INTERIM REPORT

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ACKNOWLEDGMENTS

The authors wish to acknowledge the assistance and support of the staff of the ORNL PWR Blowdown Heat Transfer Program in the testing of heated thermocouple sensors during THTF Test 3.07.9. The cooperation of Combustion Engineering in supplying a device for test and for technical support is acknowledged. We are grateful to D. G. Thomas for assistance in test planning and to M. C. Adair for preparation of the manuscript.

1. INTRODUCTION

On September 11, 13, and 23, and October 1, 1980, a series of quasi-steady-state film boiling experiments (THTF Test 3.07.9) was conducted in the Thermal Hydraulic Test Facility (THTF) at the Oak Ridge National Laboratory. Tests were run at the request of the U.S. Nuclear Regulatory Commission (NRC) to obtain rod bundle heat transfer data over certain pressure, flow rate, and bundle power ranges.[1] Two heaced junction thermocouple (HTC) sensors were installed in the upper plenum of the THTF test section and monitored during those tests. It was intended that data from the HTCs would be useful in evaluation of such devices (thermal-type level or coolant sensors) as candidates for use in determining the extent, if any, of inadequate core cooling in a pressurized water reactor.

Funding for the HTC testing was provided by the NRC Division of Reactor Safety Research as part of the NRC Action Plan[2] following the Three Mile Island Accident.

An important criterion in evaluating the devices is whether the test instrument's response can be clearly related to fluid conditions at the sensor location. In particular, can the instrument be used to provide early-warning of degradation of cooling conditions in the core (electrically heated rod bundle) during similar thermal-hydraulic conditions?

This report presents the experimental data obtained from an HTC and some other facility instrumentation that are considered important in the interpretation of HTC response. An interim report covering data and preliminary analysis pertinent to the heat transfer information required by NRC is to be issued separately by the PWR Blowdown Heat Transfer Separate Effects Program at ORNL.

2. EXPERIMENT DESCRIPTION

2.1 Facility Description

The THTF (Fig. 1) is a high-pressure, single-loop separate-effects facility used to run experiments that simulate some aspects of a loss-of-coolant accident in a PWR. A detailed description of the THTF may be found in Ref. 3. In the THTF test section, an 8 x 8 square array of 12-ft-long, electrically heated rods geometrically models part of a 17 x 17 PWR fuel assembly. The rod-bundle axial power profile is flat. At steady state, fluid flows from the pump through the horizontal inlet and vertical inlet spool pieces, respectively (Fig. 1). From the vertical inlet spool piece, fluid enters the external downcomer piping and flows through the external downcomer spool pieces into the test section lower plenum. Fluid flows from the lower plenum through the heated length of the bundle, into the test section upper plenum, through the outlet spool pieces, into the main heat exchangers and back to the pump suction.

The THTF rod bundle is instrumented at a number of axial heights (Fig. 2) to allow accurate determination of local electric fuel rod simulator surface temperatures and heat fluxes. Piping spool pieces located at several positions around the loop are used to measure fluid properties such as pressure, temperature, volume rate of flow, fluid density and momentum flux.

2.2 HTC and Associated Hardware

Two HTCs were installed in the THTF upper plenum, near the test section outlet nozzle, as shown in Fig. 3. One of the sensors was fabricated at ORNL. The other was provided for testing by an outside vendor (Combustion Engineering). The results to be presented here were obtained from the vendor-supplied device.

The C-E HTC was functionally similar to HTCs described elsewhere.[4] The active portion of the HTC consisted of a single cylinder with a stainless steel sheath, containing a heater element and two thermocouples. One of the thermocouples was preferentially heated, while the other was influenced primarily by the ambient fluid temperature. Output of the device was the differential voltage between the two thermocouples. C-E states that their device represents a stage in their development program and should not be considered as their completed design. Other specific information regarding the probe and splash shield configuration are considered proprietary by C-E.

Electrical setup used for the HTC test is described here. Data acquisition methods are described in Section 2.5. A manually-controlled voltage-regulated dc power supply was used to provide power to the probe heater. Probe current was monitored as the voltage drop across a precision resistor connected in series. Applied voltage (and resulting probe current) were chosen based on the system pressure as specified by the HTC supplier. In general, higher voltages were used at higher THTF system pressures.

2.3 Test Procedure for Test 3.07.9

Conditions attained for the film boiling tests are listed in Table 1. Flow rate-bundle power combinations for these tests corresponded generally to those calculated to occur for a hypothetical PWR small break loss of coolant accident.[5] For a given test condition, the system pressure and inlet flow rate of subcooled water were maintained essentially steady. Rod bundle heater power was increased to an amount that produced film boiling in the upper part of the rod bundle. Output temperature difference (ΔT) of the HTC, generally supplied with constant heater current for a given test point, was monitored before, during, and after periods of film boiling in the rod bundle. The test objective was to record sufficient data to relate the HTC response to rod bundle temperature conditions and to the fluid conditions at the test section outlet.

Table 1. Summary of data presented on heated thermocouple response during THTF Test 3.07.9

Date	Start time	Duration (min)	Pressure Range (psia)[a]	Mass Flux[b] $lb_m/s/ft^2$[c]	Figures
9/11	11:39	55	625-720	60.9	4[d]
	13:44	28	620-722	62.7	5[d]
	19:14	83	920-1260	49.6	6
	20:36	19	1230-1326	76.4	7
	20:59	21	1230	109.0	8
	21:27	5	1200[e]	137.0	9
	21:33	34	1190	168.0	10
	22:18	41	850-938	67.8	11
9/12	00:11	16	860-900	59.5	12
	00:27	10	850-870	110.8	13
9/18	10:06	54	987-967	59.5	14
	11:00	70	876-1002	74.4	15
	12:12	48	978-1106	74.4	16
9/23	14:45	33	1780-1818	48.3	17
10/1	11:10	75	1680-1880	48.3	18
	12:24	12	1770[e]	66.8	19
	12:42	8.5	1750[e]	105.2	20
	12:51	12	1720-1770	122.2	21
	13:11	14	1800-1880	152.1	22
	13:37	23	1800-1805	153.5	23

[a] 1 psia = 6.895 kPa.

[b] Based on rod bundle flow area of 0.0635 ft^2.

[c] 1 $lb_m/s/ft^2$ = 4.90 $kg/s/m^2$.

[d] Turbine flowmeter and density data not available.

[e] Estimated.

2.4 Inverted Annular Film Boiling Test

At 2:37 A.M. on September 12, another type of film boiling experiment was conducted in the THTF. The test was initiated from saturated conditions at $\sim$1200 psia. Rod bundle power was then quickly increased to a maximum of $\sim$11 kW/ft, while the rod bundle mass flux was maintained constant at $\sim$7.5 lb_m/ft^2. It was expected that the heat transfer regime in the rod bundle during the test would be inverted annular film boiling. Such a heat transfer condition might occur in the event of a control rod ejection accident in a PWR. Data recorded from the HTC, the densitometer and the outlet turbine flowmeter beginning at 2:35 A.M. are in Fig. 24. At $\sim$2.0 min, the rod bundle power was increased. Rod bundle surface temperatures rose rapidly during the period 2.0 to 2.5 min. At $\sim$2.5 min, rod bundle power tripped when bundle temperatures exceeded the prescribed maximum ($\sim$1600°F). At $\sim$3.0 min a rupture disk on the THTF pressurizer burst, causing depressurization of the system (blowdown) during the period 3 to 9 min. The main coolant pump continued to run into the blowdown period.

2.5 Data Acquisition

Three analog chart recorders were used during the test. Chart speed for each was 1 in./s (2.5 cm/s). Signals recorded on the strip charts during the test included:

1. HTC output ΔT (mV)
2. Test section outlet densitometer (DE-204B) raw output
3. Test section vertical outlet spool piece densitometer (DE-218) raw output
4. Test section horizontal outlet spool piece densitometer (DE-36) raw output
5. Test section inlet turbine flowmeter (FE-260) output
6. Test section outlet nozzle turbine flowmeter (FE-202) output

The primary objective of this test was the acquisition of steady-state film boiling heat transfer data. Therefore, the THTF computer data acquisition system was used only when the THTF had reached the desired steady-state condition. Much of the information desired for evaluation of the HTC occurred during periods leading up to attainment of those conditions. So a separate data acquisition was used for the HTC and related instruments. Additional useful data on bundle fluid conditions and bundle temperatures will be available subsequently when the THTF data tapes have been processed.

A multi-track, analog FM-tape recorder was used to record amplified voltage drop across the shunt resistor (proportional to heater current) and amplified output of the HTC. The FM recordings were not made continuously, but were made during periods of representative HTC behavior, to allow posttest data processing and signal analysis of HTC characteristics under various flow conditions.

3. DATA PRESENTATION

3.1 Methods of Data Reduction

The data graphs shown in this repc . were obtained by digitization of data from the analog chart recordings. A software package was used to produce plots with the desired dimensions and scales. Each set of data, i.e., raw HTC ΔT output, outlet turbine reading and outlet densitometer reading, was plotted for the same time interval, consisting of a period when system pressure and test section flow rate were maintained essentially constant. Notations of the bundle temperatures and the extent of film boiling (see Fig. 2) are made at various times, where they are available.

Only the reduced data from DE-204B, the diametral beam of a 3-beam gamma attenuation densitometer, are shown in this report. That instrument, mounted on the outlet nozzle of the test section, was thought to be the most representative indication of void fraction at the HTC location in the upper plenum. Raw output from DE-204B has been converted to indicated chordal-average density using

$$\rho = A \ln (B/V) \quad , \tag{1}$$

where A and B were determined from the best calibration data available at this time.

Turbine data are given in terms of measured volumetric flow rate in the 8.9-cm-ID (3.5-in.-ID) outlet nozzle. A linear conversion from blade passage frequency to output voltage is made by the turbine monitor electronics. This value, recorded on the analog strip chart, was converted to the velocities shown here using a constant multiplier (K-factor) developed from single-phase calibration tests with the turbine. A rough estimate of the average velocity in the THTF upper plenum may be made using the turbine readings shown here and the fact that the upper plenum tranverse flow area (Fig. 3) is 222 cm^2 (0.2387 ft^2).

Digitization frequency was chosen such that the important data features were retained. In the case of the HTC output, an effort was made to show signal character, e.g., smooth or with spikes. Because of their low frequency, oscillations shown in the HTC plots are believed to represent thermal-hydraulic phenomena and not electrical noise. In the case of densitometer and turbine flowmeter data, a lower digitization frequency was used. There were often severe oscillations of fairly high frequency in those signals; a best-estimate mean value of those signals was plotted with digitization frequencies of a few points per minute. The oscillatory character of densitometer and turbine signals was representative of the two-phase flow regime — not electrical noise. (The data recorders used could not respond to high-frequency oscillations.) However, the original data recordings should be consulted, if HTC response is to be related to flow regime.

3.3 Estimate of Errors

A rigorous error analysis has not been performed. The most important questions to be answered by the HTC testing were (1) could the HTC mechanically survive LOCA thermal-hydraulic environments for extensive periods, (2) would the HTC output behavior correspond to that of the heated rod bundle, and (3) what were the flow conditions, e.g., pressure, mean velocity and density, existing in the vicinity of the HTC at various times during the test? In the case of the HTC output, the measured values were accurate to within 1 mV. However, neither the velocity nor void fraction data obtained at the outlet spool are direct indications of the fluid conditions at the HTC sensor location, because of the significant geometry differences between the HTC location and the outlet spool piece. Therefore, determination of error in measured density and velocity — a monumental task for high-temperature two-phase flow — is in fact not crucial, in this case.

Our experience with a densitometer like DE-218 has shown that chordal-average density measurments accurate to within ±5% of full scale may be attained. However, due to difficulties in determining accurate calibration constants for this test, the error in the THTF density measurements reported here may be as large as ±10% of full scale (±6 lb_m/ft^3).

The turbine flowmeter, FE-202, is an accurate instrument in single-phase flow. At this time, no completely satisfactory model has been presented for turbine response in two-phase flow. Experiments at ORNL with a similar turbine in horizontal air-water flow have shown that the turbine speed approximates the mean liquid velocity at relatively low flow rates. At higher flow rates, the turbine registers a velocity intermediate to the liquid and vapor velocities. The volumetric flow rates shown in this report, based on FE-202, should probably be used only as an indicator of approximate magnitude of outlet flow and of changes (increase or decrease) in the flow. A quantitative estimate of error in velocity measurement is not possible. Considering the location of the HTC relative to the turbine (Fig. 3), such an estimate is probably not necessary.

Errors in output signals from all three instruments, resulting from the digitization process itself, are believed to be negligible (see discussion of oscillations in densitometer and turbine signals, above). Because of uncertainties in chart speeds and recorded times, there may be an error of ±5% of full-scale on the time axis.

3.4 Preliminary Conclusions

Available information relating to the three test objectives given in Section 3.3 will be presented here.

1. The HTC survived THTF Test 3.07.9. After the test, both heater and TC circuits were intact and remained well-insulated from each other and from ground.

2 and 3. Preliminary analysis indicates that, for relatively low test section mass fluxes during THTF Test 3.07.9, the HTC ΔT increased to $\geq$ 10 mV, prior to onset of film boiling (rod surface heat flux exceeding the critical heat flux) in the rod bundle. However, it appears that when the test section mass flux was relatively high, the HTC output remained <2 mV, even when parts of the rod bundle were in film boiling. Refer to Figs. 8, 9, 10, 21, and 22. During those periods, the outlet turbine flowmeter indicated a velocity of at least 11 m/s (40 ft/s). The ratio of the transverse flow area in the upper plenum (Section A-A in Fig. 3) to the pipe area at the outlet test section turbine flowmeter is 3.57. Therefore, velocities in the vicinity of the shielded HTC may have been in excess of 3 m/s (10 ft/s). Note that neither the velocity nor void fraction data obtained at the outlet spool are direct indications of the fluid conditions at the HTC sensor location because of the significant geometry differences between the HTC location and the outlet spool piece. An indication of the system pressure and outlet density during the subject periods may be found by refering to Table 1 and to the density plots in Figs. 8, 9, 10, 21, and 22.

