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SODIUM NATURAL CONVECTION TESTING IN THE THERMAL-HYDRAULIC OUT-OF-REACTOR SAFETY (THORS) FACILITY*

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ABSTRACT

A comparison is made between experimental data and analytical results for a single-phase natural convection test in an experimental sodium loop. The test was conducted in the Thermal-Hydraulic Out-of-Reactor Safety (THORS) facility, an engineering-scale high temperature sodium loop at the Oak Ridge National Laboratory (ORNL), used for thermal-hydraulic testing of simulated Liquid Metal Fast Breeder Reactor (LMFBR) subassemblies at normal and off-normal operating conditions. Electrical heating in the 19-pin assembly during the test was typical of decay heat levels. The test chosen for analysis in this paper was one of seven natural convection runs conducted in the facility. In this test the bypass line was open to simulate a parallel heated assembly and the test was begun with a pump coastdown from a small initial forced flow. The computer program used to analyze the test, LONAC (LOw flow and NAtural Convection), is an ORNL-developed, fast running, one-dimensional, single-phase, finite-difference model used for simulating forced and free convection transients in the THORS loop.

Reasonably good agreement was obtained between experimentally-measured and LONAC-predicted temperatures, demonstrating the ability of a simplified computer code to model the THORS loop. The experimental facility was designed a decade ago with no intent to determine detailed loop temperature measurements required for testing under natural convection conditons. Insights have been obtained which will be utilized in planning future tests under natural convection conditions and in code improvements for simulating long transients.

The next configuration to be tested in the THORS facility, designated as the Shutdown Heat Removal System (SHRS) Assembly 1, will consist of two 19-pin bundles in parallel, an upper plenum tank, and a sodium-to-sodium intermediate heat exchanger. Loop instrumentation will be extensive and the thermal characteristics of loop components will be known. Necessary modifications to LONAC will be made including a more detailed model of the upper plenum tank. Forced convection and thermal convection testing will be conducted with both single-phase and two-phase (boiling) flow.

INTRODUCTION

The Thermal-Hydraulic Out-of-Reactor Safety (THORS) facility at the Oak Ridge National Laboratory (ORNL) is an engineering-scale forced-convection sodium loop (40 ℓ/s, 2MW) in which simulated (electrically heated) LMFBR fuel subassemblies are tested at normal and off-normal operating conditions. The facility, which has been in operation for over ten years, was originally designated as the Fuel Failure Mockup (FFM) facility and was intended for steady-state single-phase bundle testing. Initial testing was done on relatively short (460 to 610 mm-length) 19-pin bundles at conditions characteristic of reactor flow and power, and with various inlet and heated-zone blockages. For the past five years sodium boiling tests have been conducted with various loop modifications made to provide dynamic simulation of bundle conditions for transient testing. However the facility was intended for bundle testing only and the loop was neither designed nor instrumented to obtain data in the loop components (pump, heat exchanger, etc.). Bundle 6 was a 19-pin bundle fabricated for boiling tests. This bundle had the same configuration as a fuel subassembly in the Fast Flux Facility (FFTF). In the test program for Bundle 6, seven single-phase free-convection tests were conducted.

THORS FACILITY

An isometric drawing of the primary piping and major components of the THORS facility as they were at the time of this testing is shown in Fig. 1. Forced flow is provided by a variable-speed vertical-shaft centrifugal pump capable of delivering 40 ℓ/s sodium at a pressure difference of 960 kPa. Flow from the pump was divided into two flow paths, one through the test bundle and one through a bypass line which simulates the hydraulics of flow through a subassembly in parallel with the test bundle. Flows from the test bundle and the bypass line mix in an expansion tank simulating the sodium plenum above the reactor core. The expansion tank also serves to mix hot sodium from the test bundle and relatively cold sodium from the bypass line so that the remainder of the loop is not subjected to excessive sodium temperatures. The expansion tank contains argon cover gas which simulates the reactor vessel cover gas volume. The centrifugal pump also has a free surface with an argon cover gas volume. The pressure of the pump cover gas is normally regulated at a fixed rate of 34 kPa above atmospheric pressure. The sodium levels in both the expansion tank and the centrifugal pump bowl must not exceed prescribed maximum and minimum values placing some constraint on the severity of transient tests run. The pressure of the cover gas above the free surface of the expansion tank may either be fixed at the same value as that of the pump bowl cover gas by opening the cover gas equalizing value (HV-256, Fig. 1) or allowed to "float" (HV-256 closed). The test section inlet valve could be adjusted to simulate the pressure drop of the reactor inlet flow paths, and the bypass line had a control valve which could be adjusted to control the ratio of the bypass flow to the test section flow. The ratio of the bypass line cross-sectional area to that of the test section was approximately 13 to 1.

