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in LMFBRs

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ABSTRACT

Natural circulation experiments have been performed at the Oak Ridge National Laboratory using simulated liquid metal fast breeder reactor fuel assemblies in the Thermal-Hydraulic Out-of-Reactor Safety (THORS) facility, an engineering-scale sodium loop. The objective of these tests has been to provide experimental data under conditions that might be encountered during a partial or total loss of the shutdown heat removal system (SHRS) in a reactor. The experiments have included single- and two-phase tests under quasi-steady and transient conditions, at both nominal and non-nominal system conditions. Results from these tests indicate that the potential for reactor damage during degraded SHRS operation is extremely slight, and that natural circulation can be a major contributor to safe operation of the system in both single- and two-phase flow during such operation.

INTRODUCTION

Natural circulation can be a significant contributor to the ability to maintain adequate core cooling in an LMFBR during a partial or total loss of pumping power, such as might arise from a failure of the shutdown heat removal system (SHRS). To define this ability, from both the system design and analytical modeling standpoints, data from natural circulation tests in LMFBR bundles are required. Tests are now under way at the Oak Ridge National Laboratory (ORNL) in the Thermal-Hydraulic Out-of-Reactor Safety (THORS) facility. The sodium loop configuration, designated SHRS Assembly 1, incorporates two parallel, simulated LMFBR fuel assemblies. An objective of the test program is the study of natural circulation single- and two-phase flow behavior under both quasi-steady and transient conditions. Additional tests have been run to investigate the effects of mixed convection (thermal augmentation of low forced-convection flow), and another phase of testing is due to begin shortly to study system behavior during forced-to-natural convection transitions.

This paper describes briefly the THORS facility and the SHRS Assembly 1 test loop, and discusses test procedures for and preliminary results from the natural circulation tests.

FACILITY DESCRIPTION

The THORS facility is an engineering-scale sodium loop for the testing of simulated, electrically heated LMFBR fuel assemblies. The SHRS Assembly 1 configuration is shown in Fig. 1. It consists of two 19-pin, simulated fuel assemblies connected to common upper and lower plena, with a return line to complete the natural circulation circuit. A sodium-to-sodium intermediate heat exchanger (IHX) is included in the return line. Secondary flow to the IHX is supplied by a 40 L/s electromagnetic (EM) pump, with ultimate heat rejection by the 2 MW sodium-to-air heat exchanger.

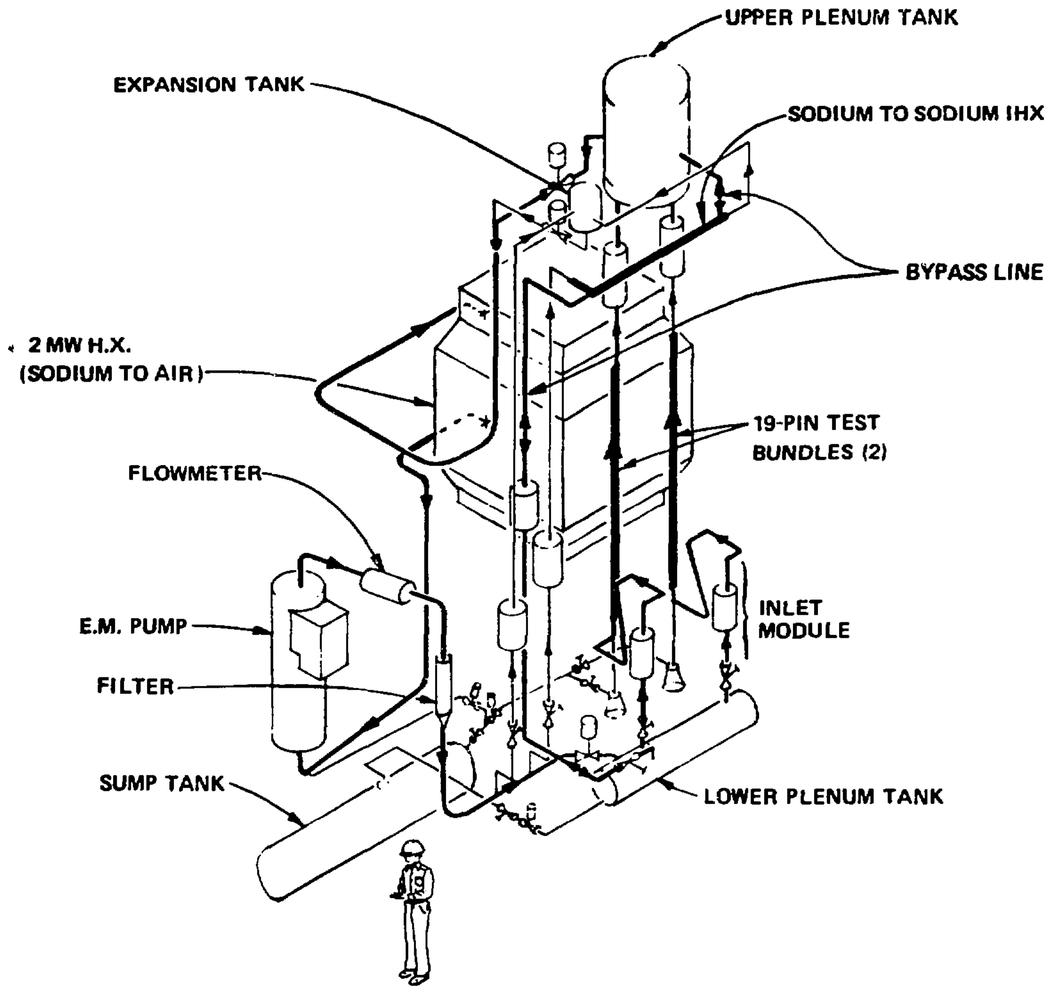

Fig. 1. THORS-SHRS facility isometric flow sheet.

