COMMIX ANALYSIS OF FOUR CONSTANT FLOW THERMAL UPRAMP EXPERIMENTS PERFORMED IN A THERMAL HYDRAULIC MODEL OF AN ADVANCED LMR

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ABSTRACT

The three-dimensional thermal hydraulics computer code COMMIX-1AR was used to analyze four constant flow thermal upramp experiments performed in the thermal hydraulic model of an advanced LMR. An objective of these analyses was the validation of COMMIX-1AR for buoyancy affected flows. The COMMIX calculated temperature histories of some thermocouples in the model were compared with the corresponding measured data. The conclusions of this work are presented.

I. INTRODUCTION

A thermal hydraulic model[1,2] of an advanced liquid metal reactor (LMR) was built at the Argonne National Laboratory (ANL) to simulate buoyancy influenced flows. The ANL model is made of transparent plastic, and uses water as coolant. J. J. Oras et al.,[1] performed four constant flow thermal upramp experiments in the model to examine the influence of water flow rate on thermal stratification in the lower plenum. These experiments were slow transients (duration ~ 2000 - 5500 sec.), and had four different inlet flow rates: 5%, 15%, 30%, and 60% nominal flow. They are analyzed here using the three-dimensional thermal hydraulics computer code COMMIX-1AR (a modified version of the code COMMIX-1A[3]; an objective of these analyses was the validation of COMMIX-1AR for buoyancy affected flows.

II. THE ANL THERMAL HYDRAULIC MODEL AND THE CONSTANT FLOW THERMAL UPRAMP EXPERIMENTS

An elevation view of the thermal hydraulic model[1] showing internal component arrangement and important thermocouple locations is presented in Figure 1. It has two IHX's, four coolant pumps, eight core inlet pipes, a core barrel and a radial shield. In the model, an immersion heater represented the thermal output of core while a collection of perforated plates represented pressure drop across the core of the LMR.

Oras et al.,[1] conducted the constant flow thermal upramp experiments in the following way:

(i)   the model was filled with water at the required initial temperature with the immersion heater and the internal pumps turned off;

(ii)   a steady state flow was established in the vessel by supplying water through a bottom inlet at a constant flow and temperature equal to the filled water, and by discharging the water through an exit manifold located in the lower plenum;

and

    (iii)   a thermal upramp experiment was initiated by raising the temperature of water at the inlet to a specified higher value in a short period of time while keeping the steady state flow; the temperature and flow rate levels were then maintained constant until the end of the experiment.

The water flow path in the model during these experiments was as follows: water at a specified flow rate and temperature entered the thermal hydraulic model through a bottom inlet, flowed up through the core barrel into the upper plenum, from the upper plenum it entered the IHX's, from the IHX's water flowed down into an annular spacing between the radial shield and the vessel wall passing through the IHX exit pipes, from the annulus it entered the lower plenum and flowed up into the inside of the radial shield. From the radial shield it flowed through pumps into pump outlet plenums, from each pump outlet plenum water flowed down through two core inlet pipes into an exit manifold, and from the exit manifold water exited the model. Thermal front (an interface between the hot and cold fluids in the thermal upramp experiments) formed during the transient also traveled along the same path.

Thermocouples were placed at several locations along the flow path in the model by Oras et al.,[1] to record temperature histories. The placement of some important thermocouples is shown in Fig. 1. In particular, eleven thermocouples (LP1 through LP11) located on a vertical string, slightly inside of the radial shield at the bottom left of the vessel in the lower plenum, can be seen in Fig. 1.

III.   COMMIX STEADY-STATE AND TRANSIENT MODELING

COMMIX-1AR is a modified version of the three-dimensional thermal hydraulic code COMMIX-1A[3] with several improvements. It can be run in either steady-state or transient mode. The improvements in COMMIX-1AR that are relevant to the present analysis are double precision arithmetic, conjugate gradient solution technique in the pressure equation solver, an improved energy equation solver, and region dependent specification of turbulent transport properties as opposed to one constant value for each property in the whole vessel. These modifications made the code COMMIX-1AR run faster and produced higher precision in the calculations than was possible with COMMIX-1A[3].

