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WIND TUNNEL TESTS OF SPACE SHUTTLE EXTERNAL TANK INSULATION MATERIAL IN THE AEROTHERMAL TUNNEL AT ELEVATED (1440°F) TOTAL TEMPERATURES

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Calspan Field Services, Inc.

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APPROVAL STATEMENT

This report has been reviewed and approved.

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Approved for publication:

FOR THE COMMANDER

J M Rampy

JOHN M. RAMPY, Director
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Wind tunnel tests of the space shuttle External Tank Foam Insulation were conducted in the von Karman Gas Dynamics Facility Tunnel C. For these tests, Tunnel C was run at Mach 4 with a total temperature of 1440 °F and a total pressure which varied from 30-100 psia. Cold wall heating rates were changed by varying the test article support wedge angle and by adding and removing a shock generator or a cylindrical protuberance. Selected results are presented to illustrate the test techniques and typical data obtained.

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NOMENCLATURE

ALPHI	Indicated pitch angle, deg
b, (THICK)	Model skin thickness, in.
c	Model material specific heat, Btu/lbm-°R
C1	Laboratory gage calibration factor, Btu/ft^2-sec-mv
C2	Temperature corrected gage calibration factor, Btu/ft^2-sec-mv
CAL	Calibration
CAMERA	Denotes camera locations: TOP - top of tunnel, OS - operating side of tunnel (right side looking downstream) SHG - Shadowgraph
CP	Free-stream specific heat, Btu/lbm-°R
CR	Center of rotation, axial station along the tunnel centerline about which the model rotates in pitch, in.
DTW/DT	Derivative of the model wall temperature with respect to time, °R/sec
E	Gardon gage output, mv
fps	Frames per sec
H(TRT)	Heat transfer coefficient based on the theoretical recovery temperature for turbulent flow (TRT), QDOT/(TRT-TW), Btu/ft^2-sec-°F
H(TT)	Heat transfer coefficient based on TT, QDOT/(TT-TW), Btu/ft^2-sec-°F
ITT	Enthalpy based on TT, Btu/lbm
KG	Gardon gage temperature calibration factor, °R/mv
M	Free-stream Mach number
MU	Dynamic viscosity based on free-stream temperature, lbf-sec/ft^2

P	Free-stream static pressure, psia
PIC NO	Picture number, corresponds to number on each frame of contact print XXXX - XXX RUN NUMBER FRAME NUMBER
PROTUB	Protuberance number
PT	Tunnel stilling chamber pressure, psia
Q	Free-stream dynamic pressure, psia
QDOT	Heat flux, Btu/ft^2-sec
QDOT-O	Cold wall (i.e., 0°F) heat flux calculated from QDOT = H(TT)(TT-460), Btu/ft^2-sec
RE	Free-stream Reynolds number, ft^{-1}
RHO, ρ	Free-stream density, lbm/ft^3
ROLL NO	Identification number for each roll of film
RUN	Data set identification number
SAMPLE	Specimen number
SGA	Shock generator angle, deg (see Fig. 3b)
ST	Stanton number based on TT and free stream conditions, H(TT)/(RHO*V*CP)
STREX.2	Heat transfer correlation parameter $ST(RE*X)^{0.2}$
T	Free-stream static temperature, °R
T/C	Thermocouple identification number
TGE	Gardon gage edge temperature, °R
TGDEL	Temperature differential from the center to the edge of Gardon gage disc, °R
TI	Initial wall temperature
TIME	Elapsed time from lift-off, sec
TIMECL	Time at which the model reached tunnel centerline, Central Standard Time

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TIMEEXP	Time of exposure to the tunnel flow when the data were recorded, [TIME - $\frac{32}{57}$ (TIMEINJ)], sec
TIMEEXPT	Total exposure time for a RUN, sec
TIMEINJ	Elapsed time from lift-off to arrival at tunnel centerline, sec
TP	Wedge plate temperature, °R
TT	Tunnel stilling chamber temperature, °R
TW	Model surface temperature, °R
V	Free-stream velocity, ft/sec
WA	Wedge angle, deg (see Fig. 3)
X, Y, Z	Orthogonal body axis system directions (see Fig. 3)

1.0 INTRODUCTION

The work reported herein was performed by the Arnold Engineering Development Center (AEDC), Air Force Systems Command (AFSC), under Program Element 921E02, Control Number 9E02, at the request of the National Aeronautics and Space Administration (NASA), Marshall Space Flight Center (MSFC), Huntsville, Alabama for the Martin Marietta Corporation (Michoud Operations), New Orleans, Louisiana. The Martin Marietta Corporation project engineer was Mr. S. Copsey and the NASA/MSFC project manager was Mr. L. Foster. The results were obtained by Calspan Field Services, Inc./AEDC Division, operating contractor for the Aerospace Flight Dynamics testing effort at the AEDC, AFSC, Arnold Air Force Station, Tennessee. The test was performed in the von Karman Gas Dynamics Facility (VKF), Hypersonic Wind Tunnel (C), in two entries on April 12, 1982 and August 27, 1982 under AEDC Project No. C739VC (Calspan No. V41C-1P).

The objective of this test was to measure the response to convective and interference heating of the material used on the space shuttle's External Tank Thermal Protection System (ET-TPS) at a total temperature in excess of 1860°R (1400°F). The wedge technique with a shock generator was used to produce an augmented local heating rate. Data from this test will be used to evaluate a possible reduction in weight of the space shuttle external tank by reducing the amount of insulative material or replacing it with a lighter material.

Data were recorded at Mach number 4 with tunnel stilling chamber pressures of 30-100 psia at a stilling chamber temperature of 1900°R (1440°F). The cold wall heating rates of 0.5 to 25.0 Btu/ft^2-sec were obtained by varying the nominal wedge angle (WA) and by adding or removing a shock generator.

All test data including detailed logs and other information required to use the data have been transmitted to the user and sponsor as described in Table 1. Inquiries to obtain copies of the test data should be directed to NASA/MSFC/ED33, Marshall Space Flight Center, Huntsville, Alabama, 35812. A microfilm record has been retained in the VKF at AEDC.

2.0 APPARATUS

2.1 TEST FACILITY

The Mach 4 Aerothermal Tunnel C is a closed-circuit, high temperature, supersonic free-jet wind tunnel with an axisymmetric contoured nozzle and a 25 in.-diam nozzle exit, Fig. 1. This tunnel utilizes parts of the Tunnel C circuit (the electric air heater, the Tunnel C test section and injection system) and operates continuously over a range of pressures from nominally 15 psia at a minimum stagnation temperature of 710°R to 180 psia at a maximum temperature of 1570°R. Using the normal Tunnel C Mach 10 circuit (Series Heater Circuit), the Aerothermal Mach 4 nozzle operates at a maximum pressure and temperature of 100 psia and 1900°R, respectively. The air temperatures and pressures are normally achieved by mixing high temperature air (up to 2250°R) from the primary flow discharged from the electric heater with the bypass air flow (at 1440°R) from the natural gas-fired heater. The primary and the bypass air flows discharge into a mixing chamber just upstream of the Aerothermal Tunnel stilling chamber. The entire Aerothermal nozzle insert (the mixing chamber, throat and nozzle sections) is water cooled by integral, external water jackets. Since the test unit utilizes the Tunnel C model injection system, it allows for the removal of the model from the test section while the free-jet tunnel remains in operation. A description of the Tunnel C equipment may be found in the Test Facilities Handbook, Ref. 1.

2.2 TEST ARTICLE

The test article was designed to simulate the flow conditions over a section of material used on the ET-TPS. To provide the desired flow conditions over the material, the wedge technique developed for material testing was used. The oblique shock wave generated by the wedge reduces the free stream flow properties to the desired flow conditions. The flow field conditions over the wedge can be controlled by changing the wedge angle and, if desired, by adjusting the tunnel stilling chamber conditions.

The test article was supported by a sting which was attached to the Tunnel "C" mounting hardware. An installation photograph and sketch of the fixture in Tunnel C are shown in Fig. 2. The test article is comprised of three parts: testing wedge, shock generator, and material specimen, and is shown in Fig. 3. The testing wedge is a 12 in. x 34 in. long wedge. Mounted to the wedge were three rows of 0.032 in. diam boundary layer trip spheres. Placement and orientation of spheres are shown in Fig. 3. A detachable shock generator was used on some runs to provide augmented heating rates on the material specimen. The shock generator angle could be varied between 0° and 25° in increments of 5°, to change the position of the interference region. A thin-skin calibration plate was used with the shock generator to obtain heat transfer levels at a total temperature of 1900°R (1440°F). This plate is shown in Fig. 4. For a complete list of material specimens see Table 2. A typical test specimen consisted of a 12 in. x 10 in. x 0.125 in. aluminum support plate covered with a 1.0 ± 0.25 in. layer of spray-on foam insulation (SOFI) or a 0.50 ±0.05 in. layer of super light ablator (SLA). On a few specimens the SOFI was removed in a 14.0 in. x 4.0 in. area and replaced by a repair patch of different material Two specimens tested the lighting protection system and one specimen had a 5.0 in. diam x 3.0 in. tall cylindrical protuberance. Two 5.0 in. diam x 3.0 in. tall cylindrical protuberance specimens were mounted to a 12 in. x 20 in. x 0.625 in., 321 SST plate. Several 12 in. x 10 in. x 0.50 in. specimens of SLA-561 were also run. Examples of the material specimens are shown in Fig. 5.

2.3 TEST INSTRUMENTATION

The instrumentation, recording devices, and calibration methods used to measure the primary tunnel and test data parameters are listed in Table 3a along with the estimated measurement uncertainties. The range and estimated uncertainties for primary parameters that were calculated from the measured parameters are listed in Table 3b.

A variety of cameras was used to record the test results. Color motion pictures (2 cameras) and 70mm sequence color stills recorded any changes in the samples as they were tested. The movie cameras were operated at frame rates of 24 fps (see Table 4). A shadowgraph still or high speed shadowgraph movie was taken for each run to aid in visualizing the shock wave patterns about the protuberances. A black and white video tape was also made for general coverage during the test. All photographic data taken during the test are identified in Table 4.

During both entries Gardon gages were used to define the heating levels upstream of the test samples. The coordinate locations of the Gardon gages are listed in Table 5a.

The Gardon gages used in the wedge were a special high temperature type, 0.25-in. diam, with a 0.010-in. thick sensing disk. Each gage had a Chromel®-Alumel® thermocouple to provide the gage edge temperature. These temperatures, together with the gage output, were used to determine the gage surface temperatures and corresponding heat transfer rate, which was then used to calculate the local heat transfer coefficient.

The calibration plate temperatures were measured with FE-CN thermocouples. The thermocouple locations are shown in Fig. 4 and their coordinates and corresponding skin thickness are listed in Table 5.

3.0 TEST DESCRIPTION

3.1 TEST CONDITIONS

A summary of the nominal test condition is given below:

Date	M	PT, psia	TT, °R	RUNS
April 1982	4.0	30-100	1900	1-42
August 1982	4.0	30-100	1900	43-99

A test summary showing the configurations tested and the variables for each is presented in Table 6.

3.2 TEST PROCEDURES

In the VKF continuous flow wind tunnels (A, B, C), the model is mounted on a sting support mechanism in an installation tank directly underneath the tunnel test section. The tank is separated from the tunnel by a pair of fairing doors and a safety door. When closed, the fairing doors, except for a slot for the pitch sector, cover the opening to the tank and the safety door seals the tunnel from the tank area. After the model is prepared for a data run, the personnel access door to the installation tank is closed, the tank is vented to the tunnel flow, the safety and fairing doors are opened, the model is injected into the airstream, and the fairing doors are closed. After the data are obtained, the model is retracted into the tank and the sequence is reversed with the tank being vented to atmosphere to allow access to the model in preparation for the next run. The sequence is repeated for each configuration change.

The required local flow conditions over the test specimens are produced by attaching the panel to a large wedge. The oblique shock wave generated by the wedge reduces the free-stream Mach number to the desired local Mach number. Since the free-stream Mach number is fixed, the local Mach number is varied by pitching the wedge. With the free-stream Mach number and the wedge angle defined, the pressure and temperature ratios across the shock wave are established. The pressure and temperature along the wedge surface can then be set as desired by adjusting the tunnel stilling chamber pressure and temperature. A complete description of this technique as used in Tunnel C is given in Ref. 2.

3.3 DATA REDUCTION

Measured stilling chamber pressure and temperature and the calibrated test section Mach number are used to compute the free-stream parameters. The equations for a perfect gas isentropic expansion from stilling chamber to test section are modified to account for real gas effects.

Data measurements obtained from the Gardon gages are gage output (E) and gage edge temperature (TGE). The gages are direct reading heat flux transducers and the gage output is converted to heating rate by means of a laboratory calibrated gage scale factor (C1). The scale factor has been found to be a function of gage temperature and therefore must be corrected for gage temperature changes,

$$C2 = C1\ f(TGE) \tag{1}$$

Heat flux to the gage is then calculated for each data point by the following equation:

$$QDOT = (E)(C2) \tag{2}$$

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The gage wall temperature used in computing the gage heat-transfer coefficient is obtained from two measurements - the output of the gage edge thermocouple (TGE) and the temperature difference (TGDEL) from the gage center to its edge. TGDEL is proportional to the gage output, E, and is calculated by:

$$TGDEL = (KG)(E) \tag{3}$$

The gage wall temperature is then computed as

$$TW = TGE + 0.75\ TGDEL \tag{4}$$

where the factor 0.75 represents the average, or integrated value across the gage.

The standard Gardon gage data reduction procedure was used to compute model local heat transfer-coefficents. The procedu-e averages five consecutive samples of gage output, (E) commencing with the data loop recorded at approximately the time the model arrives at tunnel centerline. The gage edge temperature (TGE) was averaged in the same manner.

The heat transfer coefficient for each gage was computed using the following equation,

$$H(TT) = \frac{QDOT}{(TT-TW)} \tag{5}$$

QDOT-0 is the heat flux calculated when the gage wall temperature (TW) is assumed to be 460°R (0°F). It is computed using the following equation,

$$QDOT\text{-}0 = H(TT)(TT-460) \tag{6}$$

The reduction of thin skin temperature data to coefficient form normally involves only the calorimeter heat balance for the thin skin as follows:

$$QDOT = \rho bc\ DTW/DT \tag{7}$$

$$H(TT) = \frac{QDOT}{TT-TW} = \frac{\rho bc\ DTW/DT}{TT-TW} \tag{8}$$

Thermal radiation and heat conduction effects on the thin-skin element are neglected in the above relationship and the skin temperature response is assumed to be due to convective heating only. It can be shown that for constant TR, the following relationship is true:

$$\frac{d}{dt}\left[\ln\left(\frac{TT-TI}{TT-TW}\right)\right] = \frac{DTW/DT}{TT-TW} \tag{9}$$

Substituting Eq. (9) in Eq. (8) and rearranging terms yields:

$$\frac{H(TT)}{\rho bc} = \frac{d}{dt}\left[\ln\left(\frac{TT-TI}{TT-TW}\right)\right] \tag{10}$$

By assuming that the value of $H(T\dot{T})/\rho bc$ is a constant, it can be seen that the derivative (or slope) must also be constant. Hence, the term

$$\ln\left(\frac{TT-TI}{TT-TW}\right)$$

is linear with time. This linearity assumes the validity of Eq. (8) which applies for convective heating only. The evaluation of conduction effects will be discussed later.

