CONF-761001--18

TEMPERATURE NOISE ANALYSIS AND SODIUM BOILING DETECTION IN THE FUEL FAILURE MOCKUP

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UNION CARBIDE CORPORATION
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ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION

*Research sponsored by the Energy Research and Development Administration under contract with the Union Carbide Corporation.

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ABSTRACT

Sodium temperature noise was measured at the exist of simulated, fast-reactor fuel subassemblies in the Fuel Failure Mockup (FFM) to determine the feasibility of using temperature noise monitors to detect flow blockages in fast reactors. Also, acoustic noise was measured to determine whether sodium boiling in the FFM could be detected acoustically and whether noncondensable gas entrained in the sodium coolant would affect the sensitivity of the acoustic noise detection system. Information from these studies would be applied to the design of safety systems for operating liquid-metal fast breeder reactors (LMFBRs).

We determined that the statistical properties of temperature noise are dependent on the shape of temperature profiles across the subassemblies, and that a blockage upstream of a thermocouple that increases the gradient of the profile near the blockage will also increase the temperature noise at the thermocouple. Amplitude probability analysis of temperature noise shows a skewed amplitude density function about the mean temperature that varies with the location of the thermocouple with respect to the blockage location.

We concluded that sodium boiling in the FFM could be detected acoustically. However, entrained noncondensable gas in the sodium coolant at void fractions greater than 0.4% attenuated the acoustic signals sufficiently that boiling was not detected. At a void fraction of 0.1%, boiling was indicated only by the two acoustic detectors closest to the boiling site.

INTRODUCTION

The Failed Fuel Mockup (FFM) [1], is a sodium flow facility which simulates the hydraulic characteristics of a fast reactor fuel subassembly. In the measurements reported here, the facility was used to investigate a method of detecting a coolant channel blockage by measuring and analyzing the exit sodium temperature noise [2] and a method of detecting sodium subcooled nucleate boiling by detecting [3,4] and analyzing acoustic noise.

Temperature noise measured at the exit of both blocked and unblocked test bundles was characterized using various noise signal descriptors such as power spectral density (PSD), amplitude probability density (APD), and root mean square (RMS). Previous work [5] indicated that a blockage in the coolant channels of an LMFBR operating at power might be detected by measuring the change in the temperature noise at the coolant channel outlet. The noise, caused by turbulent mixing of the sodium flowing from the coolant channels at different temperatures, had been observed to depend on the sodium flow and heat flux [6]. Recently, some types of blockages in water test sections were identified by measurement of the skewness factor of the APD of rod-bundle exit temperature noise [7]. This work in the FFM extended these previous investigations to include partially blocked, simulated fuel bundles, as well as the unblocked bundles used in the previous work.

The main objectives of the work in acoustic detection of sodium boiling were twofold: to compare the amplitude of the signal from the acoustic sensors caused by boiling with the amplitude of the background noise sources in the FFM, and to determine the effects of an entrained, noncondensable gas (argon) on the detection system. These objectives were accomplished during flow-reduction-to-boiling experiments in the FFM which were performed to measure the transient temperatures throughout the bundle to the start of boiling and to generate an acoustic signal for tests of the boiling detection system. The production and movement of sodium voids in these simulated fuel bundles were not typical of that expected in an LMFBR, because the facility was not designed for this purpose [8].

DESCRIPTION OF THE FFM FACILITY

The FFM is a facility for simulating fuel subassemblies, using electric cartridge heaters, so that their configuration, power density, pressure, specific flow, and temperature would be typical of subassemblies for the Fast Test Reactor (FTR) [1]. The simulated subassemblies for these tests were 19-rod bundles with a heated length approximately one-half that of the core fuel designed for the FTR. Each simulated fuel rod, 0.58 cm OD, within a subassembly was wrapped with 0.14-cm-OD wire spacers pitched 30.5-cm. The bundle of 19 rods was enclosed, and the bundle was cooled by a closed-loop, circulating-sodium system with a 420-kW air-cooled radiator heat dump. A variable speed pump and throttle valves controlled the sodium flow. Power to the individual rods could be varied from 0 to 24.5 kW per rod.

During later tests, a system was added for injecting small amounts of argon into the sodium stream at the inlet of the test section [9,10] to simulate entrained argon cover gas or fission gas escaping from a leak in the fuel cladding.

EXIT TEMPERATURE NOISE ANALYSIS

Sources and Interpretation of Temperature Noise

Temperature fluctuations in a fluid are caused by turbulent mixing of various portions of the fluid which are at different temperatures. The amplitude of temperature fluctuations detected by a thermocouple immersed in the fluid depends on the lateral temperature gradient across the bundle, the degree of mixing or turbulence, and the location and response time of the thermocouple.

