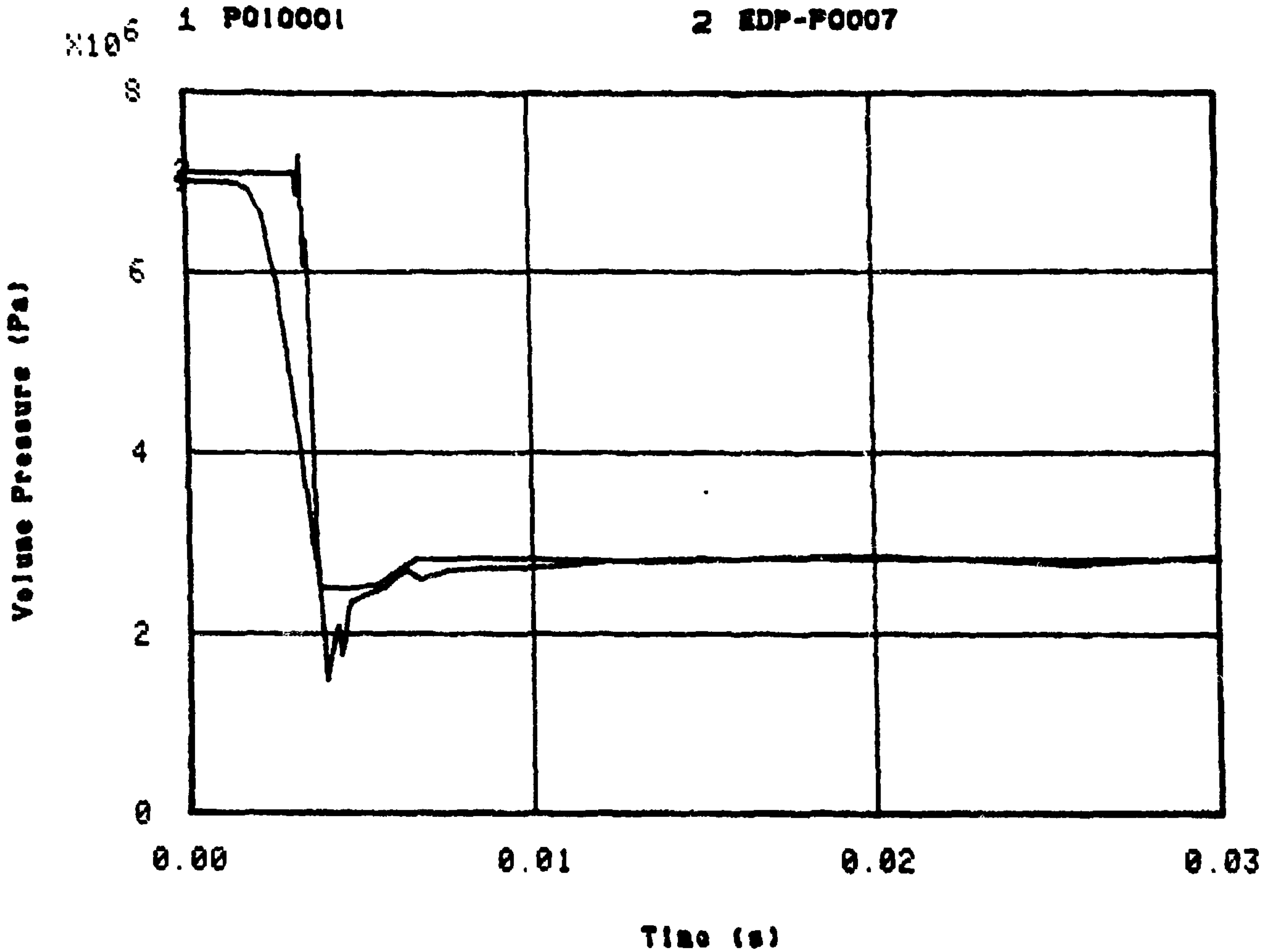


Figure 9. Comparison of TRAC-BD1 Predictions with Edwards Pipe Blowdown Pressure Data at Gauge Station 7