The assumption that H(TT) and c are constant is reasonable for this test although small variations do occur in these parameters. The variations of H(TT) caused by changing wall temperature and by transition movement with wall temperature are trivial for the small wall temperature changes that occur during data reduction. The value of the model material specific heat, c, was computed by the relation

$$c = 8.86196 \times 10^{-2} + 3.98668 \times 10^{-5}(TW), \text{ (316 stainless steel)} \tag{11}$$

The maximum variation of c over any curve fit was less than 1.5 percent. Thus, the assumption of constant c used to derive Equation 10 was reasonable. The value of density used for the 316 stainless steel skin was, $\rho = 501$ lbm/ft^3, and the skin thickness, b, for each thermocouple is listed in Table 5.

The right side of Equation 10 was evaluated using a linear least squares curve fit of 7 consecutive data points to determine the slope. The curve fit was started at approximately the time the model arrived on the tunnel centerline. For each thermocouple the tabulated value of H(TT) was calculated from the slope and the appropriate values of ρbc; i.e.,

$$H(TT) = \rho bc \frac{d}{dt}\left[\ln\left(\frac{TT-TI}{TT-TW}\right)\right] \tag{12}$$

To investigate conduction effects a second value of H(TT) was calculated at a time one second later. A comparison of these two values was used to identify those thermocouples that were influenced by significant conduction (or system noise). Conduction and/or noise effects were found to be negligible.

3.4 UNCERTAINTY OF MEASUREMENTS

In general, instrumentation calibrations and data uncertainty estimates were made using methods recognized by the National Bureau of Standards (NBS). Measurement uncertainty is a combination of bias and precision errors defined as:

$$U = \pm(B + t_{95}S)$$

where B is the bias limit, S is the sample standard deviation and t_{95} is the 95th percentile point for the two-tailed Student's "t" distribution (95-percent confidence interval), which for sample sizes greater than 30 is taken equal to 2.

Estimates of the measured data uncertainties for this test are given in Table 3a. The data uncertainties for the measurements are determined from in-place calibrations through the data recording system and data reduction program.

Propagation of the bias and precision errors of measured data through the calculated data was made in accordance with Ref. 3 and the results are given in Table 3b.

4.0 DATA PACKAGE PRESENTATION

A complete set of all photographic data and tabulated data for this test has been provided to Martin Marietta Corporation. Photographic data which showed significant testing results and a complete set of tabulated data have been provided to NASA/Marshall Space Flight Center/ED33, Huntsville, Alabama. All test specimens for this test have been returned to the Martin Marietta Corporation.

Representative posttest photographs are shown in Fig. 6.

Samples of the tabulated and plotted data from the calibration and materials specimen runs are presented in Appendix III. A copy of all tabulated data has been retained on microfilm in the VKF.

Agreement of the test data to a flat plate solution using the Echert reference method was good and an example can be seen in Fig. 7. Data repeatability from run to run was excellent and an example can be seen in Fig. 8.

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2. Matthews, R. K. and Stallings, D. W. "Materials Testing in the VKF Continuous Flow Wind Tunnels," Presented at AIAA 9th Aerodynamic Testing Conference, Arlington, TX, June 7-9, 1976.

3. Thompson, J. W. and Abernethy, R. B. et. al., "Handbook Uncertainty in Gas Turbine Measurements," AEDC-TR-73-5 (AD755356) February 1973.

APPENDIX I

ILLUSTRATIONS

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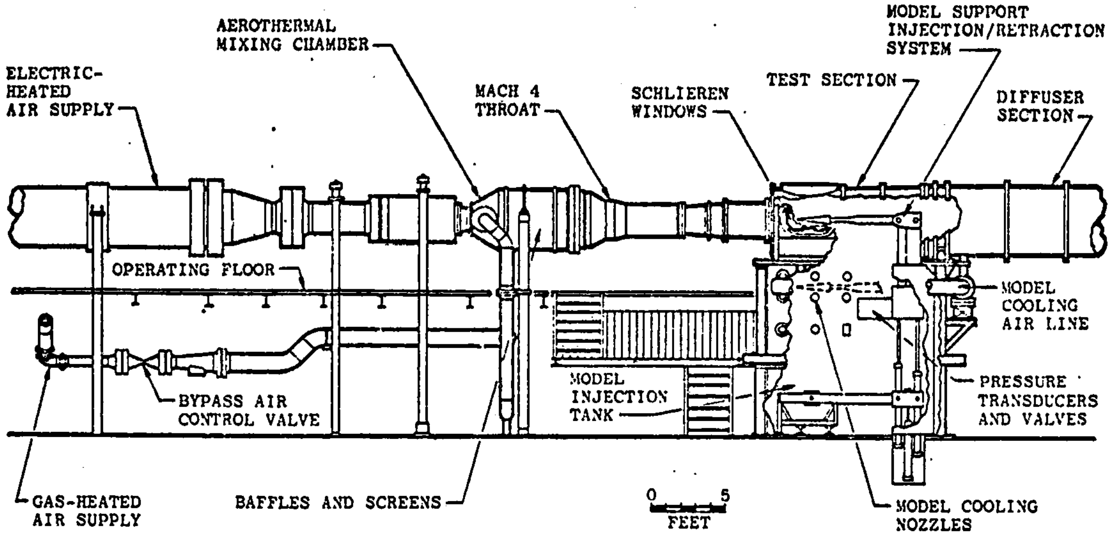
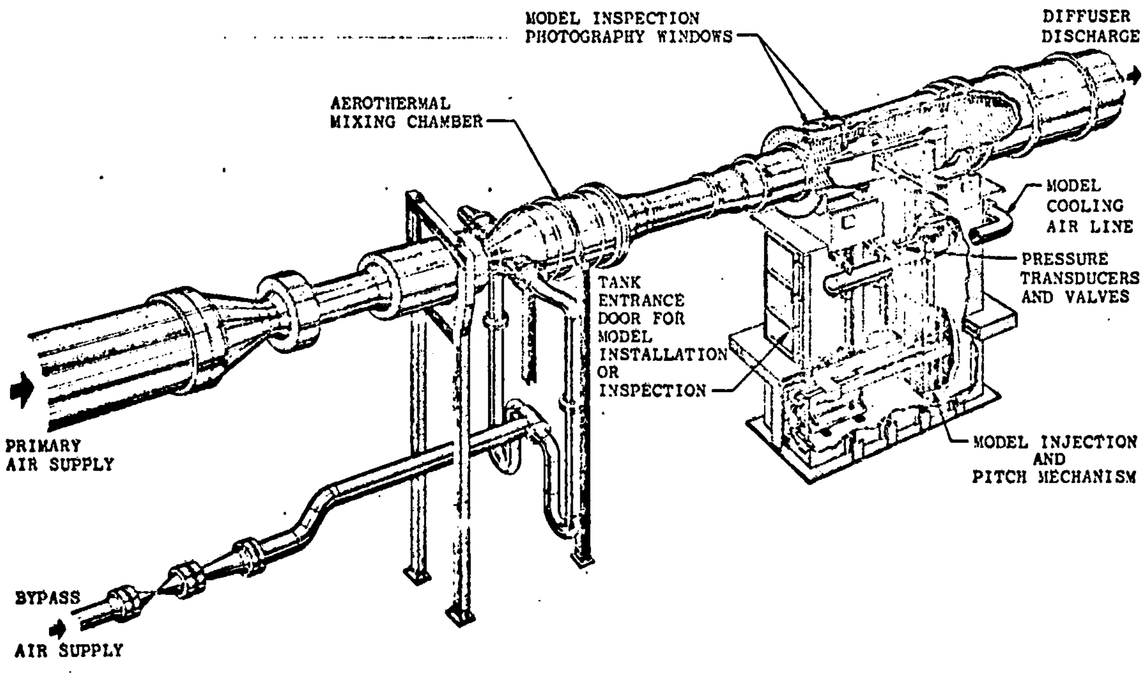


a. Tunnel assembly



b. Perspective of tunnel test section area

Fig. 1 Tunnel C Mach 4.0 Configuration

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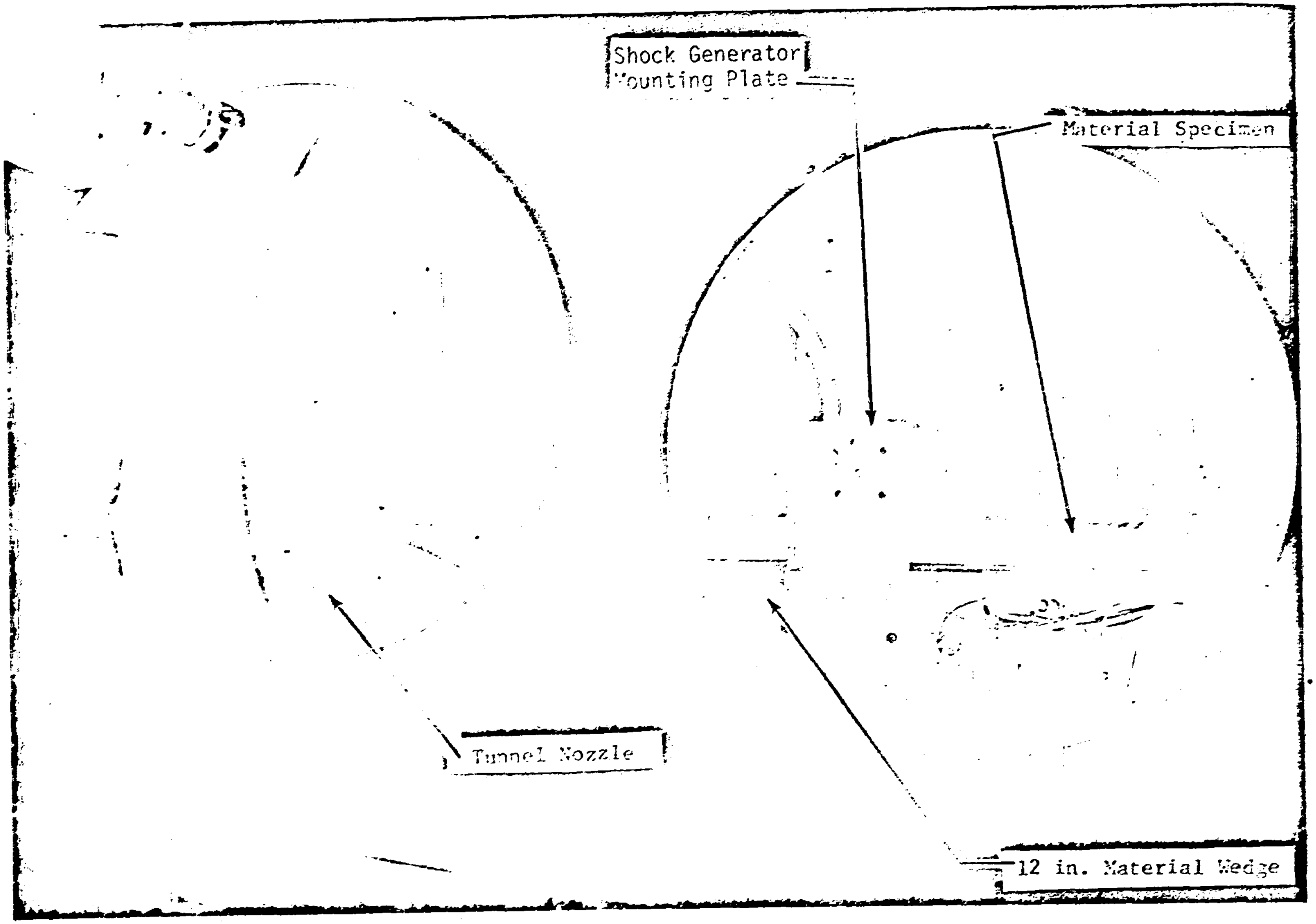
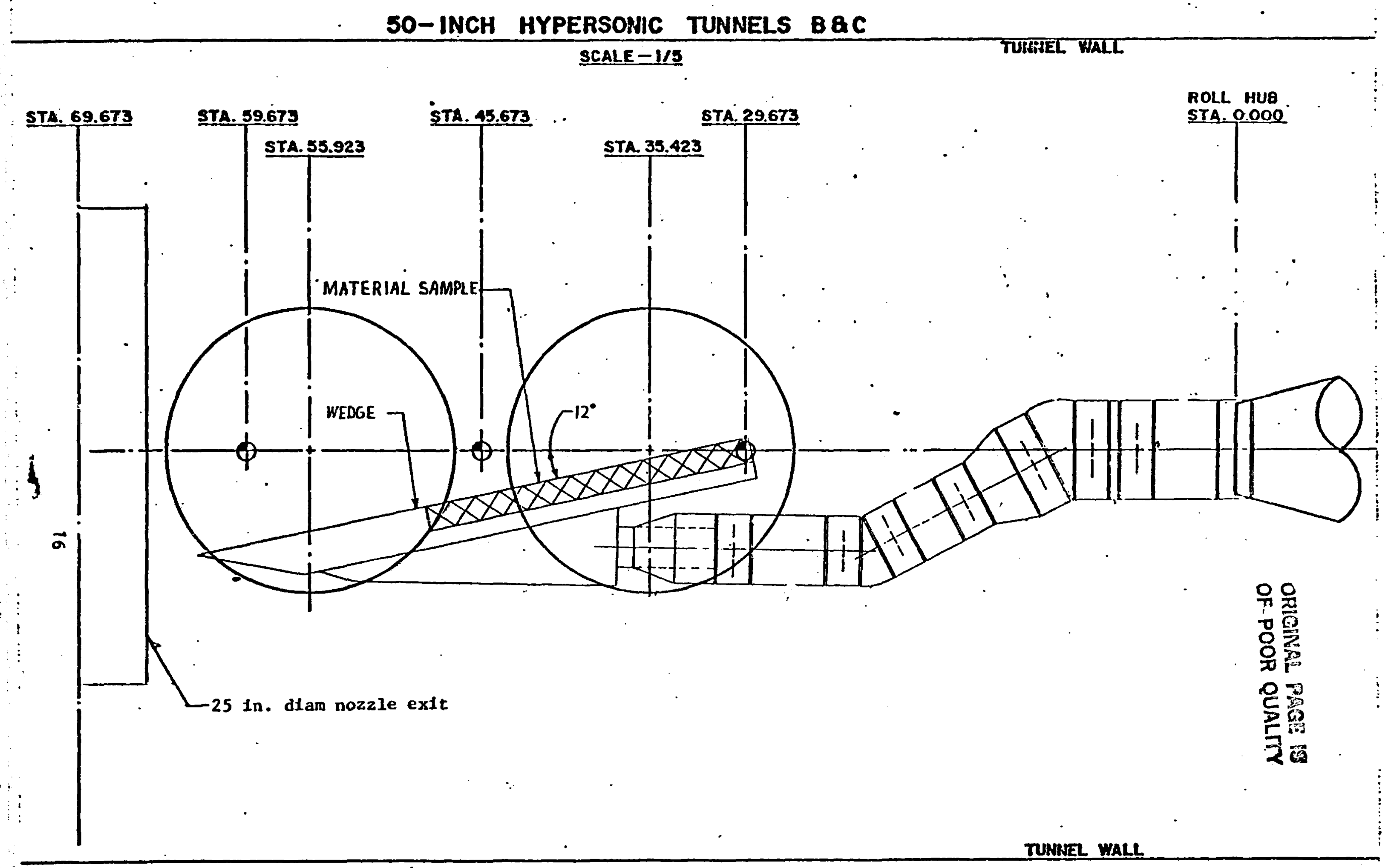