The thermal hydraulic model has a cylindrical shape and has a four-fold symmetry around the vertical axis. Hence, one quarter of the experimental model (i.e., a cylindrical 90° sector) was chosen for the calculational model; it had a 90° sector of core barrel, one pump, half of the IHX, 90° sector of radial shield, two core inlet pipes and one exit manifold. Nodalization was chosen so as to make a balance between the need for reproducing three-dimensional flow patterns accurately on the one hand and the need for reducing the computational time on the other hand; design level noding was used in the calculations. The calculational model had 1402 computational cells with 8 radial nodes, 7 angular nodes and 27 axial nodes.

The velocity and temperature boundary conditions must be supplied in both steady-state and transient calculations while using the code COMMIX-1AR; the results of the steady-state calculation become the initial conditions for the transient. The boundary conditions for the transient calculation are the product of an initial steady-state value times a transient scaling factor. Since the flow rate was constant in the thermal upramp experiments, the transient scaling factor for velocity had a value of unity. The transient scaling factor for temperature had a maximum value equal to the ratio of hot and cold water temperatures. This value was acquired in the experiments in a short period of time relative to transient duration (i.e., the thermal upramp was not sudden at time t = 0). The measured transient scale factor data were used in the calculations.

The four thermal upramp experiments differed mainly in the inlet flow rate, but there were some differences among them in the in initial temperature of water in the vessel (24.25°C, 21.2°C, 23.9°C, and 21.6°C for the 5%, 15%, 30%, and 60% nominal flow, respectively). The inlet hot water temperature was also slightly different in the four experiments (37.8°C, 38.2°C, 38.9°C, and 37°C for the 5%, 15%, 30%, and 60% nominal flow, respectively).

The computational data of the transients are as follows:

(i) Even though design level noding was used, comparatively finer axial mesh size (1.5") was used in the lower plenum.

(ii) Measured core pressure drop data was utilized in the calculations.

(iii)   All regions of the model were thermally connected, and pressure drop due to frictional forces was included in the computations.

(iv)   The convergence criterion for the three velocity components and energy was set at 1.0×10^{-6} at each time step.

(v)   During the transients, both momentum and energy equations were solved at every time step.

(vi)   All calculations were done on CRAY X-MP/14 computer with an accuracy equivalent to double precision on IBM-3033.

IV.   RESULTS OF COMMIX ANALYSIS

The four constant flow thermal upramp experiments measured the effect of thermal buoyancy on forced flow, especially in the lower plenum. In each experiment, temperature histories at several important locations along the flow path in the thermal hydraulic model were recorded by Oras et al.[1]. To measure the global temperature distribution, they placed thermocouples sparingly at the entrances and exits of key regions along the flow path, but to measure the detailed local axial temperature distribution in the lower plenum, they put eleven thermocouples on a vertical string there (see Fig. 1). The calculated and measured temperature histories of some representative global and local thermocouples are compared here.

IV.1   The Global Temperature Histories

The calculated and measured temperature histories in the 60%, 30%, 15%, and 5% nominal flow experiments are compared in Figures 2 and 3 at two representative global thermocouples, namely those located at the core outlet and IHX exit in the model. In these figures, the calculated temperature history is denoted by a solid line, and the measured temperature history is denoted by a wiggly line – a trace of the experimental data[1]. In all four transients, the calculated and the corresponding measured thermal front arrival times (i.e., the time when the temperature begins to increase) agreed well with each other. Further, in the 60%, 30%, and 15% nominal flow transients, the calculated and the measured global temperature histories are also in very

good agreement. In the 5% flow transient, however, the calculated temperature histories are slightly below the corresponding measured temperature histories during the entire transient. This deviation could be the result of non-isothermal conditions in the experiment at time t = 0 (initial temperatures of global thermocouples were higher than the initial temperature of local thermocouples in the lower plenum); the calculation, however, used a uniform value corresponding to that of local thermocouples for the initial temperature in the vessel. Similarly, an excellent agreement between the calculated and the measured temperature histories was also found at other global thermocouples in the model.