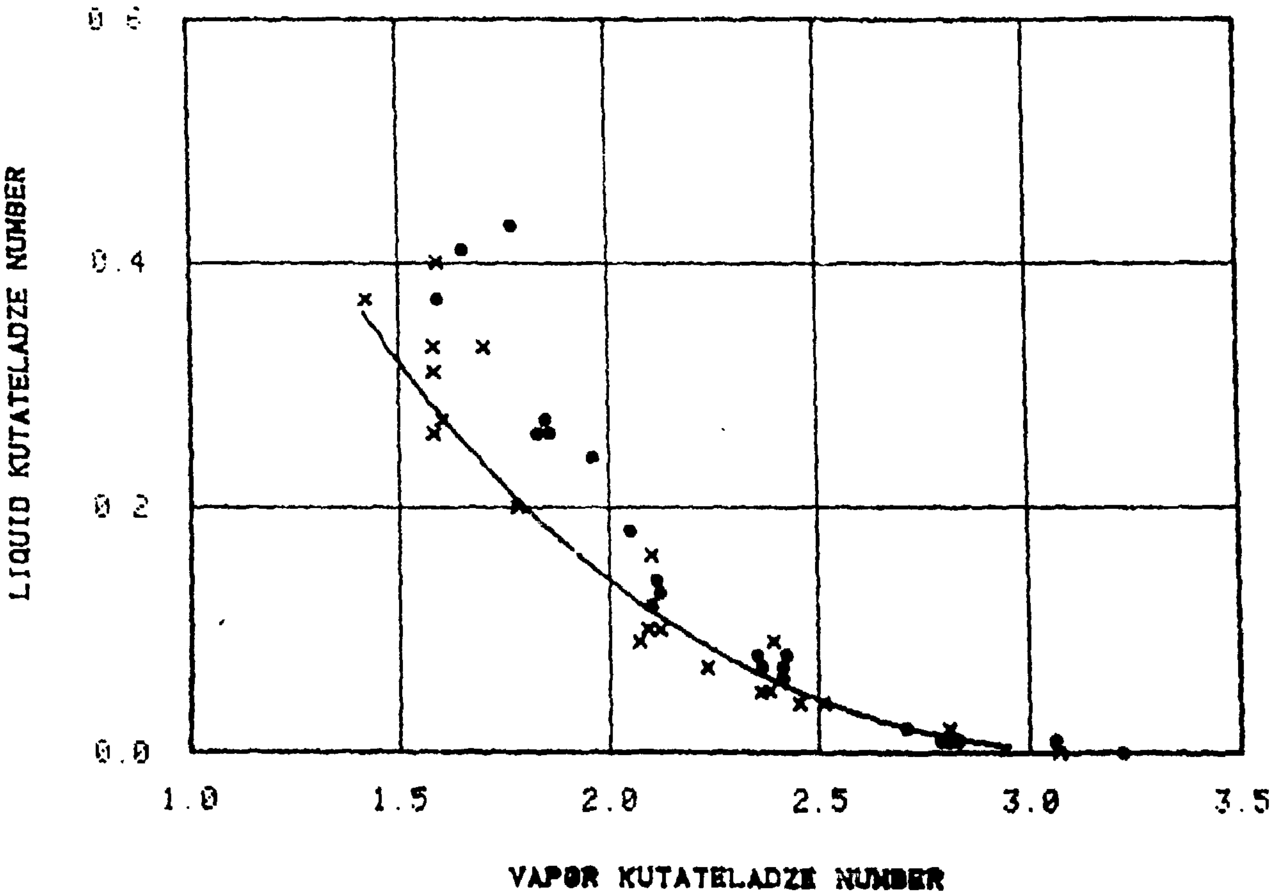


Figure 10. Comparison of TRAC-BD1 Predictions with CCFL Data for a BWR Upper Tie Plate