a. Installation Photograph

Figure 2. Installation in Tunnel C Mach 4



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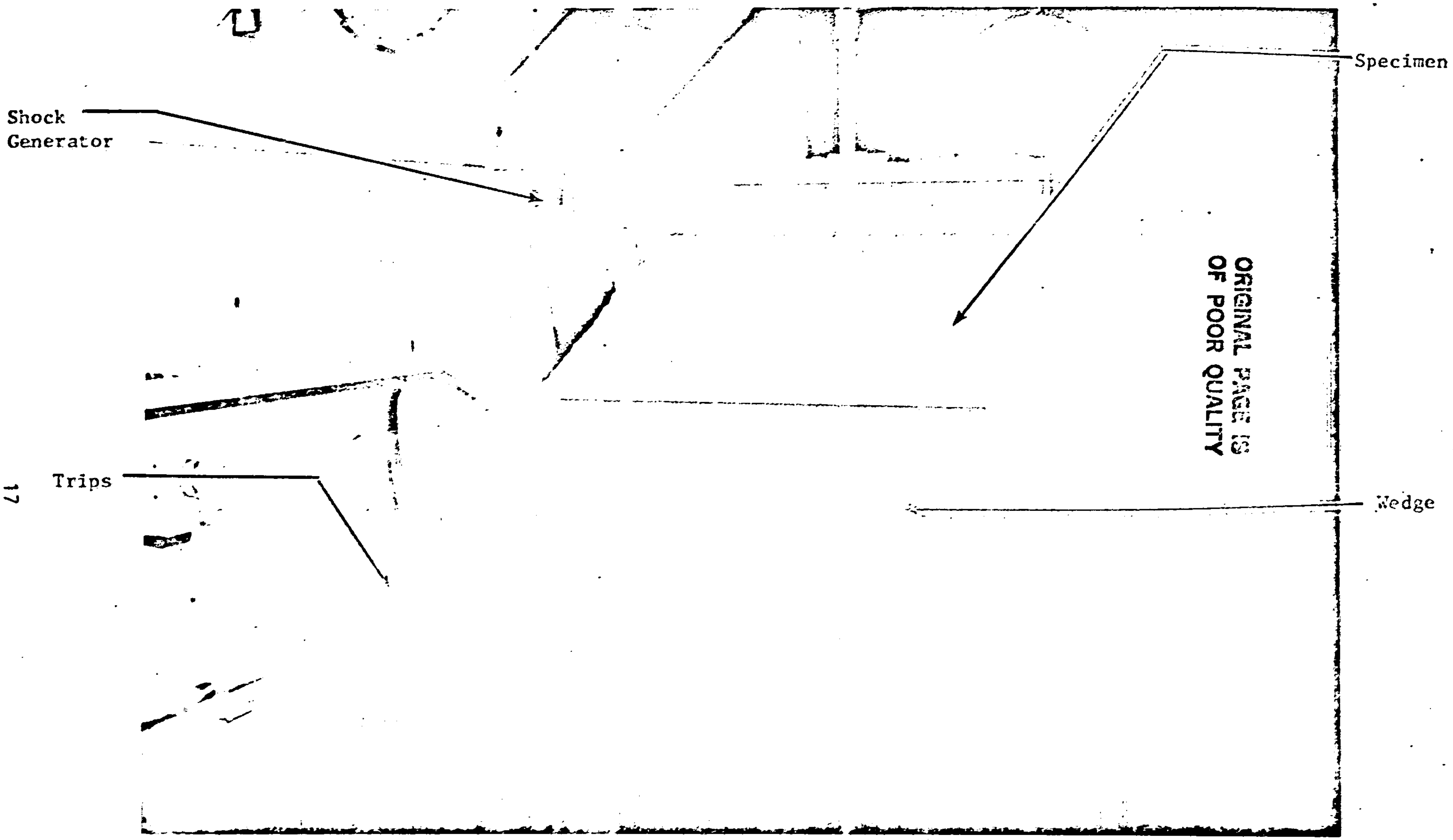
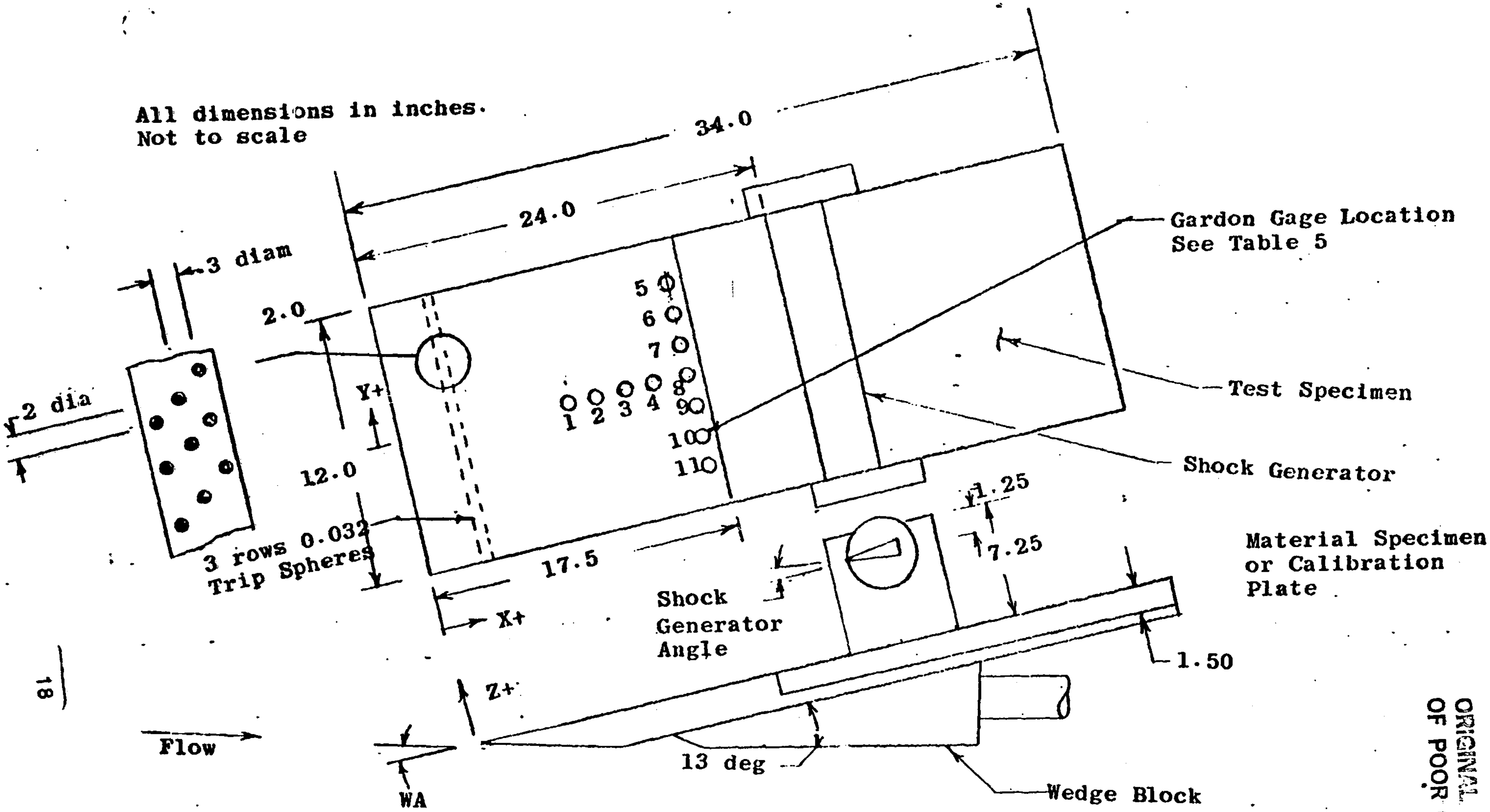
b. Installation Sketch for Mach 4 Entry
Figure 2. Continued



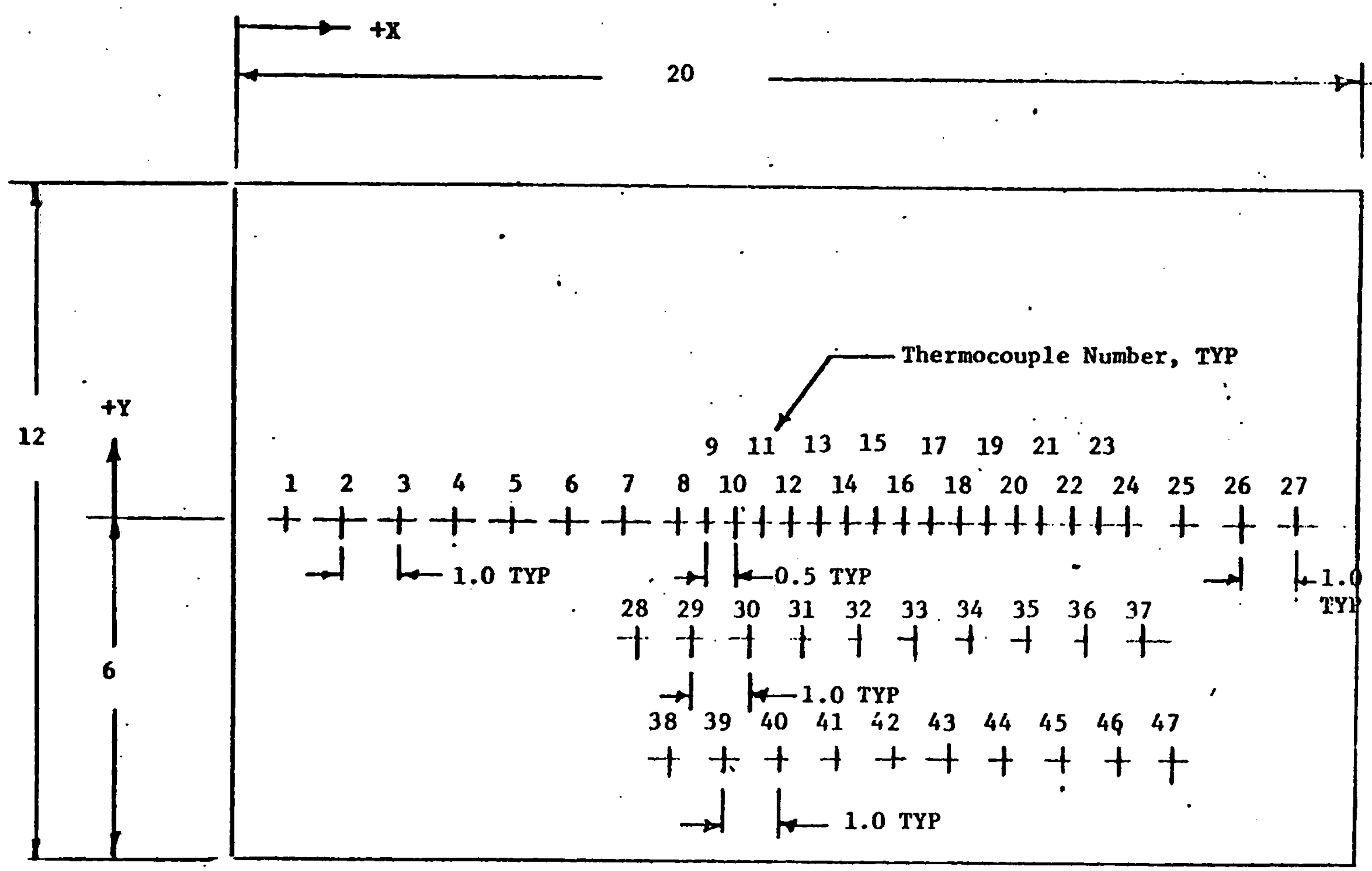
a. Photograph in Tank
Figure 3. Test Article Details



