PROGRESS IN REALISTIC LOCA ANALYSIS

M. Y. Young, S. M. Bajorek, K. Ohkawa
Westinghouse Electric Corporation
P.O. Box 355
Pittsburgh, PA, USA
(412) 374-4875

INTRODUCTION

In 1988 the USNRC revised the ECCS rule contained in Appendix K and Section 50.46 of 10 CFR Part 50[1], which governs the analysis of the Loss Of Coolant Accident (LOCA). The revised regulation allows the use of realistic computer models to calculate the loss of coolant accident. In addition, the new regulation allows the use of high probability estimates of peak cladding temperature (PCT), rather than upper bound estimates.

Prior to this modification, the regulations were a prescriptive set of rules which defined what assumptions must be made about the plant initial conditions and how various physical processes should be modeled. The resulting analyses were highly conservative in their prediction of the performance of the ECCS, and placed tight constraints on core power distributions, ECCS set points and functional requirements, and surveillance and testing.

These restrictions, if relaxed, will allow for additional economy, flexibility, and in some cases, improved reliability and safety as well. For example, additional economy and operating flexibility can be achieved by implementing several available core and fuel rod designs to increase fuel discharge burnup and reduce neutron flux on the reactor vessel.

The benefits of application of best estimate methods to LOCA analyses have typically been associated with reductions in fuel costs, resulting from optimized fuel designs, or increased revenue from power upratings. Fuel cost savings are relatively easy to quantify, and have been estimated at several millions of dollars per cycle for an individual plant. Best estimate methods are also likely to contribute significantly to reductions in O&M costs, although these reductions are more difficult to quantify. Examples of O&M cost reductions are:

1) Delaying equipment replacement. With best estimate methods, LOCA is no longer a factor in limiting power levels for plants with high tube plugging levels or degraded safety injection systems. If other requirements for plant operation can be met, replacement of pumps and steam generators can be delayed several cycles, or permanently in some cases.

2) Extending fuel cycles. Aside from the obvious long term saving in fuel costs, extended cycles reduce the number of outages. The total annual savings resulting from extending fuel cycles from 12 to 18 months has been estimated at several million dollars per plant. Similar savings should result from extending cycles to 24 months, as long as maintenance and surveillance issues associated with these cycle lengths can be solved.

3) Reduced surveillance and simplified Technical Specifications. Best estimate methods are expected to show that several technical specifications can be relaxed or even eliminated without compromising plant safety. For example, the frequent surveillance of accumulator water levels and pressures may not be necessary if it can be shown that wide variations in these parameters do not significantly affect PCT.

4) Reduced fluence on the reactor vessel. Early implementation of low leakage loading patterns, which are made possible by the margin generated from best estimate methods, can save significant costs as plants approach the end of their current license, or if license extensions are sought, when assurance will be required that vessel integrity can be maintained.

5) Best estimate methods provide a wealth of information of the response of the plant to changes in plant conditions (sensitivity studies are a basic part of a best estimate methodology). This information can be used by the utility to perform timely, high quality safety evaluations to determine whether a plant change affects the margin of safety of the plant.

The benefits outlined above have prompted significant industry activity to develop methods which comply with the revised rule. Some recent work is described in the next section.

RECENT WORK IN REALISTIC LOCA ANALYSIS

Shortly after the rule change, the USNRC issued a regulatory guide[2] and a ECCS research compendium[3], and sponsored a program to develop a structured method for evaluating the uncertainties affecting the PCT for large break LOCA. The Code Scaling Applicability, and Uncertainty (CSAU) methodology was developed[4], and has been used by industry developers as a guide for their own applications. The structured method basically involves the following steps:

1) Select the LOCA transient (i.e. large or small break LOCA) and the computer code.

2) Assess the code, demonstrate its applicability, and estimate its bias and uncertainty relative to appropriate tests and relative to scaling.

3) Evaluate the overall PCT uncertainty, taking into account code uncertainty, reactor initial conditions, and accident boundary conditions.

