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BOUNDARY LAYER MEASUREMENT PROGRAM

Volume I—Boundary Layer Acoustic Monitor
Development Characterization and Installation
(PVM 12 and 13, STM-12)

Kaman Sciences Corporation
P.O. Box 7463
Colorado Springs, Colorado 80933

30 June 1978

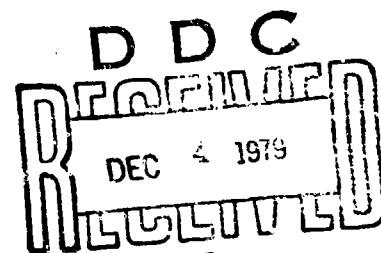
Final Report for Period 1 August 1975—30 June 1978

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) A Boundary Layer Acoustic Monitor (BLAM) was developed for determining boundary layer characteristics by sensing the external surface pressure fluctuation transmitted through to the inside surface of the heatshield by acoustical stress waves. Laboratory and wind tunnel tests were conducted to characterize and evaluate the BLAM. Flight hardware was developed and flight qualification tests were conducted for the PVM 12, PVM 13 and STM 12 flights.		

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PREFACE

The work accomplished on the Defense Nuclear Agency "Boundary Layer Measurement Program," DNA001-76-C-0080 is described in a two volume set of final reports as follows:

1. Volume I - Boundary Layer Measurement Program -
Boundary Layer Acoustic Monitor Development,
Characterization and Installation (PVM 12 and
13, STM-12), K-79-54(R), DNA 4873-1.
2. Volume II - Boundary Layer Measurement Program -
Aerodynamic Phenomena Transducer Development,
K-79-54(R), DNA 4873-2.

Volume I describes the development of the Boundary Layer Acoustic Monitor (BLAM) in addition to the laboratory and wind tunnel tests which characterized and evaluated the BLAM. Also described in Volume I are the flight qualification tests and flight hardware characteristics used on the PVM 12, PVM 13 and STM-12 flights.

Volume II describes the laboratory development and evaluation of the Aerodynamic Phenomena Transducer (APT) which is designed to simultaneously monitor the presence of acoustic fluctuations (turbulent flow) and measure the static pressure exerted on a heatshield during flight. Arc heater test results are included.

The authors wish to acknowledge the efforts of Lt. Cmdr. R. Nibe and Major T. Swartz of the Defense Nuclear Agency, Lt. Col. J. McCormack and Capt. M. Elliot of SAMSO (ABRES)/RSSE and Lt. Col. R. Jackson of SAMSO/MNNR, in addition to Mr. Wally Grabowski of the Aerospace Corporation. Each of these individuals contributed significantly to the success of this overall program. The KSC program manager for these efforts was Mr. T. Meagher.

CONVERSION FACTORS FOR U. S. CUSTOMARY TO METRIC (SI) **UNITS OF MEASUREMENT**

To Convert From	To	Multiply By
angstrom	meters (m)	1.000 000 X E -10
atmosphere (normal)	kilo pascal (kPa)	1.013 25 X E +2
bar	kilo pascal (kPa)	1.000 000 X E +2
barn	meter ² (m ²)	1.000 000 X E -28
British thermal unit (thermochemical)	joule (J)	1.054 350 X E +3
calorie (thermochemical)	joule (J)	4.184 000
cal (thermochemical)/cm ²	mega joule/m ² (MJ/m ²)	4.184 000 X E -2
curie	giga becquerel (GBq)*	3.700 000 X E +1
degree (angle)	radian (rad)	1.745 329 X E -2
degree Fahrenheit	degree kelvin (K)	$T_K = (T_F + 459.67)/1.8$
electron volt	joule (J)	1.602 19 X E -19
erg	joule (J)	1.000 000 X E -7
erg/second	watt (W)	1.000 000 X E -7
foot	meter (m)	3.048 000 X E -1
foot-pound-force	joule (J)	1.355 818
gallon (U.S. liquid)	meter ³ (m ³)	3.785 412 X E -3
inch	meter (m)	2.540 000 X E -2
jerk	joule (J)	1.000 000 X E +9
joule/kilogram (J/kg) (radiation dose absorbed)	Gray (Gy)**	1.000 000
kilotons	terajoules	4.184
kip (1000 lbf)	newton (N)	4.448 222 X E +3
kip/inch ² (ksi)	kilo pascal (kPa)	6.894 757 X E +3
klup	newton-second/m ² (N-s/m ²)	1.000 000 X E +2
micron	meter (m)	1.000 000 X E -6
mil	meter (m)	2.540 000 X E -5
mile (international)	meter (m)	1.609 344 X E +3
ounce	kilogram (kg)	2.834 952 X E -2
pound-force (lbf avoirdupois)	newton (N)	4.448 222
pound-force inch	newton-meter (N-m)	1.129 848 X E -1
pound-force/inch	newton/meter (N/m)	1.751 268 X E +2
pound-force/foot ²	kilo pascal (kPa)	4.788 026 X E -2
pound-force/inch ² (psi)	kilo pascal (kPa)	6.894 757
pound-mass (lbm avoirdupois)	kilogram (kg)	4.535 924 X E -1
pound-mass-foot ² (moment of inertia)	kilogram-meter ² (kg-m ²)	4.214 011 X E -2
pound-mass/foot ³	kilogram/meter ³ (kg/m ³)	1.601 846 X E +1
rad (radiation dose absorbed)	Gray (Gy)**	1.000 000 X E -2
roentgen	coulomb/kilogram (C/kg)	2.579 760 X E -4
shake	second (s)	1.000 000 X E -8
slug	kilogram (kg)	1.459 390 X E +1
torr (mm Hg, 0° C)	kilo pascal (kPa)	1.333 22 X E -1

*The becquerel (Bq) is the SI unit of radioactivity; 1 Bq = 1 event/s.

**The Gray (Gy) is the SI unit of absorbed radiation.

A more complete listing of conversions may be found in "Metric Practice Guide E 380-74," American Society for Testing and Materials.

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SECTION 1

INTRODUCTION

PVM PROGRAM

The PVM Boundary Layer Acoustic Monitor (BLAM) had the major objective of placing acoustic instruments on flight test RV's which would acquire data on boundary layer transition during reentry.

The BLAM is a new concept for determining boundary layer characteristics by sensing the external surface pressure fluctuation transmitted through to the inside surface of the heatshield by acoustical stress waves. This concept had first been tested on a Flame^{*} flight sponsored by DNA; the results of that test indicated that significant acoustic amplitudes were present and that transition phenomena were detected.

The positive results obtained on the flame experiment stimulated additional flight and reported herein. The flight data was generated on MK-12 type reentry bodies of the Space and Missile Systems Organization (SAMSO). Two BLAM channels were on each of two reentry bodies on two Production Vehicle Monitor (PVM) 12 and 13 flights (total of 8 channels). Subsequently, four BLAMS were installed on the System Test Monitor (STM) 12W flight. These data were all generated on ICBM trajectories on the Western Test Range.

* Flight-Launched Advanced Material Experiment.

Before the BLAM could be applied to a full-scale RV, several equipment modifications and tests were necessary which were included as tasks in the PVM BLAM effort. The contract called for work to be accomplished in the following areas:

- 1) Sensor design and fabrication;
- 2) Electronics modification;
- 3) Flight qualification testing;
- 4) Liaison with RV contractor and DoD organizations involved with the flight test;
- 5) Participation in an on-going wind tunnel test program.

The primary objective of the STM-12 effort was that of instrumenting the RV's with small BLAM sensors which occupied smaller volume than the PVM sensors. The sensor was designed with half the diameter and approximately the same height as the PVM gage. In addition to flight test installation and qualification tests, more extensive data were taken of the installed BLAM frequency and directionality responses.

Sections 2 through 5 of this report relate the work accomplished on the PVM/STM BLAM efforts. In Section 2 the sensor optimization, characterization and electronics design modifications are described. Section 3 describes the flight qualification tests and Section 4 is a summary of flight test activities. Section 5 reports the results of ground tests, principally in two wind tunnels, and conclusions are reported in Section 6.

SECTION 2

GAGE OPTIMIZATION AND CHARACTERIZATION

2.1 SENSOR DESIGN

The Flame and PVM-12 BLAM utilizes a 2.54-cm diameter quartz crystal which converts acoustical stress waves into electric charge. This charge is converted to a voltage in a high impedance load at the input to a transistor preamplifier, which in turn, drives a coaxial cable connected at its other end to a signal conditioner. The output voltage of the signal conditioner (or electronics) provides a 5-volt full-scale signal to the RV telemetry which is related to the acoustic pressure fluctuation amplitude on the RV surface.

This gage, a photo of which is shown in Figure 1, is identical to that used on Flame with the exception of material added on the outside surfaces to provide electrical isolation from the heatshield. Fibreglass sheet (.025-cm thick) was placed on the front face of the crystal and .0076-cm mylar on the exposed crystal cylindrical surface.

Mechanical mounting is provided by bonding the front surface to the heatshield with a thin uniform layer of epoxy glue. Additional strength is given by three screws through a flange to the substructure of the RV. The screws can be insulated from the aluminum case by fiber shoulder washers as required.

The electrical voltage output of the sensor is in direct proportion to the stress in the crystal. Stress is applied to the crystal by external acoustic pressures being transmitted through the heatshield to the sensor located on the inside



Figure 1 BLAM SENSOR

surface. The mounting face (as seen in Figure 1) is coated with thin metal and is also connected to the cable shield. The back face of the crystal is connected to the internal preamplifier. This construction ensures good shielding from stray electric fields.

Two simulation techniques were applied during the PVM effort to provide characterization data on the frequency response of the BLAM. The first was that of applying a known sine wave voltage to a crystal which was acoustically coupled to the heatshield at the BLAM position. The second method imposed a sinusoidal force on a small area surface of the heatshield by an electrostatic technique. Because the crystal exciter used in the first method was itself resonant, it was used only for qualitative checks of the BLAM installation. A drawing of the exciter and application technique is shown in Figure 2. The output of the BLAM during these tests appeared at frequencies associated principally with the exciter crystal resonances. However, the technique proved very useful to check the entire as-installed BLAM system.

The electrostatic or capacitive simulator was used to determine frequency response functions of the BLAM installation. A typical response curve is shown in Figure 3; peaks are seen to occur at frequencies of 50, 113, and 168 kHz. Lower amplitude responses below 30 kHz and above 300 kHz are also exhibited by the gage but are not shown on the plot. The response can be electrically filtered by the signal conditioner as appropriate to remove the low or high frequency content. The data in Figure 3 were taken with the sensor mounted on 1.27-cm thick carbon phenolic material and a surface acoustic pressure of approximately 35 N/m^2 .

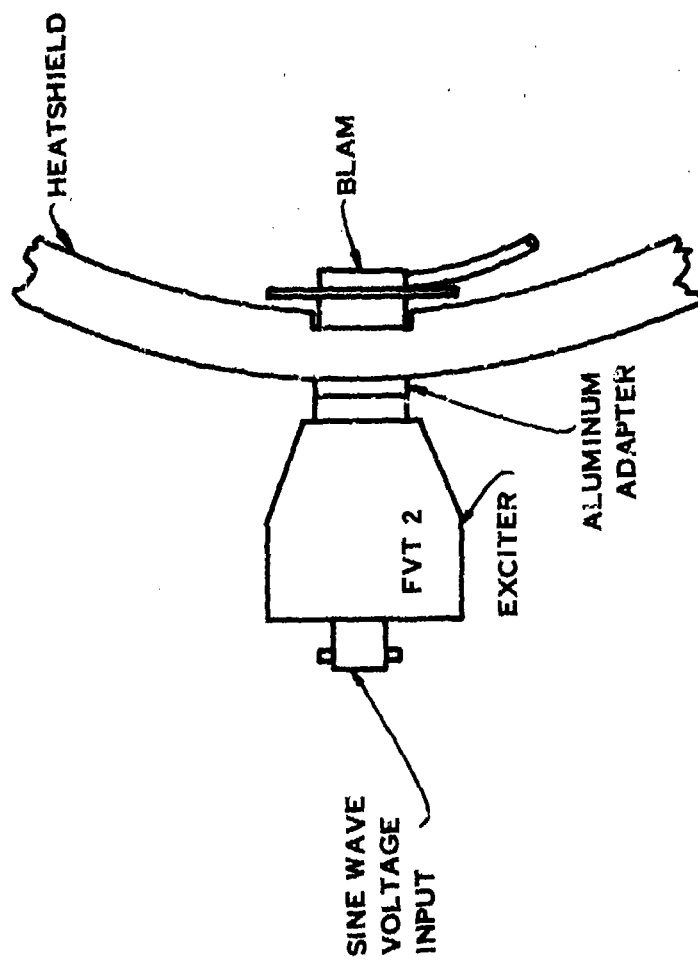


FIGURE 2 FVT-2 CRYSTAL EXCITER APPLICATION

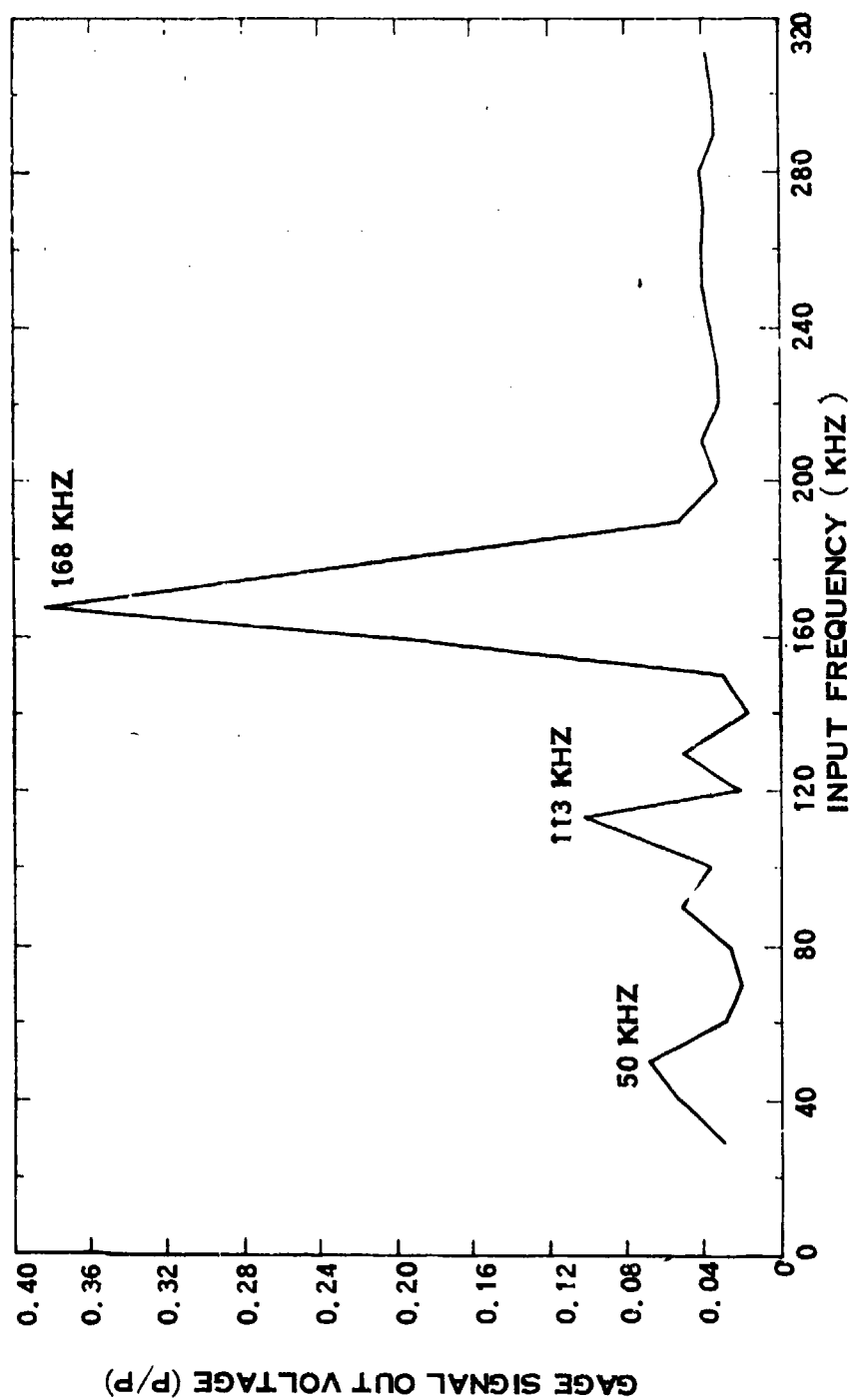


FIGURE 3 PVM ACOUSTIC MONITOR RESPONSE

STM-12

The BLAM developed for the STM-12 application is similar to the PVM gage excepting for a smaller diameter. The STM-12 sensor includes a 1.27-cm diameter quartz crystal and the case size is proportioned accordingly. A photograph of this BLAM is shown in Figure 4.

The BLAM's installed on the STM-12 vehicles were tested using a portable electrostatic stimulator built for that purpose. This apparatus included a high output voltage amplifier and a variable frequency oscillator. Approximately 500 volts peak-to-peak sine wave from 10 to 150 kHz was obtained for exciting the acoustic waves on the surface of the RV. The surface of the RV was protected from the high voltage by placing an intermediate aluminum electrode between the exciter and heatshield. A thin RTV membrane coupled the acoustic wave from this auxiliary electrode to the heatshield.

Results of the as-installed BLAM tests are shown in Figures 5, 6, 7 and 8. Each gage was measured at two frequencies at which resonance peaks had been observed. These curves show the directionality of the gages vary with location but consistently drop off in response within one to four gage diameters. Transducers 1 and 2 were installed at an aft station which has lower curvature and exhibit greater rate of amplitude decrease with distance when compared with number 3 which is behind a highly-curved surface farther forward on the RV.

A frequency response curve for one of these gages is shown in Figure 9; this curve exhibits a typical BLAM response showing resonance peaks at 34, 80, 140 and 280 kHz. All four gages had similar frequency responses.



FIGURE 4 STM 12 BLAM

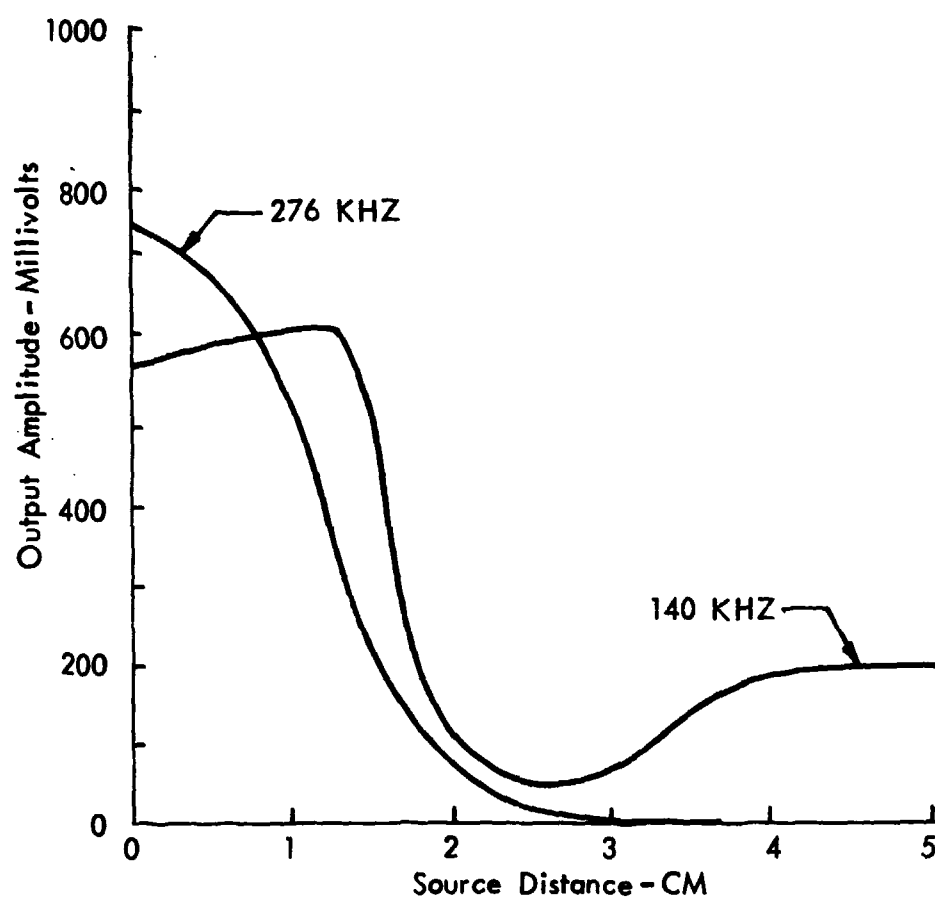


FIGURE 5 DIRECTIONALITY DATA; STM 12 BLAM 1

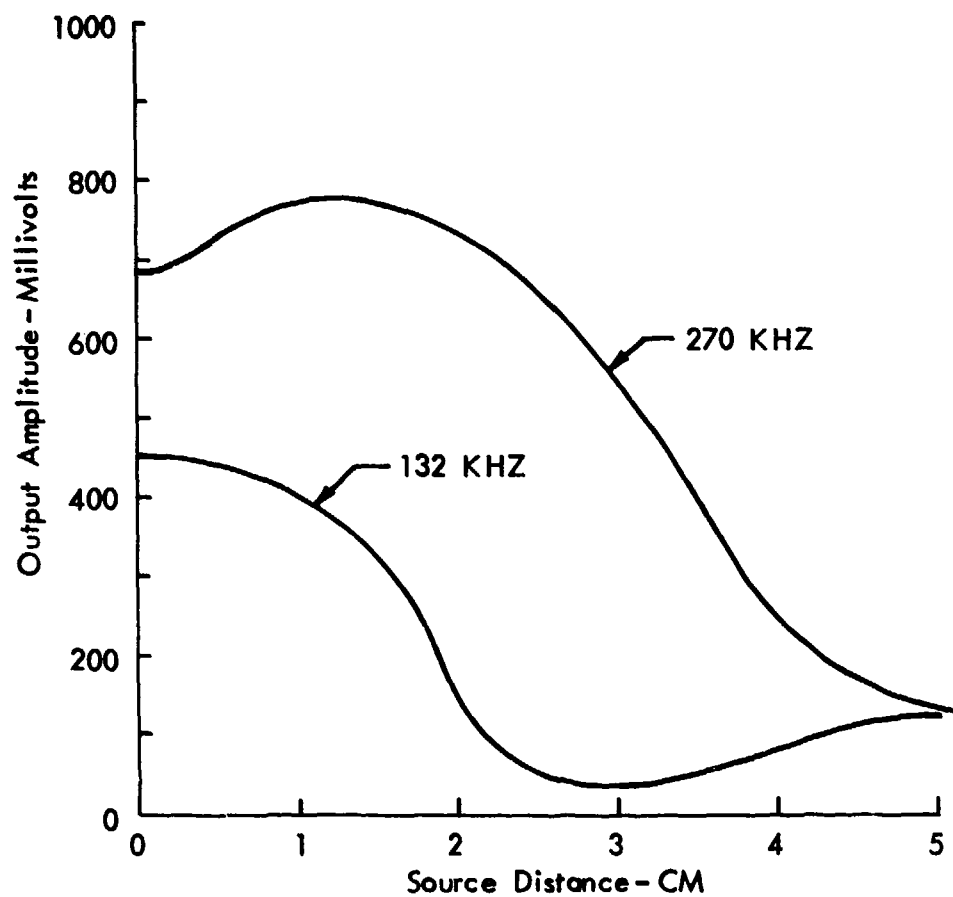


FIGURE 6 Directionality Data; STM 12 BLAM 2

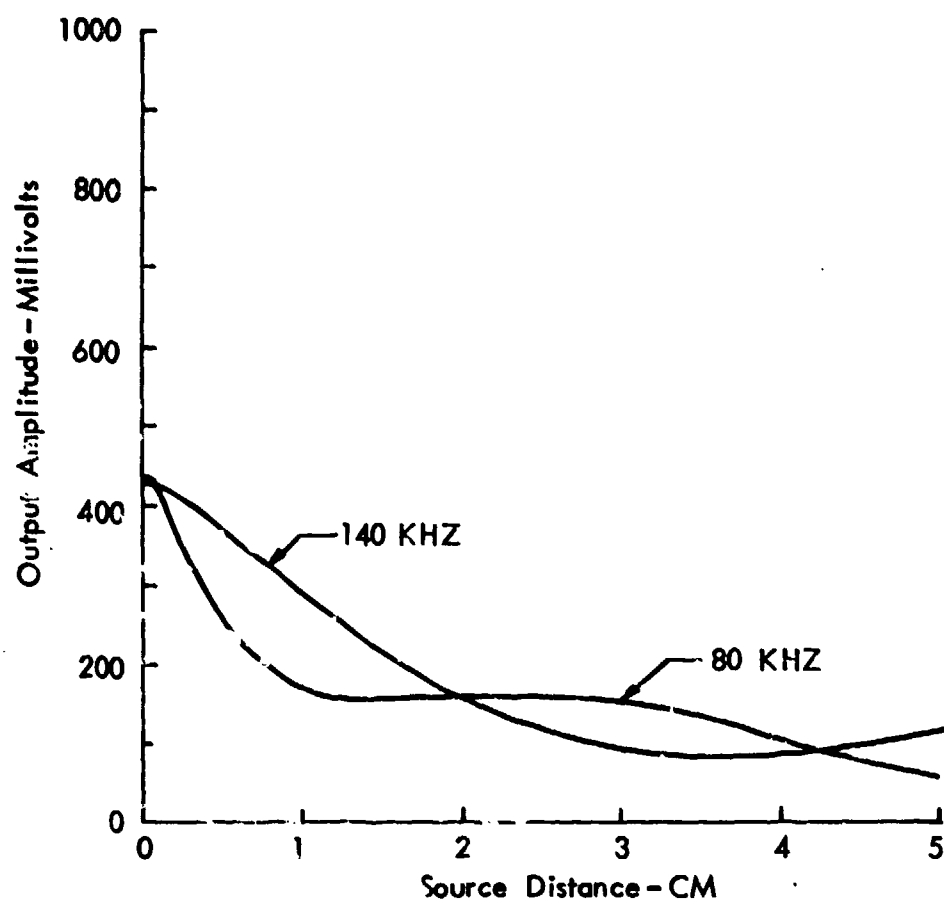


FIGURE 7 DIRECTIONALITY DATA; STM 12 BLAM 3

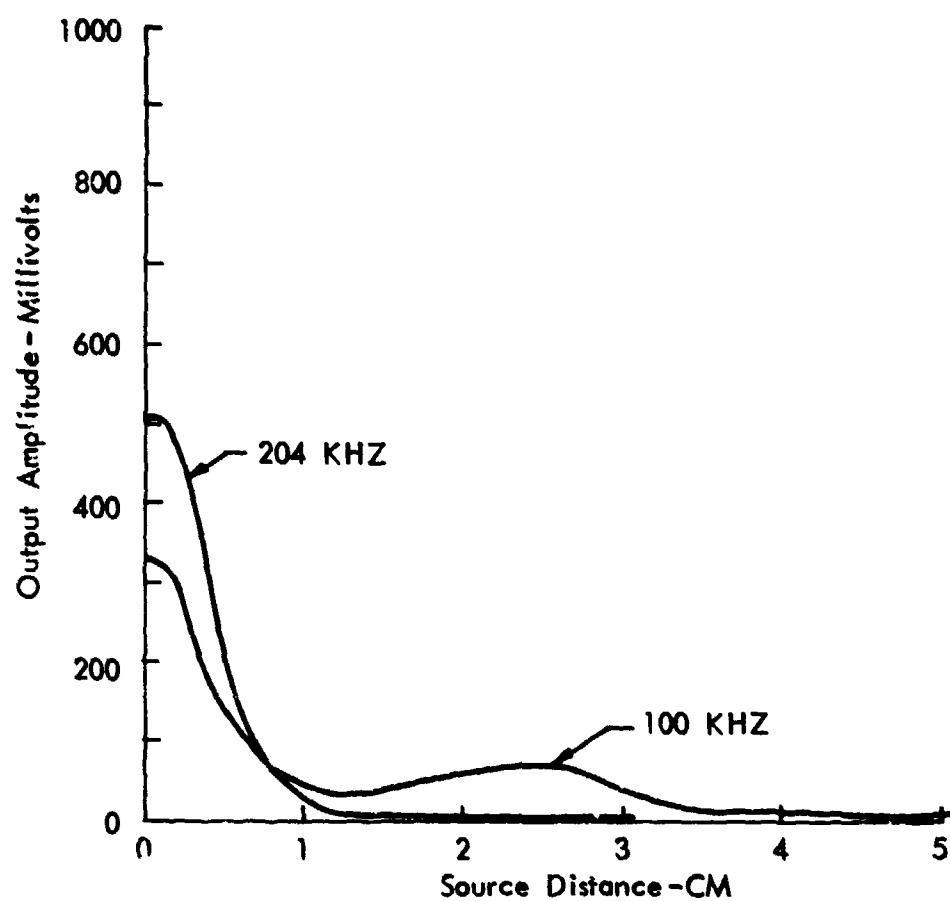


FIGURE 8 DIRECTIONALITY DATA; STM 12 BLAM 4

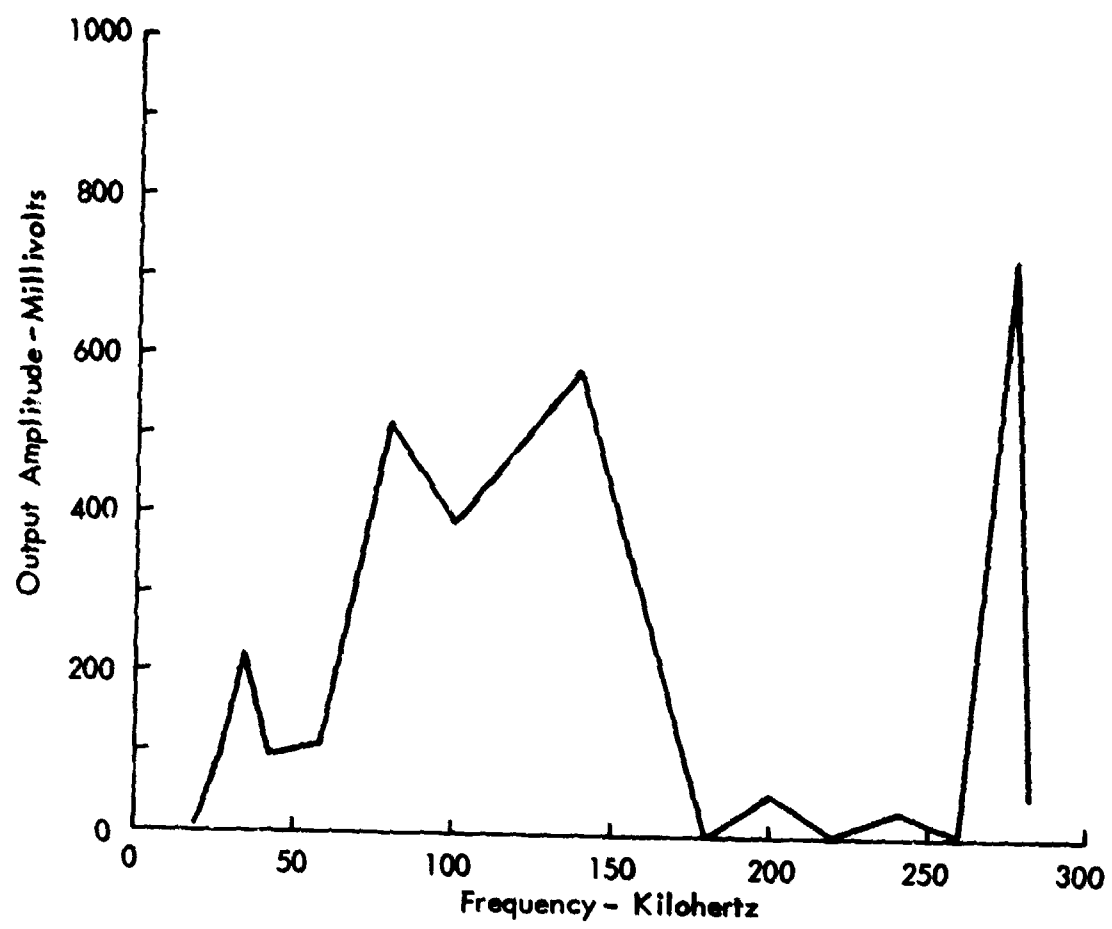


FIGURE 9 STM 12 BLAM INSTALLATION FREQUENCY RESPONSE

2.2 ELECTRONICS DESIGN

An extensive optimization of the electronics was undertaken to improve performance over that obtained from the Flame gage. In Flame, an automatic gain control (AGC) amplifier was used producing the input-output voltage characteristic curve shown in Figure 10. It can be seen that resolution above 2 volts output is poor, thus necessitating a modification of the circuit. Because the magnitude of the noise to be detected was unknown, it was decided to continue with the non-linear amplifier principle used on Flame, but design it to have a linear characteristic when plotted logarithmically.