b. Sketch of 12 in. Wedge with Shock Generator

Figure 3. Continued

THERMOCOUPLE COORDINATES GIVEN IN TABLE 5



All dimensions in inches

Figure 4. Calibration Plate

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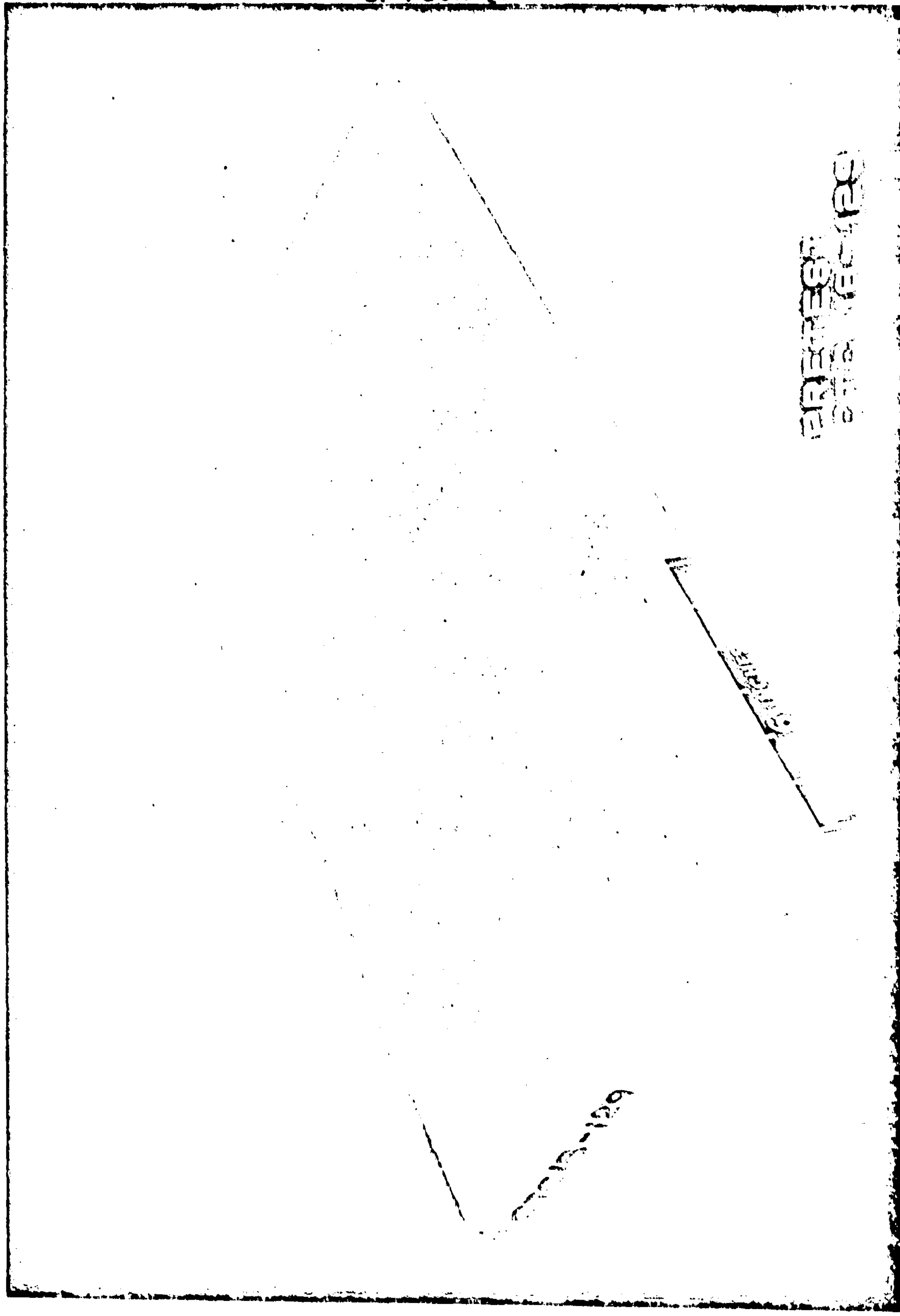
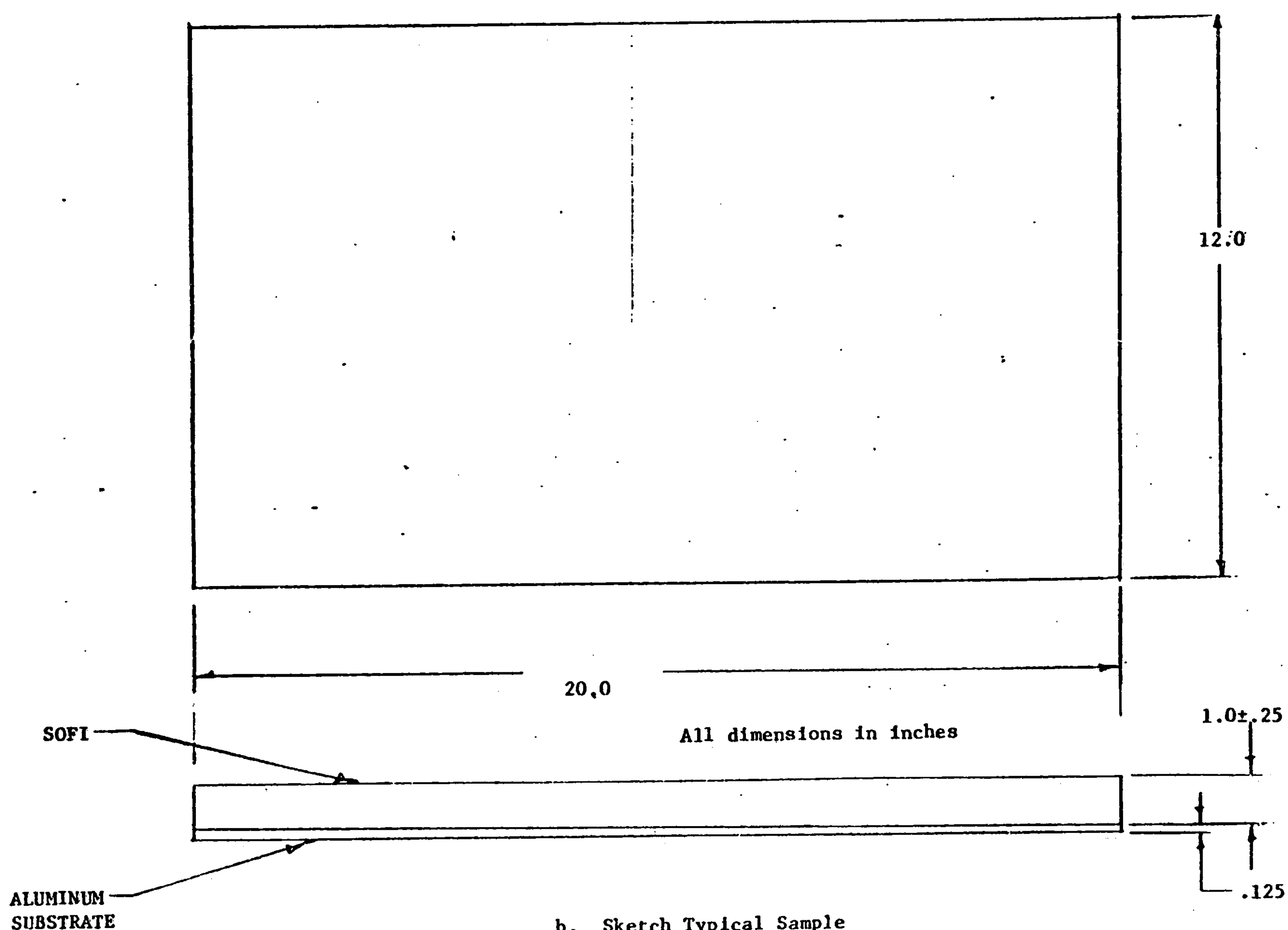
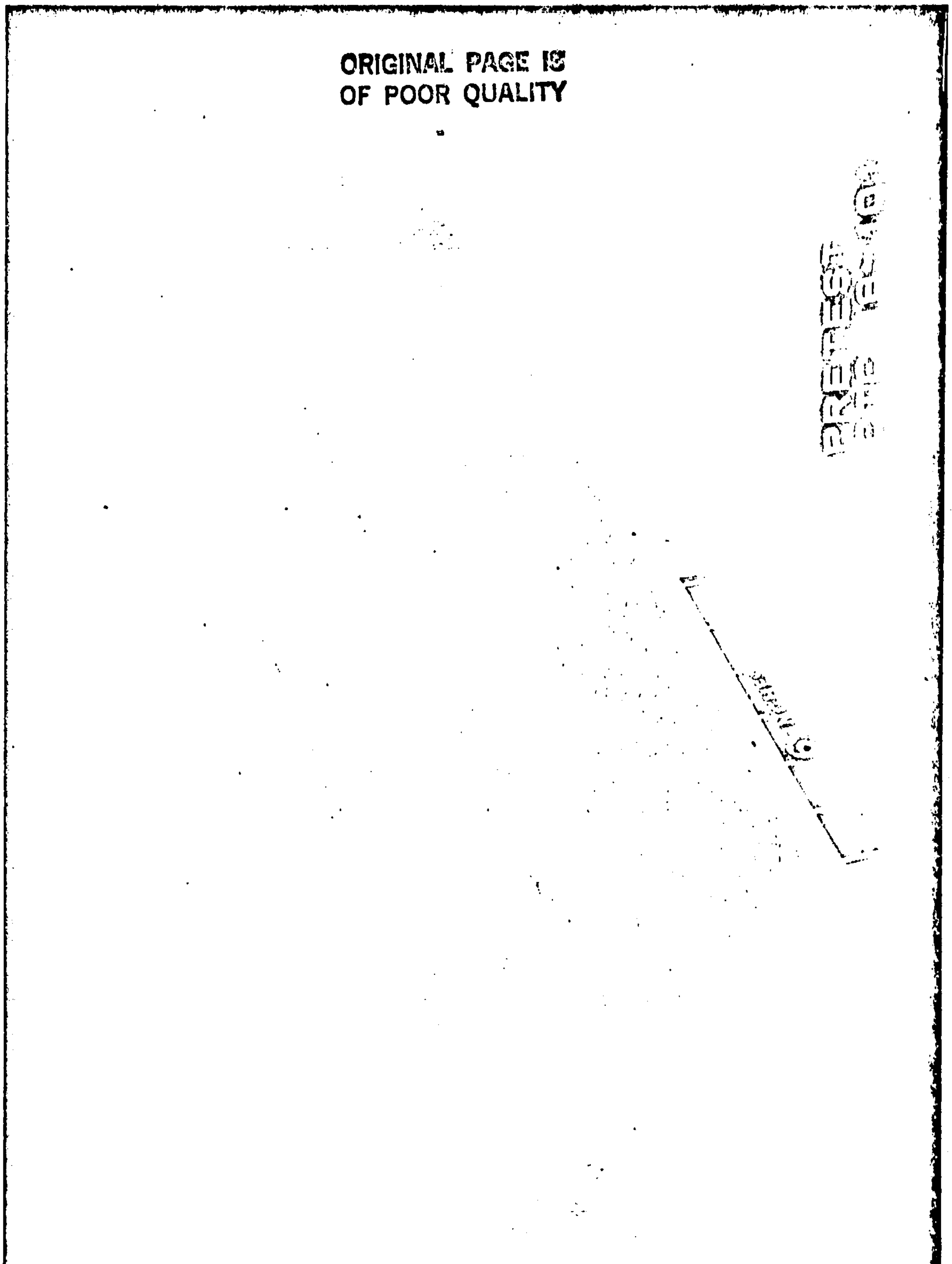


