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THE RELAP5/MOD3 COMPUTER CODE

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ABSTRACT

RELAP5/MOD3 is a pressurized water reactor (PWR) system analysis code being developed jointly by the U. S. Nuclear Regulatory Commission (USNRC) and a consortium consisting of several of the countries and domestic organizations that are members of the International Code Assessment and Applications Program (ICAP). The mission of the RELAP5/MOD3 code development program is to develop a code version suitable for the analysis of all transients and postulated accidents in PWR systems including both large and small break loss of coolant accidents (LOCA's) as well as the full range of operational transients. Although the emphasis of the RELAP5/MOD3 development is on large break LOCA, improvements to existing code models, based on the results of assessments against small break LOCA and operational transient test data, are also being made. This paper discusses the new code models as well as improvements to existing models.

I. Background

Prior to the formation of the RELAP5/MOD3 improvement consortium, the members of the ICAP program performed assessment calculations using "frozen" versions of the RELAP5/MOD2 computer program. The results of these assessment calculations were sent to the Idaho National Engineering Laboratory (INEL) for the correction of code errors and the evaluation of code deficiencies. In accordance with the rules of the ICAP program, code errors were corrected with the issuance of a new "frozen" code version, while code deficiencies were logged and remained uncorrected in the several "frozen" versions of RELAP5/MOD2. As the list of code deficiencies grew and with the desire of the USNRC and ICAP program members to extend the mission of the RELAP5/MOD2 code to include the analysis of large break LOCA's , the RELAP5/MOD3 code development program was developed and initiated in the spring of 1988. Table I is a list of the phenomena and code models that are being addressed by the RELAP5/MOD3 code development program. In contrast to the ICAP program in which the participants only performed assessment calculations, the RELAP5/MOD3 code development consortium members have developed, coded and tested improvements to the RELAP5/MOD3 code and will perform developmental assessment calculations using an interim version of RELAP5/MOD3 containing all of the planned improvements. Depending upon the particular circumstances, the FORTRAN coding and associated documentation were sent to the INEL for installation into RELAP5/MOD3 by personnel at INEL or the individual model developer came to the INEL to install and test his new code model. In addition to listing the areas in which code improvements were made, Table I also shows the countries and/or organizations that submitted code improvements developed by their own staff members. The models developed by the participating ICAP members and the code improvements developed by personnel at the INEL were assembled into a single interim version of RELAP5/MOD3 which was released to the ICAP code development consortium members on June 1, 1989. The code is currently undergoing a period of developmental assessment which is being performed at the INEL and by members of the ICAP consortium. Current plans are to finish the developmental assessment and release a "frozen" version of RELAP5/MOD3 by September 30, 1989. This code will then be the code upon which future code assessment activities of the full ICAP program will be based.

The areas for code improvement which are listed in Table I were chosen based on the results of the assessments performed using RELAP5/MOD2 or as a result of the application of the TRAC-PF1 and TRAC-PF1/MOD1 codes in the USNRC's 2D/3D experimental program. In addition to the improvements of code simulation capability through the model improvements listed in Table I, several other tasks were included in the RELAP5/MOD3 code improvement plan. These areas include code speedup through vectorization for the CRAY computer and enhanced code portability. Code portability was enhanced through the conversion of the FORTRAN coding to adhere to the FORTRAN 77 standard as much as is practicable. The converted code was tested at INEL on CRAY X-MP(UNICOS), CYBER (NOS/VE), IBM 3090 (MVS), and VAX (ULTRIX) computers by executing a suite of ten test cases. The results of these cases were compared to insure the proper execution of RELAP5/MOD3 on each of these systems. Finally, the development of RELAP5/MOD3 has been conducted under a quality assurance plan that allows the complete documentation of each line of coding added to the program, including the person adding the change, when the change was added to the code and the reason for the change.

II. Model Improvements

Table I lists the areas of effort for the RELAP5/MOD3 development program. Some of the tasks listed in Table I represent improvements to existing models such as the vapor pullthru, liquid entrainment task while others represent development and/or implementation of new models such as the counter-current flow limiting model or ECCS mixing and condensation model.

Each of the tasks will be discussed briefly in the following sections along with sample results of the assessment of the performance of individual models, where appropriate.