The CSAU program developed methods for each of these steps. However the methodology was intended as a demonstration rather than a practical licensing application. Therefore, despite the extensive guidance provided by the USNRC, the application of the revised rule to operating PWR's remains a complex task. In practical terms, the following elements must be part of any best estimate evaluation model:

- Develop a best estimate computer code.
- Prepare a models and correlations document which describes the computer code in detail, and demonstrates its applicability.
- Perform "frozen" code verification and quantify code uncertainty.
- Develop an uncertainty methodology for use with the best estimate computer code.
- Estimate the 95 percent probability PCT with all uncertainties accounted for.
- Submit necessary documentation for USNRC review and approval.

Westinghouse and the Electric Power Research Institute (EPRI) have recently completed the development of a methodology to implement the revised Appendix K rule which incorporates the elements outlined above, and submitted this methodology to the NRC for review. Some basic results, lessons learned, and issues encountered during the implementation are the main topics of this paper and are discussed below.

WESTINGHOUSE /EPRI METHODOLOGY:

SELECTION OF THE COMPUTER CODE

Several codes are available today which contain most, if not all of the essential features required for a realistic analysis of the LOCA. These minimum required features are well known to the industry (a good summary is contained in the Reg Guide[2]). A key requirement is a full treatment of nonequilibrium two phase flow. Westinghouse selected the COBRA/TRAC[5] code as the base source code for best estimate LOCA, and added additional models. WCOBRA/TRAC combines two-fluid, three-field, multidimensional fluid equations used in the vessel with one-dimensional, drift-flux equations used in the loops to allow a complete and detailed simulation of a PWR. Westinghouse selected COBRA/TRAC for the following reasons:

a) The use of three-fields (vapor, continuous liquid, and entrained liquid) in the vessel allows realistic modeling of entrainment, de-entrainment, droplet flow, and liquid pooling.

b) The code is capable of modeling two and three dimensional flows in the vessel.

c) The channel noding approach in the vessel is extremely flexible and useful in differentiating between fuel assemblies under different upper plenum structures and in examining the thermal-hydraulic behavior in the highest power assembly.

d) Westinghouse had gained considerable experience in using and developing COBRA/TRAC during the FLECHT-SEASET program. Results of this program indicated that WCOBRA/TRAC could accurately predict reflood thermal-hydraulics.

e) In its review of state-of-the-art computer codes in the ECCS research compendium[3], the COBRA/TRAC code was found to satisfy the basic requirements of a best estimate thermal-hydraulic code.

WCOBRA/TRAC is particularly appropriate for this application because of its resolution of the liquid field into continuous and dispersed fields. Three mass and momentum equations are solved in the vessel in each of up to three dimensions, allowing the liquid and entrained liquid fields to flow with different velocities relative to the vapor field. This permits more mechanistic modeling of several LOCA related phenomena occurring inside the vessel, such as:

- Multidimensional flow phenomena
- Countercurrent flow of liquid films and drops
- Entrainment and de-entrainment
- Droplet flow

CODE ASSESSMENT

Computer programs that are used to realistically simulate the thermal-hydraulic response of a PWR to a postulated large break LOCA must be evaluated to demonstrate the adequacy of the two-phase models and to quantify the degree of uncertainty for the computational techniques. An important part of this evaluation is the computer code assessment that compares the results of simulations of relevant experiments to the measured data from experiments.

In order to obtain a meaningful estimate of the code uncertainty, the assessment must be comprehensive, simulating a wide variety of experimental facilities and test conditions. The assessment test matrix used for WCOBRA/TRAC is shown in Tables 1 to 3. The tables show the important LOCA phenomena, as identified by the CSAU study[4], and which tests were simulated to demonstrate the code's ability to predict those phenomena. For most phenomena, both a separate effects test and an integral effects test were simulated, in order to investigate if a dependence on scale existed in the calculations. In all, over 90 seperate simulations were carried out on 15 experimental facilities. Fifty-four of the simulations were for tests which generated a peak cladding temperature that could be used to determine the code overall bias and uncertainty. Figure 1 shows the comparison of predicted and measured PCTs for the reflood tests. Rod locations with temperatures within two standard deviations of the test peak temperature are shown, resulting in 2-4 points on the figure per simulation.