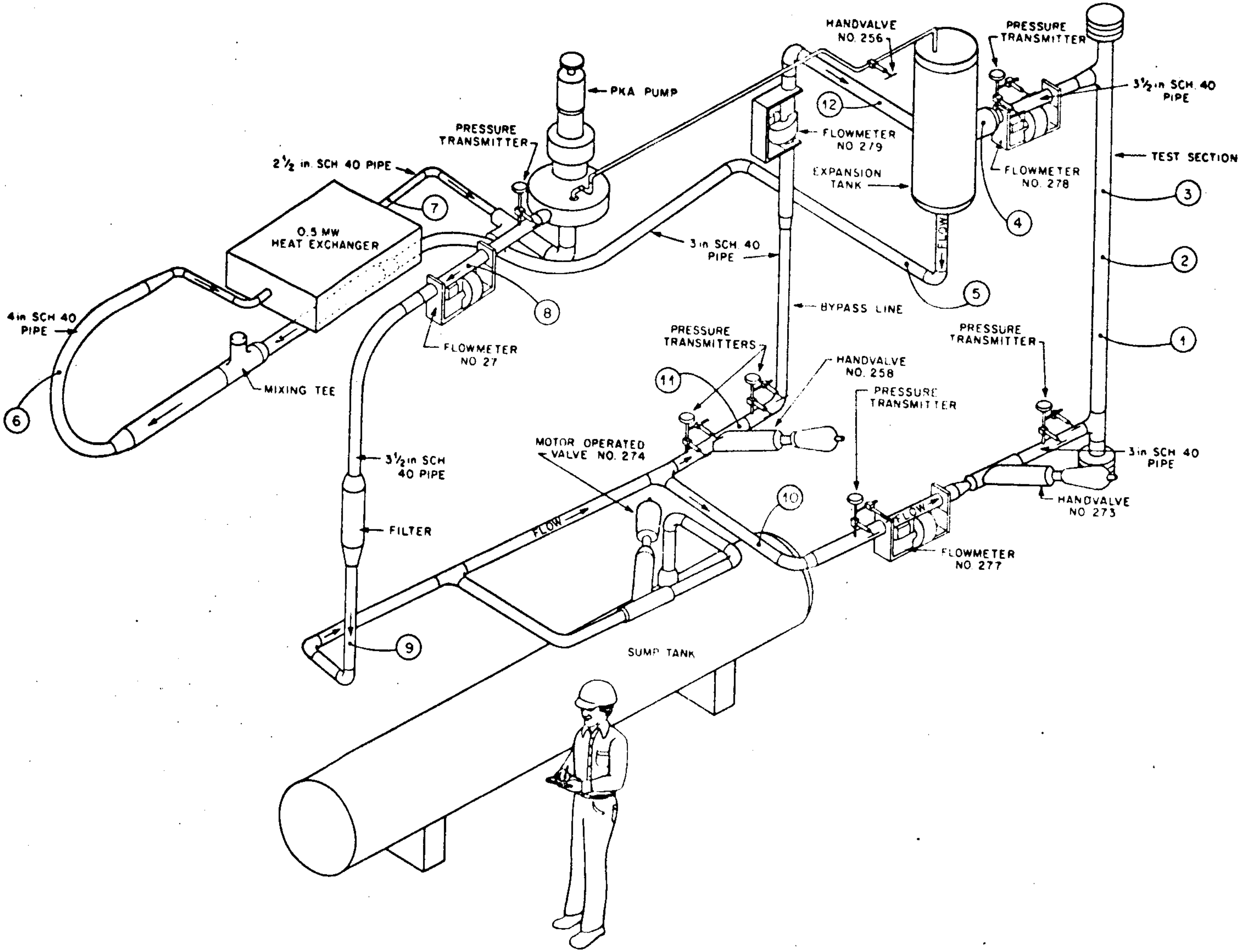

Fig. 1. Isometric drawing of the THORS Facility for Bundle 6 testing. Circled numbers indicate the locations of the thermocouples used for comparisons of experimental and analytical results given in Figs. 2 through 5.

Automatic control of power and pump speed were provided so that prescribed and reproductible flow and/or power transients could be performed. Pressure transducers, flow meters and 27 pipe-wall thermocouples (strapped to the loop piping) were installed to measure system operating parameters. Electrical trace heaters were installed on all system lines (which were also insulated) to preheat the system prior to filling and to minimize loop heat losses during operation. A complete description of the facility configuration and bundle for this testing is given in reference 1.

BUNDLE DESCRIPTION

The test section used for this testing was designated as THORS Bundle 6[1]. It was a 19-pin bundle of the same configuration as fuel subassemblies the Fast Flux Test Facility (FFTF). The electrically heated pins were 5.84 mm in diameter spaced by 1.42-mm-diam helical wire-wrap spacers on a 305-mm helical pitch. The gap between the peripheral pins and the hexagonal container was 0.71 mm, one-half the nominal pin-to-pin spacing. This configuration was used to flatten the sodium temperature across the bundle. In order to give a better simulation of the central region of a full reactor subassembly, block thermal insulation surrounded the bundle hexagonal container. During prior operation, a leak had developed in the insulating containment and sodium had permeated the porous insulation. An estimate was made of the thermal properties of the sodium-permeated insulation and these values were used in analyses of this test.