The parallel bundles, one of which is shown in Fig. 2, are of identical design, with fuel pin simulators (FPSs) of Large-Scale Prototype Breeder (LSPB) dimensions: 6.99-mm diameter pins with 1.22 mm wire wraps on a 305-mm axial helical pitch. The edge gaps are half-size (0.61 mm) to flatten the radial temperature profile. The heated zone is 1016 mm in length, with a chopped-cosine axial power shape having a peak-to-average ratio of ~ 1.28. Each FPS has a 356-mm-long unheated length immediately up- and downstream of the heated zone to simulate the lower and upper axial blankets, respectively. The simulated upper axial blanket is filled with sintered (porous) stainless steel pellets to approximate the thermal characteristics of the depleted uranium in the blanket of a nuclear fuel pin. Downstream of the upper axial blanket region is a simulated fission gas plenum (empty tube) 813 mm in length.

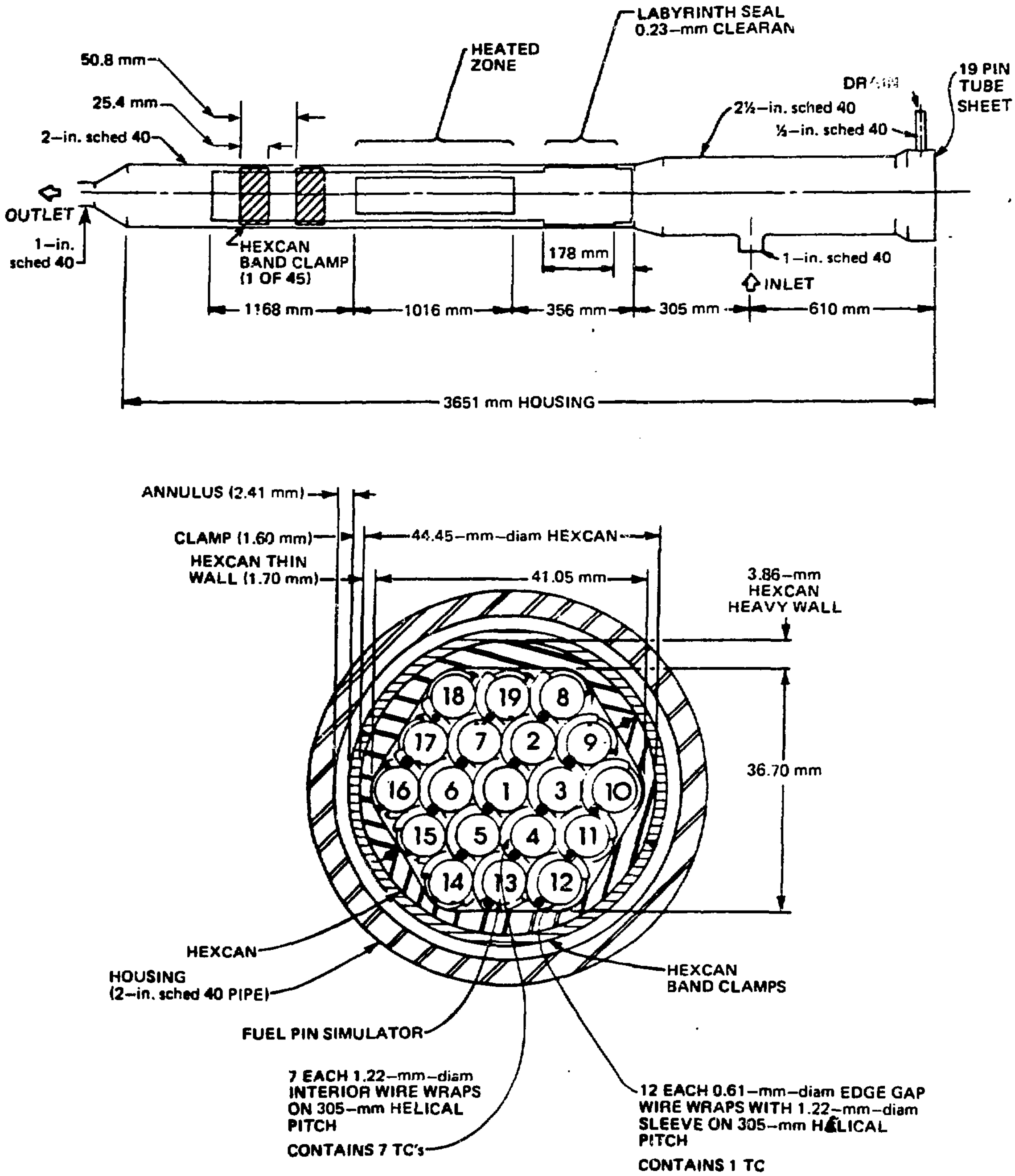

Fig. 2. Longitudinal and cross-sectional views of THORS-SHRS Assembly 1 bundle.