The block diagram of the resulting circuit is shown in Figure 11 and its amplitude input-output characteristic is plotted in Figure 12. While the curve is not fully linear, the resolution was improved greatly over the previous circuit; approximately 4.5 orders of magnitude are spanned by the amplifier. The circuit includes a simple input voltage regulator and a temperature-compensated differential detector in the output. The circuit performs well up to 1 MHz and has a low frequency roll-off starting at about 100 kHz. The curves of Figure 13 show the amplifier frequency response at two output levels.

Components of the amplifier are mounted on a small printed circuit board which is placed in an aluminum box and hard-potted with epoxy. Mechanical design of the amplifier box is shown in Figure 14. Weight of this amplifier is 80 grams.

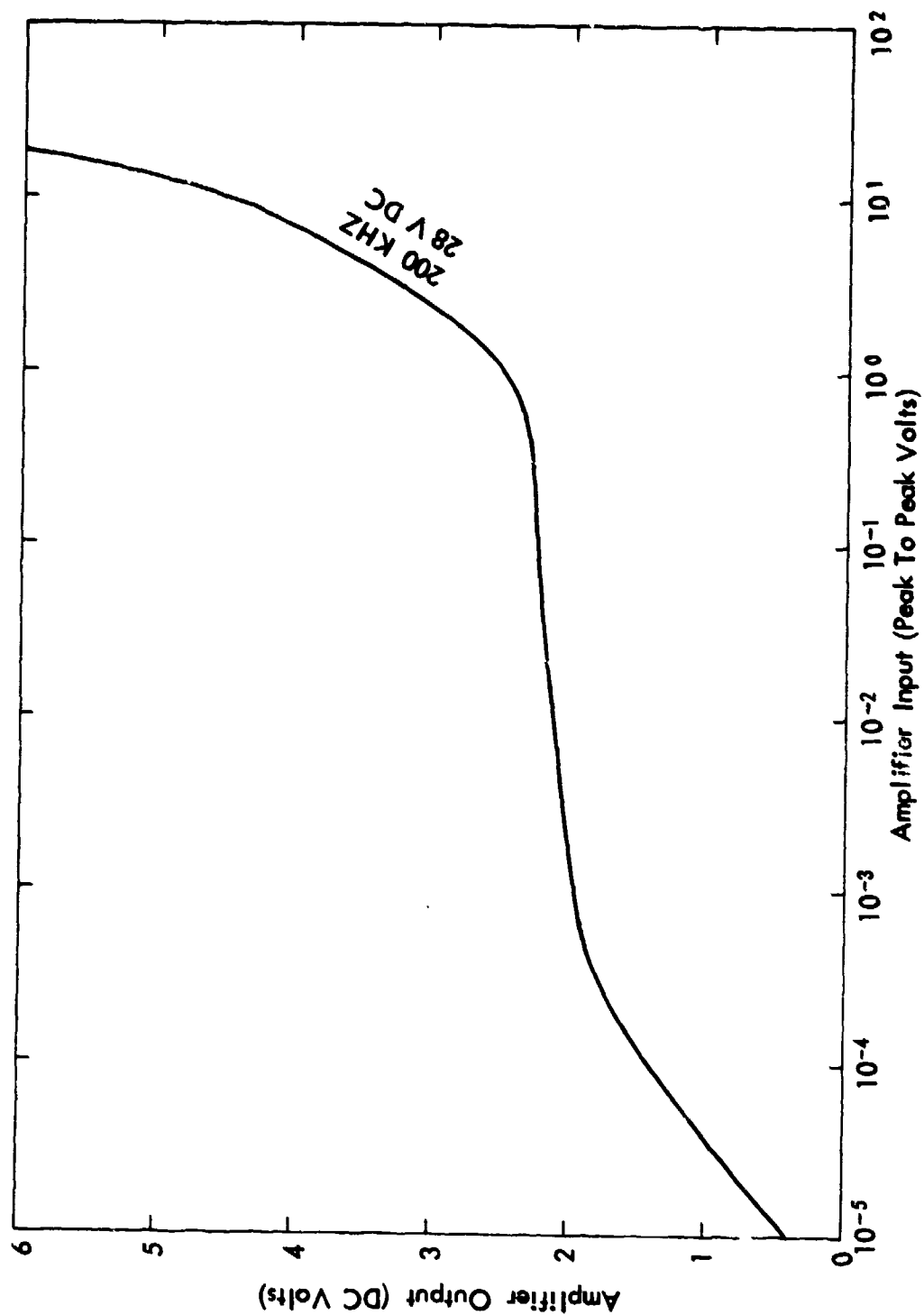


FIGURE 10 BOUNDARY LAYER ACOUSTIC MONITOR AMPLIFIER GAIN CHARACTERISTICS FLAME VERSION

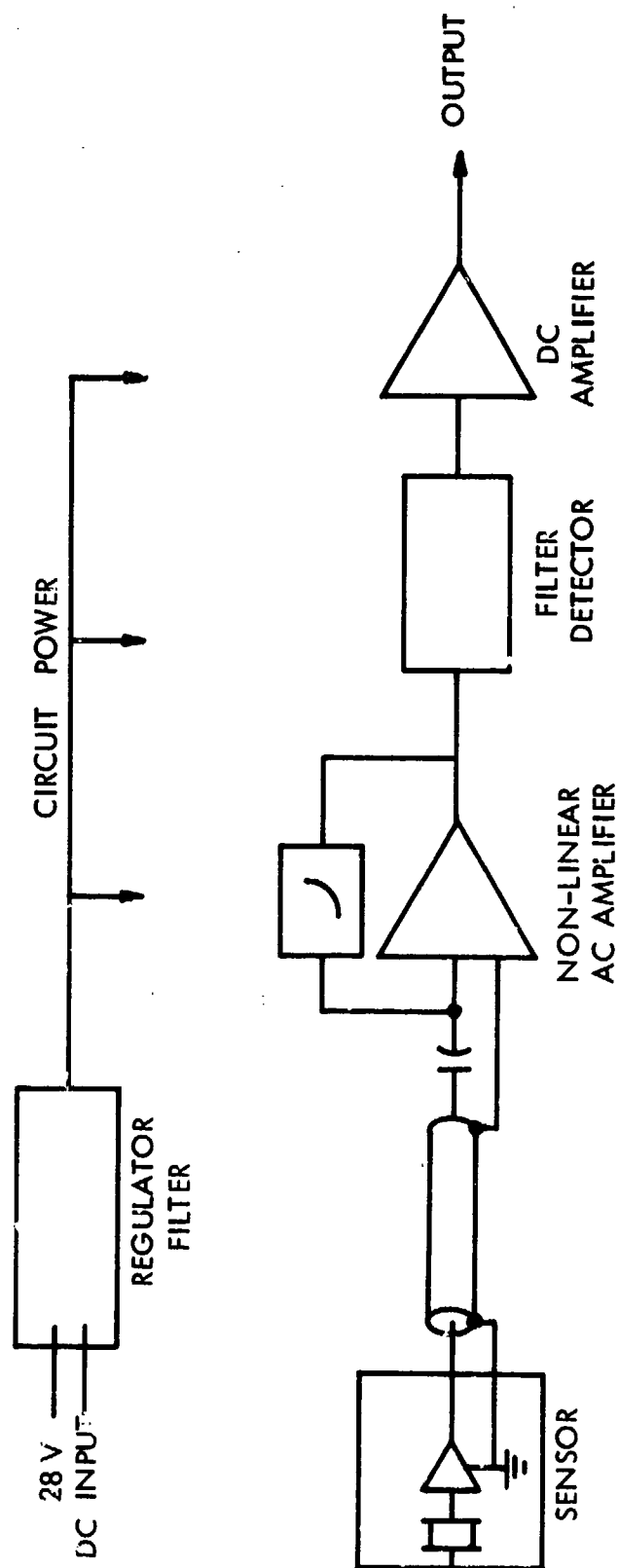


FIGURE 11 BLAM AMPLIFIER BLOCK DIAGRAM

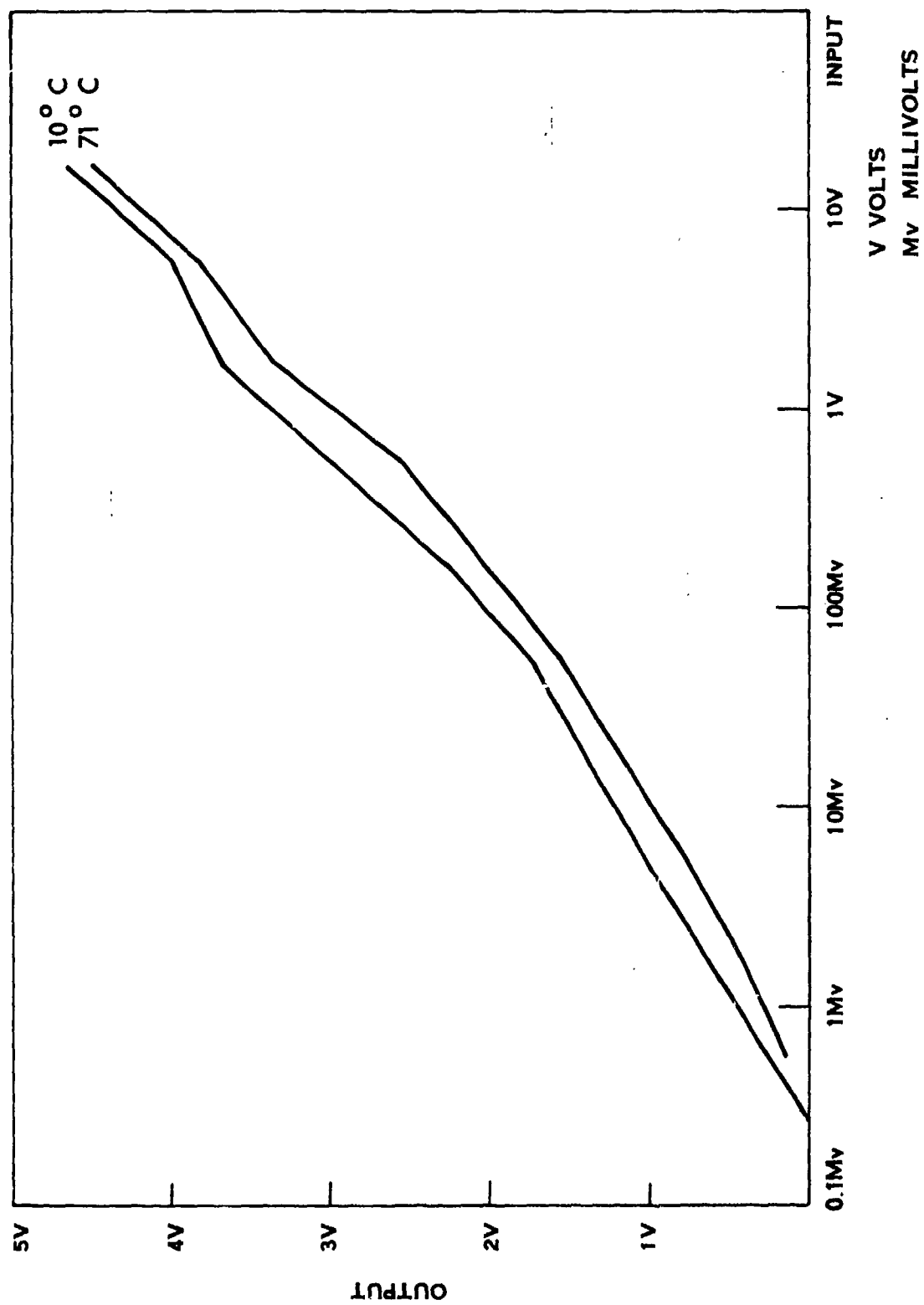


FIGURE 12 ACOUSTIC MONITOR AMPLIFIER CHARACTERISTICS

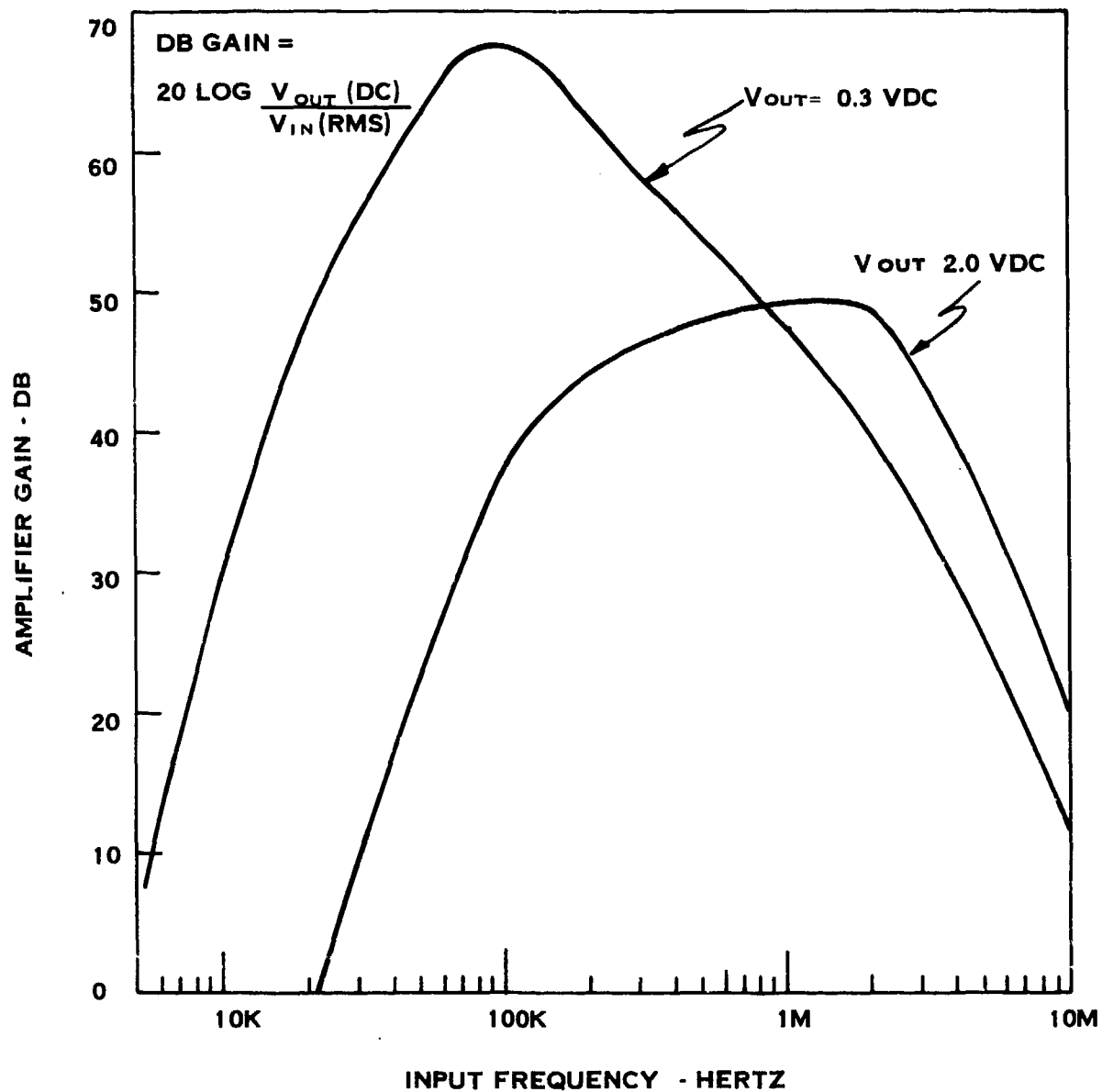
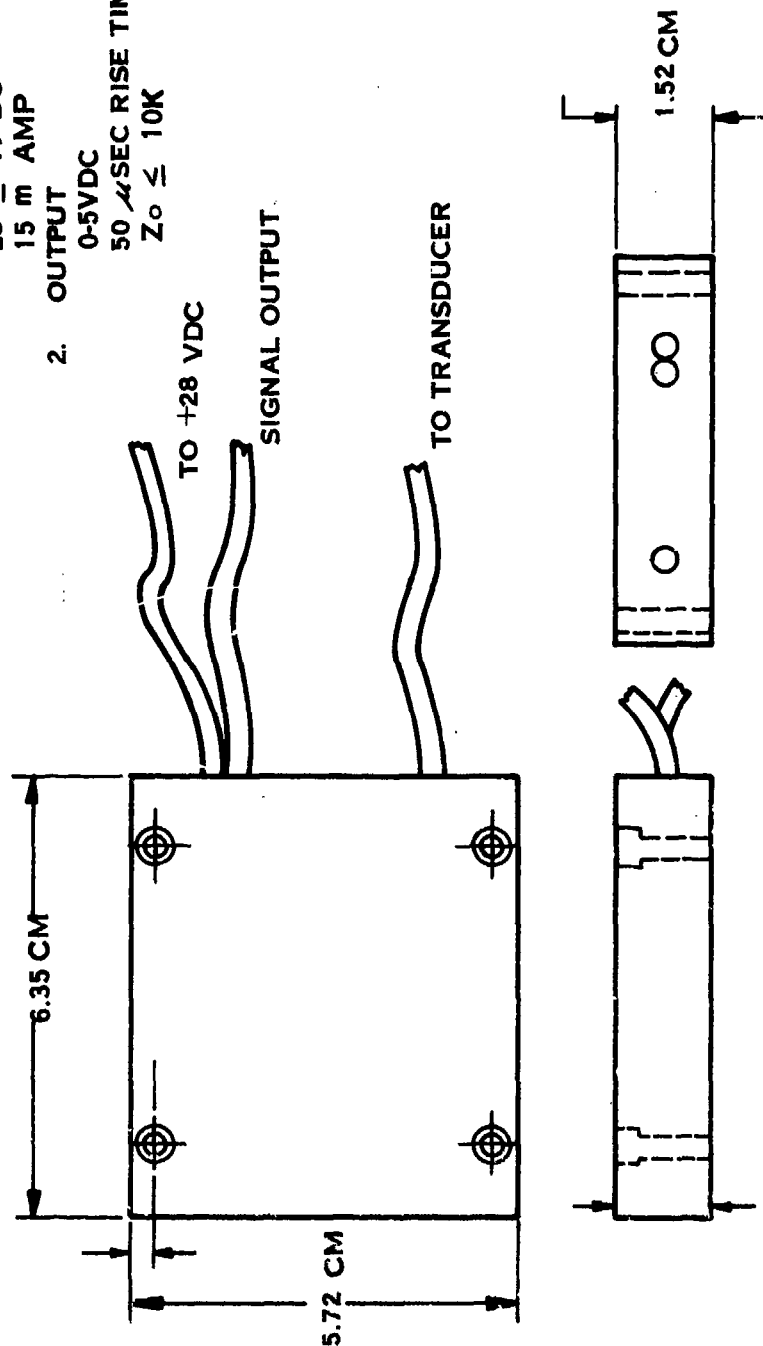


FIGURE 13 BLAM AMPLIFIER FREQ. RESPONSE

ELECTRICAL SPECIFICATIONS

1. INPUT REQUIREMENTS
 $28 \pm 4V$ DC
15 m AMP
2. OUTPUT
0-5VDC
50 μ SEC RISE TIME
 $Z_o \leq 10K$



- NOTES:
1. CABLE LENGTHS TO BE SPECIFIED FOR EACH APPLICATION.
 2. CONNECTOR TYPES OR PIGTAILS TO BE SPECIFIED FOR EACH APPLICATION
 3. CABLE MASS - 3.6 g PER FOOT

FIGURE 14 AMPLIFIER FOR BOUNDARY LAYER ACOUSTIC MONITOR

SECTION 3

FLIGHT QUALIFICATION TESTS

To establish reliability of the BLAM, a comprehensive set of environmental tests were conducted. The criteria for these tests were established during discussions with Aerospace, General Electric Company, TRW, and SAMSO personnel directly concerned with the PVM 12 and 13 flights.

The types and levels of environments resulting from these communications are given in Table 1. Tests were conducted on two complete PVM BLAM channels as per Table 1 and were 100% successful. A report of this work was completed and forwarded to concerned organizations⁸. Additional tests of the same type and level were completed on the sensor developed for the STM-12 RV's. As with the PVM sensor, the results were successful (no failures). A report was completed and forwarded¹⁰.

TABLE 1 FLIGHT QUALIFICATION ENVIRONMENTS

Vibration-Powered Flight	Random. Level 25g rms distributed as per required spectrum.
Shock-Powered Flight	Up to 825g as per required shock spectrum.
Acceleration-Linear	140 g's 2 minutes
Temperature	71.1°C one hour
Spin/Spin Acceleration	2000°/sec ² to 2000°/sec operating 2000°/sec ² to 8000°/sec non-operating
Endurance	150 hours
Electromagnetic Interference	
Conducted Emission	Less than 50 MV p-p
Conducted Susceptibility	Less than 25 MV p-p for specified input conditions.
Humidity (Non-operating)	MIL-STD-310 Method 507.1 Temperature 57.2°C max.

SECTION 4

FLIGHT TEST ACTIVITIES

4.1 GAGE CHARACTERIZATION TESTS

Each of the PVM and STM-12 BLAM channels fabricated for delivery to G.E. for later installation or for spares were subjected to a series of tests for operational assurability purposes. Statements governing the Operational Assurability tests were included in a specification for the BLAM⁹. The OA tests included temperature soak at 71.1°C and sinusoid-swept vibration from 60 to 2000 Hz at 3.5 g rms level.

All flight test amplifiers were tested for their input-output voltage transfer characteristic in accordance with the specification⁹. The data for the amplifiers delivered to G.E. are included in this report in Appendix A. These curves are obtained by exciting a preamplifier at its input and recording the d.c. voltage output; the input frequency used was 200 kHz for both PVM and STM amplifiers.

4.2 LIAISON/ICD ACTIVITIES

Early meetings were held at G.E. in order to agree on Interface Control Drawing details necessary for the installation of the BLAM's on the PVM and STM RV's. Documentation provided by KSC included circuit diagram, sensor and electronics mechanical drawings, cabling and connection data. The drawing was produced by G.E. and signed off by all organizations.

Installation of the sensors on the RV's was to be physically effected by G.E. with KSC present and monitoring. To facilitate this operation KSC prepared an instruction memorandum detailing the steps to be followed. After installation and with electronics connected, a checkout procedure was written which would permit a qualitative excitation of the BLAM to ensure that the channels are operative.

All gages were installed successfully and produced good results as reported elsewhere.

SECTION 5

GROUND TESTS

5.1 INTRODUCTION

Wind tunnel tests were planned and carried out to test the BLAM in a controlled flow environment with the purpose of characterizing its mode of operation. It was hoped that the results of the ground tests would then be used to provide better understanding of BLAM flight test data.

The first test was completed in the small laboratory, room temperature, continuous running Mach 3 tunnel at Aerodynamic Ford^{*} in Newport Beach, California. Dr. A. Demetriades is in charge of this facility and assisted in planning and carrying out the test.

The second test utilized Tunnel 8 at the Naval Surface Weapons Center in White Oak, Maryland. Dr. Fred Morrison and Mr. Frank Baltakis provided planning and test assistance.

In both tests, the approach was similar; the free-stream Reynolds number of the flow was varied to cause transition in the boundary layer to move across the positions where the BLAM's were installed. Output from the BLAM's were compared with temperature and pressure sensors. The following sections describe the individual tests in greater detail.

* Now Ford Aerospace and Communications Corporation.

5.2 AERONUTRONIC FORD SUPERSONIC WIND TUNNEL TEST

The test arrangement is shown in Figure 15. The BLAM was placed at various locations on the exterior surface of the tunnel side wall. A ported pressure transducer was installed 28 cm downstream from the nozzle. The tunnel side wall is 1.9-cm thick lucite. Flow parameters for the test were as follows:

Mach No.:	$3.0 \pm .03$
Total Temperature:	38°C
Supply Pressure P_0 :	210 to 730 mm Hg abs
Reynolds Number:	$1,970,000$ to $6,693,000$ meter ⁻¹

By varying the supply pressure from low to high, the transition region was caused to traverse the side walls from downstream at low pressure thence upstream past the BLAM location towards the nozzle.

Results from a pressure sweep are shown in Figure 16 for both transducers: BLAM and ported pressure. It can be seen that the pressure gage responded very well to transition on the side wall. The BLAM output, however, appears to be linearly related to the total pressure, not indicating a significant change in output in the transition zone.

An explanation for the apparent lack of BLAM response to transition is that the frequency response of the blam extends from 75 kHz upward to 500 kHz while the ported pressure gage responds to frequencies below 20 kHz. In wind tunnel experiments of this type, transition pressure fluctuations in the boundary layer may be significantly higher at low frequencies.