A. Counter-Current Flow Limiting

Counter-current flow limiting (CCFL) is an important phenomena which can inhibit the downward penetration of liquid due to the upflow of steam. RELAP5/MOD2 has been shown to compute the correct downflow of liquid for a long straight vertical tube when the so called " special treatments" are removed from the interfacial friction model [1] but cannot correctly compute the counter current flow through geometrically complex passages such as an upper tieplate. For this, a counter-current flow limiting model in the form of a counter current flow limiting correlation based on the actual geometry is needed. The Bankoff CCFL correlation [2] has been implemented in RELAP5/MOD3 and can be activated by the user at each junction in the system model. The correlation as implemented in RELAP5/MOD3 replaces the difference momentum equation whenever the counter-current flow limit is exceeded. Figure 1 shows the results of a simulation of an air water CCFL test performed by Dukler. The test consists of a series of steady states at various air flow rates in which the downflow rate of liquid was measured. Shown in Figure 1 is the experimentally measured data (circles), a RELAP5/MOD3 simulation without the CCFL model (crosses) and a RELAP5/MOD3 simulation with the CCFL model activated (squares). The figure shows that the regular RELAP5/MOD3 drag model allows too much liquid downflow for a given air upflow rate while the simulation using the CCFL model accurately reproduces the measured data.

B. Interfacial Friction in the Bubbly-Slug Flow Regime

Several of the ICAP assessments have pointed out deficiencies in the interfacial friction model in RELAP5/MOD2 in the bubbly slug flow regime for rod bundle geometry and in large diameter vertical pipes. As an interim measure the Bestion [3] correlation for rod bundle geometry as recommended ay Analytis [4] of the Paul Scherrer Institute in Switzerland was implemented in a preliminary version of RELAP5/MOD3 to address the rod bundle portion of this deficiency. However, a new interfacial friction model for all types of geometry (rod bundles, small tubes, and large pipes) was developed by the Central Electricity Generating Board (CEGB) of the United Kingdom for the bubbly-slug flow regime in vertical flow passages which supersedes the Bestion correlation for rod bundle geometry and addresses the issue of slug flow in large vertical pipes. The recommended correlations are the EPRI void correlation for rod bundles and high mass fluxes (G >100 kg/m^2s) in pipes and a combination of the Zuber-Findley slug flow and Ishii churn-turbulent flow correlations for low mass fluxes (G <50kg/m^2s) in pipes. This model has been assessed against a variety of test data [5].

Figure 2 shows the steady state axial void profile in the simulation of THTF test 3.09.10K. The figure shows the maximum and minimum values of the measured data as well as two simulations using RELAP5/MOD2 and a modified version of RELAP5/MOD2 containing the new interfacial drag model. This figure shows that the new interfacial drag model significantly improves the prediction of the void profile in this rod bundle test. The CEGB proposed other changes to the RELAP5/MOD2 interfacial drag model for the bubbly-slug to annular-mist flow regime transition criterion for vertical flows which were implemented in RELAP5/MOD3 after testing.

C. Vapor Pullthru, Liquid Entrainment in Horizontal Pipes

One of the significant deficiencies found in the RELAP5/MOD2 code concerns the fluid quality convected through a small break situated on the side, top or bottom of a large horizontal pipe. Depending upon the stratified fluid level in the pipe relative to the break elevation, the flow can be either single phase liquid, a two phase mixture or single phase vapor. Correct computation of the fluid state existing through the break has been shown through ICAP assessment to be extremely important in the simulations of small break LOCA'S. The United Kingdom Atomic Energy Authority has developed a model of this phenomena [6] for incorporation into the RELAP5/MOD3 computer code based on the work of Smoglie at KfK [7] and Schrock at the University of California [8]. Figure 3 shows a comparison of the fluid quality convected through a break on the side of a large horizontal pipe as computed by a stand alone code compared to a large amount of measured data. The abscissa shows the normalized height (h_b is the height at which vapor pullthrough or liquid entrainment begins) of the stratified level relative to the break locations. The figure shows that the model gives good agreement with the measured data. Similar results are obtained for break locations on the top and bottom of the horizontal pipe.