The test bundles are extensively instrumented, as shown in Fig. 3. Each bundle contains 118 thermocouples: 57 in the FPSs and 61 in the wire wraps. The upper plenum tank contains 61 thermocouples, arranged in four planes, to monitor temperature distributions and help study temperature stratification patterns. In addition, the remainder of the loop (IHX, return line, and lower plenum tank) contains a number of thermocouples to help quantify loop heat losses, temperature distributions, and component performance. Flows in the return line and test section inlet and outlet are measured using permanent magnet flowmeters. System pressures are monitored using NaK-filled pressure transducers. All bundle and loop instrumentation is connected to the THORS computer-controlled data acquisition system, which can scan 1000 channels at up to 10,000 points per second.

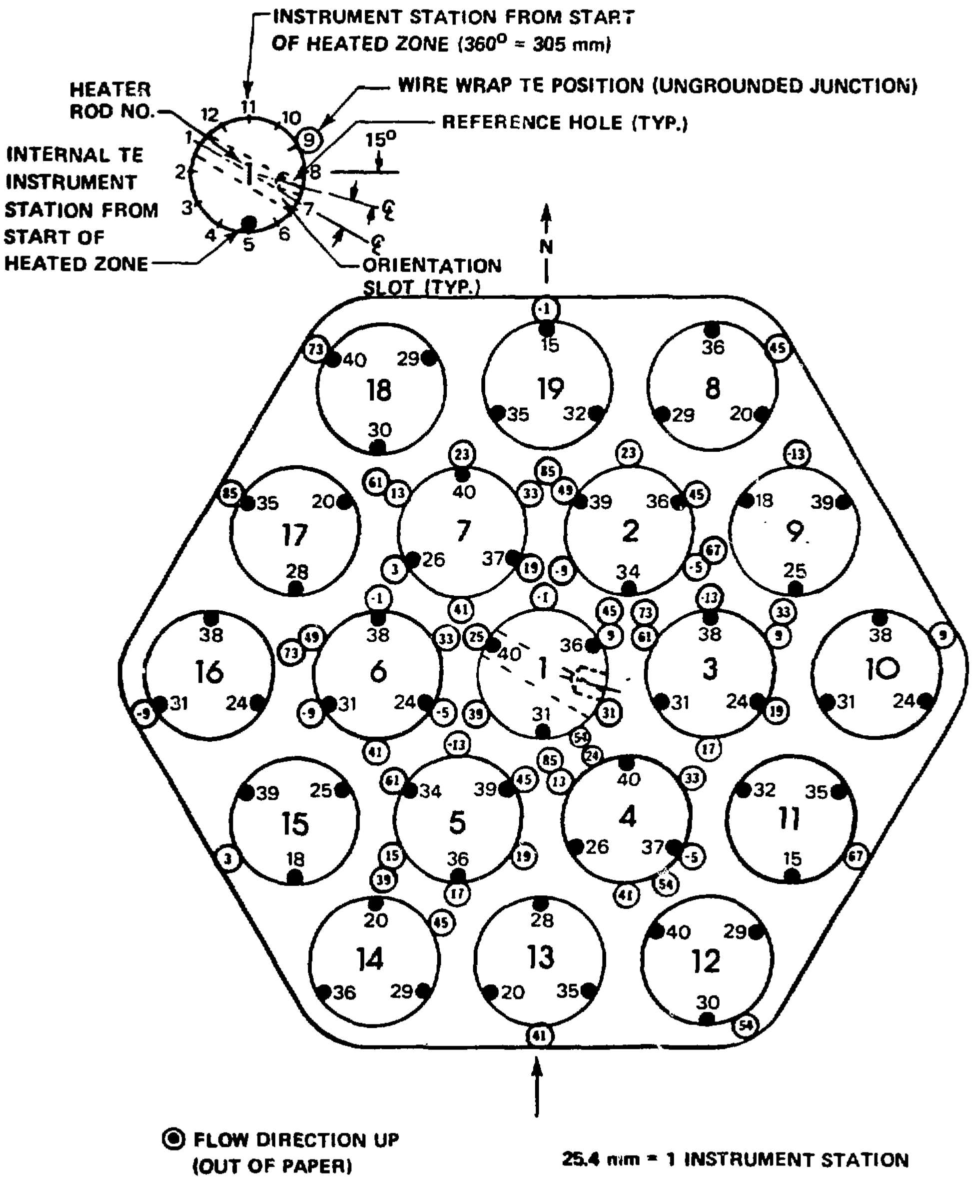

Fig. 3. THORS-SHRS Assembly 1 bundle thermocouple layout.

TEST PROCEDURES

The tests performed in THORS-SHRS Assembly 1 can, in general, be categorized as either quasi-steady state or transient. Each general category contains several different types of tests. Quasi-steady-state natural circulation tests have included:

1) Uniform bundle power profile tests at nominal inlet temperatures in single and parallel bundles
2) Internally skewed bundle power profile tests at nominal inlet temperatures in single and parallel bundles
3) Uniform bundle power profile tests at elevated inlet temperatures in single and parallel bundles
4) Unequal bundle power tests
5) Increased inlet pressure drop tests
6) Tests with zero bundle inlet flow

In cases 1-4, the test procedure consisted of gradually increasing the bundle power in a series of steps up to boiling and dryout, allowing the flows and temperatures to stabilize at each step. Tests at higher-than-nominal inlet pressure drops (case 5) were run in two ways. The first method corresponded to the procedure in cases 1-4, with the bundle inlet valve(s) partially closed to create a higher inlet resistance. In the second method, the bundle power was first set at a maximum decay heat level (~7% of nominal), and the bundle inlet valve was then gradually closed stepwise until boiling and dryout were obtained. The last type of test (case 6) was run by closing the bundle inlet valve (or lower plenum tank valve) completely and once again gradually increasing the power to cause boiling and dryout. Cooling in this case was accomplished by reflux from the upper plenum, aided by intra-bundle recirculation.