The heated length of Bundle 6 was 914 mm. A variable-pitch helical heater winding was used to produce a 1.3 peak-to-mean axial chopped-cosine power distribution. Downstream of the heated length, there was a nickel reflector and a simulated fission gas plenum which had the same lengths and thermal properties as those of an FFTF fuel subassembly.

Both the heated length and the simulated fission gas plenum were instrumented with wire-wrap thermocouples (magnesium oxide insulated chromel-alumel junctions inside the wire wraps) and duct-wall thermocouples (sheathed chromel-alumel thermocouples inserted into holes bored to within 0.10-0.20 mm of the inside surface of the hexagonal bundle container). In addition the heated section was instrumented with "heater-internal" thermocouples (chromel-alumel junctions spot-welded to the inner surface of the heater sheath). At the time of this testing there were 33 wire-wrap, 45 duct-wall and 43 heater-internal thermocouples operating reliably in the bundle. All bundle thermocouples and pertinent loop instrumentation were recorded on magnetic tape during testing using a fast-response Data Acquisition System (DAS) controlled by PDP-8E computer.[2]

TEST PROCEDURE

Seven natural convection tests were run.[3] The test herein described was designated Test 39. It was the only natural convection test in which the bypass line valve was open to simulate hydrodynamically a bundle in parallel with the test bundle. Due to the parallel thermal convection flow paths, it was the most prototypic test and was the most difficult to analyze. This test is described in detail in reference 4.

During preliminary testing, loop trace heater settings were determined for minimum loop heat losses in the temperature range of interest. The appropriate settings were used for the thermal convection tests. Prior to running Test 39, the valve in the bypass line was positioned at a setting which was thought to give approximately equal pressure drops in the test section and bypass line for equal flows. The pressure loss coefficient for this valve setting had been previously measured at higher flows but the existing flow meters were not sufficiently sensitive to make this measurement in the thermal convection flow range. The test-section inlet valve was set fully open. The pump speed was adjusted to give a test section flow of approximately 0.13 ℓ/s, the bundle power was set at 7.3 kW total, and the trace heaters on the bypass line were set at their maximum output (6.6 kW) to simulate a parallel heated subassembly. After bundle and loop temperatures had equilibrated, the pump was turned off and the cover gas equalization valve, HV-256, was opened to begin the test. Data were recorded for approximately two hours. Useful data consisted primarily of bundle and loop temperatures. Existing flow meters and pressure transducers were not sufficiently accurate in the thermal convection range to be useful.

METHOD OF ANALYSIS

THORS Bundle 6 natural-convection tests were analyzed using LONAC (LOw flow and NAtural Convection), a one-dimensional transient, single-phase, finite difference representation of the equations of conservation of mass, energy, and momentum. LONAC is described in detail in reference 5. Inclusion of structural thermal inertia and of a reasonably well detailed model for the sodium-permeated insulation around the test bundle was found to be essential for accurate analytical modeling. The heat sink resulting from the sodium permeated insulation had to be carefully modeled due to its close proximity to the pin bundle. Other structural components such as piping, the pump, expansion tank and the heat exchanger were thermally modeled as single nodes in intimate contact with the adjacent sodium node.

The loop and bundle are divided into 36 energy nodes, 34 of which are of fixed volume. The other two represent the sodium in the expansion tank and the sodium in the pump bowl. The sodium levels in these two nodes are calculated by the code. A five-node fuel pin radial heat conduction model for the insulation surrounding the test bundle and its containment is coupled to the test section axial nodes. Other than in the test section, piping and other components were assumed to be at the same temperature as the contiguous sodium. Whereas pipe heat capacity is less than half that of the contained sodium for the large pipes used in a full scale reactor,[6] pipe heat capacity ranges from 80 to 120% of the sodium in the small diameter pipes in the THORS loop. The estimated or calculated masses of other loop components which were included in the thermal analysis were: heat exchanger (but not its support structure), 279 kg; expansion tank, 261 kg; top and bottom flanges of test section, 45 kg; and pump (impeller and bowl only), 241 kg.

The momentum equations are set up using the momentum integral method discussed by Meyer.[7] Momentum nodes are set up in a staggered arrangement so that mass flows are computed at the edges of the mass/energy nodes rather than at their centers where thermodynamic properties (density and energy) are defined. Frictional losses, thermal heads, etc., are computed locally at each momentum node. Since the flow through a line at any point may be expressed in terms of the flow at the inlet to that line plus a correction because of thermal expansion or contraction up to that point, it is possible to combine the momentum equations for a series of nodes into one equation for the whole string. With the bypass line open, four separate momentum equations result: one for the main line from the pump to the tee, one for the bypass line from the tee to the expansion tank, one for the test-section line from the tee to the expansion tank, and one for the main line from the expansion tank back through the heat exchanger to the pump bowl. These equations are algebraically manipulated to eliminate the pressure at the tee. The technique provides for the transient flow redistribution because of different thermal heads in the bypass and the test section. Data of Engel, et al.[8] were used for laminar and transition friction factors in the pin bundle. The stopped-rotor pressure drop of the pump was assumed to be negligible.

