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ABSTRACT

Forced-convection tests have been carried out at the Oak Ridge National Laboratory using parallel simulated Liquid Metal Reactor fuel assemblies in an engineering-scale sodium loop, the Thermal-Hydraulic Out-of-Reactor Safety facility. The tests, performed under single- and two-phase conditions, have shown that for low forced-convection flow there is significant flow augmentation by thermal convection, an important phenomenon under degraded shutdown heat removal conditions in an LMR. The power and flows required for boiling and dryout to occur are much higher than decay heat levels. The experimental evidence supports analytical results that heat removal from an LMR is possible with a degraded shutdown heat removal system.

INTRODUCTION

An extensive series of tests has been completed in the Thermal-Hydraulic Out-of-Reactor Safety (THORS) facility at Oak Ridge National Laboratory (ORNL) providing detailed experimental data under conditions that may occur during a partial or total loss of the shutdown heat removal system (SHRS) in a Liquid Metal Reactor (LMR). The THORS facility is an engineering-scale sodium loop in which thermal-hydraulic tests are performed with simulated (electrically heated) segments of LMR core assemblies. The THORS-SHRS Assembly 1, a convection loop in the THORS facility, is arranged so that forced-convection tests, natural-convection tests, and forced-to-natural-convection transition tests can be run. Steady state and transient tests have been run to boiling and dryout in the bundles to provide thermal-hydraulic data that are pertinent to degraded SHRS conditions in an LMR. This paper encompasses results and analyses of forced-convection tests.

DESCRIPTION OF THORS-SHRS ASSEMBLY 1

The THORS-SHRS Assembly 1 (1) is a convection loop in the THORS facility that consists of two 19-pin bundles and a bypass line connected to common upper and lower plena. A third line contains a sodium-to-sodium intermediate heat exchanger (IHX) coupled to the main loop.

A schematic of the THORS-SHRS Assembly 1 configuration is shown in Fig. 1. The two 19-pin, simulated fuel assemblies are connected to common lower and upper plena with the upflow bypass line being used in forced-convection testing. A 40-L/s electromagnetic (EM) pump provides the main facility flow. Power is supplied by a 2-MW adjustable transformer bank, and ultimate heat rejection is through a 2-MW sodium-to-air heat exchanger. Core segments or complete loops simulating reactor vessel flow paths can be tested.

The fuel pin simulators (FPSs) shown in Fig. 2 are 6.99 mm in diameter, spaced by 1.22-mm-diam wire-wraps on a 305-mm axial pitch. The edge gaps are half-size (0.61 mm) to reduce the flow-to-power ratio in the edge subchannels and, thus, flatten the radial temperature profile. The heated zone is 1.016 m long with a chopped cosine power distribution with an axial peak-to-mean ratio of 1.28:1. Unheated 356-mm lengths above and below the heated section simulate axial blankets, and a simulated fission gas plenum (hollow tube) 813 mm in length is included above the simulated upper axial blanket. The simulated upper axial blanket is filled with sintered stainless steel pellets to approximate

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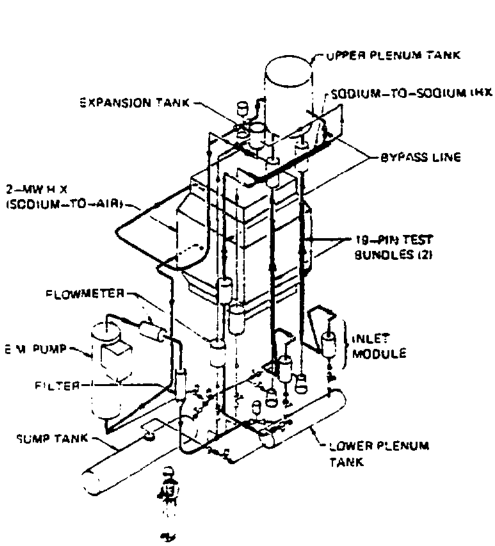


FIG. 1 THORS-SHRS ASSEMBLY 1 FACILITY FLOW DIAGRAM

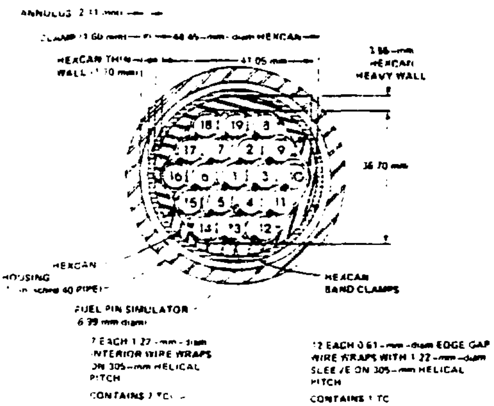


FIG. 2 THORS-SHRS ASSEMBLY 1 BUNDLE CROSS SECTION

the thermal characteristics of depleted uranium in a nuclear fuel pin blanket.