IV.2.   The Local Temperature Histories in the Lower Plenum

The calculated and the measured temperature histories in the 60%, 30%, 15% and 5% nominal flow transients are compared in Figures 4 and 5 at two representative local thermocouples, LP4 and LP11, which are located in the top and bottom regions of the lower plenum, respectively. In these figures, as before, the calculated temperature history is denoted by a solid line, and the measured temperature history is represented by a wiggly line - a trace of the experimental data[1]. In comparison to global thermocouples, the agreement between the calculated and the corresponding measured local temperature histories is not as good in all four transients. In particular, the calculated and the measured slopes of the temperature history curves differ significantly in all transients. During these transients, the lower plenum was thermally stratified, and while the existence of a stratified zone and the location of its interface was predicted by the code, the time evolution of the temperatures in the zone was not well predicted by the code. An earlier detailed COMMIX-1A calculation[2], with localized geometry models, of a variant of the 15% nominal flow transient showed that a very fine axial mesh and an advanced turbulence model, to handle localized recirculatory flows, would be needed to improve the agreement between the calculated and the measured histories in the lower plenum. These inferences are expected to be valid also in the work reported here.

V.   CONCLUSIONS

In each thermal upramp transient, the temperature histories of thermocouples located along the flow path (i.e., global thermocouples) were well predicted by the code.   