REFERENCES

1. Memorandum from Harold Denton, Director, Office of Nuclear Reactor Regulation, to Saul Levine, Director, Office of Nuclear Regulatory Research, Subject: Request for Confirmatory Research on LWR Heat Transfer (RR-NRR-79-20), August 17, 1979.

2. NRC Action Plan Developed as a Result of the TMI-2 Accident, NUREG-0660 (May 1980), Sec. 1.D.5 and Sec. 2.F.2.

3. Project Description ORNL PWR Blowdown Heat Transfer Separate Effects Program — Thermal Hydraulic Test Facility (THTF), ORNL/NUREG/TM-2 (NRC-1, -2), (February 1976).

4. K. G. Turnage et al., Advanced Two-Phase Flow Instrumentation Program Quarterly Progress Report for January-March 1980, NUREG/CR-1647 (ORNL/NUREG/TM-403), (September 1980).

5. J. D. White, et al., Quarterly Progress Report on Blowdown Heat Transfer Separate-Effects Program for July-September 1980, NUREG/CR-1837 (ORNL/NUREG/TM-425), (December 1980).

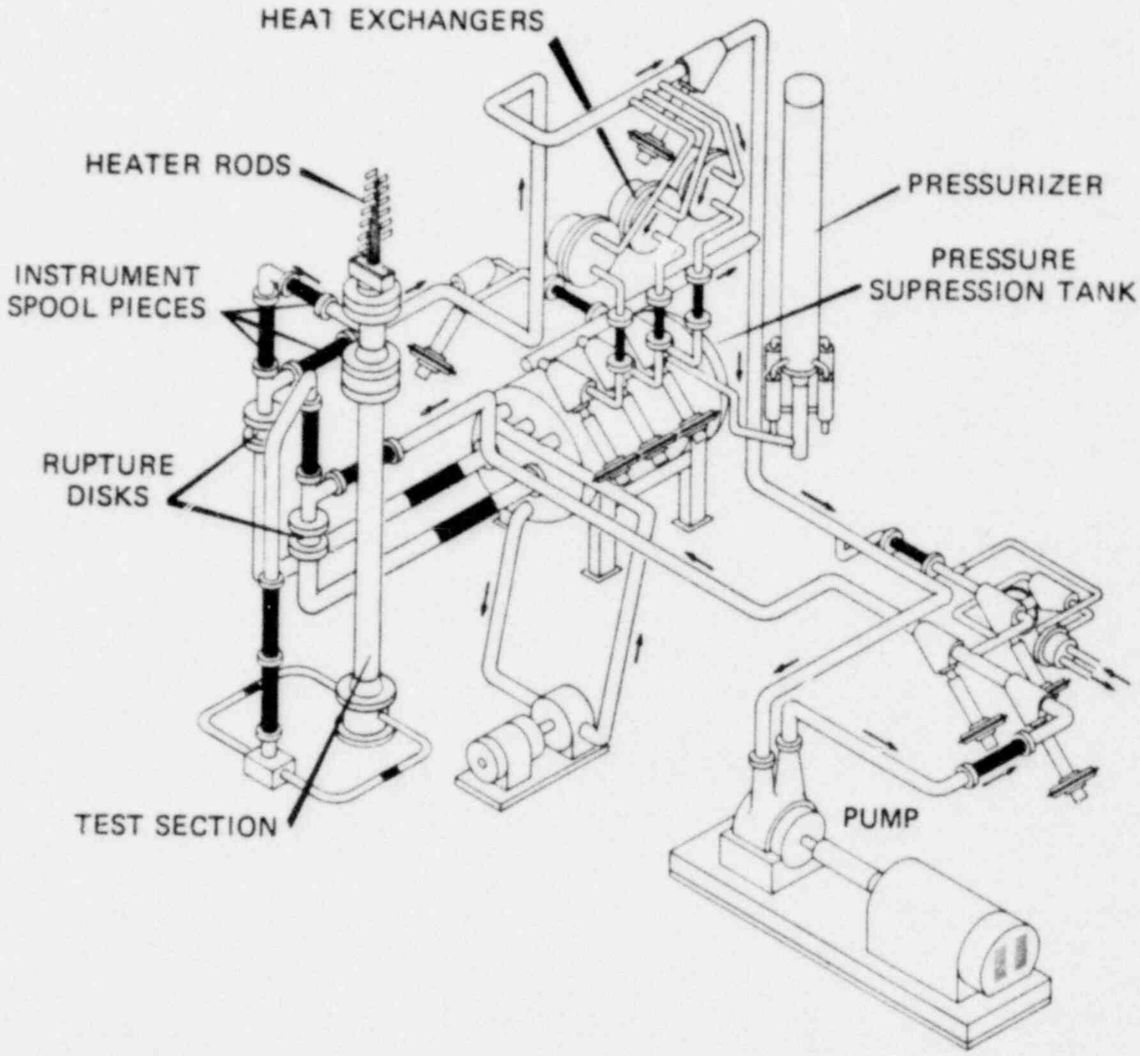

Fig. 1. Isometric drawing of Thermal Hydraulic Test Facility.

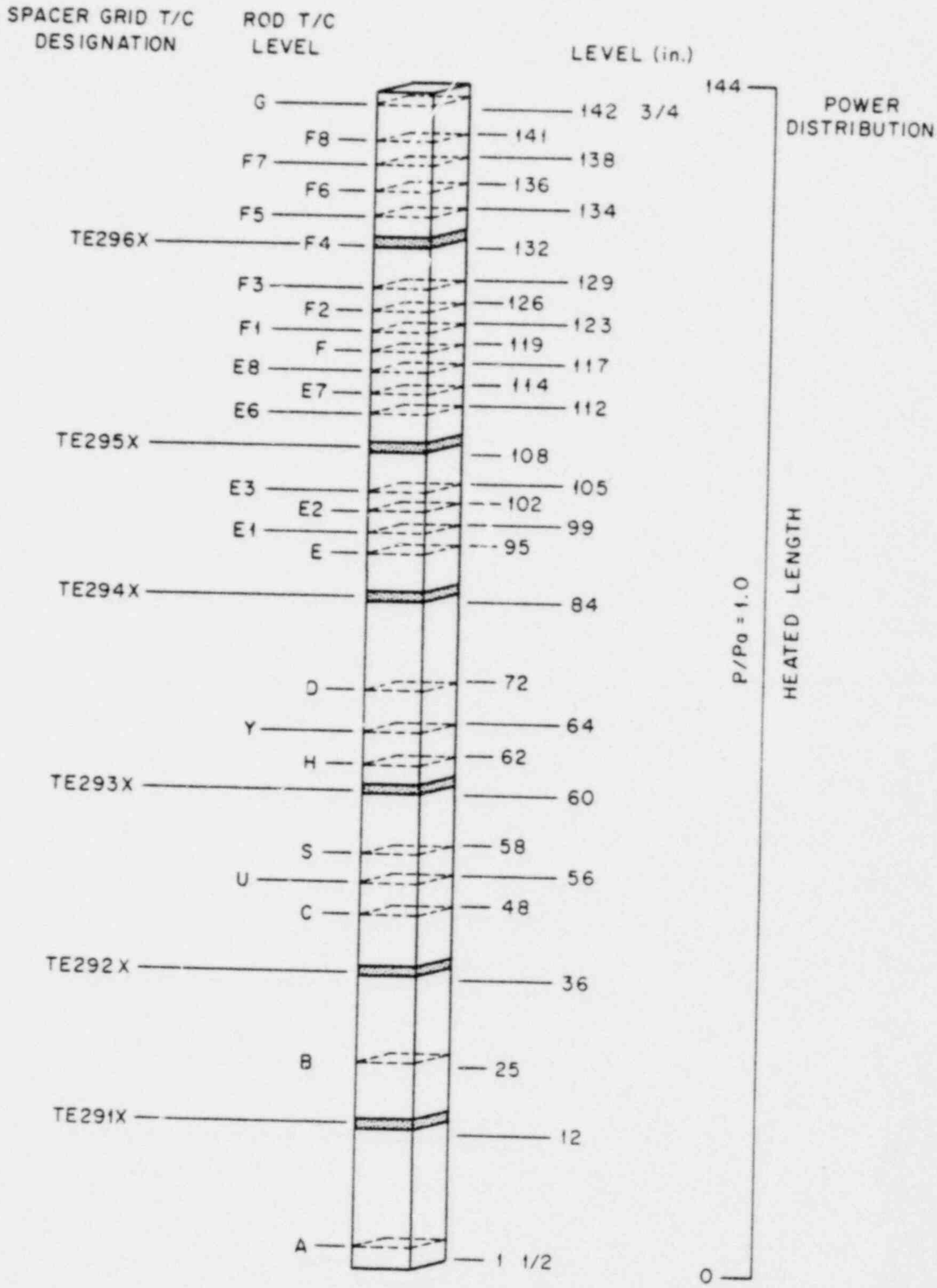

Fig. 2. Axial location of spacer grids and fuel rod simulator thermocouples.

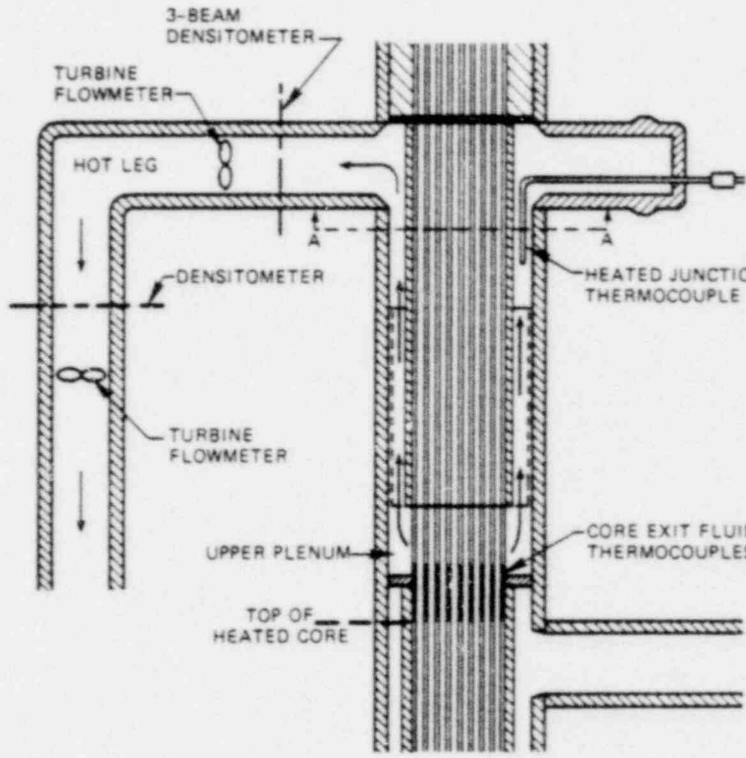

Fig. 3a. Schematic of upper part of THTF test section and outlet piping showing locations of HTC and other instrumentation.

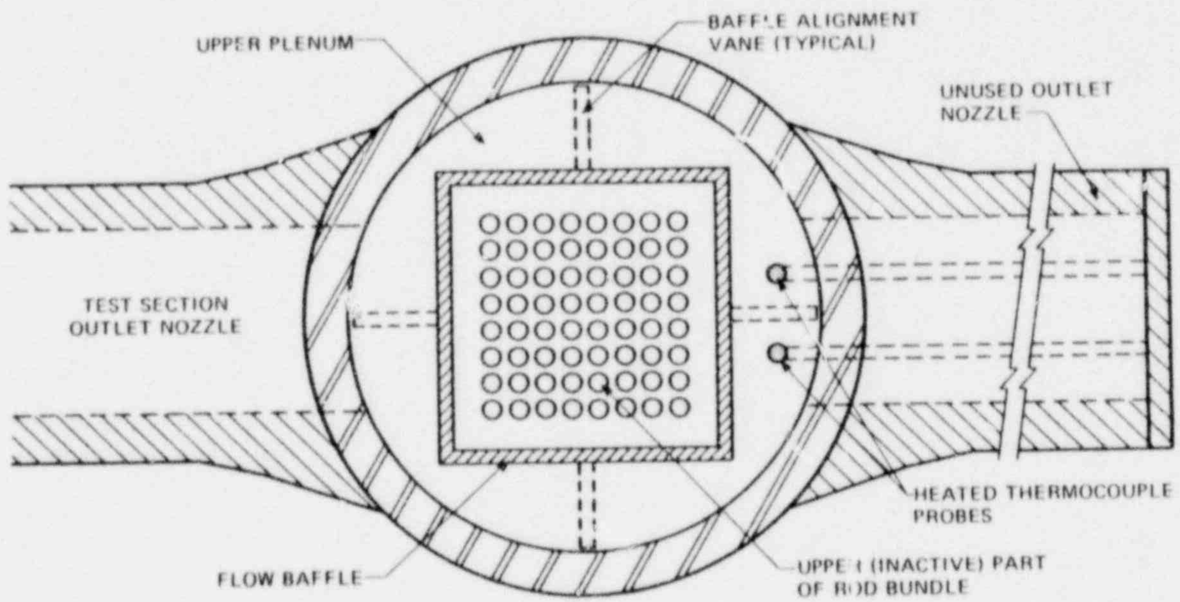

Fig. 3b. Cross-sectional view of THTF at plane A-A.

