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EVALUATION OF THE RELAP4/MOD6 THERMAL-HYDRAULIC CODE

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I. INTRODUCTION

The NRC RELAP4/MOD6 computer code[a] was recently released to the public for use in thermal-hydraulic analysis. This code has a unique new capability permitting analysis of both the blowdown and reflood portions of a postulated pressurized water reactor (PWR) loss-of-coolant accident (LOCA). Evaluation of this code after its release represents the "quality control" phase of the research program.

A principal code evaluation objective is to assess the accuracy of the code for computing LOCA behavior over a wide range of system sizes and scaling concepts. The scales of interest include all LOCA experiments and will ultimately encompass full-sized PWR systems for which no experiments or data are available.

Quantitative assessment of the accuracy of the code when it is applied to large PWR systems is still in the future. With RELAP4/MOD6, however, a technique has been demonstrated for using results derived from small-scale blowdown and reflood experiments to predict the accuracy of calculations for similar experiments of significantly different scale or component size. This demonstration is considered a first step in establishing confidence levels for the accuracy of calculations of a postulated LOCA.

[a] This code was formally released to the Argonne Code Center for public use in January 1978. It is on file at the Idaho National Engineering Laboratory, as RELAP4/MOD6, Update 4, EG&G Idaho, Inc., Configuration Control Number C00100006. Associated steam tables are controlled in File H002011B.

II. DESCRIPTION OF PROCEDURES

This RELAP4/MOD6 evaluation study used established statistical procedures[1] to aid in the engineering evaluation of the code and its accuracy. In general, the procedure consists of the following steps:

(1) An initial data set is established for LOCA blowdown and reflood regimes using results of multiple loss-of-coolant experiments performed in several facilities of approximately the same scale.

(2) Key variables (such as cladding temperature) calculated by the code are then compared with the data set, a set of code errors (calculated – measured) is formed, and statistical properties of the set (mean, standard deviation) are estimated. Further, the confidence intervals for the mean and standard deviation at a desired confidence level, such as 50%, are computed.

(3) Comparisons of the code calculations with new data from other facilities differing in scale or component size are postulated to be similar (in a statistical sense) to comparisons with data from the facilities providing the initial set. From the information obtained in Step (2), a prediction interval is computed for the expected code error for comparison with individual measurements from the new data set. Again, a confidence level, such as 50%, is associated with the prediction interval.

(4) The validity of the prediction interval is tested by comparing code results with experimental data from the new facilities. If the fraction of individual errors falling within the prediction interval is consistent with the confidence interval, the evidence would indicate that the new set of errors belong to the same population as the original set. Further, the new data could then be assimilated into the original data set and the process could be repeated on larger scale facilities.

III. EXPERIMENTAL SELECTION AND ANALYTICAL MODELING

The blowdown and reflood experimental facilities and tests selected for the code assessment study are briefly described in Table I. The results from three groups[2,3,4] of experimental programs were used: the Semiscale Program of blowdown and reflood experiments at EG&G Idaho Inc., the Full-Length Emergency Core Heat Transfer (FLECHT and FLECHT-SET) series of reflood programs at Westinghouse Electric Corporation, and the

TABLE I

RELAP4/MOD6 VERIFICATION DATA USED

Test Facility	Description	Tests Used	Test Objectives/Conditions
Westinghouse FLECHT:			
FLECHT LFR (Low Flooding Rate) Cosine Bundle	Full-length 10 x 10 electrically heated rod bundle separate-effects tests, heated core housing ECC injection into lower plenum	4019	Stepped flooding rate of 0.1524 and 0.0381 m/s at 269 kPa
FLECHT LFR Skewed Bundle	Full-length 105-rod bundle in circular array; thin-wall adiabatic core housing; separate-effects tests ECC injection into lower plenum	11003	Top skewed axial power profile 276 kPa pressure 0.0381 m/s flooding rate
FLECHT-SET, Phase B	Systems reflood 10 x 10 rod bundle Intact and broken loops with steam generators Resistance-simulated pumps ECC injection into bottom of downcomer	2714B	138 kPa pressure 42 K subcooling Constant 4.27-m downcomer head
Semiscale:			
Forced-Feed Mod-1 Reflood	Separate effects core reflood with 40-rod, electrically heated bundle 1.68 m long ECC injection into lower plenum	S-03-D	414 kPa pressure 22 K subcooling

TABLE I (continued)

