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INDEPENDENT ASSESSMENT OF TRAC AND RELAP5 CODES THROUGH SEPARATE EFFECTS TESTS *

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1. INTRODUCTION

Independent assessment of TRAC-PF1 (Version 7.0), TRAC-BD1 (Version 12.0) and RELAP5/MOD1 (Cycle 14) that was initiated at BNL in FY 1982, has been completed in FY 1983. As in the previous years, emphasis at Brookhaven has been in simulating various separate-effects tests with these advanced codes and identifying the areas where further thermal-hydraulic modeling improvements are needed. The following six catetories of tests were simulated with the above codes:

1. Critical flow tests (Moby-Dick nitrogen-water, BNL flashing flow, Marviken Test 24),
2. Counter-Current Flow Limiting (CCFL) tests (University of Houston, Dartmouth College single and parallel tube tests),
3. Level swell tests (G. E. large vessel test),
4. Steam Generator tests (B&W 19-tube model S.G. tests, FLECHT-SEASET U-tube S.G. tests),
5. Natural circulation tests (FRIGG loop tests),
6. Post-CHF tests (Oak Ridge steady-state test).

As shown in Table 1, TRAC-PF1 and RELAP5/MOD1 were applied to all of the above categories, whereas TRAC-BD1 was applied only to the CCFL and post-CHF tests. The number of experiments simulated in each category is also indicated in Table 1.

Because of space limitation, we will only discuss the details of the CCFL and post-CHF test simulations here. Details of the other test simulations can be found in References 1 through 4. We will, however, summarize all the results here and draw some overall conclusions.

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Table 1. BNL Code Assessment Matrix (FY 1982-83)

TESTS	TRAC-PF1 (Version 7.0)	TRAC-BD1 (Version 12.0)	RELAP5/MOD1 (Cycle 14)
1. Critical Flow			
- Moby-Dick N_2-water(2)	X		X
- BNL Nozzle (4)	X		X
- Marviken (Test 24)	X		X
2. CCFL			
- Univ. of Houston (2)	X	X	X
- Dartmouth single tube (2)	X	X	X
- Dartmouth parallel tube (1)	X	X	
3. Level Swell			
- G.E. Large Vessel (1)	X		X
4. Steam Generator			
- B&W 19-tube OTSG (1) and IEOTSG (2)	X		X
- FLECHT-SEASET U-tube (2)	X		X
5. Natural Circulation FRIGG Loop (3)	X		X
6. Post-CHF - ORNL Rod Bundle (1)	X	X	X

2. CCFL TEST SIMULATION

2.1 Test Description

Counter-current flow limiting tests conducted at the University of Houston [5] and Dartmouth College [6] were used for code assessment at BNL. The test apparatus used are shown in Figure 1. Notice that the two set-ups differed in the way water was introduced into the test section. In the University of Houston facility, water was injected at the middle of the test section through a porous block. However, in the Dartmouth College facility, water was introduced into the upper plenum where a water level was maintained through an overflow drain tube. Air was, of course, introduced at the bottom of the test section in both facilities.

The inside diameter of the University of Houston test section was 0.051m (2-inch), whereas pipes of various inside diameters were used in the Dartmouth college tests. For our assessment work, the Dartmouth tests conducted in 0.0254m (1-inch) and 0.152m (6-inch) I.D. pipes with square-edge entrance were selected. Water downflow rates for various air upflow rates were measured, and the code predictions were compared to these data.

The Dartmouth College parallel tube test facility [7] had the same general configuration as the single-tube facility shown in Figure 1. The tests conducted with three parallel tubes each of 0.0254m (1-inch) I.D. were selected for simulation. The pressure drop across the test section for various air flow rate was measured and the code predictions were compared with these data.

2.2 Comparison of Code Predictions with Data

2.2.1 University of Houston Test

Two test series with water feed rates of 100 lb/hr and 1000 lb/hr were simulated with TRAC-PF1, TRAC-BD1 and RELAP5/MOD1 codes. The results for the water feed rate of 1000 lb/hr are shown in Figure 2. It is clear that TRAC-BD1 produced the best agreement with the data. Similar results were also obtained for the 100 lb/hr water feed rate.