COMPARISON OF EXPERIMENTAL AND ANALYTICAL RESULTS

Experimental and analytical temperatures have been compared for Run 39 at twelve locations around the loop designated by circled numbers in Fig. 1:

1. 0.53 m into the 0.91 m test-section heated length,
2. Downstream end of the test-section heated length,
3. In the simulated fission gas plenum 1.35 m downstream from the beginning of the test-section heated length,
4. Test section outlet,
5. Expansion tank outlet,
6. Heat dump inlet,
7. Heat dump outlet,
8. Pump outlet,
9. Filter outlet,
10. Test section inlet,
11. Bypass line inlet,
12. Bypass line outlet.

These comparisons are shown in Figs. 2 through 5. LONAC overpredicted the temperatures within the heated section (location 1) and at the end of the

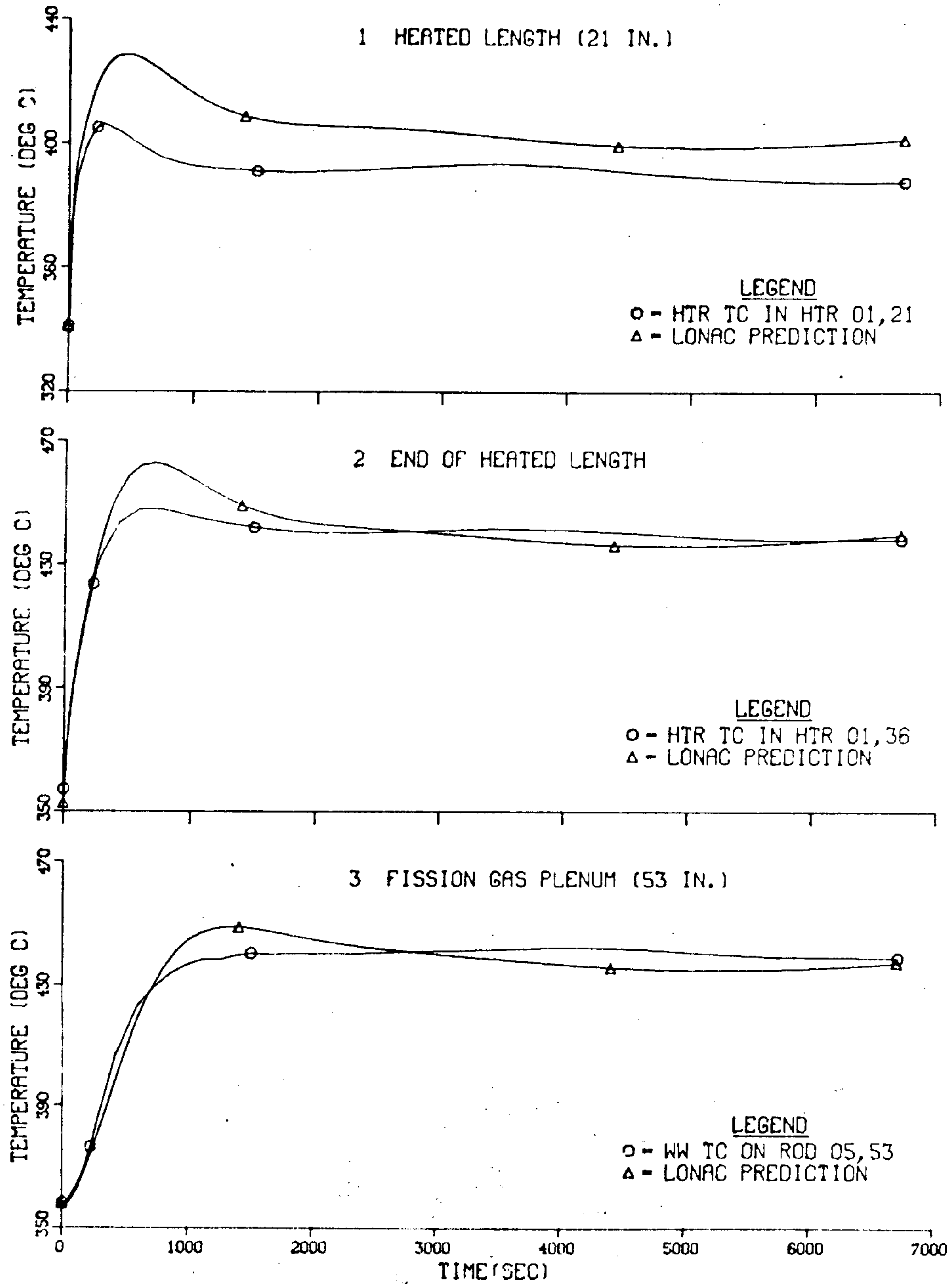

Fig. 2. Comparison of experimental temperatures with those calculated by LONAC at locations 1 through 3 as designated in Fig. 1, THORS Bundle 6, natural convection Test 39.