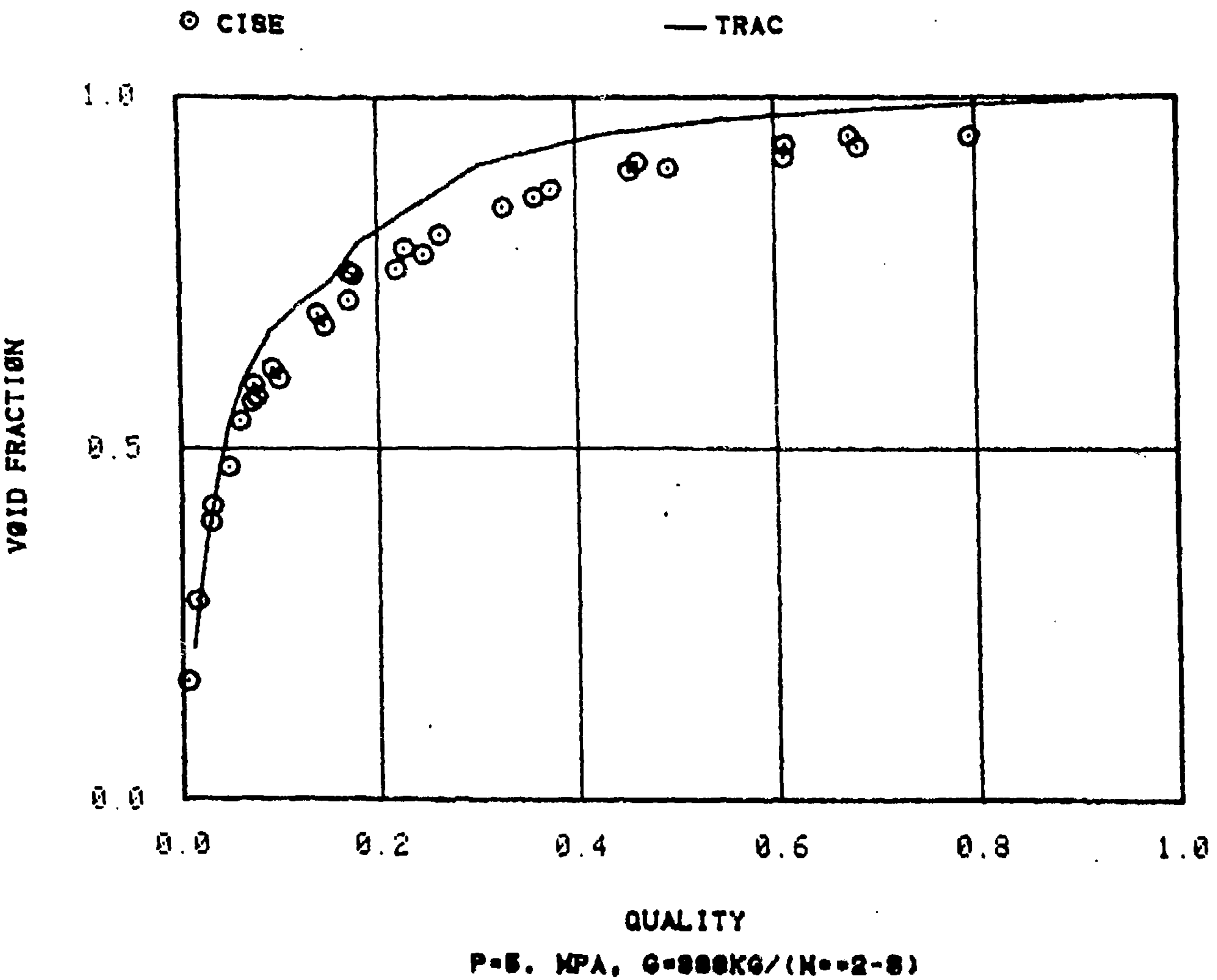


Figure 11. Comparison of TRAC-BD1 Predictions with CISE Void Fraction Data

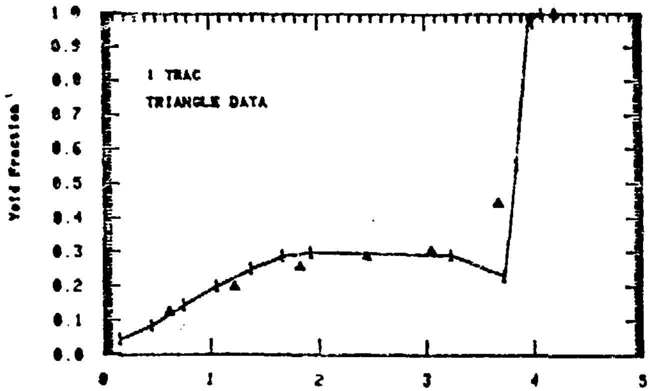


Figure 12. GE SMALL VESSEL LEVEL SWELL RUN 1004-3