TRAC-PF1 results were not as good as the TRAC-BD1 results, although they were much better than the RELAP5/MOD1 results. RELAP5/MOD1 assumed a droplet flow regime for void fraction greater than 0.95. However, in the University of Houston test an annular flow regime was formed even though the void fraction was greater than 0.95. RELAP5 was unable to recognize this annular flow regime, and thus predicted a total upflow of water even at the small air flow rate of 50 lb/hr. A change in the RELAP5/MOD1 flow regime map at high void fraction is clearly needed. It is our understanding that such a change has been made in the newer version of RELAP5.

The differences between the TRAC-PF1 and TRAC-BD1 results are, of course, due to the different interfacial shear and entrainment correlations used in these codes. TRAC-PF1 predicts an earlier entrainment inception point and a higher rate of entrainment than the TRAC-BD1 code. This is the main reason why the TRAC-PF1 liquid downflow rate is lower than that predicted by the TRAC-BD1 code. It should be mentioned that in the University of Houston tests, the liquid upflow was initiated by the droplet entrainment from the falling liquid film. Thus the entrainment inception and rate correlations play a major role in the accurate prediction of the University of Houston CCFL data.

2.2.2 Dartmouth College Single Tube Tests

Figures 3 and 4 show the results of the computed liquid downflow rates for given air flow rates for the 0.0254m (1-inch) and 0.152m (6-inch) I.D. pipes, respectively. For the smaller diameter tube, the TRAC-PF1 results are in good agreement with the data. The code also predicted a dumping behavior for an air flow rate less than 0.005 kg/s ($\sqrt{j^*_f} = 0.241$), which is closer to the experimental conditions. TRAC-BD1 was also applied to this test, but it predicted dumping at much higher air flow rates. However, it did compute a stable countercurrent flow at higher air flow rates and the liquid downflow rates were overpredicted. This behavior of the TRAC-BD1 solution indicates that the interfacial shear stress used in the code is lower than the actual. It is worth mentioning that the TRAC-BD1 interfacial shear stress is close to the Wallis correlation [8] whereas TRAC-PF1 uses the Dukler correlation [9]. Also, there was very little entrainment in the Dartmouth College tests. Therefore, unlike the University of Houston tests, the Dartmouth College tests are more appropriate for assessing the interfacial shear stress correlations in a counter-current flow situation.

Many attempts were made to simulate the above tests with RELAP5/MOD1. However, the code results were so unstable that no useful results were obtained.

Figure 4 shows the comparison between the predicted liquid downflow rates and the data for various air injection rates for the 0.152m (6-inch) I.D. pipe. TRAC-BD1 predicted qualitatively correct behavior but in most cases overpredicted the liquid downflow rate. This is consistent with TRAC-BD1 results for the 1-inch I.D. pipe tests. TRAC-PF1, on the other hand, predicted an anomalous behavior in the range of air flow rates of 0.191 kg/s ($\sqrt{j^*_g} =$ 0.47) to 0.103 kg/s ($\sqrt{j^*_g} = 0.36$). The computed liquid filling rate decreased with decreasing air flow rate which is incorrect. A discontinuity in the Dukler's interfacial shear correlation has caused this anomalous behavior. However, the code predicted correct behavior for air flow rates below 0.103 kg/s. As in the other cases, RELAP5/MOD1 predictions for these tests were very poor.

2.2.3 Dartmouth College Parallel Tube Test

For this test, only the TRAC-BD1 code produced some useful results. In spite of several attempts, TRAC-PF1 did not produce any useful results, and the RELAP5/MOD1 code was not applied to this test because of its poor prediction of the single tube tests as discussed before.

Figure 5 shows the TRAC-BD1 results and the measured ΔP^* as a function of total j^*_g. The alphabets A-B-C-D-E represent the experimental path as the air flow rate was decreased in steps, whereas the numbers 1-2-3-4-5 denote the TRAC-BD1 results. For j^*_g greater than approximately 1.0, the code prediction is in close agreement with the data (see Paths A-B and 1-2). This was expected since in this region only air flowed through all the pipes and no water was able to flow down.