a. Typical Specimen

Figure 5. Specimen Configuration

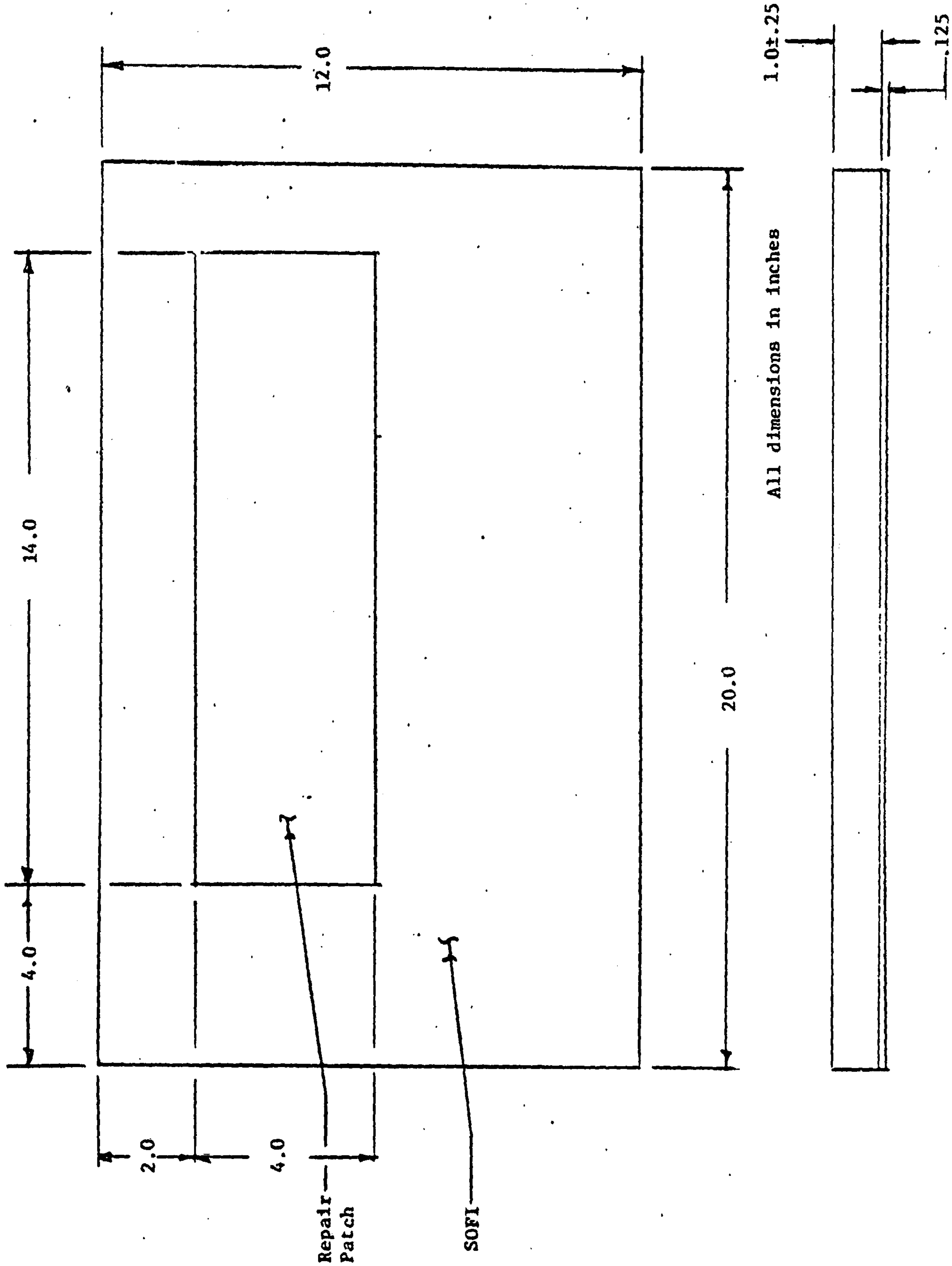


b. Sketch Typical Sample
Figure 5. Specimen Configuration

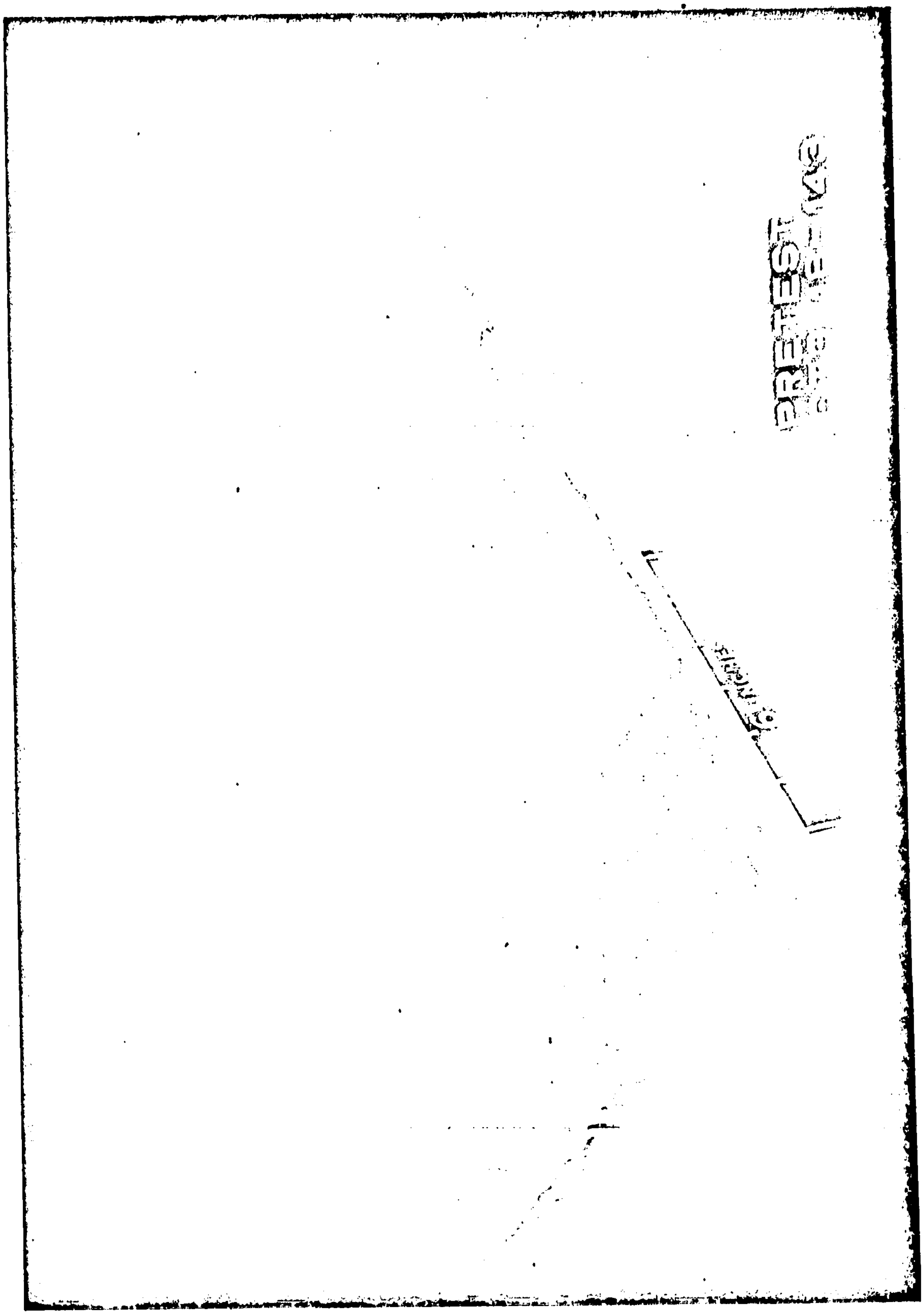


c. Repair Panel

Figure 5. Continued

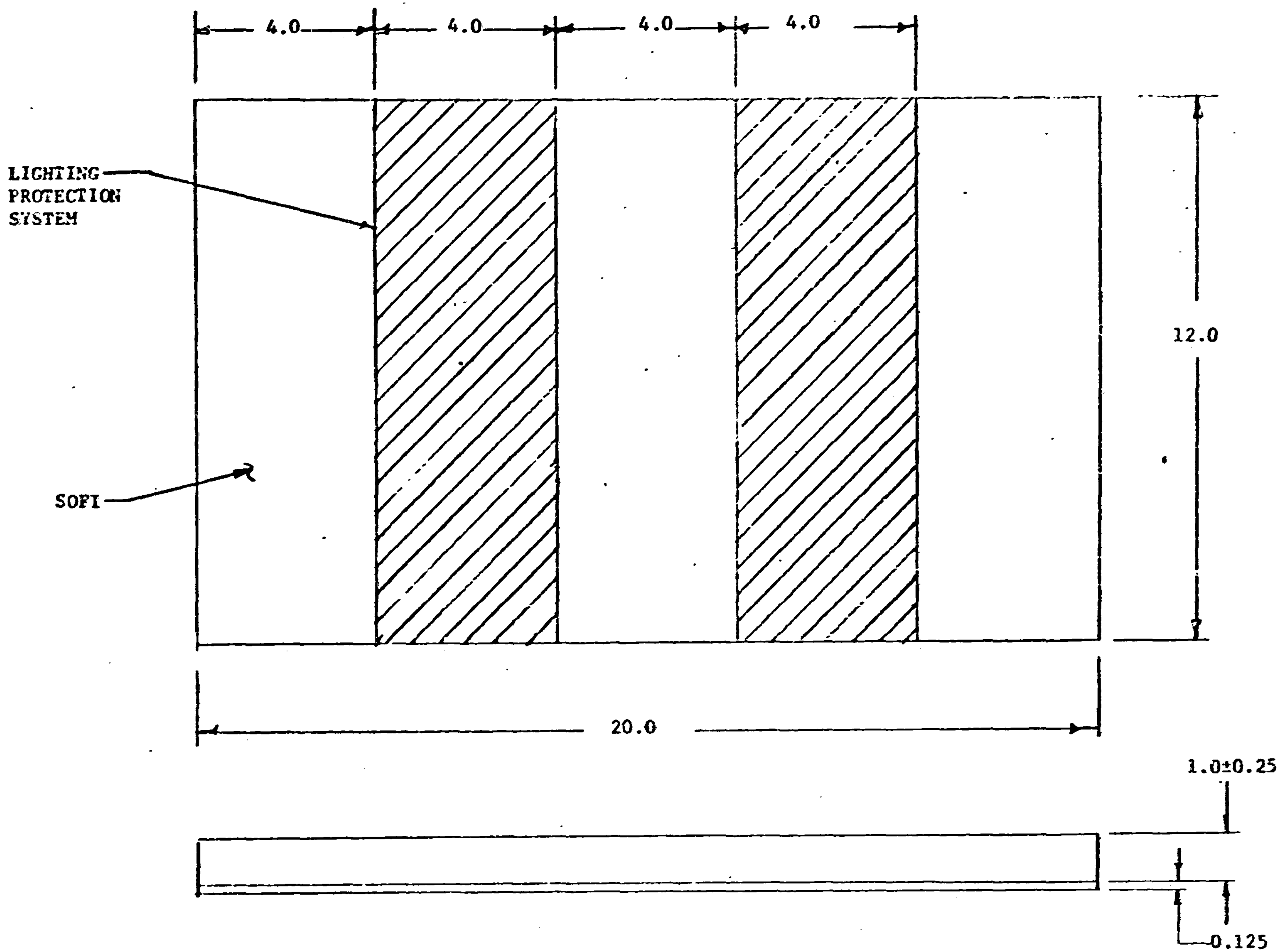


d. Sketch Repair Panel
Figure 5. Continued