D. Critical Heat Flux

RELAP5/MOD2 uses the Biasi critical heat flux correlation in the wall heat transfer package to initiate the transition from nucleate boiling to film boiling on a heated surface. Assessment has shown that the Biasi correlation overpredicts the maximum nucleate boiling heat flux in rod bundles by up to 60%. There are several recently developed critical heat flux correlations for rod bundles which are based on large data tables for tubes with modifying factors for such things as rod bundle geometry, non uniform heat flux, bundle spacer effects, etc. The table with the widest range of applicability was developed by Groeneveld [9]. After some testing against data in the USNRC Data Bank at the INEL using a stand alone driver code, this tabular correlation was chosen for implementation in RELAP5/MOD3. Figure 4 show the assessment of the Groeneveld correlation against Bennett test 5294, as well as the performance of the Biasi correlation used in RELAP5/MOD2. Figure 4 shows the axial wall temperature profile at a mass flux of 1953 kg/m^{2}s. The Groeneveld correlation improves the prediction of the CHF location compared to the Biasi correlation for this medium mass flux test as well as for a wide range of tests at other mass fluxes.

E. Interfacial Condensation on Subcooled ECCS Liquid in Horizontal Pipes

One of the more difficult processes to model in a LOCA is the interfacial condensation in large horizontal pipes due to the injection of subcooled ECCS liquid. Assessment of RELAP5/MOD2 using Upper Plenum Test Facility (UPTF) data has shown a large underprediction of the depressurization due to the condensation of steam on the jet of subcooled ECCS liquid. A new component called the ECCMIX component [10] was developed for RELAP5/MOD3 for the modelling of the mixing of the subcooled ECCS liquid and the resulting interfacial condensation. The model utilizes the flow regime map of Tandon et. al., [11] with the addition of a bubbly flow regime at low void fractions. The flow regimes in the new component model include bubbly, wavy and plug, slug, annular-mist, and dispersed droplet flow. Appropriate correlations for the interfacial area density and interfacial heat transfer coefficients in each flow regime were obtained from the heat transfer literature. The model also includes the momentum mixing of the high speed liquid jet with the main flow in the horizontal pipe. Figure 5 shows the results of the assessment of the new ECCMIX component using data from UPTF test 5A. Figure 5 shows that RELAP5/MOD2 underpredicts the depressurization at 25 sec in the test due to the injection of subcooled ECCS liquid while RELAP5/MOD3 with the new ECCMIX component accurately predicts this depressurization.

F. Horizontal Stratification Inception Criterion.

Assessment of RELAP5/MOD2 using void fraction data in horizontal pipes from the Two Phase Test Facility (TPTF) at Japan Atomic Energy Research Institute (JAERI) has shown that the Taitel-Dukler horizontal stratification inception criterion used in RELAP5/MOD2 is inadequate for the prediction of the flow regime transition between horizontally stratified flow and dispersed flow. The Taitel-Dukler correlation was developed assuming negligible liquid flow in the horizontal pipe while the assessments were performed with significant liquid flow. JAERI [12] recommended that the Taitel-Dukler correlation be modified to test the relative velocity between the phases rather than the vapor velocity against the transition criterion to capture the effect of the liquid flow. Figure 6 shows a simulation of one of the TPTF tests in which the void profile along a horizontal pipe discharging into a large vessel was measured using gamma densitometers. The figure shows that the prediction of the void profile is significantly improved by the implementation of the new horizontal stratification inception criterion except at the discharge end of the pipe (i.e. Volume 15) which is attached to the large vessel. The overprediction of the void fraction at the end of the pipe is due to the way in which the interfacial friction forces are calculated in RELAP5/MOD2. In RELAP5/MOD2 the interfacial friction force is calculated at the center of each volume and the value of the interfacial friction force in the junction connecting two volumes is a volume averaged quantity using the volume centered values in the two volume between which the junction is connected. This formulation for the interfacial friction is inappropriate when the flow regimes in the two volumes are significantly different. The volume averaging leads to a value of interfacial friction which is not representative of the interfacial friction in either of the two flow regimes. RELAP5/MOD3 has been modified to use the fluid conditions in the junction for the calculation of the interfacial friction so that the interfacial friction forces in the junction are consistent with the state of the fluid being connected thru it. The third curve in Figure 6 shows that the prediction of the void profile near the discharge end of the pipe has been significantly improved by the change in the formulation of the interfacial friction force for a junction.