As the air flow rate was decreased further, i.e., $j^*_g < 1.0$, water started to flow down through one of the pipes while only air continued to flow up through two pipes. In the experiment, there was two-phase counter-current annular flow in one pipe and single-phase air upflow in two pipes. This corresponds to Point C in Figure 5. Notice that the non-dimensional pressure drop ΔP^* increased as the flow pattern changed from Point B to C. A change in flow pattern was also observed in the calculation (Point 2 to 3). However, instead of having one pipe in the annular flow regime, TRAC-BD1 calculated the pipe to be in a low-void ($\alpha \approx 5\%$) two-phase downflow regime and the other two pipes in the single-phase air upflow regime. This resulted in higher air flow rates through the air-filled pipes and caused higher ΔP^* across the parallel tubes (compare Point 3 with C). As the total air flow rate was decreased further, the calculated P^* started to decrease as it should be (Path 3-4). However, when the total j^*_g became lower than approximately 0.7, another pipe switched to the low-void two-phase flow regime and air was flowing up only through one pipe. This resulted in a sharp increase in the calculated value of ΔP^* (see Path 4 to 5), which was in contradiction with the experimental path D-E. Calculations could not be continued below j^*_g of approximately 0.5 because of code failure in the water property routine.

In short, some qualitative aspects of the experiment were predicted by TRAC-BD1. However, there were significant disagreements between the code prediction and the experimental data regarding ΔP^* and flow pattern below the total j^*_g of approximately 1.0 when water starts to flow down through one or more tubes. The main reason for this discrepancy is because the code uses a Wallis-type correlation for the annular flow regime which increases the interfacial shear as water starts to flow down. This tends to increase the ΔP^* and reduce the air flow rate through that tube. The calculation eventually stabilizes when the tube becomes almost water-filled and a very low-void two-phase mixture flows down. As a result, the air flow rate through the other two tubes increases significantly ($\sim 50\%$) and the total ΔP^* across the tubes jumps appreciably (from Point 2 to 3) in Figure 5. Therefore, it is clear that the interfacial shear package used in the code has to be modified in order to better represent the multi-tube CCFL phenomenon.

3. ORNL POST-CHF TEST SIMULATION

3.1 Test Description

A series of high pressure and high temperature steady-state experiments [10] were conducted with water flowing upward through an 8x8 rod bundle with rod diameter and rod pitch typical of PWRs with 17x17 fuel assemblies. There were four unheated rods in the bundle and the axial and radial power profiles were uniform.

Subcooled water was introduced into the lower plenum at prescribed rates. Sufficiently high electrical power was applied to the bundle so that transition to CHF occurs somewhere in the upper half of the bundle. Rod surface temperatures were measured at 30 axial locations in different groups of rods at each axial level.

Only one test, namely Run No. 3.07.9H, was simulated with TRAC-PF1, TRAC-BD1 and RELAP5/MOD1 codes. The test conditions for this run were as follows:

System pressure:	88.9 bar
Bundle power:	2.733 MW
Inlet water velocity:	0.3264 m/s
Inlet water temperature:	537.3°K (~40°K subcooling)

3.2 Comparison of Code Predictions with Data

Figure 6 shows the comparison between the experimental values of rod surface temperature (averaged over a number of rods) and the code predictions. It can be seen that TRAC-BD1 yielded the best results including the correct CHF location and the subsequent temperature rise in the post-CHF region. TRAC-PF1 and RELAP5/MOD1, on the other hand, predicted an early CHF and thus could not satisfactorily predict the subsequent temperature rise. It should be noted that these three codes use three different CHF correlations. TRAC-PF1 uses the Biasi local correlation, TRAC-BD1 uses the Biasi critical quality-boiling length correlation and RELAP5/MOD1 uses the modified Zuber correlation for the low flow rate corresponding to this particular ORNL test. Thus, different predictions for the CHF location are not surprising.

It should also be noted that at low flow rates, significant vapor superheating develops downstream of the CHF location. This causes the rod surface temperature to continuously increase downstream of the CHF location as shown in Figure 6. TRAC-BD1 and TRAC-PF1 capture this vapor superheating phenomenon quite well. However, RELAP5/MOD1 does not predict any vapor superheating until all the droplets in the post-CHF region is completely evaporated. This explains why the RELAP5 rod surface temperature decreases in the post-CHF region. Clearly, the RELAP5/MOD1 heat transfer package including the nonequilibrium phase change rate in the post-CHF regime needs improvement.

4. SUMMARY OF RESULTS

4.1 Critical Flow

Both TRAC-PF1 (Version 7.0) and RELAP5/MOD1 (Cycle 14) tend to underpredict the subcooled critical flow rate. Although the RELAP5 critical flow rate was in better agreement with the Marviken Test 24 data, neither RELAP5 nor TRAC-PF1 could satisfactorily predict both the break flow rate and the vessel inside pressure. Further improvement of the subcooled critical flow model is recommended for both codes. (See References 1 and 2 for details.)