Transient tests in natural circulation have included only power transients, run in two different ways. In the first type, each bundle was set at a steady-state power, and the power in one bundle was changed rapidly (either increased or decreased). The second type of transient began from a condition of zero power and zero bundle flow; the power was then increased in a single step or rapidly through a small number of steps to a final value and held at that point while the flows and temperatures stabilized.

The objectives of the quasi-steady-state tests were basically:

1. To establish a base of steady-state single- and two-phase natural circulation data in LMFBR bundles.
2. To determine the powers at boiling and dryout over a range of inlet pressure drops, bundle power distributions, and inlet temperatures.
3. To determine the extent to which a bundle inlet must be blocked to cause boiling and dryout at maximum decay power levels.
4. To determine the maximum amount of power that can be removed in a bundle whose inlet is totally blocked.
5. To determine the extent to which parallel bundle behavior differs from that of a single bundle under the same thermal-hydraulic conditions.

The transient tests had two basic objectives. They were, first, to study the behavior of parallel bundles to see if post-transient steady-state conditions were approached smoothly, and second, to determine the effects of rapid changes in power on bundle boiling and dryout behavior. In addition, the quasi-steady-state tests approached boiling and dryout in the most benign manner, while the power ramp tests from zero power and zero initial flow provided the most severe conditions to establish boiling and dryout. The difference in boiling and dryout powers for these two types of tests would then provide the upper and lower bounds for boiling and dryout under any set of initial and transient conditions.

RESULTS AND DISCUSSION

The data from THORS-SHRS Assembly 1 natural circulation tests are currently being analyzed. Several preliminary results have been ascertained. These include:

1. In steady-state tests at nominal inlet temperatures, up to 16% of nominal power can be removed before boiling inception. The maximum flow is ~4% of its nominal value. After boiling inception, up to ~ 20% of nominal power can be removed before dryout occurs.
2. Under the most severe conditions - a power step from zero power and zero initial flow - boiling inception occurs at ~ 9% of nominal power, with a short period of boiling followed by reversion to single-phase flow. Dryout under these test conditions occurs at ~ 13% of nominal power.
3. To induce boiling at decay power (7% of nominal), the bundle inlet pressure drop must be increased to ~12 times its nominal value. To induce dryout, the pressure drop must be further increased to ~ 125 times nominal. (Determination of the pressure drop ratios was done after completion of the test by setting the inlet valve at the positions at which boiling inception and dryout occurred and measuring the inlet pressure drop at reference forced flow of 10% of nominal.)
4. With the bundle inlet totally blocked (zero bundle inlet flow) and an upper plenum temperature of ~ 550°C, boiling can be maintained at ~0.7% of nominal power. However, dryout does not occur until the power is increased to ~ 3.5% of nominal. Because the mode of cooling in this case is reflux from the upper plenum, changing the upper plenum temperature has an effect on the dryout power. For instance, raising the upper plenum temperature to ~ 700°C reduces the dryout power to ~ 3.1% of nominal.
5. The boiling and dryout powers with internal, radially skewed bundle power profiles are approximately the same as those observed using uniform power profiles. This indicates that, at the low power levels and low flows typical in natural circulation, boiling and dryout are global, rather than local, phenomena. The bundle subchannel flows adjust themselves to match the power skew.
6. The natural circulation flow is a function of power only over the range of temperatures tested. The decreased driving head, due to a higher temperature in the return line, is offset almost exactly by the reduced sodium density in the test section. In addition, at an inlet temperature of ~ 480°C, boiling and dryout powers (~ 12% and ~ 17% of nominal, respectively) are substantially higher than decay levels.
7. Boiling is accompanied by several different types of flow oscillations, including compressibility, density wave, and "enthalpy wave" (thermosiphon) instabilities. Dryout is accompanied by a pressure drop-flow (Ledinegg) excursion, except when the inlet pressure drop is increased significantly.

The flow behavior during steady state boiling, as described above, is one of the most interesting phenomena observed during these tests. The different types of oscillatory behavior observed are clearly shown in Figs. 4-7. Figure 4 shows the cyclical progression from single-phase flow to boiling during Test 231A, one of the single-bundle, steady state tests. At boiling inception, the oscillations are caused by vapor compressibility, and are similar to those seen during boiling tests in previous THORS bundles. As boiling continues, the period of the oscillations becomes somewhat longer. This is probably a density-wave phenomenon, since the period is roughly equal to the transit time of fluid through the test section. Finally, as more vapor builds up in the test section, a "geysering" oscillation is seen, where the flow increases to ~2.5 times its previous value. Flow increases of the order of a factor of four were observed during geysering in other tests. This oscillation, also called an enthalpy wave or thermosiphon instability, pushes most of the vapor out of the bundle and allows the ingress of colder sodium from both the lower and upper plena, which condenses any vapor remaining, and the cycle then repeats. The time between cycles is inversely proportional to the power. The effect of this oscillatory cycle is also evident in observing test section temperatures. Figure 5 shows several temperature traces at various elevations in the bundle. The small oscillations seen at boiling inception and shortly thereafter correspond to the initial small-scale flow oscillations, while the large drop in temperature seen in the boiling region corresponds to the reentry of cold sodium into the bundle during the "geyser."

