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UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D. C. 20555

MAY 2 2 1980

MEMORANDUM FOR: Harold Denton, Director
Office of Nuclear Reactor Regulation

FROM: Robert J. Budnitz, Director
Office of Nuclear Regulatory Research

SUBJECT: RESEARCH INFORMATION LETTER # 90 - RELAP-4/MOD6 ASSESSMENT

Reference:

1. Memo, S. Levine to H. Denton, November 27, 1978, "Research Information Letter #39 - RELAP-4/MOD6."
2. D. G. Hall, "An Assessment of the RELAP-4/MOD6 Computer Code Using Data from the Marviken CFT Project," EGG-CAAP-5032, prepared for NRC by EG&G Idaho, October 1979, (contains proprietary data).

INTRODUCTION

The purpose of this Research Information Letter is to transmit the results of the first RES sponsored independent assessment of a LOCA code. The information presented pertains to RELAP-4/MOD6, the latest available LOCA code at the time of assessment initiation. This code was described in Research Information Letter #39 (Ref. 1). The goal of independent assessment of codes is to critically evaluate the capability of the code to predict important events taking place in a full size LWR during a postulated accident. The measure of the code capability is reflected in the degree of uncertainty with which the actual events are predicted. That degree of uncertainty is comprised of (a) uncertainties in the code input (such as initial state of the plant, boundary conditions, and empirical correlations for such things as heat transfer coefficients, flow resistances, etc.) and (b) the code's modeling inadequacy - here referred to as the code error. Both of these contributions define the probability distribution around the Best Estimate prediction of certain key parameters.

To achieve this task, RES has scoped out an extensive program involving four national laboratories. This task will not be completed until all of the important experiments have been performed and code results compared against test data to arrive at the quantification of code "error" and its extrapolation to LWRs. Due to large resource requirements, only the advanced best estimate code (TRAC) will be subjected to the complete assessment process, aimed at producing the needed information to quantify the margin of safety in LWRs.

The independent assessment of the RELAP-4/MOD6 computer code, described in this Research Information Letter, does not constitute the total picture because the code was not judged to merit the full treatment - being

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superseded with advanced best estimate codes. Nevertheless, since this code was the only best estimate code available for independent assessment at the beginning of FY 78, RES thought it would be useful to exercise, test and "shake down" the assessment methodology.

The RELAP-4/MOD6 physical models and solution technique for the blowdown phase of LOCA are similar to those employed in the vendors' codes, especially when the latter are used for analyses of Standard Problems which require removal of certain Appendix K specified restrictions.

For analyses of the reflood phase of LOCA the vendors' codes often employ empirical correlations derived from their own test data base. There is no doubt that the RELAP-4/MOD6 will not predict the vendors' experiments as well as the vendors' codes would, and for obvious reasons. On the other hand, RELAP-4/MOD6 treatment of reflood is much more general and not constrained to a particular core length, shape, fluid pressure, fuel rod initial temperature, and the particular core inlet flow rate. Systems effects, e.g. steam binding, are dominated by the core reflood process, i.e. by the rate of steam generation due to rod quenching; both are tightly coupled in the RELAP code. Coupling of a global correlation for core reflood with the rest of the system - as in the vendors' codes - cannot be that tight.

Due to these and other "best-estimate" features, the RELAP-4/MOD6 code was thought to have a potential for evaluating the effects of conservatisms built into vendors' codes, thus offering a valuable licensing audit tool. The in-depth study of this code's capabilities described in this Research Letter greatly aids the code user in understanding the uncertainties with which this code predicts the reality.

SUMMARY

Comparisons with experimental data from ten test facilities showed that RELAP-4/MOD6 predictions* provide an adequate representation of system hydraulics for the blowdown period of large break LOCA. Comparisons of performance evaluators such as maximum clad temperature and pressure to experimental data were, in general, satisfactory. The code's capability to calculate refill behavior was found to be poor, primarily due to the constraints of the homogeneous equilibrium assumptions. Predictions of reflood were found to be influenced by the treatment of entrainment and phase separation. Hence, good agreements could be obtained with test data for a given test facility (and for a particular region of the simulated core) through assignments of certain (input) values. However, those same input values gave inferior results for other regions of the core or for other test facilities.

Inadequate information concerning the uncertainty of experimental measurements prevented a quantification of the code error.

* Prediction as used here refers to a code calculation. We do not necessarily imply the calculation was performed prior to the test.

A preliminary uncertainty analysis conducted with MOD6 established the feasibility of the statistical approach based upon application of a large LOCA code to a PWR. Although the results were not intended to represent a quantitative evaluation of PWR behavior at this stage in the application, they are interesting. The most probable peak temperature during the blowdown phase of LOCA was about 1200°F, with more than 99 percent of the points below 1500°F.

CODE ASSESSMENT

Eighteen subtasks were performed under the RES funded assessment program at INEL, each designed to investigate certain features of the loss-of-coolant experiments. Information used at INEL in the assessment of MOD6 is categorized in Table 1, which links the experiments to the code capabilities to be evaluated. Where possible, data from different facilities and at different physical scales were used to provide a broad data base. The details of this work are shown in Enclosures 1 through 3 and Ref. 2.

The RELAP-4/MOD6 code was also widely used by the participants in the International Standard Problems Nos. 7 and 8, sponsored by CSNI/OECD. Enclosure 4 is an excerpt from the CSNI letter report pertaining to the results of ISP Nos. 7 and 8, while Enclosure 5 describes the detailed observations of the RELAP-4/MOD6 users from Finland while applying this code to the International Standard Problem No. 7.

At this juncture it should be pointed out that RELAP-4/MOD6 performed rather poorly as compared with other, more advanced foreign codes such as NORCOOL, DRUFAN and FLIRA, when applied to the ISP No. 7 that featured a reflood separate effects test in the ERSEC test facility (Grenoble, France). Better performance was observed with the domestic (FLECHT) separate effects tests, probably because some of their results were previously employed by code developers in selecting and/or adjusting reflood models.

The results of RELAP-4/MOD6 assessment, which summarize findings from all sources, are presented in two parts; the first part pertaining to the blowdown and the second part to the reflood regimes of LOCA. This code is not recommended for prediction of the refill phase of LOCA.

MOD6 Blowdown Capabilities

RELAP-4/MOD6 adequately represents most hydraulics during blowdown. Figs. 1 and 2 illustrate hydraulic results for LOFT Test L1-5 (Subtask 16). Fig. 1 shows system pressure error* to be negligible through subcooled and saturated blowdown until the onset of accumulator injection (20 s), when the depressurization rate increased substantially, as did the error. Fig. 2 shows

* We use error in this discussion to represent the difference between calculated and experimental behavior. This approach does not account for error in the experimental data, and assumes the data represent "truth."

downcomer fluid temperature error at the intact and broken loop sides of the vessel. The error increase at 20 seconds corresponds to the time of ECC penetration into the downcomer and to the pressure error shown in Fig. 1. The variation in temperature error after accumulator injection is a result of nonequilibrium effects which the code does not consider. Fig. 3 shows the pressure error at the top of the vessel for five Marviken blowdown tests (Subtask 10), when the critical flow models and multipliers used in each evaluation were adjusted to force agreement with discharge flow data from the corresponding test. The error was generally negative, representing an underprediction of pressure during subcooled blowdown. The mean of the maximum pressure error was 2.1 percent in the subcooled regime. The mass flow rate prediction error using both a RELAP-4 system model of the Marviken facility and a separate effects model of the vessel discharge nozzle is shown in Fig. 4. In the separate effects model the measured fluid pressure and temperature histories at the nozzle inlet were supplied as boundary conditions. The system calculation error is as much as 40 percent of the measured flow rate. The separate effects model error is lower, but still significant.

RELAP-4/MOD6 calculated core clad temperatures well except where delayed Critical Heat Flux (CHF) occurred in the experiments, primarily in the upper core regions. Film boiling heat transfer was well represented by the optional Condie-Bengston III correlation. Fig. 5 shows calculated and measured local maximum clad temperature for Semiscale Test S-06-5 and THTF Test 105 (Subtask 1). Satisfactory predictions are obtained below core midplane. Above core midplane the delayed CHF was not calculated, resulting in the maximum clad temperature overprediction of 124 K and 110 K for the Semiscale and THTF tests, respectively. Standard deviations were 103 K and 77 K, respectively. It should be noted that the results shown in Fig. 5 are generally representative of all diabatic (heated) blowdowns analyzed in the assessment, although differences in bias were encountered from test to test. No cases were found in which the maximum clad temperature was underpredicted by more than 50° F, and generally the code overpredicted temperature.