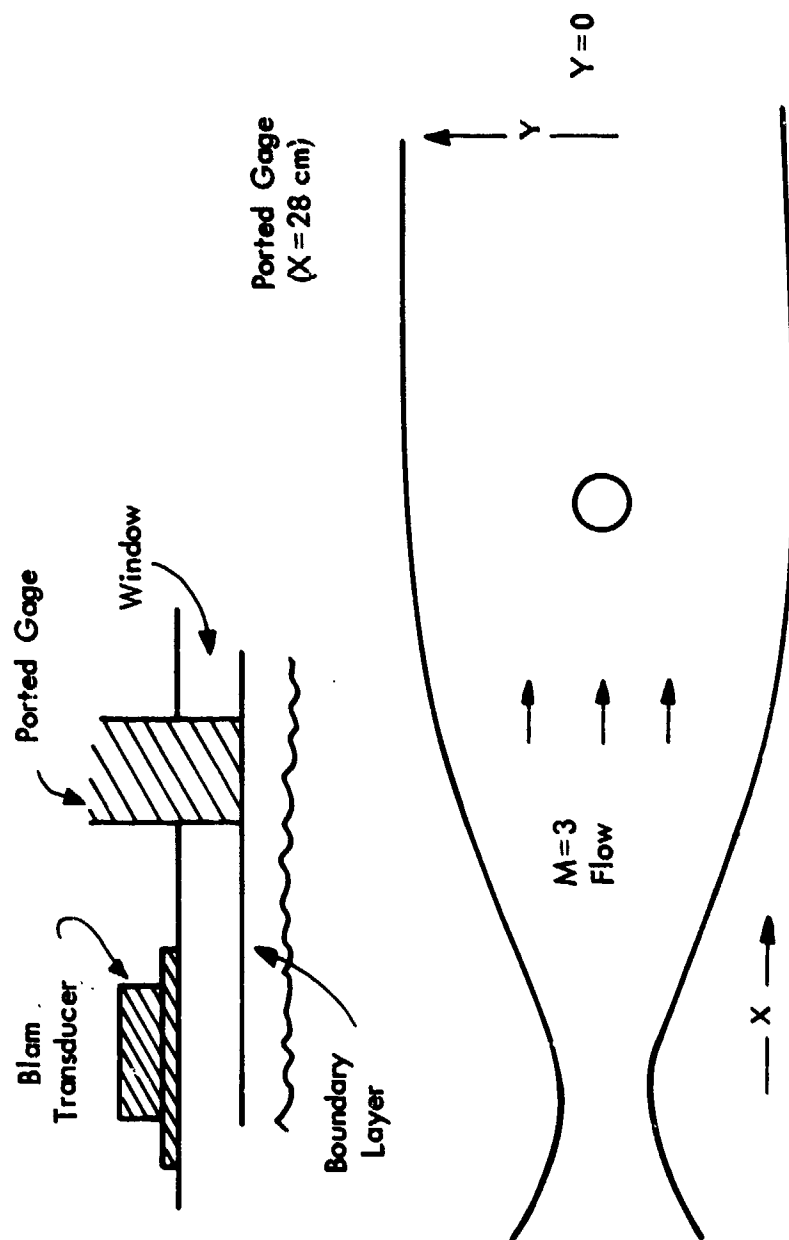


FIGURE 15 TEST INSTALLATION

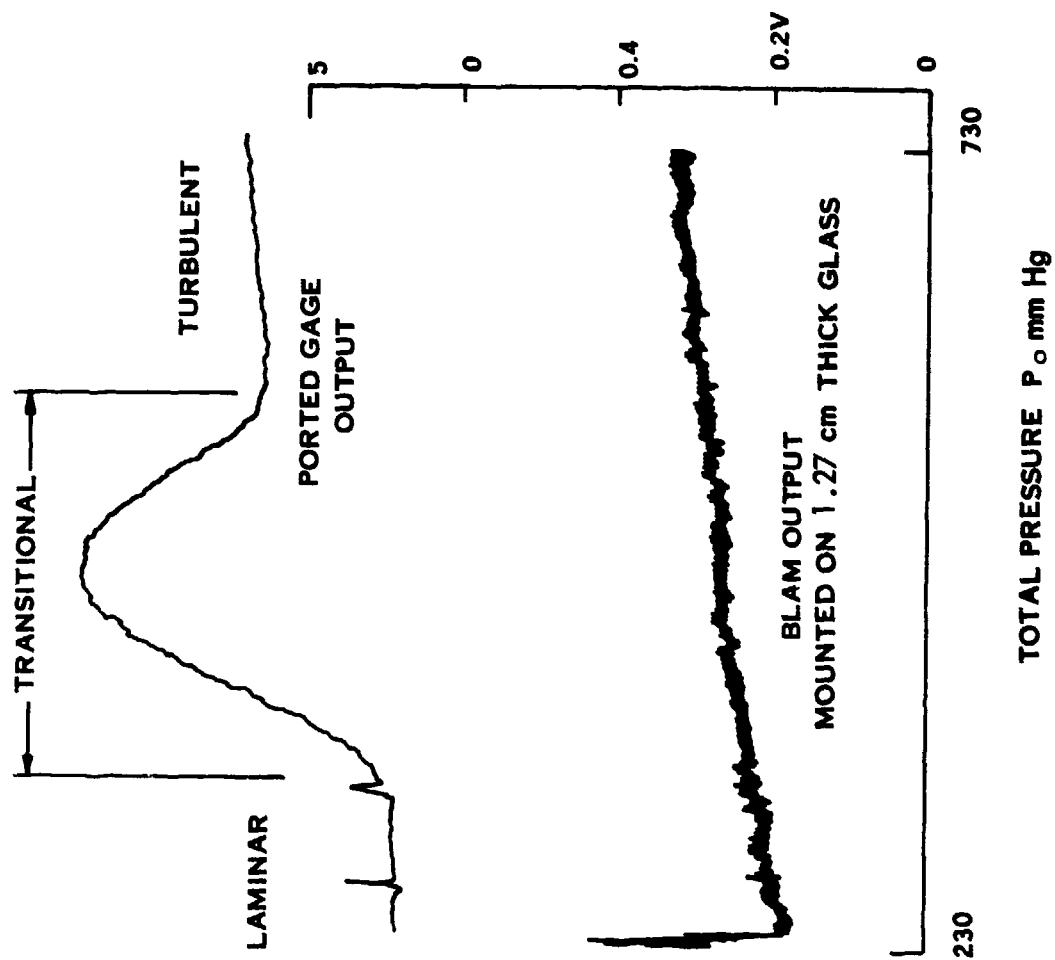


FIGURE 16 TRANSDUCER OUTPUT COMPARISON

High frequency components in the boundary layer are not lacking but must compete with the relatively high noise background from the nozzle and other upstream disturbances.

In addition to radiated tunnel noise, the tunnel wall vibrating in a diaphragm mode added to the sensor output. During the test, both d.c. voltage from the electronics signal conditioner and the a.c. output from the sensor were monitored. It was noticed that the sensor output had a dominant frequency of 16 kHz or 25 kHz depending on the thickness of the tunnel side wall window. For 1.27-cm optical glass, the frequency was 25 kHz and for 2.54-cm lucite it was 16 kHz. While higher than the lowest plate resonance, such frequencies could well be excited on walls of these thicknesses.

Table 2 is a listing of BLAM data from the test. Listed are the d.c. output levels, corresponding sensor a.c. levels and the amplifier midband gain compared to the ratio of sensor and d.c. outputs. These data show that the dominant frequencies in the sensor output, even though amplified much less, could have obscured the presence of high frequencies generated by transitional/turbulent boundary layers.

TABLE 2 BLAM DATA - AF/SWT

$P_o = 730 \text{ mm Hg}$

<u>RUN</u>	<u>PREDOMINANT FREQUENCY kHz</u>	<u>SENSOR OUTPUT mv r.m.s.</u>	<u>ELECTRONICS D.C. OUTPUT mv</u>	<u>RATIO DC/AC</u>	<u>MEASURED MIDLAND AMPL. GAIN</u>
2	25	3.6	320	88.9	3900
4	25				
5	16	4.4	190	43.2	4090
6	16				

Overall conclusions from this test were that low frequency attenuation or mechanical mounting to eliminate acceleration response must be added prior to future wind tunnel tests. Some indication of transition was present in the data of Figure 16 in that the slope at lower pressures was steeper than that after transition. The signal-to-noise in the data is too low to permit a positive conclusion in this feature.

5.3 NSW TUNNEL 8 TEST

5.3.1 Summary

This test was planned with the following objectives

- BLAM characterization
- Correlation of the acoustic level and thermal transition monitors
- Measurement of transition movement over the model surface
- Provide backup data for the PVM flight tests.

The facility NSWC Tunnel 8, was chosen because it provided parameters suitable for measurement of boundary layer transition phenomena on conical models. This tunnel is well calibrated and has the performance characteristics seen in Figure 17 for the Mach 8 nozzle. Additionally, another DNA program with contractor Prototype Development Associates (PDA) was being planned in the same facility and it was requested by DNA that KSC implement this test in a cooperative effort, using PDA hardware and entry to Tunnel 8. Since PDA had designed the sting interface and data acquisition system, KSC then designed the mating heatshield and nosetip. After some liaison, this approach was worked out and the remainder of the test was designed.

The test matrix is shown in Table 3. Test variables included angle of attack, spin rate, and Reynolds number (or total pressure - see Figure 17). Runs were patterned to provide increasing complexity of conditions and to permit comparisons of parameters before proceeding with the next run. The four runs shown in the matrix were completed over a two day period.

The test model was a 9° half-angle sharp cone with 20.3 cm base diameter; the nosetip was stainless steel fabricated by KSC and the frustum was carbon-phenolic heatshield procured from Hitco. The frustum thickness was 0.953 cm. The frustum was instrumented with six BLAM's and six thermal sensors installed as shown in Figure 18.

The BLAM's installed on the heatshield for this test were identical to those described in Section 2.0 which were installed on the PVM-12 and PVM-13 reentry vehicles. The thermal sensors were similar to calorimeters and are illustrated in the cross-section drawing of Figure 19. The thermal sensors were fabricated from a short piece of ceramic

TABLE 3 NSWC TEST MATRIX

<u>RUN NO.</u>	<u>CONDITIONS</u>	<u>ACTIVITY</u>
1	$\alpha = 0$ Non-Spinning R_E Sweep	● Tunnel and Instrumentation Set Up
2	$\alpha = 0$ Non-Spinning R_E Sweep	● Acoustic-Thermal Comparison ● Shadowgraph Correlation
3	$\alpha = 0$ Non-Spinning Tunnel Pre-Heat R_E Sweep	● Acoustic-Thermal Comparison ● Shadowgraph Correlation
4	$\alpha = 2.5^\circ$ Spinning Tunnel Pre-Heat R_E Plateau	● Acoustic Directionality ● Shadowgraph Correlation

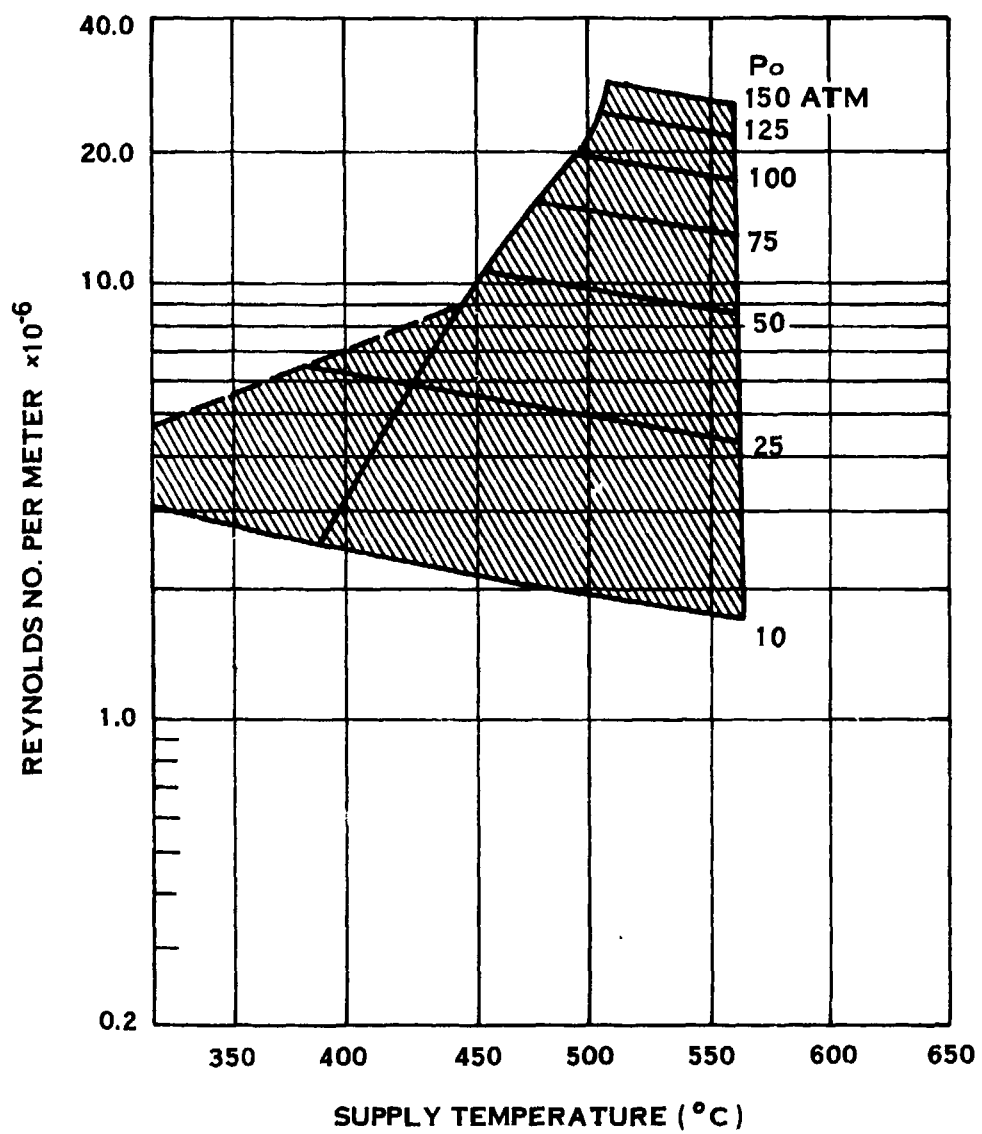


FIGURE 17 MACH 8 NOZZLE CAPABILITY

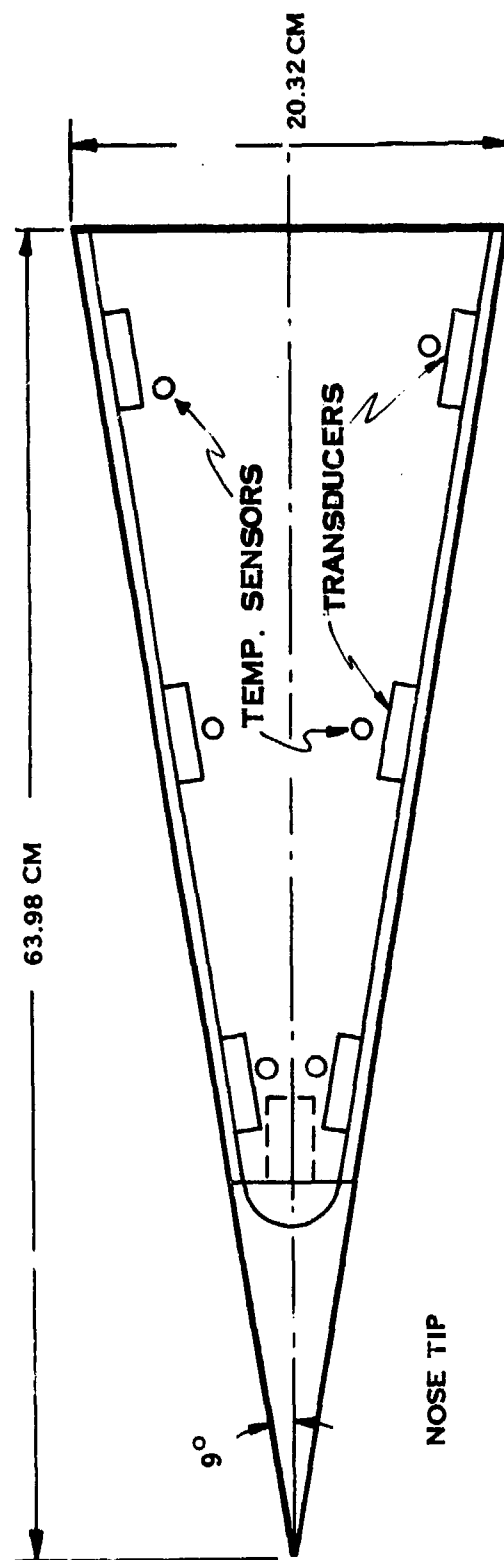


FIGURE 18 WIND TUNNEL TEST MODEL, THERMAL AND
BLAM SENSORS MOUNTED

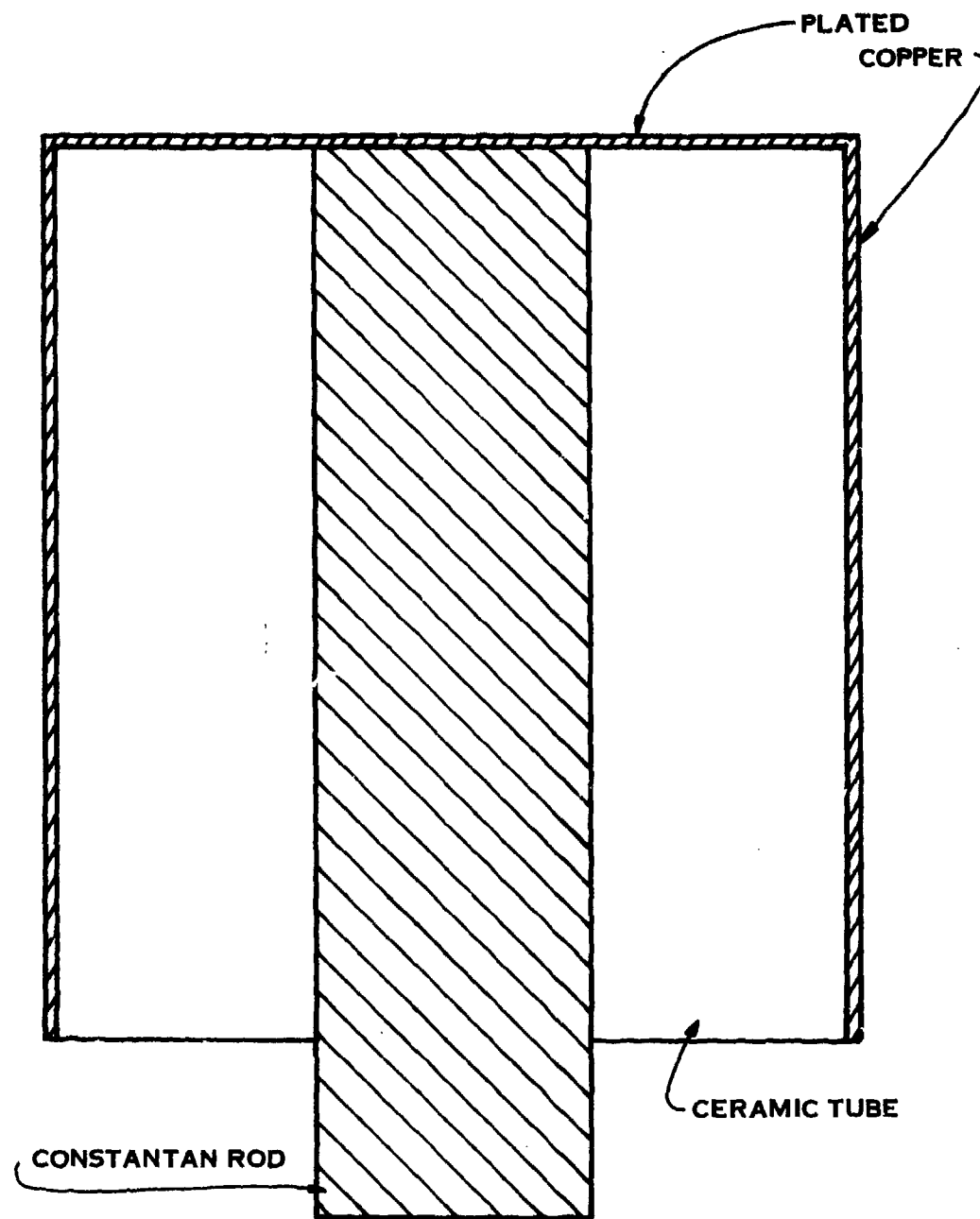


FIGURE 19 WIND TUNNEL MODEL THERMOCOUPLE SENSOR

tube, one end of which a copper film was vapor deposited. A constantan wire was then inserted in the tube and peened over to hold it in place. The final step was to plate the end of this assembly with copper to form a .005 cm end covering. The sensing thermocouple junction was formed by the copper plating in contact with the constantan rod. This sensor exhibited a time constant near 15 msec.

After the Aeronutronic-Ford test, it was recognized that additional filtering and acoustic isolation would be needed to obtain good signal-to-noise ratio. Two specific measures were undertaken: 1) Provide acoustic isolation for the heatshield to decouple it from the sting vibration and 2) electronically filter out the low frequency components picked up by the BLAM sensor. Figure 20 illustrates the method used to isolate the heatshield from the substructure. "O" rings were used between support rings and a silicone rubber damping wafer was placed between the nosetip and heatshield.

To filter out the low frequency components in the sensor output, an amplifier was designed to have sharp rolloff below 200 kHz. The frequency response function of this amplifier is shown in Figure 21. This amplifier was also designed to have a linear amplitude function as contrasted with the BLAM amplifier. A linear gain was used because the boundary layer noise was expected to be very low in amplitude due to low static pressures on the model.

5.3.2 Tunnel 8 Test Results

Data from the test model were recorded by NSWC either digitally with a computerized sampling system or on analog tape with a Honeywell 5500 c.c. recorder. Model thermal sensors

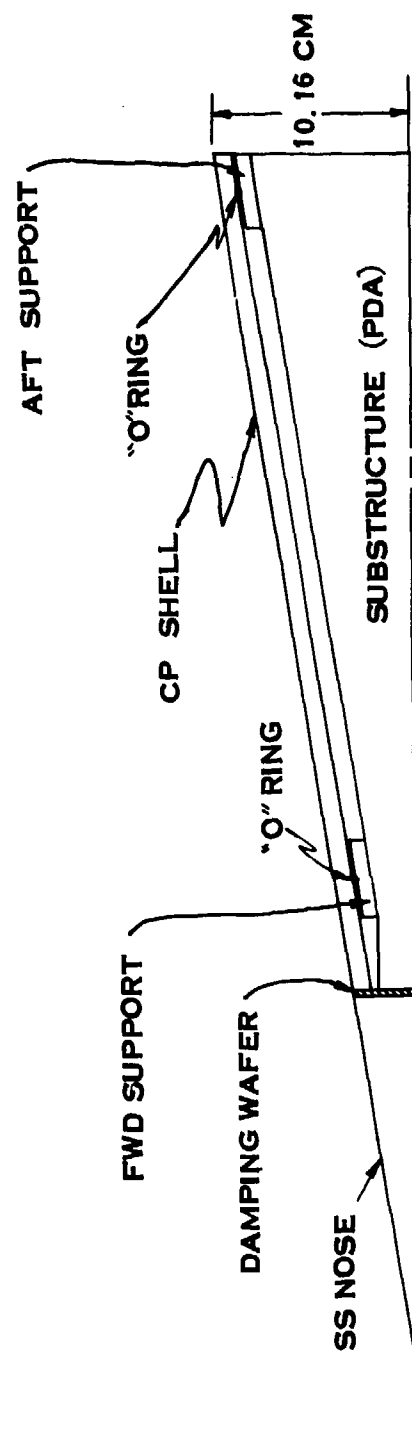


FIGURE 20 VIBRATION ISOLATION NSWC 9° TEST MODEL

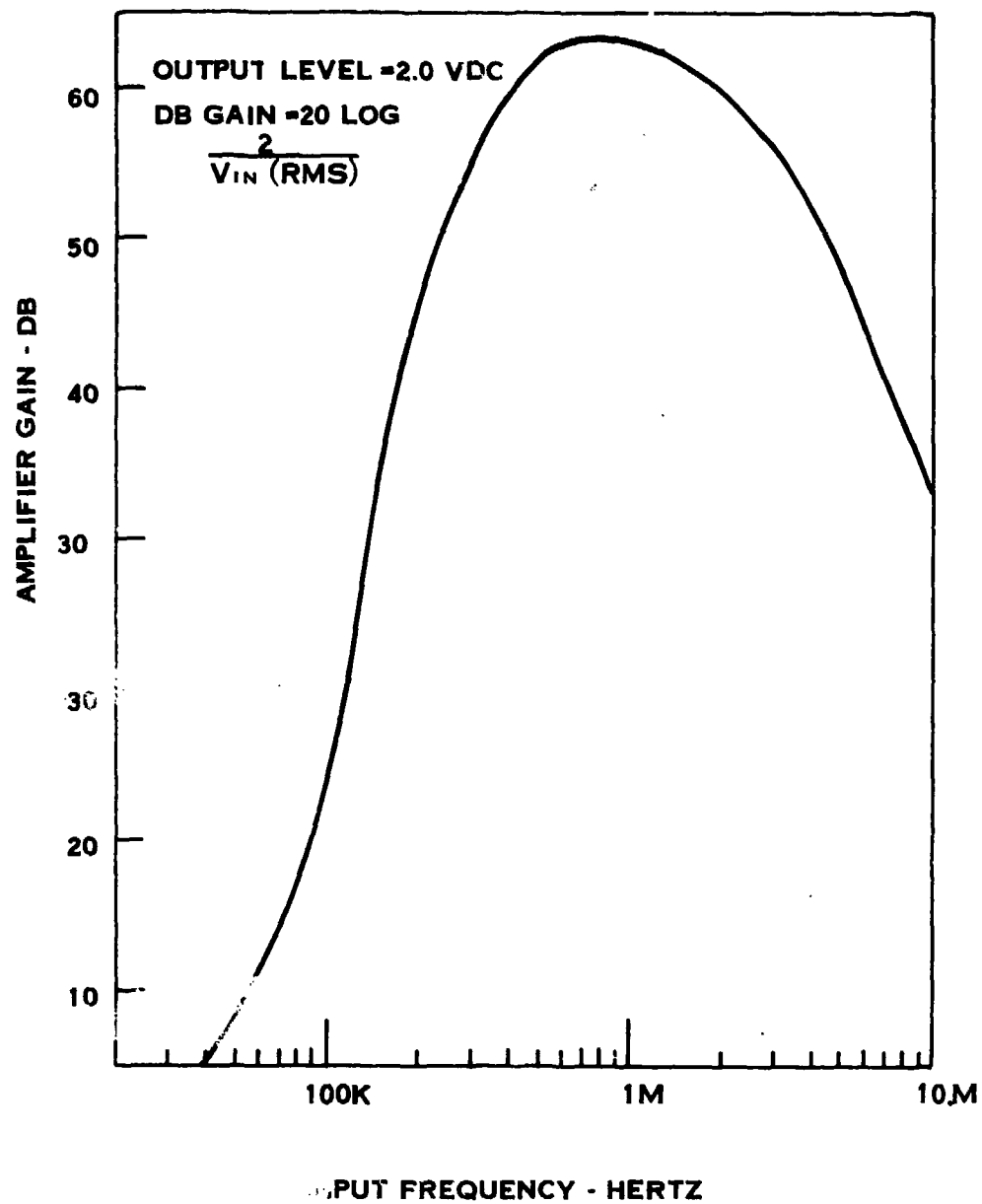


FIGURE 21 WIND TUNNEL TEST AMPLIFIER FREQ. RESPONSE

and tunnel conditions plus a timing signal were recorded on the digital system at a rate of approximately 50 samples per second. Data channel allocations are shown in Table 4.

TABLE 4 TUNNEL 8 TEST DATA CHANNELS

Digital

0 through 7	PDA Force balance outputs
8	Time shared: P_o scan 1 T_o scan 2
9	α - angle of attack
10 through 15	KSC thermal sensors T1 through T6
16	Time

Analog Recorder

1 through 6	KSC BLAM outputs
7	IRIG Time

5.3.2.1 Run 1. This test was a 20 sec. run intended to establish data quality and levels prior to a data run. It was found that a large low-frequency noise content obscured BLAM data and that the thermocouple output was very low. Filters were added to the BLAM circuitry and gain was increased in the thermocouple channels prior to Run 2.

5.3.2.2 Run 2. During this 25 second test, P_o was increased gradually over the test period to provide a R_{∞} sweep. A plot of the tunnel conditions is given in Figure 22 showing P_o and R_{∞} versus time. The R_{∞} data were obtained using P_o and T_o plus the conditions of Figure 17. The tunnel was not pre-heated prior to taking data.