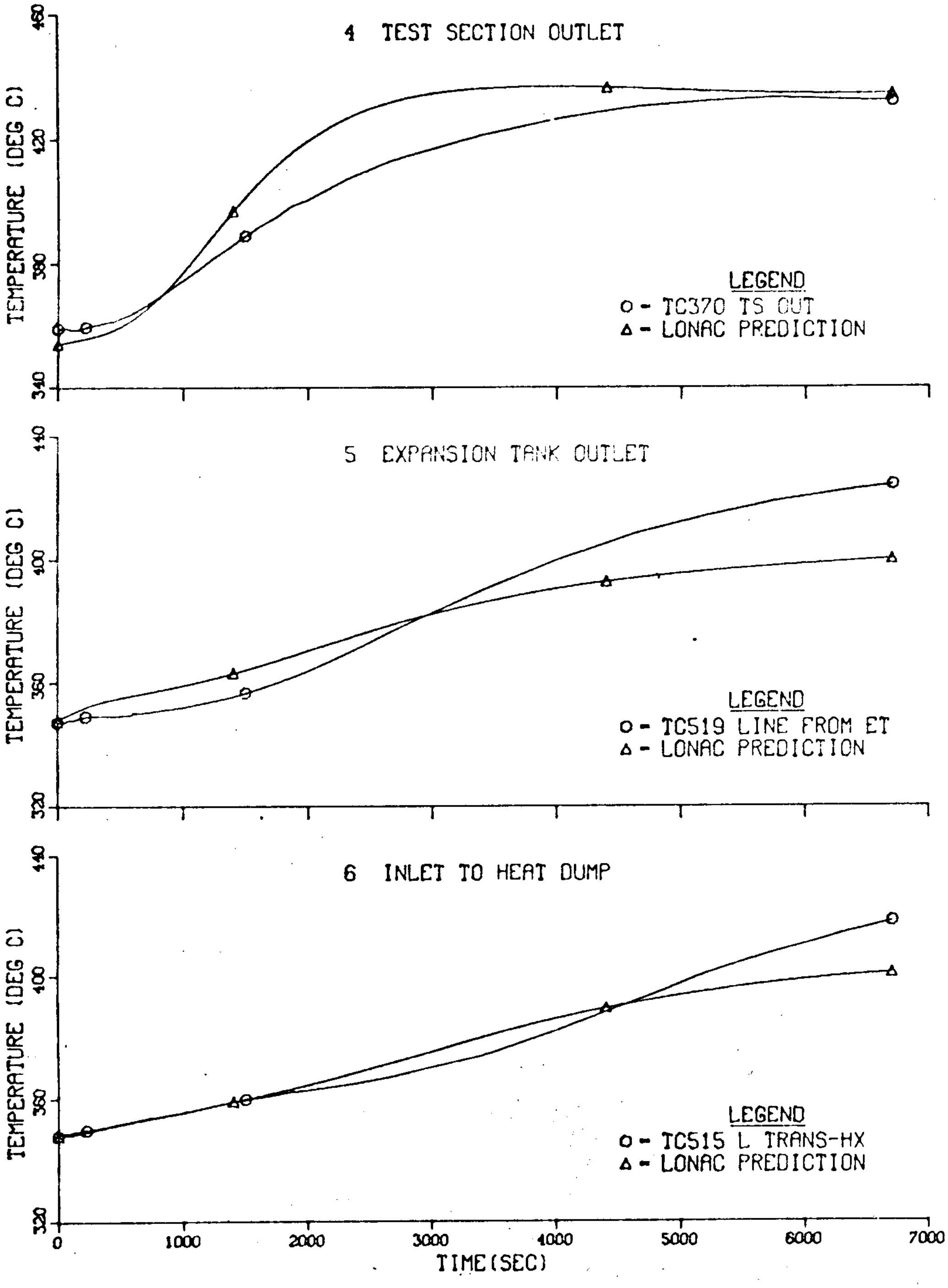

Fig. 3. Comparison of experimental temperatures with those calculated by LONAC at locations 4 through 6 as designated in Fig. 1, THORS Bundle 6, natural convection Test 39.