MOD6 Blowdown Prediction Deficiencies

The following deficiencies were found during code assessment:

1) Core heat transfer is poorly calculated when delayed CHF occurs in the experiments, primarily because the CHF correlations employed in the core are inadequate in the high-quality regime.

2) The use of modified Tong-Young transition boiling correlation sometimes causes prediction of premature clad rewet toward the end of blowdown, with a corresponding clad temperature error.

3) Current user guides for the critical-flow multiplier are inadequate, especially for the untested nozzle geometries.

4) The thermal equilibrium mixing assumption in RELAP-4/MOD6 causes the calculation of excessive local depressurization following ECC injection.

5) The slip model gives unrealistically large phase slip velocities in the reactor core.

6) Two-phase form losses and the hydraulics of the pressurizer surge-line are not necessarily modeled.

MOD6 Reflood Prediction Capabilities

The general characteristics of system hydraulic response are well calculated. Initiation and cessation of flow oscillations due to core steam generation are reproduced realistically. For FLECHT Test 4019 (Subtask 6), the liquid inventory was calculated to within 4 percent of the measured value at the time of midplane quench.

Thermal response, represented by peak cladding temperature, quench time, and turnaround time is calculated well for the lower and midcore regions in the system experiments (Subtask 7). Fig. 6 shows the calculated and measured thermal response for KWU PKL Test K5A, where the error in quench time, turnaround time, and maximum local clad temperature is shown as a function of the normalized core height, h/h_c. Above the core midplane, errors in the calculated response are large, primarily because of poor modeling of dispersed-flow cooling in core regions featuring low clad temperature.

Fig. 7 illustrates several comparisons for the reflood regime. The local maximum clad temperature is calculated well (generally within 100° K) for the forced feed reflood separate effects test (FLECHT #4019, Subtask 6). Temperature turnaround time was calculated well throughout the core for Test 4019. The core midplane quench time was calculated well for all FLECHT experiments. However, similar calculations for Semiscale were less successful.

Reflood Prediction Deficiencies

Although qualitative hydraulic response characteristics are well represented, some details are inadequately calculated. There is inadequate modeling of liquid fallback in the core. The original code input guidelines were inadequate, particularly pertaining to transition and dispersed-flow heat transfer. Calculation inadequacy for the dispersed-flow heat transfer is partially caused by poor modeling of core liquid entrainment, particularly under oscillatory hydraulic conditions. Calculated amplitudes of hydraulic oscillations are generally larger than measured. Calculated depressurization due to steam condensation is larger than measured, which contributes to driving the oscillations. The thermal equilibrium assumption also causes calculation of nonrealistic oscillations within the steam generator.

Fig. 7 shows that the original user guidelines led to unsatisfactory predictions of time to turn around and quench for the separate-effects forced-reflood tests, except for FLECHT Test 4019. The code frequently overpredicted the clad temperature, particularly above the core midplane. Based on the inadequate results shown in Fig. 7, the user guidelines were modified. Subtasks 17 and 18 were performed to evaluate these new guidelines. The latter yielded results which were as good as, or better than, the results obtained with the original guidelines. This is illustrated in Figs. 8 - 11. Fig. 8 shows a run in which the results of the original and the revised guidelines are compared. The latter provided satisfactory agreement. In Fig. 9, a significant improvement is shown with a revised guideline. Fig. 10 shows an excellent agreement, but in Fig. 11 the results are clearly still not satisfactory. Note that, in general, better results may be obtained by an experienced user if he deviates from the guidelines. Of course, the difficulty in this approach is that the results become user dependent.

Calculation of reflood hydraulic phenomena for the Semiscale Mod3 Test S-07-6 was found to be inadequate. As shown in Fig. 12, the measurements indicated repetitive refilling and voiding of the downcomer. In contrast, the code predicted a liquid full downcomer after about 100 seconds. The calculational error is related to deficiencies in modeling of heat transfer from the downcomer wall, together with deficiency in the downcomer phase separation model.

CODE ERROR QUANTIFICATION

None of the domestic test data sources provided directly applicable information concerning the measurement uncertainty, which is critical to code assessment. The available information on test data uncertainty was found to be inadequate for quantification of the code error.

Statistical analyses were performed which demonstrated methods for quantifying code errors and for identifying the conservative or best-estimate performance of the code. An example based on early CHF data in the Semiscale Mod-1 experiments indicated a best-estimate behavior of the code since population mean error in peak cladding temperature was in the range of -7.1 to 14.5 K with a 95 percent confidence. For the delayed CHF cases the mean overprediction, with 95 percent confidence, was in the range of 123 to 145 K, indicating a conservative, rather than best estimate, code characteristic.

A large degree of conservatism was indicated for the reflood analyses made using the original user guidelines, particularly for the forced-feed reflood experiments. In these cases the 95 percent confidence level prediction interval for error in the clad temperature lay between 88 and 442 K. The revised user guidelines served to reduce this conservatism, althougn the reduction has not been quantified.

UNCERTAINTY ANALYSES

Effects of the code input parameters uncertainties on the predicted peak clad temperature in a four loop PWR were studied at the Sandia Laboratories. These studies were limited to the blowdown phase of the design basis LOCA, primarily because the RELAP-4/MOD6 code was incapable of a continuous coverage of an integral LOCA event. The studies are presented in Enclosure 6.

One hundred thirty-four separate calculations were performed with the code while varying the 20 selected input parameters that were believed to have significant impact on the peak clad temperature in the blowdown regime.

The peak clad temperatures resulting from these calculations were fitted by a multidimensional surface termed a "response surface." The surface was, in turn, utilized to calculate peak clad temperatures from a Monte Carlo selection of the 20 parameters from distributions which represented their uncertainty. Table II identifies the parameters. Fig. 13 shows a typical result from a 10,000 sample calculation. The most probable peak clad temperature during blowdown due to a 200 percent cold leg break is seen to be about 1200°F in this example. (The distribution is approximately normal, and the median temperature was 1227°F with 99 percent of all cases studied giving peak clad temperatures at or below 1493°F.)

This investigation establishes that the use of a response surface approach is useful to a statistical investigation of LOCA. What must be kept in mind, however, is that the statistical uncertainty study gives no information about the validity of the code's physical models, about their completeness, and about the numerical solution accuracy. That information comes from the numerous code comparisons with test data and from comparisons with analytic solutions.

OVERALL FINDINGS

RELAP-4/MOD6 calculations have been compared to a variety of LOCE facilities. This code was found to be adequate for blowdown analyses, spotty for reflood analyses and inadequate for refill. In addition, the code cannot generally be applied to a single calculation of the entire (blowdown-refill-reflood) LOCA, without resubmittals to the computer since changes in input are needed during the computation. This deficiency will be removed in the MOD7 version of the RELAP-4 code which is soon to be released to the public.

The RELAP-4/MOD6 code has also been used in the study of uncertainty of the predicted peak clad temperature in a four loop PWR (Zion) during the blowdown phase of the design basis LOCA. The results appear reasonable and demonstrate the feasibility of the statistical approach. This technique will be utilized in the future uncertainty studies covering the entire LOCA accident and utilizing the TRAC code.

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Enclosures: see next page

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Enclosures:

1. Appendix: NRC Guidelines for Code Usage, RELAP-4/MOD6, May 1980.

2. Assessment of the RELAP-4/MOD6 Thermal-Hydraulic Transient Code for PWR Experimental Applications, Vol. I, "Assessment Analyses"; Vol. II, "Appendices," CAAP-TR-78-035, EG&G Idaho, December 1978.

3. Assessment of the RELAP-4/MOD6 Thermal-Hydraulic Transient Code for PWR Experimental Applications-Addendum-Analyses Completed and Reported in FY 1979, EGG-CAAP-5022, EG&G Idaho, February 1980.

4. "Summary Record of the Decisions and Conclusions Reached at a Workshop on the Comparison of Calculations for CSNI Standard Problems Nos. 7 and 8 on Loss-of-Coolant Accidents, held at Idaho Falls, Idaho USA, from 25th to 27th September, 1979," Organization for Economic Cooperation and Development, Nuclear Energy Agency, SEN/SIN (79)39, Paris, (9th October, 1979).

5. "CSNI LOCA Standard Problem No. 7, A Calculation by Finland Using RELAP-4/MOD6," Organization for Economic Cooperation and Development, Nuclear Energy Agency, SINDOC(80)11, Paris, (7th January 1980).