Test Facility	Description	Tests Used	Test Objectives/Conditions
Semiscale (continued):			
Gravity-Feed Mod-1 Reflood	Systems-effects reflood with 40-rod bundle, 1.68 m long ECC injection into lower plenum Two coolant loops with intact loop steam generator and pump	S-03-5	2.49 kw/m power 78 K subcooling 414 kPa pressure
Blowdown Mod-1	Systems effects blowdown with 40-rod bundle, 1.68 m long	S-04-6	1.44 MW power 15.5 MPa pressure
Blowdown Mod-3	Systems-effects blowdown with full-length 25-rod bundle Two coolant loops with steam generators and pumps ECC injection into lower plenum	S-07-1	2.0 MW power 15.5 MPa pressure
KWU (Kraftwerk Union) PKL Reflood Facility, Erlangen, West Germany	Three-loop, systems-effects reflood facility with steam generators and simulated pumps 340-rod, full-length electrically heated bundle, 3.9 m long, with hot, average, and cool radial zones	K5A	200% cold-leg break Cold-leg ECC injection 93 K initial subcooling Injection rate equivalent to design values for five injection locations

Primary Coolant Loop (PKL) reflood experiments at Kraftwerk Union (KWU). The assessment approach treated comparisons of the code results with the Semiscale Mod-1 and FLECHT/FLECHT-SET data as the initial data sets, and prediction intervals were computed for the Semiscale Mod-3 and PKL results. Semiscale Mod-3 represents an increase in core length (3.66 m) over Semiscale Mod-1 (1.68 m). PKL (with 340 full-length rods) represents a significant radial and axial scale increase over FLECHT (about 100 full-length rods).

Calculations that were made to predict the performance of Semiscale Mod-3 Test S-07-1 and of PKL Test K5A used code input and modeling guidelines that were as consistent as possible with those used in acquiring the initial data sets. The conceptual difference in the calculations was that the PKL and Mod-3 simulations were in the form of blind test predictions: that is, data were not available, or access to the experimental data was restricted, until after the code calculations were completed.

The procedures used in the code assessment calculations reflect a user-oriented point of view designed to ensure objectivity of evaluation. The approach taken was to formulate a firm set of ground rules prior to conducting analyses. These ground rules pertained to modeling techniques, code option selection, and code user input values and were based on the best published information from all prior code-checkout studies. The use of a fixed set of ground rules throughout eliminates code tuning[a] and provides consistency among the several blowdown and reflood studies.

IV. APPLICATION OF THE PROCEDURES

Calculations were made using the RELAP4 analytical models developed for the selected Semiscale Mod-1, FLECHT, and FLECHT-SET experiments. From the results, heater-rod cladding temperature was selected as a key variable for comparison to illustrate the results of this code-evaluation study. A representative range of temperature levels was ensured for each code-data comparison by using measurements of temperature obtained in the lower, middle, and upper regions of the test sections. In all cases, the maximum predicted temperature at various vertical locations in the core was compared with the maximum measured temperature, irrespective of the time at which the peaks occurred. A typical, individual error obtained by this procedure for Semiscale Mod-1 Test S-04-6 near the core midplane is shown in Figure 1.

Figure 2 illustrates the errors obtained from code-data comparisons in a display that relates the calculated maximum cladding surface temperatures to the maximum values measured in the Semiscale Mod-1 blowdown test, Test S-04-6. The measured temperatures were obtained from experimental histories of 14 thermocouples presented in Reference 5. RELAP4 calculations accounted for actual location of the thermocouples at the inside

[a] This is the process of optimizing code calculations to match results of a single experiment.