A fundamental requirement of the assessment under the CSAU guidelines is that the code version be "frozen" during implementation of the entire matrix. If, during the assessment, code performance is found to be unsatisfactory, improvements can be made, but the entire assessment matrix must be repeated. Tables 1 to 3 represent simulations performed with the same version of WCOBRA/TRAC, and do not include any of the earlier assessment studies performed on earlier versions.

The code uncertainty, which is derived from experiments, must be shown to be applicable to PWR simulations. To achieve this, strict one-to-one correspondence between the noding used in the experiment simulations and that used in the PWR simulation must be maintained. In the Westinghouse methodology, correspondence with axial cell lengths is maintained wherever possible between tests and PWR's.

Although the PCT is the key LOCA parameter, other parameters must be compared to assess the code predictive capability, and must be part of the code qualification document. Typical comparisons made were:

- Quench time
- Mass inventories in the system
- Vapor temperatures
- Loop flows and pressure drops
- Void fractions
- Counter-current flow limits (CCFL)

Finally, a scaling analysis must be performed. The objective of this analysis is to establish whether the code exhibits a bias with increasing scale in any of several key LOCA parameters. This scaling analysis was performed with WCOBRA/TRAC[4], and demonstrated that a scaling bias and uncertainty did not have to be applied for WCOBRA/TRAC.

Table 1. Blowdown LOCA Phenomena Assessment

LOCA PROCESS: / TEST SIMULATION	Number of Simulations	Fuel Stored Energy	Core Post-CHF	Core Rewet	Pressurizer	Pump Two-Phase Performance	Break Critical Flow	Loop Two-Phase Δp
Expert Ranking		9	7	8	7	9	9	7
Separate Effects Tests:								
G-1 Blowdown	6		✓	✓				
G-2 Blowdown	6		✓	✓				
ORNL Blowdown	3		✓	✓				
Marviken	16						✓	
Integral Effects Tests:								
LOFT	4	✓	✓	✓	✓	✓	✓	✓

Table 2. Refill LOCA Phenomena Assessment

LOCA PROCESS: / TEST SIMULATION	Number of Simulations	Core Post-CHF	Core Rewet	Cold Leg/Accumulator Condensation	Downcomer Entrainment	Downcomer Condensation	Downcomer 3D Flow	Lower Plenum Sweepout	Break Critical Flow	Loop Oscillations	Loop Flow Split
Expert Ranking		8	7	9	8	9	9	7	7	7	7
Separate Effects Tests:											
G-1 Blowdown	6	✓	✓								
G-2 Blowdown	6	✓	✓								
G-2 Refill	4	✓	✓								
1/3 Scale S/W Mix.	11			✓							
Marviken	16								✓		
Creare	4				✓	✓	✓				
Integral Effects Tests:											
LOFT	4	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
UPTF Test 6	6				✓	✓	✓	✓			
UPTF Test 8	1			✓							

Table 3. Reflood LOCA Phenomena Assessment

LOCA PROCESS : / TEST SIMULATION	Number of Simulations	Fuel Rod Oxidation	Fuel Rod Decay	Fuel Rod Gas Conductivity	Core Reflood Heat Transfer	3D Flow Void Generation	3D Flow Entrainment	Upper Plenum Entrainment	Hot Leg Entrainment	Steam Generator Steam Binding	Pump Two-Phase Performance	Cold Leg/Accumulator Non-Cond.	Downcomer Hot Wall	Lower Plenum Hot Wall	Loop Oscillations
Expert Ranking		*8*	*8*	*8*	*9*	*9*	*9*	*9*	*9*	*9*	*8*	*9*	*7*	*7*	*9*
Separate Effects Tests:															
FLECHT-SEASET	5				✓	✓	✓								
FLECHT-LFR	3				✓	✓	✓								
FLECHT-Skewed	5				✓	✓	✓								
FEBA	4				✓										
NRU	2			✓	✓										
G-2 Reflood	3				✓	✓									
1/3 Scale S/W Mix.	11											✓			
Integral Effects Tests:															
LOFT	4		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
SCTF	5				✓	✓	✓								✓
CCTF	5				✓	✓	✓			✓			✓		✓
UPTF 8	1											✓			
UPTF 10b	1							✓							
UPTF 25	1						✓						✓		✓
UPTF 29	1							✓							