4.2 CCFL

For the single-tube CCFL tests, TRAC-PF1 and TRAC-BD1 yielded much better results than RELAP5/MOD1. However, TRAC-BD1 tends to overpredict the liquid downflow rate for a given gas flow rate, and TRAC-PF1 sometimes predicted anomalous results (e.g., decreasing liquid downflow rate with decreasing gas flow rate for the Dartmouth College 6-inch tube test).

For the Dartmouth parallel tube test, only TRAC-BD1 predicted qualitatively reasonable results. TRAC-PF1 was unable to produce any stable result, and RELAP5/MOD1 was not applied to this test because of its poor prediction of the single tube tests.

4.3 Level Swell

TRAC-PF1 tends to overpredict the level swell rate and the void fraction below the mixture level, although it predicts the depressurization rate quite well. Higher interfacial shear in the bubbly and bubbly-slug regimes seems to be the reason.

RELAP5/MOD1, on the other hand, tends to underpredict the level swell rate and exhibits some irregularities in the axial void fraction profile. Some errors or lack of smoothing in the interfacial shear package could be the reason. (See References 1, 2 and 4 for details.)

4.4 Steam Generator Thermal Performance

For the B&W IEOTSG test, both TRAC-PF1 and RELAP5/MOD1 yielded reasonable average results, although the latter showed some numerical instabilities. Manual control of maximum time step is necessary to avoid these instabilities.

For the B&W OTSG test, TRAC-PF1 underpredicted the exit steam flow rate during a loss-of-feedwater transient. This was caused by the lower initial water inventory due to the lower rate of aspirator steam condensation. An increase in the condensation rate improved the TRAC-PF1 results. For the same test, RELAP5/MOD1 yielded a correct trend for the steam flow rate and primary exit temperature. However, the steam temperature was underpredicted by RELAP5/MOD1. (See References 1 and 2 for details.)

For the FLECHT-SEASET U-tube steam generator tests, both TRAC-PF1 and RELAP5/MOD1 codes overpredicted the secondary-to-primary heat transfer rate. One of the main reasons for this discrepancy seems to be the higher interfacial heat transfer rate in the droplet flow regime in both codes, particularly in RELAP5/MOD1 which did not produce any steam superheat until all the droplets were evaporated. There were also some numerical instabilities in RELAP5/MOD1 which disappeared when the calculations were repeated with manually controlled time step. (See References 1, 2 and 3 for details.)

4.5 Natural Circulation

Both TRAC-PF1 and RELAP5/MOD1 overpredicted the flow rates for the FRIGG-Loop natural circulation tests. However, slightly increased values of wall friction factors and/or form losses would yield reasonable agreement with the data.

The CHF correlations used in both codes, i.e., the Biasi and the W-3 correlations, were unable to predict the CHF condition in the FRIGG test. However, the RELAP4/MOD7 CHF correlation predicted the same condition quite well. (See References 1 and 2 for details.)

4.6 Post-CHF Heat Transfer

TRAC-BD1 (Version 12.0) produced the best overall result for a steady-state post-CHF test conducted at ORNL. It predicted the correct CHF location and correct trend for the rod surface temperature. TRAC-PF1 and RELAP5/MOD1, on the other hand, predicted an early CHF and the RELAP5 prediction of rod surface temperature was poor. Improvements in the CHF correlation and the post-CHF heat transfer models are recommended for both the TRAC-PF1 and RELAP5/MOD1 codes.

5. OVERALL CONCLUSIONS

The following overall conclusions can be drawn based on the code assessment activity at BNL:

a) For the CCFL and post-CHF tests, TRAC-BD1 provides the best overall results. However, the TRAC-BD1 interfacial shear package for the counter-current annular flow regime should be further improved for better prediction of CCFL phenomenon.

b) Between the TRAC-PF1 and RELAP5/MOD1 codes, the latter needs more improvements particularly in the areas of:

   - CCFL
   - Level swell
   - CHF correlation and post-CHF heat transfer
   - Numerical stability

c) The TRAC-PWR series of codes, i.e., TRAC-P1A, TRAC-PD2 and TRAC-PF1, have gradually improved. However, there is still room for improvement in almost all categories of tests/phenomena attempted at BNL.