6. Steck, G. P., et al, Sandia Laboratories, "Uncertainty Analysis for a PWR Loss-off-Coolant Accident: I. Blowdown Phase Employing the RELAP-4/MOD6 Computer Code," NUREG/CR-0940, SAND 79-1206, January 1980.

TABLE I

MATRIX FOR RELAP-4/MOD6 ASSESSMENT

TASKS	EXPERIMENTS SELECTED	FEATURES EVALUATED								
		BLOWDOWN HEAT TRANS. & HYDRAULICS	REFLOOD HEAT TRANS. AND HYDRAULICS	FUEL BEHAVIOR	SCALING EFFECTS	DIFFERENT SYSTEMS	TEST PREDIC-TION	COMPONENT EFFECTS	SYSTEMS EFFECTS	INTEGRAL EFFECTS
1. SEMISCALE, THTF CORE BLOWDOWN	SEMISCALE S-06-5, THTF 105	X				X		X		
2. SEMISCALE, LOFT PRESSURIZER BLOWDOWN	SEMISCALE S-04-4, S-06-5, LOFT L1-4				X	X		X		
3. SEMISCALE, LOFT STEAM GENERATOR BLOWDOWN	SEMISCALE S-01-4A, S-06-5, LOFT L1-4				X	X		X		
4. STANDARD PROB. 7 LOFT L1-4	LOFT L1-4						X		X	
5. SEMISCALE, LOFT ISOTHERMAL COMP.	SEMISCALE S-01-4A, LOFT L1-4				X	X			X	
6. SEMISCALE, FLECHT CORE REFLOOD	SEMISCALE S-03-0, FLECHT LFR 4019, 11003		X			X		X		
7. SEMISCALE, FLECHT-SET, PKL COMP.	SEMISCALE S-03-5 FLECHT-SET 27148 PKL K5A		X		X	X			X	
8. PKL PREDICTION	PKL K5A		X				X		X	
9. SEMISCALE INTEGRAL EXPERIMENTS (6)	SEMISCALE S-04-5, S-04-6, S-06-1, S-06-2, S-06-5, S-06-6	X	X						X	X
10. MARVIKEN CRITICAL FLOW TESTS	TESTS 6, 11, 12, 13, 15				X			X		
11. SEMISCALE MOD-3 BLOWDOWN	SEMISCALE S-07-1	X				X	X		X	
12. SEMISCALE MOD-3 REFLOOD	SEMISCALE S-07-4		X			X	X		X	
13. SEMISCALE MOD-3 INTEGRAL	SEMISCALE S-07-6	X	X			X	X		X	X
14. PBF LOCA SERIES	LOC-11, LOC-3	X		X				X		
15. ADDITIONAL THTF TEST (Extension to Subtask 1)	THTF 177	X					X	X		
16. LOFT L1-5 PREDIC-TION	LOFT L1-5						X		X	
17. ADDITIONAL SEMI-SCALE, FLECHT CORE REFLOOD (Extension to Subtask 6)	SEMISCALE S-03-A FLECHT LFR 2414, 13404, 13609		X			X		X		
18. ADDITIONAL SYSTEM REFLOOD TESTS (Extension to Subtask 7)	SEMISCALE S-03-B, FLECHT-SET 22130 PKL K7A		X		X	X			X	

TABLE II: VARIABLES USED IN UNCERTAINTY STUDY

1. Subcooled breakflow (Henry-Fauske) multiplier
2. Saturated break flow (HEM) multiplier
3. Slip (relative velocity of liquid and vapor phases)
4. Frictional and form losses in two phase flow
5. DNB (departure from nucleate boiling or critical heat flux)
6. High flow film boiling heat transfer
7. Low flow rate high void fraction heat transfer (including radiation)
8. Reversed forced convection to vapor (Ditters-Boelter)
9. Low flow rate low void fraction heat transfer (Bromley-Pomeranz film boiling)
10. Flow blockage
11. Power level (initial
12. Specified (time function) containment pressure
13. Pump degradation due to voids
14. Emergency core cooling water temperature
15. Accumulator initial pressure
16. Time in life
17. Peaking factor
18. Fuel Thermal Conductivity
19. Fuel to clad cold gap width
20. Decay heat generation rate

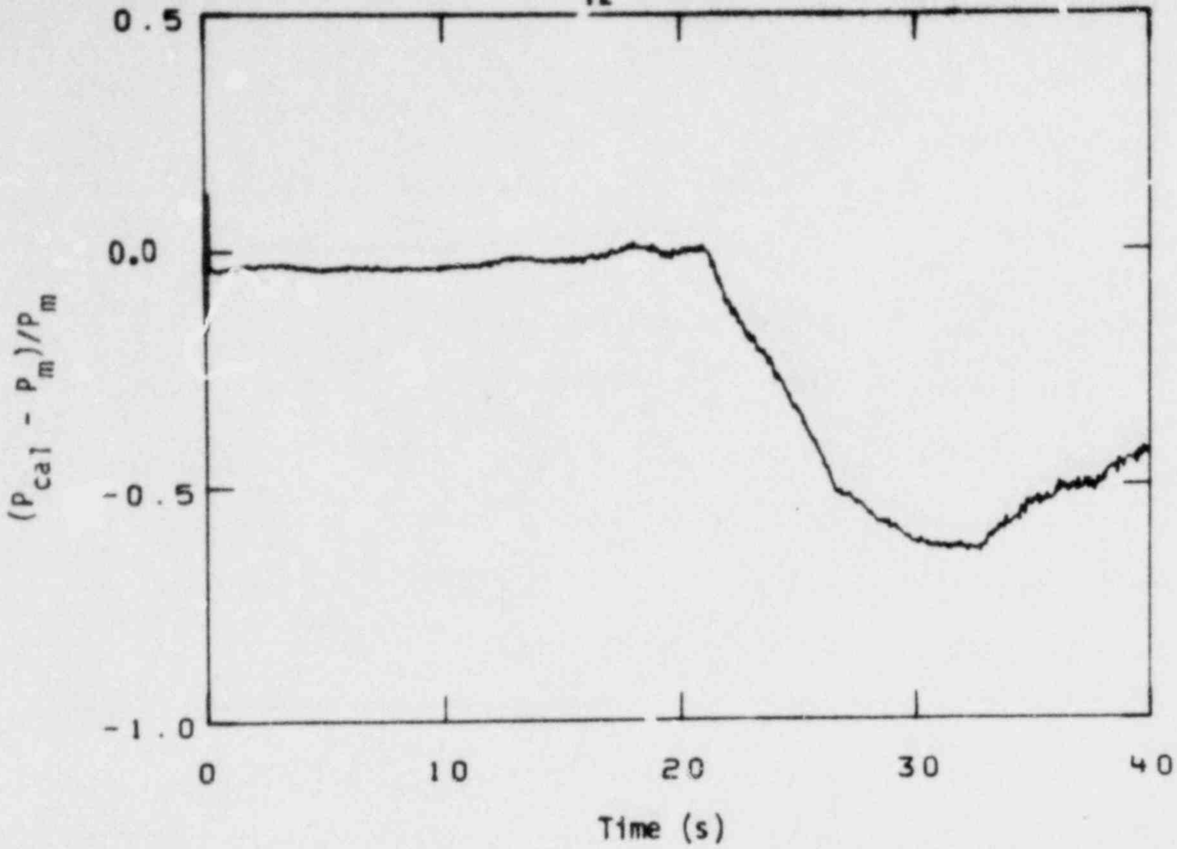


Fig. 1 Error in RELAP4/MOD6 calculation of system pressure for LOFT Test L1-5.