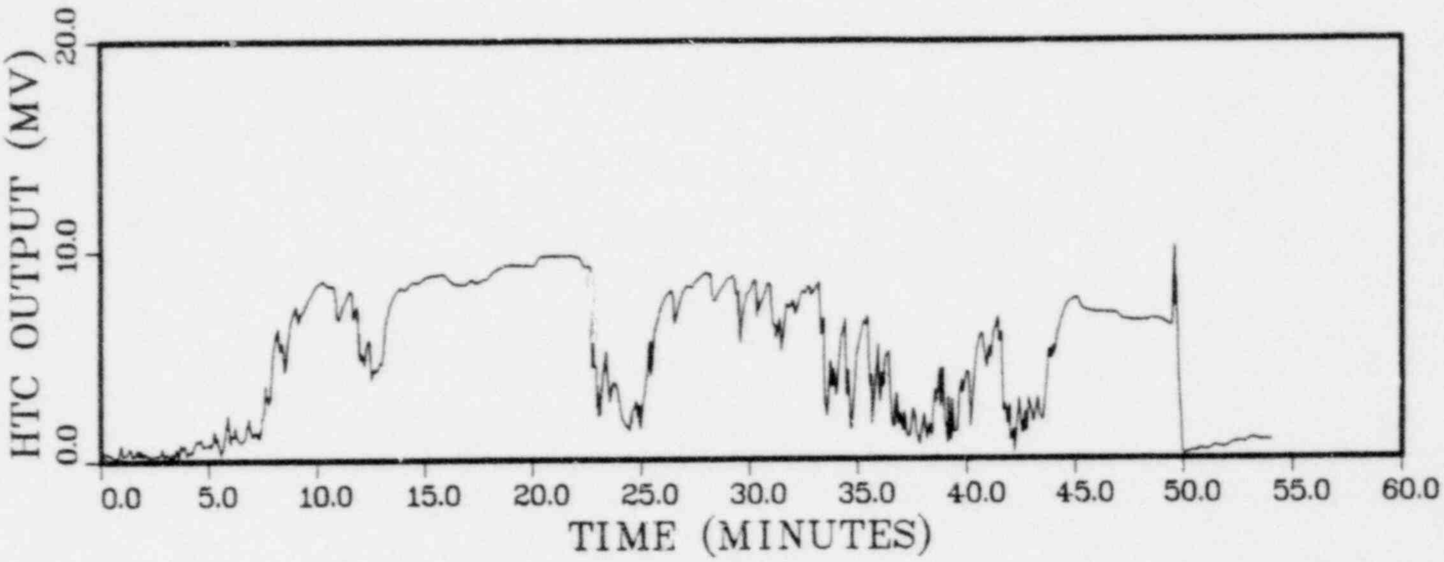

Fig. 4. Heated thermocouple output beginning at 11:39 on 9/11. Film boiling occurred in upper bundle at 18 min and at 44 min. Reflood occurred at 49 min upon bundle power trip.

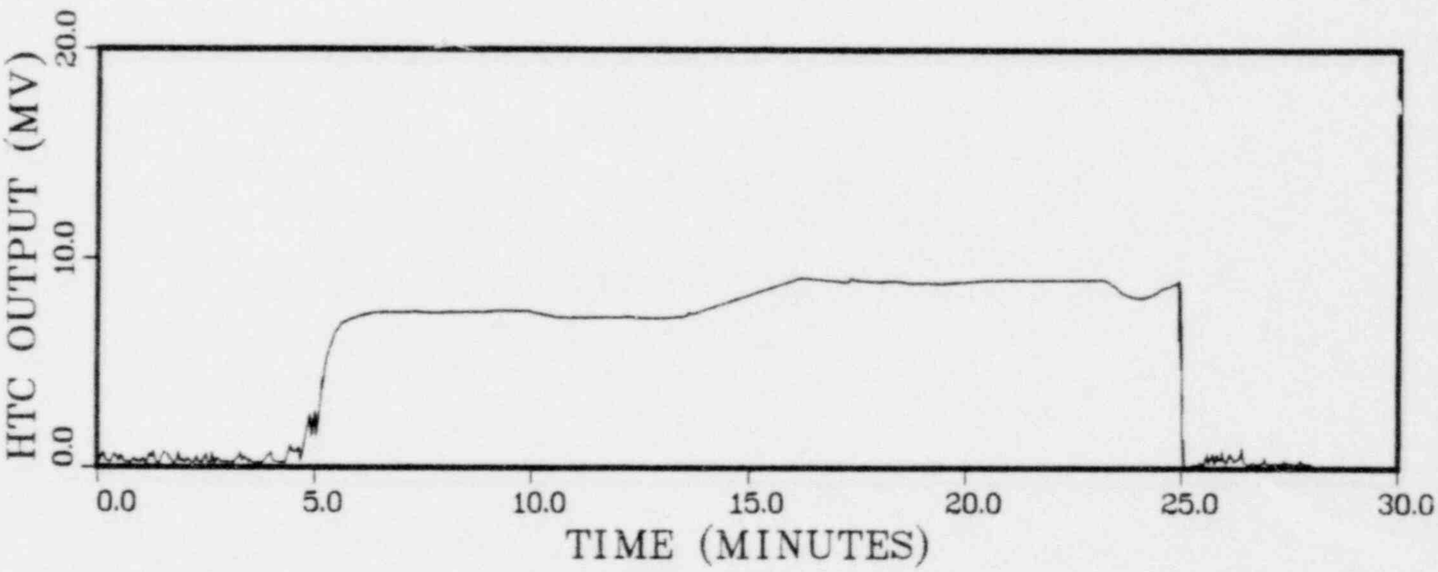

Fig. 5. Heated thermocouple output beginning at 13:44 on 9/11. Upper rod bundle uncovered at 6 min, quenched at 25 min.

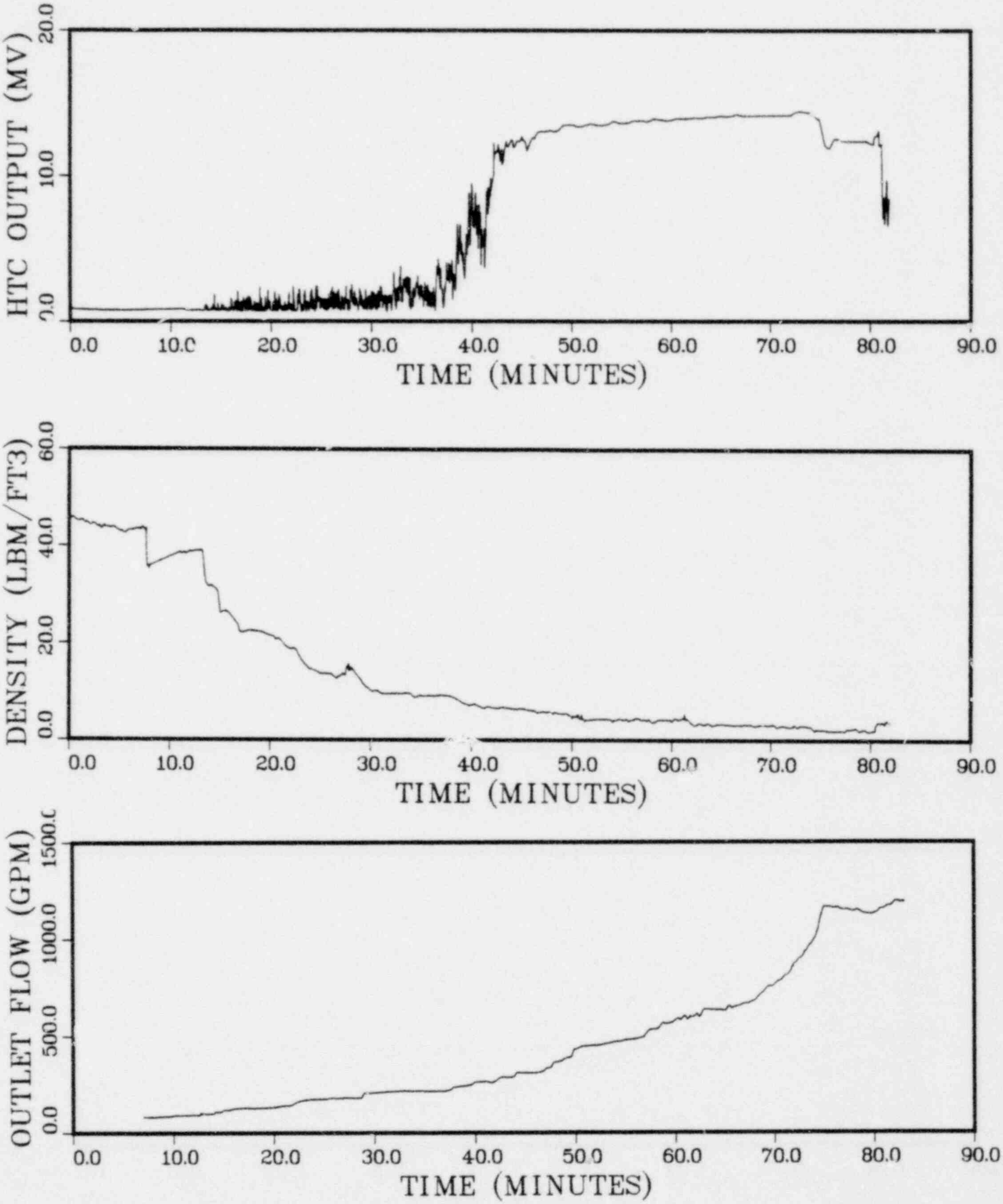

Fig. 6. Heated thermocouple output, measured density, and measured volumetric flow at test section outlet beginning at 19:14 on 9/11. Level F was in film boiling from about 70 min to 80 min.

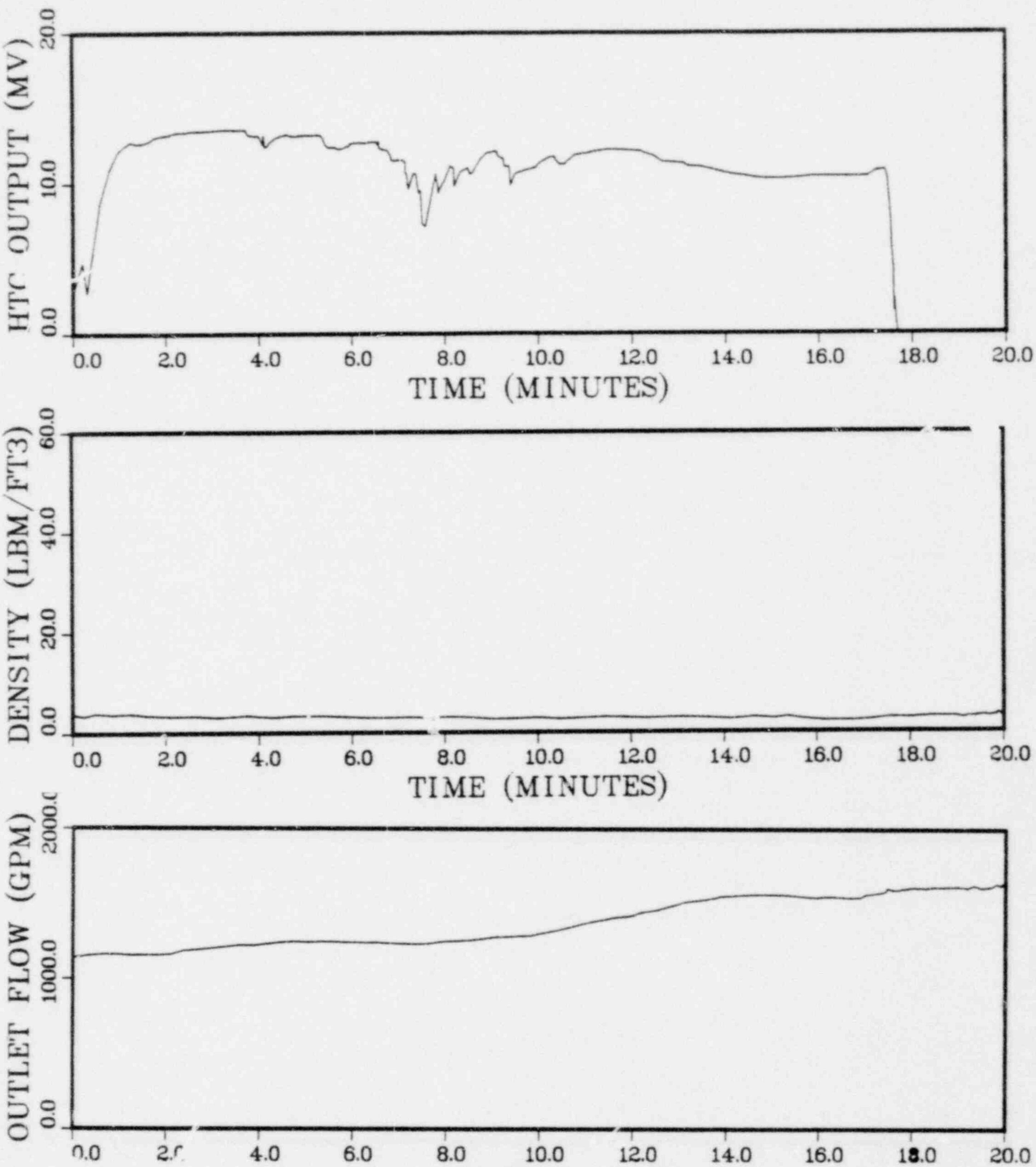

Fig. 7. Heated thermocouple output, measured density, and measured volumetric flow at test section outlet beginning at 20:36 on 9/11. Levels F and G were in film boiling at 16 min. Quenching occurred at about 17 min due to increasing inlet flow.