A blockage in the rod bundle could increase the temperature fluctuations downstream because it would cause an increase in the lateral temperature gradient. However, a skewed power distribution in the bundle could also cause an increased lateral temperature gradient which could cause temperature noise similar to that caused by a blockage.

The existence of a temperature gradient in the vicinity of the thermocouple can be deduced from the distribution of amplitudes of the fluctuations in the thermocouple signal about the mean temperature. If the fluctuations are predominately less than the mean (negative), the thermocouple is located at or near a maximum in the fluid temperature gradient. Conversely, predominately above the mean (positive) amplitudes indicate a thermocouple position near a minimum in the gradient. The skew of the amplitude probability density (APD) function distribution is a measure of asymmetry about the mean value. The APD of a Gaussian noise signal is symmetric about the mean; its skew value is zero. The APD formed from a signal with predominately positive or negative amplitude values is asymmetric with respect to the mean; the skew values are positive or negative, respectively. Ohlmer and Schwalm concluded that the location and size of a blockage in a bundle can be inferred from the skew value of the APD function of the temperature fluctuations at a fixed thermocouple location downstream from the exit of a rod bundle [7].

Location of Blockages and Thermocouples for Noise Measurements

Two partially blocked and one unblocked bundle were tested. In bundle 3A the central six channels were blocked by a non-heat-generating, stainless-steel plate, 0.64 cm thick which was brazed to the center rod (Fig. 1). The blockage was 38.1 cm downstream from the start of the 53.3 cm heated length. Chromel-Alumel thermocouples were positioned at the nominal centers of flow channels at the bundle exit, ~7.6 cm of unheated rod before the exit. The thermocouple time constant of ~150 msec allowed analysis of temperature fluctuations from 0 to ~1 Hz.

In bundle 5B (Fig. 2) an edge blockage was located 10.2 cm downstream from the start of the 45.7 cm heated length. The blockage, covering about one-third of the flow cross-sectional area, was displaced 0.036 cm from the channel wall. The exit thermocouples were ~43.2 cm downstream of the blockage. The same bundle was also tested in an unblocked configuration (labeled bundle 5C).

Data Acquisition and Processing

The thermocouple signals were amplified and recorded in analog form. Background noise was measured with the bundle heaters off and the test loop at an isothermal condition. Three types of analyses were performed on the thermocouple signals: power spectral density (PSD), root-mean-square (RMS), and amplitude probability density (APD).

Results and Discussion

The PSD of the signals obtained with and without the edge blockage (bundles 5A and 5C, respectively) are shown in Figs. 3 and 4. The magnitude of the PSD increased significantly at both thermocouple locations when the flow was blocked because the lateral temperature profile was distorted (Figs. 5 and 6). The profile of the mean temperature at the exit of the unblocked bundle was much flatter; there was only ~2°C variation between thermocouples EC11 and EC38. However, there was an ~20°C variation in temperature between these same thermocouples when the blockage was present. (EC39 was located adjacent to the test section wall. The 0.036-cm gap between the blockage plate and the wall may have allowed cooler sodium to bypass into this region.)

The slope of the PSD in unblocked bundle 5C (Fig. 4) at frequencies below 0.5 Hz implies that there are two mechanisms of temperature noise: turbulent mixing and an unknown mechanism. Measured background and extraneous noise in the signal were negligible. The temperature gradient in the vicinity of thermocouple EC19 (Fig. 5), was approximately zero, which indicates that there was little driving force for temperature noise due to turbulent mixing. In the absence of mixing, the observed PSD of the temperature fluctuations has a frequency dependence given by

$$\phi(f) = \phi_o/f .$$

Nishihara [11] observed this effect, and he attributed it to bulk temperature fluctuations typical of laminar flow. The flow in the FFM, however, was turbulent at a velocity a ~7 m/sec, having a Reynolds number of ~30,000. The source of this noise in the FFM is unknown.

Root-mean-square analysis of noise signals reduces a PSD or an APD function to a single number that represents the degree of noise in the signal. Others [5] have shown experimentally that the root-mean-square noise varies inversely with flow and increases with increasing heat flux. The results from bundles 5B and 5C at a heat flux of 71 W/cm^2 for thermocouple EC04 (Fig. 7) compare well with those in ref. 5 for both blocked and unblocked flow. The RMS temperature fluctuation was greater at all the flow velocities tested when the flow was blocked.