TIME = 10 SEC

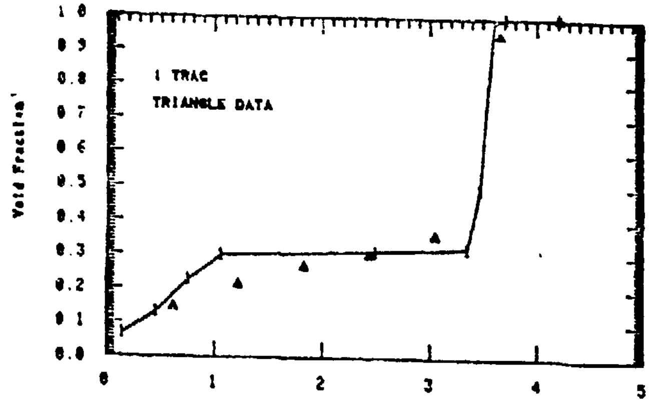


Figure 13. GE SMALL VESSEL LEVEL SWELL RUN 1004-3
TIME = 40 SEC

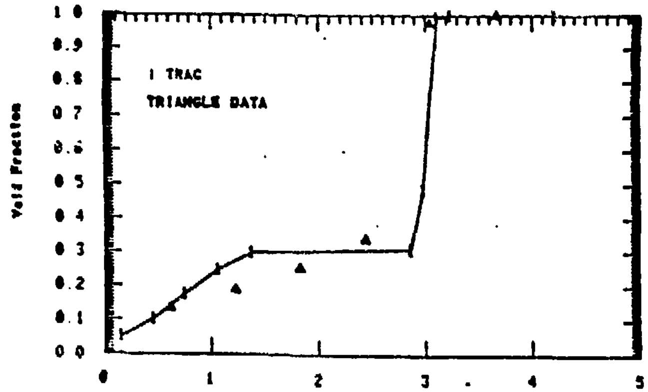