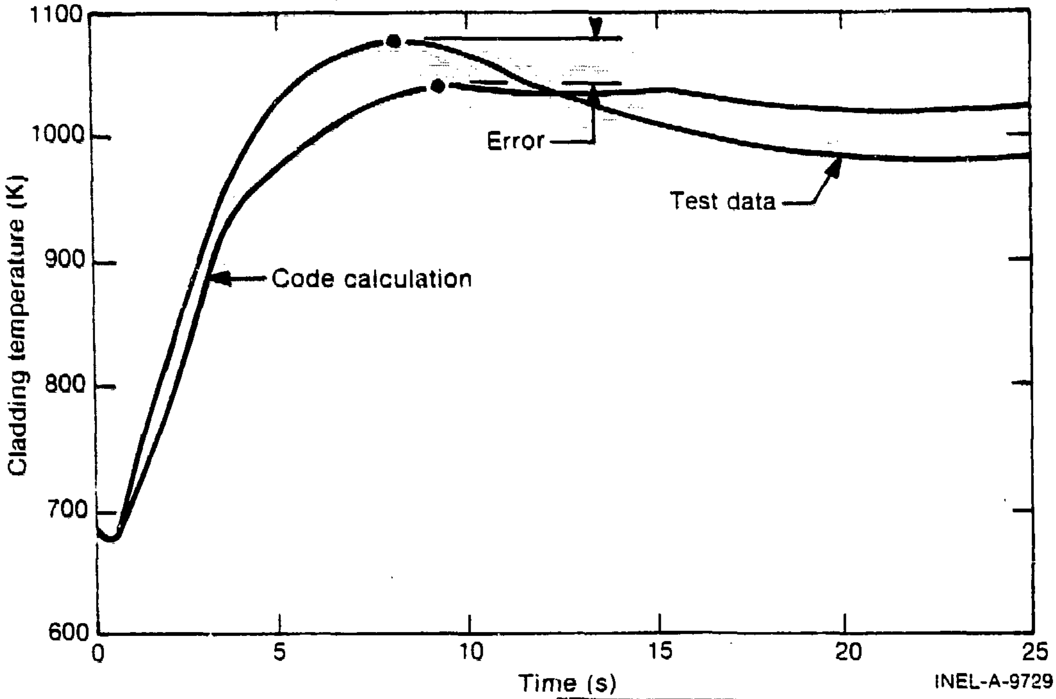

Fig. 1 Typical results for Semiscale Mod-1 Test S-04-6.

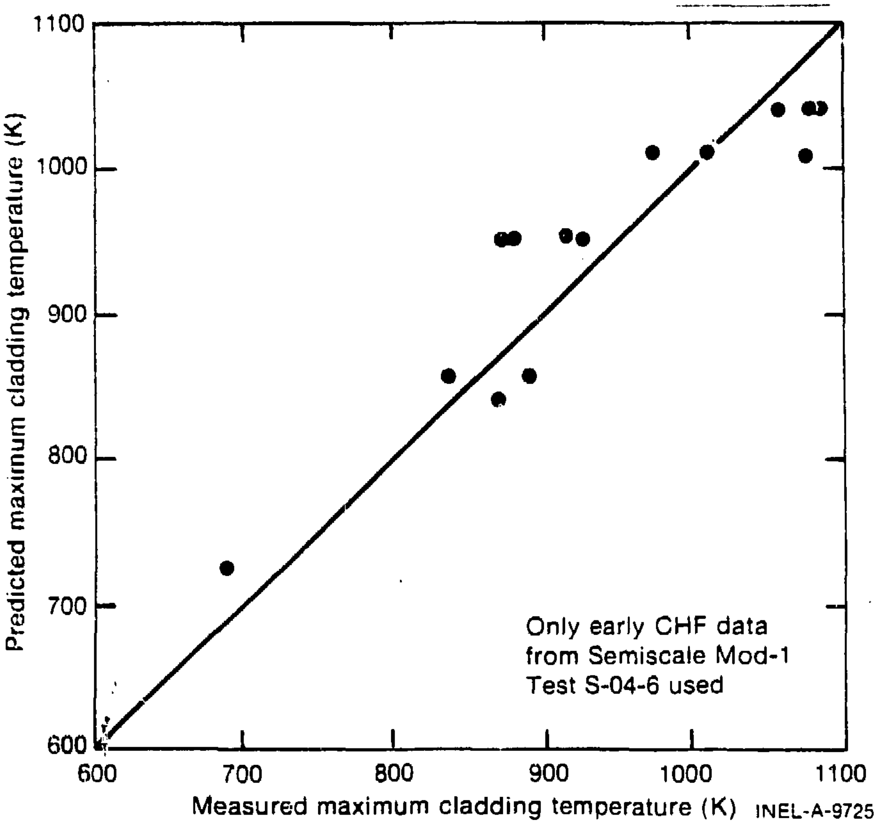

Fig. 2 Semiscale Test S-04-6 data set.

surface of the heater-rod cladding. The errors were calculated by subtracting the maximum measured temperature from the maximum calculated temperature at corresponding axial locations.

Because the incidence of delayed CHF has been demonstrated experimentally to be nonrepeatable, even within the same facility, the data presented in the figure represent only those measurements indicative of the early occurrence of CHF. Moreover, the use of early CHF data give a best estimate of maximum cladding temperatures that are representative of the overall core, rather than of selected rods. The calculations were determined to have a mean error of +12 K and a standard deviation of 43 K.