The results from other thermocouples in bundle 5 (Table I), confirm previous observations. However, the RMS noise at a heat flux of 85 W/cm^2 and a flow velocity of 2.8 m/sec was greater in the unblocked bundle than in the blocked bundle. This latter result is due to the locations of the thermocouples. Bentley [5] has stated that thermocouples should be far downstream from a bundle exit to assure that local turbulence at the bundle exit does not mask the temperature noise of interest. The FFM exit thermocouples were at the exit of the bundle (there was a 7.6-cm unheated length, as shown in Fig. 2). The inconsistencies in the RMS results shown in Table I may have been due to the local temperature profile and turbulence in the wake zone at the ends of the rods; i.e., the thermocouples may not have been placed sufficiently far downstream of the bundle exit to produce reliable results for blockage detection. (Thermocouple locations were selected to obtain steady-state data for the FFM project.)

The skew values of the APD functions at each thermocouple position, the RMS values, and the lateral temperature profile for centrally blocked bundle 3A are shown in Fig. 8. From a comparison of the skew values obtained with thermocouples located downstream from the blockage with the skew values obtained with thermocouples similarly located in the unblocked region, it is apparent that the skew values are sensitive to the location of the thermocouples with respect to the lateral temperature profile. For example, thermocouple EC17 in the unblocked flow area indicates the lowest mean temperature (369.9°C) and a small positive skew (0.082), but EC03 behind the blockage indicates a higher mean temperature (392.6°C) and a negative skew (-0.239). In addition, although the skew values of the APD functions for EC06 and EC03 (in symmetric locations) are both negative, the magnitude of the skew is ~5 times larger for EC03. Also, the APD of EC16 has a larger positive skew than that of either EC17 or EC08. Neither result is understood. The results from bundles 5B and 5C (Figs. 5 and 6) are similarly inconsistent. In the blocked bundle (5B), the skew values vary from -0.919 to 1.271 for the two thermocouples located nearest the center of the bundle exit (EC01 and EC04), but the model of ref. 7 predicts a positive skew of ~0.5 to 1 for an edge blockage like that in bundle 5B. Our results in the FFM indicate that the skew value is strongly dependent on both the lateral and the axial location of the thermocouple.

TABLE I

RMS of Exit Sodium Temperature Fluctuation in FFM Bundle 5
With and Without an Edge Blockage

Heat Flux (W/cm^2)	Flow Velocity (m/sec)	RMS Temperature Fluctuations[a] (°C)			
		EC01	EC04	EC19	EC20
		Blocked Bundle 5B			
8[illegible]	7.2	0.394	0.176	0.115	0.161
85	5.5	0.710	0.242	0.272	0.239
85	2.8	0.3[illegible]3	0.172	0.149	0.289
71	7.2	0.148	0.082	0.135	0.142
71	5.5	0.161	0.102	0.160	0.149
71	2.8	0.334	0.299	0.333	0.315
		Unblocked Bundle 5C			
85	7.2	0.031	0.038	0.035	0.031
85	5.5	0.088	0.052	0.041	0.036
85	2.8	0.894	0.222	0.318	0.322
71	7.2	0.060	0.031	0.026	0.025
71	5.5	0.069	0.042	0.028	0.030
71	2.8	0.324	0.098	0.091	0.148

[a]These results are based on a 53-min data record and an 8-Hz analysis bandwidth, which yields an estimated uncertainty of ±0.3%.

From examination of the overall range of temperature values for the APD functions, the measured amplitude of the temperature fluctuations is always less than ~2°C, even though the potential amplitude is 22°C (bundle 5B, Fig. 6). We believe that this result substantiates the hypothesis that the thermocouples were measuring predominately local temperature fluctuations in the wake zone of the bundle rods and that bulk mixing in this region was insufficient to cause more than a minor effect. We propose that the relationship between skew and thermocouple position be studied in future FFM experiments.

Conclusions and Recommendations

From PSD analysis, we conclude that the magnitude of the temperature noise is dependent on the degree of mixing and on the shape of the lateral temperature profile. The frequency content depends on the degree of mixing and on the thermocouple time response. A blockage of the type investigated increases the temperature gradient at a given thermocouple location and increases the noise measured at that location, if adequate mixing occurs.

The degree of asymmetry, or skew, of the APD function is strongly dependent on the location of the thermocouple with respect to the lateral temperature profile. Little bulk mixing of the sodium occurred at the thermocouple locations.

Future studies in the FFM should determine the optimum locations for thermocouples in subassembly exits to monitor the temperature fluctuations for blockage detection. Our reason for this recommendation is that, on the one hand, if the thermocouples were located farther downstream from the exit than those used in this study, the analysis techniques might give a more consistent result for blockage detection. On the other hand, the high thermal conductivity of sodium, which would tend to reduce downstream temperature fluctuations, would have to be considered. Thus, a movable thermocouple wake assembly whose axial position could be varied would be required.