G. Reflood Heat Transfer

RELAP5/MOD2 utilizes a "fine mesh" conduction solution for the computation of the fuel rod behavior during the reflood phase of a LOCA. A special set of wall heat transfer correlations appropriate for reflood conditions (i.e. low flow, low pressure) were used to improve the predictive behavior of the reflood process. Unfortunately, there were large discontinuities in the computed fuel rod temperatures when the reflood model was activated due to the large differences in the computed wall heat transfer coefficients. RELAP5/MOD3 has be modified to use a single set of wall heat transfer correlations for the complete transient while retaining the "fine mesh" option for reflood modeling. The performance of this modified reflood model is currently being assessed.

H. Vertical Stratification

Assessments of RELAP5/MOD2 showed that there were several problems with the vertical stratification model which sometimes lead to excess activation of the water packing logic. Both the vertical stratification and water packing models were placed under user control so that they could be deactivated by the user thru input. The vertical stratification inception logic was modified to be consistent with the inception logic developed for the TRAC-BWR code. The logic which deactivates the vertical stratification model as the volume fills or empties of liquid was also improved to reduce the interaction between the vertical stratification model and the water packing logic. The water packing logic was extended to horizontal volume because condensation induced water packing had been observed in RELAP5/MOD2.

I. Metal-Water Reaction

The Cathcart-Powel zirconium-water reaction model has been implemented to model the exothermic energy production on the surface of zirconium cladding material at high temperature. This model is also activated on the inner surface of the fuel cladding if the clad has burst due to internal pressure at high temperature.

J. Fuel Mechanical Model

RELAP5/MOD2 has a gap conductance model which computes the transient gap conductance using a simplified model based on the FRAP-T6 fuel behavior code. Differential thermal expansion between clad and full material was considered but clad balloning due to plastic deformation was not considered. A simple plastic strain model has been added to RELAP5/MOD3 as well as a clad burst criterion. The plastic strain and burst criterion are taken from NUREG-0630 [13]. A simple radiation heat transfer term has also been added to the gap conductance model. Once the clad had burst, the metal water reaction model is activated on the inside clad surface.

K. Radiation Heat Transfer Model

A radiation heat transfer model has been implemented in RELAP5/MOD3. Multiple radiation enclosures are allowed and are defined thru user input. Each RELAP5 heat structure may be include in only one radiation enclosure and the fluid within the enclosure is considered optically transparent (i.e. can't absorb or emit radiation at the relevant wavelengths.)

L. Non-Condensible Gas Modeling

Several problems with the modeling of noncondensible gas using RELAP5/MOD2 were reported. The code often failed when the accumulators emptied discharging noncondensible gas into the system and the code behavior at high noncondensible gas qualities was erratic. The code logic which computes the partial pressure of noncondensible gas from the noncondensible gas quality was modified to make it more robust and the computation of the time advancement matrix elements was modified to allow for the presence of very small amounts of steam in an almost pure noncondensible gas. Small amounts of steam cause a problem because the saturation temperature based on the steam partial pressure can be below the triple point temperature which leads to problems with the steam table computations. Similar problems with the matrix elements and steam tables occur when trying to exceed the critical point pressure or temperature. Fixes have also been implemented to allow the code to exceed the critical point.

M. Downcomer Penetration, ECCS Bypass, and Upper Plenum Deentrainment

Problems were encountered in the application of the USNRC's TRAC-PF1/MOD1 code to the full scale UPTF downcomer penetration and upper plenum deentrainment data and since the modeling of the interfacial friction in RELAP5/MOD2 and TRAC-PF1/MOD1 were somewhat similar, the downcomer penetration, ECCS bypass, and upper plenum deentrainment capabilities of RELAP5/MOD3 were included as code capabilities to be investigated and improved as needed. This task was delayed until all of the code modifications for interfacial friction were implemented and has been undertaken as part of the developmental assessment currently underway.