The blowdown error data were used in the calculation of prediction intervals, based on confidence levels of 50 and 95%. These intervals are shown in Figure 3, which retains the same format used in Figure 2. The data obtained from Semiscale Mod-3 Test S-07-1 are plotted against the corresponding calculated maximum cladding surface temperature at the same core elevation and are superimposed on the prediction-interval plot. All 45 data points were used. Of these, three fell outside the region of 95% confidence, although the majority of the high-temperature points lie outside the region of 50% confidence.

Figure 4 summarizes comparisons of code results with test data from the complete initial set of FLECHT, FLECHT-SET, and Semiscale reflood data. RELAP4/MOD6 was

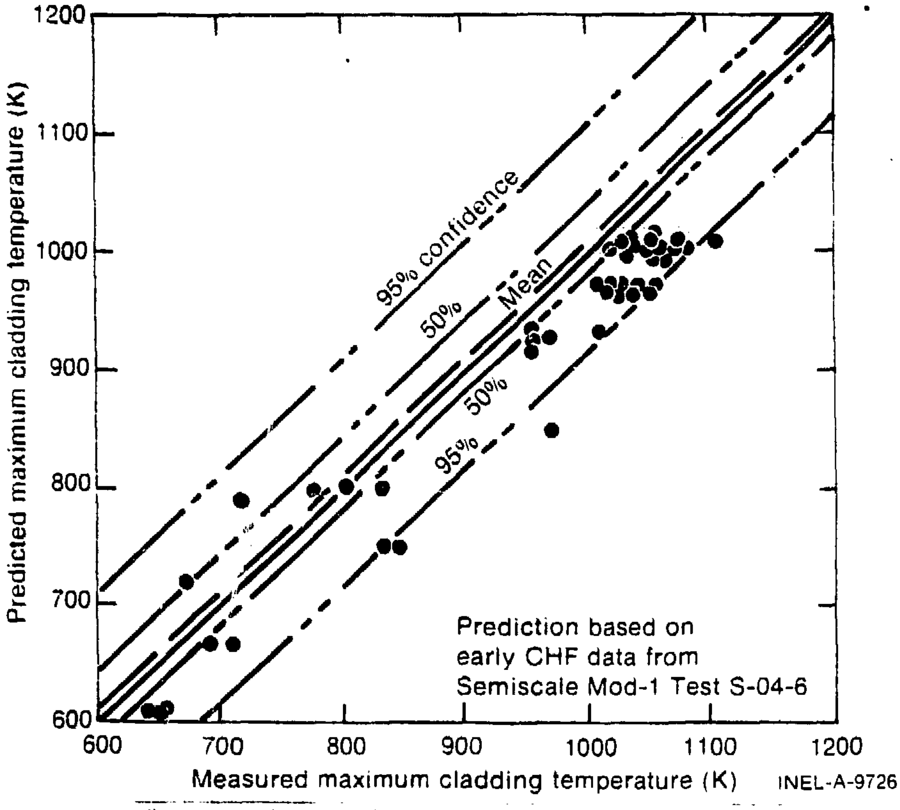

Fig. 3 Comparison of Semiscale Mod-3 Test S-07-1 data with prediction.