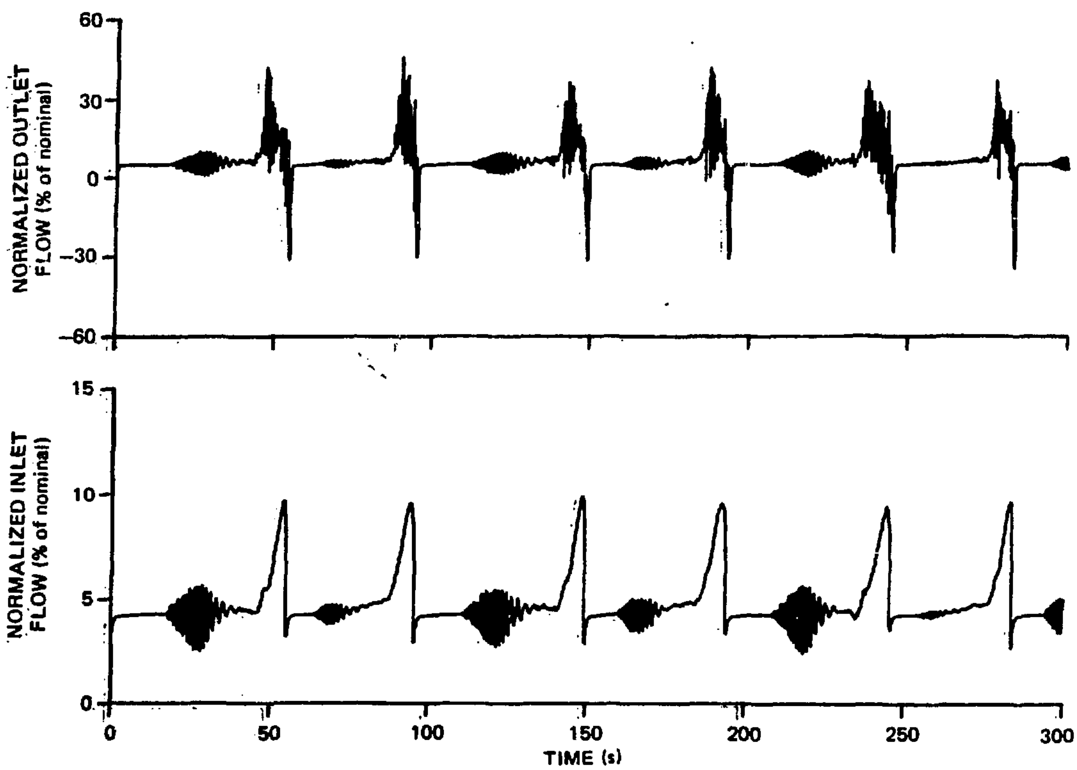

Fig. 4. Test section inlet and outlet flows during THORS-SHRS Assembly 1 Test 231A.