The instrumentation in each test bundle is extensive: 118 thermocouples (TCs) with 57 in the FPSs and 61 in the wire-wraps. The loop is also well instrumented with TCs, permanent magnet flowmeters, and NaK-filled pressure transducers. All instruments are connected to the THORS computer-controlled data acquisition system, which can scan 1000 channels at rates as high as 10,000 points per second.

## DESCRIPTION OF FORCED-FLOW BOILING TESTS

The forced-convection tests in THORS-SHRS Assembly 1 were designed to provide thermal-hydraulic information for degraded SHRS conditions. In the event of partial failure of the primary pump pony motors, forced-convection flows would be lower than those of normal SHRS operation. However, flow augmentation, due to thermally induced density gradients, could occur. One of the objectives of the test program was to determine the effectiveness of flow augmentation in removing decay heat from the core. The tests were performed under quasi-steady-state and transient, controlled flow-reduction conditions. The effects of parallel-bundle interactions were investigated at equal and unequal powers, including bundle power skews and tests at elevated inlet temperatures. Several of the controlled flow-reduction tests were analogous to those run in the 19-pin THORS Bundle 6A (2) and 61-pin THORS Bundle 9 (3) test programs. These tests helped determine the effects of parallel-bundle interactions during short (<90-s) boiling-to-dryout transients. Quasi-steady-state tests were performed by gradually increasing the bundle power in a series of small steps up to boiling and then to dryout. The temperatures and flows were allowed to stabilize at each step.

In summary, the objectives of the forced-convection tests were to investigate the following phenomena:

1. quasi-steady-state forced-convection boiling and dryout in single and parallel bundles with uniform power profiles;
2. quasi-steady-state forced-convection boiling and dryout in single and parallel bundles with radially skewed power profiles;
3. controlled-flow coastdown behavior in THORS-SHRS Assembly 1, including comparisons to previous THORS bundles, comparisons between the two bundles, and comparison of single-bundle to parallel-bundle behavior;
4. quantification of the effects of mixed convection (thermal augmentation of forced-convection flow) at various forced flows; and
5. effects of elevated inlet temperatures on boiling inception, dryout, and mixed-convection augmentation.

## RESULTS AND ANALYSIS

The objectives of forced-convection testing were achieved, and several useful results were obtained:

1. The method chosen for performing the quasi-steady-state tests — establishment of a flow at isothermal conditions and allowance for subsequent mixed convection (without adjustment) as power increased — has shown that mixed-convection effects are significant at flows up to 17% of the nominal flow. Augmentation of the lowest flow tested, ~4.3% of nominal flow, raised the total flow to ~7.3% of nominal at boiling inception (a 70% increase). At 17% of nominal, the augmentation was ~7%, an increase

to ~18% of nominal, still a significant increase.

2. During the power skew tests, the bundle temperature profiles were flatter at lower flows because of mixed convection and the increased importance of transverse thermal conduction at lower flows. This result, previously observed in 61-pin bundle tests, is much less apparent at high flows and is consistent with the preceding observation.

3. Boiling at lower powers and flows is a global phenomenon (4), tending to begin at the center of the bundle and to spread radially from there. At higher powers and flows, the boiling behavior becomes more localized. At these powers small variations or power skews can cause boiling in isolated regions of the bundle, which could be difficult to detect if there is a reliance on bundle-flow fluctuations as an indication of boiling. These powers and flows, however, are far in excess of those expected during shutdown heat removal conditions, degraded or nominal.

4. Consistent with the preceding observation, dryout at low and moderate bundle flows was accompanied by a pressure drop-flow (Ledinegg) excursion as boiling spread throughout the bundle. However, at the highest flow tested, dryout apparently occurred without such a flow instability because the boiling behavior was more localized.

5. Consistent with natural-convection results, the density-induced flow augmentation (mixed convection) is a function of power but not of inlet temperature over the range of inlet temperatures tested. However, the augmentation observed with the bundle power skews is somewhat less, at a given power, than that seen with a uniform power profile. This difference probably results from slightly higher frictional losses with skewed power profiles because of increased intrabundle flow redistribution.