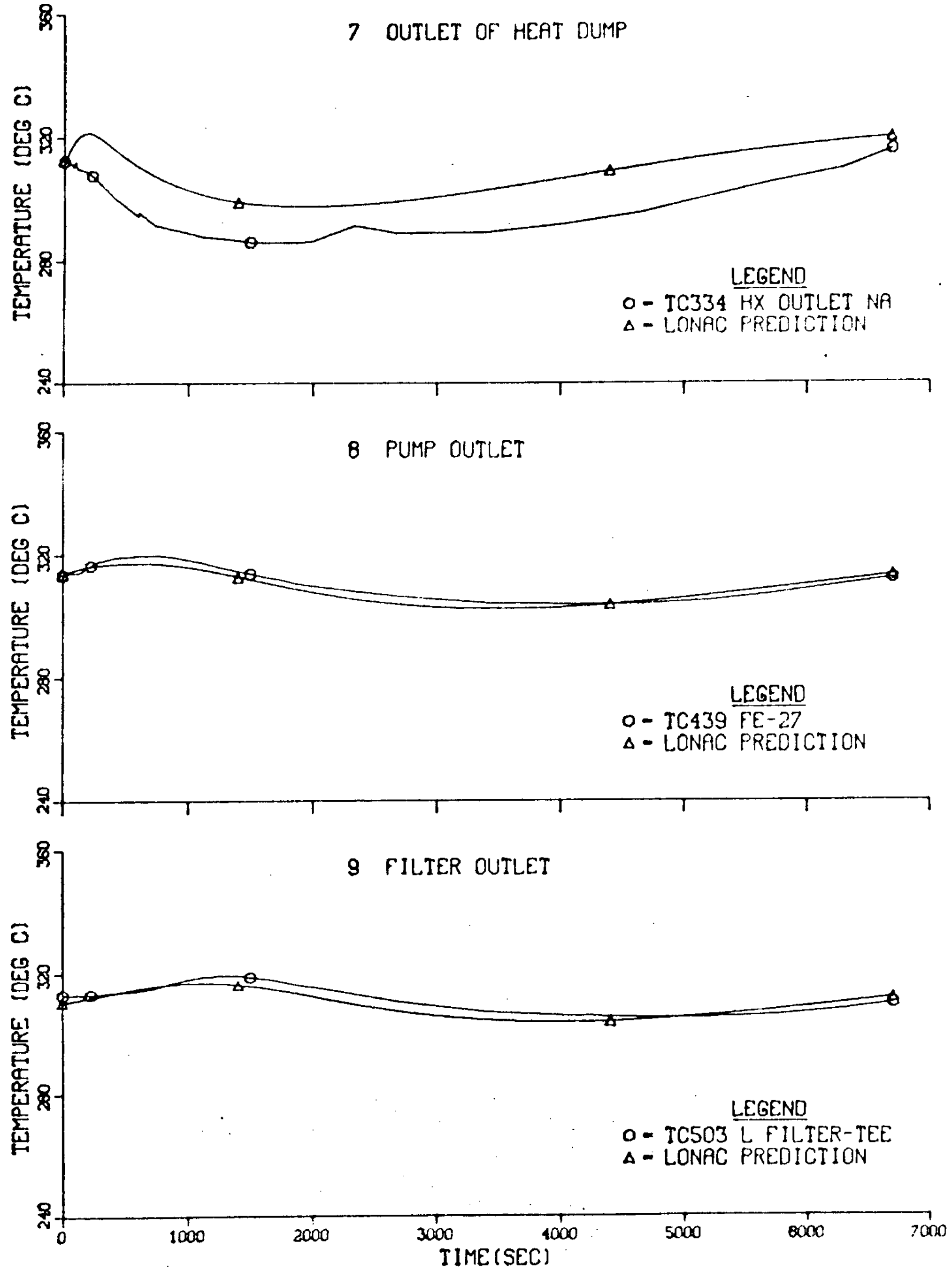

Fig. 4. Comparison of experimental temperatures with those calculated by LONAC at locations 7 through 9 as designated in Fig. 1, THORS Bundle 6, natural convection Test 39.