These recommended tests would aid LMFBR design engineers to better locate thermocouple positions for subassembly monitoring for blockage detection, if early detection of blockages is required for safe reactor operation.

DETECTION OF SODIUM BOILING

In subcooled nucleate boiling, vapor bubbles are formed at nucleation sites on a heated surface. These bubbles become larger until they break free of the surface and enter a region of liquid where the temperature is below the boiling point; there they condense and collapse. The detection of the acoustic pressure pulse emitted by a collapsing bubble formed the basis for detection of boiling by acoustic means in the FFM experiments.

Eight acoustic sensors were used in the FFM tests: four model LC-10 and two model LC-6 (Celesco Industries, Costa Mesa, California) hydrophones, all with lead zirconate-titanate sensing elements; and two model HT-9 sodium-immersible sensors [12], with lithium niobate sensing elements, developed by Argonne National Laboratory (ANL) to operate in sodium to 650°C. The results from the sodium-immersible sensors in the FFM experiments are reported in ref. 13. The locations of the sensors in the test section are shown in Figs. 1 and 2. The hydrophones were mounted in stainless steel cups on 0.95-cm-OD, 30-cm-long, stainless steel stubs welded to the test section housing at four locations. The cups were filled with mineral oil to provide acoustic coupling from the stainless steel to the sensor. The hydrophone signals were high-pass filtered above 1 kHz to discriminate against noise from pumps, blowers, and other equipment. The signals were recorded in analog form on magnetic tape; the frequency range of the tape was from 1 to 300 kHz. During analysis, the frequency range was 70 to 300 kHz.

Experiments and Results

Three experiments were performed in the FFM, two with bundle 5D and one with bundle 3B which had a stainless steel plate that blocked the six flow channels surrounding the center rod at a location 38 cm downstream from the start of the heated zone.

In the tests in bundle 5D, a controlled sodium flow transient from 2.6 to ~0.25 liter/sec was produced in the test section by manually closing the test section inlet valve. This transient simulated the transient that probably would result from the coastdown of the Fast Test Reactor sodium coolant pump. The bundle 5D experiments consisted of flow coastdowns with and without argon gas injection under boiling and nonboiling conditions.

The hydrophone signals obtained during coastdowns without gas injection and under nonboiling conditions (no heater power and at 5.4 kW per rod) indicated little change in the background noise level of ~0.5 mbar, except an approximate twofold increase in the acoustic signals at the bottom hydrophone at flows <0.6 liter/sec, believed to be caused by cavitation in the test section inlet valve. When argon was injected at a rate of 0.15 kg/hr during coastdown under nonboiling conditions, the cavitation noise was not observed. The estimated void fraction of the argon was 10% at a sodium flow of 0.25 liter/sec.

The hydrophone and sodium flow signals during flow coastdown without gas injection under boiling conditions (12.5 kW per rod) are shown in Fig. 9. Boiling occurred from ~25 to 32 sec in the figure and was detected by all sensors. The signals obtained during a similar run, but with argon injected at 0.15 kg/hr, are shown in Fig. 10. The start of gas injection is indicated by the large "spike" on the flow signal at ~7 sec in the figure and by an increase in noise detected by the hydrophones. As the flow decreased, however, no evidence of boiling was observed. Measurements of temperatures in the bundle during this run indicated that the saturation temperature of sodium was reached during the last 20 sec [14]. Subsequent inspection of the bundle revealed substantial damage due to overheating [14,15].

The objectives of the experiments in bundle 3B were to determine the threshold for detection of boiling with a noncondensable entrained gas present and to study the effect of localized boiling downstream of the blockage of six coolant flow channels. The experiments included sodium flow reductions to boiling with and without injection of argon. The flow reductions were slower than those for the simulated pump coastdowns used in bundle 5D. Two rates of argon injection were used: 0.0054 and 0.0014 kg/hr, factors of 25 and 100, respectively, below that (0.15 kg/hr) used in bundle 5D. The estimated void fractions were ~0.4 and 0.1%, respectively, at a sodium flow of ~0.3 liter/sec.

Boiling was produced in bundle 3B by reduction of the sodium flow from 1.4 to ~0.4 liter/sec at a heater power of 8.8 kW per rod. In the experiment without gas injection, boiling was detected by all hydrophones each time the flow was reduced.