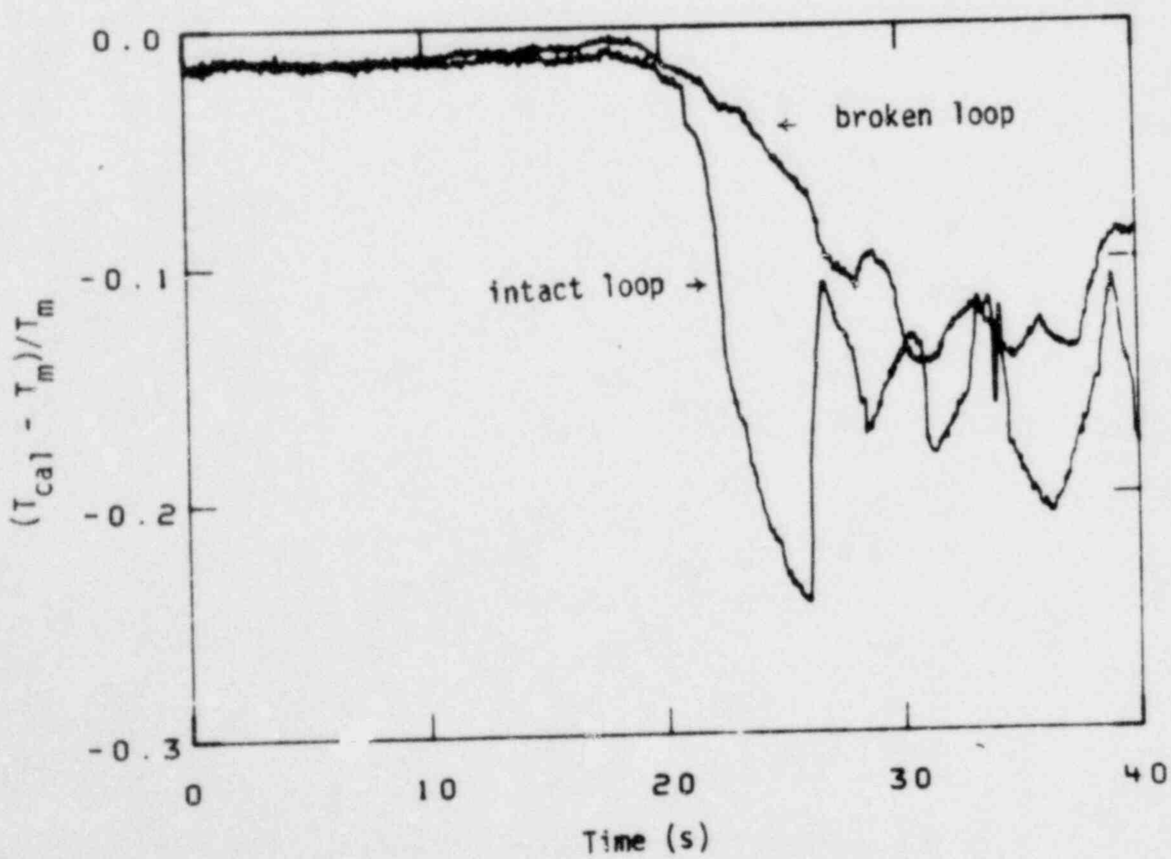


Fig. 2 Error in RELAP4/MOD6 calculation of the downcomer fluid temperatures for LOFT Test L1-5.

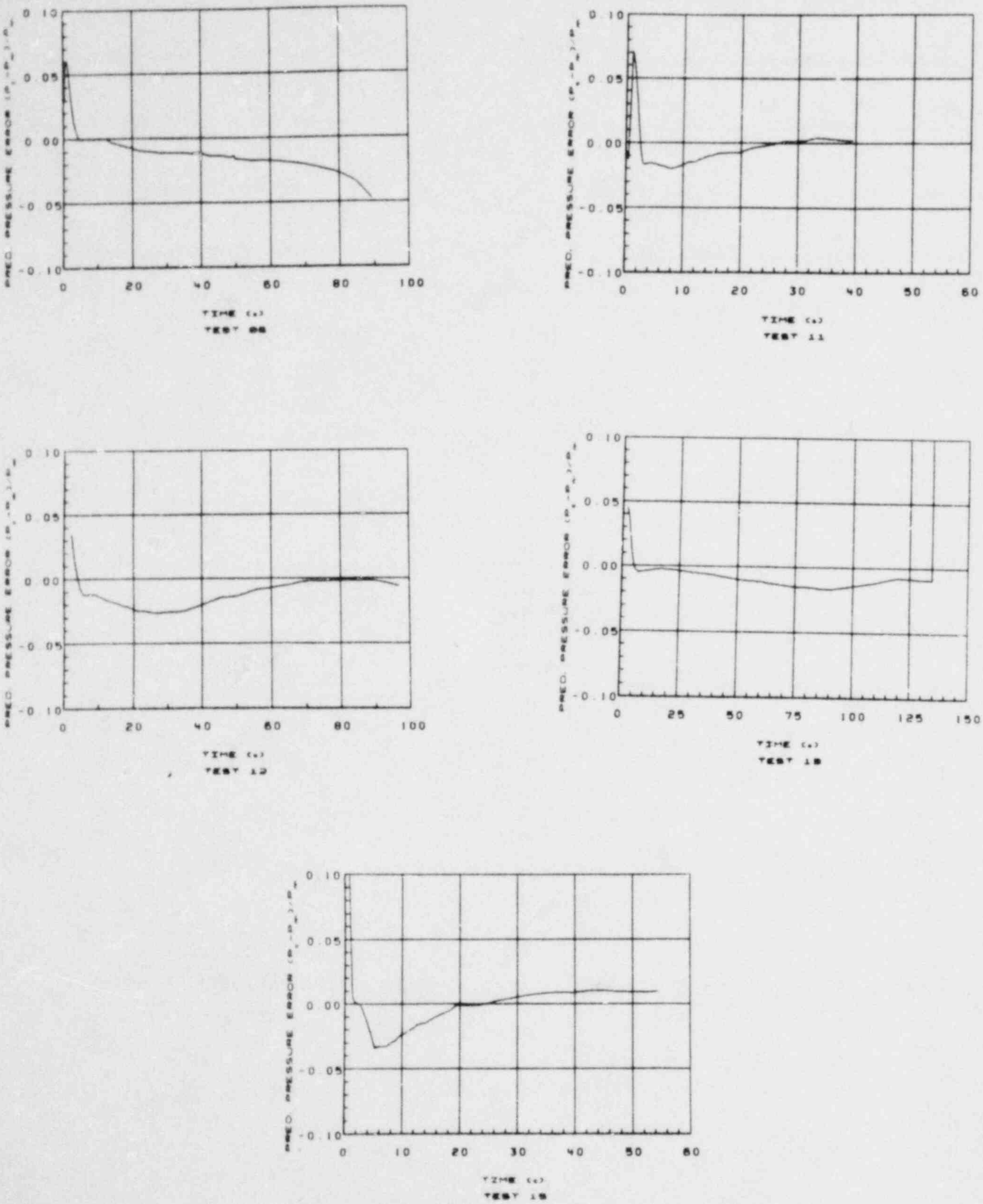


Fig. 3 Error in the RELAP4/MOD6 calculated pressure at the vessel top for Marviken Tests 6, 11, 12, 13 and 15.

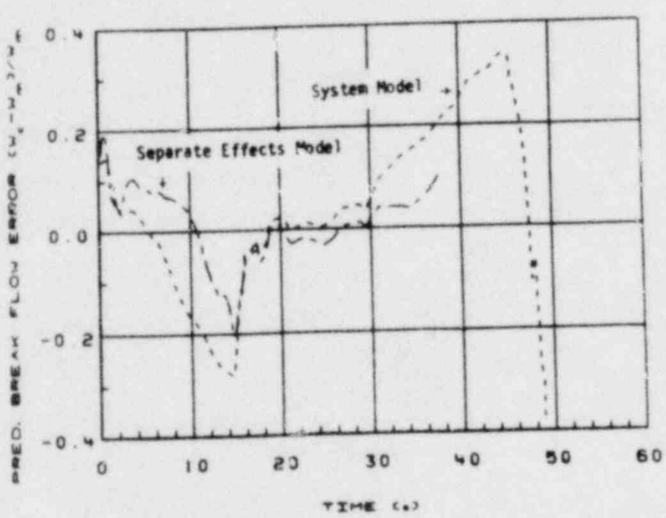


Fig. 4 Error in the RELAP4/MOD6 calculated mass flow rate for Marviken Test 11.