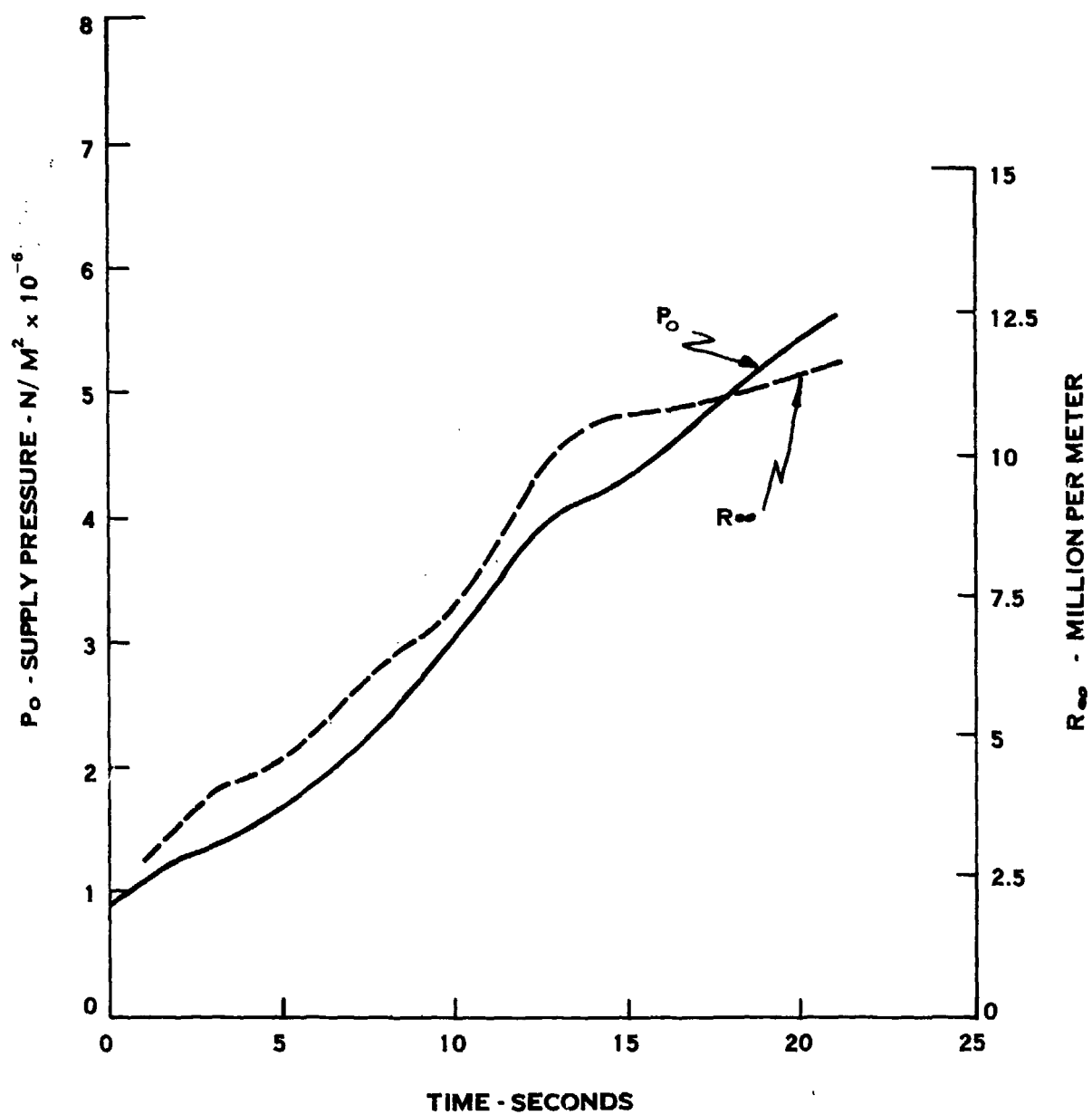


FIGURE 22 RUN 2 FLOW PARAMETERS M8

Data from the BLAM and temperature sensors are plotted in Figures 23 through 28. The adjacent thermocouples and BLAM's have been assigned the same numbers and plotted in the same figures. There is some uncertainty as to the relative placement of the BLAM data on the time scale because time code was not recorded during Run 2. By using discontinuities in the data, an attempt was made to line up the traces, but a one or two second error could exist. Sensors numbered 1 and 4 are at the forward-most station on the model, diametrically opposed. Numbers 2 and 5 are located in the center and 3 and 6 are near the aft end. Sensors 1, 2, and 3 are on one azimuth as are 4, 5, and 6 (see Figure 18 for reference locations).

Several features are of particular importance in these figures relating measured noise level to flow characteristics. First, it can be noted that the BLAM channels exhibit a change of level between 10 and 12 seconds into the run and that all except the forward thermocouple traces show a change of slope at about the same time. The tunnel flow conditions at this time are pressure of $3 \text{ to } 4 \times 10^6 \text{ N/m}^2$ and Reynolds number of 6.9 to 7.5 million per meter.

Other investigators^{1,2,3,4,5,6} who made measurements of boundary layer noise in wind tunnels have reported similar noise amplitude characteristics, showing that the root-mean-square noise level in the transitional boundary layer increased orders of magnitude over that of laminar flow. The transition noise level was also larger than that from the boundary layer at Reynolds numbers (R_∞) where full turbulence had been just achieved. These same researchers also noted that the boundary layer condition can be related to R_∞ ; i.e. the flow progressed from laminar to transitional to full turbulence as R_∞ was increased.

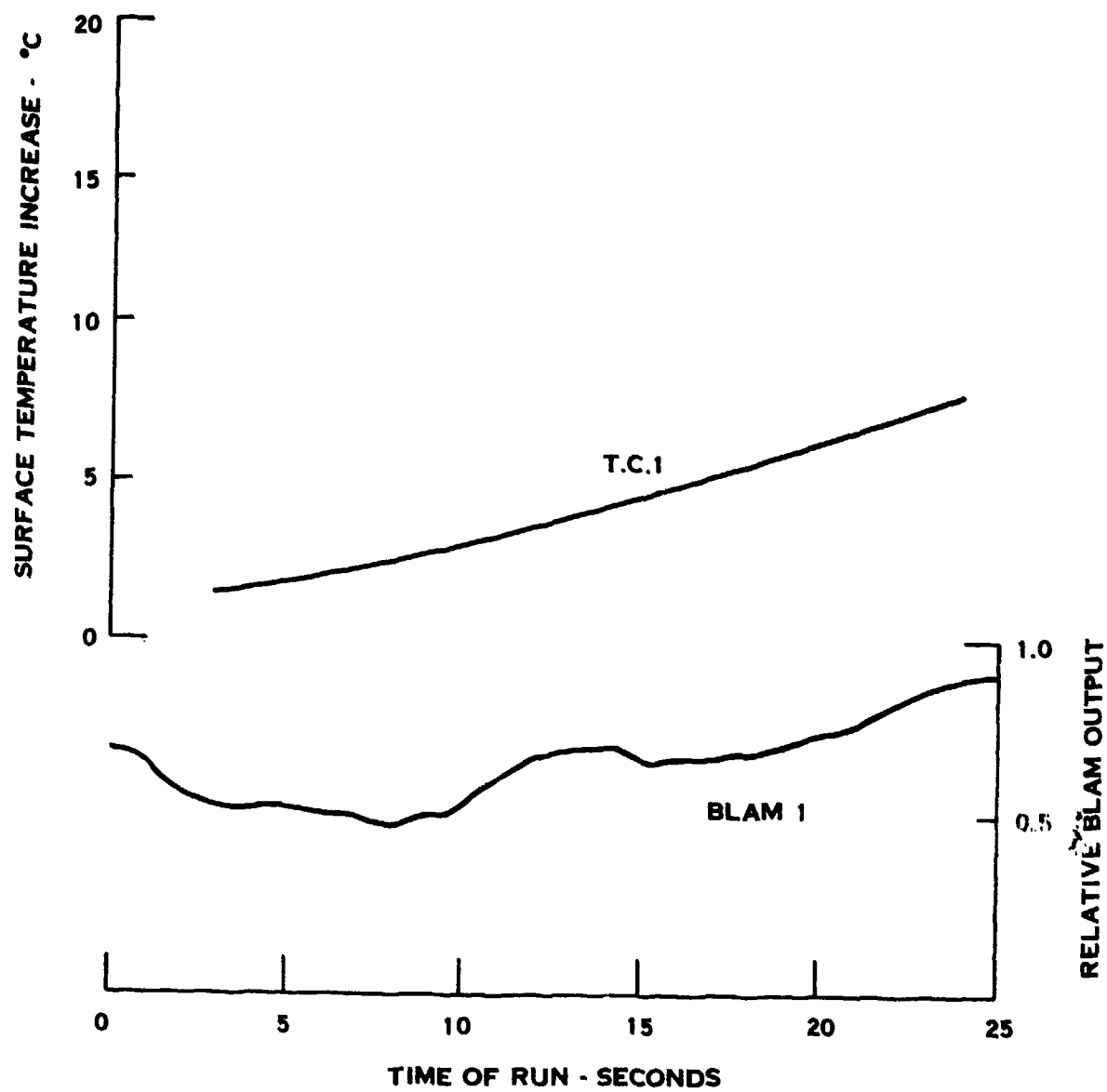


FIGURE 23 RUN 2, BLAM CHANNEL 1, TEMP. SENSOR 1

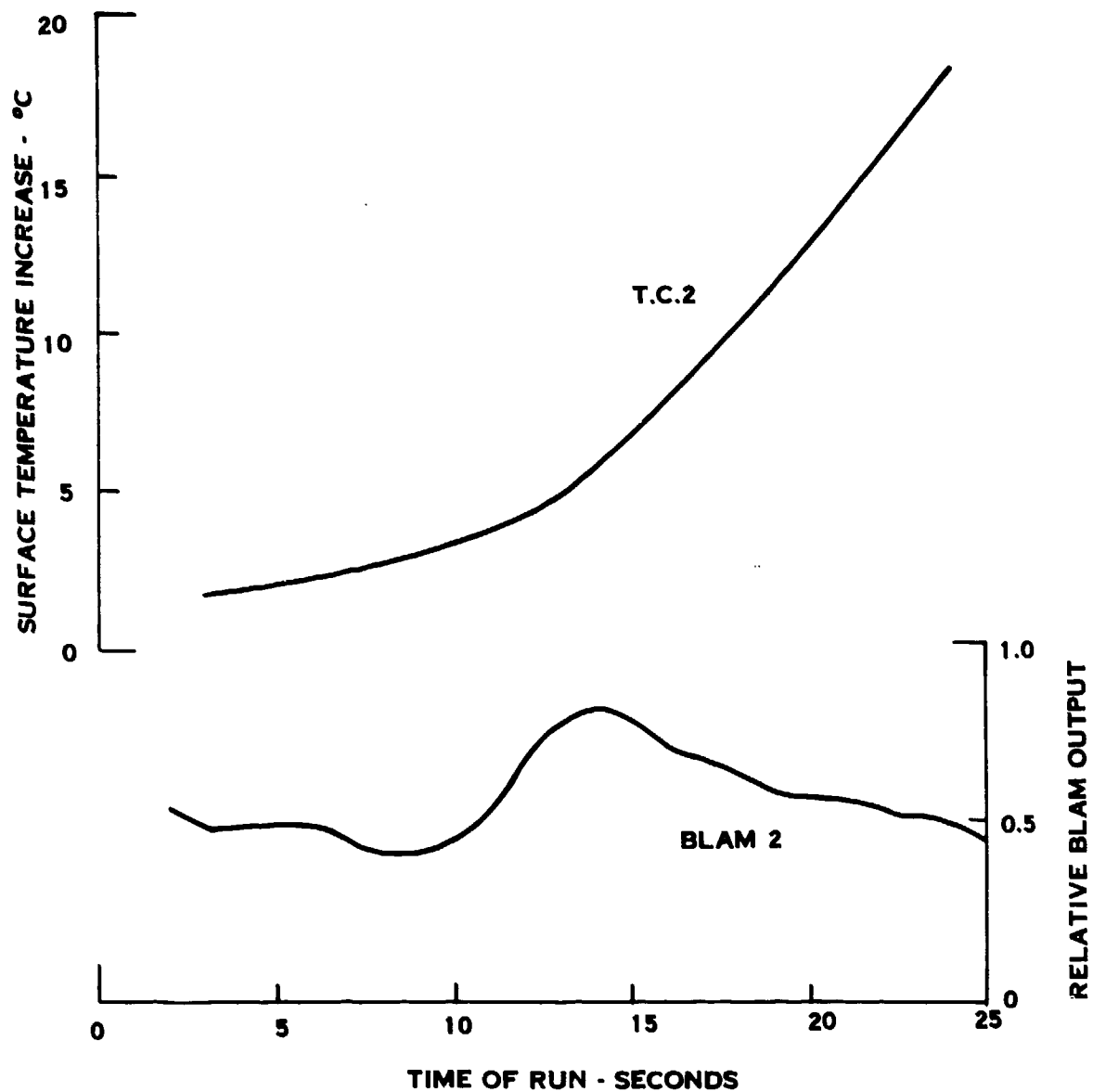


FIGURE 24 RUN 2, BLAM CHANNEL 2, TEMP. SENSOR 2

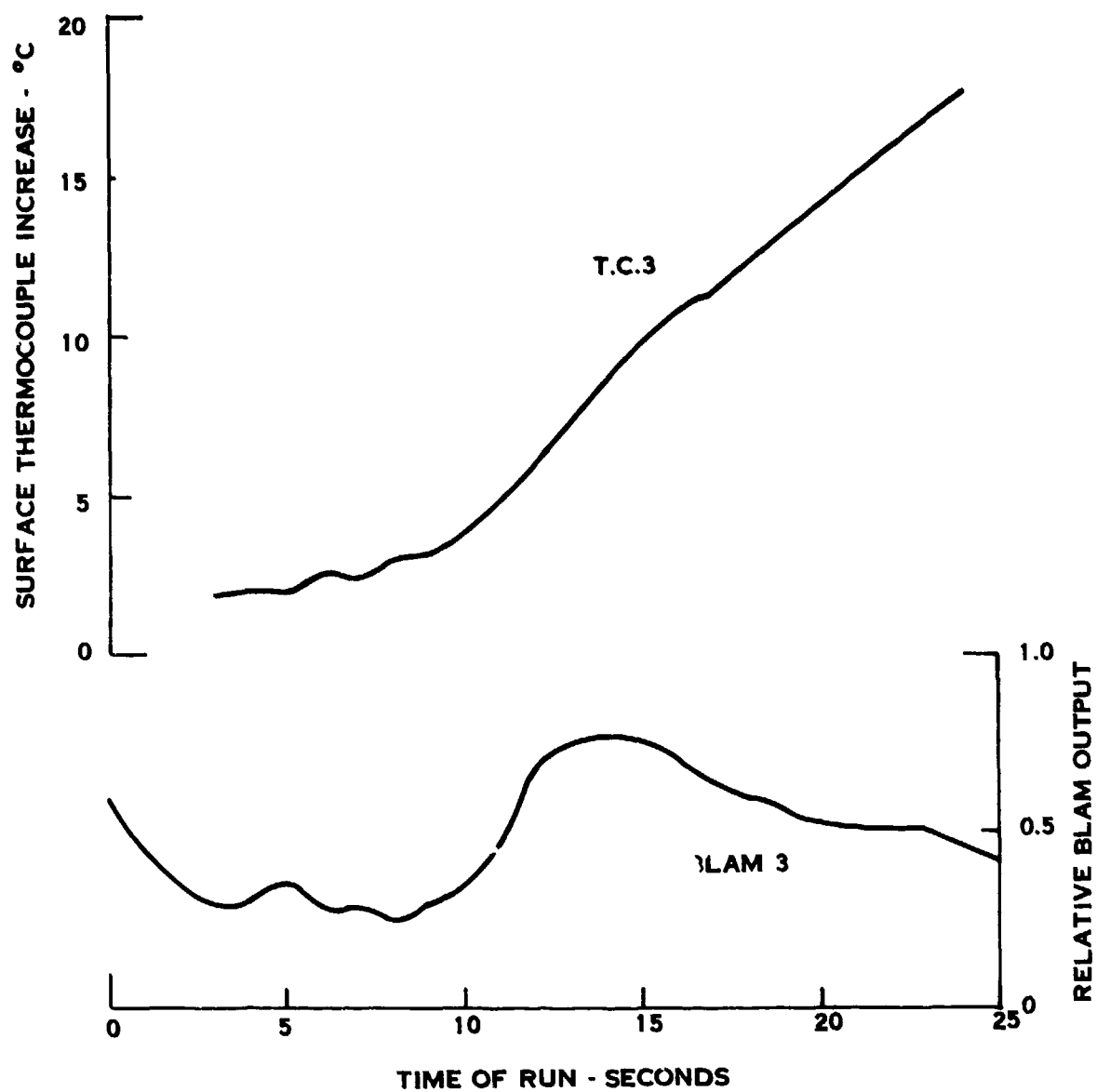


FIGURE 25 RUN 2, BLAM CHANNEL 3, TEMP. SENSOR 3

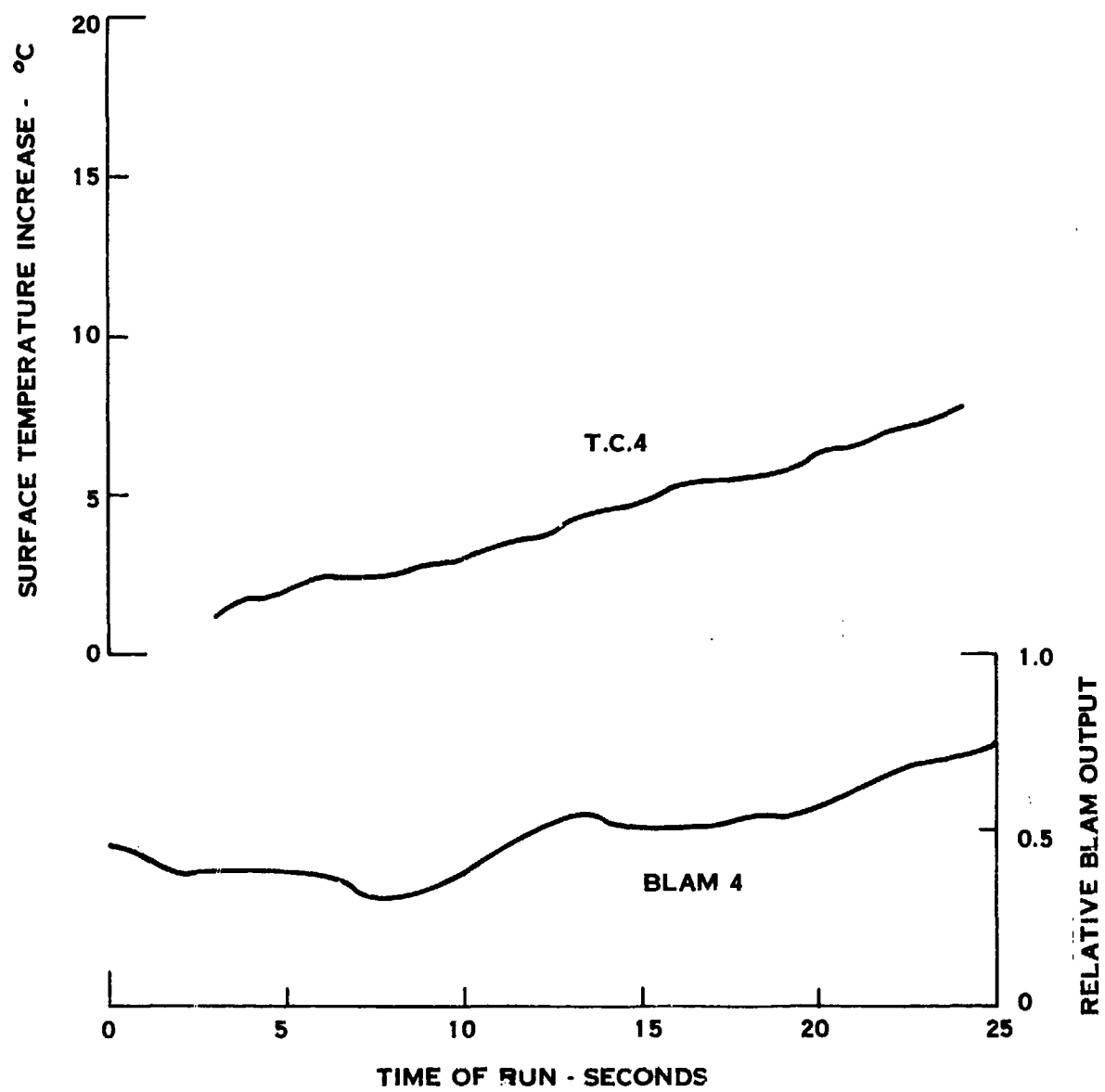


FIGURE 26 RUN 2, BLAM CHANNEL 4, TEMP. SENSOR 4

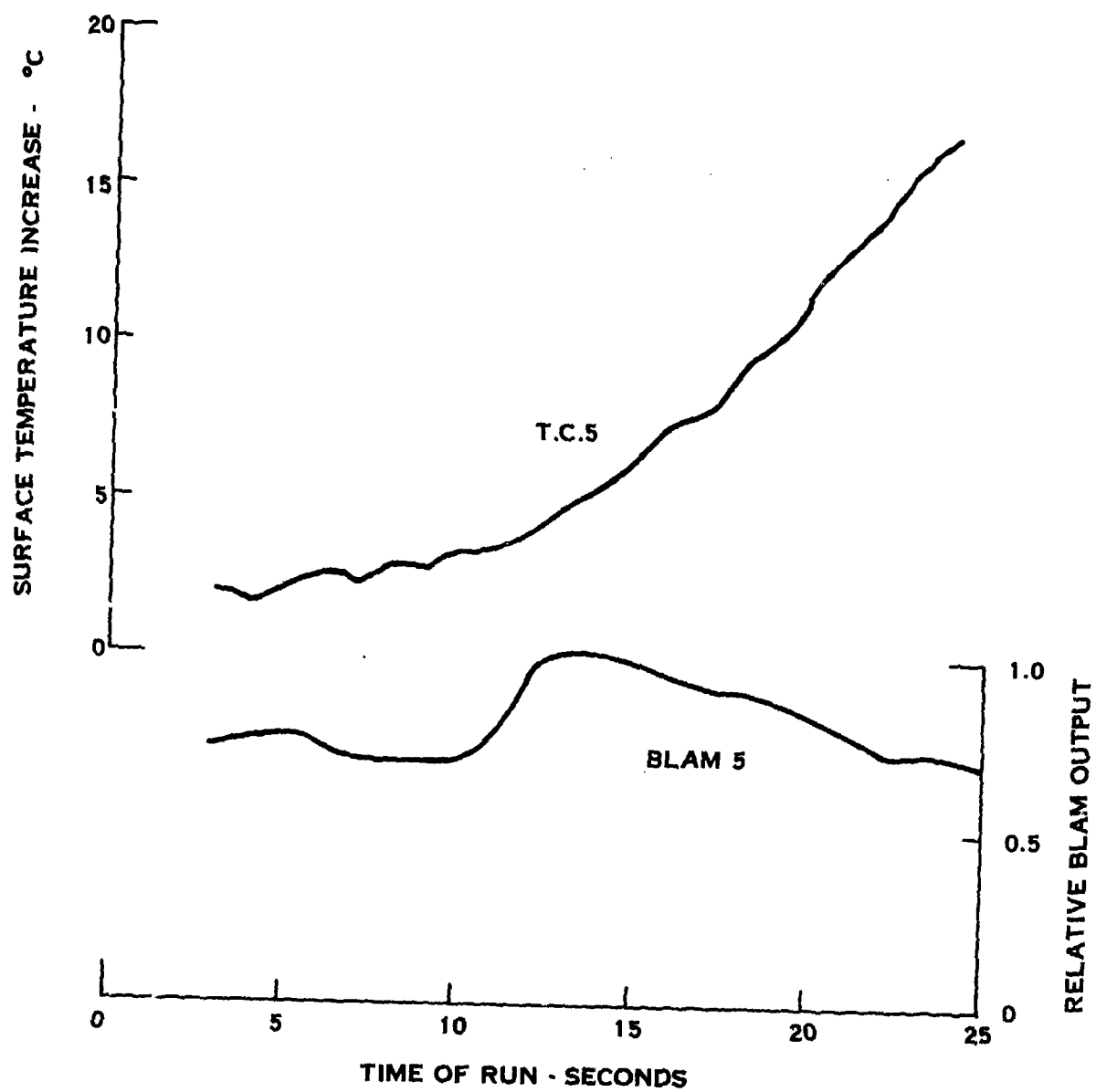


FIGURE 27 RUN 2, BLAM CHANNEL 5, TEMP. SENSOR 5

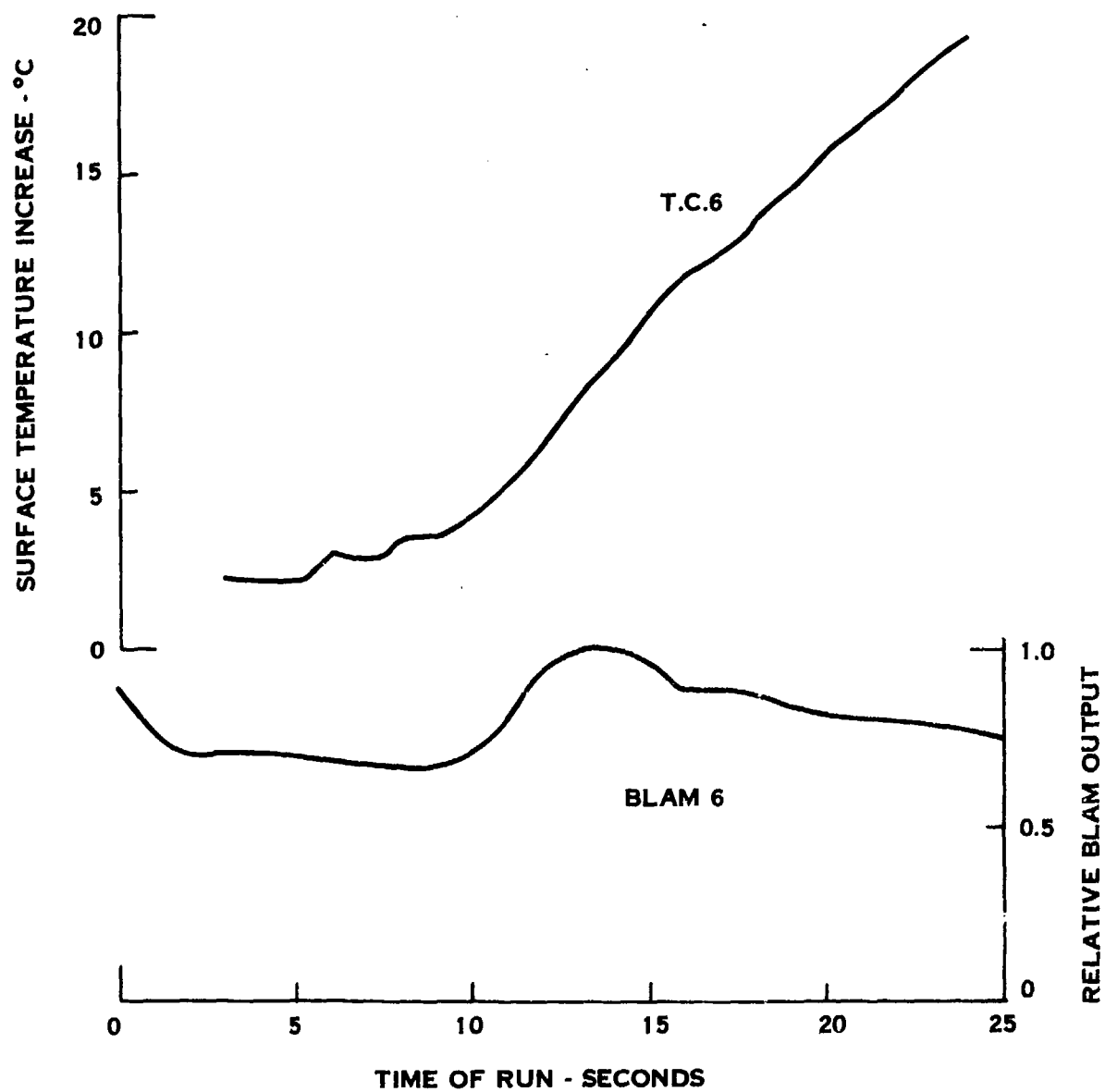


FIGURE 28 RUN 2, BLAM SENSOR 6, TEMP. SENSOR 6

The acoustic level traces in Figures 23-28 early in the run were high then decreased immediately, a feature which can be attributed to tunnel or tape recorder transient. As R_{∞} increased and the boundary layer entered transition, peak noise was measured near 14 seconds on all channels corresponding to R_{∞} of about 10^7 m^{-1} .

The thermal sensors which were placed along side the BLAM's indicated a significant change in heating rate occurring at about 9 or 10 seconds. This heating rate change is seen in the slope of the temperature curves which are plotted in Figures 23-28. The forward stations (Transducers 1 and 4, Figures 23 and 26) did not show this characteristic in the thermal data, whereas the BLAM's at these forward stations did show a small transitional bump in the data. The transition bumps in transducers 5 and 6 were much greater in amplitude and closely correlated with the temperature rate increase.

5.3.2.3 Run 3. This test was similar to Run 2 in that a pressure sweep was used to vary the boundary layer conditions in an attempt to record transition on the model. The major difference was that a higher pressure was achieved in Run 3 and the tunnel was pre-heated to obtain more uniform flow. Tunnel flow parameters and sensor data are plotted in Figures 29 through 35.

Data from the BLAM's prior to 8 seconds were not recorded in this test due to the tape recorder not being turned on in time. The aft and center stations, channels 2, 3, 5 and 6 do not show transition except for a slight increase at the beginning of the traces. The thermal data for these stations indicate transition occurring prior to 8 seconds which would be consistent with the Reynolds number at which transition occurred in Run 2.