It is our understanding that both TRAC-PF1 and RELAP5/MOD1 codes have been improved significantly so that the newer versions of these codes, i.e., TRAC-PF1/MOD1 and RELAP5/MOD2, should produce better results.

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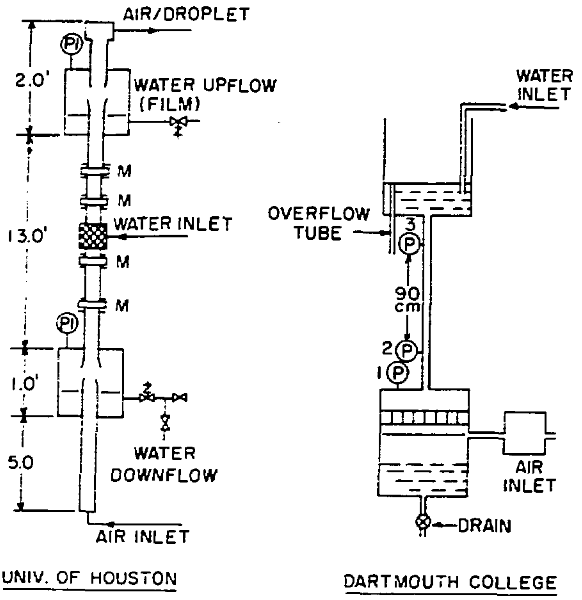

Figure 1. Schematic of the University of Houston and Dartmouth College Single Tube Test Facilities.

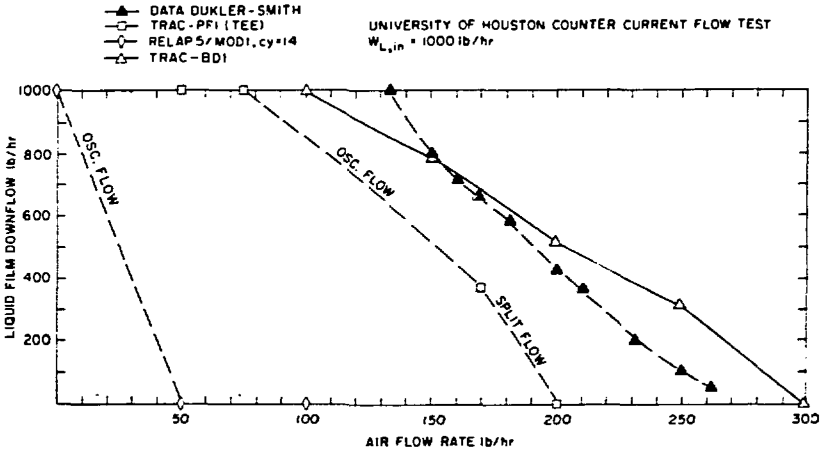

Figure 2. Comparison between the Experimental Data and Code Predictions for the University of Houston Test with Water Feed Rate of 1000 lb/hr.

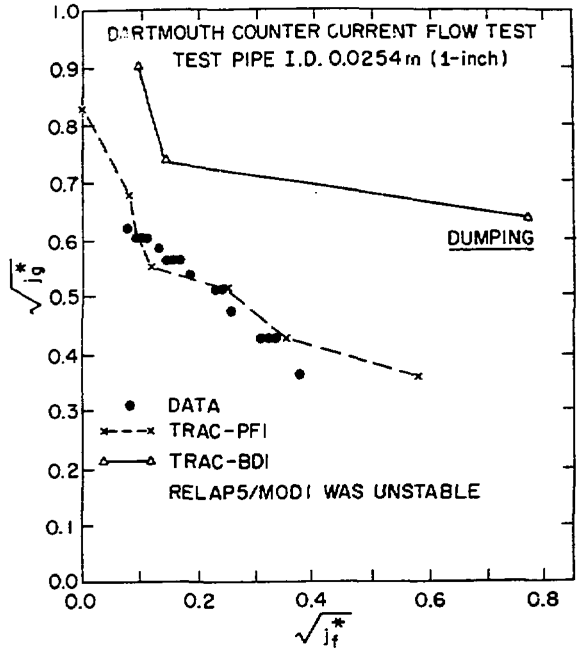

Figure 3. Comparison between the Experimental Data and Code Predictions for the Dartmouth College 1-Inch I.D. Tube Test.