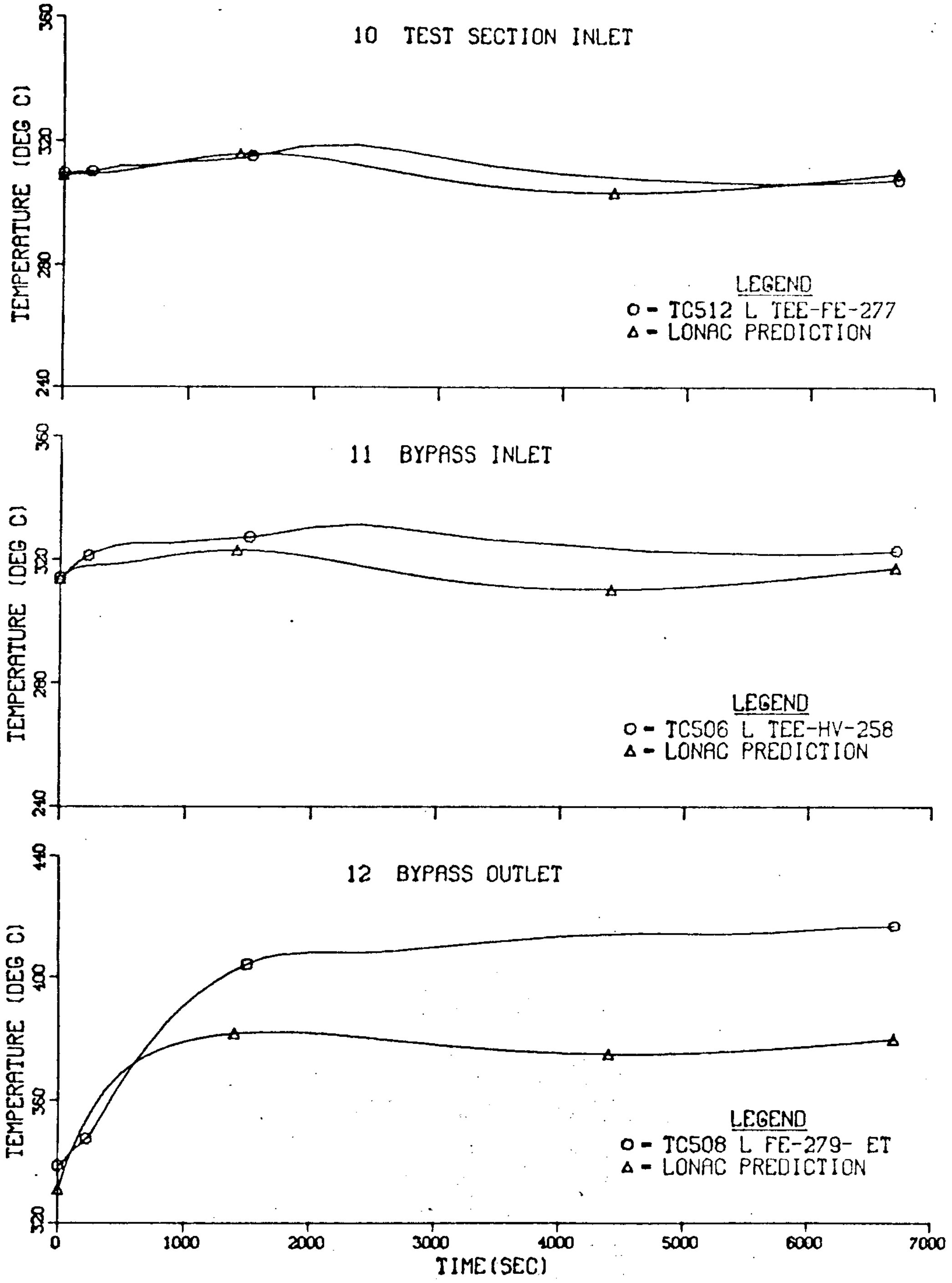

Fig. 5. Comparison of experimental temperatures with those calculated by LONAC at locations 10 through 12 as designated in Fig. 1, THORS Bundle 6, natural convection Test 39.

heated section (location 2). The peak temperature predicted by LONAC was 462°C at 690 seconds vs the 448°C observed in the loop at about 600 seconds. At a representative point in the simulated fission gas plenum (location 3) the comparison is somewhat better. At location 4, which is commonly referred to as the "test section outlet" but is actually much closer to the expansion tank inlet, the prototype is seen to respond more sluggishly than the simulation. The heat capacity of some hardware in this area, principally the flow meter, was not included in this simulation and could account for the difference.

At the next location (5, expansion tank outlet) LONAC first overpredicts and after about 3000 seconds underpredicts. It is highly likely that the discrepancy is caused by the fact that the fluid in the expansion tank is thermally stratified, while in the one node LONAC representation, it is assumed to be well-mixed. For this reason the LONAC expansion tank outlet value is representative of the mean rather than of the temperature at the bottom of the tank. The characteristic thermal diffusion time computed for a layer of sodium of a thickness equal to that of the free surface height in the expansion tank is about 900 seconds. This is approximately the same as the time it would take to flush the expansion tank sodium inventory using the computed test section and bypass line flows. This suggests that insufficient time for thermal equilibration occurs and that hot fluid is added to the top while cold fluid (whose temperature is being measured) is drawn off the bottom. For times greater than 3000 seconds, the low LONAC prediction is probably due to the bypass flow being larger (hence colder) than intended.

Location 6 has been chosen some distance upstream from the heat exchanger because the thermocouple just at the inlet reflects the large losses in the heat exchanger and its vicinity rather than being representative of the incoming fluid, that is, the losses at the heat exchanger are really not confined to the heat exchanger itself while in the LONAC simulation they are. With this proviso the LONAC results are reasonable although the effect of the stratification in the expansion tank is still apparent.

Temperatures at locations 7, 8, 9, and 10 (Figs. 4 and 5) show reasonable agreement although it should be emphasized that trace heat in the cold leg of the loop was set to attempt to maintain 320°C temperatures throughout the transient. Recorded values did not deviate much from this value. In contrast both measured and computed temperatures in the hot leg did vary significantly from the 480°C trace heater set point.

Temperatures at locations in the bypass line (11 and 12, Fig. 5) seem to indicate that the flow in the bypass line has been overpredicted. This is presumably the result of poor extrapolation of the valve pressure drop coefficient to low flow conditions. The slower transient response seen in both the experimental data and the simulation is directly attributable to the greater sodium inventory in the bypass line than in the test section.

CONCLUSIONS AND RECOMMENDATIONS FROM THIS TESTING

Reasonably good agreement was obtained between experimentally-measured and LONAC-predicted temperatures during this test. This demonstrates the ability of a simplified computer code to model the THORS loop, the older segments of which were designed a decade ago with no intent to determine detailed loop temperature measurements required for testing under natural convection conditions. Insights have been obtained which will be utilized in planning future tests under natural convection conditions and will help in code improvements for simulating long transients.

It is apparent that better loop instrumentation (including properly ranged flow meters and pressure transducers) and a detailed knowledge of loop component thermal characteristics are needed. Analytically, a more detailed model of the expansion tank is needed.