However, the agreement between the calculated and measured temperature histories was not as good in the thermally stratified lower plenum in all four transients. These calculations show that design level noding is too coarse for stratified lower plenum and that improvements relative to the constant diffusivity turbulence modeling available in COMMIX-1AR are needed.   These needs are currently being addressed as a part of the ongoing refinement of COMMIX.
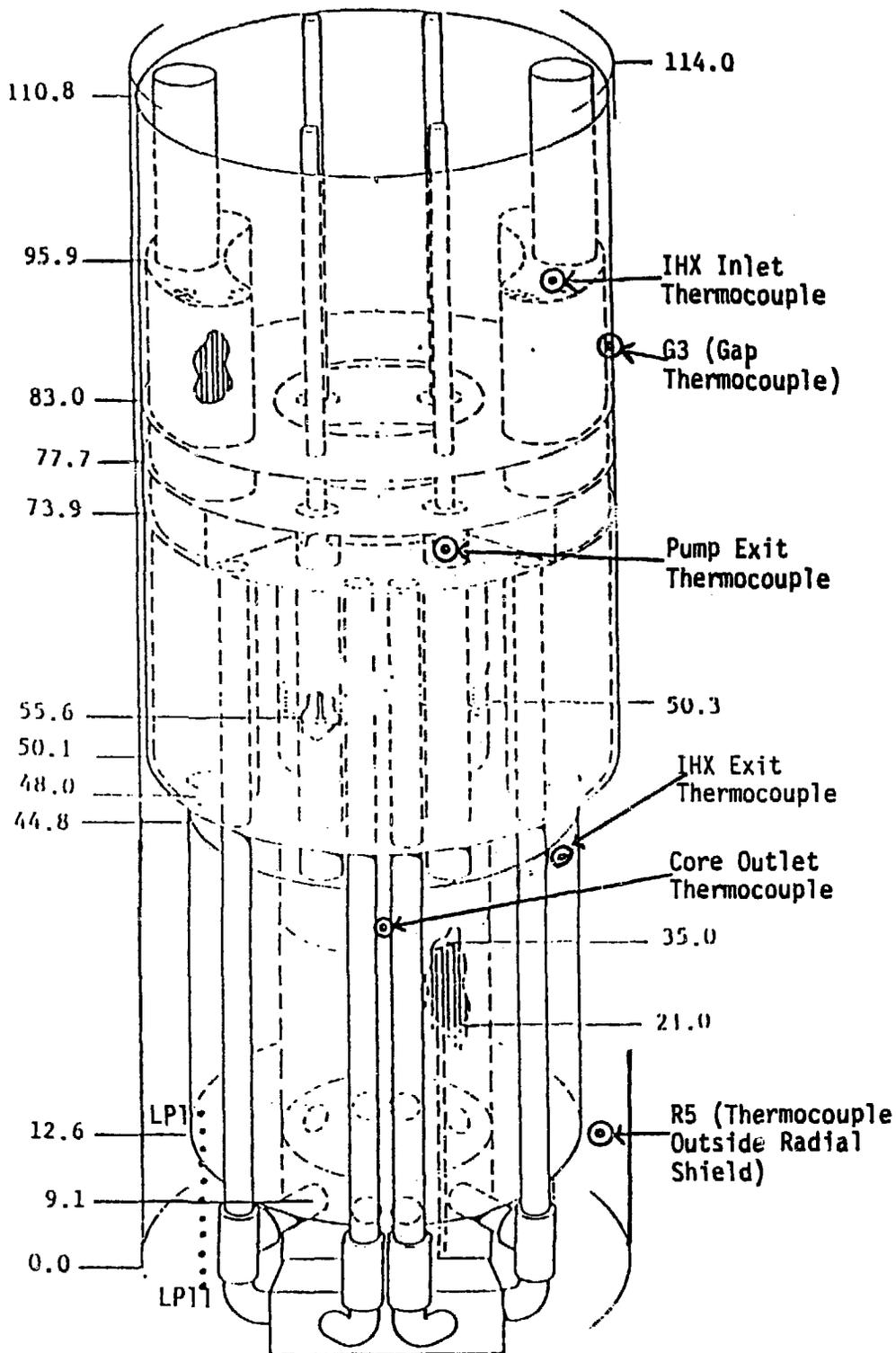
FIGURE 1. ELEVATION VIEW OF THE ANL THERMAL HYDRAULIC MODEL SHOWING THERMOCOUPLE LOCATIONS AND AXIAL DIMENSIONS (inches above floor of model)
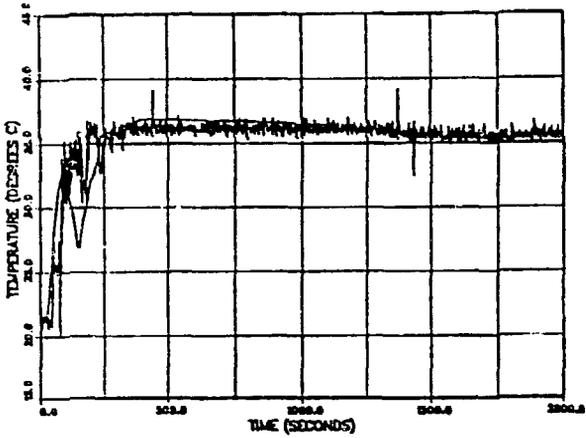
a) 60% nominal flow
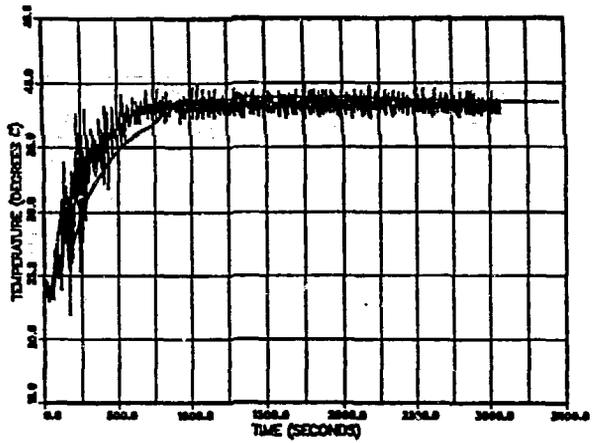
b) 30% nominal flow
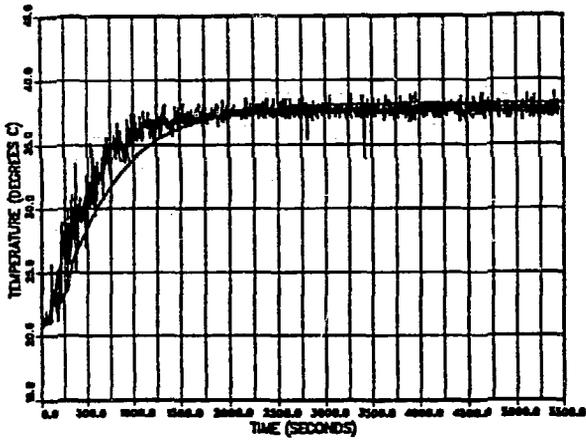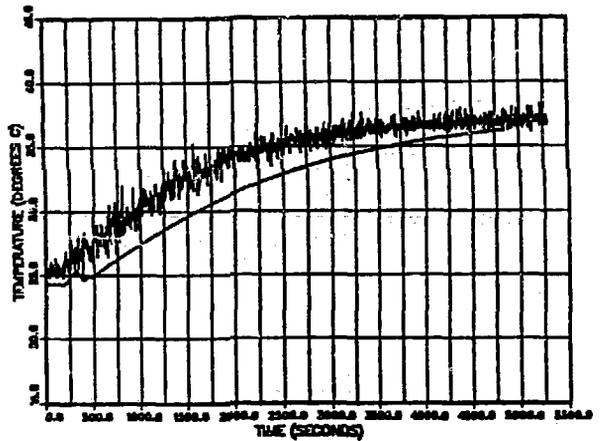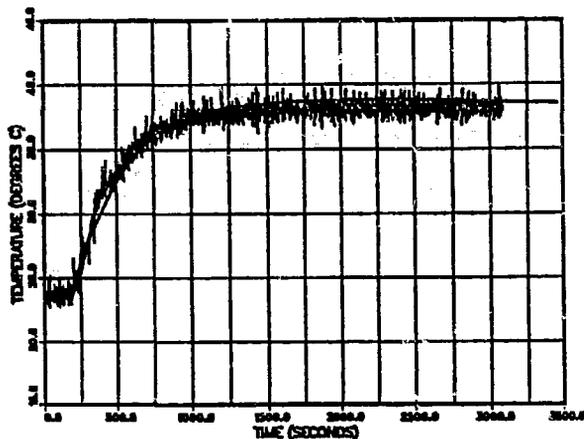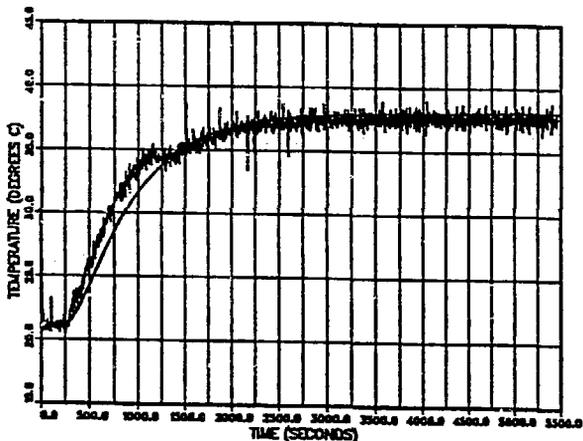
c) 15% nominal flow