III. Summary

In summary, an ambitious program of code development was undertaken under the sponsorship of the ICAP program to develop RELAP5/MOD3 for the simulation of all transients and accidents in PWR systems including both large and small break LOCA's. An interim version of RELAP5/MOD3 was released to the ICAP consortium members on June 1, 1989 and the code has been undergoing developmental assessment since that time. The developmental assessment is being performed by several of the ICAP members as well as at EG&G Idaho. Completion of RELAP5/MOD3 will provide a single code for the analysis of all phases of accidents and transients in PWR systems.

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Table I RELAP5/MOD3 Model Improvements

Counter Current And Flow Limiting

Interfacial Friction in Bubbly/Slug Flow Regime (Central Electricity Generating Board, UK)

Vapor Pullthru, Liquid Entrainment in Horizontal Pipes (UK Atomic Energy Authority)

Critical Heat Flux

Interfacial Condensation on Subcooled ECCS Liquid in Horizontal Pipes

Horizontal Stratification Inception Criterion (JAERI)

Reflood Heat Transfer (Paul Sherrer Instutute, Switzerland)

Vertical Stratification

Metal-Water Reaction (Studsvik, Sweden)

Fuel Mechanical Model (Studsvik, Sweden)

Radiation Heat Transfer Model (Studsvik, Sweden)