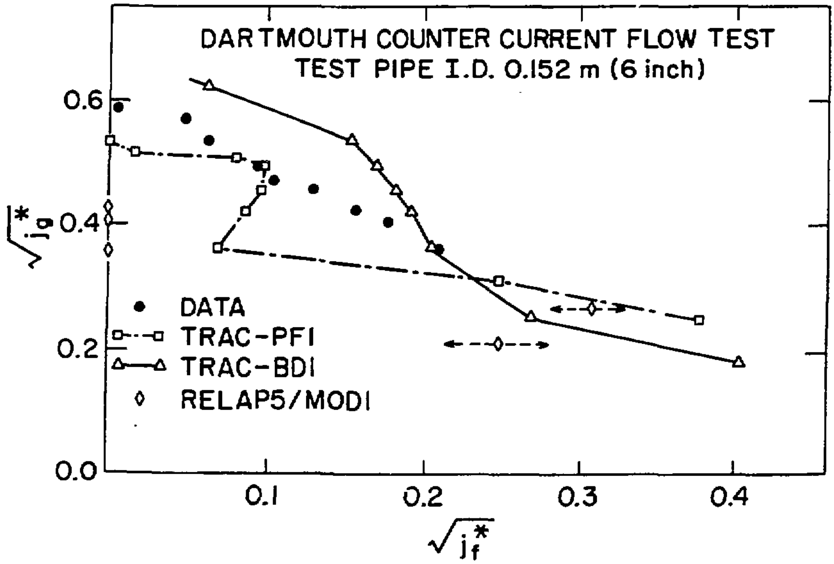

Figure 4. Comparison between the Experimental Data and Code Predictions for the Dartmouth College 6-Inch I.D. Tube Test.

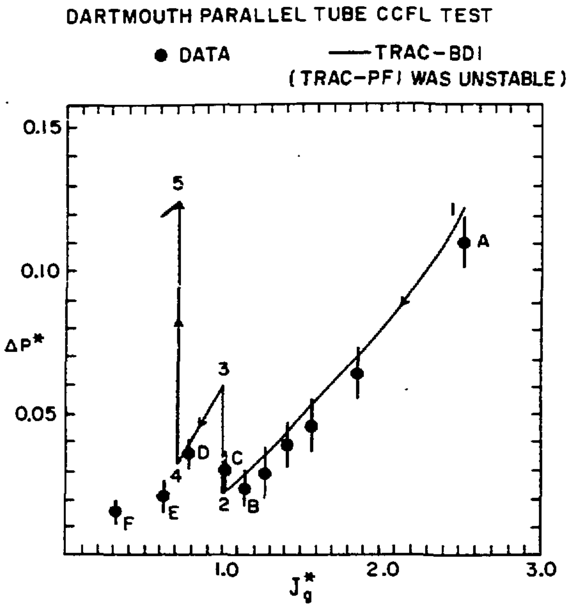

Figure 5. Comparison between the Experimental Data and TRAC-BD1 Prediction for the Dartmouth College Parallel Tube Test.

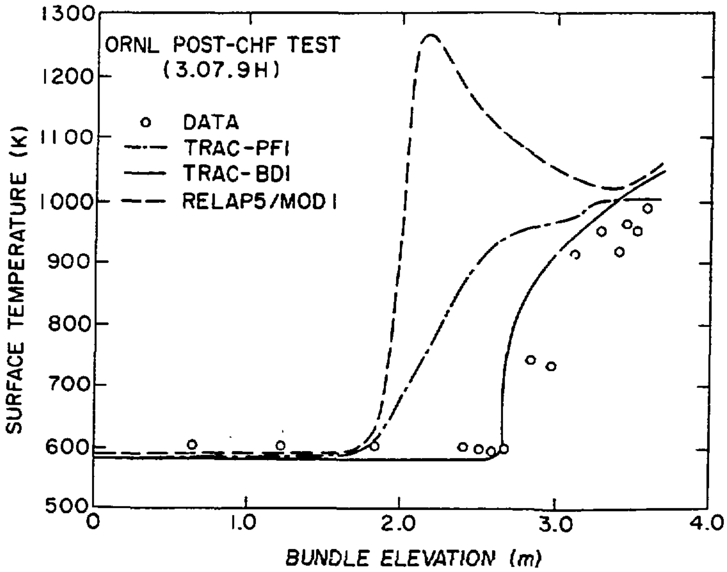

Figure 6. Comparison between the Experimental Data and Code Predictions for an ORNL Steady-State Post-CHF Test.