6. The "boiling window," or increase of power required to move from boiling inception to dryout, is considerably less than for natural-convection tests. The window is relatively constant at a value of ~1% of nominal power, which is about one-third that of natural-convection tests. Stable boiling without dryout was maintained at a flow of ~25% nominal (isothermal); the power at boiling inception was ~95% of the nominal power. Also, this power-to-flow ratio of ~4:1 is consistent with the natural-convection boiling tests (5).

7. Also consistent with natural convection tests, there appears to be little difference in the behavior of the bundles individually and little interaction between the two bundles when they are operated in parallel. The latter result is, in all likelihood, caused by the large resistances and inertances[1] of the bundle inlet modules, which effectively decouple the bundles during conditions of changing flows.

To provide guidance in conducting the SHRS Assembly 1 Test Program and to perform pretest calculations and aid in performing posttest analyses, computer codes were utilized (6, 7). Calculations have been performed with the following three codes:

1. THORAX, a two-dimensional bundle code (8);
2. LOOP-1, a one-dimensional loop code (9); and
3. LOOP-TH, a combination of these with two-dimensional bundle modeling and one-dimensional loop modeling.

The LOOP-1 code has two designations: LOOP-1C, specific to free-convection tests, and LOOP-1F, a modified version of LOOP-1 with the addition of a fourth leg with the pump and, therefore, specific to forced-convection tests. In addition, a sodium dryout correlation (10) has also been used to predict times to dryout in controlled flow-reduction tests.

The THORAX code used two interacting flow channels to represent the flow in the hexagonal bundle. As shown in Fig. 3, one channel represents the interior subchannels and the other the edge subchannels; this is a natural way to divide the flow field because of the different power-to-flow ratios in the interior and edge regions of the bundle. The total axial length of the bundle is divided into 50 evenly spaced axial nodes. The vicinity of an arbitrary axial node J is shown in Fig. 4. The bundle is divided into the two flow channels, and the surrounding structure is nodalized, as shown in this figure. Heat transfer from the bundle duct wall radially outward to the outer housing is explicitly modeled in THORAX, and the effect of the heat transfer for any given test can be computed. A staggered pressure-velocity grid is utilized in the fluid flow domain.

The basic assumptions of the two-phase flow model are those of a compressible equilibrium two-phase mixture flow in which the difference in the component velocities is obtained from a correlation for slip ratio. The spatial integration of the mixture void fraction involves

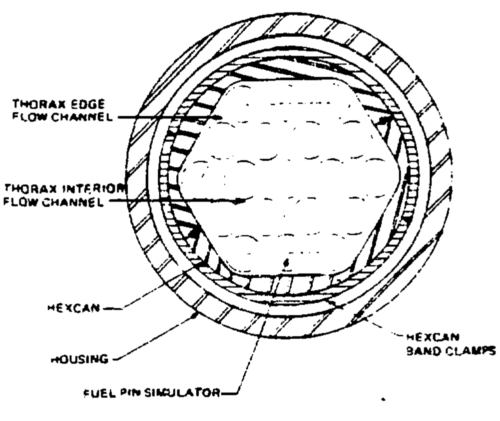


FIG. 3 CROSS SECTION OF THORS-SHRS ASSEMBLY 1 SHOWING TWO THORAX COMPUTATIONAL FLOW CHANNELS

[1] Inertance is defined as the summation of the ratio of the fluid path lengths to the flow areas along the flow path through the system.

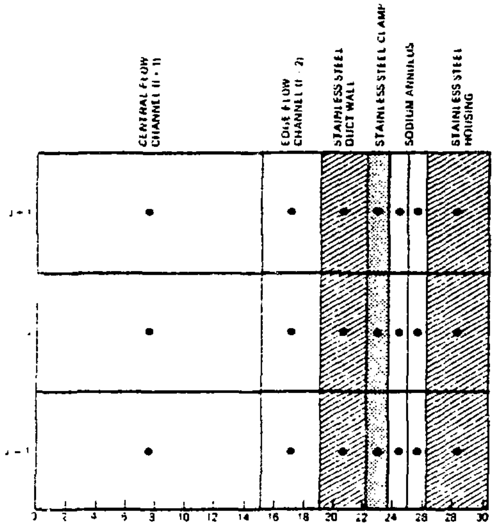


FIG. 4 CONTROL VOLUME SCHEME USED IN THORAX AT ARBITRARY AXIAL NODE J FOR SHRS ASSEMBLY 1

assumptions as to the form of the transverse enthalpy profile. There is a provision for temporally relaxing the two-phase density to smooth out dynamic instabilities. Film dryout is assumed to occur when the calculated quality at a horizontal location becomes unity.