Non-Condensible Gas Modeling

Downcomer Penetration and ECCS Bypass

Upper Plenum De-entrainment

Figures

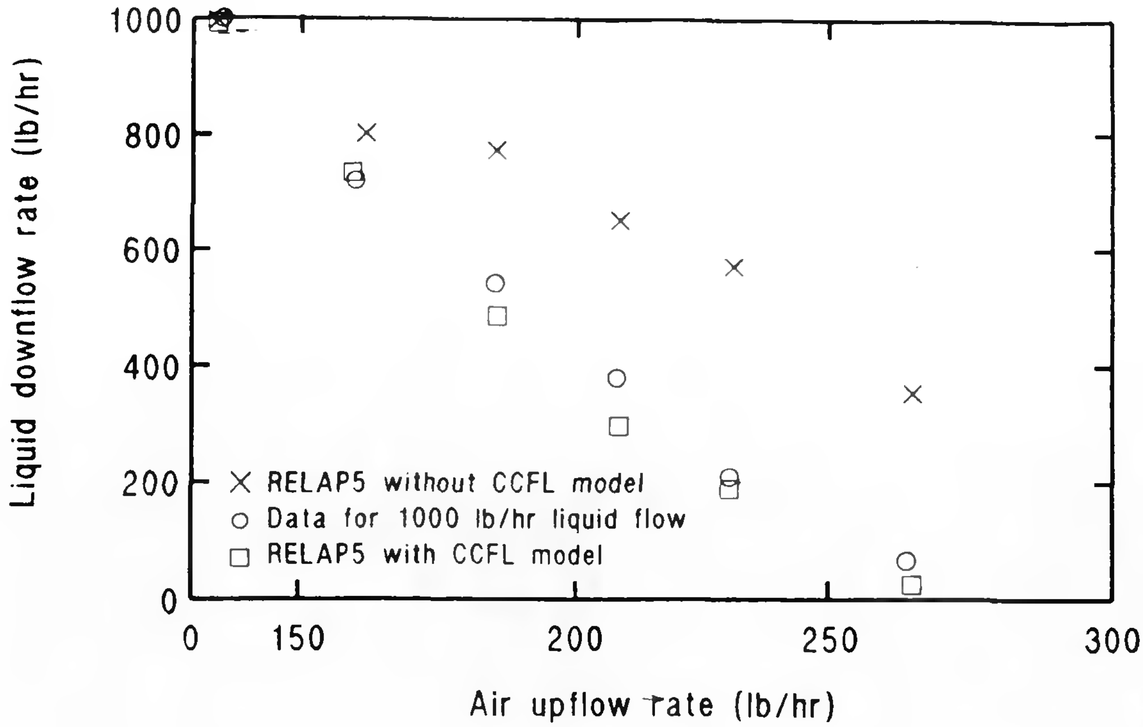

Figure 1. Results of Dukler Air-Water Test

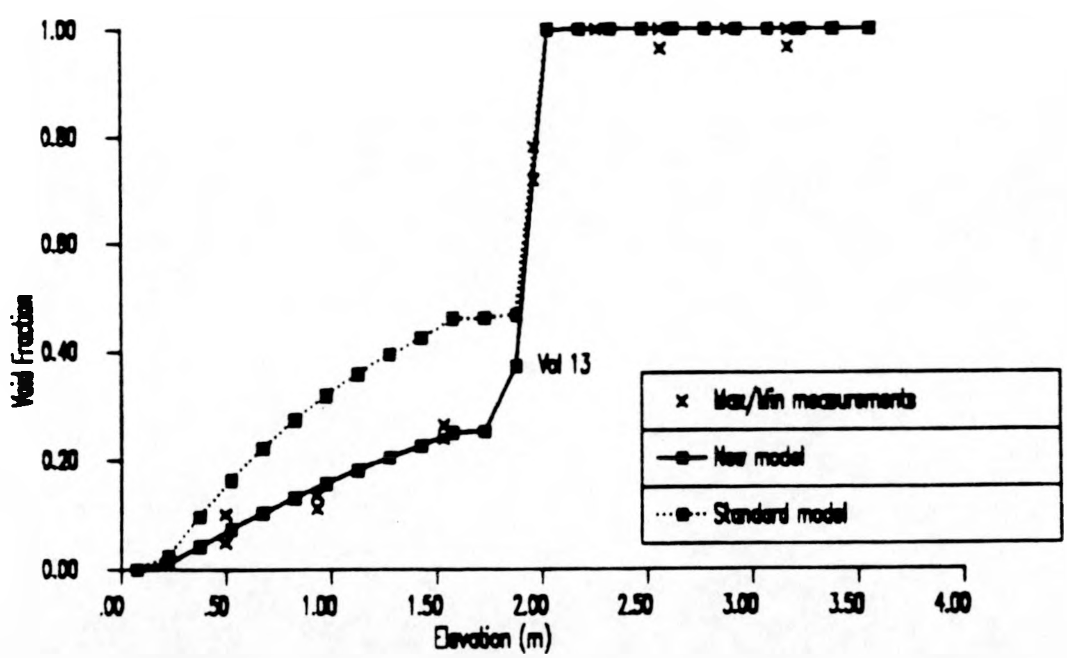

Figure 2. Axial Void Profile in THTF Test 3.09.10K

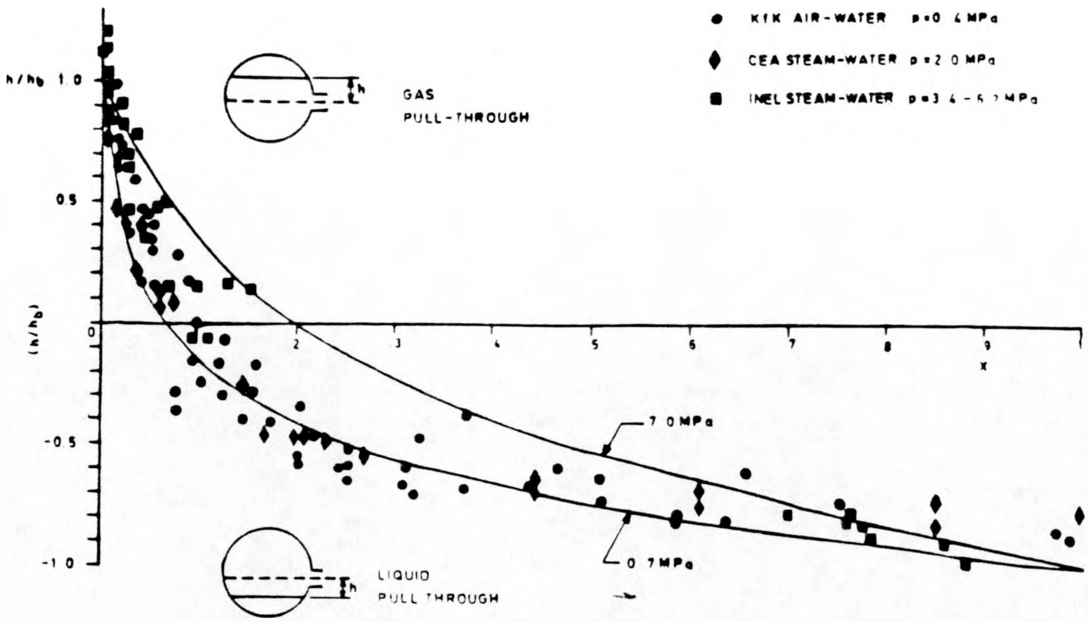

Figure 3. Convected Fluid Quality thru Side Break as Function of Normalized Stratified Liquid Level