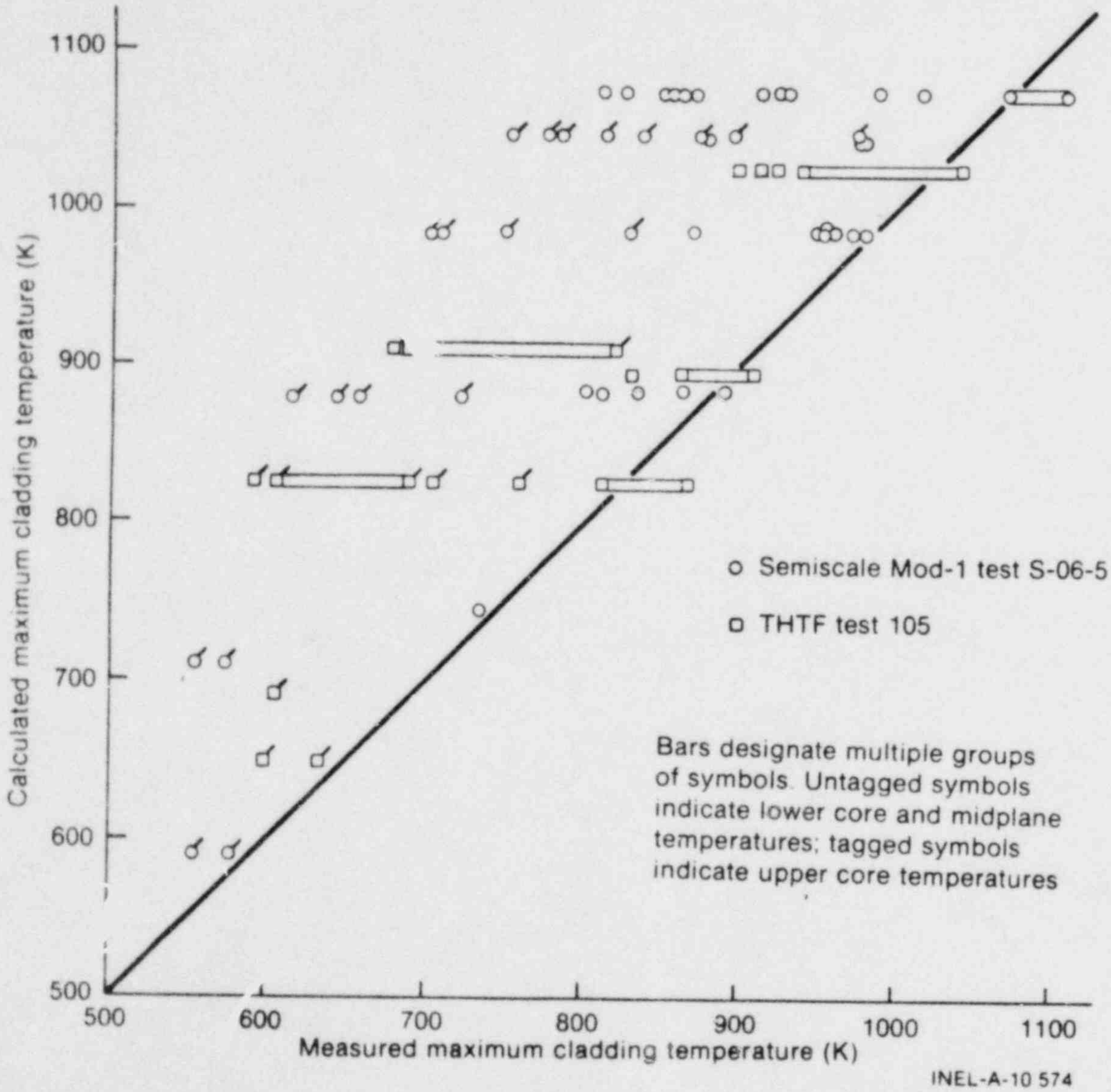
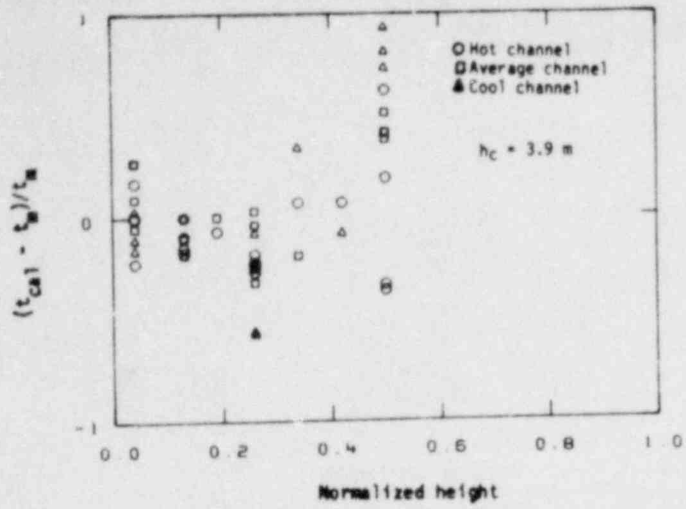
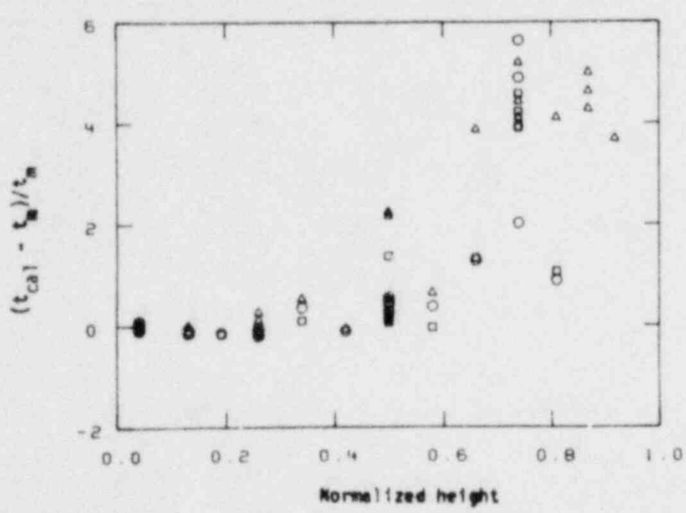


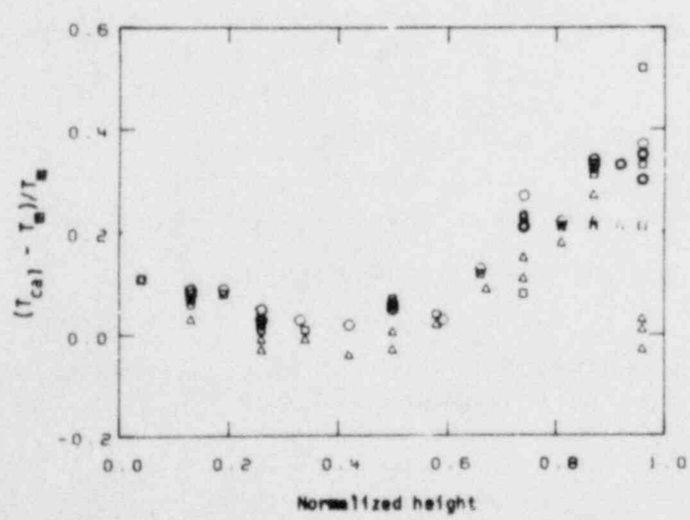
Fig. 5 Measured and RELAP4/MOD6 calculated local maximum cladding temperatures for the Semiscale Mod-1 and THTF cores.



(a) Errors in time to quench.