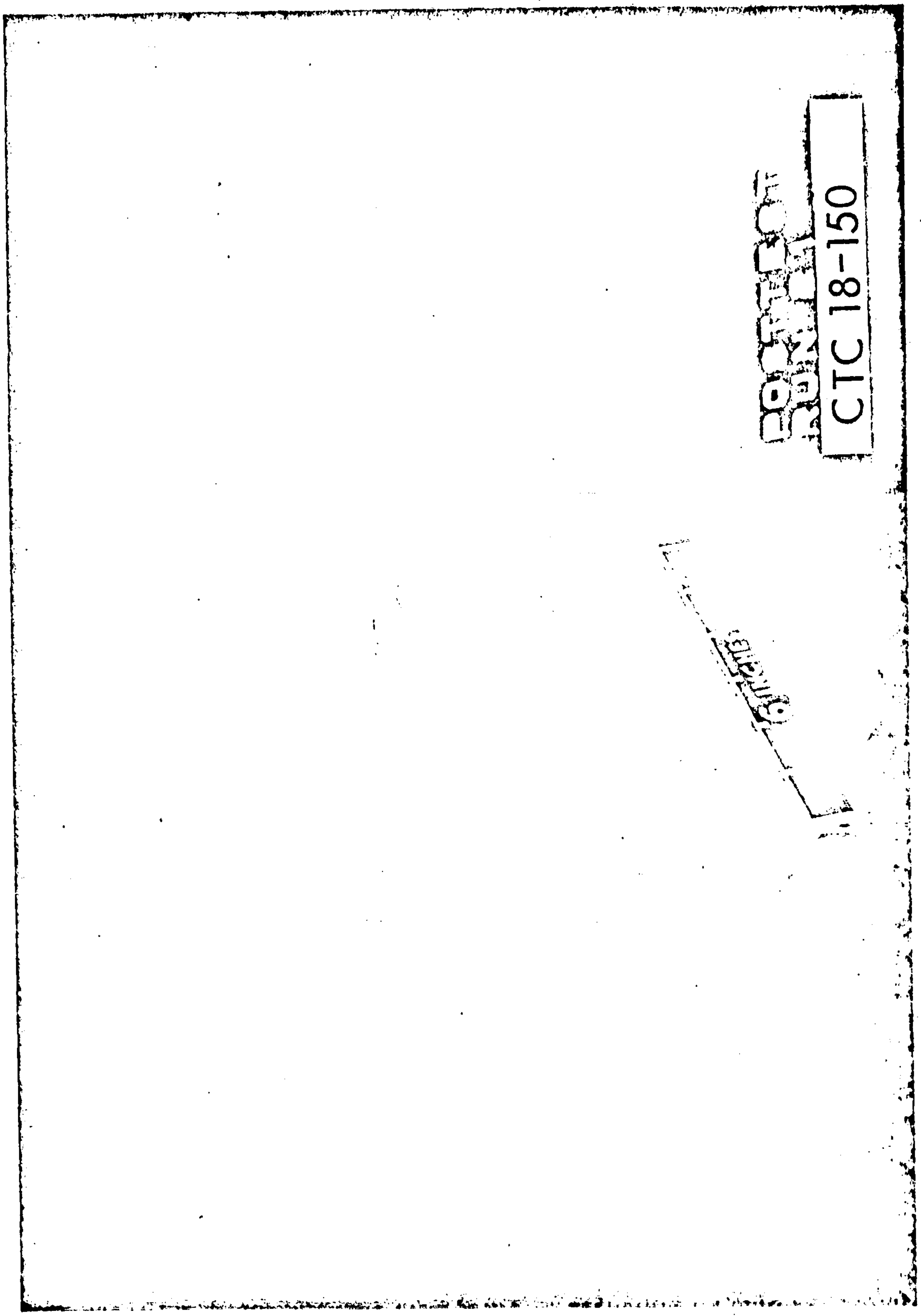
e. Lighting Protection System

Figure 5. Continued

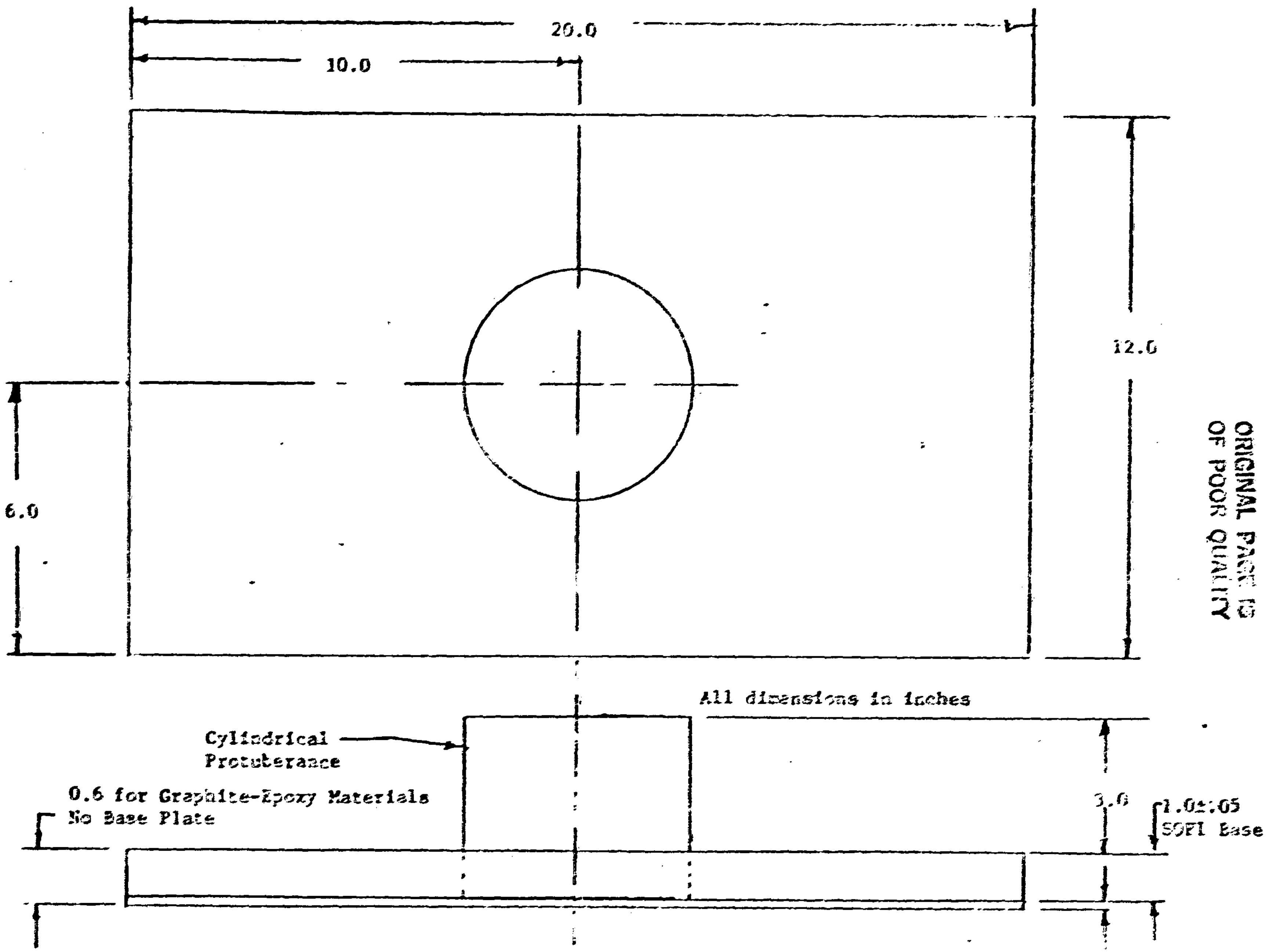


f. Sketch Lighting Protection System

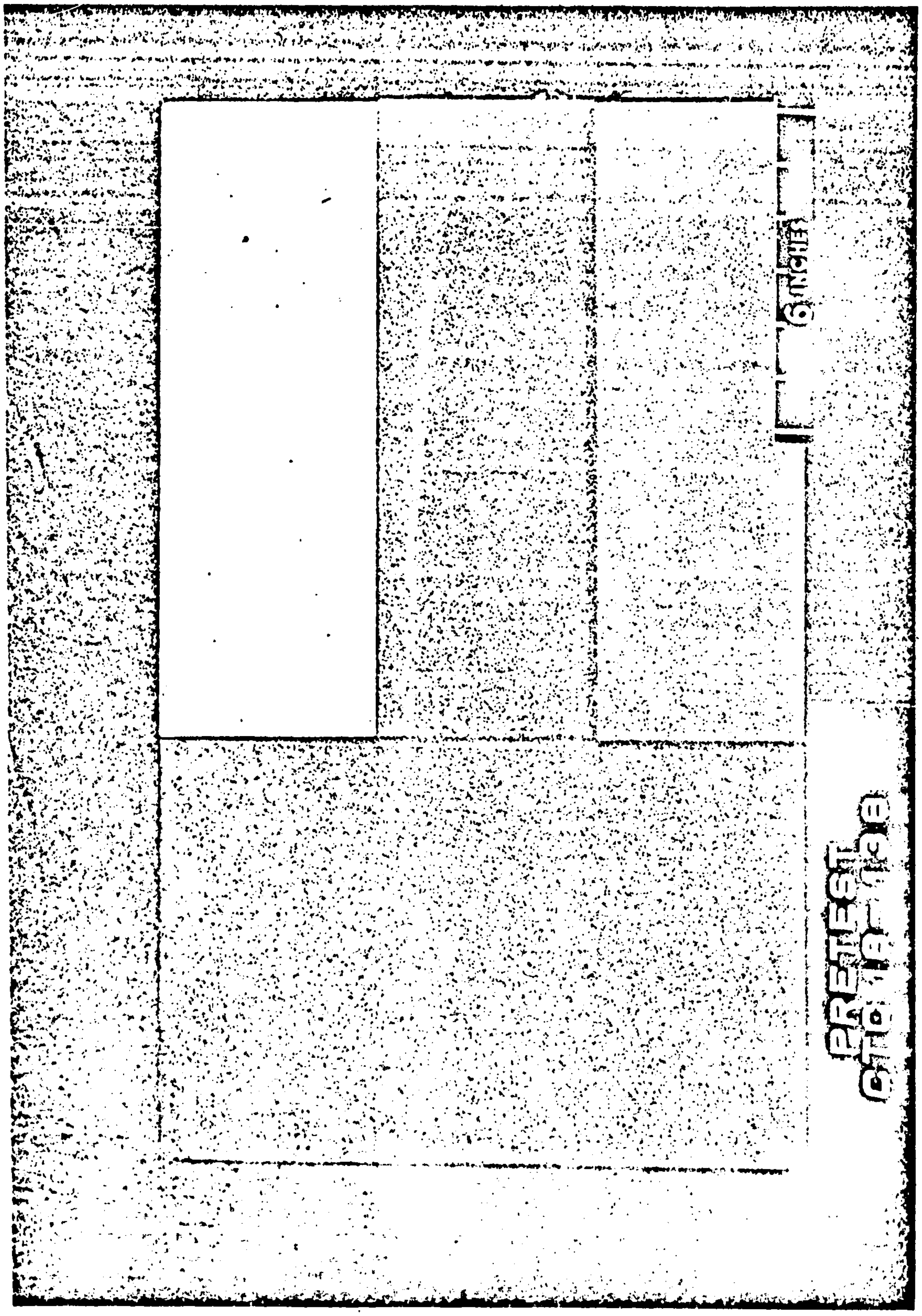
Figure 5. Continued



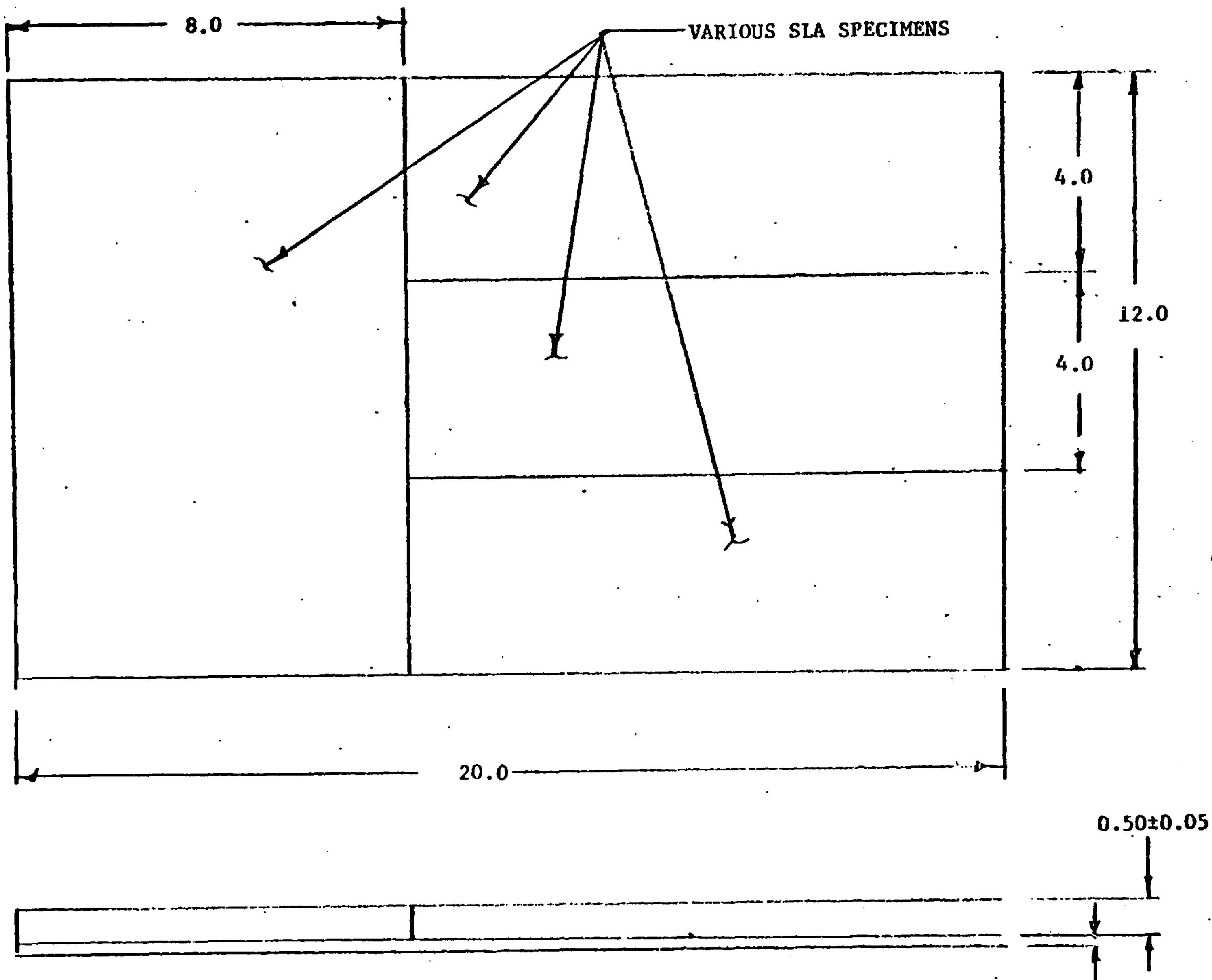
8. Protuberance Specimen
Figure 5. Continued