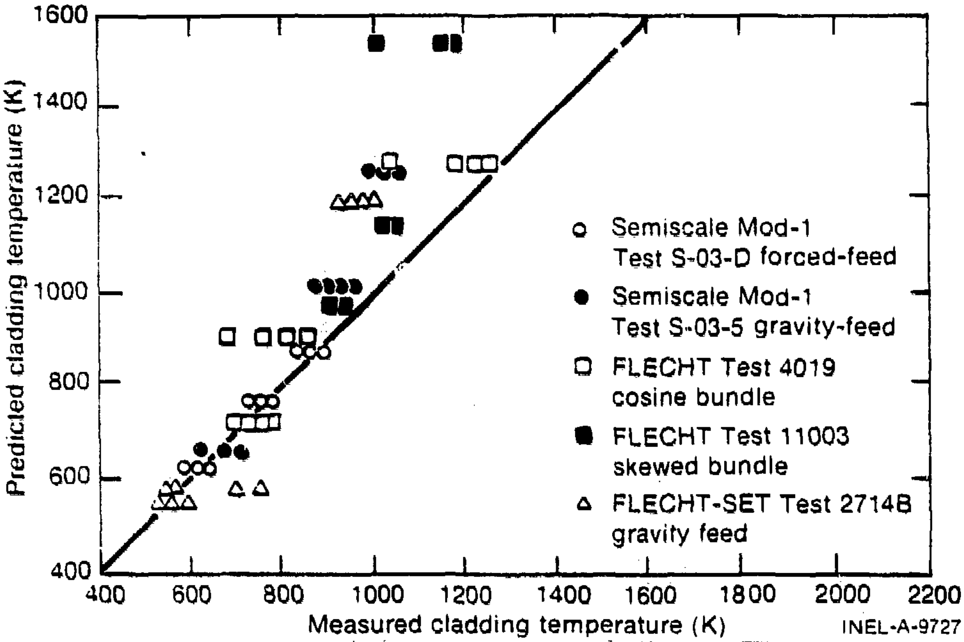

Fig. 4 Summary of cladding temperatures – initial data set.

found to compute reflood maximum cladding temperature with an estimated mean error of +95 K. The estimated standard deviation of the mean is 134 K.

Through use of the aggregate results shown in Figure 4, a prediction interval was determined for the error in reflood maximum cladding temperature anticipated in the PKL facility. At a 50% confidence level the calculation error for any single thermocouple should be between -4 K and +187 K. This prediction interval is shown in Figure 5, which summarizes the comparison of RELAP4/MOD6 reflood temperature calculations with the representative PKL Test K5A data set.

These results are encouraging in that the PKL comparisons are consistent with the prediction interval. Since this interval is at a 50% confidence level, 17 of 34 measurements would be expected to fall within this range. Of the data points taken, 25 out of 34 were found to fall within the prediction interval.

V. CLOSING STATEMENT

A method has been proposed and successfully tested using the RELAP4/MOD6 code comparisons with reference sets of data to predict the accuracy of calculations of behavior in new experiments. The method appears to be a powerful tool in extrapolating from scale to scale in thermal-hydraulic analysis. Further testing of this technique is planned for predictions of additional experiments, including the Loss-of-Fluid Test (LOFT). Ultimately, this method may be applied to specify the accuracy of code predictions of postulated PWR LOCA behavior.

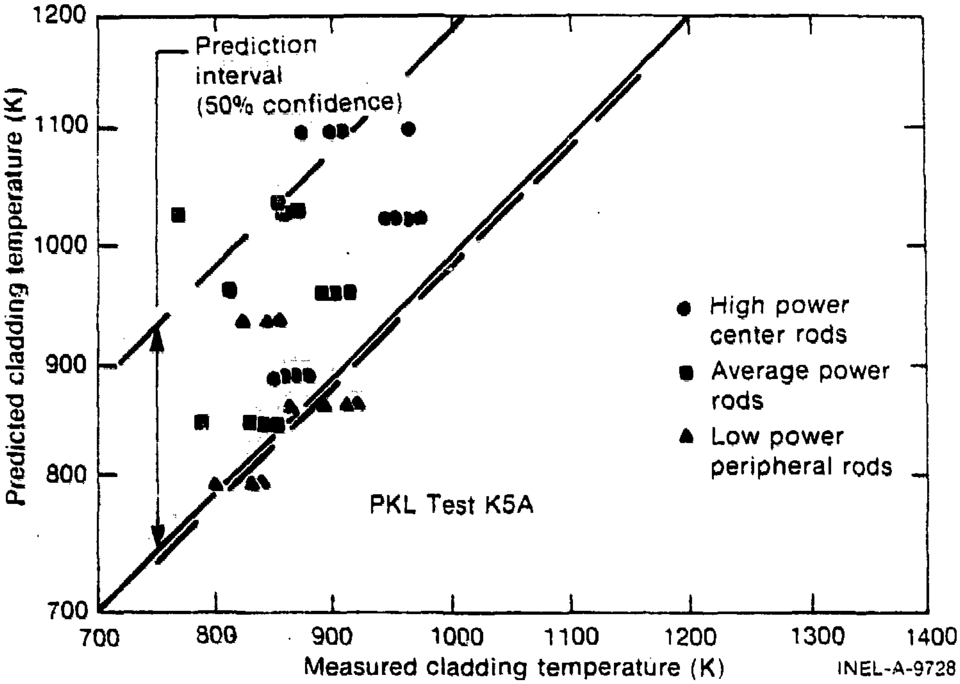

Fig. 5 Summary of cladding temperatures – PKL data set.

VI. REFERENCES

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