d) 5% nominal flow

FIGURE 2.   COMPARISON OF THE CALCULATED AND THE MEASURED GLOBAL
TEMPERATURE HISTORIES AT THE <u>CORE OUTLET</u> IN THE CONSTANT
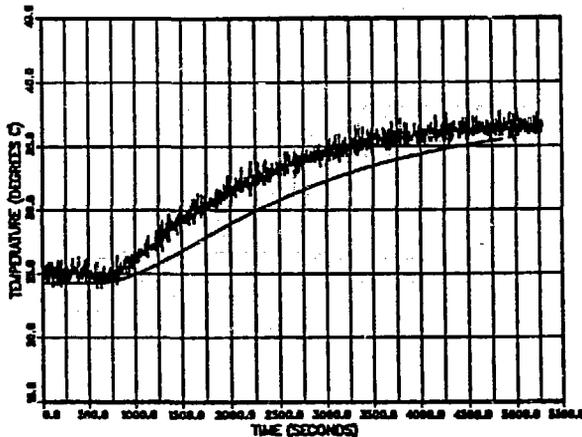FLOW THERMAL UPRAMP TRANSIENTS
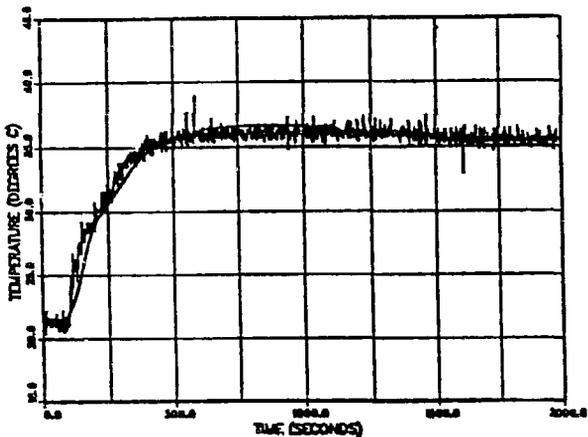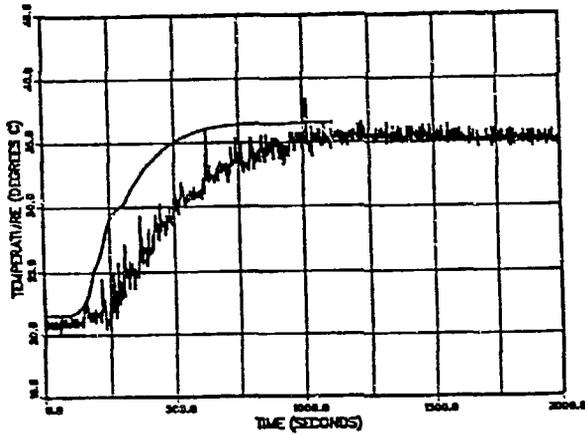
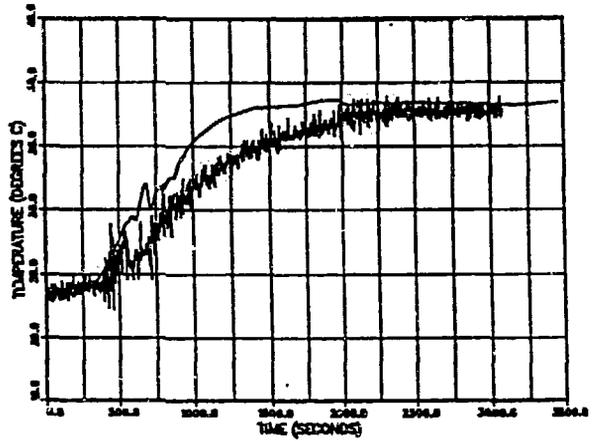a)   60% nominal flow

b)   30% nominal flow
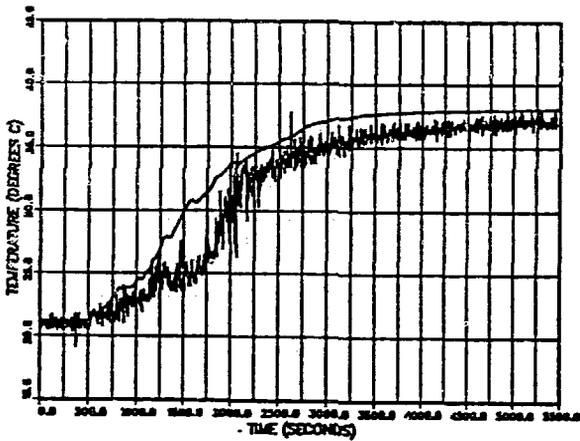
c)   15% nominal flow

d)   5% nominal flow

FIGURE 3.   COMPARISON OF THE CALCULATED AND THE MEASURED GLOBAL
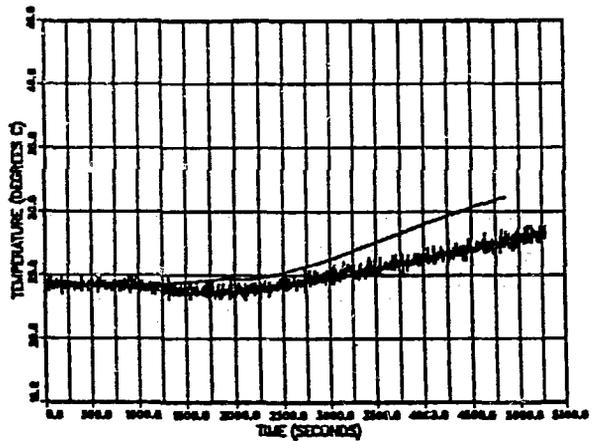TEMPERATURE HISTORIES AT THE IHX EXIT IN THE CONSTANT FLOW
THERMAL UPRAMP TRANSIENTS