When argon was injected at a rate of 0.0014 kg/hr during a similar run, indications of boiling were observed on the signal from the north hydrophone (closest to the boiling site, Fig. 2), but were not seen at the other locations. When the rate of argon injection was increased to 0.0054 kg/hr, no indications of boiling were detected by the acoustic sensors. The presence of boiling events was confirmed, however, by measurement of temperature in bundle [16].

Conclusions and Recommendations

Nucleate sodium boiling was detected in the FFM by LC-10 and LC-6 hydrophones externally mounted on the test section housing. Acoustic pulses of ~2 to 5 mbar pressure were detected in the frequency range from 70 to 300 kHz during boiling, compared to a background of 0.5 to 1 mbar.

Entrained noncondensable gas (argon) at void fractions greater than 0.1% prevented detection of boiling by the acoustic detection system in the FFM. At a void fraction of 0.1%, only marginal detection was achieved by the sensors closest to the boiling site. Consequently, we recommend that further study and analysis of this phenomenon be pursued to assess its ramifications on proposed boiling detection systems for sodium-cooled reactors. Since a boiling site on the surface of a fuel rod may coincide with the location of a fission gas leak during overpower conditions, the adverse effect of the gas on the sensitivity of the boiling detection system must be understood and quantified if reliable acoustic detection of boiling is to be realized. Likewise, the void fraction of entrained argon cover gas must be known and its effect assessed.

ACKNOWLEDGMENTS

This research was sponsored by the Energy Research and Development Administration under contract with the Union Carbide Corporation.

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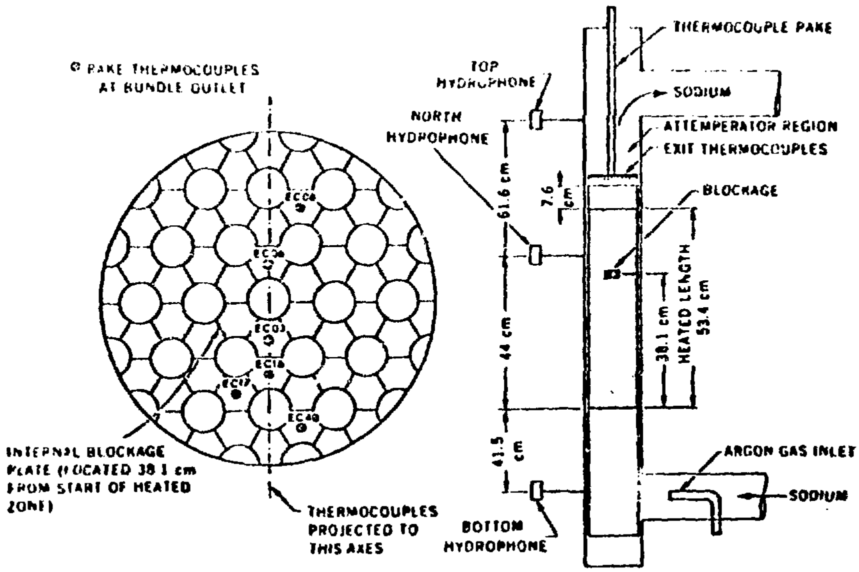

Fig. 1. Bundle 3A blockage, exit thermocouple, and hydrophone locations.

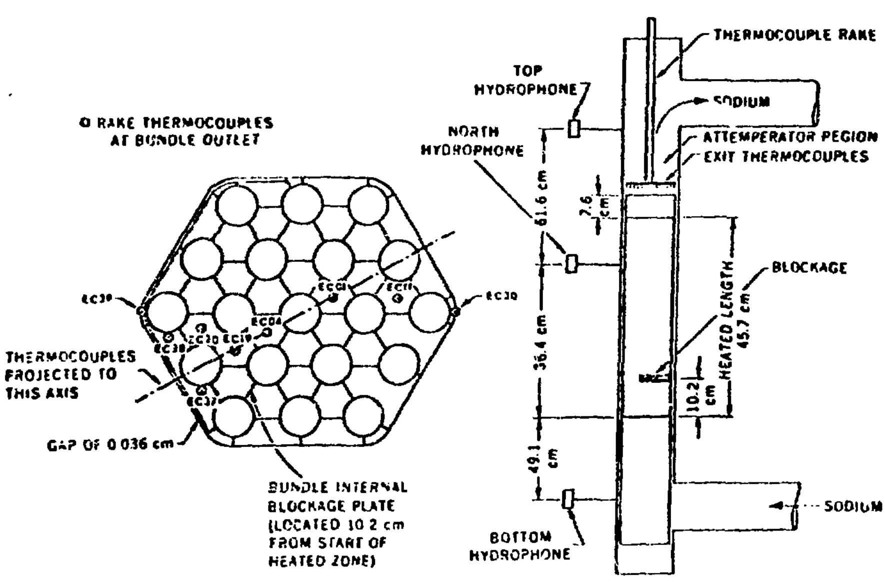

Fig. 2. Bundle 5B blockage and exit thermocouple locations.