The highly nonlinear equations, a coupled set that describes the two-dimensional, transient, two-phase fluid flow and heat transfer, are solved using the SIMPLE algorithm of Spalding and Patankar (11). This algorithm involves evaluating the necessary coefficients to put the conservation equations in linear form. The system of linearized equations is solved on an iterative cycle that involves techniques of successive point overrelaxation and successive line relaxation.

The THORAX code has been successful in the analysis of both forced- and natural-convection boiling transients (1, 2). This code is most suitable for short transients (approximately <90 s) in which the important characteristics of the boiling phenomena are dominated by bundle rather than loop effects.

Part of the forced-convection boiling tests involved controlled-flow reduction tests to investigate boiling propagation and dryout under flow coastdown conditions. The THORAX code has been used to analyze two of the dryout runs performed at 37 and 56% of nominal power.

The test performed at 37% of nominal power (Test 351A Run 1022) was with a constant inlet temperature of 386°C. The inlet flow was reduced from an initial steady state value of 19.5% of nominal to 7.7% of nominal in ~6 s; this value was low enough to initiate boiling, which occurred at ~16.5 s. The static instability reduced the inlet flow to almost zero at the time of dryout, ~34 s. The corresponding experimental and THORAX-predicted test section inlet velocity values are shown in Fig. 5.

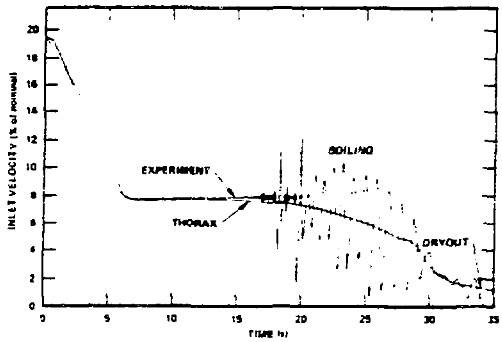


FIG. 5 THORS-SHRS ASSEMBLY 1 EXPERIMENTAL AND THORAX NORMALIZED INLET VELOCITY FOR CONTROLLED FLOW-REDUCTION TEST AT 37% NOMINAL POWER (TEST 351A RUN 1022)

The inlet velocity calculated by THORAX is near the mean experimental value. The oscillations in the experimental inlet flow are probably caused by loop interactions with the test bundle. The effects of these oscillations on overall system behavior are not well understood; however, experience has shown (1) that THORAX predicts system average behavior accurately without the necessity of modeling these oscillations. The calculation performed with a saturation temperature of 950°C produces a time of boiling $t_{boil}$ of 11.7 s and a dryout time $t_{dryout}$ of 35.3 s. Experimentally, superheat was observed, and boiling did not occur until the temperatures in the bundle reached ~1000°C. The delay in the onset of boiling, due to the superheat, was simulated by performing a THORAX calculation with a superheat value of 70°C; the corresponding boiling time was 16.3 s, in good agreement with the experimental value.

The test at the 56% of nominal power level (Test 351A Run 103) was performed in Bundle A with an inlet temperature maintained at 455°C. The initial steady state inlet flow, 41.3% of nominal, was reduced by a linear ramp to a low value of 16.3%. Boiling initiation occurred at ~13.5 s and dryout at ~32 s, as is shown in Fig. 6. The flow decay is more rapid at this power than for the previous run due to a more rapidly expanding boiling region. A THORAX calculation performed with a saturation temperature of 960°C gives the correct mean inlet velocity and predicts dryout at the correct time, ~32 s. Boiling initiation is, however, predicted early at 11.2 s. Again, this difference is explained by superheat, and the calculation performed with a superheat temperature of 20°C yields the correct boiling time of 13.5 s.