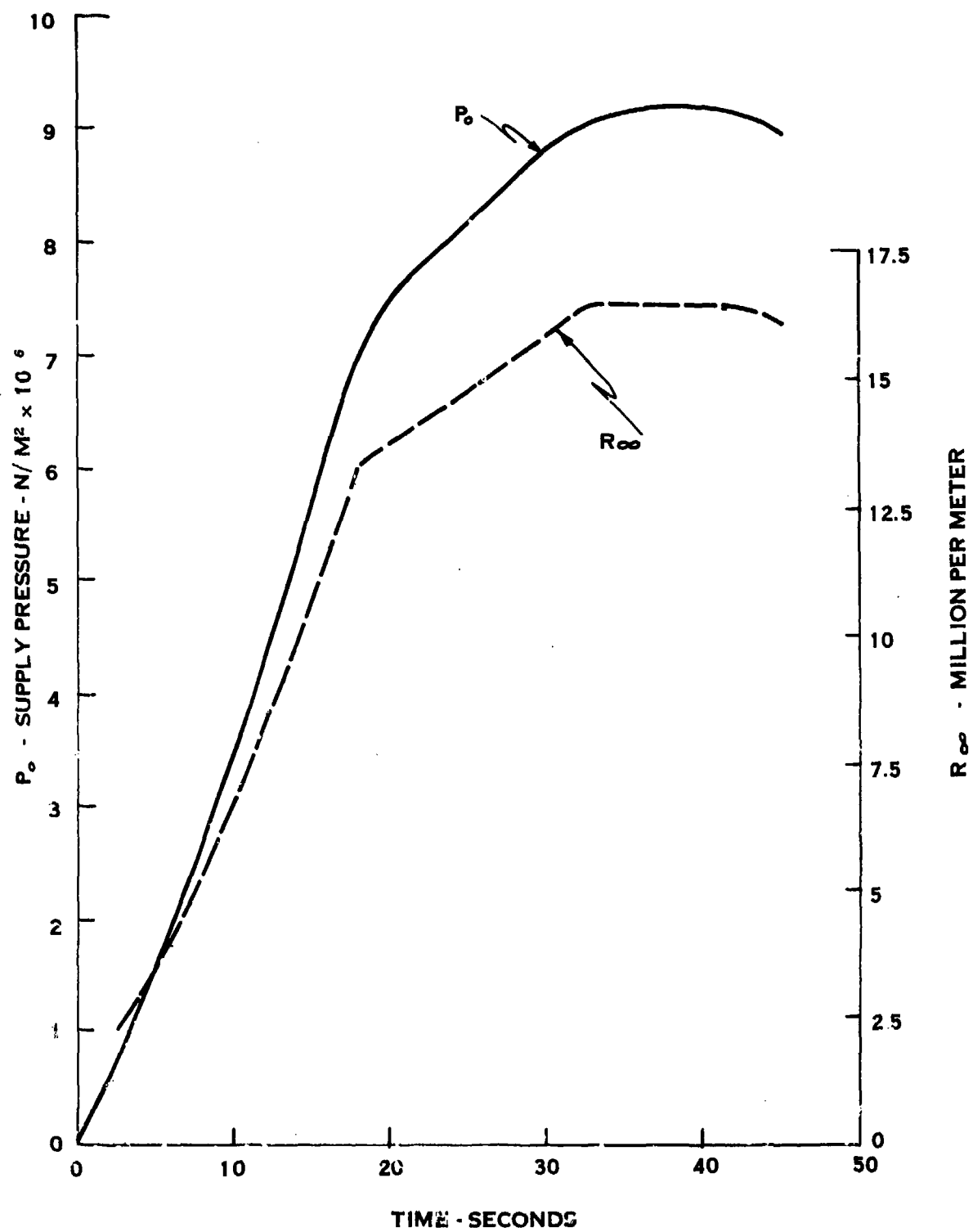


FIGURE 27 RUN 3, FLOW PARAMETERS

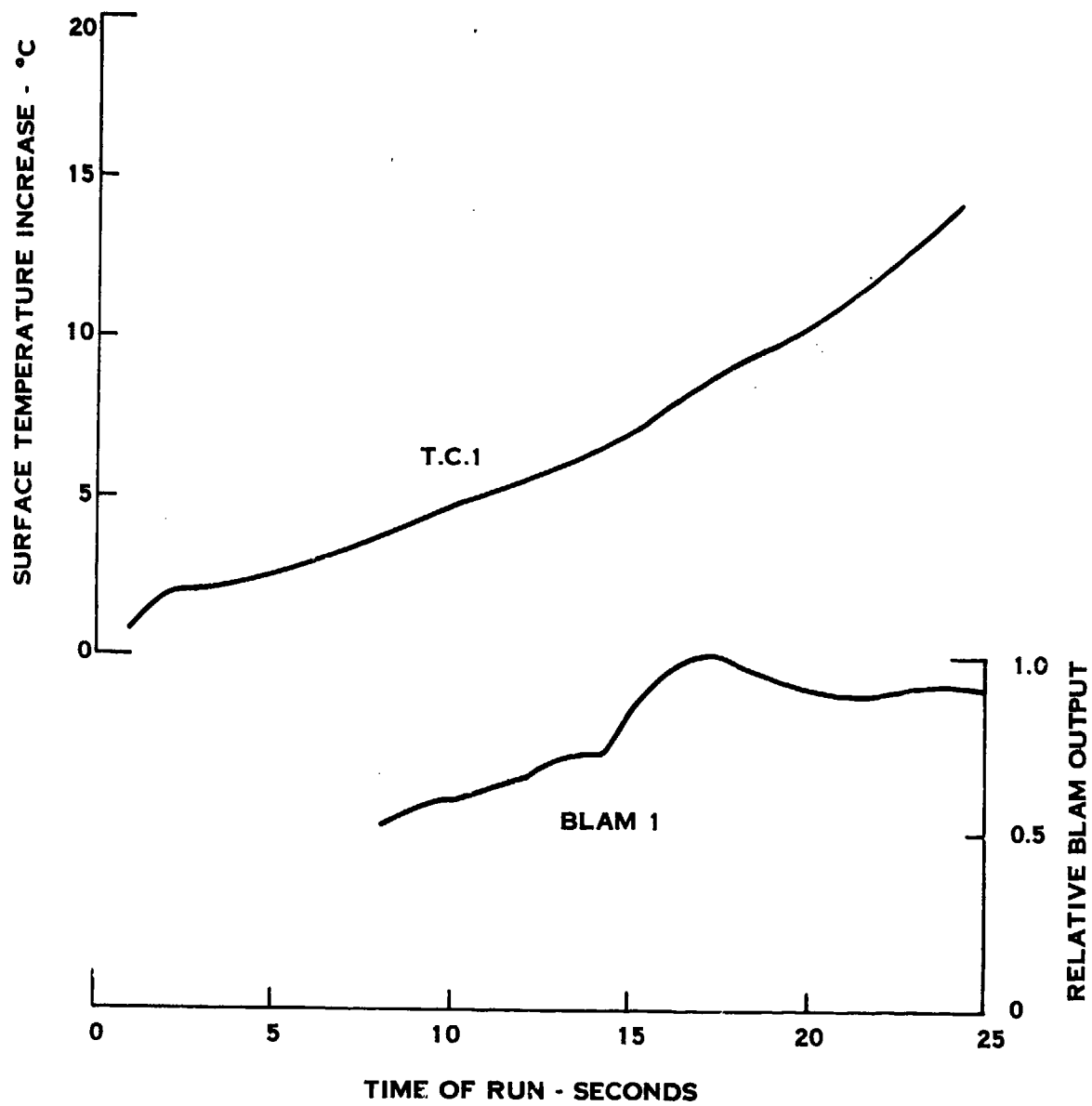


FIGURE 30 RUN 3, BLAM CHANNEL 1, TEMP. SENSOR 1

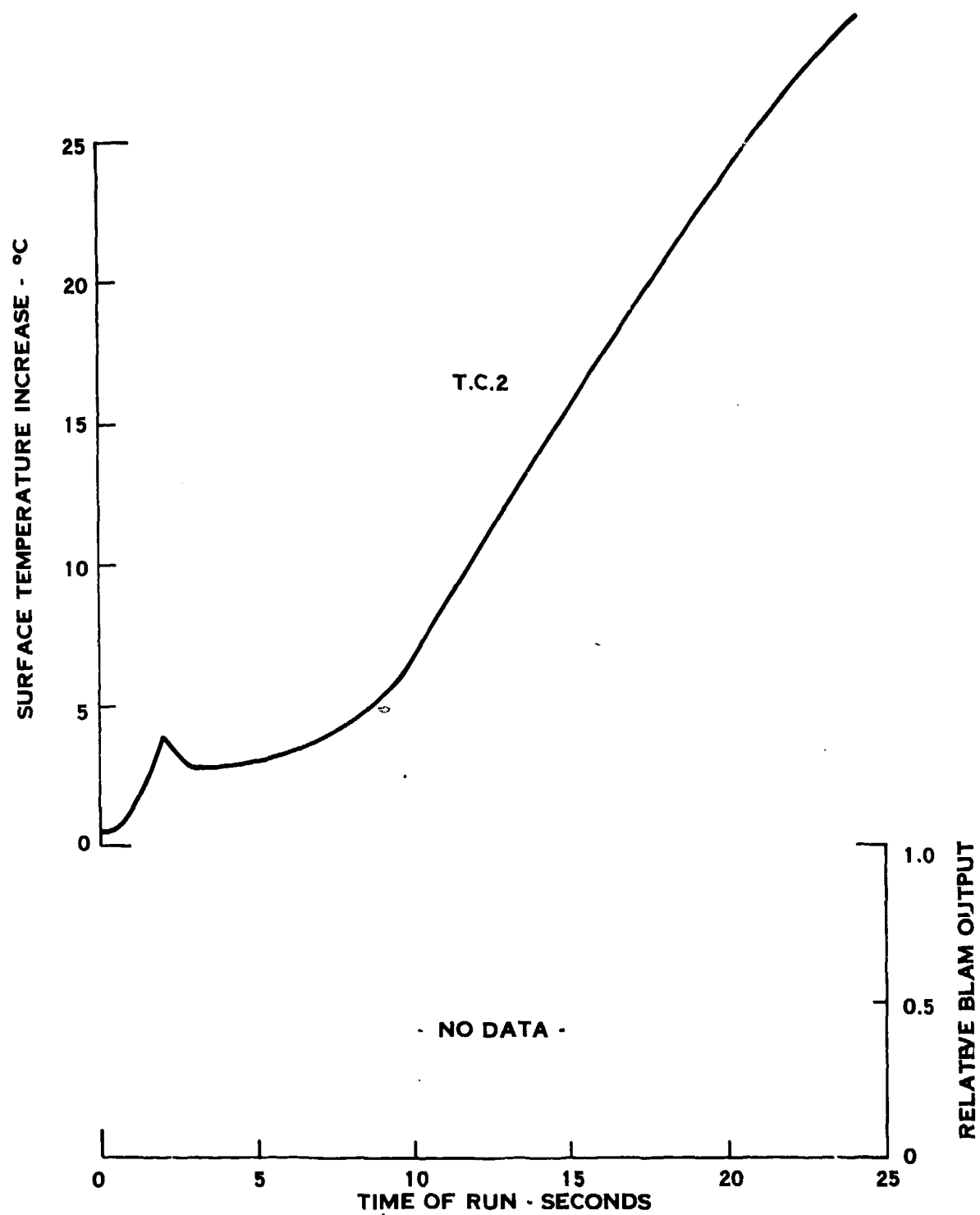


FIGURE 31 RUN 3, BLAM CHANNEL 2, TEMP. SENSOR

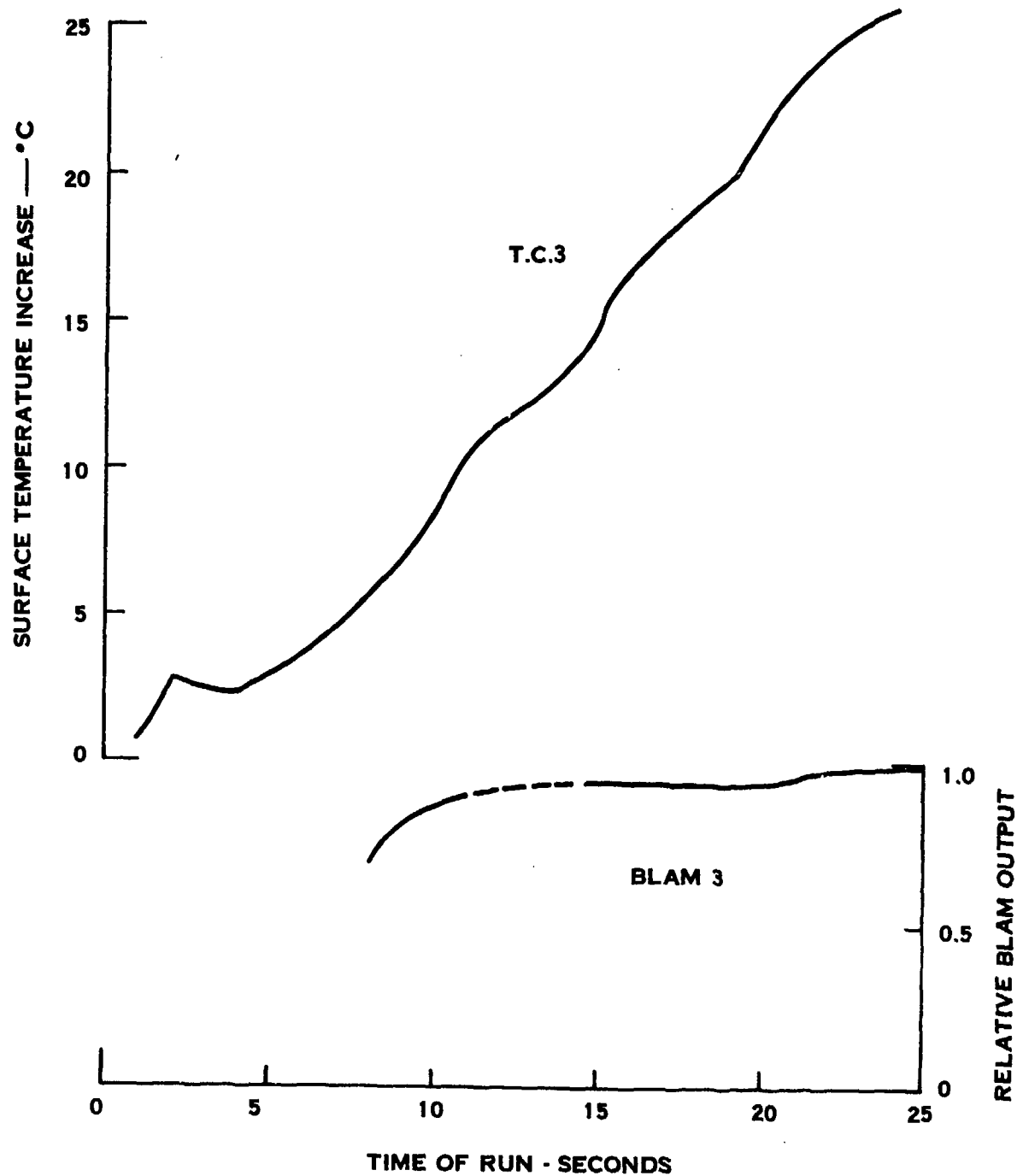


FIGURE 32 RUN 3, BLAM CHANNEL 3, TEMP. SENSOR 3

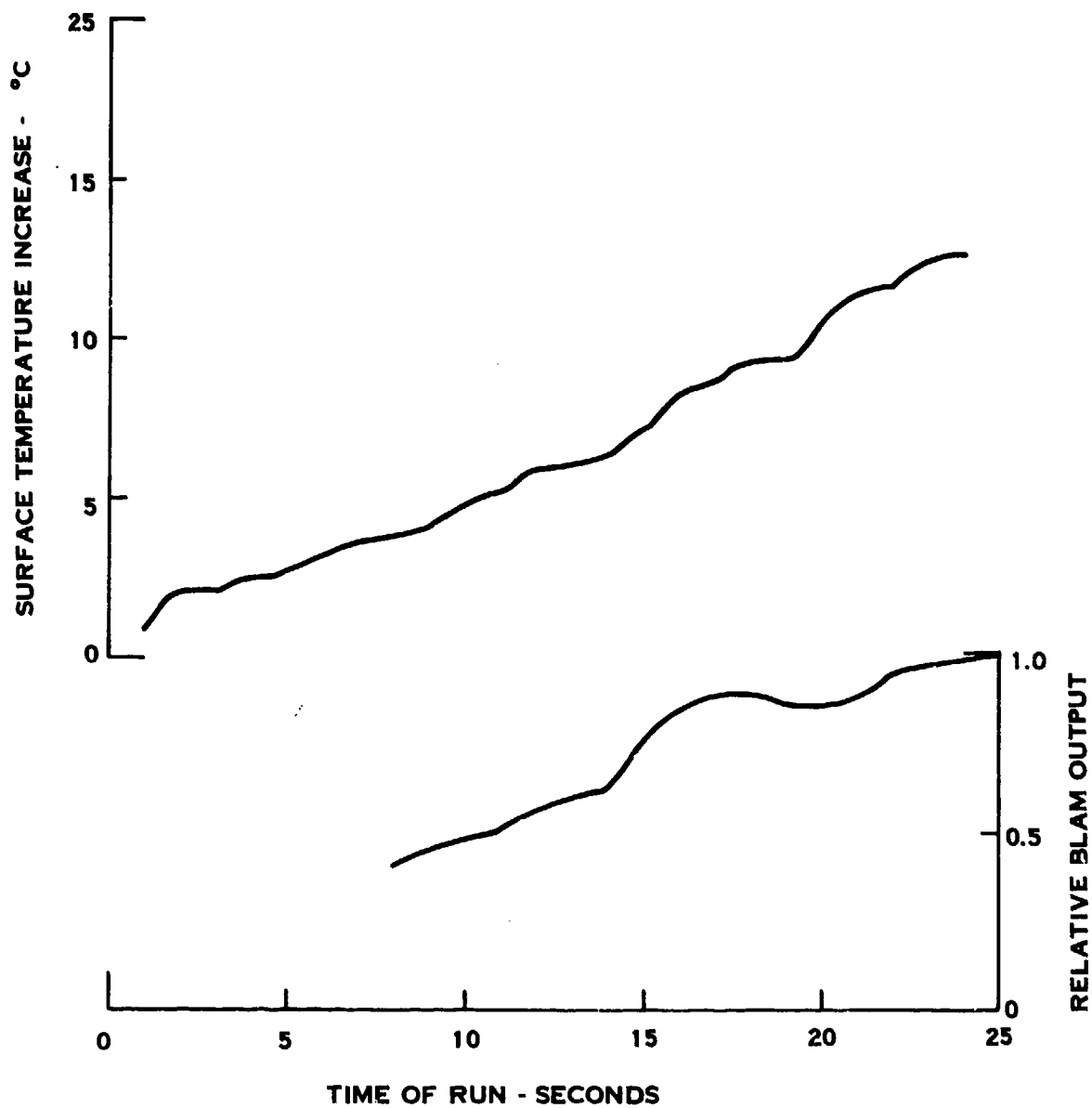


FIGURE 33 RUN 3, BLAM CHANNEL 4, TEMP. SENSOR 4

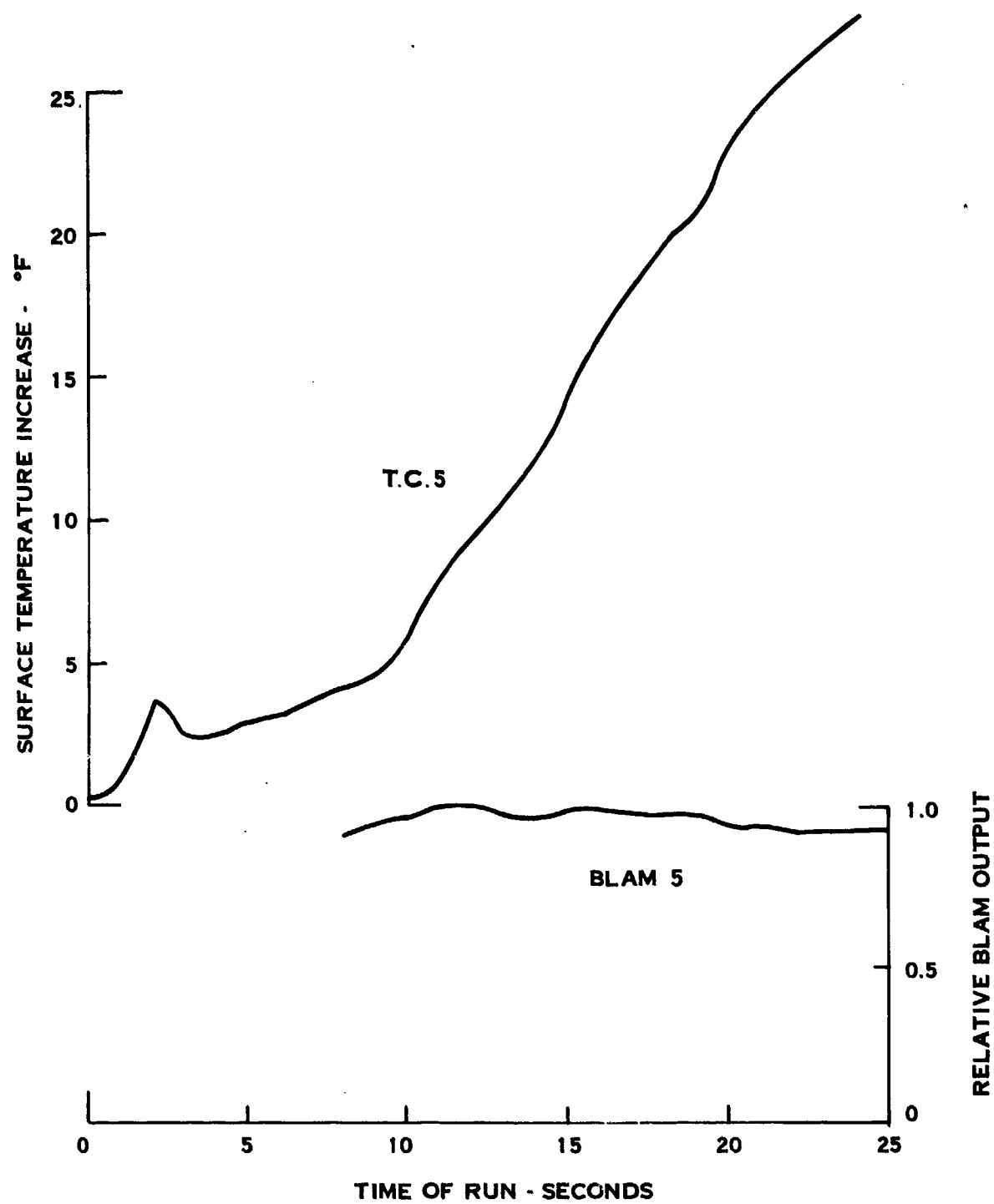


FIGURE 34 RUN 3, BLAM CHANNEL 5, TEMP. SENSOR 5

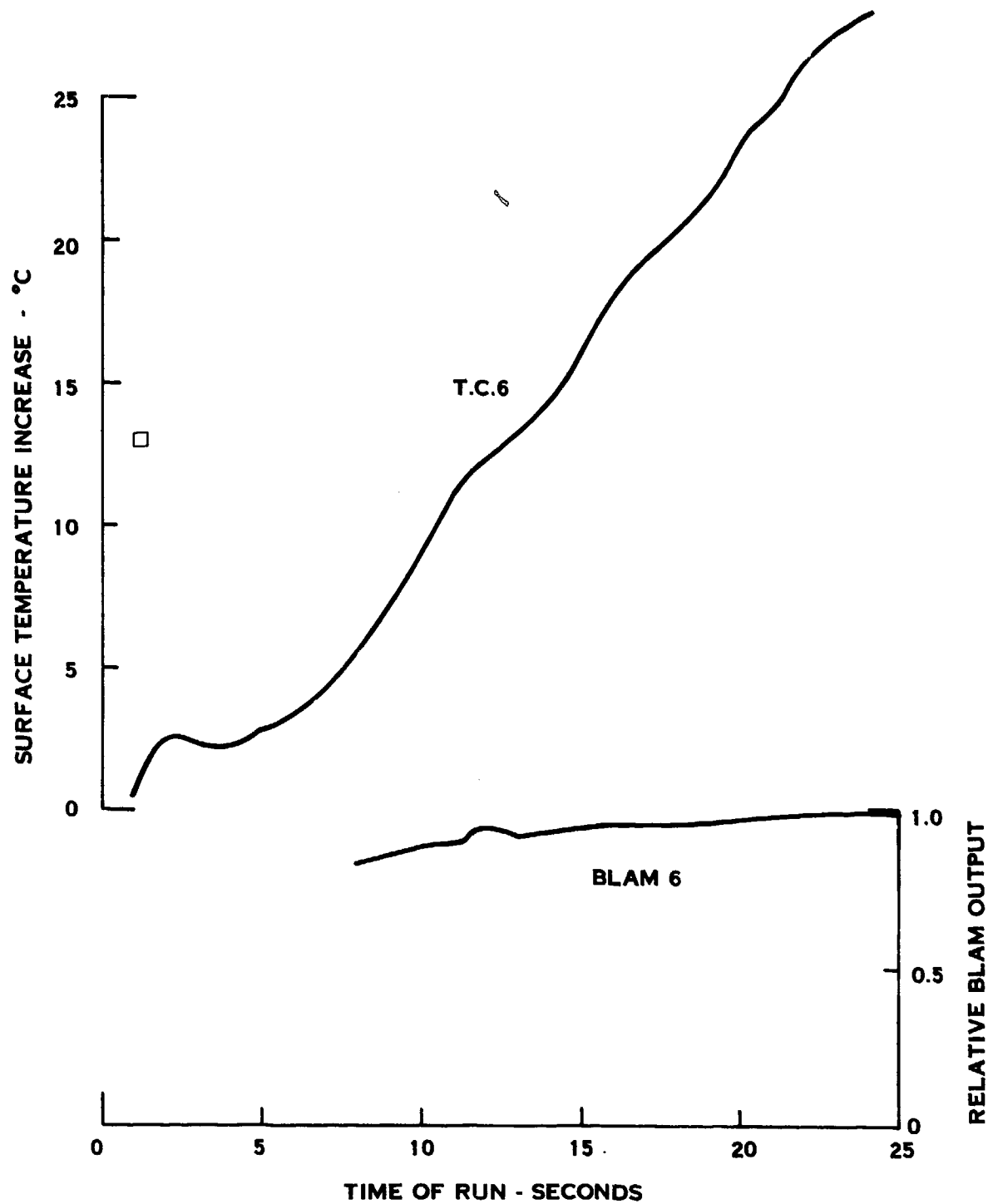


FIGURE 35 RUN 3, BLAM CHANNEL 6, TEMP. SENSOR 6

BLAM channels 1 and 4, on the forward part of the model, show the characteristic transition bump but at a higher R_∞ that was experienced in Run 2. This bump is a good indicator of transition since it is known that transition on a cone moves forward as R_∞ increases. Thermal sensors 1 and 4 show slight increases in slope at the acoustic transition time indicated by the BLAM's.

A series of Schleiren photos taken during Run 3 are included in Appendix B, Figures 54 through 59. These photos show progression of boundary layer turbulence from aft toward the model tip as the flow Reynolds number increases. While not having the best contrast, the primary indicator in the photos showing turbulence is the fine white line close to the model wall. This line is not visible where full turbulence exists.

While the correlation of optical indicators and acoustical signals has not been established, the photos show transition near BLAM's 2 and 5 at 10 to 12 seconds in the run. This corresponds reasonably well with acoustic and thermal data shown in Figure 34. It is believed that the acoustic signal is generated in the transition zone in the boundary layer forward of the zone of breakup seen in the Schleiren photographs.

5.3.2.4 Run 4. In this run, data were taken with the model spinning and at a 2.5° angle of attack with respect to the flow. Tunnel operating parameters are given in Figure 36 which shows three R_∞ plateaus of $4.6 \times 10^6 \text{ m}^{-1}$, $6.6 \times 10^6 \text{ m}^{-1}$ and $10 \times 10^6 \text{ m}^{-1}$. Data were taken during each of these plateaus from the BLAM channels. Due to the long duration of the test, temperature data were meaningless due to thermal saturation.

BLAM data from channels 1 and 4, the forward-most sensors, indicated a fluctuating level corresponding to the spin rate of the model. The traces obtained are shown in Figure 37.