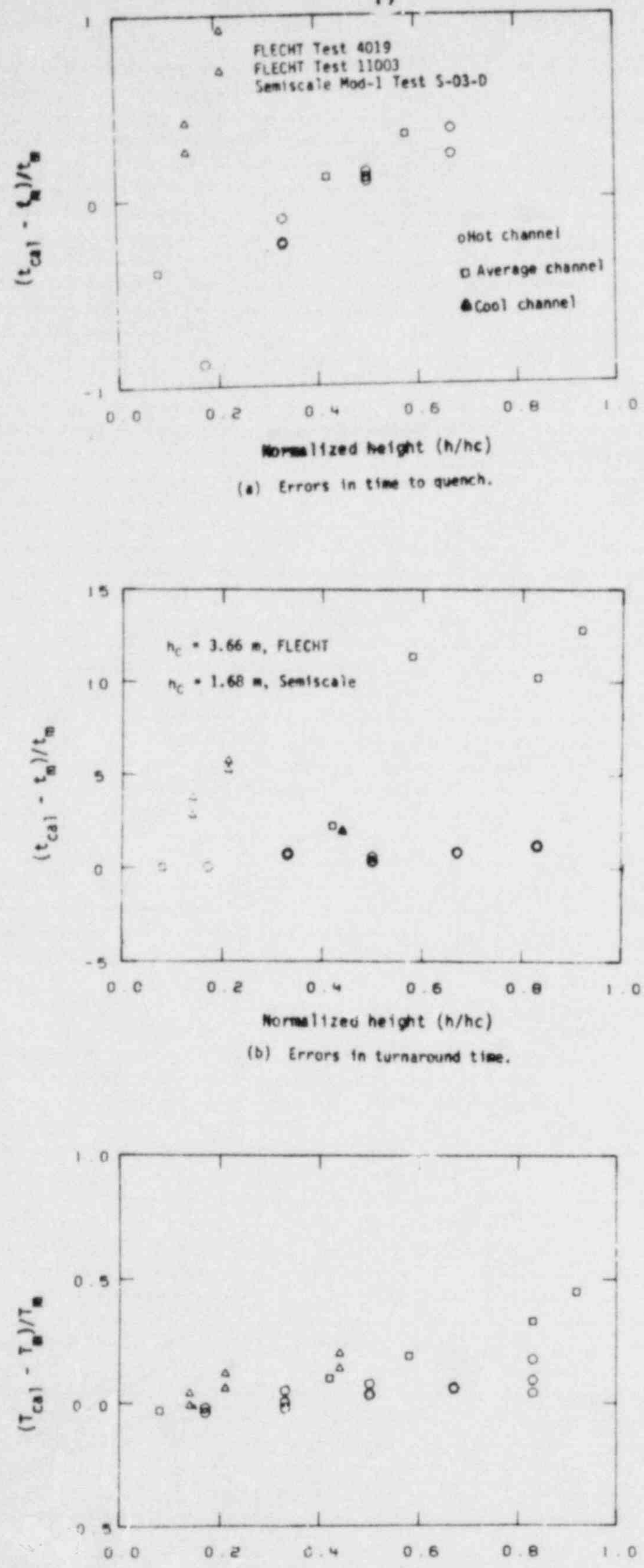


(b) Errors in turnaround time.



(c) Errors in local maximum cladding temperature.

Fig. 6 Errors in the RELAP4/MOD6 calculated time to quench, time to turnaround and local maximum cladding temperature for the PKL Test K5A.



(a) Errors in time to quench.

(b) Errors in turnaround time.

(c) Errors in local maximum cladding temperature.

Fig. 7 Errors in the RELAP4/MOD6 calculated time to quench, time to turnaround and local maximum cladding temperature for FLECHT Tests 4019 and 11003 and for Semiscale Mod-1 Test S-03-D.