A sodium dryout correlation (10) was previously obtained from natural-convection and

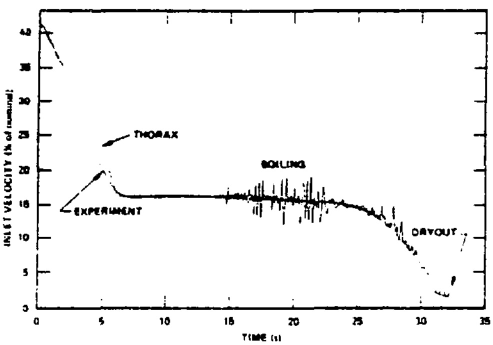


FIG. 6 THORS-SHRS ASSEMBLY 1 EXPERIMENTAL AND THORAX NORMALIZED INLET VELOCITY FOR CONTROLLED FLOW-REDUCTION TEST AT 56% NOMINAL POWER (TEST 351A RUN 103)

controlled flow-reduction tests performed in 19-pin Bundle 6A (2) and 61-pin Bundle 9 (3). Similar tests have been performed in the forced-convection phase of testing of the THORS-SHRS Assembly 1 facility. Data and values calculated from five forced-flow Assembly 1 tests using the dryout correlation are given in Table 1. The last two columns give the boiling time to dryout $t_d$(s), calculated using the dryout correlation and the value obtained from the experimental data.

The dryout index $I_d$ is defined by Eqs. (1), (2), and (3).

$$I_d = K_1^{-1} K_2^{0.5} , \qquad (1)$$

$$K_1 = \frac{P}{F \rho_{in} \Delta h_{sub}} , \qquad (2)$$

$$K_2 = 1000 \frac{LA}{NF} . \qquad (3)$$

The variables in these equations are

$P$ = total power (kW),
$F$ = initial low flow ($m^3/s$),
$\rho_{in}$ = density of liquid sodium at bundle inlet ($kg/m^3$),
$\Delta h_{sub}$ = specific enthalpy rise from bundle inlet to saturated liquid at conditions at the downstream end of the heated section (kJ/kg),
$L$ = housing perimeter (m),
$A$ = cross-sectional flow area ($m^2$),
$N$ = number of pins.

The dryout correlation gives the boiling time to dryout $t_d$(s) as a function of $I_d$ in two parts: for forced convection,

$$t_d = 10^{(0.76 I_d - 0.32)} , \qquad (4)$$

valid for the limits $1.6 < I_d < 2.5$; for natural convection,

$$t_d = 10^{[0.32(I_d)^3 - 0.98(I_d)^2 + 2.7]} , \qquad (5)$$

which is valid for $2.5 < I_d < 3.15$.

Figure 7 shows the dryout correlation curve of $I_d$ vs $t_d$, together with the SHRS Assembly 1 data. Agreement for both Test 351A Run 103 and Test 351A Run 104 was excellent. Test 351A Run 1022 and Test 351B Run 102 gave fair agreement to the correlation. Test 351A Run 101 gave poor agreement because the dryout correlation indicated a longer boiling time to dryout than that observed experimentally in SHRS Assembly 1, possibly due to the buoyancy-induced flow augmentation that raised the low flow value from the intended 3.6 to 5.3% of nominal. A lower flow would reduce the calculated dryout index and improve the agreement.

Pretest predictions made with THORAX and LOOP-TH (6) indicated that the power to achieve boiling in tests in which the power was gradually increased in quasi-steady-state steps could be expressed by a linear relation between the power and flow. In terms of nominal power and flow values, the power necessary to achieve boiling is ~3.7 times the flow for a nominal inlet temperature of 354°C. Experimentally determined boiling power levels agree with this linear relation to within 5%. The power increase from boiling inception to dryout was predicted to be between 0.4 and 1.4% of nominal power, compared with the ~1% value measured experimentally. In general, experimental results are in reasonable agreement with the predicted values for the forced-convection boiling tests.

Table 1. Evaluation of the THORS Bundles 6A and 9 dryout correlation with SHRS Assembly 1 data

| Test | Run | Power (% nominal) | Low initial inlet flow (% nominal) | $t_{boil}$ (°C) | $T_{in}$ (°C) | $K_1$ | $K_2$ | $I_d$ | $t_d$ calculated (s) | $t_d$ measured (s) |
|---|---|---|---|---|---|---|---|---|---|---|
| 351A | 101 | 25.4 | 5.3 | 929 | 389 | 1.43 | 16.71 | 2.80 | 110.0 | 33 |
| 351A | 1022 | 37.2 | 7.7 | 932 | 386 | 1.42 | 11.50 | 2.39 | 31.4 | 22 |
| 351A | 103 | 55.8 | 16.3 | 937 | 455 | 1.14 | 5.40 | 2.04 | 17.3 | 19 |
| 351A | 104 | 54.1 | 14.6 | 937 | 393 | 1.09 | 6.05 | 2.25 | 24.7 | 25 |
| 351B | 102 | 36.4 | 7.7 | 921 | 389 | 1.43 | 11.50 | 2.38 | 30.7 | 25 |