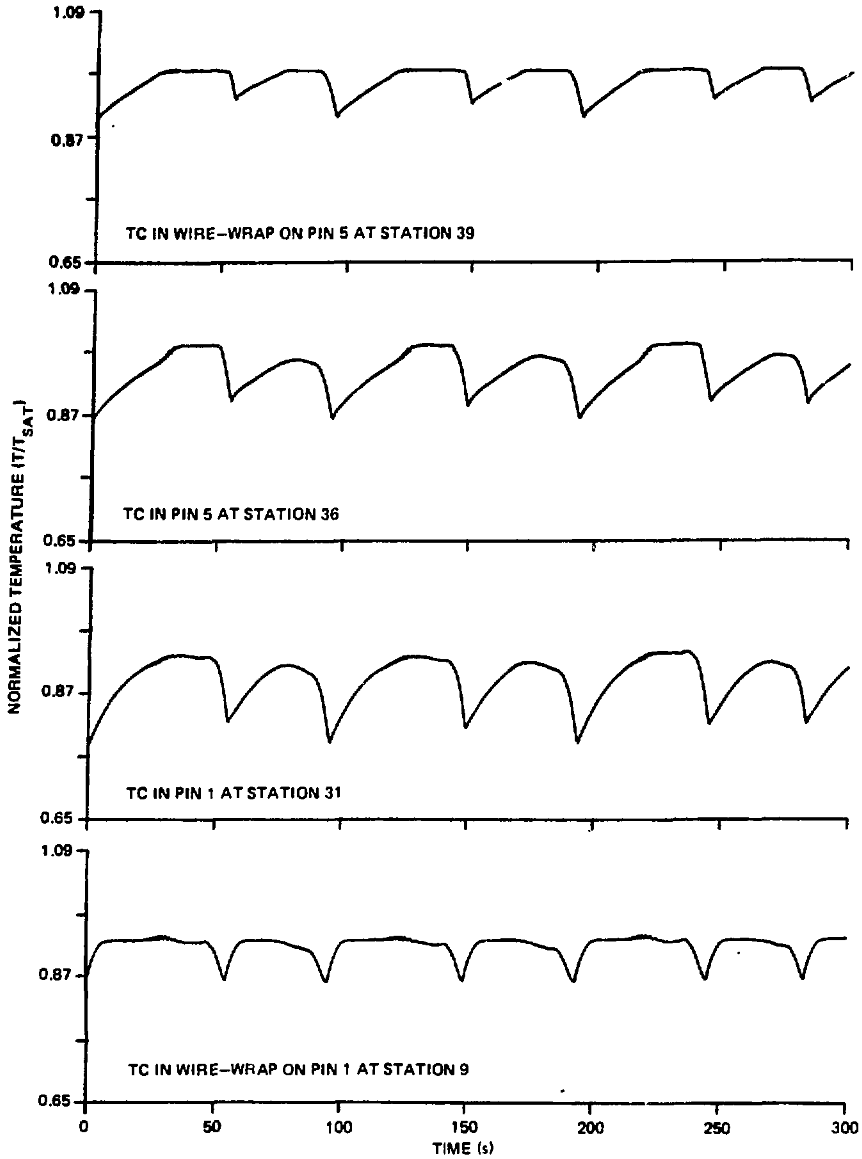

Fig. 5. Bundle temperatures during THORS-SHRS Assembly 1 Test 231A (see Fig. 3 for thermocouple locations).

The Ledinegg pressure drop-flow excursion observed at dryout is shown in Fig. 6. At this stage in the test, the power is high enough so that the two-phase pressure drop cannot be overcome by the vapor-liquid density differential to cause a geyser, and the flow continues to decrease until dryout occurs. Figure 7 shows heater-internal thermocouples during this period. The occurrence of permanent dryout is preceded by a number of dryout-rewet cycles. In addition, because of the relatively low power of these tests, there is not a rapid temperature excursion at dryout. Instead, temperatures tend to increase rather gradually. Facility temperature limits precluded an attempt to reach a steady-state post-dryout condition. However, it is conceivable that such a condition could be maintained below the temperature at which bundle damage would occur.

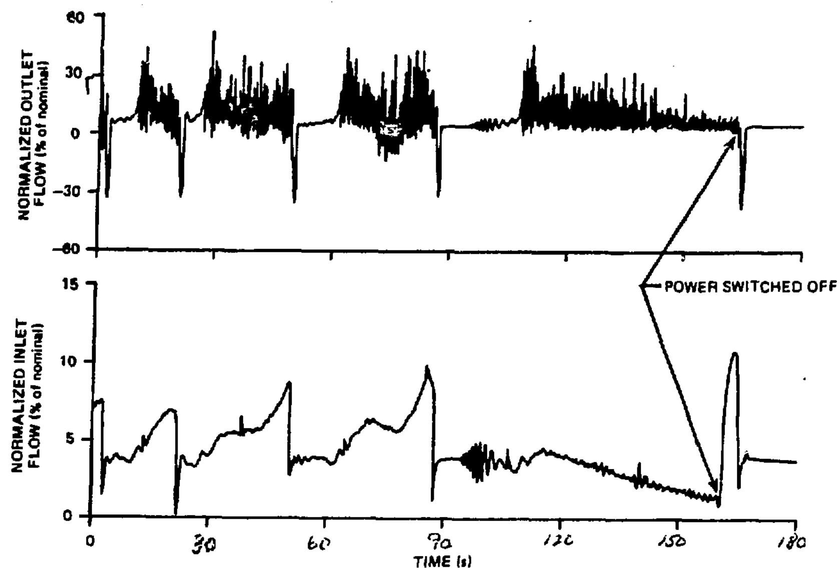

Fig. 6. Test section A inlet and outlet flows during THORS-SHRS Assembly 1 Test 241 showing Ledinegg excursion at dryout.