Fig. 8

EFFECT OF GUIDELINE CHANGE ON CORE FLUID INVENTORY, FLECHT TEST 2414

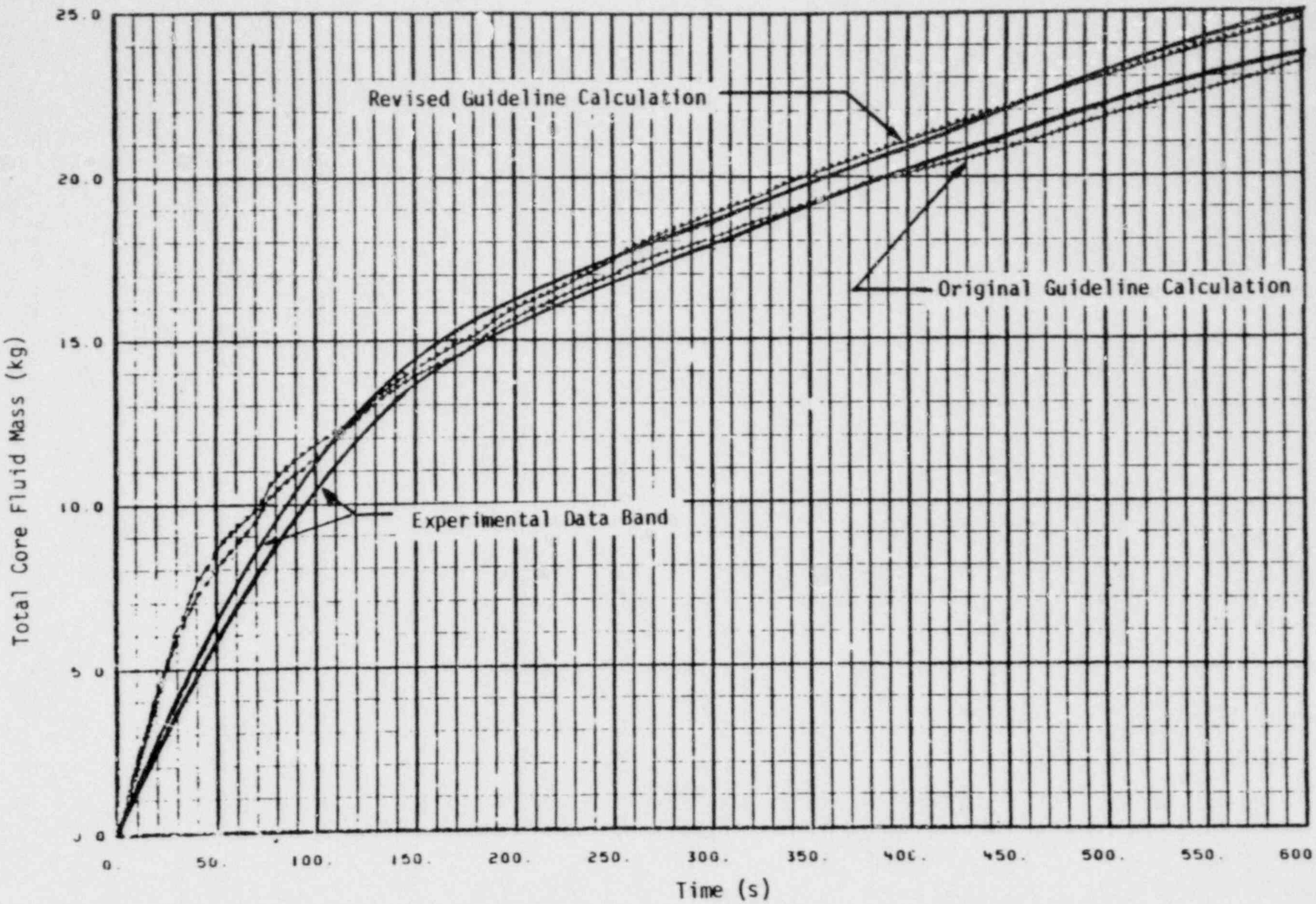


Fig. 9

EFFECT OF GUIDELINE CHANGE ON HOT-SPOT CLADDING TEMPERATURE, FLECHT TEST 11003

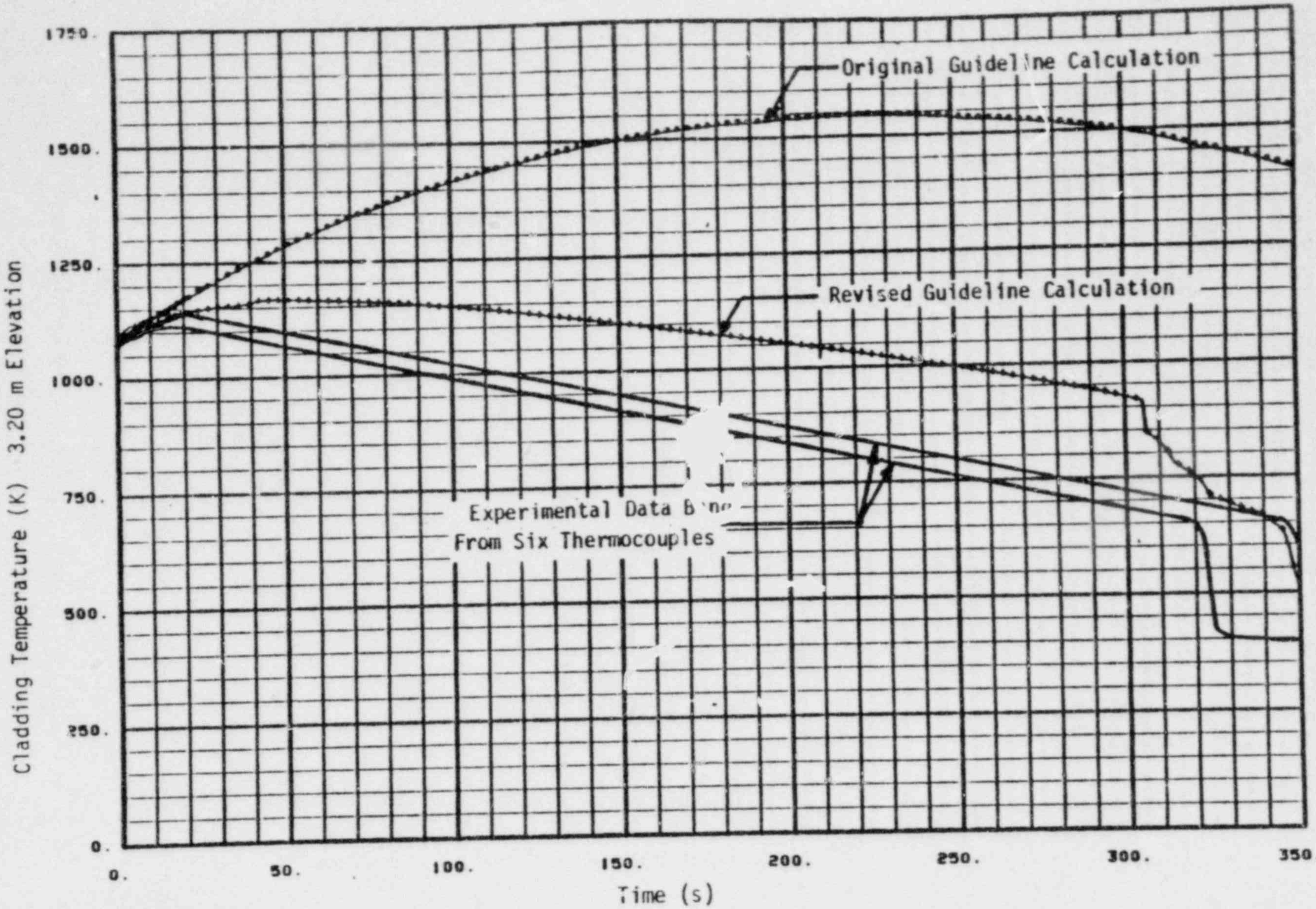


Fig. 10

EFFECT OF GUIDELINE CHANGE ON MIDPLANE CLADDING TEMPERATURE, SEMISCALE MOD-1 TEST S-03-8

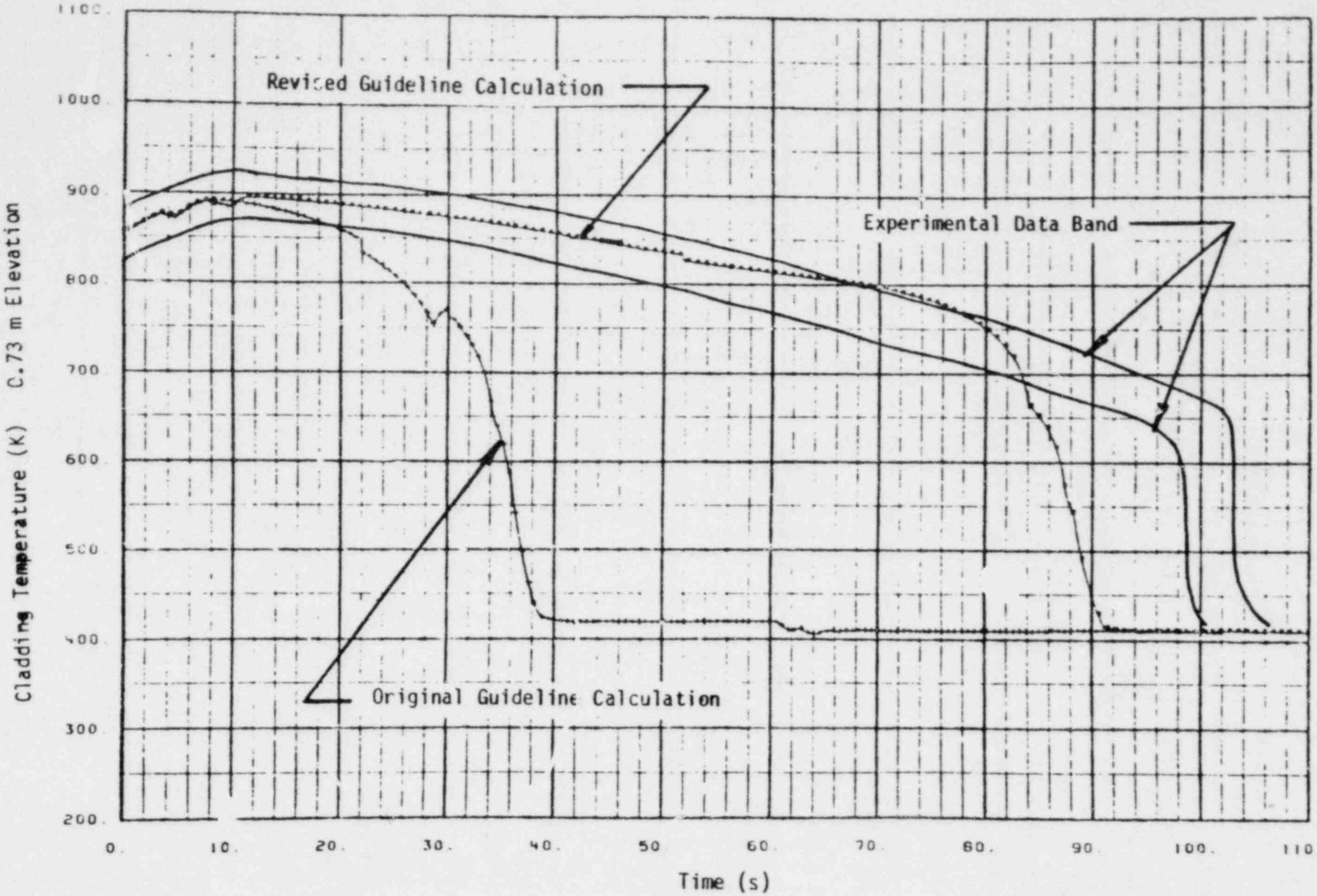
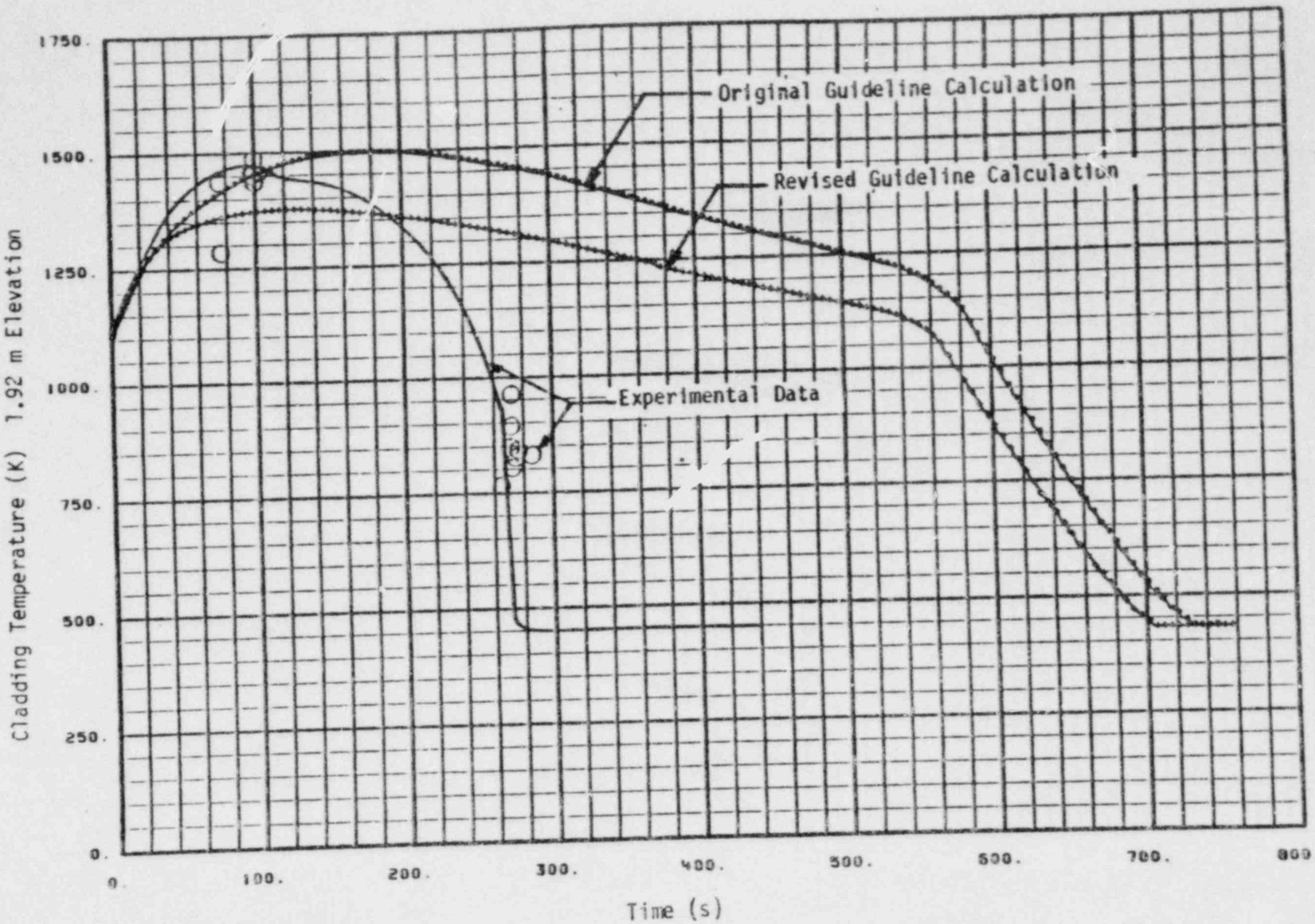