h. Protuberance Panel
Figure 5. Continued

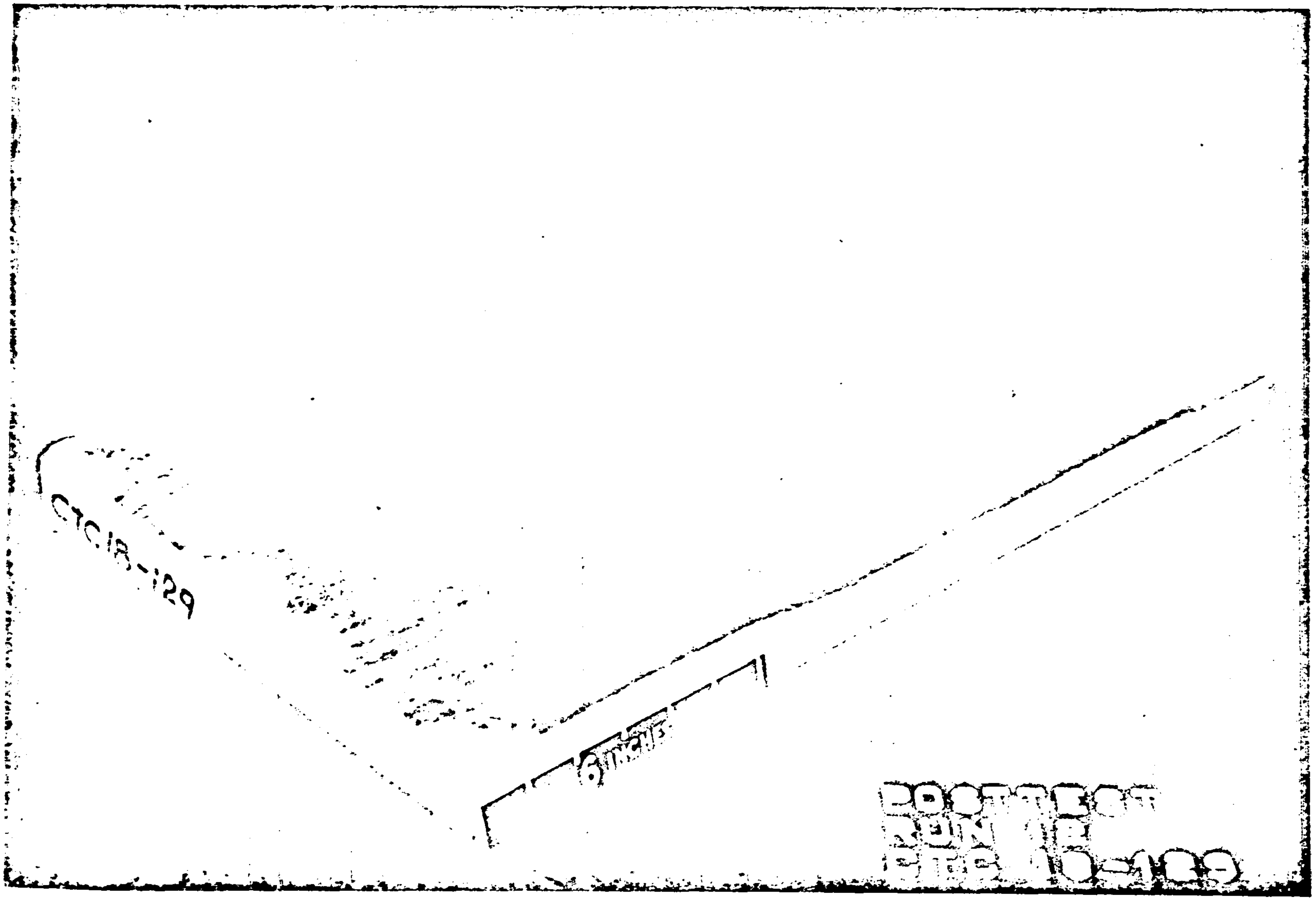


1. SLA Specimen
Figure 5. Continued



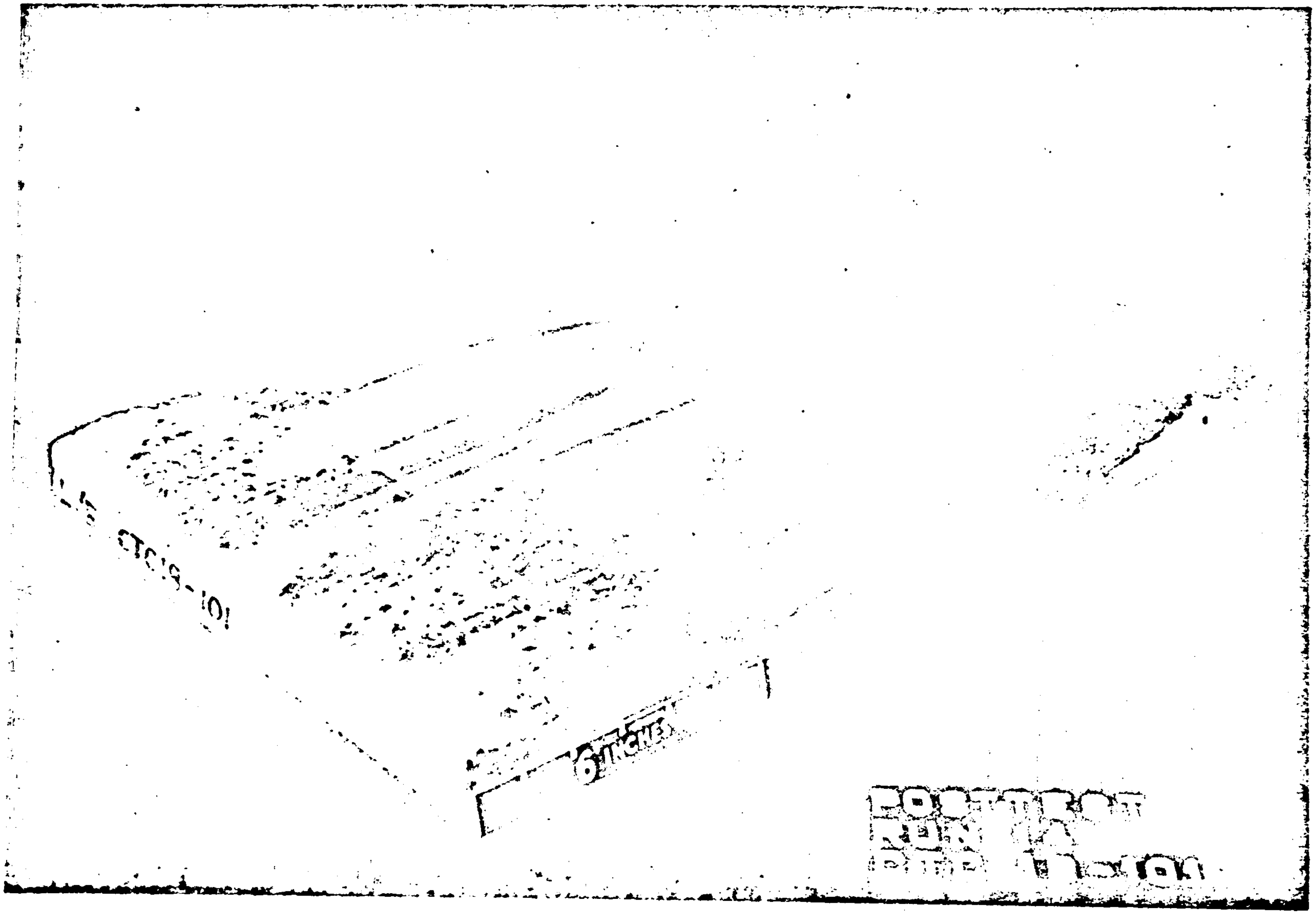
j. Sketch SLA Specimen

Figure 5. Concluded



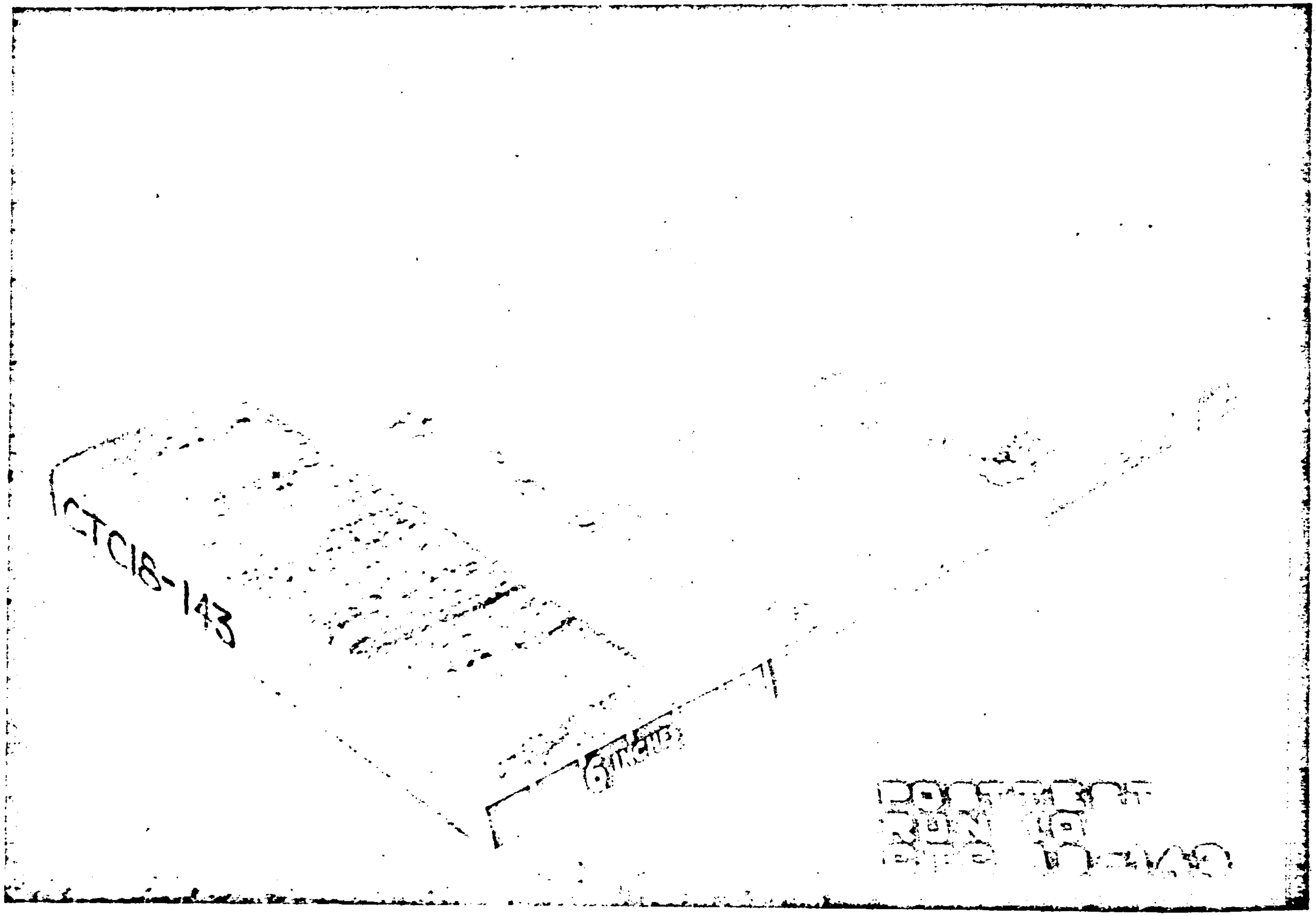
a. Typical Specimen

Figure 6. Posttest Pictures



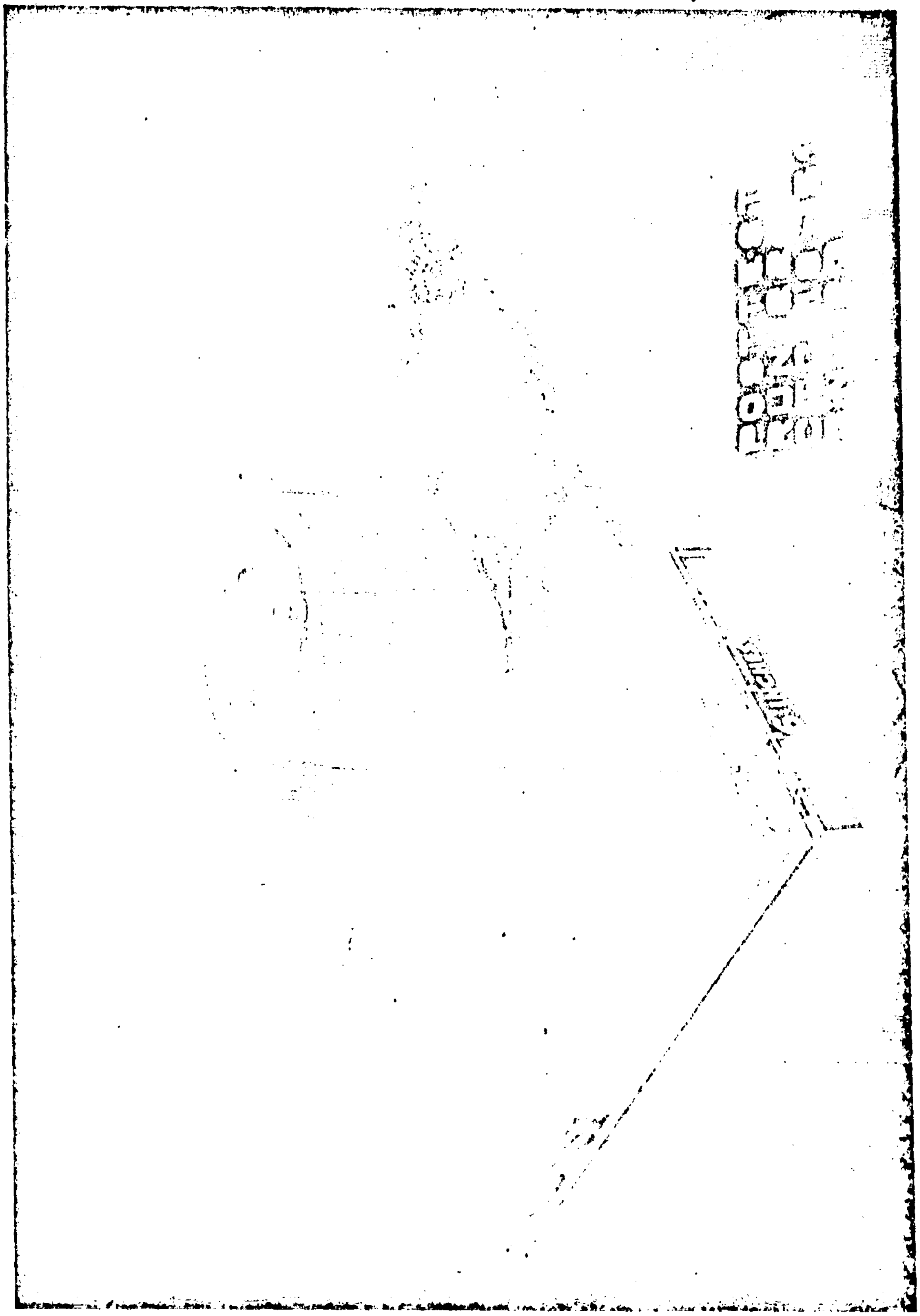
b. Repair Panel

Figure 6. Continued



c. Lighting Protection System

Figure 6. Continued



d. Protuberance Specimen

Figure 6. Concluded

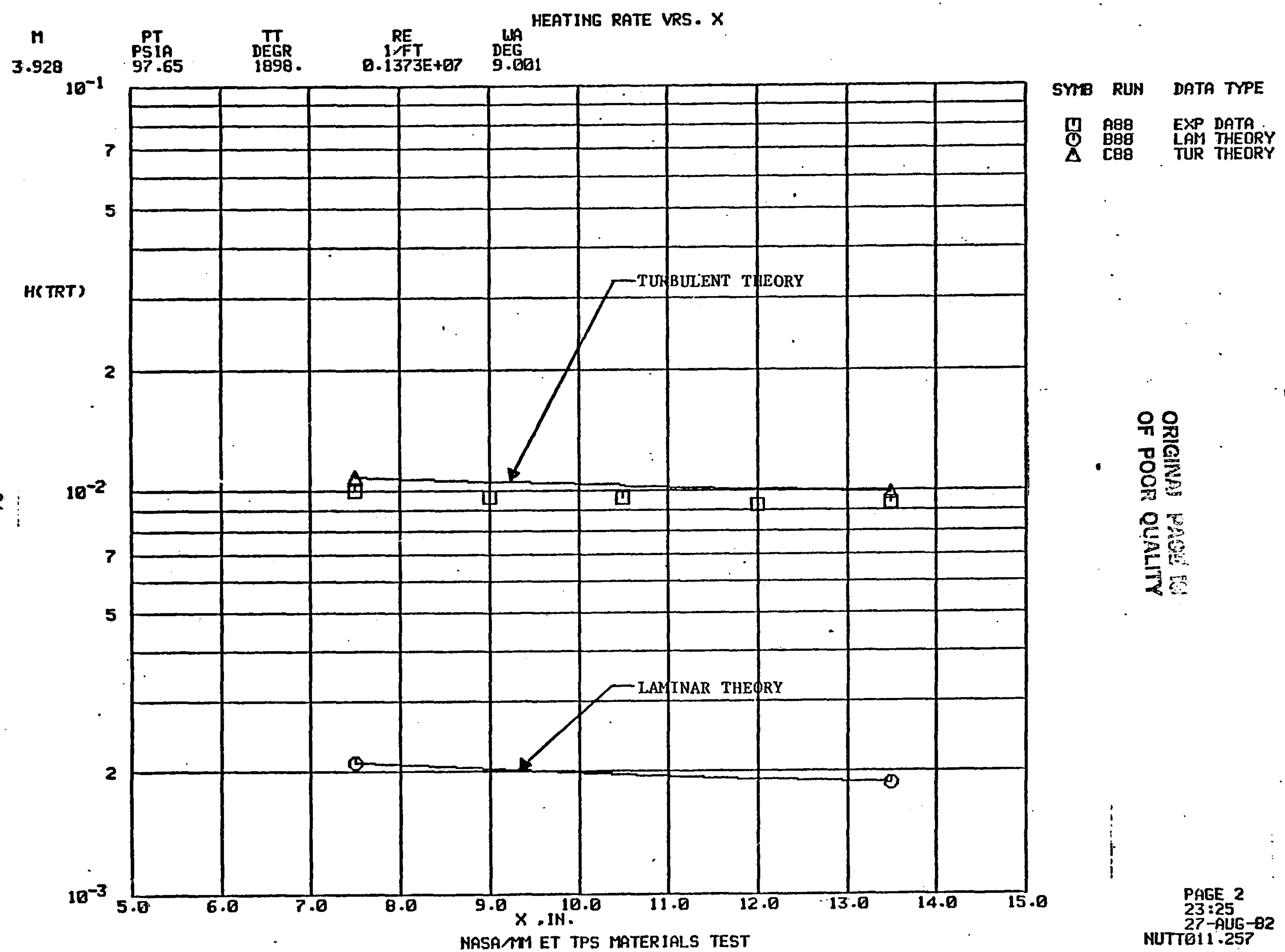


Figure 7. Comparison of Tunnel Data with Analytical Calculation

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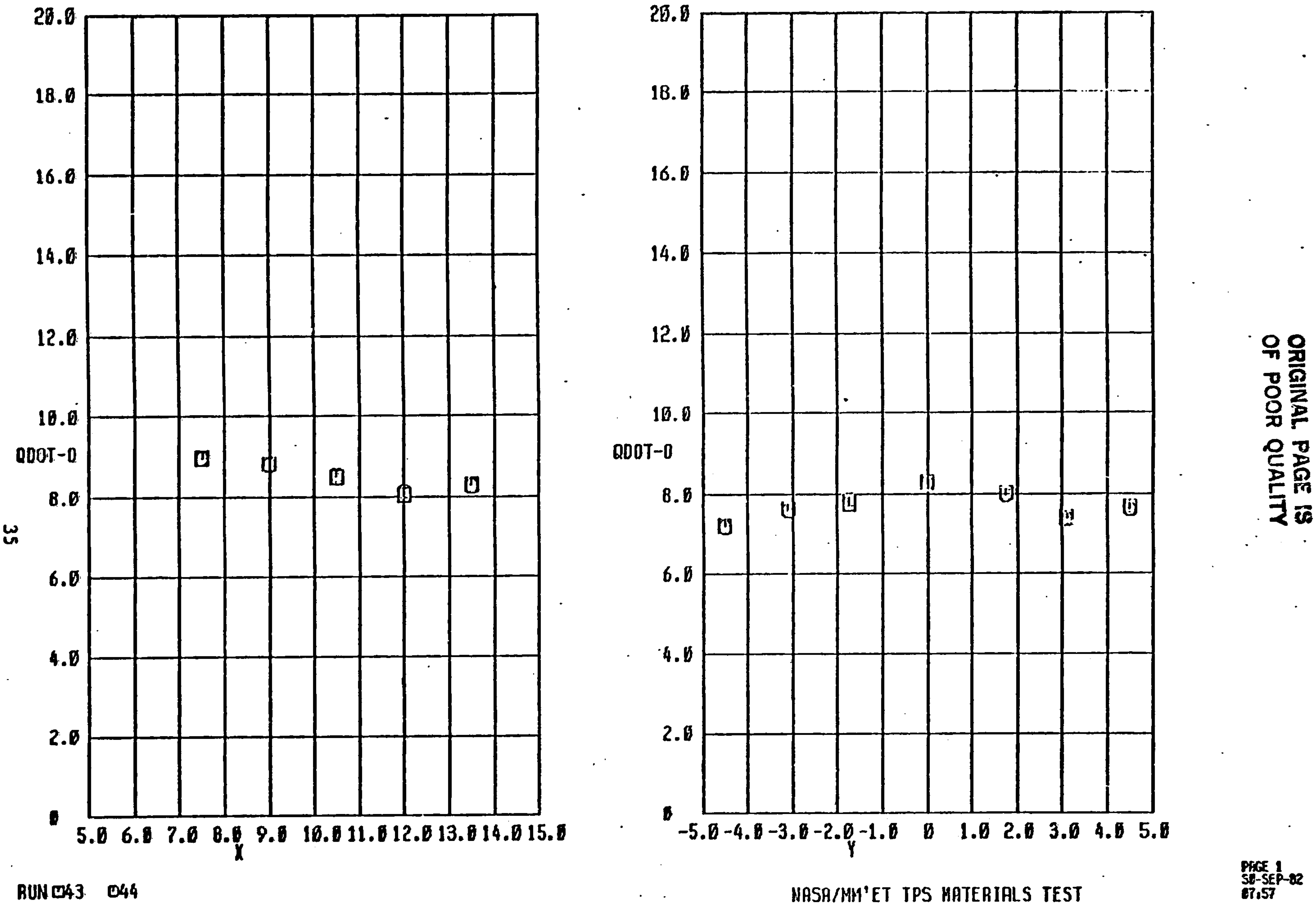

Figure 8. Data Repeatability

APPENDIX II

TABLES

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TABLE 1. Data Transmittal Summary

The following items were transmitted to the User and Sponsor:

	User	Sponsor
	Mr. Steve Copsey Martin-Marietta Michoud Operations P.O. Box 29340 New Orleans, LA 70189	Mr. Lee Foster ED/33 MSFC Marshall Space Flight Center Huntsville, AL 35812
Item	No. of Copies	No. of Copies
Final Data Package Vols. 1 and 2 of 2	3	3
Installation Photos	1 each 8x10 prints	1 each 8x10 prints
Specimen Pretest Photos	1 each 8x10 prints	1 each 8x10 prints
Specimen Posttest Photos	1 each 8x10 prints	1 each 8x10 prints
70 mm Sequence	1 contact print 1 duplicate negative	1 contact print
70 mm Shadowgraph Stills	1 contact print 1 duplicate negative	1 contact print
16 mm Direct Movies	1 work print Optical master	1 work print
16 mm Shadowgraph Movies	1 work print 1 duplicate negative	1 work print
Video tape	1 copy	1 copy

TABLE 2. Material Summary

SAMPLE NUMBER	RUN NUMBER	SAMPLE MATERIAL	FIG. NO.
SN-23	22	SLA-561 Protuberance	5g
CTC18-35	13	CPR-488 W/BX-250 repair patch	5c
-36	28	↓	5c
-51	22	CPR-488	5g
-101	14	CPR-488 X/PDL-4034 repair patch	5c
-102	17		
-103	25		
-104	30		
-105	35		
-106	37		
-107	42		
-108	80		↓
-112	59	↓	
-113	16	CPR-488	5a
-114	21		
-115	26		
-116	31		
-117	36		
-119	38		
-123	81	↓	
-125	18	NCFI-2265	
-126	33		
-127	40		
-129	12		
-130	15		
-131	19		
-132	27		
-133	82		↓
-134	83	↓	
-137	97	SLA-561M variants	5i
-138	98	↓	↓
-142	90	UTAH-1002-60P	5a
-143	10	CPR-488 W/ECCO bond 59K LPS	5e
-144	11	↓	↓
-145	20	CPR-488	5a
-146	32		
-147	39	↓	↓
-149	23	Graphite-epoxy protuberance	5g
-150	24	↓	↓
-151	96	SLA-561M variants	5i
-154	29	NCFI-2265	5a
-155	41	↓	
-156	34	CPR-488	
-201	47	NCFI-2265	
-202	53		
-203	58		
-204	64		
-205	71		
-206	78		
-207	88		
-208	95		
-209	46	↓	
-210	52		↓