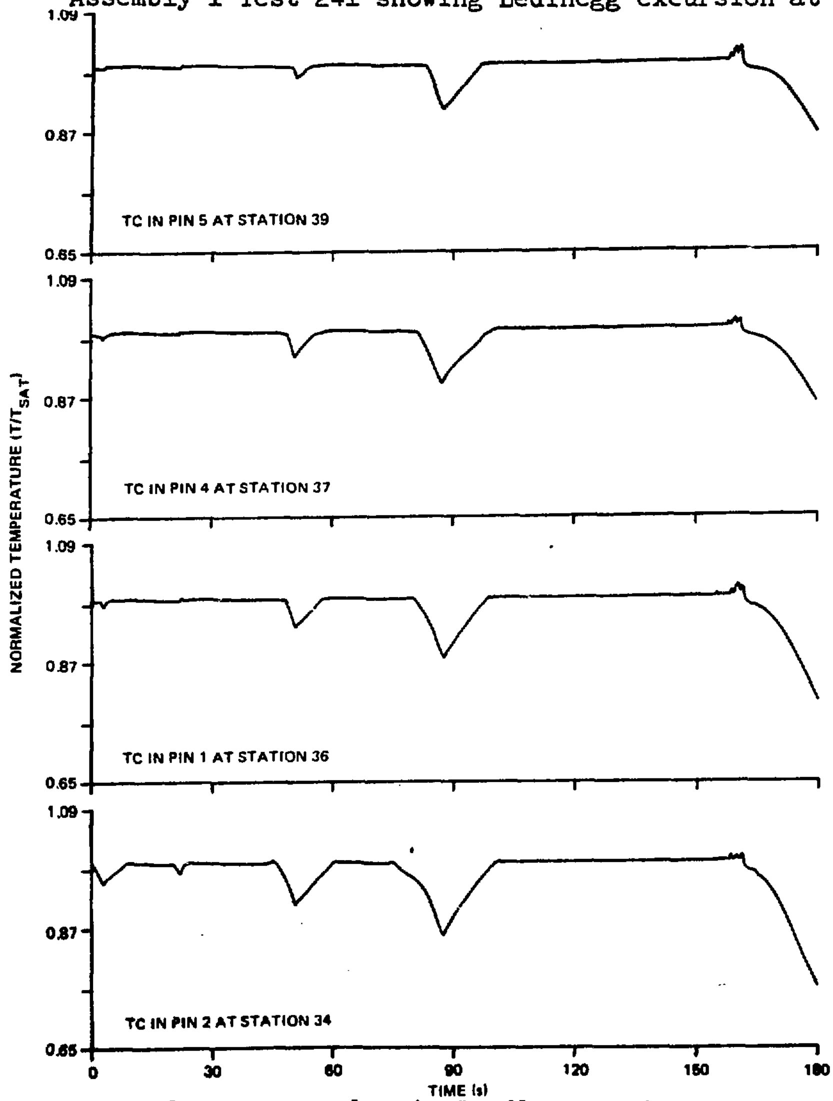

Fig. 7. Heater-internal thermocouples in Bundle A during THORS-SHRS Assembly 1 Test 241 showing response at dryout (see Fig. 3 for thermocouple locations).

One further aspect of the flow behavior in these steady state tests is of particular interest: its similarity to the flow behavior observed during natural circulation boiling tests in a single-tube, atmospheric pressure, water loop at ORNL. The Simulant Boiling Flow Visualization (SBFV) loop is shown in Fig. 8. It is a fully transparent, single tube loop, using boiling water as a simulant for boiling liquid sodium. The entire test section is constructed from Pyrex tubing. Power is supplied to the water by a counter-flow circulation of hot glycerine through a Pyrex annulus surrounding the water tube. The configuration is similar to that of the THORS bundles, with unheated zones up- and downstream of the heated section. The SBFV loop is also extensively instrumented, with thermocouples, pressure transducers, and turbine flowmeters. The thermocouples in the test sections (TE 3-9 and 11-18) are inserted into the water tube through small nipples, and held in place by Epoxy resin, allowing direct measurement of fluid temperatures. Water was chosen as the simulant fluid for this loop because of the similarity between the liquid to vapor density ratios of the two liquids. More detailed information on the SBFV loop, the test program, experimental results, and similarity and scaling considerations can be found in References 1 and 2.

Figure 9 shows the test section inlet flow and selected test section temperatures during a natural circulation boiling test in the SBFV. The geysering behavior is clearly evident in both the flow trace and the temperature data. The importance of this correspondence in behavior lies in the fact that it is highly likely that the same physical processes are responsible for the observed similarity. Therefore, significant insight may be gained using boiling water as a simulant for boiling sodium.

The results other than the flow behavior provide important data for both reactor design and accident analysis. The THORS results indicate that, even under the most severe conditions, powers well above decay heat levels are required to cause boiling inception and dryout with unblocked bundles. Under steady state conditions with the bundle inlet totally blocked, the amount of power required to cause dryout is still a substantial percentage of maximum decay heat, and is greater than the power level of the reactor only a few minutes after scram.

A substantial amount of steady state single-phase natural circulation data was also gathered during the boiling and dryout tests. These data can assist in the development of parameters for LMFBR designers.

CONCLUSIONS

The natural circulation tests performed in THORS-SHRS Assembly 1 have demonstrated that powers up to and greater than decay heat levels can be removed under both nominal and essentially all degraded conditions before dryout occurs. These results strongly suggest that a failure of the SHRS can be accommodated for a substantial length of time even if heat rejection capabilities are not available. With the ability to reject heat to either the secondary loop or an in-vessel decay heat removal system, loss of forced flow after scram may be tolerable indefinitely.

In addition, the THORS data can be of use in analytical modeling of single-and two-phase natural circulation behavior. Finally, the similarity between the boiling behavior of atmospheric pressure water and sodium