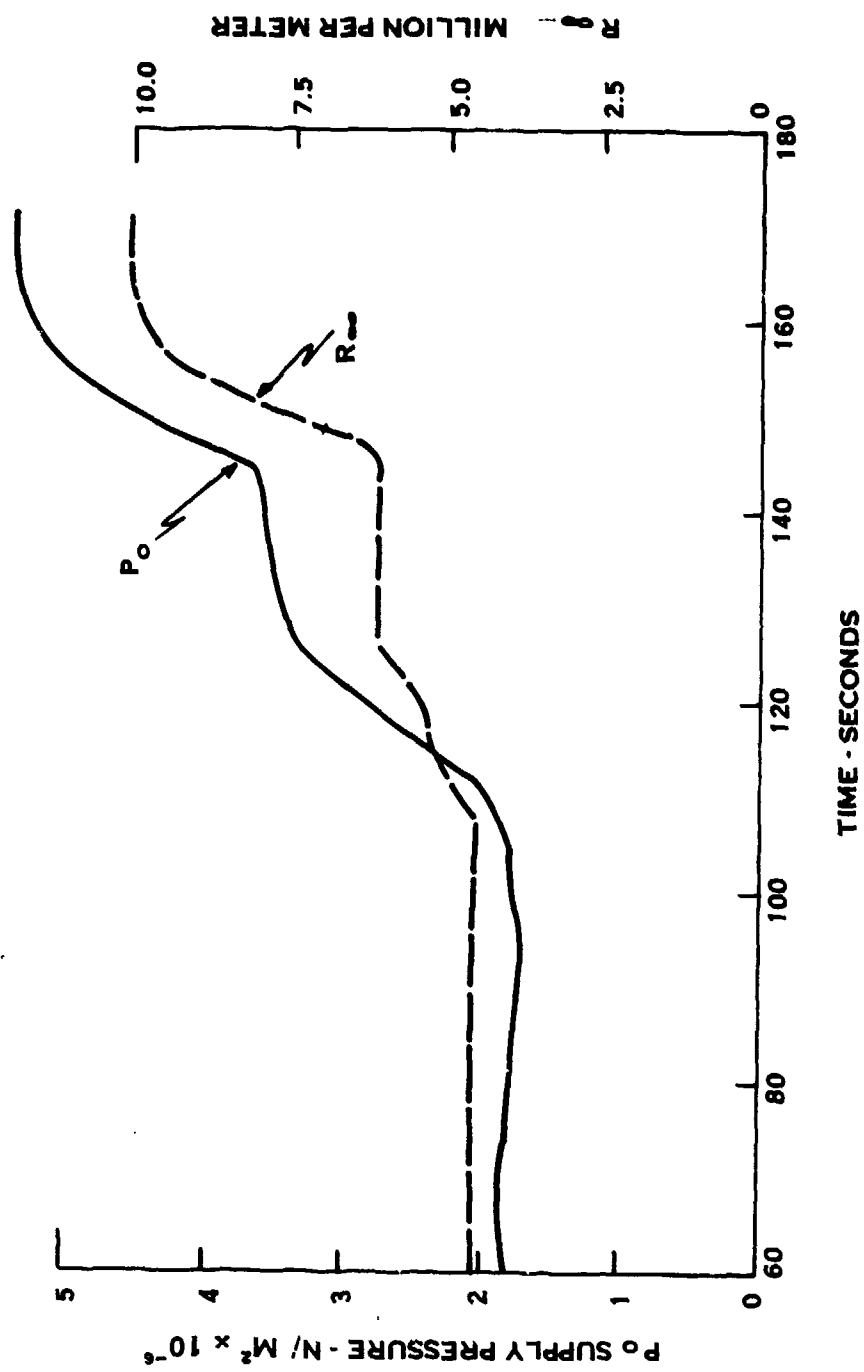


FIGURE 36 RUN4 FLOW PARAMETERS M8

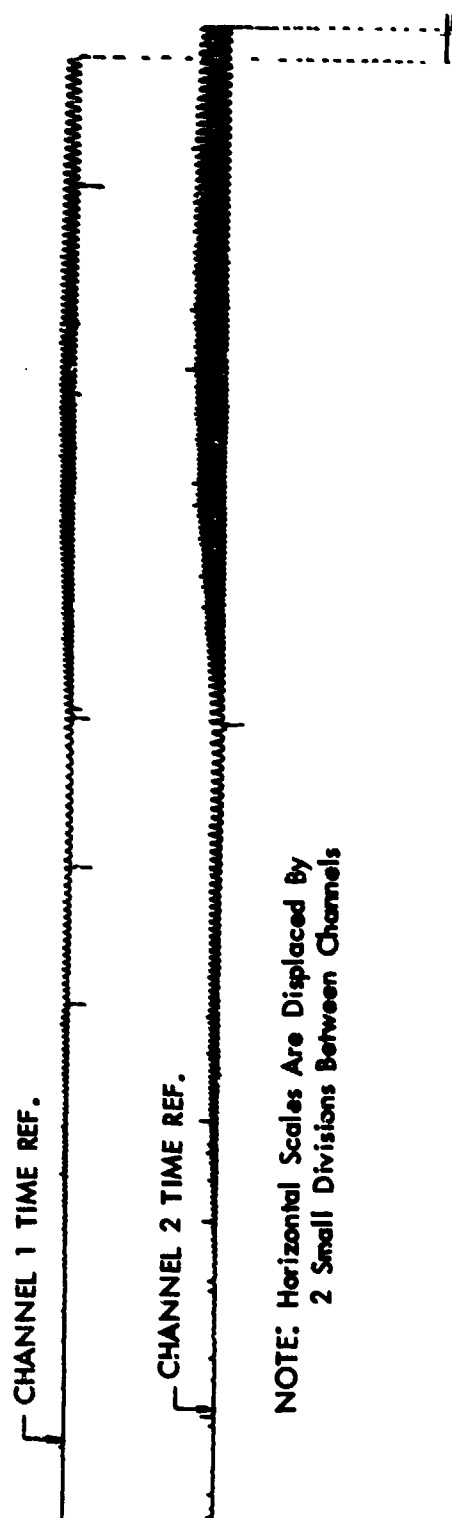


FIGURE 37 RUN 4 BLAM DATA CHANNELS 1 AND 4

Data from the remaining BLAM channels were poor in quality and are not included herein.

An analysis of the data showed that the outputs were phased 180° with respect to each other, which would be a proper indication if the noise source were greater in strength on the side of the model which was fixed with respect to the flow. A close comparison of film and BLAM records (which both had good IRIG timing marks) showed that the peak of the oscillation occurred when the BLAM was on the leeside of the model with respect to the upstream direction.

Martelucci⁷ showed that in such hypersonic flow conditions at an angle of attack transition will move forward on the lee-side ray. The relative amplitude of the BLAM sensors correspond well to that from Run 3 (e.g. Figure 30) at similar Reynolds numbers.

An expanded view of simultaneous output from channels 1 and 4 is presented in Figure 38. The BLAM output exhibits asymmetry and a central dip in amplitude on the peak, both of which features can be expected as a result of asymmetric transition on cones. The dip in the peak can be attributed to a narrow zone of full turbulence in between transition zones. The photos of Figure 38 also illustrate the directionality of the BLAM in that the zones of transition are well defined. This is particularly visible in channel 4 trace where the dip at the peak on the leeward side is apparent. Details less than 0.1 the circumference of the model can be seen, an excellent indication of directionality.

Additional confirmation of boundary layer condition was given by Schleiren photos, in Figure 39A, B, and C. Figure 39C was taken at time 50 seconds, just prior to the data shown in Figure 38. All photographs show a well-defined boundary layer

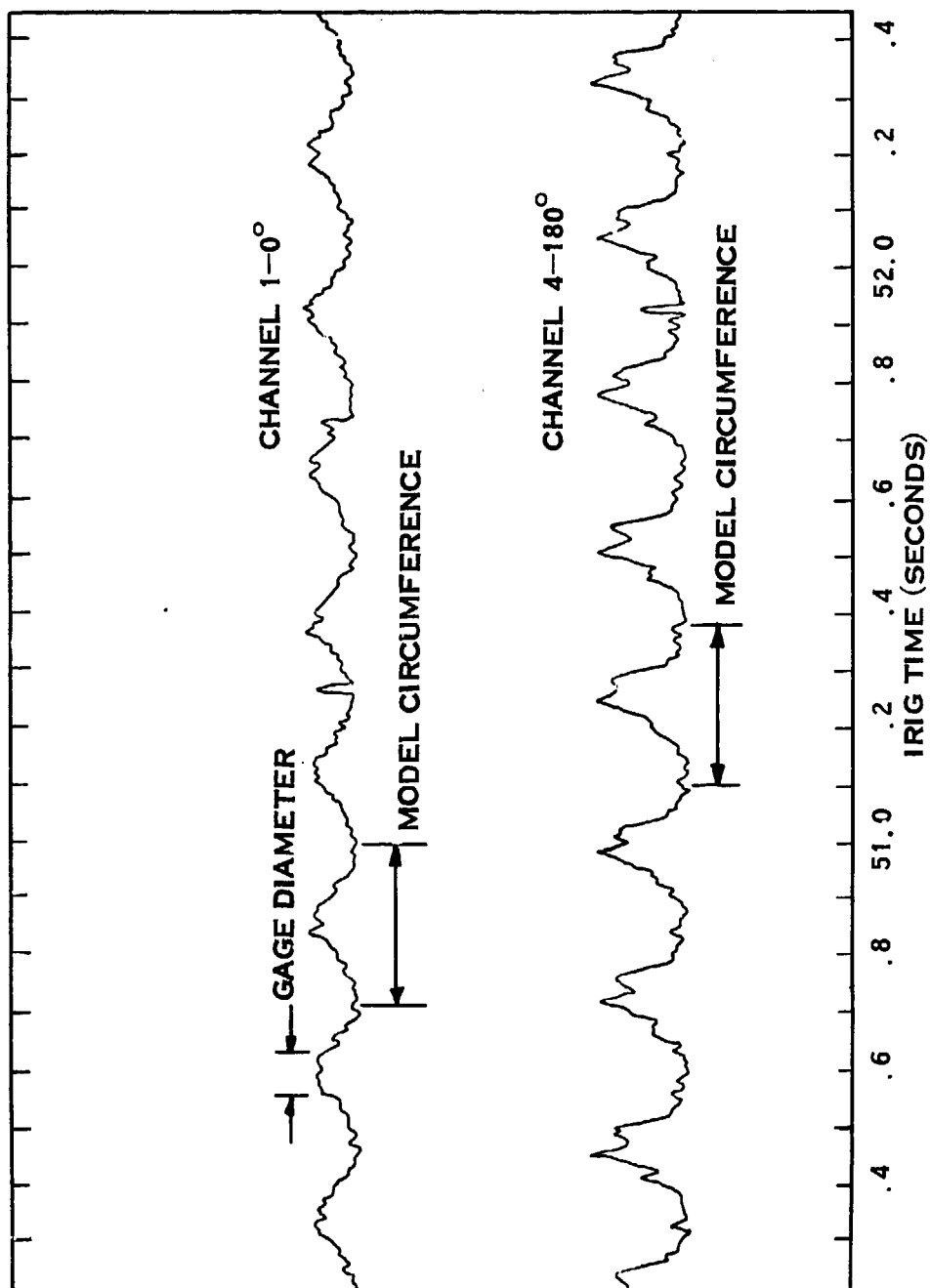


FIGURE 38 BLAM COMPARISONS SPINNING MODEL NSWC TUNNEL
8, MACH 8, $5.4 \times 10^6 \text{ N/M}^2$, $\alpha = 2.5^\circ$, $R_\infty = 10^6 \text{ M}^{-1}$



FIGURE 39A RUN 4 BOUNDARY LAYER PHOTO
 $R_{\infty} = 3.6 \times 10^6 \text{ m}^{-1}$
 $\alpha = 2.5^{\circ}$



FIGURE 39B RUN 4 BOUNDARY LAYER PHOTO

$$R_{\infty} = 6 \times 10^6 \text{ m}^{-1}$$

$$\alpha = 2.5^{\circ}$$

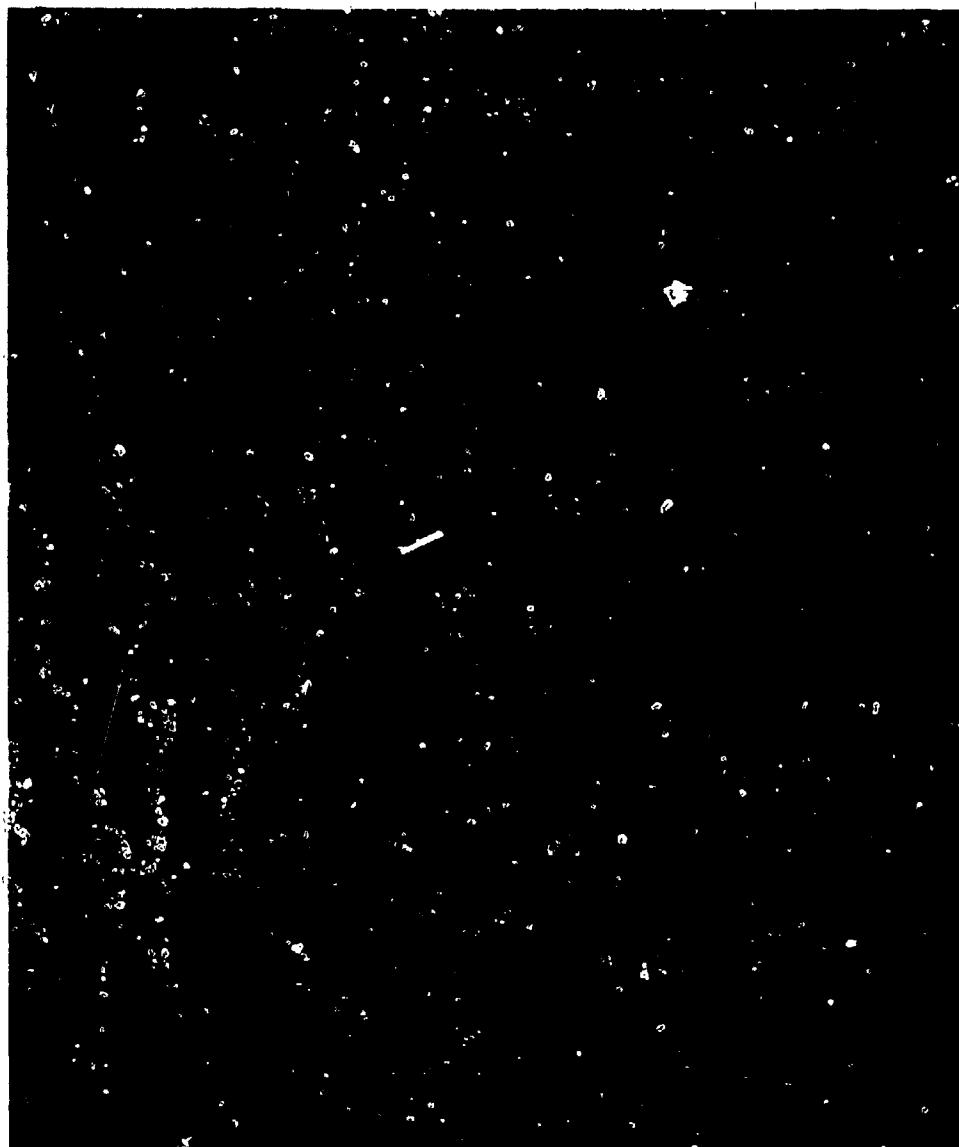


FIGURE 39C RUN 4 BOUNDARY LAYER PHOTO

$$R_{\infty} = 10^{+7} \text{ m}^{-1}$$

$$\alpha = 2.5^{\circ}$$

on the windward side; on the leeward side, no defined layer can be seen so that the flow is probably fully turbulent. The appearance of the boundary layer on the leeward side is such that turbulence extends forward to the position of transducers 1 and 4 at all these Reynolds numbers. On the windward side a forward progression can be seen in the turbulent zone as Reynolds number increases.

SECTION 6

CONCLUSIONS

BLAM sensors were successfully fabricated to meet the environmental requirements of an actual RV and were installed on schedule in both the PVM & STM vehicles. The 2.54 cm diameter sensor was characterized as having resonant peaks at 50, 113, and 168 kHz when installed on a carbon phenolic heatshield with 1.27-cm thickness. The smaller sensor developed for STM-12 application exhibited resonance peaks at 40, 80, 220, and 280 kHz. The BLAM electronics were designed to have nearly a five-order-of-magnitude dynamic range by utilizing a logarithmic technique. This amplifier permits recording of acoustic data not heretofore obtained in flight tests.

All PVM and STM-12 BLAM units successfully passed the flight qualification tests with no failures. The reliability of these units was also established by the flight test results in which 100% data were obtained.

Wind tunnel tests were partially successful and showed that the BLAM and heating rate sensors responded similarly to the boundary layer transition. In addition, the sensors produced an output which fluctuated with the aspect angle on a spinning sharp nose model. Because this output occurred on the leeside of the model, the conclusion was made that transition was being detected.

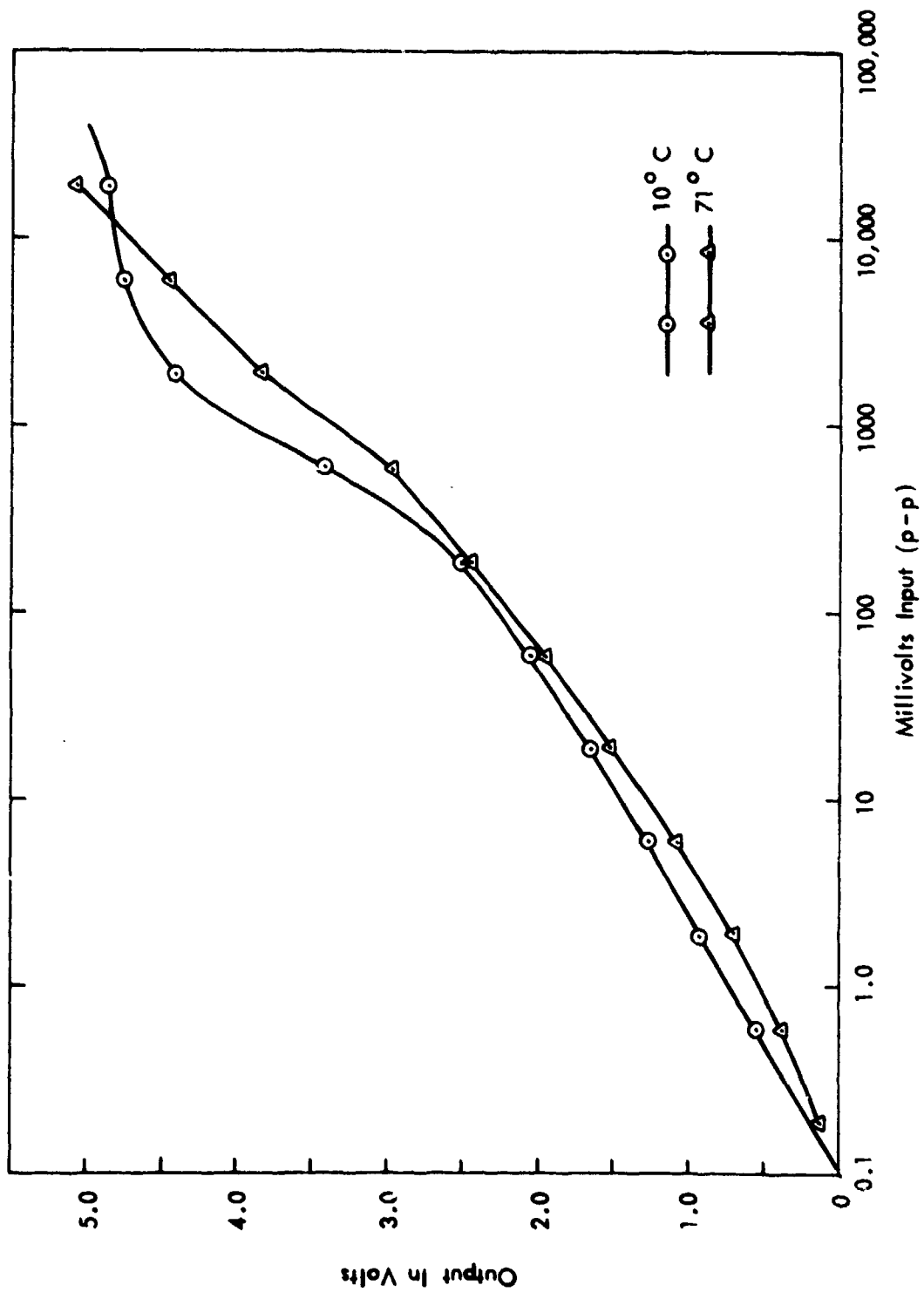
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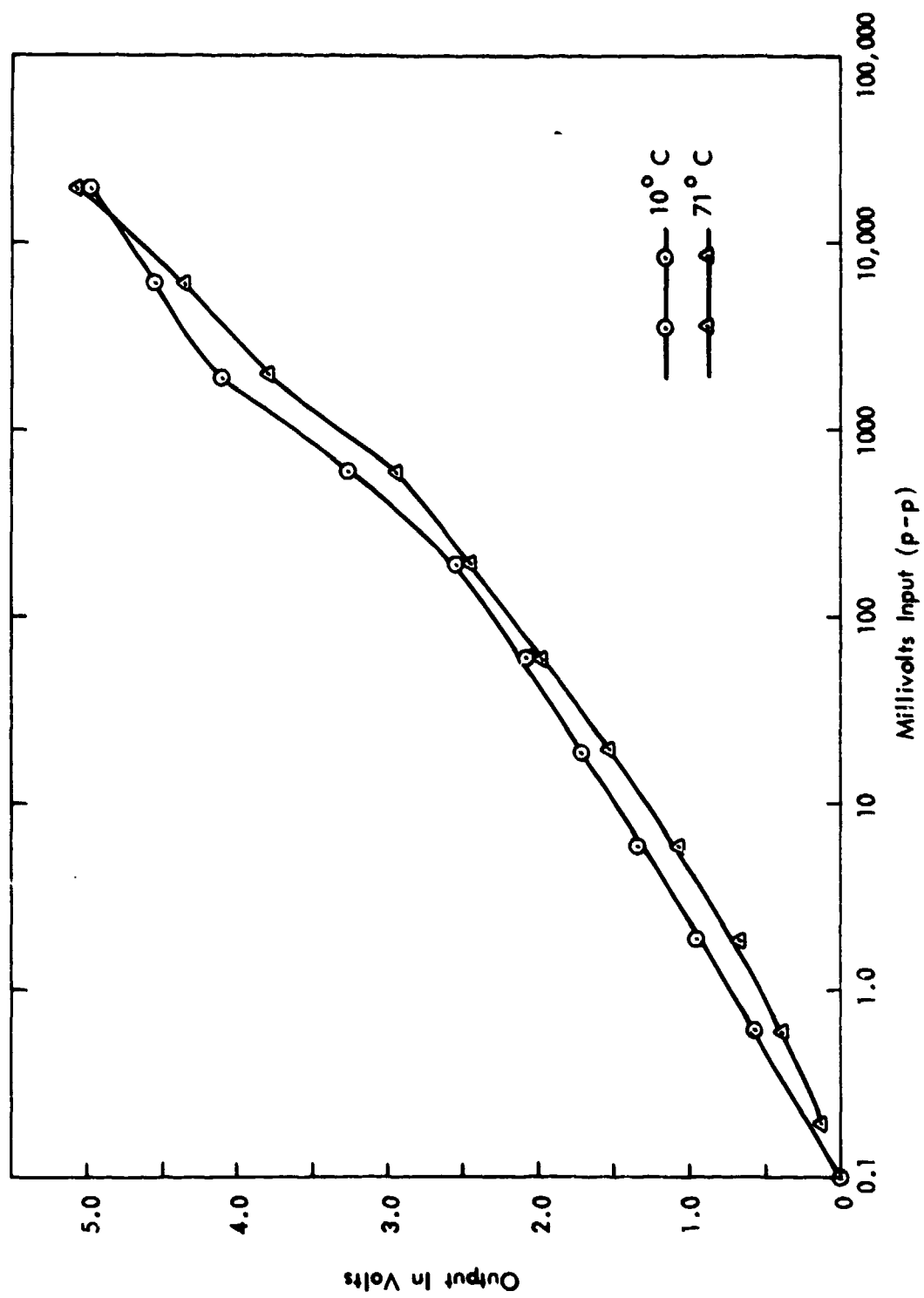
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8. Jackson, R. Flight Proof Tests of the Boundary Layer Acoustic Monitor, K-75-88U(R) Kaman Sciences Corp., 2 Oct. 1975.
9. Specification for Boundary Layer Acoustic Monitor Set, Kaman Sciences Corp. October 1975.
10. Jackson, R. Flight Proof Tests of the Boundary Layer Acoustic Monitor, NM-4 Transducer, K-76-119U CR), October 20, 1976.

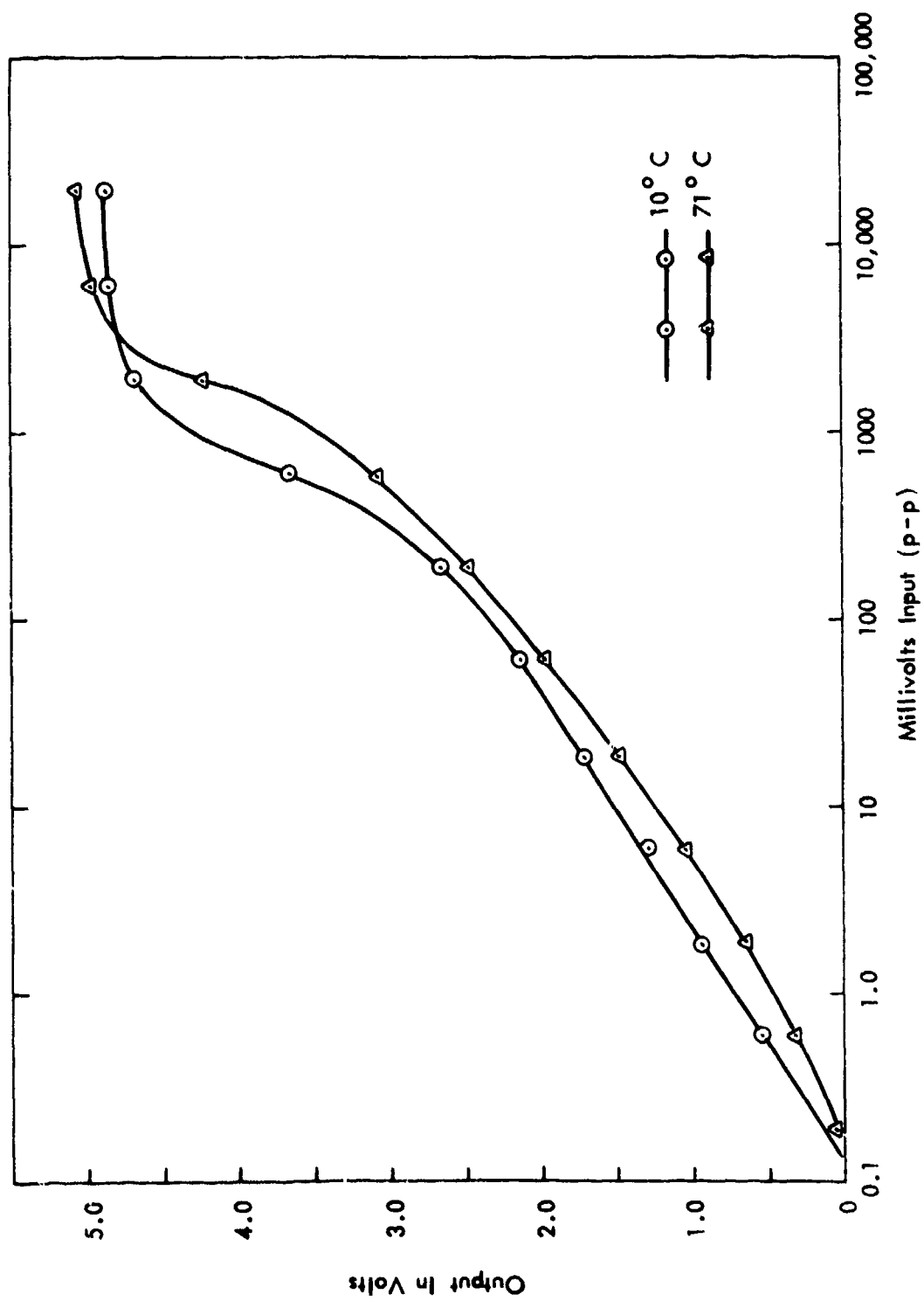
APPENDIX A
PVM AND STM
BLAM CALIBRATION CURVES



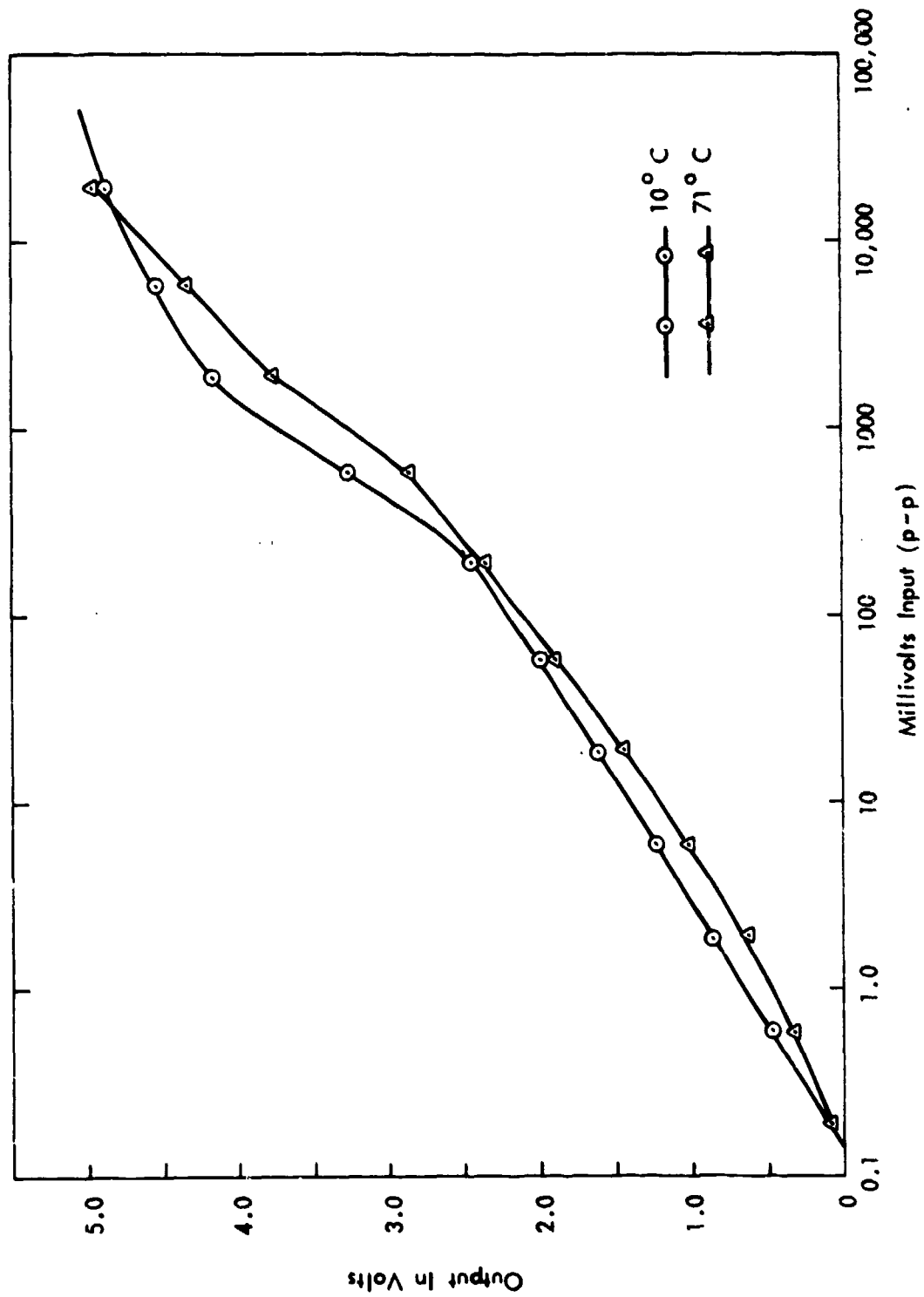
AM-2, SERIAL NUMBER 9
FIGURE 40 PVM BLAM CALIBRATION