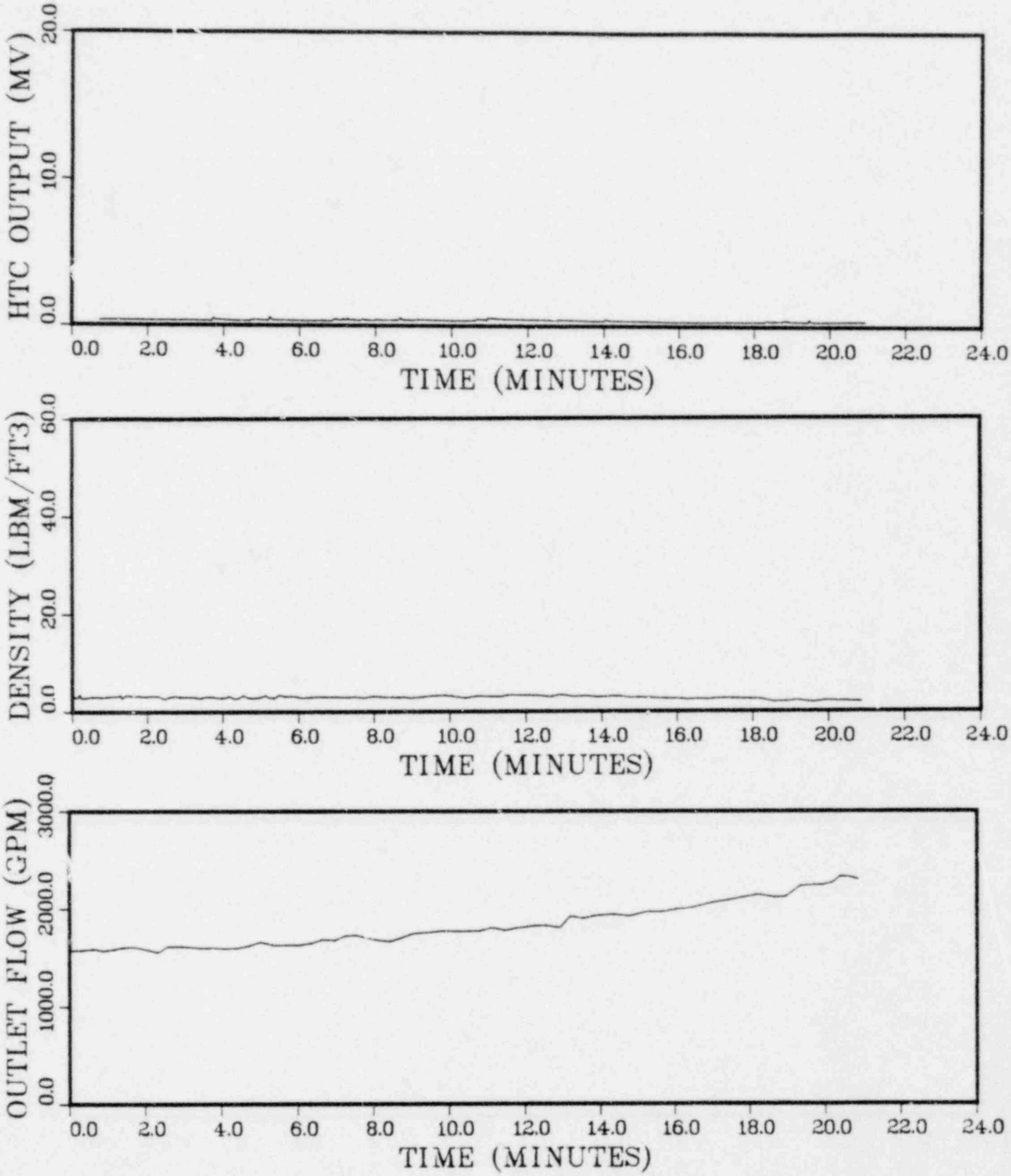

Fig. 8. Heated thermocouple output, measured density, and measured volumetric flow at test section outlet beginning at 20:59 on 9/11. Levels F and G were in film boiling at 19 min. Inlet flow was 66 gpm.

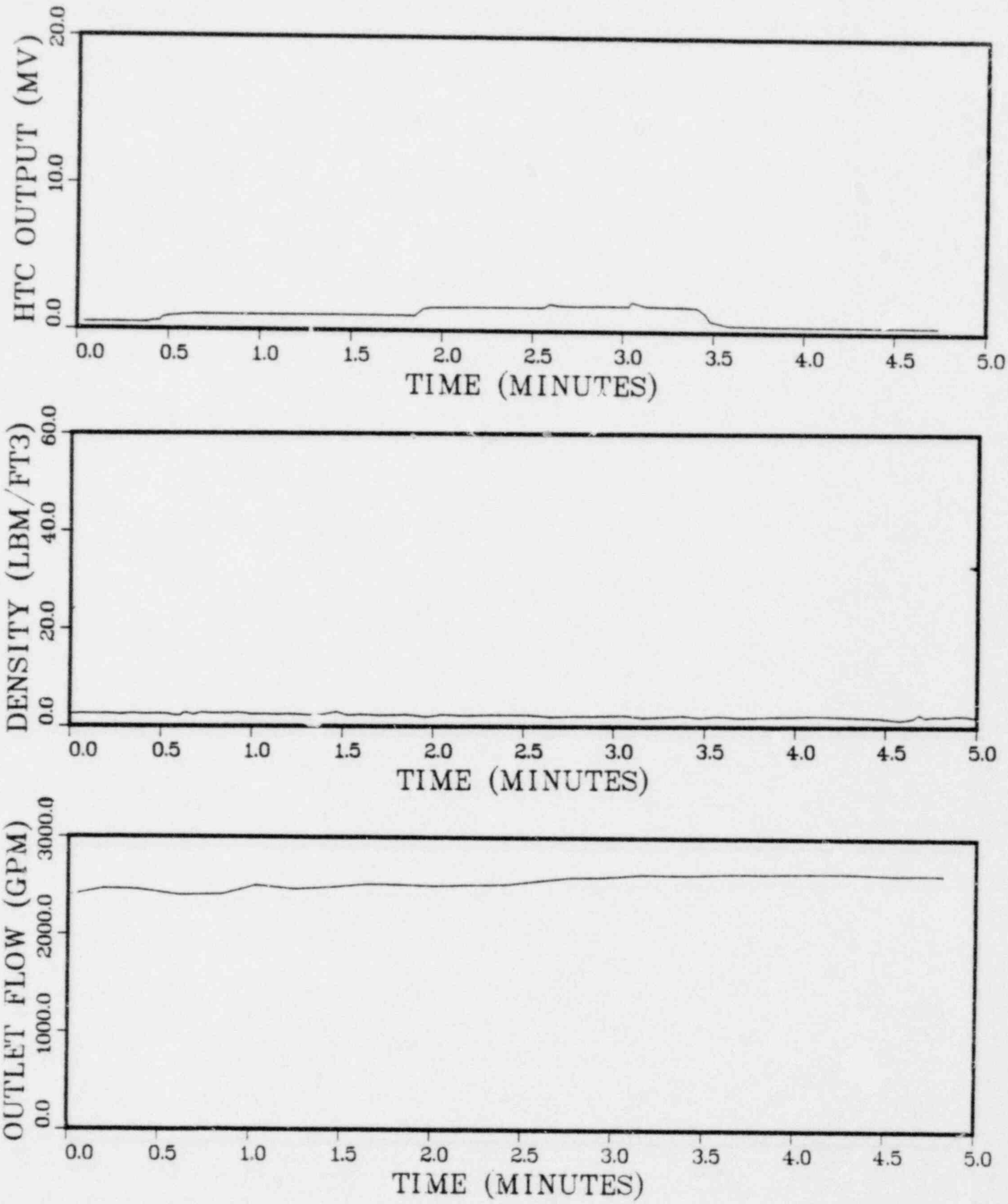

Fig. 9. Heated thermocouple output, measured density, and measured volumetric flow at test section outlet for period beginning at 21:27 on 9/11. The inlet flow was 85 gpm. The voltage applied to the probe heater changed from 17.5 to 25 V, to 30, and back to 17.5 V at 0.5, 1.8, and 3.5 min respectively. Levels F and G were in film boiling at 3 min.

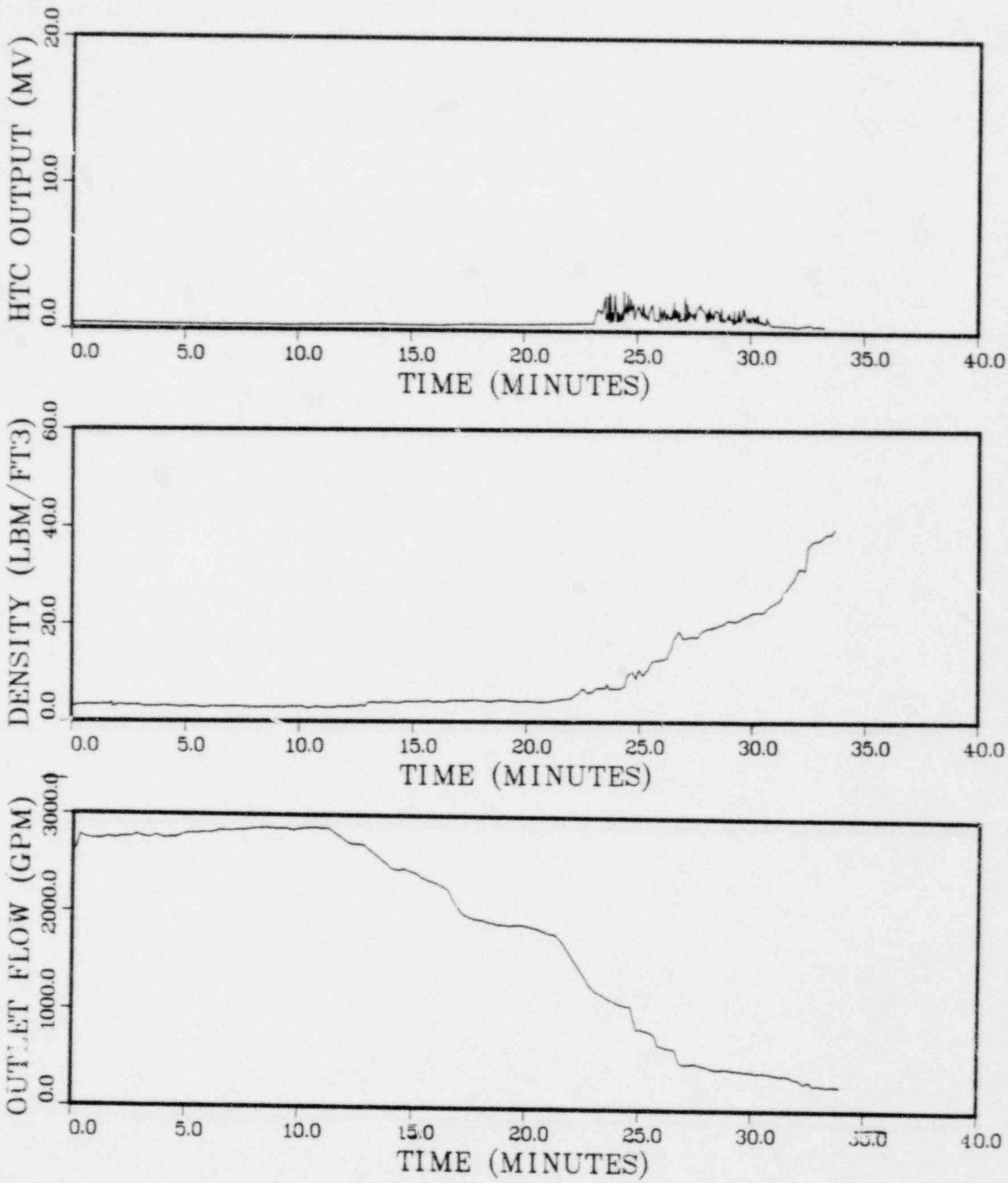

Fig. 10. Heated thermocouple output, measured density, and measured volumetric flow at test section outlet beginning at 21:33 on 9/11. Bundle inlet flow was 05 gpm. Levels F and G were in film boiling at 3 min; bundle power was 9 kW/ft at 3 min.