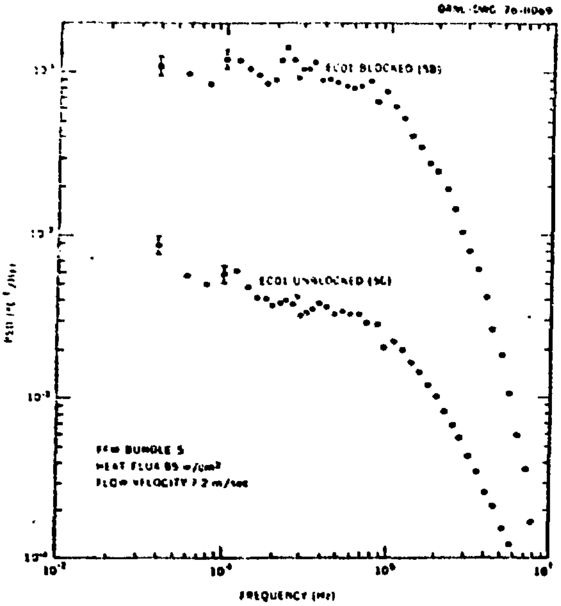

Fig. 3. Power spectra of exit rake thermocouple EC01 with and without an edge blockage.

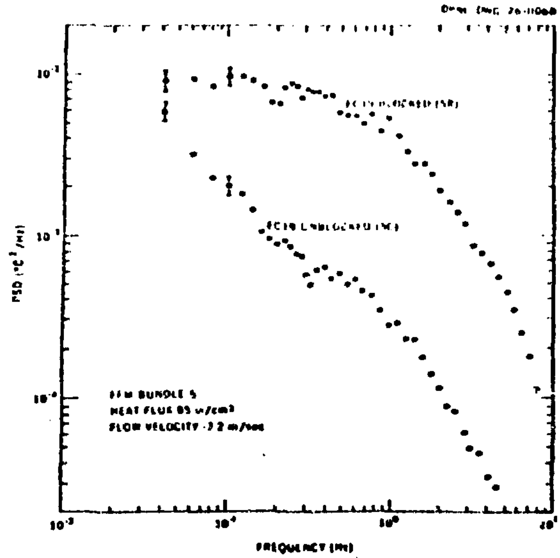

Fig. 4. Power spectra of exit rake thermocouple EC19 with and without an edge blockage.