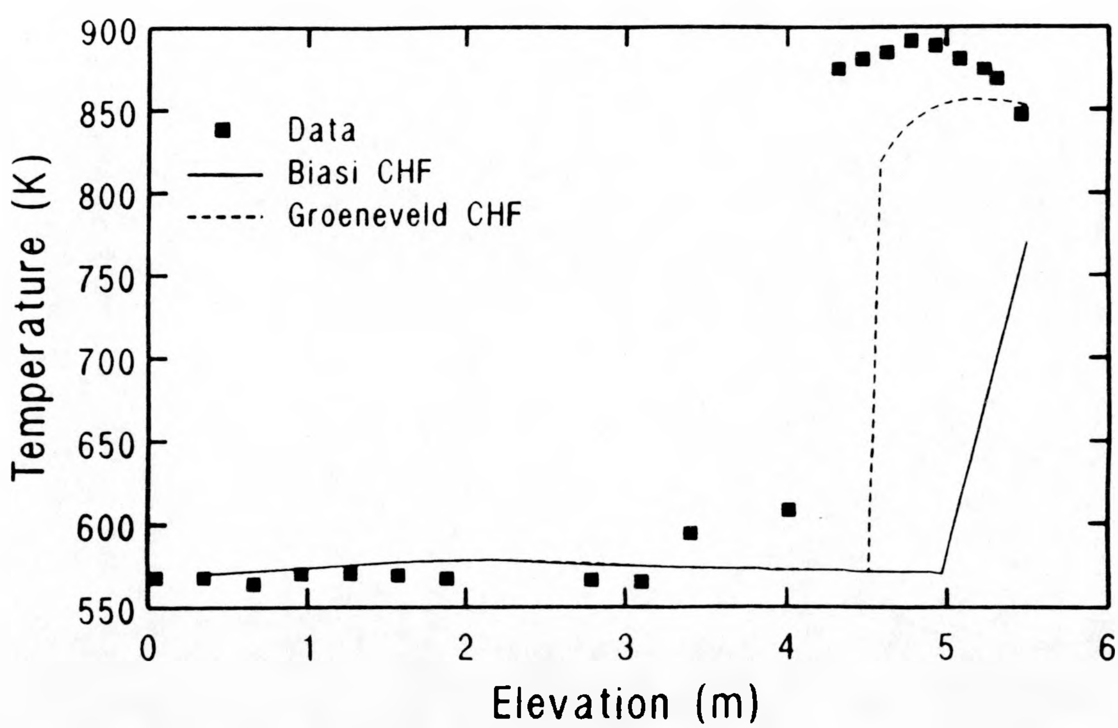

Figure 4. Axial Temperature Profile for Bennett Test 5294

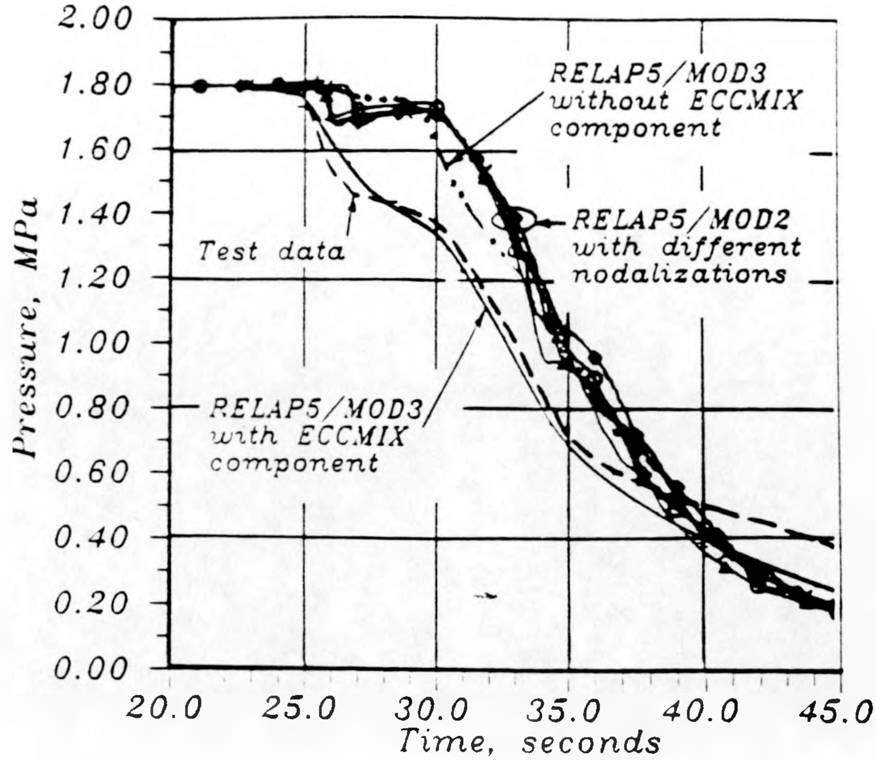