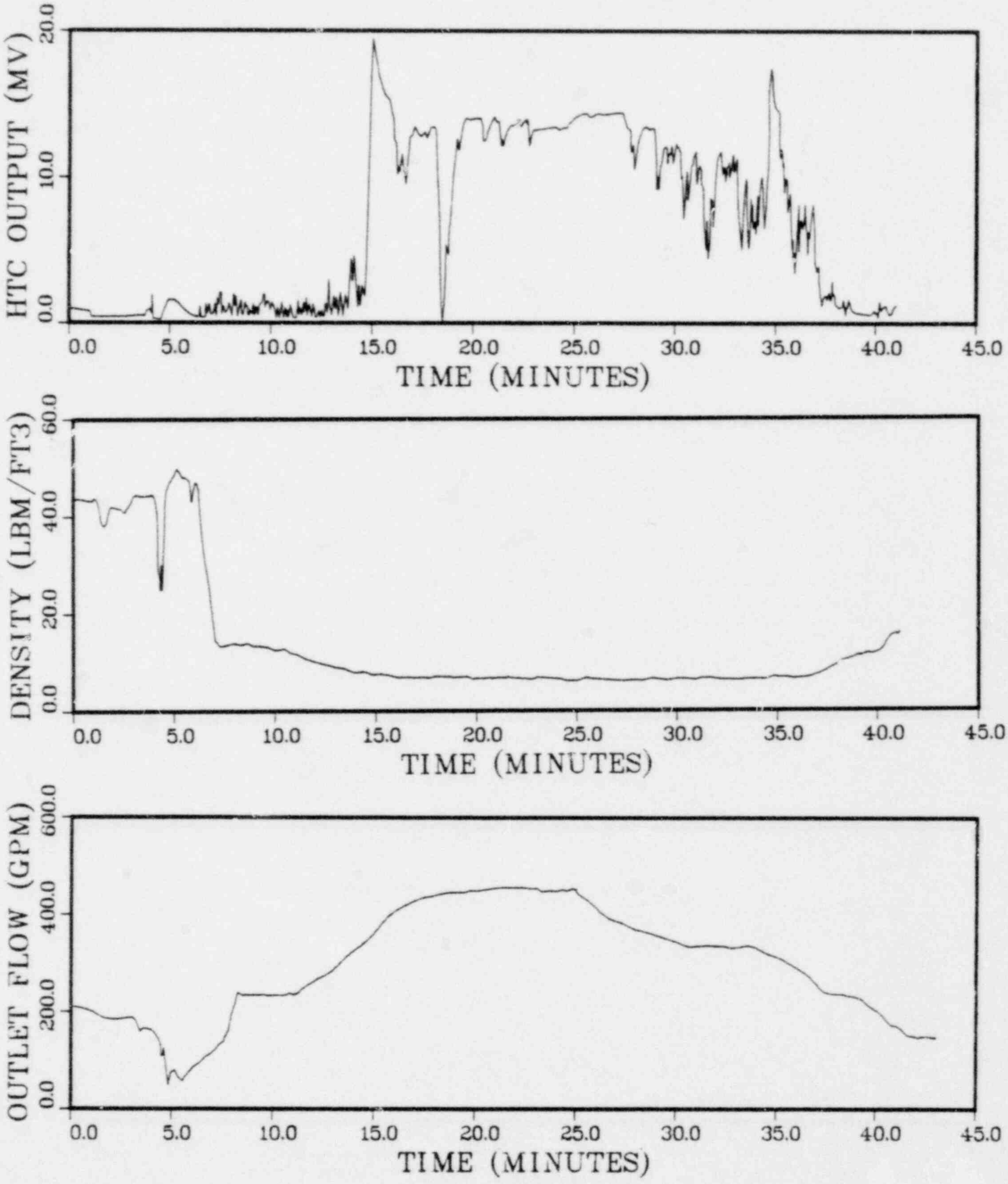

Fig. 11. Heated thermocouple output, measured density, and measured volumetric flow at test section outlet beginning at 22:18 on 9/11. At 15 min the probe voltage was changed from 17.5 to 25 V, then reduced again to 17.5 V before the signal went off scale. Probe power was turned off, then back on, at 18 min.

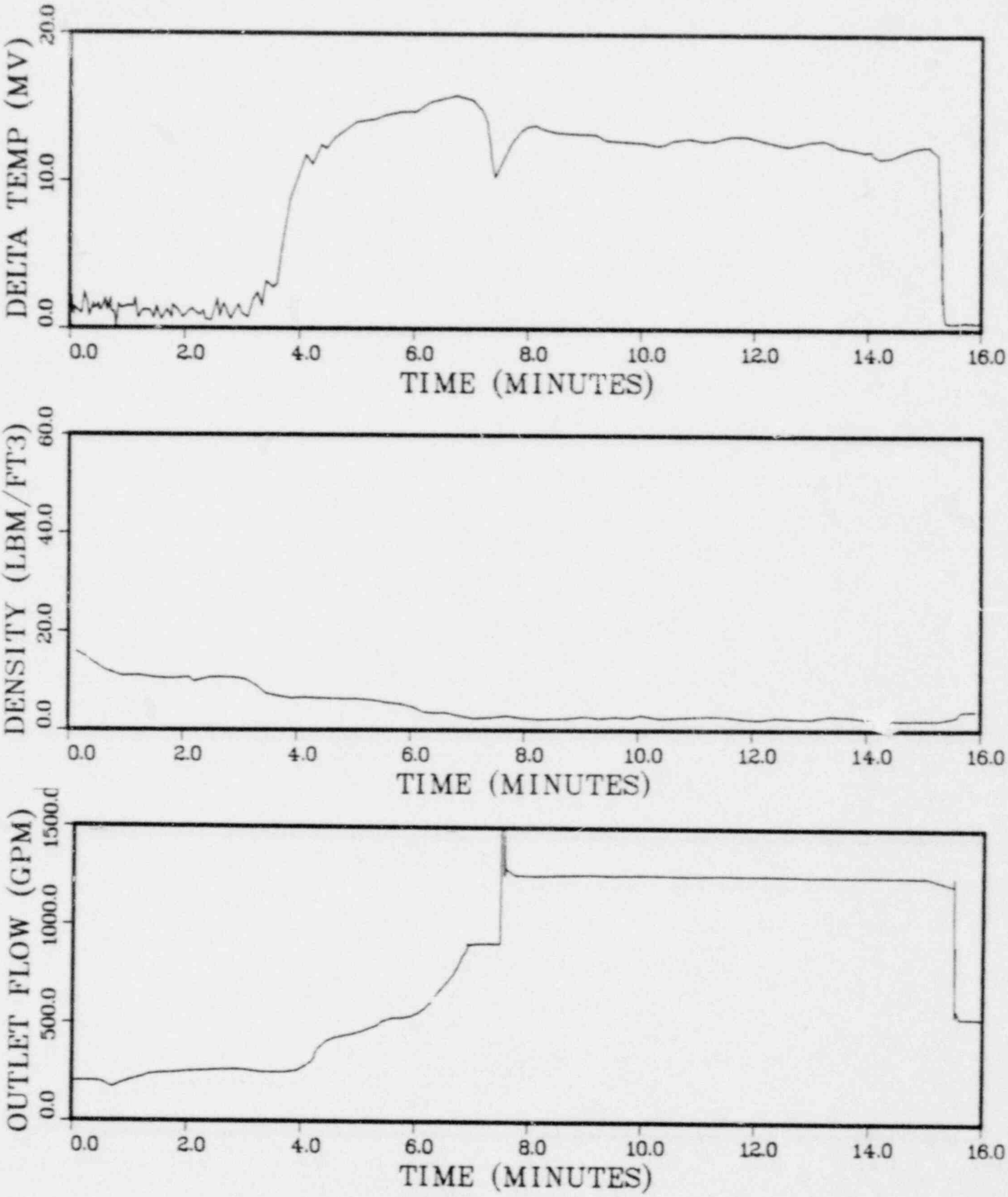

Fig. 12. Heated thermocouple output, measured density, and measured volumetric flow at test section outlet beginning at 24:11 on 9/12. Levels F and G were in film boiling at 5 min.

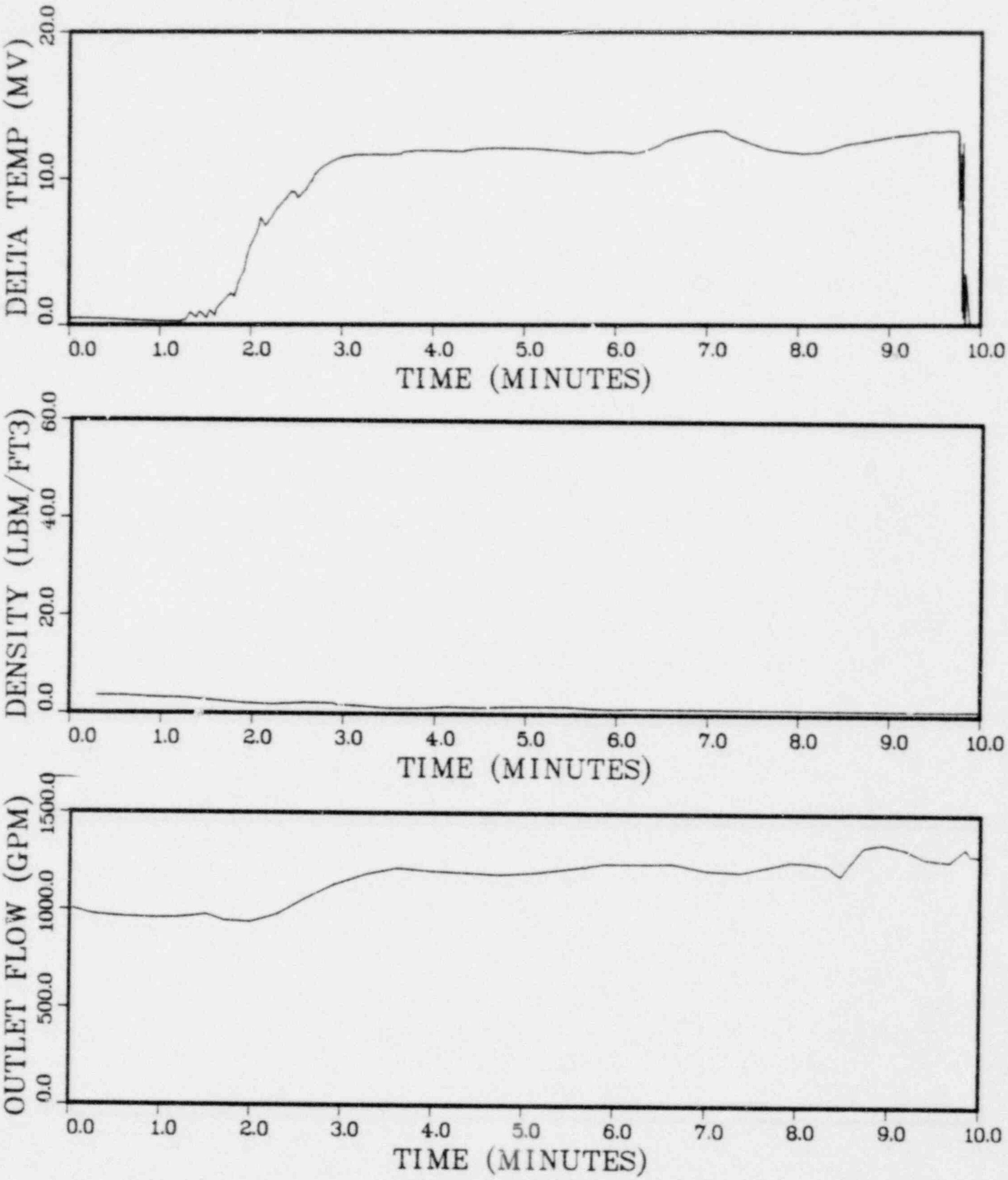

Fig. 13. Heated thermocouple output, measured density, and measured volumetric flow at test section outlet beginning at 24:27 on 9/12. Levels F and G were in film boiling from 1.5 to 9.8 min.

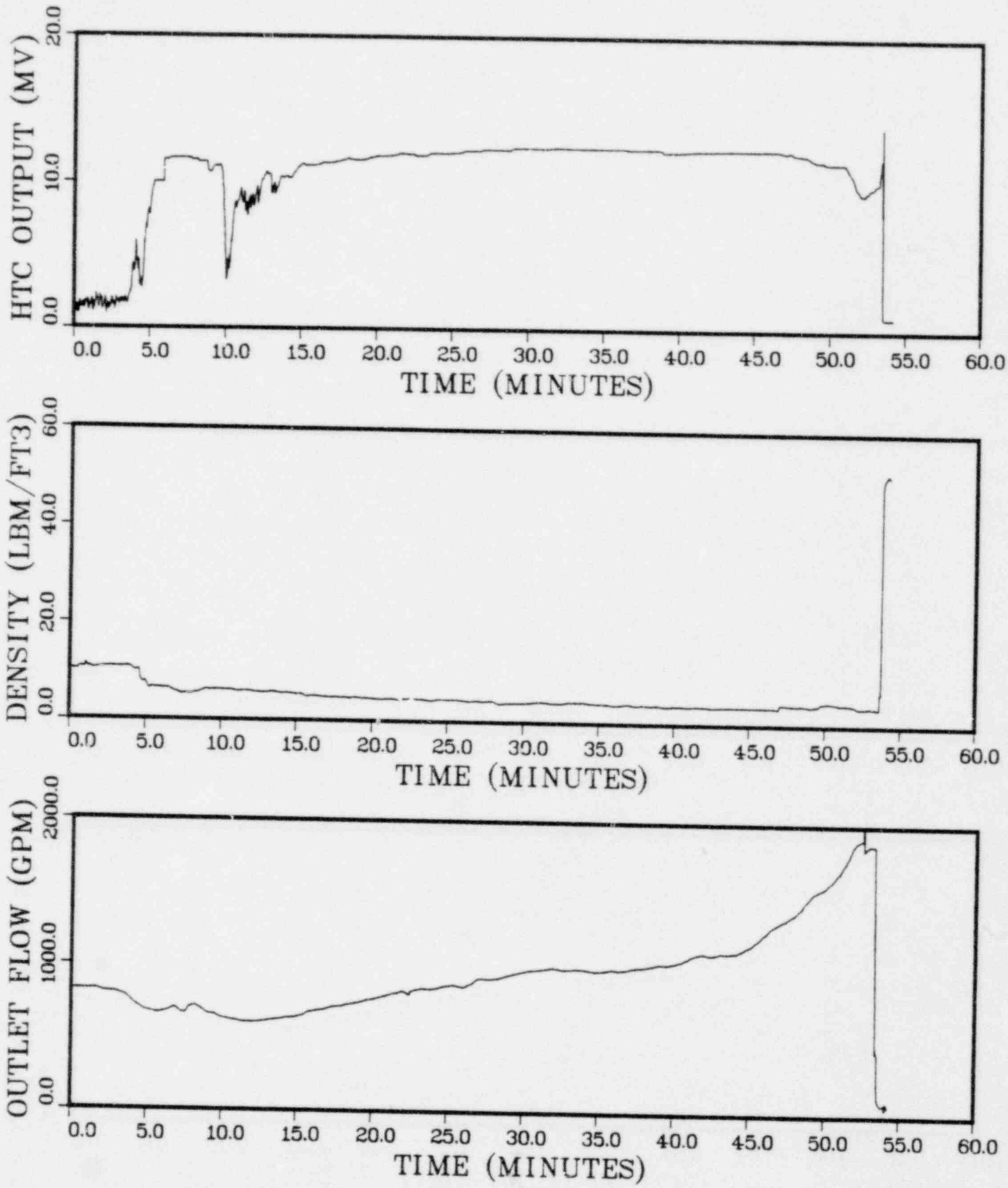

Fig. 14. Heated thermocouple output, measured density, and measured volumetric flow at test section outlet beginning at 10:06 on 9/18. Bundle inlet flow was increased at 10 min. No film boiling occurred until ~40 min. The THTF bundle power tripped at 54 min.