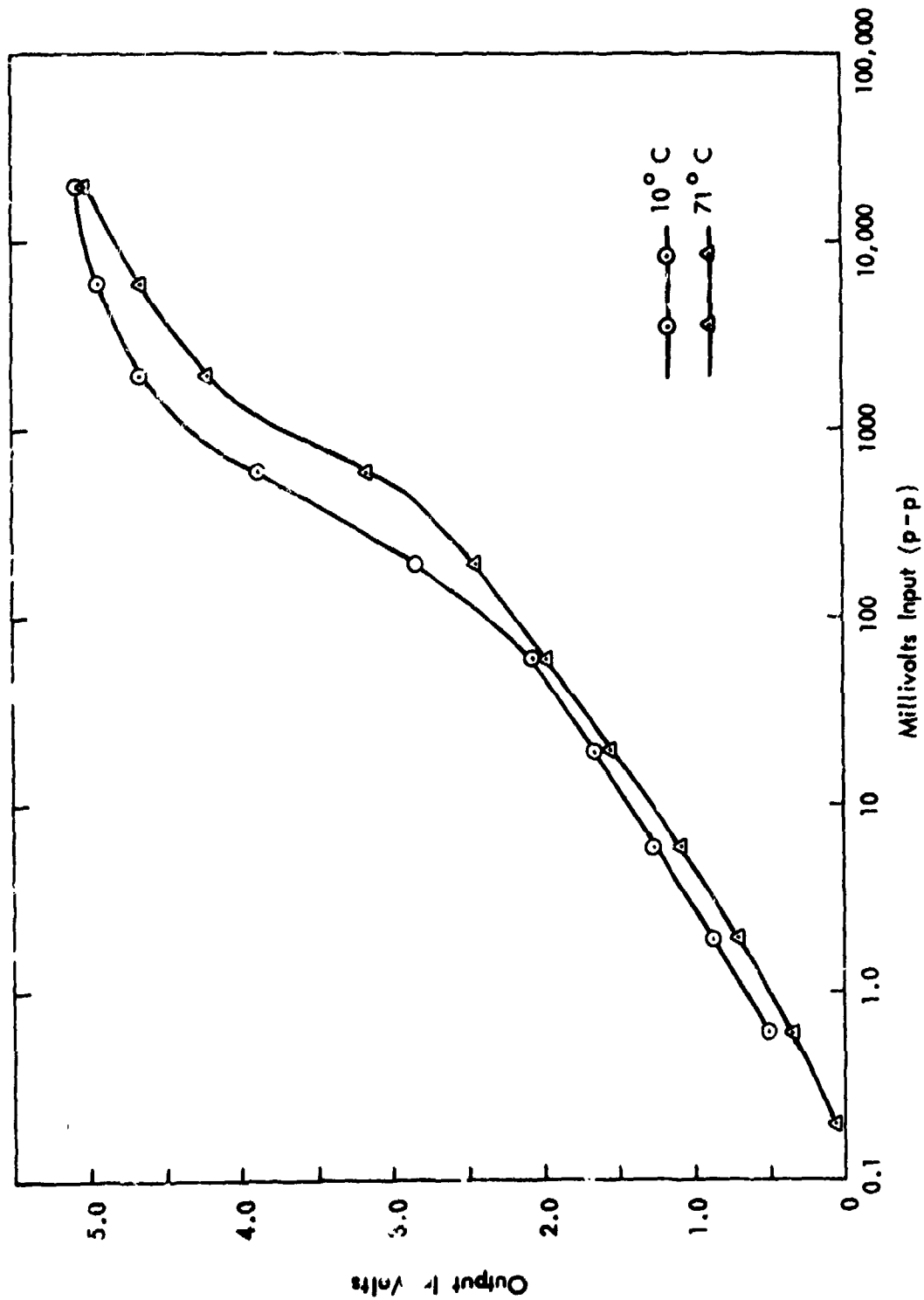
AM-2, SERIAL NUMBER 10
FIGURE 41 PVM BLAM CALIBRATION



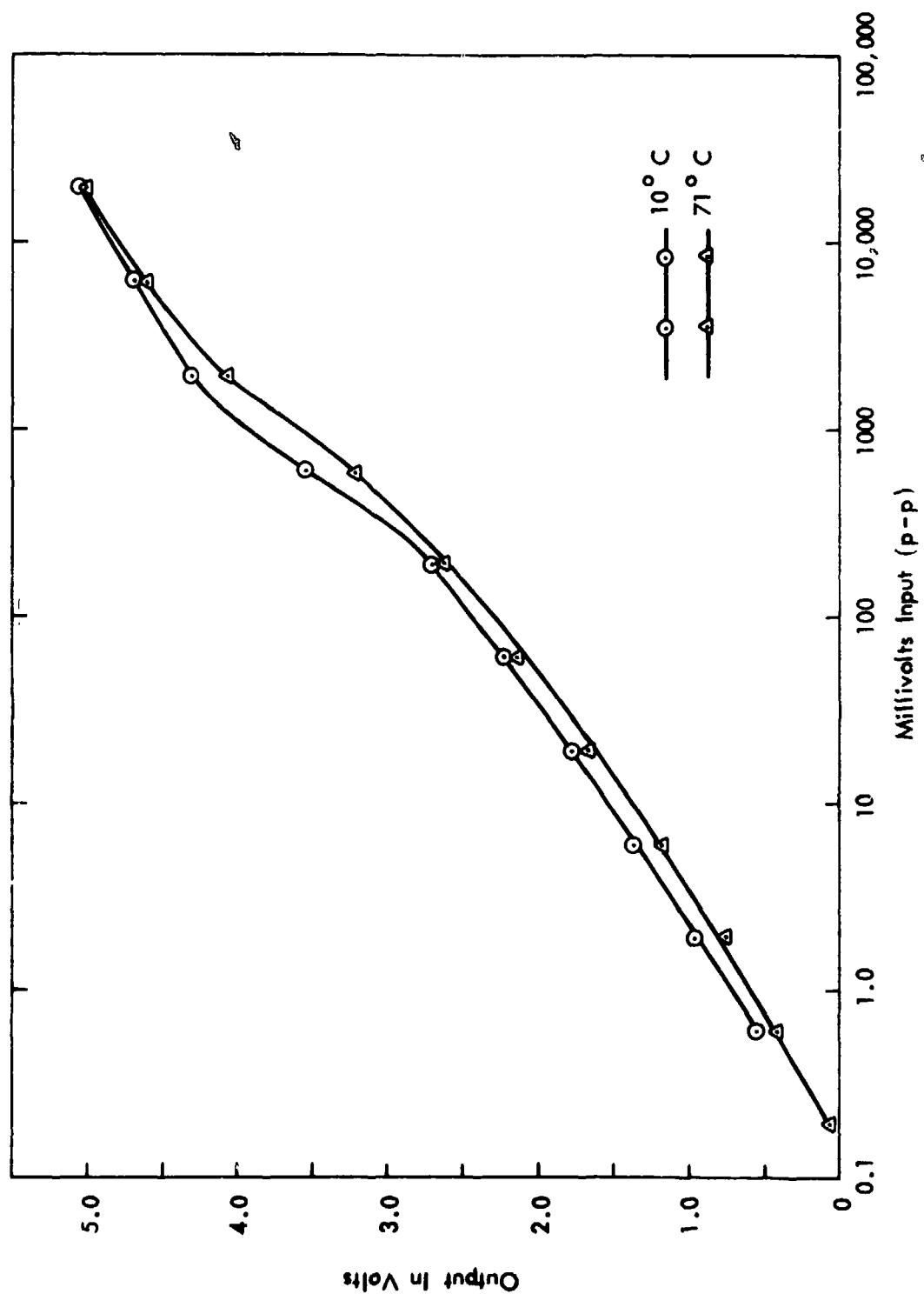
AM-2, SERIAL NUMBER 11
FIGURE 42 PVM BLAM CALIBRATION



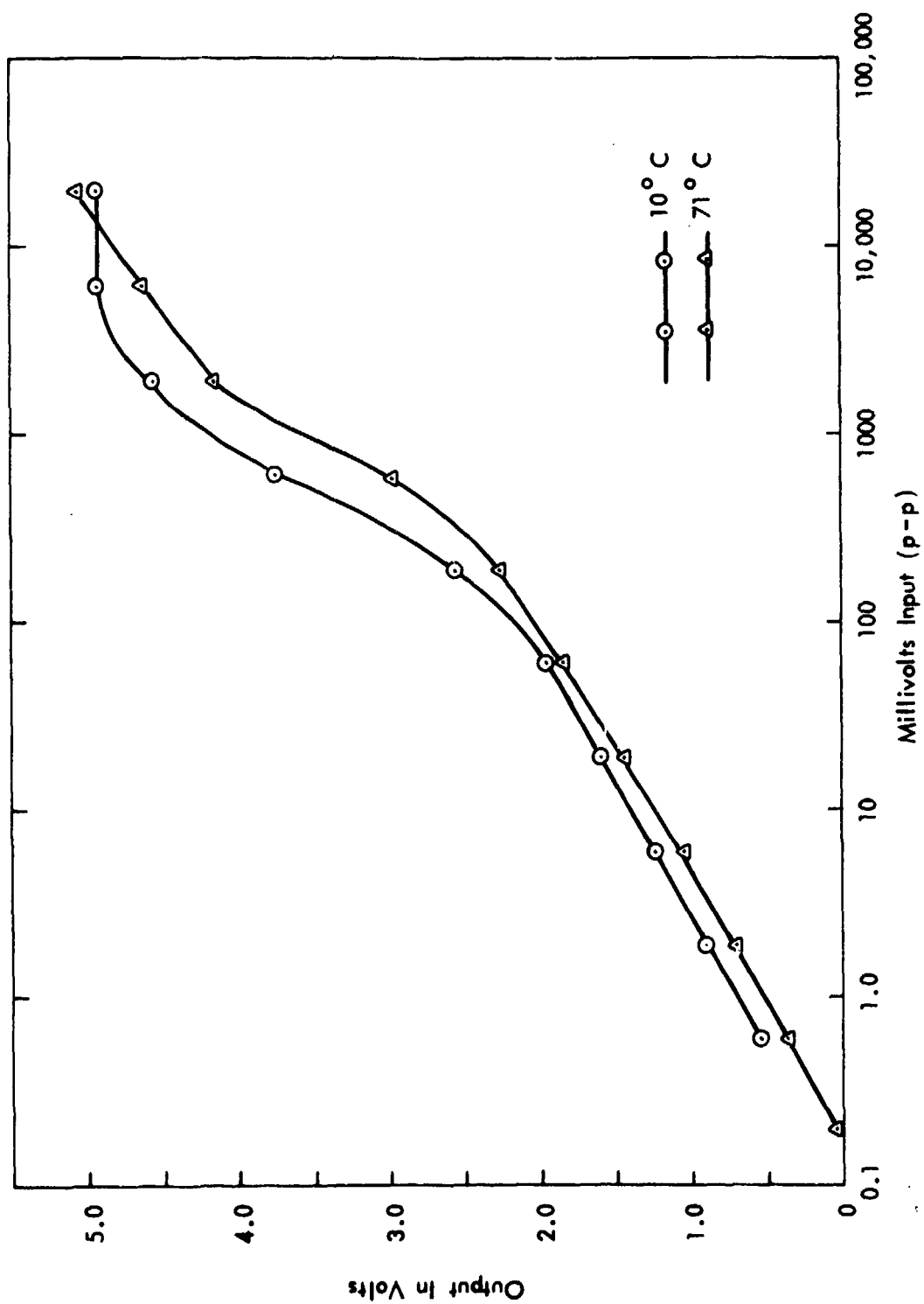
AM-2, SERIAL NUMBER 12
FIGURE 43 PVM BLAM CALIBRATION