Figure 5. System Pressure in UPTF Test 5A

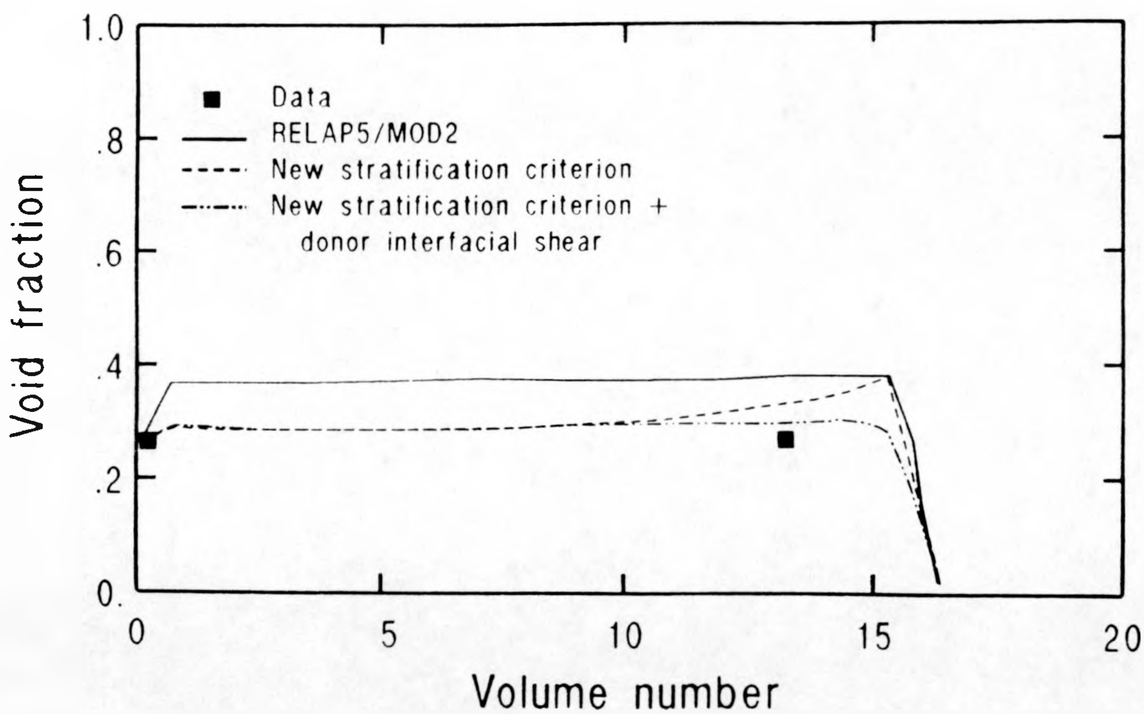

Figure 6. Axial Void Profile in TPTF High Flow Test