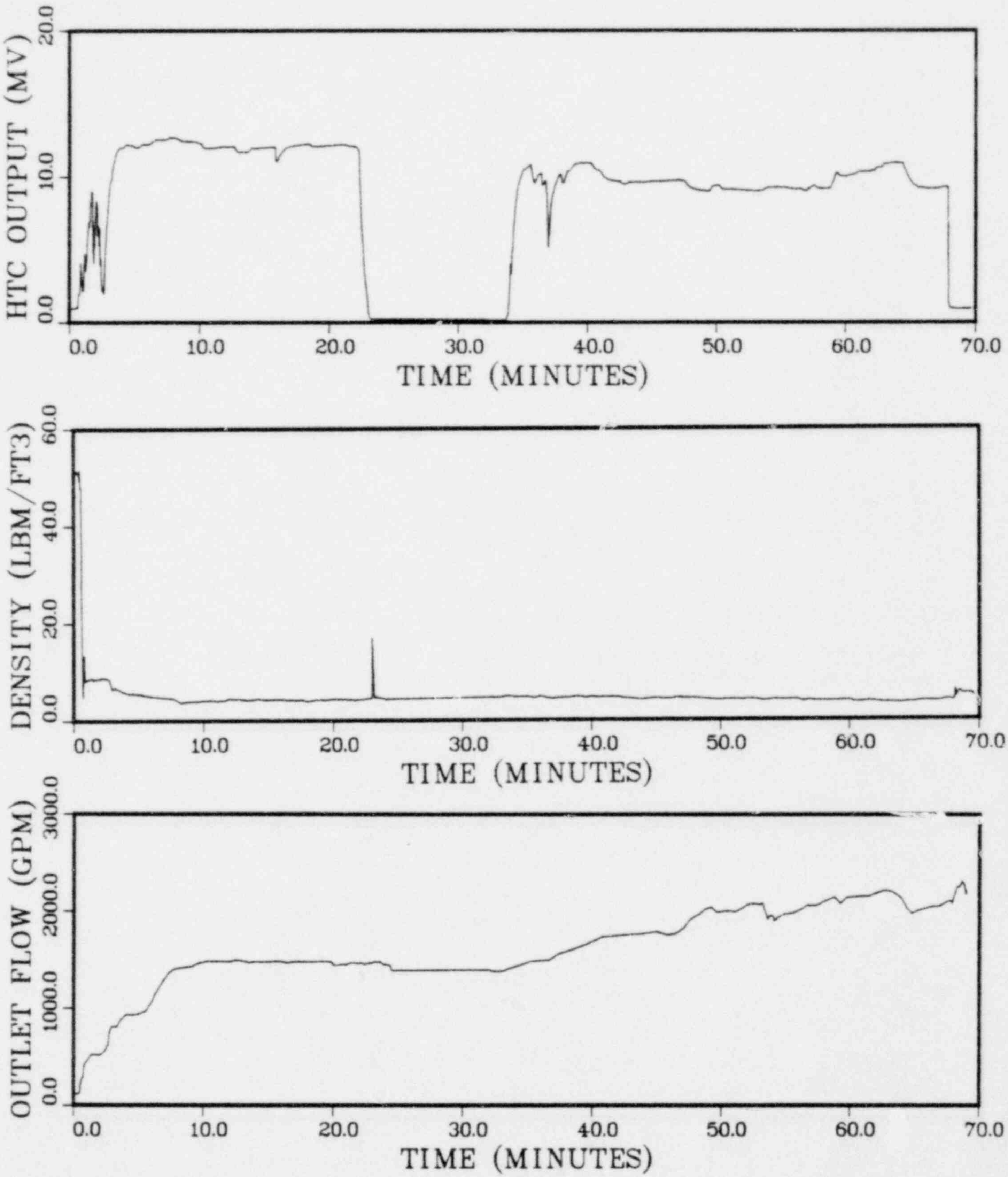

Fig. 15. Heated thermocouple output, measured density, and measured volumetric flow at test section outlet beginning at 11:00 on 9/18. Probe voltage was off at 22 min, returned to 15 V at 33 min. One rod was in film boiling at 37 min. Inlet flow was 36 gpm until 69 min when it was increased to 80 gpm. Levels F and G were in film boiling at 60 min.

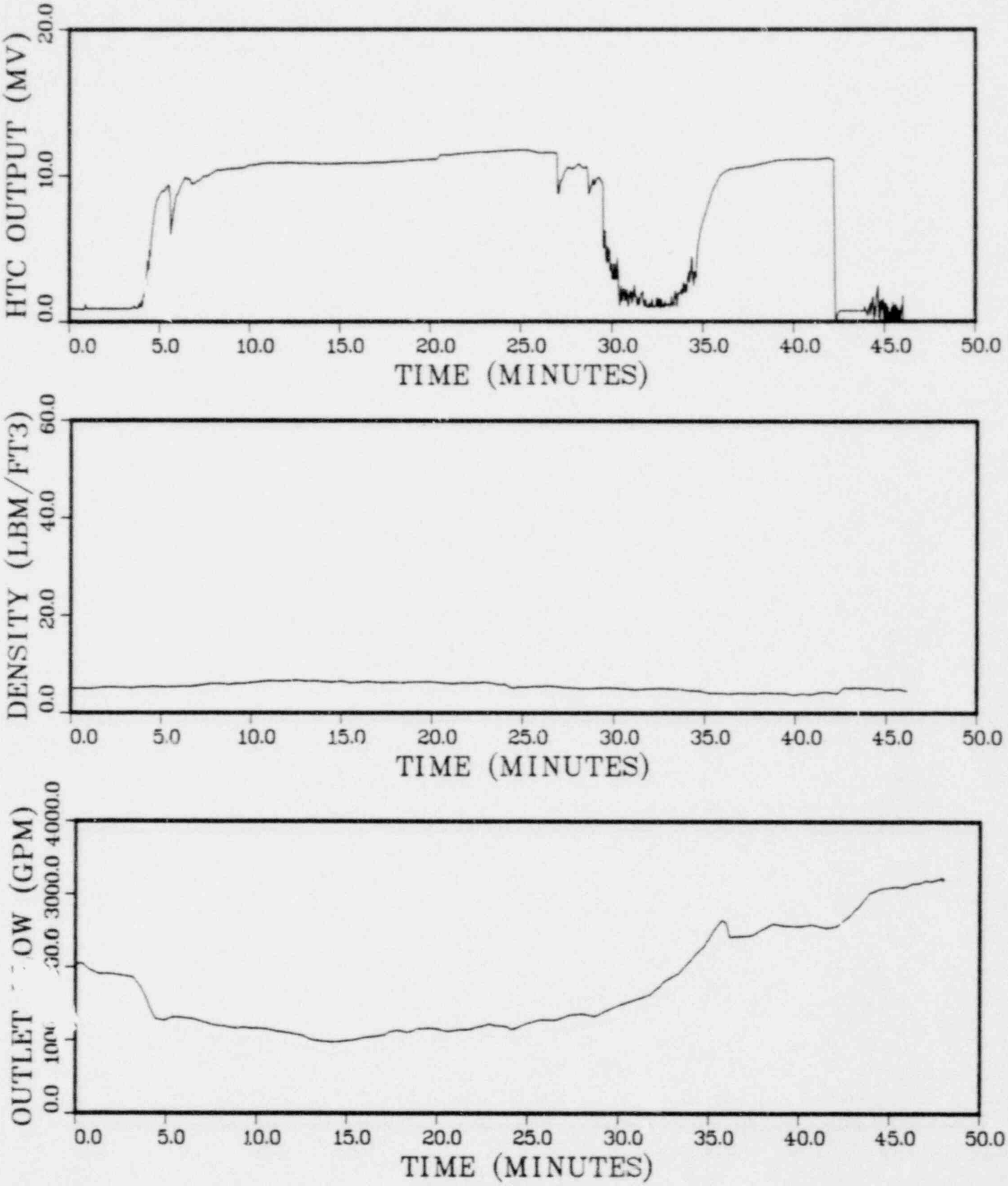

Fig. 16. Heated thermocouple output, measured density, and measured volumetric flow at test section outlet beginning at 12:12 on 9/18. Level G was in film boiling at 32 min. Levels F and G were in film boiling at 39 min.

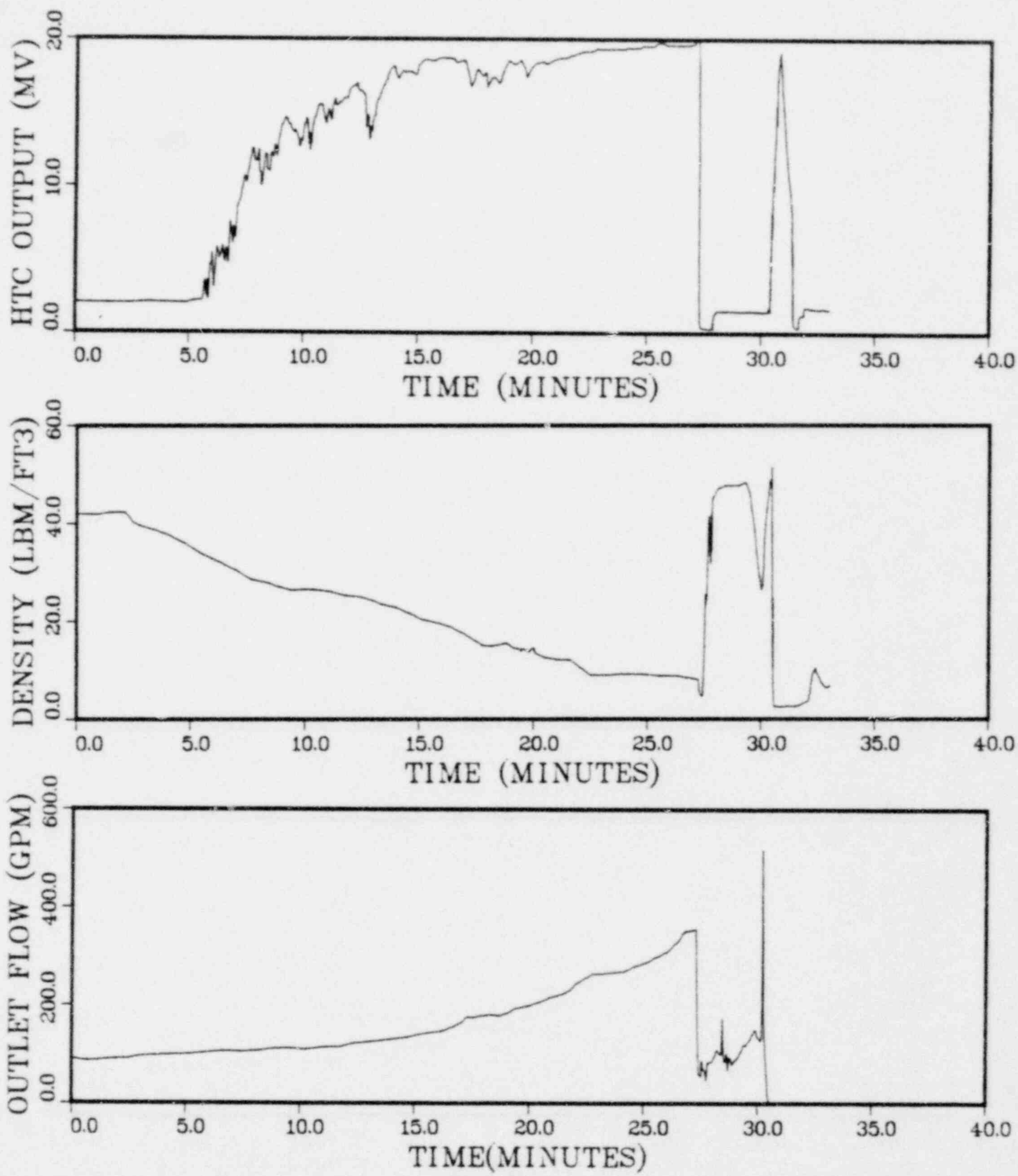

Fig. 17. Heated thermocouple output, measured density, and measured volumetric flow at test section outlet for period beginning at 14:45 on 9/23. The bundle power was tripped at 27.5 min and the pump was tripped at 30.5 min. HTC heater voltage was removed briefly at 27 and at 31 min.