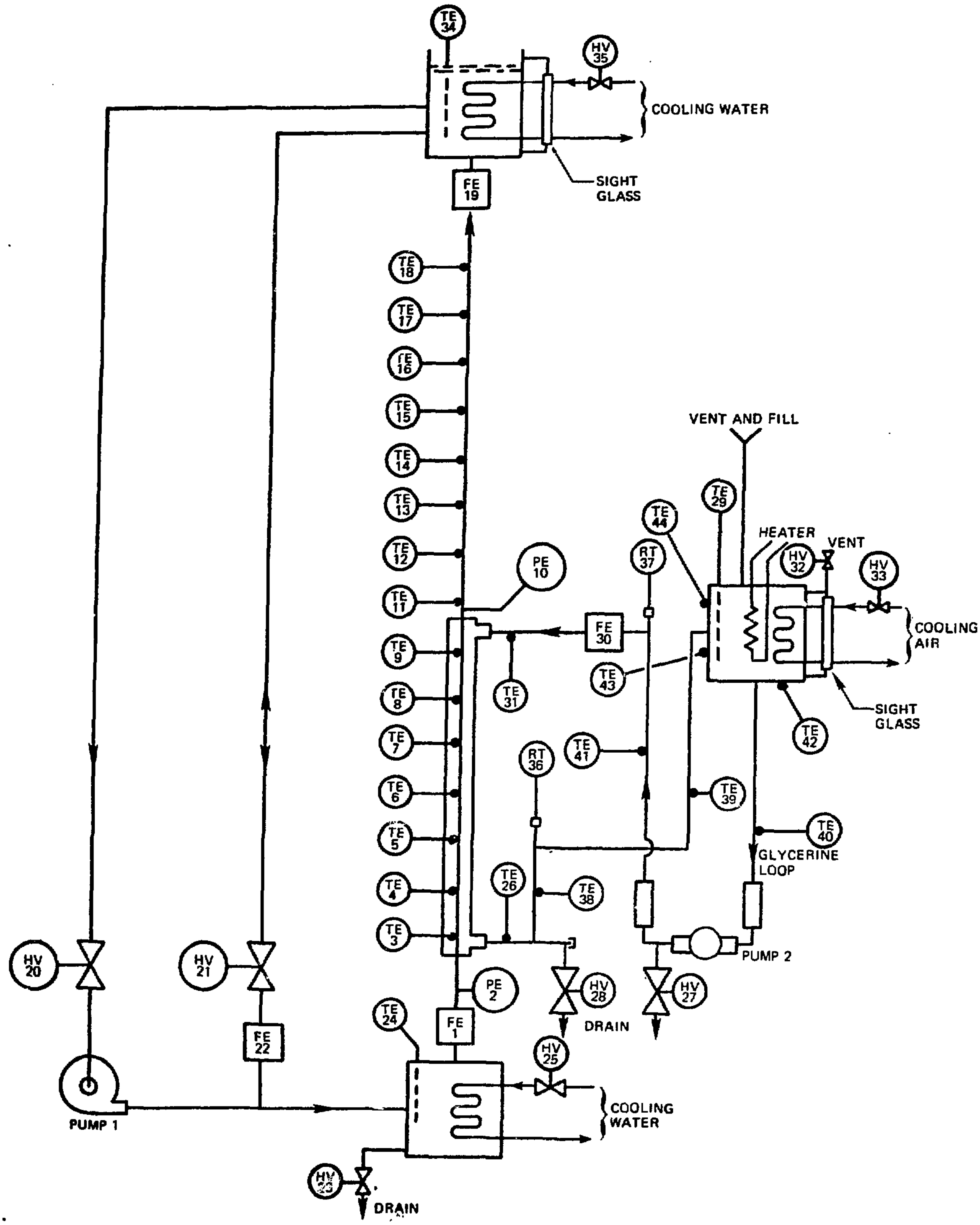

Fig. 8. SBFV loop design and instrumentation.

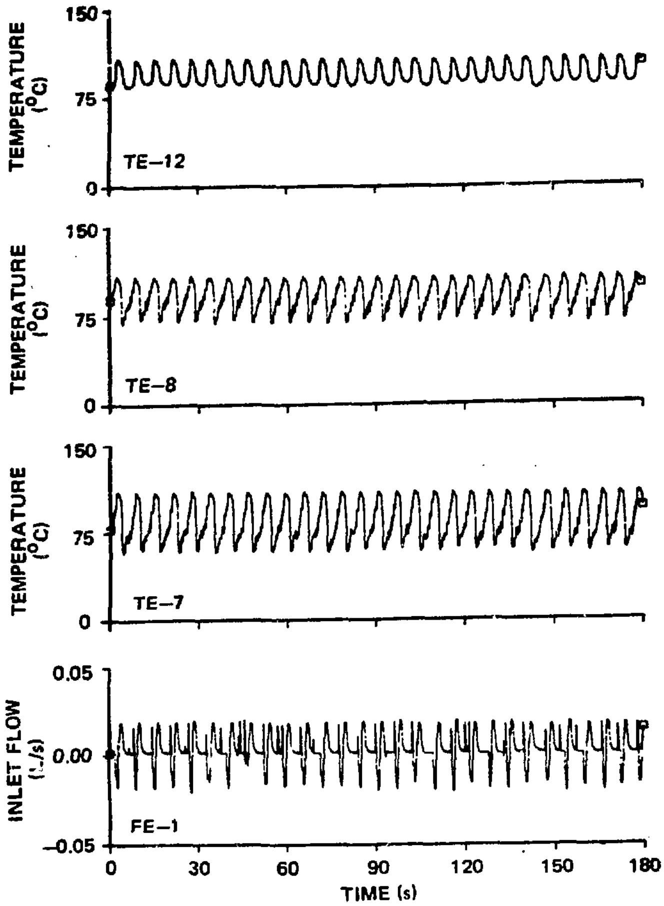

Fig. 9. Test section inlet flow, heated zone temperatures (TE 7,8), and unheated zone temperature (TE 12) during SBFV natural circulation boiling test.

indicates that simulant tests, in which the flow is directly observable (visually) as well as indirectly observable through instrumentation, may provide valuable insight into modeling two-phase sodium phenomenology.

ACKNOWLEDGEMENTS

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