PROCESS IDENTIFICATION AND RANKING

The developers of the CSAU methodology recognized the need for an assessment of the uncertainty in all LOCA phenomena and the degree to which the individual uncertainties affect the PCT. In principle, this would require a complete assessment of all models and correlations used in a realistic computer code. In practice, a less complex approach was needed. In the CSAU methodology, an expert panel was used to rank LOCA processes, and the highest ranked processes were included in the uncertainty assessment. A similar approach was followed by Westinghouse, but this was augmented by extensive plant sensitivity studies with the code, to confirm the predicted effect. In some instances, parameters not originally thought to be important were found to have a substantial effect on PCT. In general, it was found that expert opinion is effective in identifying potential important contributors; however, predictions of the impact of such contributors was less reliable, especially when previous experience with other computer calculations was not available.

SENSITIVITY CALCULATIONS

A large number of sensitivity studies were performed for several PWR designs. Typical results for a three loop plant are presented in Figures 2 to 5. Figure 2 shows the maximum PCT at all elevations during the transient, while Figure 3 shows selected elevations. Figures 4 and 5 illustrate the core and downcomer collapsed liquid levels. The oscillatory early reflood period is clearly evident. Based on sensitivity studies performed to date, there are a relatively small number of parameters which affect the LOCA transient significantly. The effects can be summarized as follows:

A. BLOWDOWN

1. Broken loop resistance: Variations in relative resistance of the path from the core to the break on the loop side, and from the core to the break on the vessel side were found to affect the PCT significantly for all plants. The relative resistance was affected, in turn, by the following:

- break discharge coefficient
- break type
- break location
- vessel inlet nozzle resistance on broken loop
- pump resistance on broken loop

2. Intact loop pump performance: On the intact loops, the most significant parameter was found to be whether the RCS pump was powered. It was found that for most plants, maintaining power to the pumps resulted in a higher PCT, because it inhibited downward flow through the core as the system de-pressurized.

3. Fuel stored energy and power: During blowdown, the most significant core power distribution parameter is the maximum average fuel temperature. This establishes the first peak cladding temperature, and generally affects the second and third peaks as well. The initial fuel temperature is affected primarily by the time in cycle and by the peak linear heat rate.

4. Hot assembly location: The assembly receives different amounts of water directly from the upper head and upper plenum depending upon its location relative to the control rod guide tubes. It was been found that there is a variety of upper plenum configurations above the assemblies. Each configuration must be evaluated to assess its impact on assembly flow during blowdown.

B. REFLOOD:

1. ECCS flow rates and temperatures: While in some cases variations in these parameters did not have a significant effect on PCT, it was clear from the calculated results that the vessel mass inventory during reflood was strongly affected by the SI flow rate and temperature, and the accumulator temperature. In addition, ECCS temperature affected the mixture level in the downcomer which in turn affected how much ECCS was entrained from the vessel during reflood. In general, higher ECCS water flow and/or lower temperature resulted in increased vessel mass inventory and improved core cooling during reflood.

2. Containment pressure: A higher containment pressure was found to significantly improve the vessel mass inventory and subsequent reflood transient.

3. Fuel residual power distribution: It was observed that the PCT location during reflood was typically high in the core. Consequently, the core power distribution as well as the hot assembly power affected the reflood PCT.

UNCERTAINTY EVALUATION

As a result of the code validation, LOCA process ranking, and sensitivity studies, the overall uncertainty was concluded to arise from four major sources:

1. Code bias and uncertainty
2. Power distribution bias and uncertainty
3. Break flow bias and uncertainty
4. Initial condition uncertainty

These elements are considered to affect the base case PCT as:

$$PCT_j = PCT_j^B + \Delta PCT_{1j} + \Delta PCT_{2j} + \Delta PCT_{3j} + \Delta PCT_{4j}$$

where:

PCT_j^B = Base case PCT: The base case PCT is calculated using WCOBRA/TRAC at nominal conditions for blowdown (j=1) and reflood (j=2)

ΔPCT_{1j} = Code bias and uncertainty: the code bias accounts for differences between the computer code prediction of tests which simulate the PWR LOCA transient, and the measured data, and is independent of the plant type. Different values are used for the blowdown and reflood PCT's.