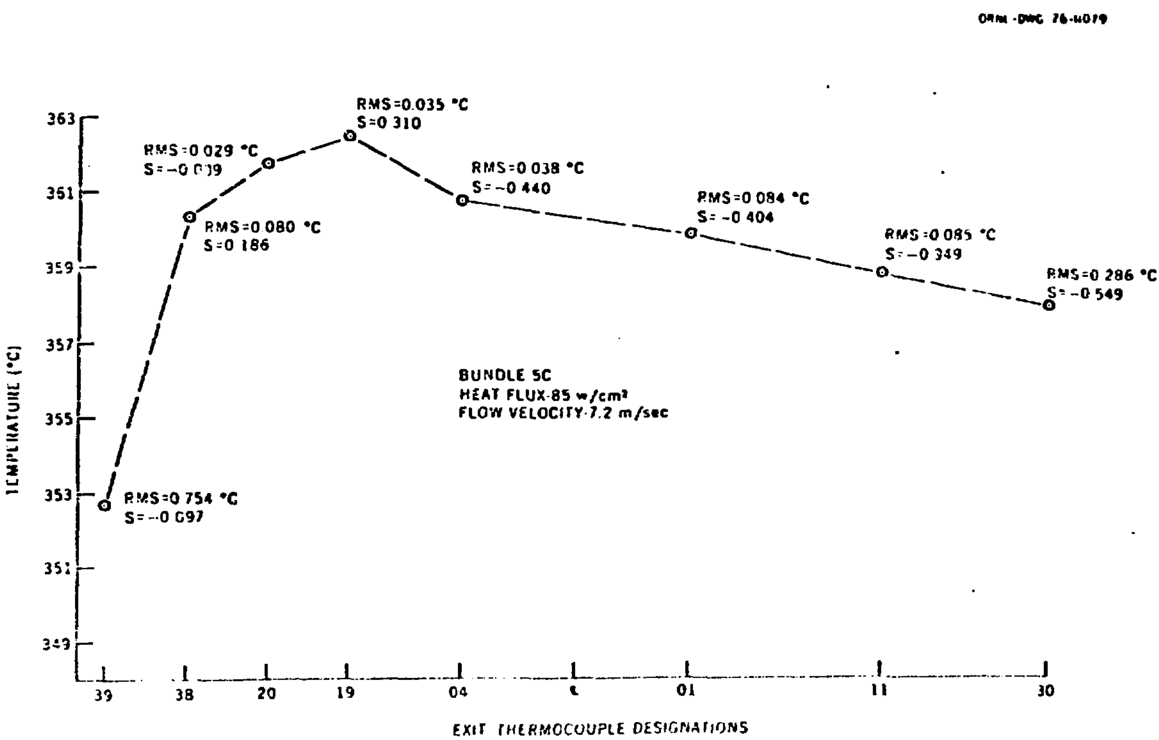

Fig. 5. Lateral temperature profile measured by exit rake thermocouples and their associated RMS and skew values for FFM bundle 5C (unblocked).

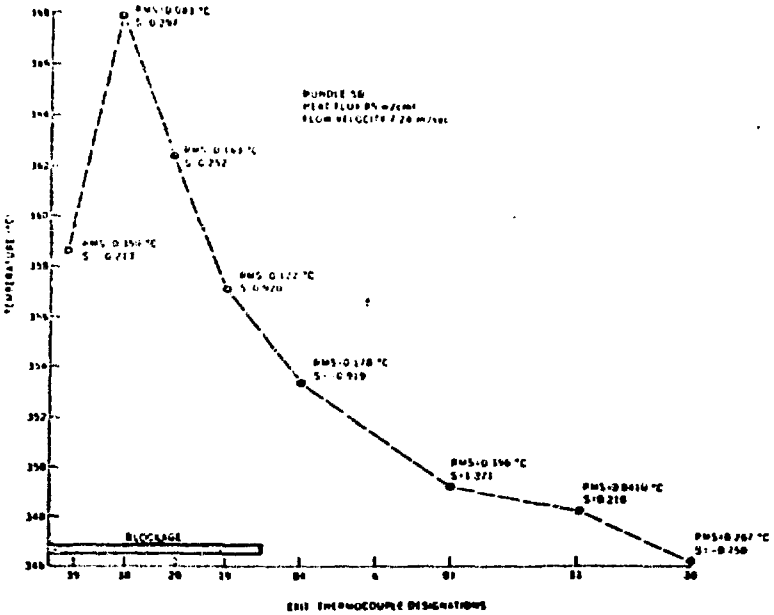

Fig. 6. Lateral temperature profile measured by exit rake thermocouples and their associated RMS and skew values for FFM bundle 5B (edge blockage).

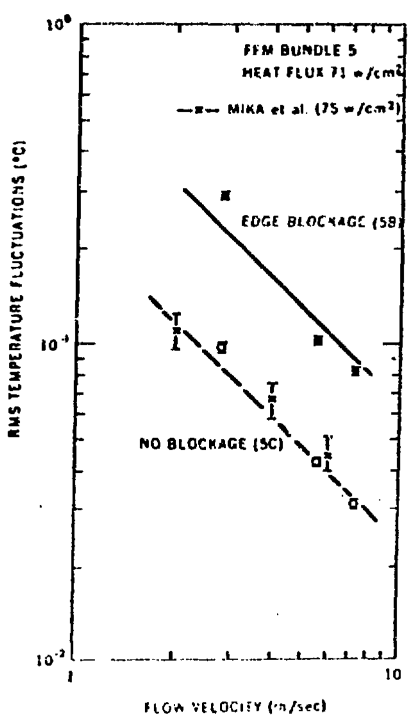

Fig. 7. RMS vs flow velocity with and without edge blockage for thermocouple EC04.