a)   60% nominal flow
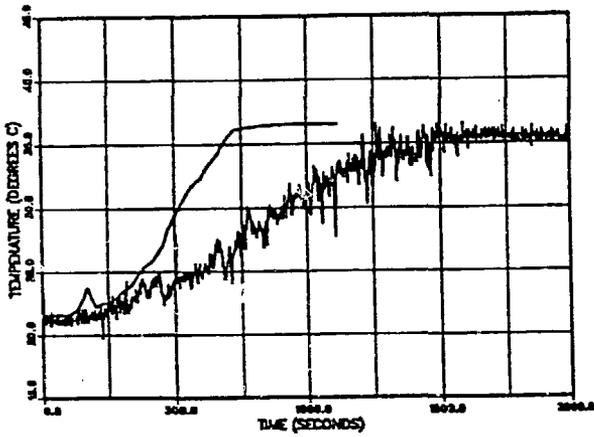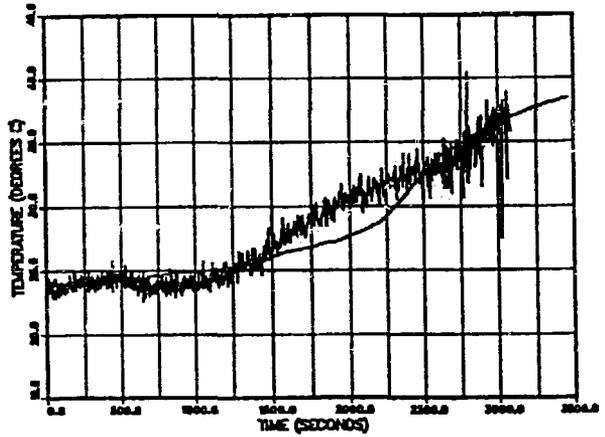
b)   30% nominal flow

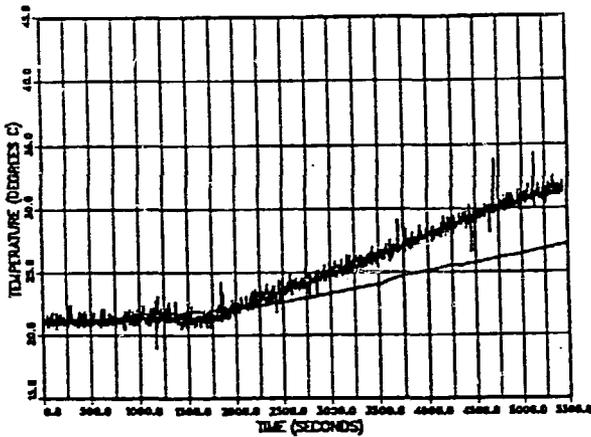c)   15% nominal flow

d)   5% nominal flow

FIGURE 4. COMPARISON OF THE CALCULATED AND THE MEASURED
TEMPERATURE HISTORIES OF THERMOCOUPLE LP4 IN THE TOP
REGION OF THE LOWER PLENUM IN CONSTANT FLOW THERMAL
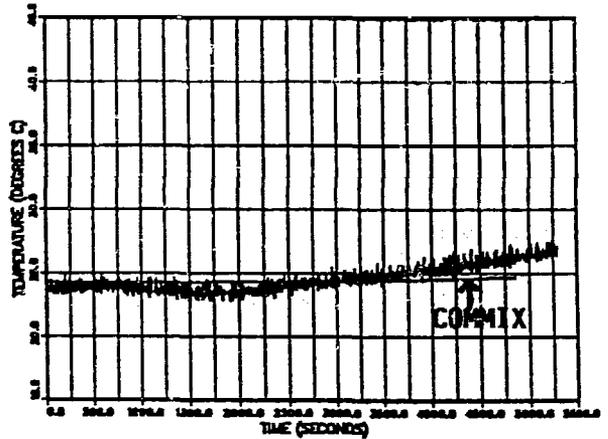UPRAMP TRANSIENTS

a) 60% nominal flow

b) 30% nominal flow

c) 15% nominal flow

d) 5% nominal flow

FIGURE 5. COMPARISON OF THE CALCULATED AND THE MEASURED
TEMPERATURE HISTORIES OF THERMOCOUPLE LP11 IN THE BOTTOM
REGION OF THE LOWER PLENUM IN CONSTANT FLOW THERMAL
UPRAMP TRANSIENTS

VI.   REFERENCES

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