Fig. 11

EFFECT OF GUIDELINE CHANGE ON MIDPLANE CLADDING TEMPERATURE, FLECHT TEST 5239



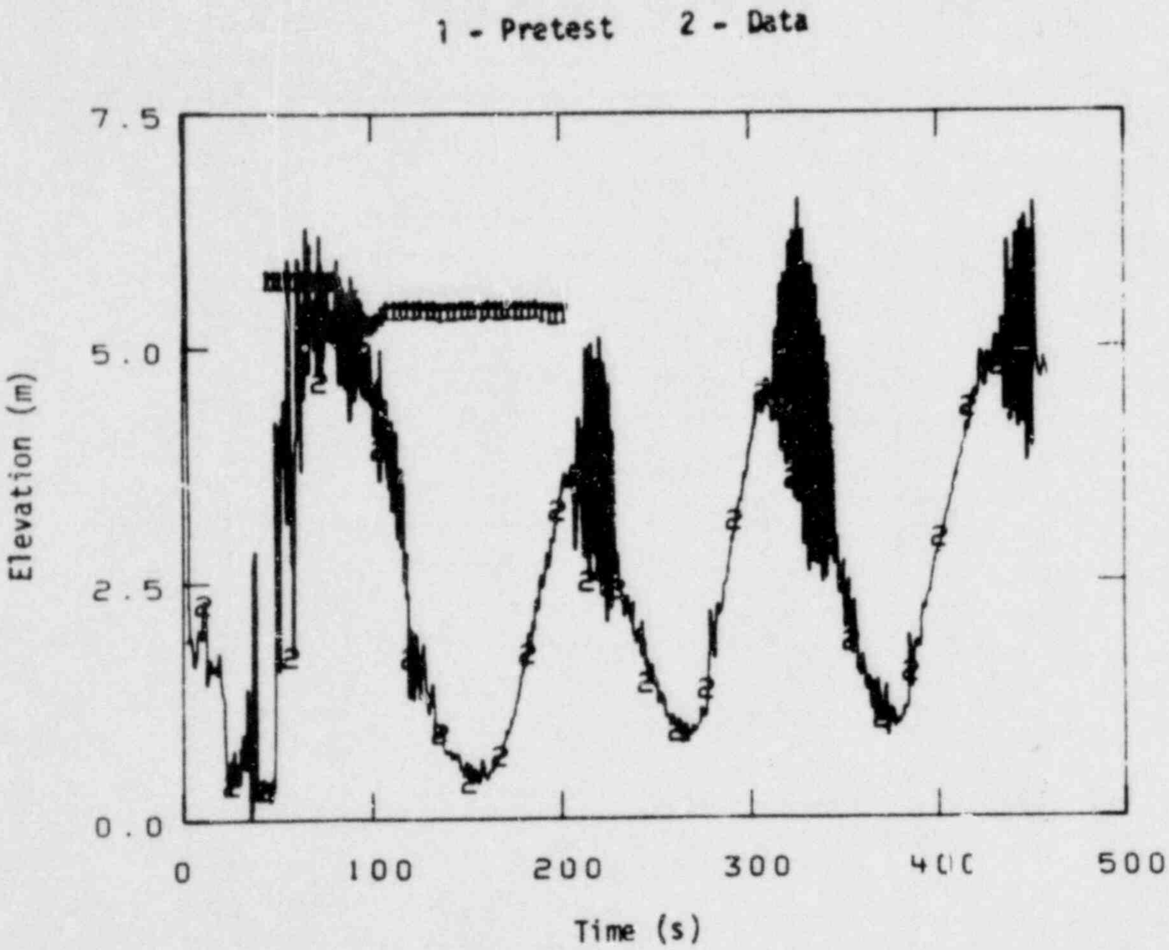


Fig. 12 Measured and RELAP/MOD6 calculated downcomer liquid level for Semiscale Mod-3 Test S-07-6.

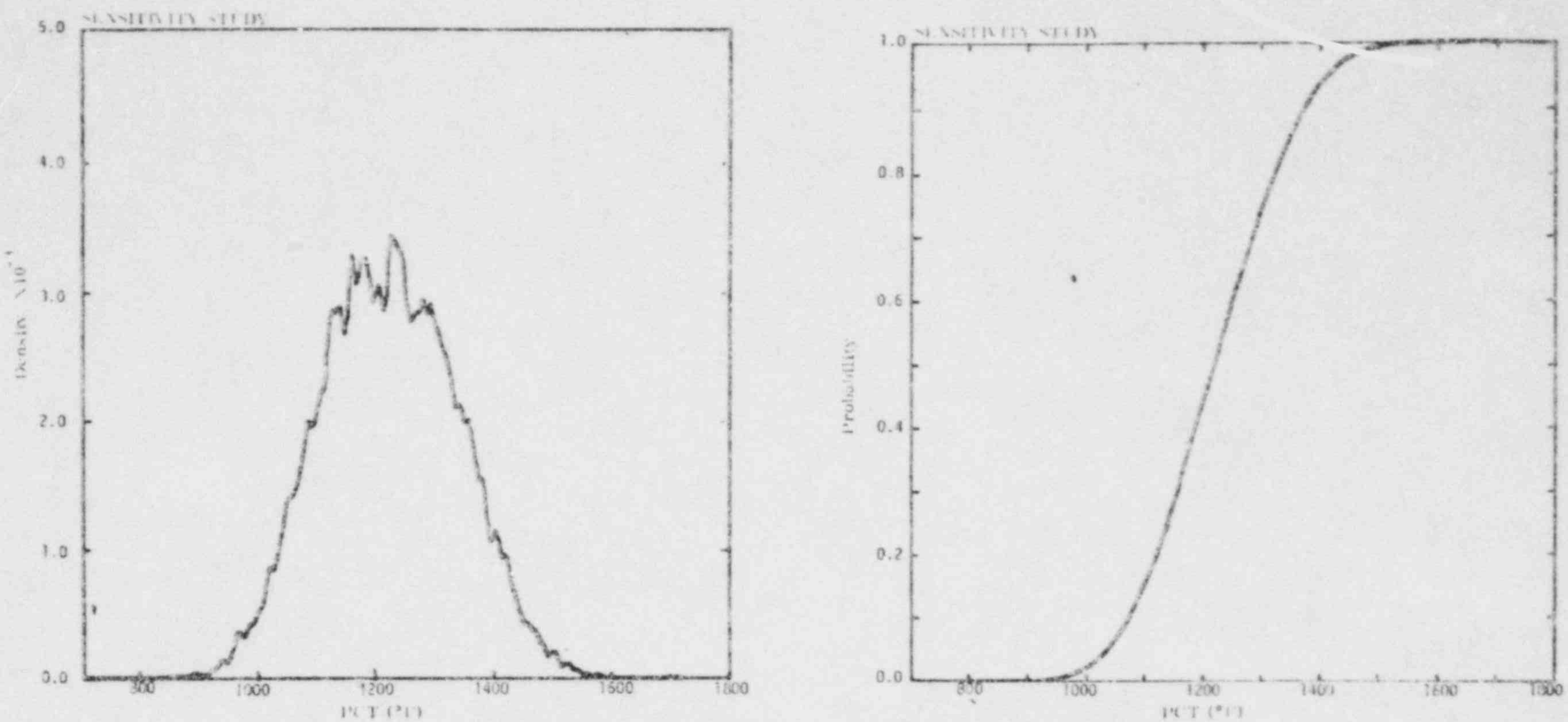


Figure 13 Plots of the Estimated Density Function and Estimated Cumulative Distribution Function for PCT Response Surface CG-11 as Determined by 10 000 Samples. (The input distributions all have means equal to nominal and standard deviations equal to 1/6 the range.)