ΔPCT_{2j} = Power distribution bias and uncertainty: This bias is the difference between the base case PCT, which assumes a nominal power distribution, and the average PCT taking into account all possible power distributions during normal plant operation. Elements which contribute to the uncertainty of this bias, are calculational uncertainties, decay heat uncertainties, and variations due to transient operation of the reactor.

ΔPCT_{3j} = Break flow bias and uncertainty: this bias is the difference between the base case PCT, which assumes best estimate break flow parameters, and the average PCT taking into account all possible values of the break flow parameters. The uncertainty of this bias takes into account the effects of break discharge coefficient and broken loop resistance.

ΔPCT_{4j} = Initial condition bias and uncertainty: this bias is the difference between the base case PCT, which assumes several nominal or average initial conditions, and the average PCT taking into account all possible values of the initial conditions. This bias takes into account plant variations which have a relatively small effect on PCT.

Each element includes a correction or bias, which is added to the base case PCT to move it closer to the expected, or average PCT. The bias from each element has an uncertainty associated with the data used to derive the bias. Each element of uncertainty is assumed independent. Demonstration of this independence must be provided, of course, and requires additional sensitivity studies. With the exception of the code uncertainty, the uncertainty components are typically plant specific.

TYPICAL RESULTS

There are plant specific differences which must be accounted for in the uncertainty evaluation. However, in general, it was found that the code uncertainty, the power distribution uncertainty, and the break flow uncertainty all contributed approximately equally to the overall uncertainty. The difference between the average, or 50% percent probability PCT (the PCT below which 50% of all sampled PCT's fall) and the 95% probability value ranged from 350 to 400 °F. This estimate is consistent with the estimates made in the CSAU methodology[4]. *Estimates of the PCT at the 95% probability level ranged from 1800 °F to 2000 °F*, after taking advantage of available margin to increase peaking factors, core power, and operating bands.

CONCLUSION

While the LOCA is a complex transient to simulate, the state of the art in thermal hydraulics has advanced sufficiently to allow its realistic prediction, and the application of advanced methods to day to day reactor design, as demonstrated by the methodology described here.

References

1. U. S. Nuclear Regulatory Commission, "Emergency Core Cooling Systems; Revisions to Acceptance Criteria," Federal Register, 52, 41, March 1988.

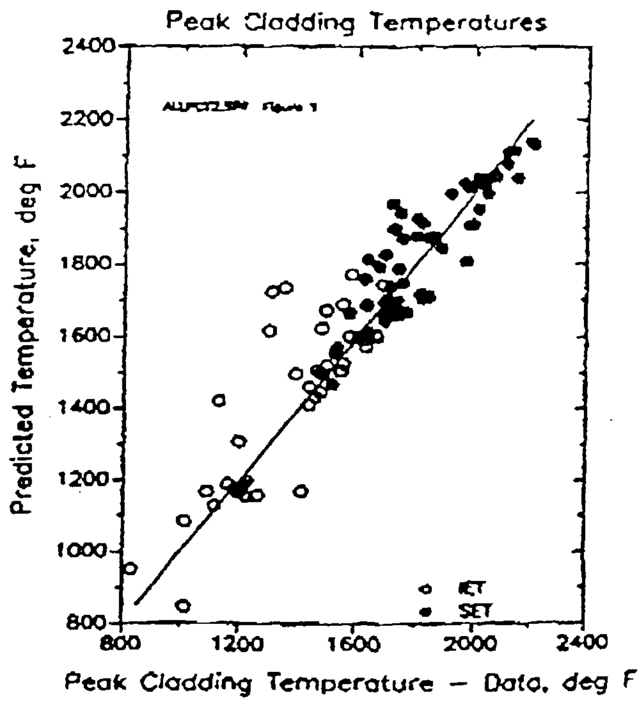
2. U. S. Nuclear Regulatory Commission, "Best Estimate Calculations of Emergency Core Cooling System Performance", Regulatory Guide 1.157, May 1989

3. U. S. Nuclear Regulatory Commission, "Compendium of ECCS Research For Realistic LOCA Analysis", 1988, NUREG-1230.

4. WILSON, et, al., "Quantifying Reactor Safety Margins", NUREG/CR-5249, 1989.

5. M. J. THURGOOD, J. M. KELLY, T. E. GUIDOTTI, R. J. KOHRT, and K. R. CROWELL, "COBRA/TRAC - A Thermal-Hydraulics Code for Transient Analysis of Nuclear Reactor Vessels and Primary Coolant Systems, Equations and Constitutive Models," NUREG/CR-3046, March 1985.