FUTURE TESTING

The next configuration to be tested in the THORS facility is designated as the Shutdown Heat Removal System (SHRS) Assembly 1 shown in Fig. 6. It will consist of two 19-pin bundles in parallel, an upper plenum tank and a sodium-to-sodium intermediate heat exchanger. The electrically heated bundles are being built to Conceptual Design Study (CDS) configuration: 6.99-mm pin diameter, 1.22-mm wire-wrap diameter, 1.016-m heated zone length, and 2.845-m total bundle length. Bundle instrumentation will be similar to that of THORS Bundle 6. Loop instrumentation will be extensive and thermal characteristics of loop components will be known accurately. Necessary modifications and improvements to LONAC will be made including a more detailed model of the expansion tank. Forced convection and thermal convection testing will be conducted with both single-phase and two-phase (boiling) flow. For boiling tests a more sophisticated bundle model will be utilized based on the code SABRE-2P[9, 10] or THORAX.[11] Testing in the THORS SHRS Assembly 1 is scheduled to begin in October 1983.

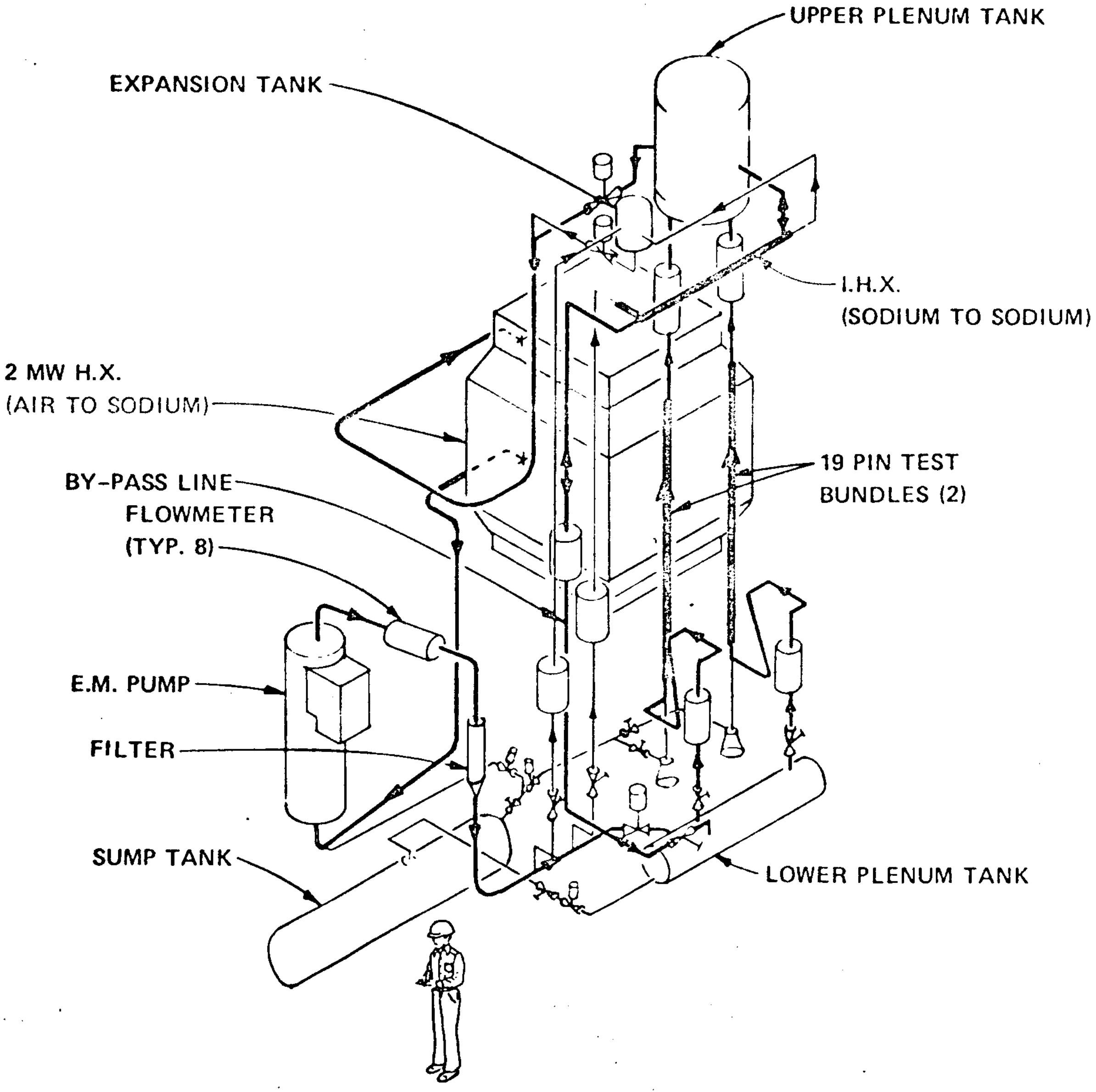

Fig. 6. Isometric drawing of the THORS facility for SHRS Assembly 1 testing. Assembly 1 will consist of two CDS-configuration 19-pin bundles, an upper plenum tank and a sodium-to-sodium intermediate heat exchanger.

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