Figure 14. GE SMALL VESSEL LEVEL SWELL RUN 1004-3
TIME = 100 SEC

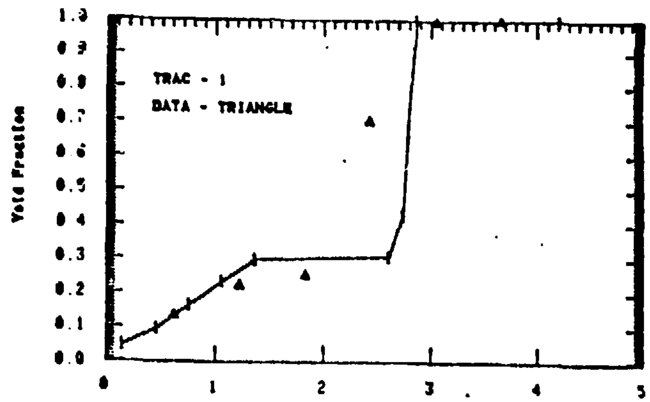


Figure 15. GE SMALL VESSEL LEVEL SWELL RUN 1004-3
TIME = 150 SEC

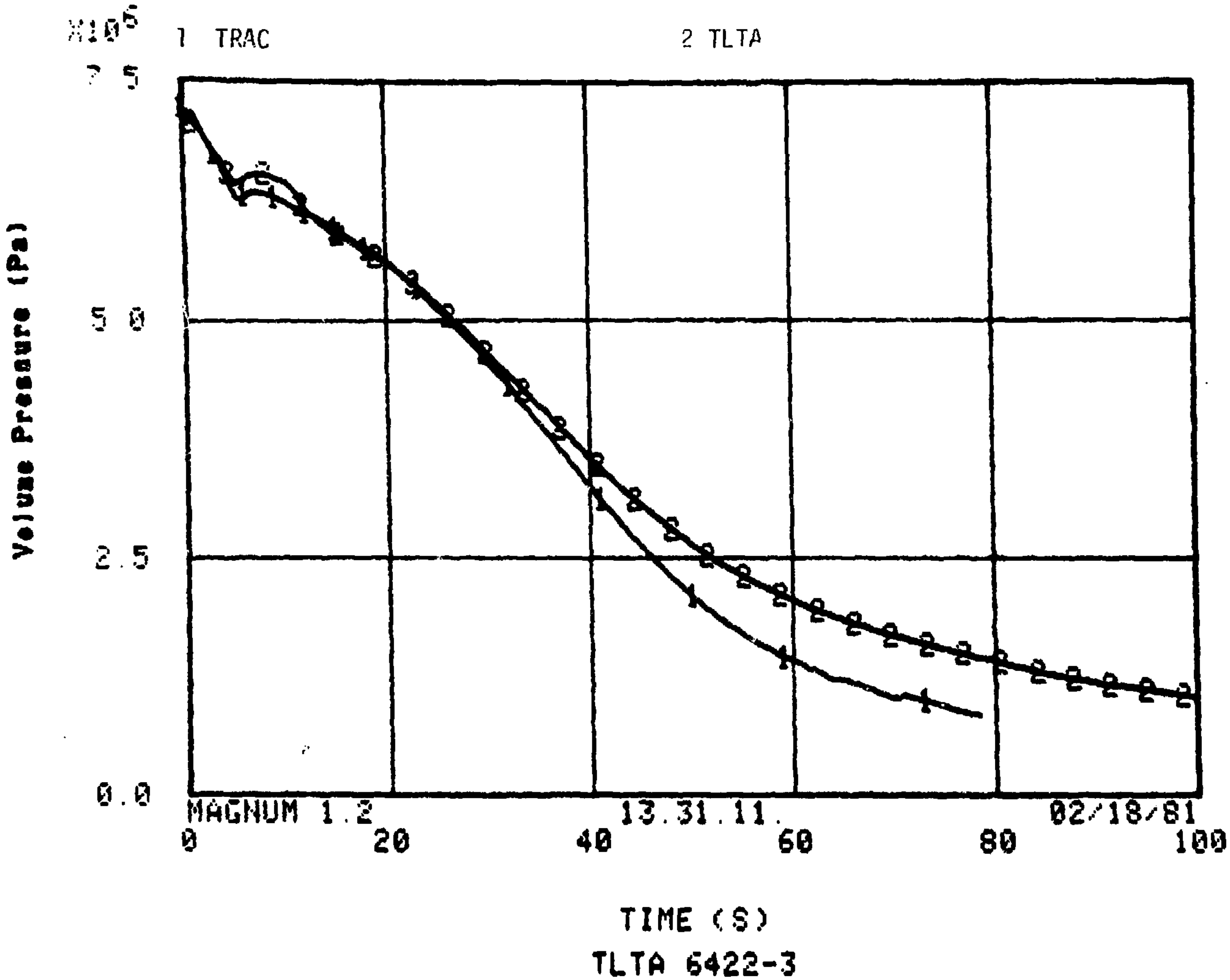


Figure 16. Comparison of TRAC-3D1 Prediction with Measured Steam Dome Pressure

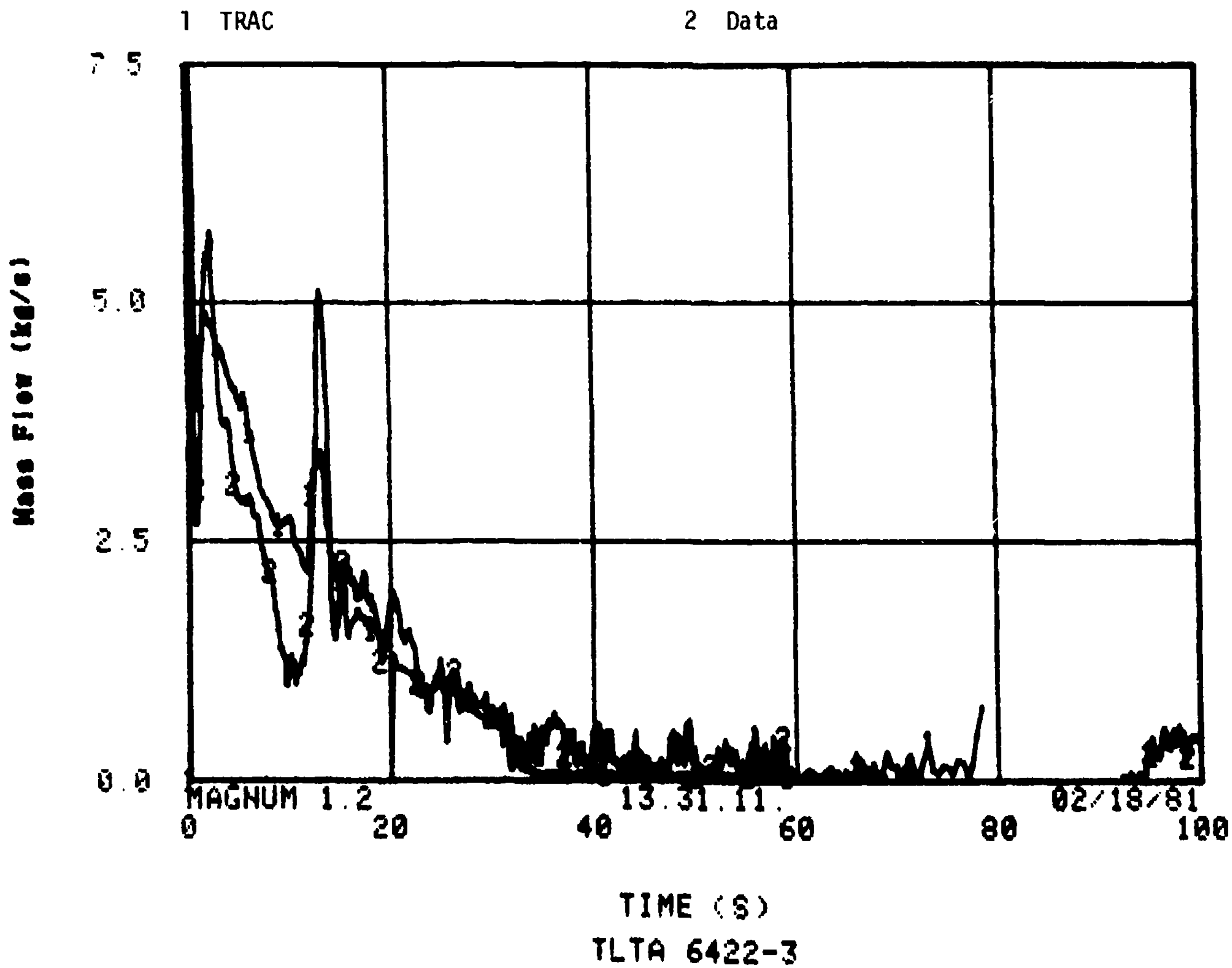


Figure 17. Comparison of TRAC-BD1 