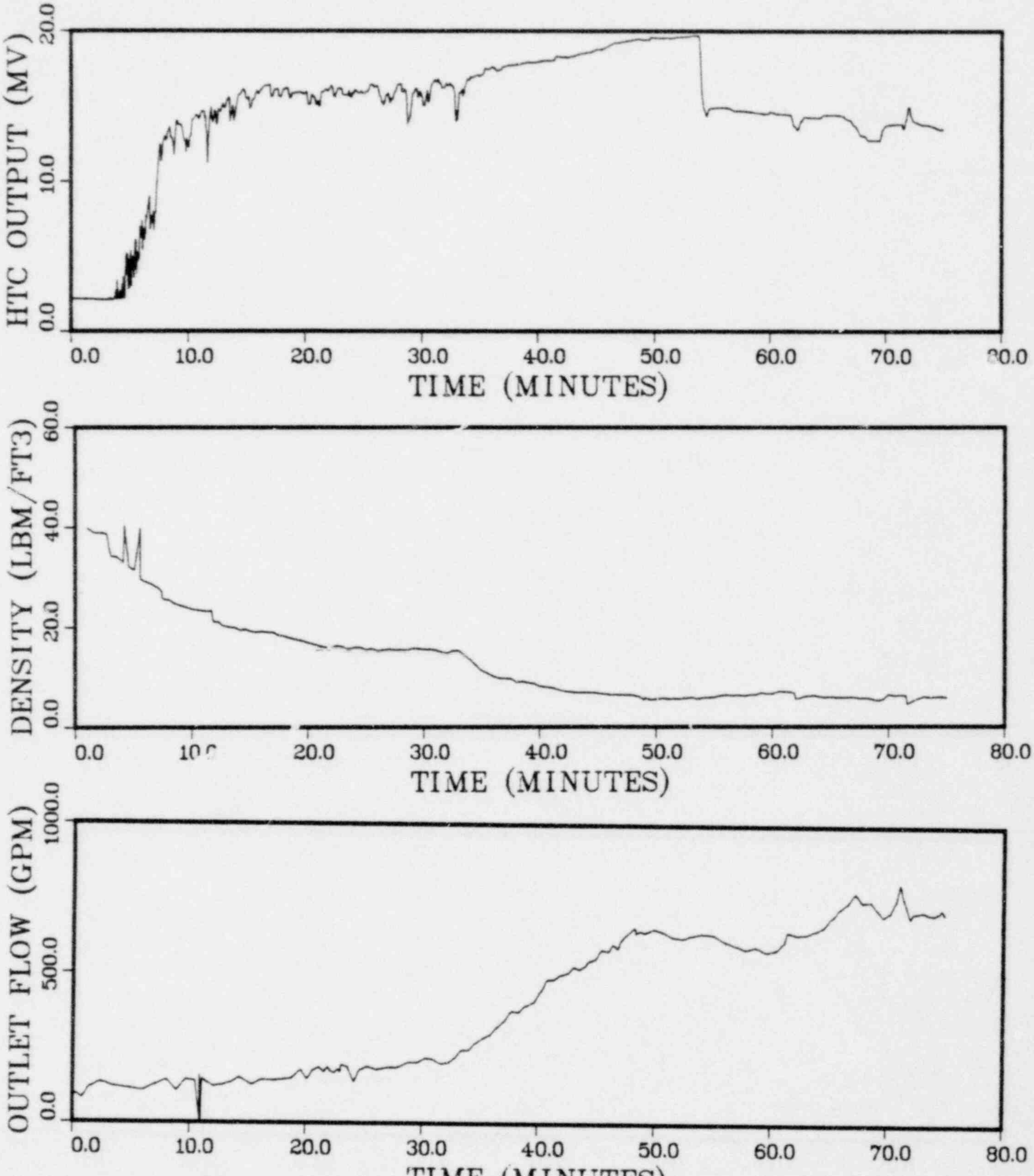

Fig. 18. Heated thermocouple output, measured density, and measured volumetric flow at test section outlet beginning at 11:10 on 10/1. Level G was in film boiling after ~45 min. Probe voltage reduced from 24 to 21 V at 54 min. Inlet flow was 30 gpm. Level G was in film boiling at 48 min. CHF occurred at level F at 63 min.

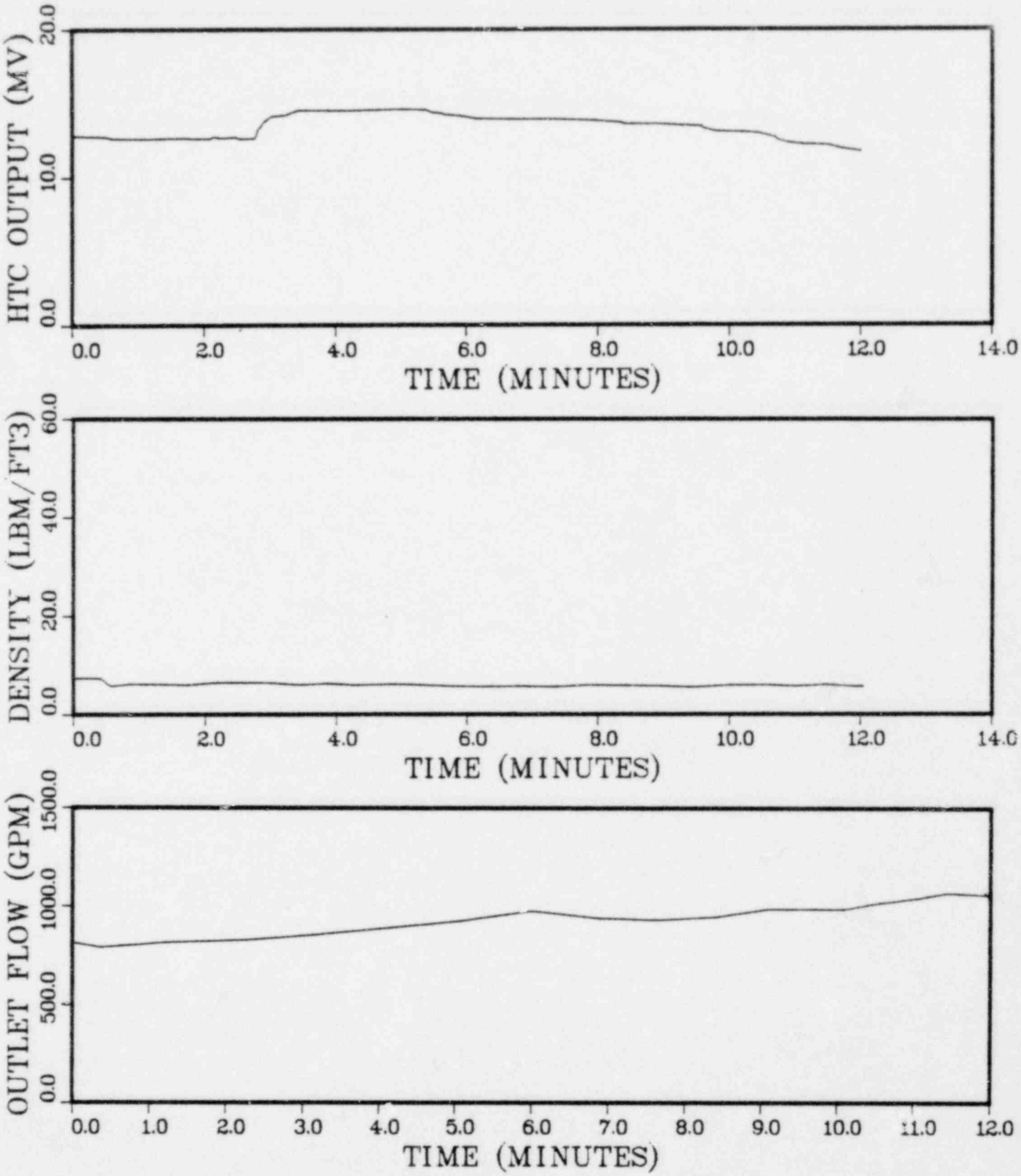

Fig. 19. Heated thermocouple output, measured density, and measured volumetric flow at test section outlet beginning at 12:24 on 10/1. Inlet flow was 30 gpm. Levels F and G were in film boiling throughout this period.

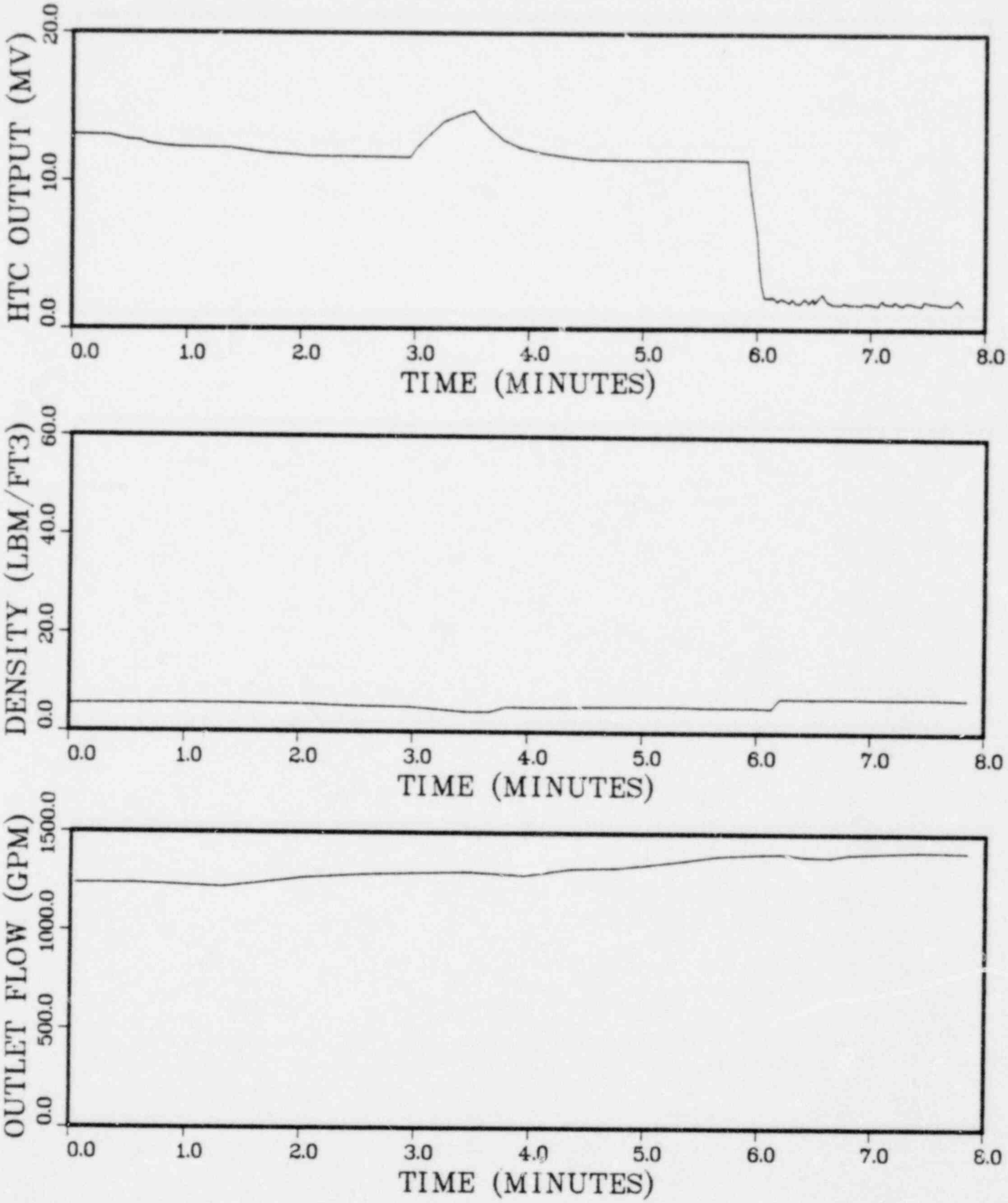

Fig. 20. Heated thermocouple output, measured density, and measured volumetric flow at test section outlet beginning at 12:42 on 10/1. Levels E, F, and G were in film boiling at 3 min. The bundle inlet flow was increased from 44 to 67 gpm at 5.9 min.

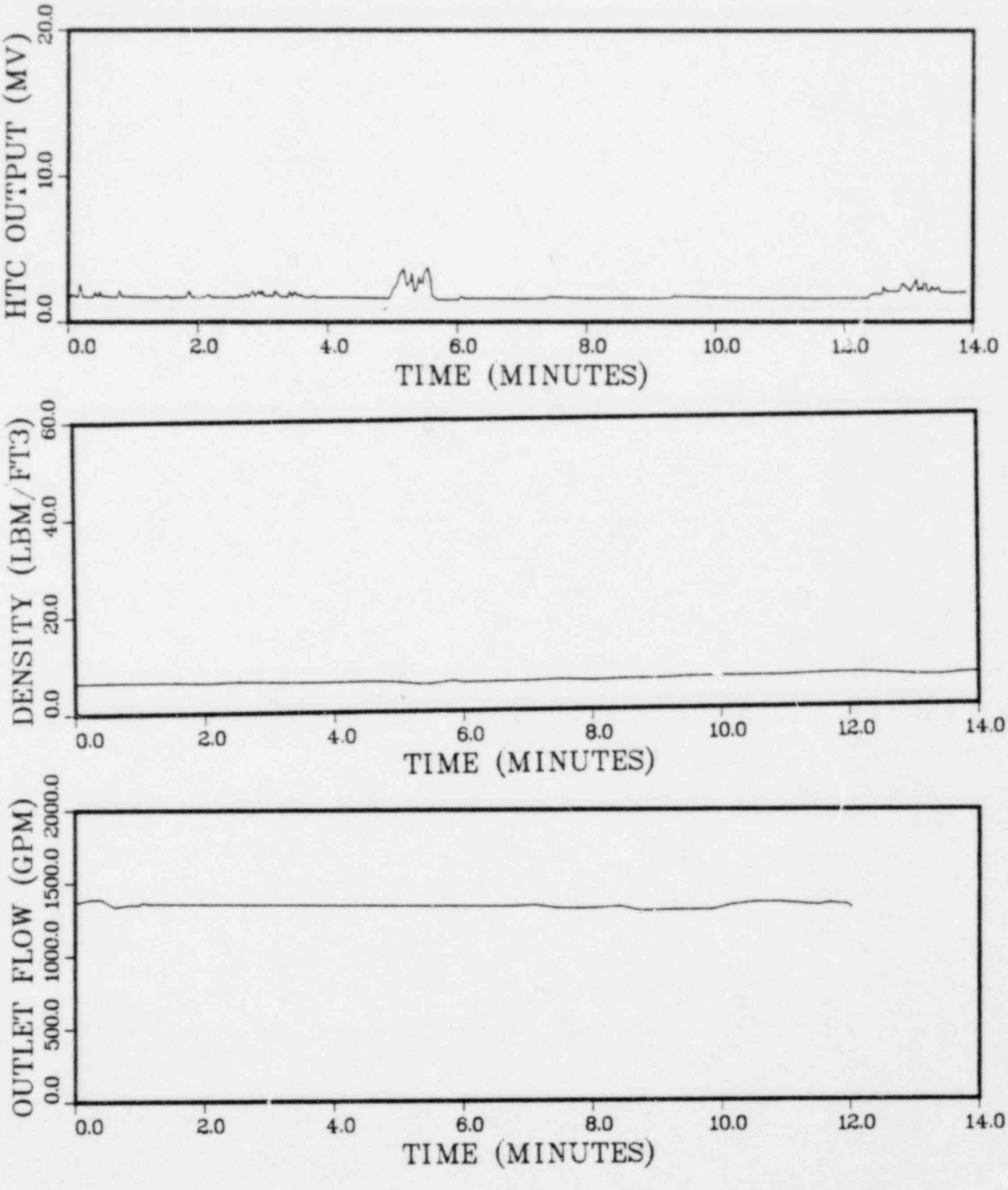

Fig. 21. Heated thermocouple output, measured density, and measured volumetric flow at test section outlet beginning at 12:51 on 10/1. Inlet flow was 86 gpm. Levels E, F, and G were in film boiling at 4 min.