AM-2, SERIAL NUMBER 13
FIGURE 44 PVM BLAM CALIBRATION

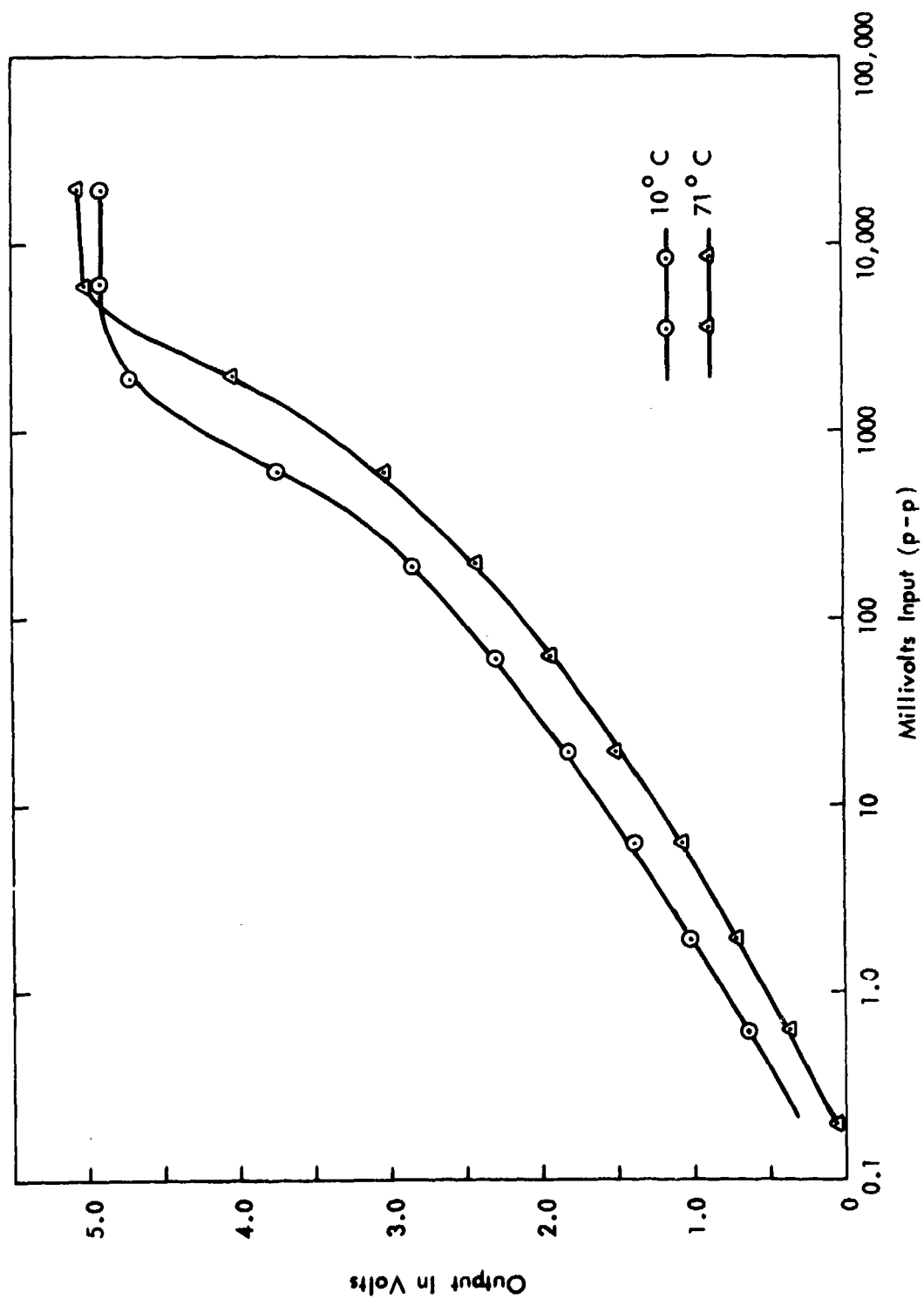


AM-2, SERIAL NUMBER 14
FIGURE 45 PVM BLAM CALIBRATION

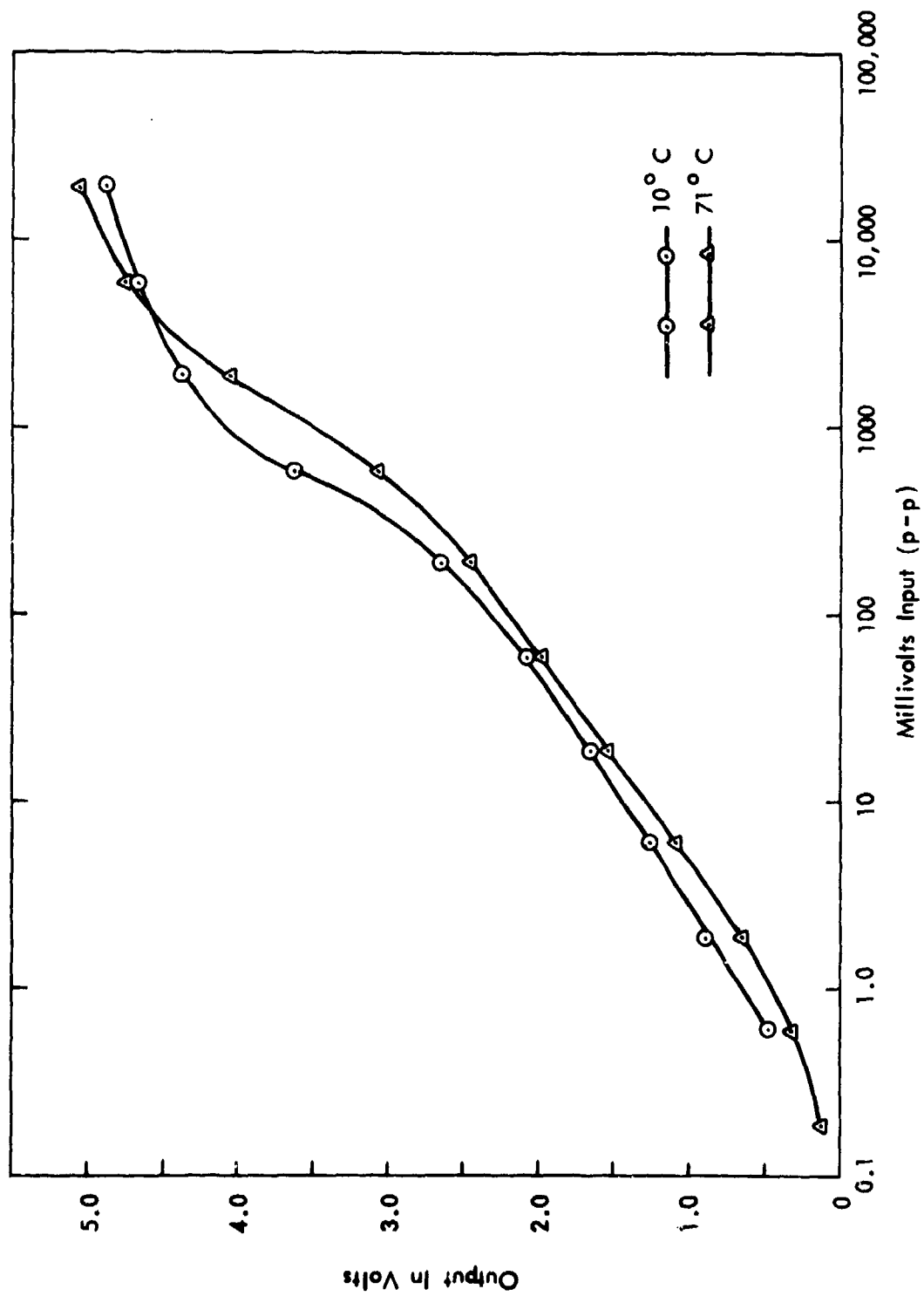


AM-2, SERIAL NUMBER 15

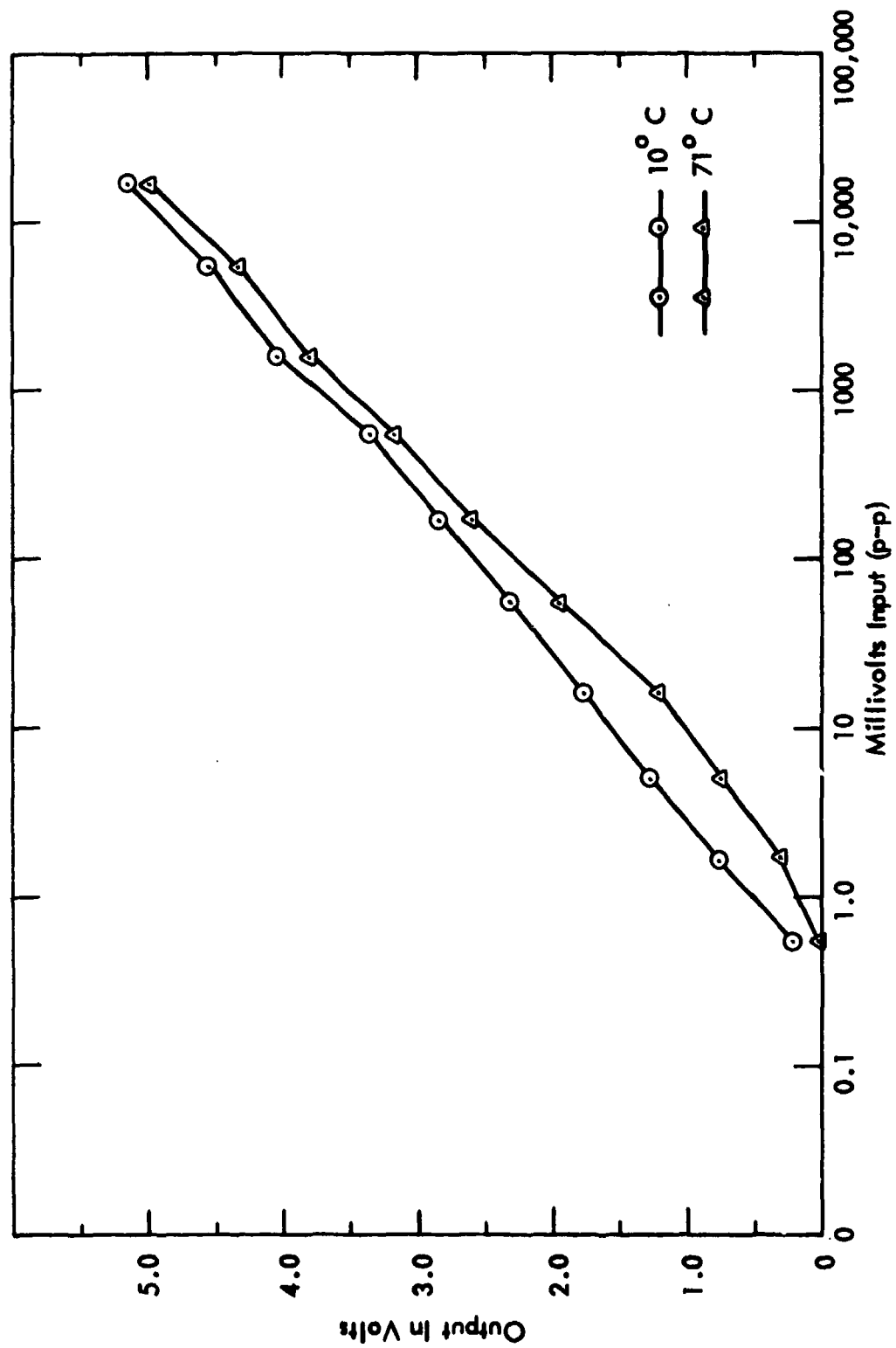
FIGURE 46 PVM BLAM CALIBRATION



AM-2, SERIAL NUMBER 16
FIGURE 47 PVM BLAM CALIBRATION

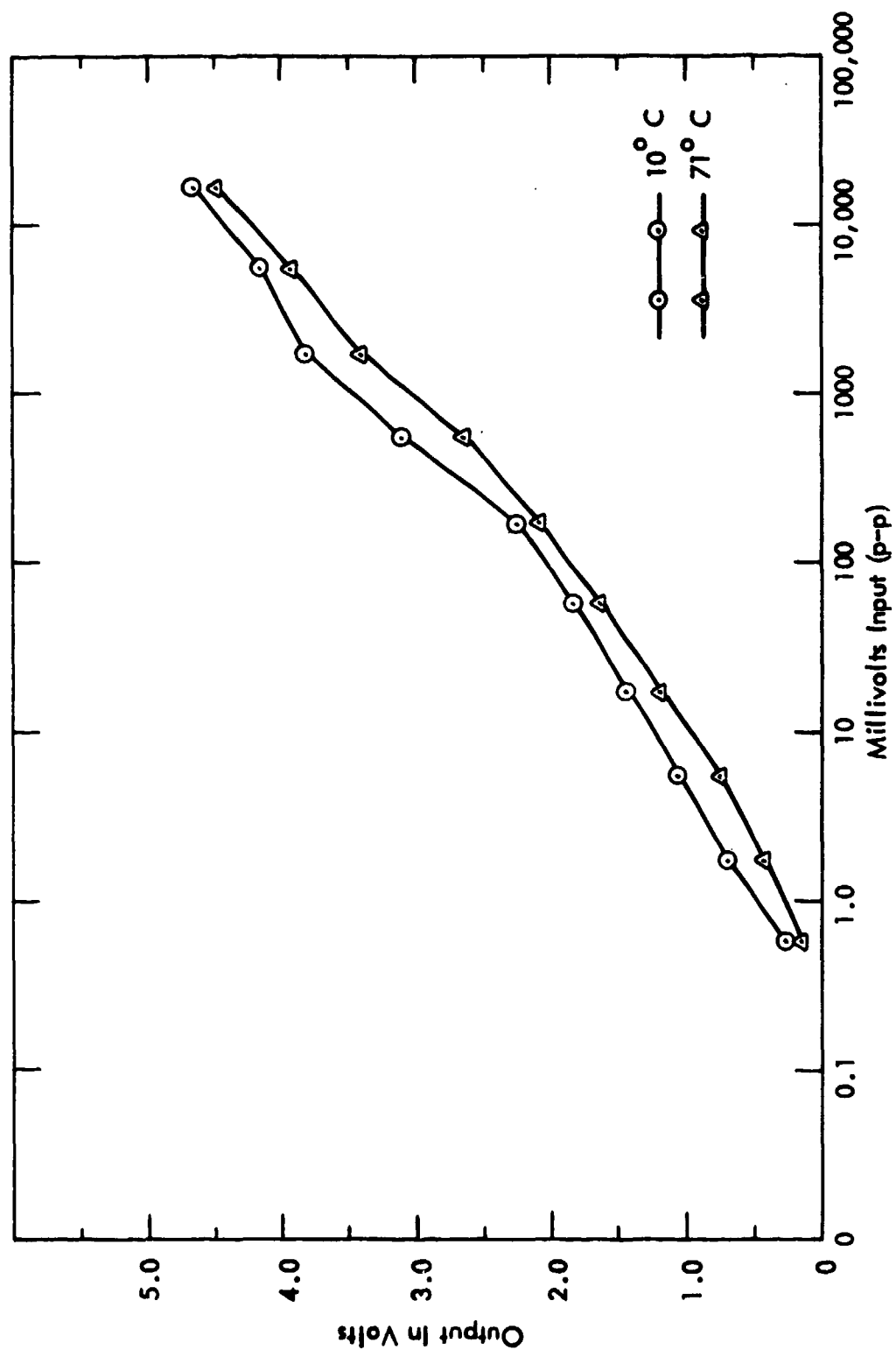


AM-2, SERIAL NUMBER 17
FIGURE 48 PVM BLAM CALIBRATION



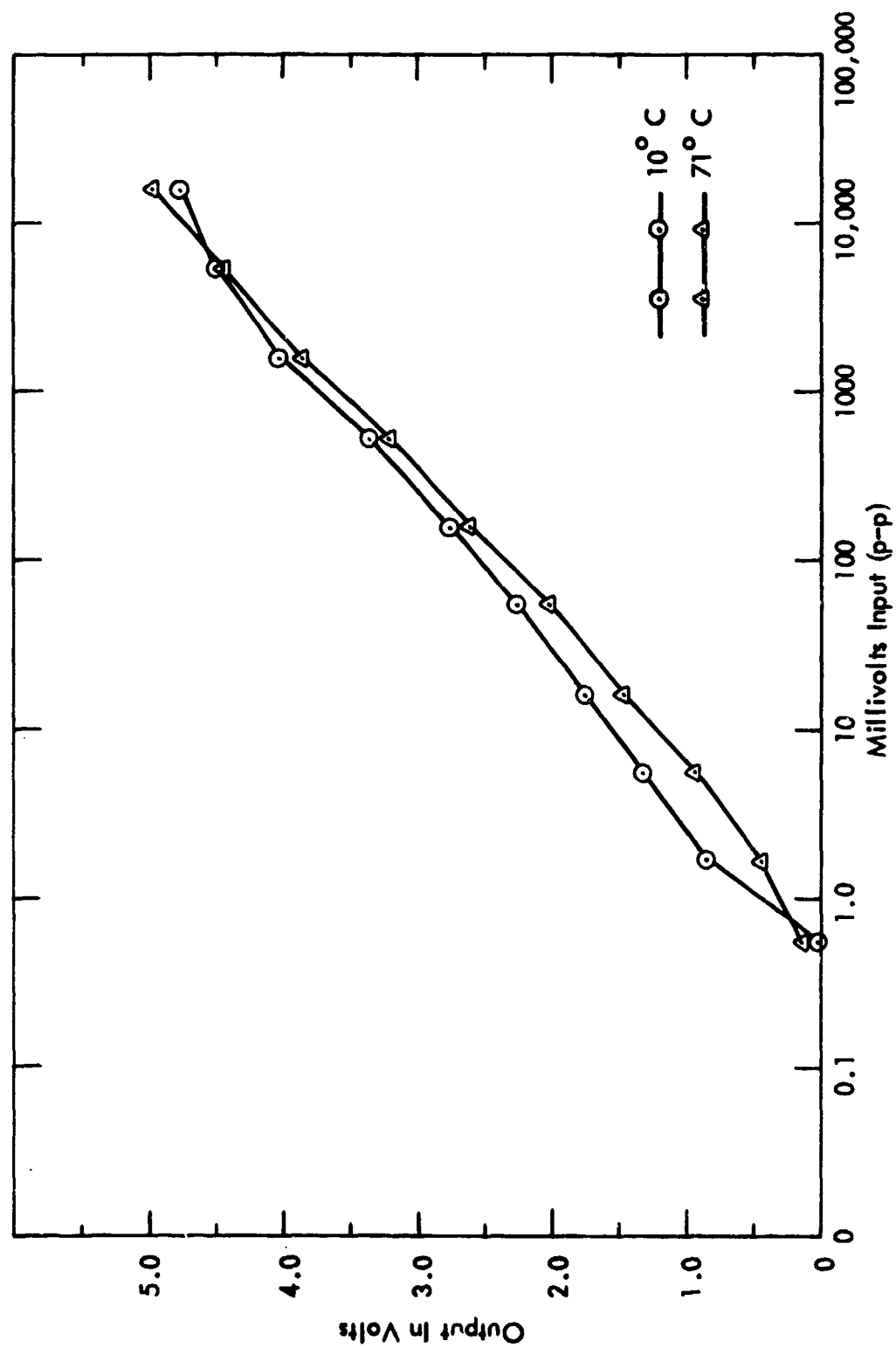
AM-2, SERIAL NUMBER 18

FIGURE 49 STM 12 BLAM CALIBRATION



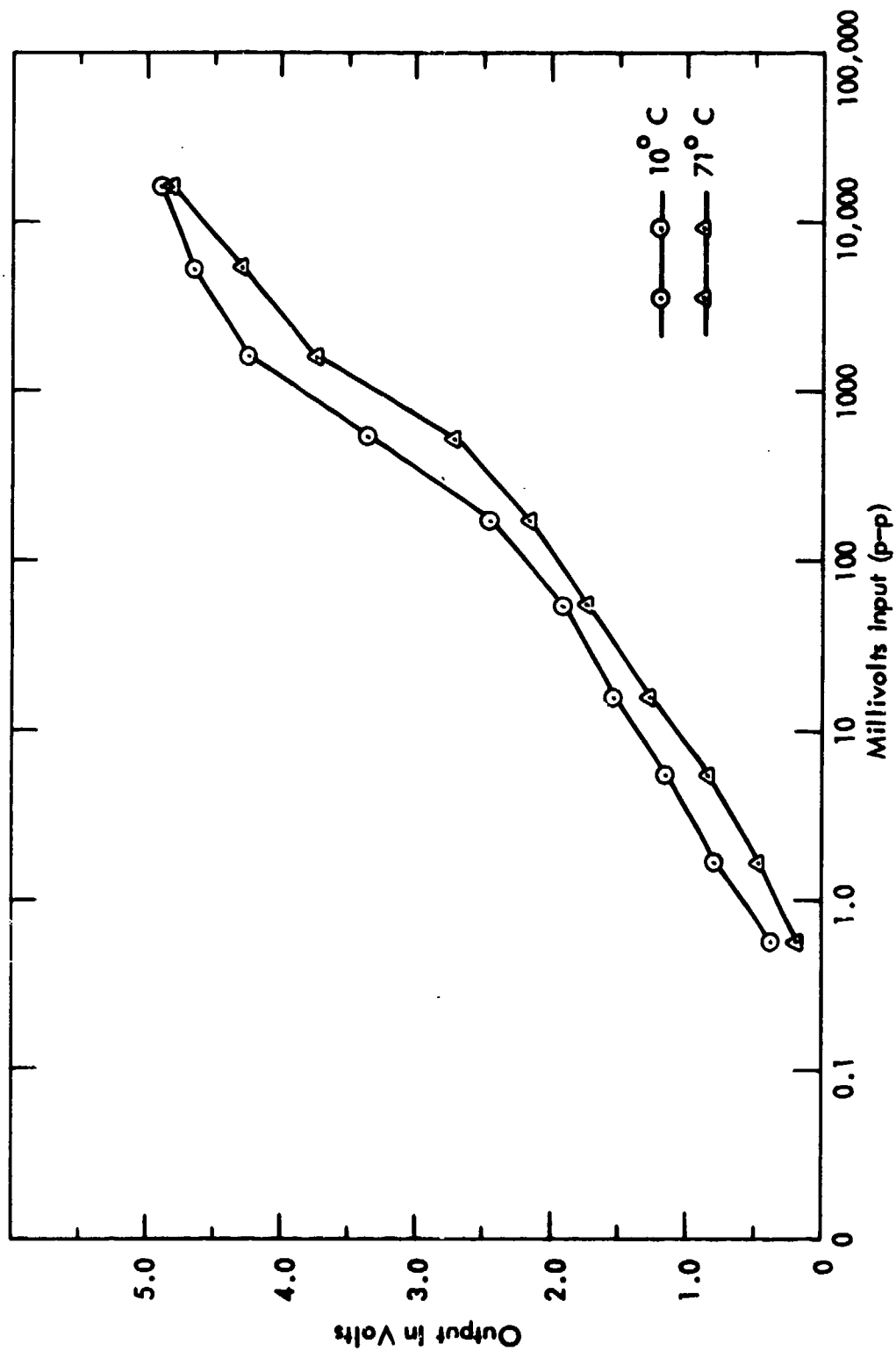
AM-2, SERIAL NUMBER 19

FIGURE 50 STM 12 BLAM CALIBRATION



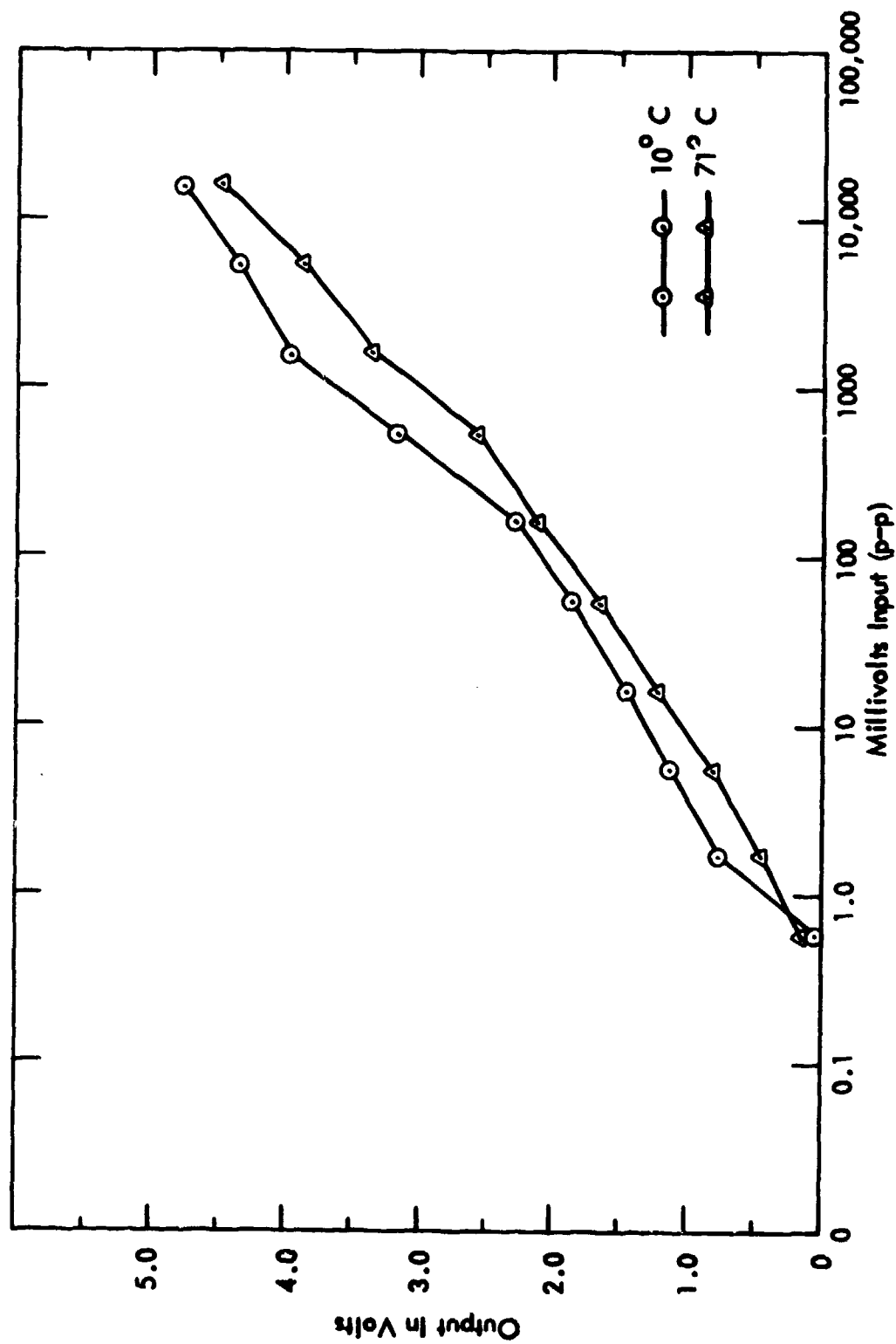
AM-2, SERIAL NUMBER 20

FIGURE 51 STM 12 BLAM CALIBRATION



AM-2, SERIAL NUMBER 22

FIGURE 52 STM 12 BLAM CALIBRATION



AM-2, SERIAL NUMBER 23

FIGURE 53 STM 12 BLAM CALIBRATION

APPENDIX B
RUN 3 SCHLEIREN PHOTOS

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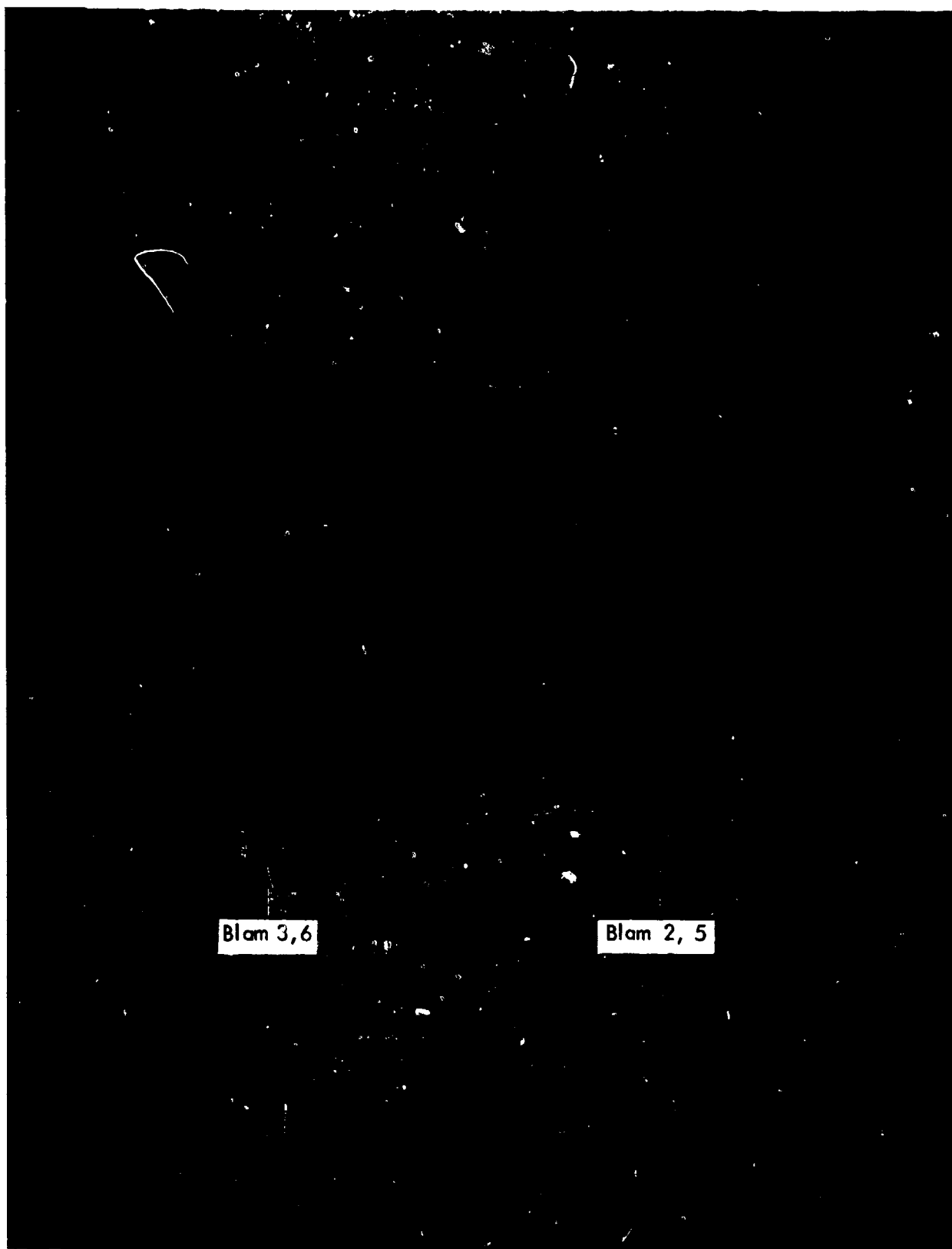


FIGURE 54 RUN 3 SCHLEIREN PHOTO
 $R_{\text{m}} = 3 \times 10^6 / \text{meter}$
Run Time = 5.7 sec.

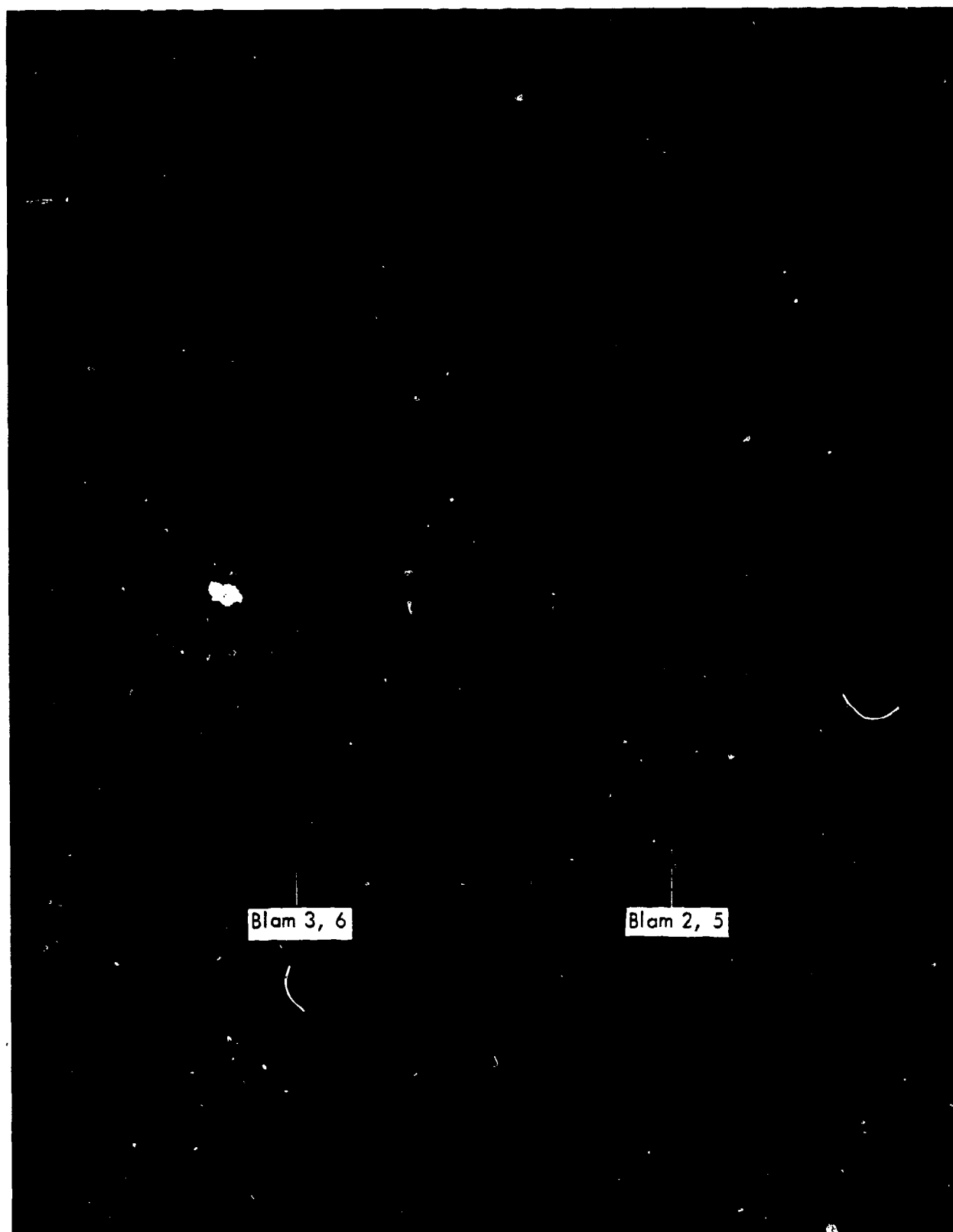


FIGURE 55 RUN 3 SCHLEIREN PHOTO
 $R_{\infty} = 4 \times 10^6/\text{meter}$
Run Time = 7.6 sec.

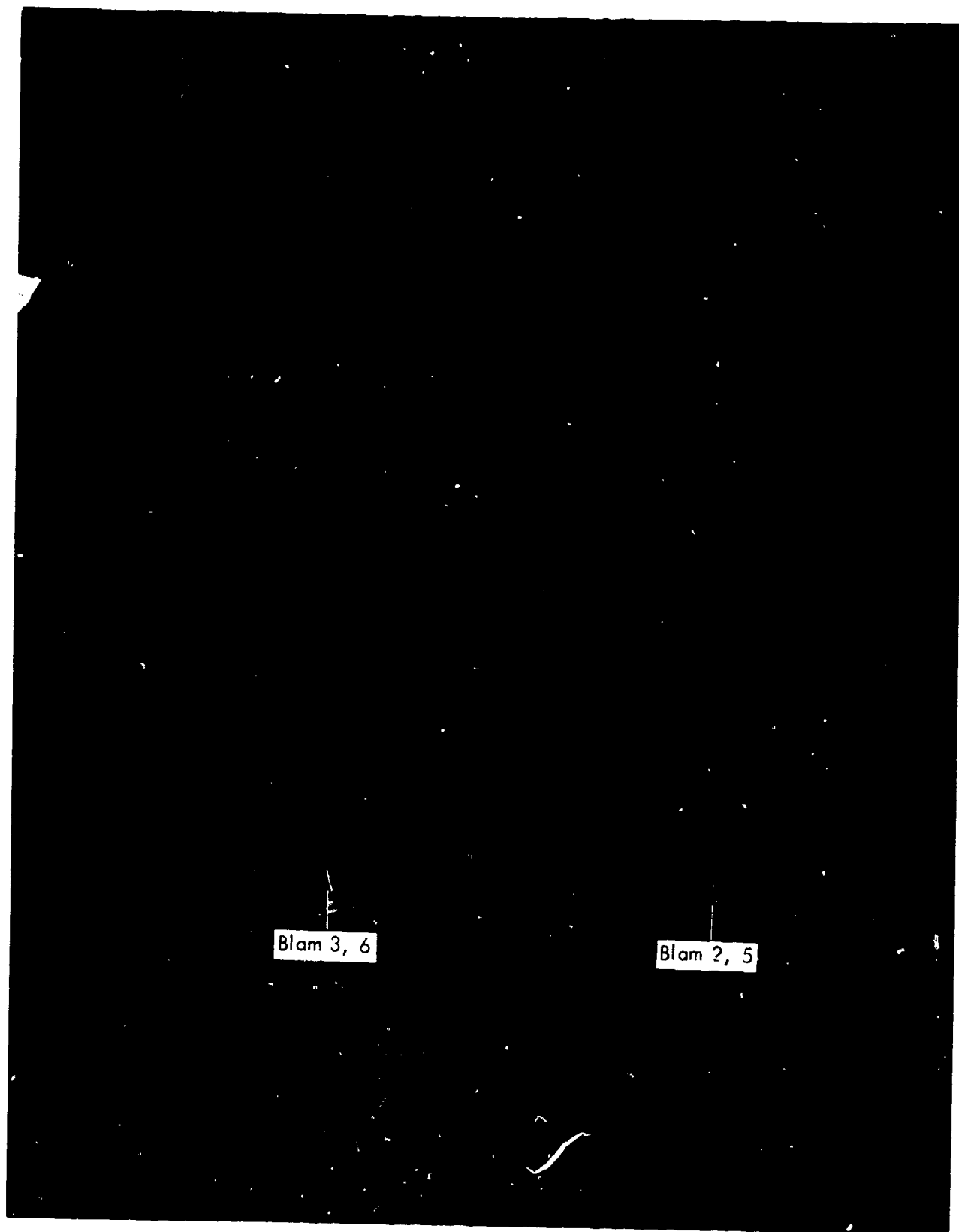


FIGURE 56 RUN 3 SCHLEIREN PHOTO
 $R_{\infty} = 5.6 \times 10^6/\text{meter}$
Run Time = 10 sec.

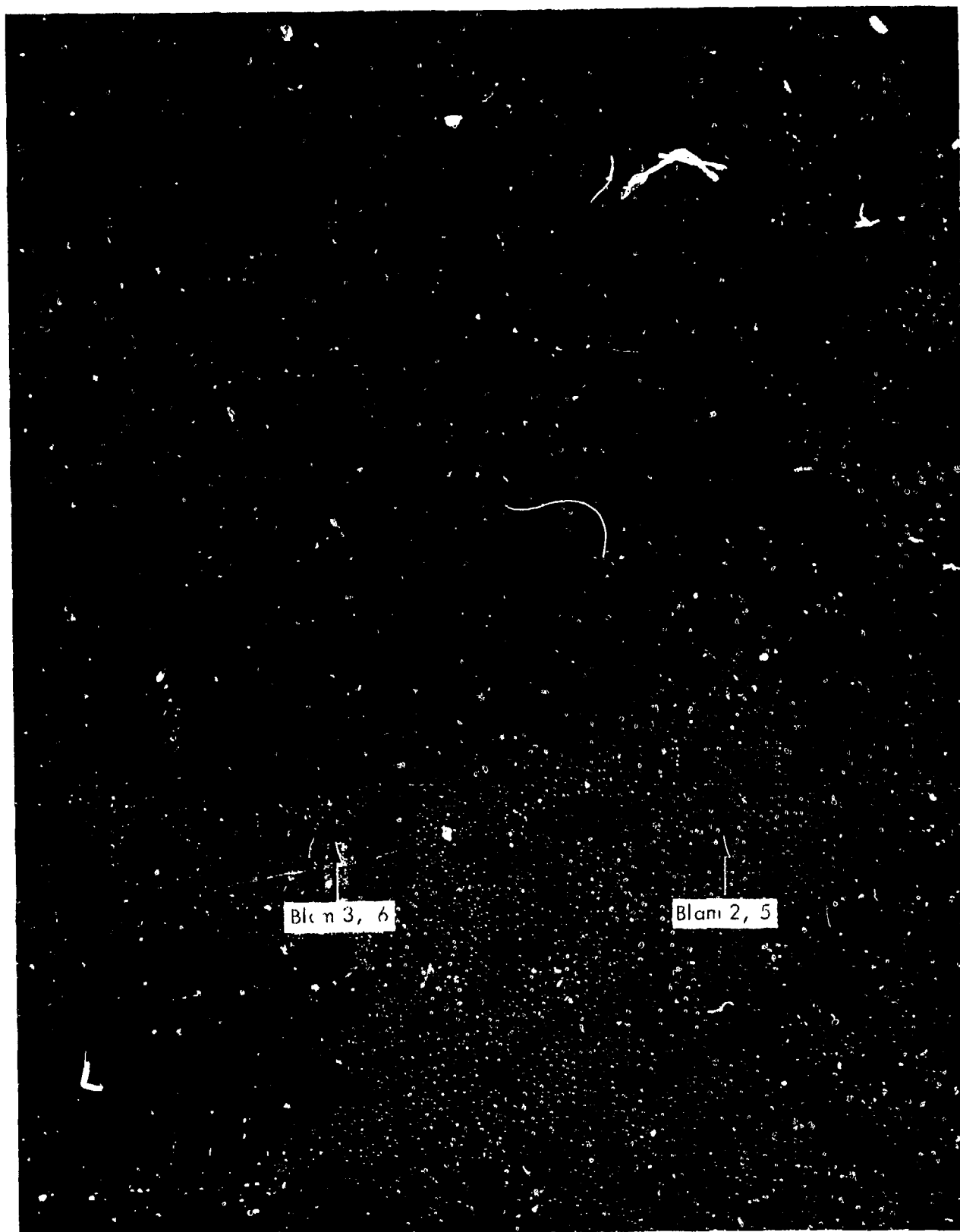


FIGURE 57 RUN 3 SCHLEIREN PHOTO
 $R_{\infty} = 7.2 \times 10^6/\text{meter}$
Run Time = 12 sec.

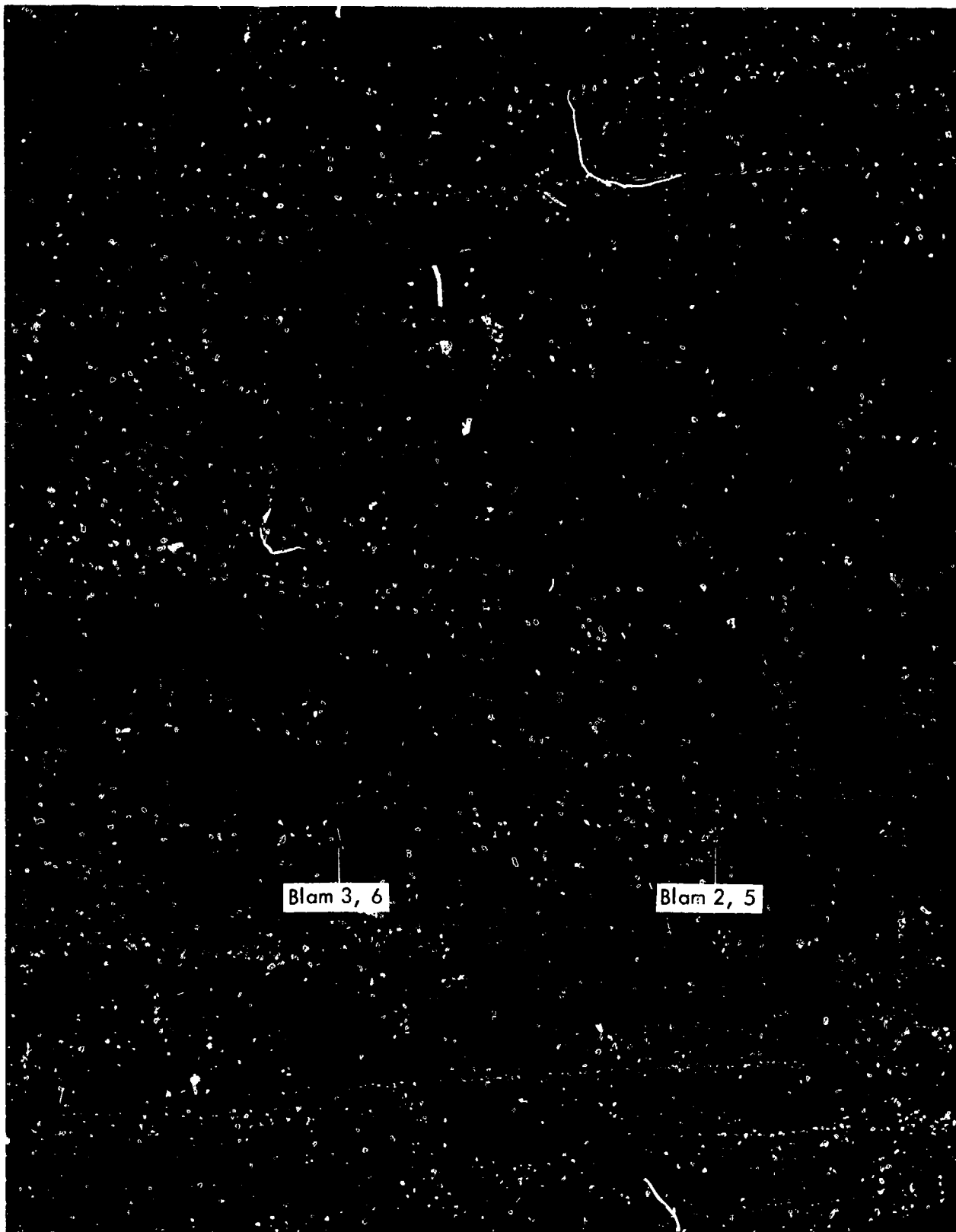


FIGURE 58 RUN 3 SCHLEIREN PHOTO

$K_{\Delta} = 12.5 \times 10^6 / \text{meter}$

Run Time = 19 sec.



FIGURE 59 RUN 3 SCHLEIREN PHOTO

$R_{\infty} = 14.5 \times 10^6/\text{meter}$

Run Time = 26 sec.

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