6. CHOW, S. K. et al., "Assessment of Scaling Uncertainties for PWR Large-Break LOCA Analysis", EPRI NP-6602, 1989.



Maximum Cladding Temperature Comparison at PCT Location — All Reflood Tests

Figure 1. Maximum Cladding Temperature Comparison.

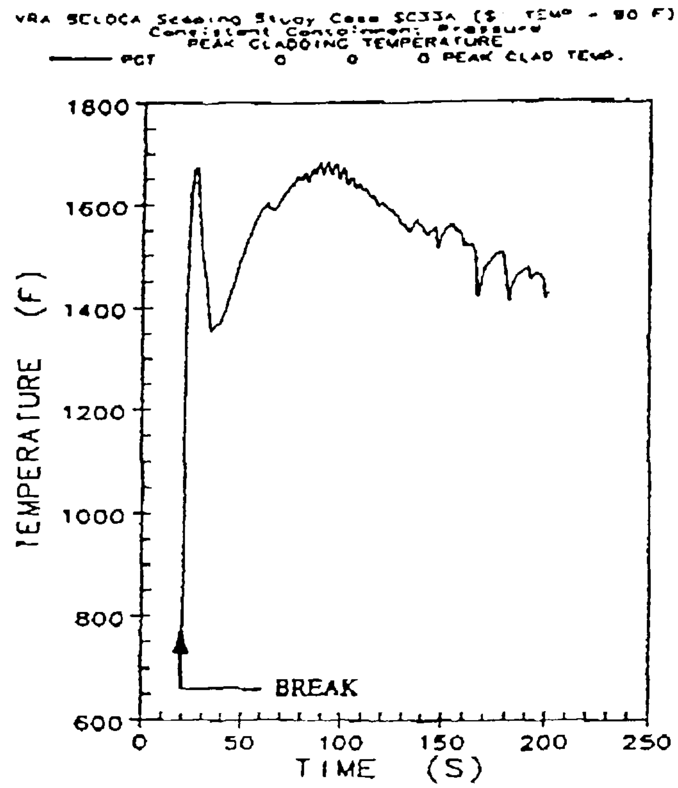


Figure 2. Locus of PCT Anywhere in the Core.

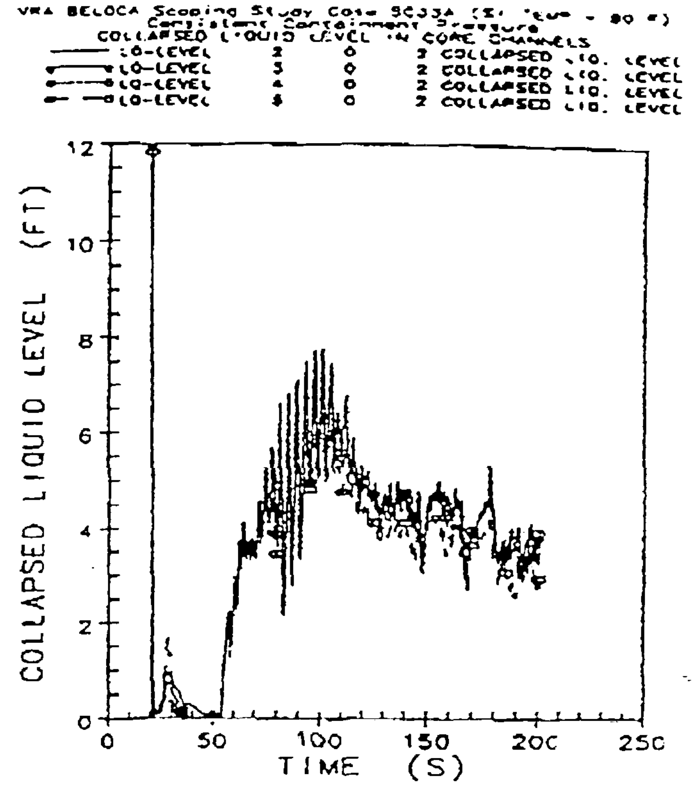


Figure 4. Collapsed Liquid Level in Core vs. Time.