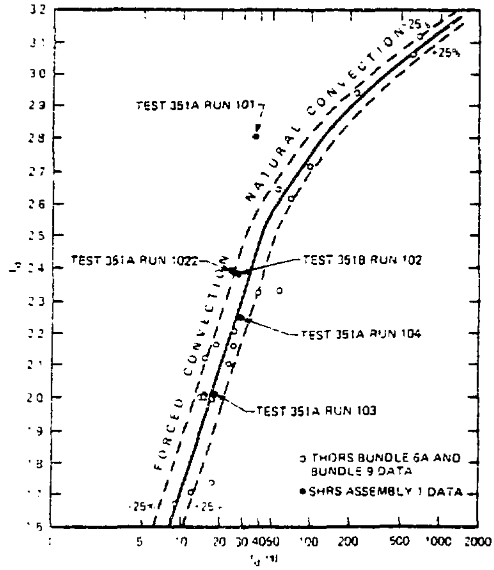


FIG. 7 SODIUM DRYOUT CORRELATION FOR THORS BUNDLE 6A AND BUNDLE 9—$I_d$ PARAMETER VS TIME TO DRYOUT, $t_d$ IN COMPARISON TO SHRS ASSEMBLY 1 DATA

Figure 8 shows data from a test to investigate the flow augmentation from an initial isothermal flow of 4.3% nominal. At boiling inception the flow has increased to ~7.3%, a 70% increase, and the power is at 27.7% nominal, which is about four times larger than the maximum decay heat power level. At ~800 s the temperature and flow plots indicate the geysering phenomenon (4) that causes the bundle to go in and out of boiling prior to dryout.

## CONCLUSION

Tests performed in THORS-SHRS Assembly 1 have shown that the augmentation of low forced-convection flow by thermal convection effects is significant, an important phenomenon under degraded shutdown heat removal conditions in an LMR. It is not possible to extrapolate directly from the experimental results to an LMR. These results do, however, provide representative data of flow augmentation effects that are useful in validating thermal-hydraulic computer codes. The powers and flows required for boiling and dryout to occur are much higher than decay heat levels, and the experimental evidence substantiates analytical results that heat removal from an LMR is possible with a degraded SHRS.

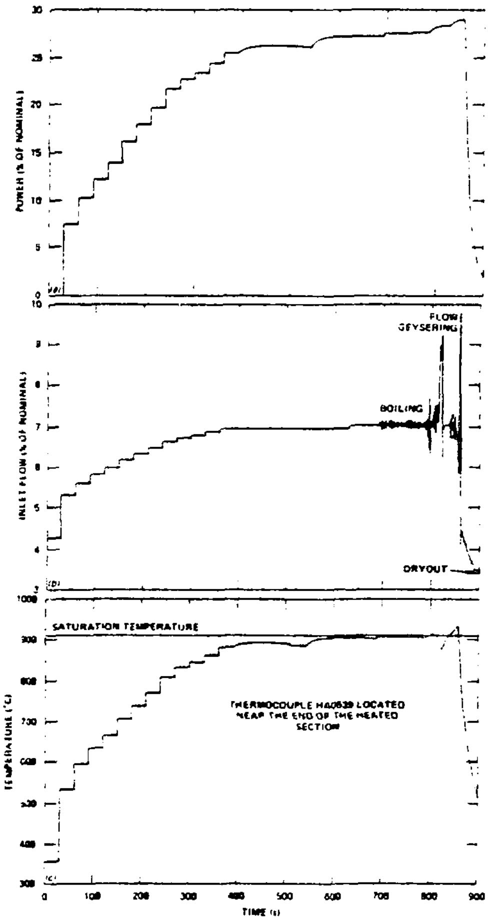


FIG. 8 (*a*) POWER, (*b*) FLOW, AND (*c*) TEMPERATURE DATA FROM MIXED CONVECTION THORS-SHRS ASSEMBLY 1 TESTS 311A AND 331A TO INVESTIGATE FLOW AUGMENTATION FROM INITIAL ISOTHERMAL FLOW OF 4.3% NOMINAL

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