Prediction for Measured Core Mass Flow

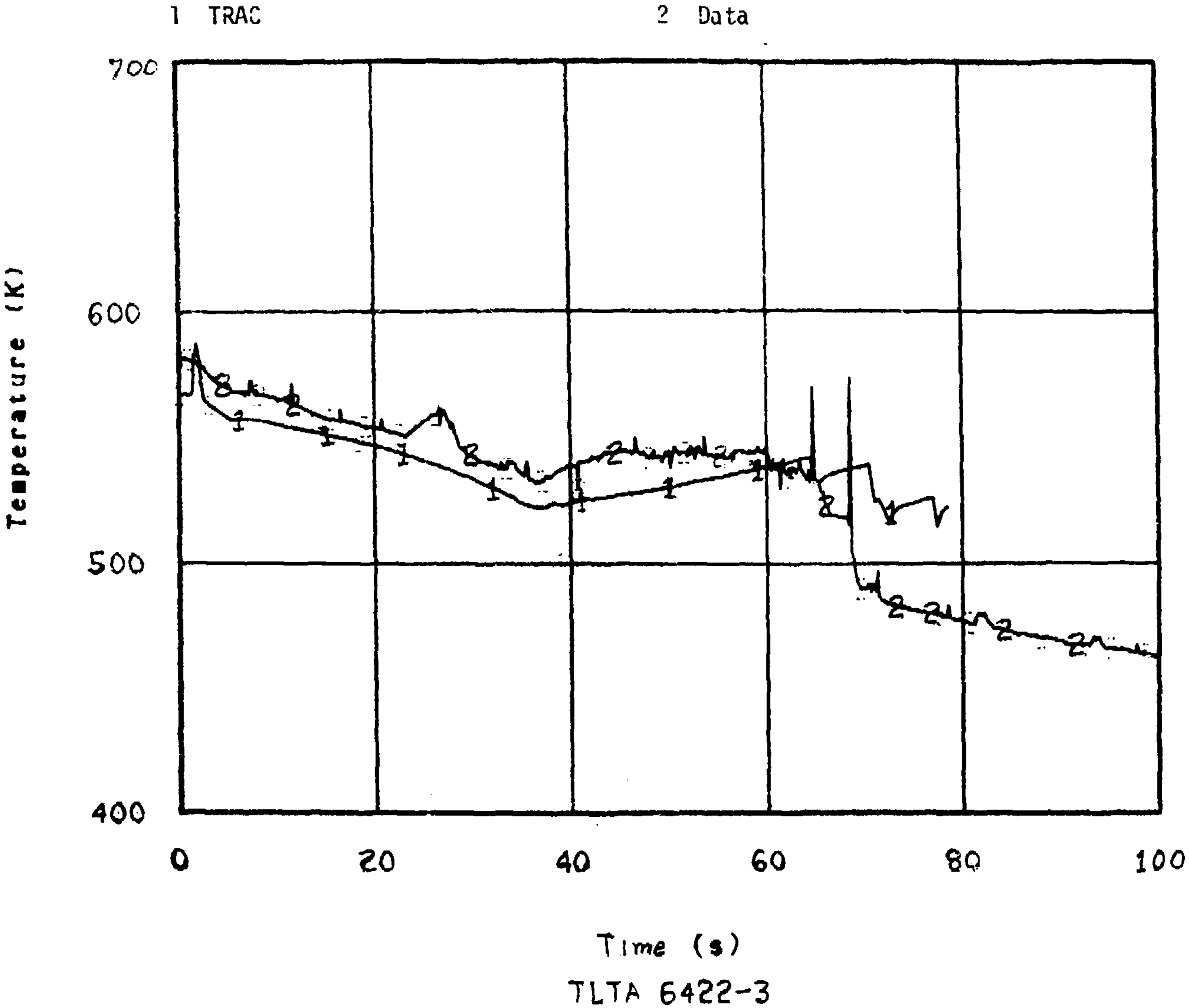


Figure 18. Comparison of TRAC-BD1 Prediction with Measured Rod Temperature at the 143-inch Elevation