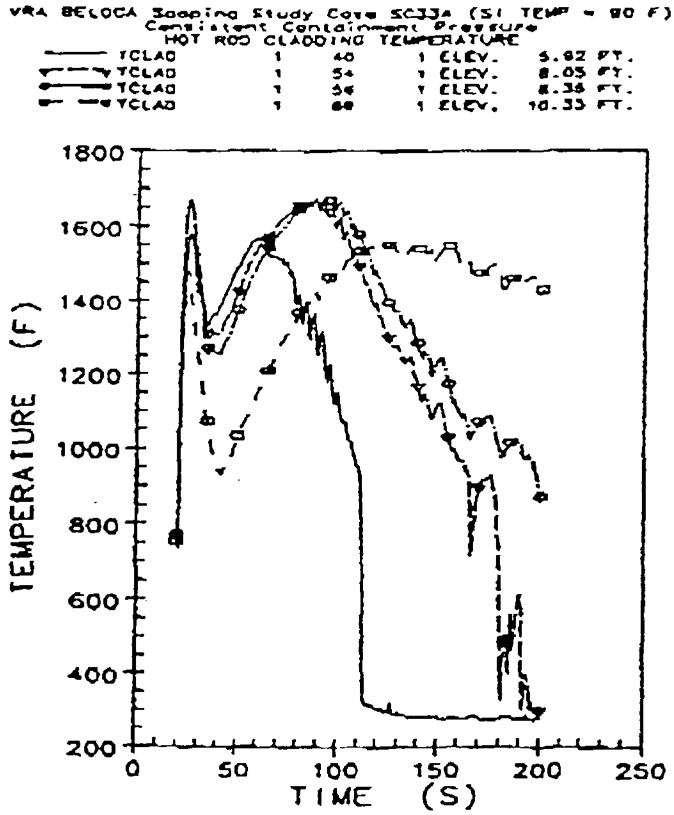


Figure 3. Cladding Temperature vs. Time at Several Elevations

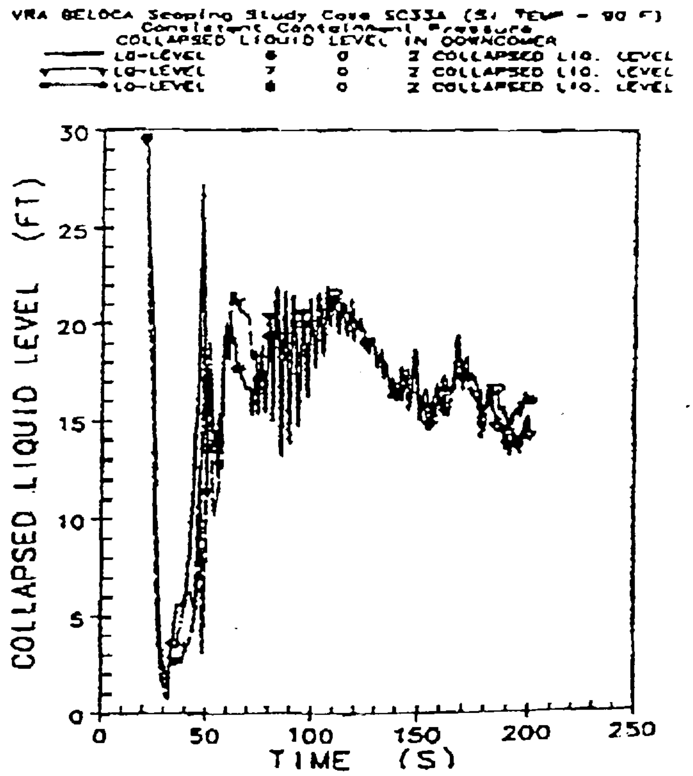


Figure 5. Collapsed Liquid Level in Downcomer vs. Time.