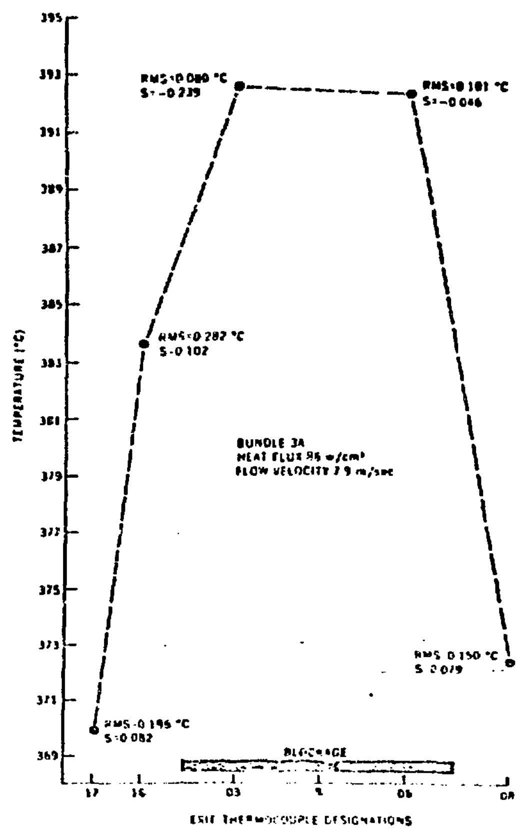

Fig. 8. Lateral temperature profile measured by exit rake thermocouples and their associated RMS and skew values for FFM bundle 3A (central blockage).

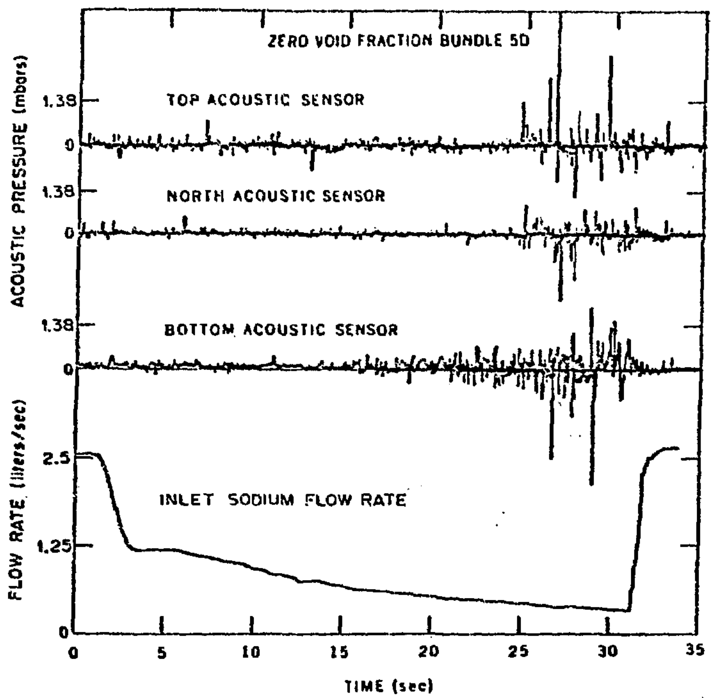

Fig. 9. Flow coastdown with boiling in bundle 5D with no gas injected.

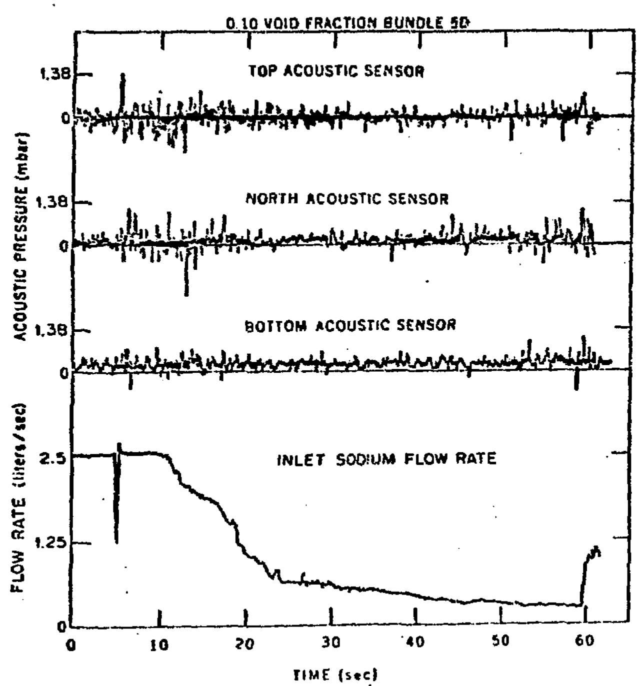

Fig. 10. Flow coastdown with boiling in bundle 5D with gas injected at 0.15 kg/hr.

CLEARANCE NOTICE

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Temperature Noise Analysis and Sodium Boiling Detection in the Fuel Failure Mockup

(Title)

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as submitted to the American Nuclear Society for inclusion in the Proceedings of the ANS/ENS International Meeting on Fast Reactor Safety and Related Physics, October 5-8, 1976, is cleared for publication. The paper contains no information that need be withheld from publication of national security interest, patent considerations, or other proprietary information interests.

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