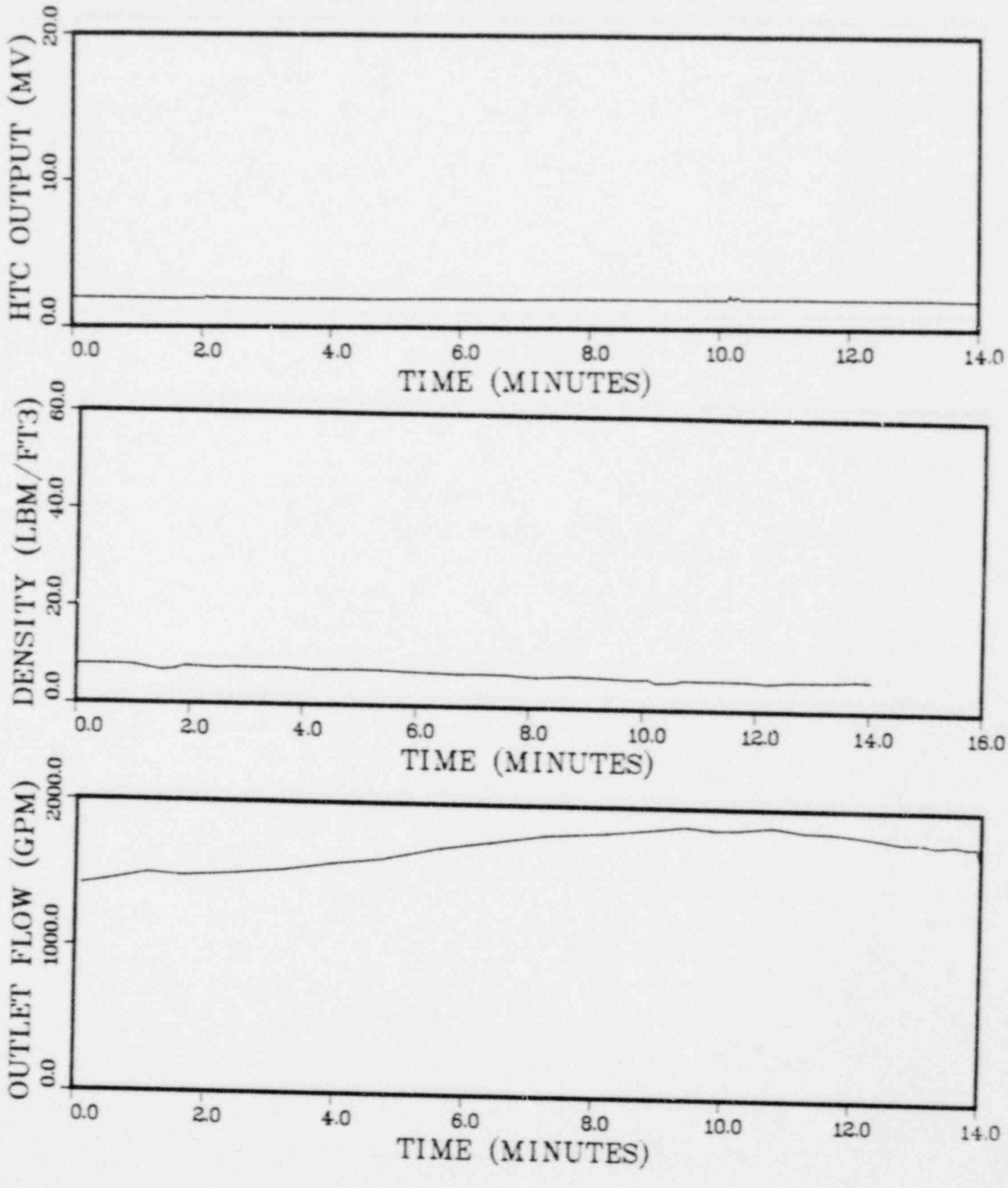

Fig. 22. Heated thermocouple output, measured density, and measured volumetric flow at test section outlet beginning at 13:11 on 10/1. Inlet flow was 100 gpm. Levels E, F, and G were in film boiling throughout. Level D was uncovered after about 12 min.

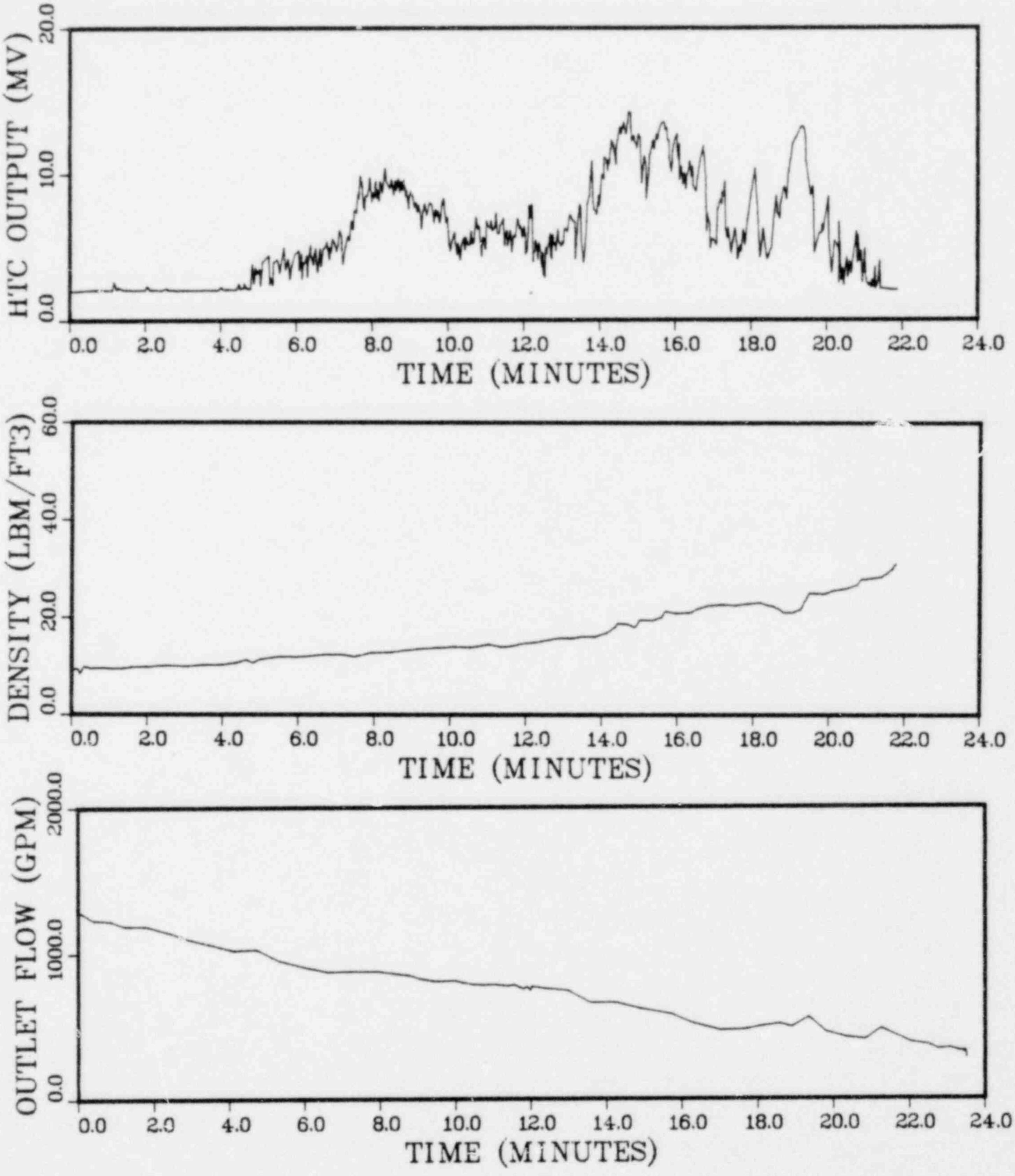

Fig. 23. Heated thermocouple output, measured density, and measured volumetric flow at test section outlet for period beginning at 13:37 on 10/1. Some film boiling occurred at level G at 14 min.

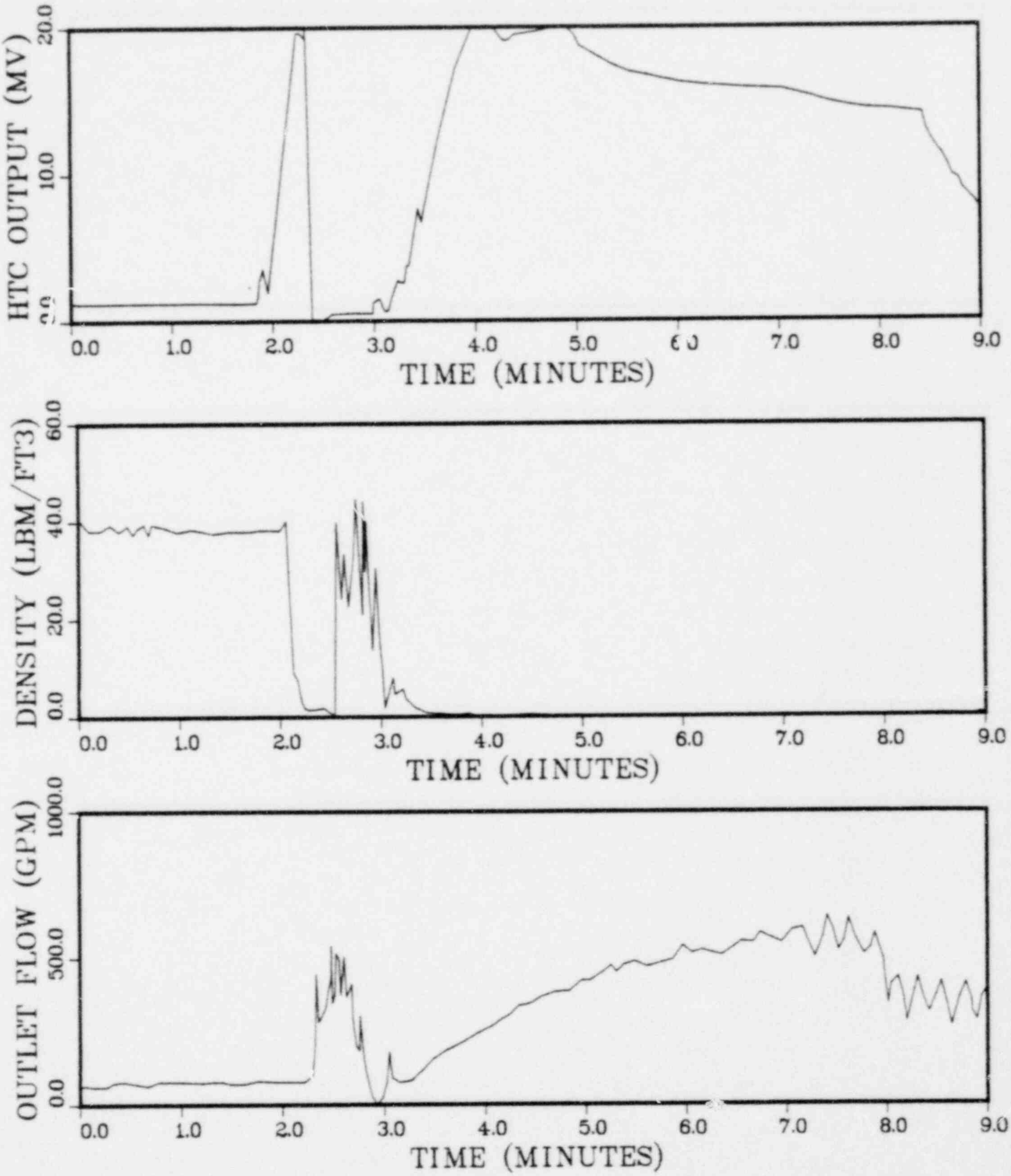

Fig. 24. Heated thermocouple output, measured density, and measured volumetric flow at test section outlet during inverted annular film boiling test and subsequent blowdown. Time zero was 02:35 on 9/12. See text for description of test.