TABLE 2. Concluded

SAMPLE NUMBER	RUN NUMBER	SAMPLE MATERIAL	FIG. NO.
CTC18-210	57	NCFI-2265	5a
-212	63	↓	↓
-213	70		
-214	77		
-215	87		
-216	94	↓	
-217	45	CPR-488	
-218	51	↓	
-219	56		
-220	62		
-221	69		
-222	76		
-223	86		
-224	93		
-225	43		
-226	49		
-227	54		
-228	60		
-229	67		
-230	74		
-231	84		
-232	91		
-233	45		
-234	50		
-235	55		
-236	61		
-237	68		
-238	75		
-239	85		
-240	92	↓	
-241	48	PDL-4034	
-242	65	↓	
-243	72		
-244	89		
-245	66		
-246	73	↓	↓
-247	99	SLA-561M variants	5i
-254	79	NCFI-2265	5a

TABLE 3. ESTIMATED UNCERTAINTIES

a. Basic Measurements

Parameter Designation	STEADY-STATE ESTIMATED MEASUREMENT* Precision Index (S) Percent of Reading	Unit of Measurement	Degree of Freedom	Bias (B) Percent of Reading	Unit of Measurement	Uncertainty ±(B + $t_{95}S$) Percent of Reading	Unit of Measurement	Range	Type of Measuring Device	Type of Recording Device	Method of System Calibration
STILLING CHAMBER, PRESSURE, PT, psia		0.12	>30		0.75		0.495	<156	Wiancko variable reluctance pressure transducer	Digital data acquisition system analog-to-digital converter	In-place application of multiple pressure levels measured with a pressure measuring device calibrated in the standards laboratory
TOTAL TEMPERATURE, TT, °F		1 1	>30 >30	0.375	2		4 ±(.375% +2°F)	32 to 530 530 to 2300	Chromel®-Alumel® thermocouple	Doric temperature instrument digital multiplexer	Thermocouple verification of NBS conformity/voltage substitution calibration
PITCH ANGLE, ALPHI, DEG		0.025	>30				0.05	15	Potentiometer		Heidenhain rotary encoder ROD700 Resolution: 0.0006° Overall accuracy: 0.001°
TIME		$5x10^{-4}$	>30	Runtime(sec)x5x 10^{-6}		Runtime(sec)x5x 10^{-6})+10^{-3}		ms to 365 days	Systron Donner time code generator	Digital data acquisition system	Instrument lab calibration against Bureau of Standards
HEAT TRANSFER, QDOT, BTU/ft²-sec	1.5	0.015	>30 >30	2 2		(0.03 + 2%) 5%		<1 1 to 10	Gardon gage	Digital data acquisition system analog-to-digital converter	Radiant heat source and secondary standard
E_{mv}	0.1		>30	0.01		(0.2% + 0.01)			DEC-10/Multiverter Preston amplifier		Millivolt standard, referenced to lab standard
TEMPERATURE, TGE, °F		1 1	>30 >30	3/8%	2	(3/8% + 2°F)	4	32 to 530 530 to 2300	CrAl thermocouple		

*Thompson, J. W. and Abernethy, R. B. et al. "Handbook Uncertainty in Gas Turbine Measurements." AEDC-TR-73-5 (AD 755356), February 1973.

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TABLE 3. Concluded

b. Calculated Parameters

Parameter Designation	STEADY-STATE ESTIMATED MEASUREMENT*							Range
	Precision Index (S)			Bias (B)		Uncertainty $\pm(B + t_{95}S)$		
	Percent of Reading	Unit of Measurement	Degree of Freedom	Percent of Reading	Unit of Measurement	Percent of Reading	Unit of Measurement	
H(TT), BTU/ft^2-sec-^{o}R GARDON GAGE	2.0		>30	2.0		6.0		
M	0.38		>30			0.76		3.9-4.0
QDOT-0, BTU/ft^2-sec GARDON GAGE	2.0		>30	2.0		6.0		
TW, ^{o}R		1	>30		2	4		All
WA, deg		0.05	>30		0$^+$		0.10	All
RE ft^{-1}	0.70		>30	0.56		1.96		0.5x10^{6}ft^{-1}
	0.36		>30	0.45		1.17		3.7x10^{6}ft^{-1}
H(TT), BTU/ft^2-sec-^{o}R	1.0		>30	6.0		8.0		1x10^{-3}
Thin Skin Thermocouple	4.0		>30	6.0		14.0		1x10^{-4} → 1x10^{-3}
	7.0		>30	6.0		20.0		< 1x10^{-4}

*Abernethy, R. B. et al. and Thompson, J. W. "Handbook Uncertainty in Gas Turbine Measurements." AEDC-TR-73-5 (AD 755356), February 1973.

+Assumed to be zero

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TABLE 4. Photographic Data Summary

	Camera Type	Frame Rate	Camera Location	Sample View	Film Roll No.	Run No.
Camera 1 See Note 1	Varitron 70 mm still	1 per 25 sec to 1 per 4 sec	Top upstream window	Top of specimen on centerline with projected grid lines	0354 0307 0356 0431 0433 0435	10-18 19-30 31-42 43-64 65-83 84-99
Camera 2 See Note 2	DBM-SS 16 mm movie	24 fps	Top upstream window	Top of specimen on centerline with protected grid lines	04709 04710 04711 04773 04775 04777 04778 04779 04780 04781	10-18 19-27 27-42 43-49 50-54 61-62 63-73 74-80 81-91 93-99
Camera 3 See Note 1	Varitron 70 mm still	1 per 2 sec to 1 per 4 sec	Operating side upstream window	Left side view of forward portion of specimen on centerline	0355 0309 0363 0432 0434 0436	10-18 19-30 31-42 43-64 65-84 85-99
Camera 4 See Note 2	DBM-SS 16 mm	24 fps	Operating side upstream window	Left side view of forward portion of specimen on centerline	04712 04713 04714 04714 04776	10-18 19-27 28-42 43-49 50-62
Camera 5	Hycam 16 mm shadowgraph	1000 fps	Upstream window	NA	04707	23
Camera 6	Hycam 16 mm shadowgraph movies	1000 fps	Downstream window	NA	04708	23

TABLE 4. Concluded

	Camera Type	Frame Rate	Camera Location	Sample View	Film Roll No.	RUN no.
Camera 7	Varitron 70 mm shadowgraph stills	1 per 15 sec to 1 per RUN	Upstream window	NA	0375	1-10,22-25 43-99
Camera 8	Varitron 70 mm shadowgraph stills	1 per 15 sec to 1 per RUN	Downstream window	NA	0376 0392	1-42 43-99
Camera 9	Video tape	NA	Top upstream window	Top of specimen on centerline	NA	43-99

NOTES: 1. Only shadowgraph camera indicates were sent to tabulated data for RUNS 1-42.

2. Camera 2 lost speed control beginning RUN 51.
RUN 55-60, 62 were lost.
Camera 4 was moved to the camera 2 position on RUN 63.

TABLE 5. Instrumentation Locations

a. Gardon Gages, Entry 1, the 12-in. Wedge

Gardon Gage No.	X, in.	Y, in.
1	7.5	0
2	9.0	0
3	10.5	0
4	12.0	0
5	13.5	4.5
6	13.5	3.1
7	13.5	1.75
8	13.5	0
9	13.5	-1.75
10	13.5	-3.1
11	13.5	-4.5

TABLE 5. Concluded

b. Flat Plate Calibration Model Thermocouple

T/C No.	X, in.	Y, in.	Skin Thickness, in.
1	15	0	0.062
2	16		
3	17		
4	18		
5	19		
6	20		
7	21		
8	22		
9	22.5		
10	23.0		
11	23.5		
12	24		
13	24.5		
14	25		
15	25.5		
16	26		
17	26.5		
18	27		
19	27.5		
20	28		
21	28.5		
22	29		
23	29.5		
24	30		
25	31		
26	32		
27	33		
28	21.2	-2	
29	22.2		
30	23.2		
31	24.2		
32	25.2		
33	26.2		
34	27.2		
35	28.2		
36	29.2		
37	30.2		
38	21.7	-4.2	0.063
39	22.7		
40	23.7		
41	24.7		
42	25.7		
43	26.7		
44	27.2		
45	28.7		
46	29.7		
47	30.7		

TABLE 6. Run Summary

RUN	SAMPLE NUMBER	PROTUB. NUMBER	PT psia	TT °R	WA deg	SGA deg	TIME EXPT.
1	Shock cal.	-	97	1905	0.9	5	5.6
2		-	98	1905	9.1		5.7
3		-	98	1896	17.2		5.8
4		-	58	1905	0.9		5.7
5		-	58	1902	9.1		5.8
6		-	58	1896	17.2		5.9
7		-	29	1903	0.9		6.0
8		-	29	1893	9.0		5.9
9		-	28	1899	17.1		6.2
10	CTC18-143	-	29	1899	0.9	-	60.4
11	-144	-	29	1897	9.0	-	61.0
12	-129	-	29	1898	9.0	-	61.9
13	-35	-	29	1899	0.9	5	47.3
14	-101	-	28	1900	0.9		60.8
15	-130	-	29	1893	0.9		61.8
16	-113	-	28	1901	0.9		60.7
17	-102	-	28	1898	9.0		31.3
18	-125	-	29	1901	9.0		41.7
19	-131	-	29	1901	9.0		42.0
20	-145	-	28	1902	9.0		37.1
21	-114	-	27	1896	9.0		41.2
22 *	-51	SN-23	30	1900	9.0		10.0
23	-	CTC18-149	29	1900	0.9	-	84.9
24	-	CTC18-150	28	1899	0.9	-	60.7
25	CTC18-102	-	58	1856	10.0	-	78.3
26	-115	-	58	1902	10.0	-	62.1
27	-132	-	58	1901	10.0	-	61.4
28	-36	-	58	1901	10.0	-	31.8
29	-154	-	58	1902	10.0	-	61.8
30	-104	-	58	1900	9.1	5	27.2
31	-116	-	58	1902	9.0		37.3
32	-146	-	58	1897	9.0		26.6
33	-126	-	58	1901	9.1		37.2
34	-156	-	58	1902	9.1		37.1
35	-105	-	58	1900	17.2		15.9
36	-117	-	58	1900	17.2		26.9
37	-106	-	97	1898	9.1	-	41.3
38	-119	-	97	1900	9.1	-	42.0
39	-147	-	98	1898	9.1	-	31.6
40	-127	-	97	1896	9.1	-	31.6
41	-155	-	97	1903	9.1	-	31.3
42	-107	-	97	1901	17.2	-	26.5
43	-225	-	58	1903	10.0	-	47.4
44	-233	-	58	1901	10.0	-	47.4
45	-217	-	58	1904	10.0	-	47.3
46	-209	-	58	1899	10.0	-	61.9
47	-201	-	58	1902	10.0	-	61.5
48	-241	-	58	1898	10.0	-	33.7
49	-226	-	58	1902	9.0	5	22.0
50	-234	-	58	1902	9.0	5	22.3

* No data taken RUN 22 nominal test conditions given.

TABLE 6. Concluded

RUN	SAMPLE NUMBER	PROTUB. NUMBER	PT psia	TT °R	WA deg	SGA deg	TIME EXPT.
51	CTC18-218	-	58	1902	9.0	5	20.7
52	-210	-	58	1901	9.0	↓	41.8
53	-202	-	58	1898	9.0	↓	40.8
54	-227	-	57	1905	17.2	↓	17.1
55	-235	-	58	1899	17.2	↓	18.0
56	-219	-	59	1896	17.2	↓	16.5
57	-211	-	59	1892	17.2	↓	31.5
58	-203	-	59	1894	17.2	↓	32.1
59	-112	-	59	1900	17.2	↓	21.7
60	-228	-	28	1896	0.9	↓	46.9
61	-236	-	28	1896	1.0	↓	45.9
62	-220	-	29	1903	0.9	↓	47.0
63	-212	-	29	1896	0.9	↓	46.6
64	-204	-	29	1893	0.9	↓	62.0
65	-242	-	29	1899	0.9	↓	31.5
66	-245	-	28	1898	0.9	↓	31.6
67	-229	-	28	1895	9.0	↓	33.3
68	-237	-	29	1899	9.0	↓	33.3
69	-221	-	29	1898	9.0	↓	32.4
70	-213	-	29	1901	9.0	↓	51.6
71	-205	-	29	1902	9.0	↓	49.2
72	-243	-	29	1898	9.0	↓	34.7
73	-246	-	29	1893	9.0	↓	33.4
74	-230	-	29	1900	9.0	-	63.2
75	-238	-	29	1900	9.0	-	61.3
76	-222	-	29	1896	9.0	-	63.2
77	-214	-	29	1901	9.0	-	61.3
78	-206	-	29	1901	9.0	-	55.3
79	-254	-	29	1897	1.0	-	91.4
80	-108	-	58	1896	10.0	-	52.6
81	-123	-	58	1901	8.9	-	24.1
82	-133	-	58	1897	8.9	5	40.9
83	-134	-	58	1900	17.2	5	36.7
84	-231	-	97	1902	9.3	-	25.8
85	-239	-	98	1900	9.0	-	25.9
86	-223	-	98	1899	9.0	-	26.6
87	-215	-	98	1895	9.0	-	46.8
88	-207	-	98	1897	9.0	-	46.3
89	-244	-	98	1899	9.0	-	21.5
90	-142	-	98	1898	9.0	-	26.7
91	-232	-	98	1900	17.2	-	18.8
92	-240	-	97	1900	17.2	-	18.6
93	-224	-	98	1899	17.2	-	18.2
94	-216	-	98	1897	17.2	-	40.7
95	-208	-	98	1897	17.2	-	44.2
96	-151	-	98	1901	17.2	5	61.4
97	-127	-	98	1903	17.3	5	60.8
98	-138	-	97	1901	17.3	5	62.4
99	-247		98	1896	17.3	5	36

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APPENDIX III

SAMPLE TABULATED AND PLOTTED DATA

ARVIN/CALSPAN FIELD SERVICES, INC.
AEDC DIVISION
VON KARMAN GAS DYNAMICS FACILITY
ARNOLD AIR FORCE STATION, TENNESSEE
NASA/RH ET TPS MATERIALS TEST
PAGE 2

DATE COMPUTED 28-AUG-82
TIME COMPUTED 00:16:47
DATE RECORDED 28-AUG-82
TIME RECORDED 0:16:23
PROJECT NUMBER V--C-1P

RUN	SAMPLE	PROTUB.	SGA DEG	ALPHI DEG	WA DEG	CR IN	TIMEINJ SEC	TIMECL HOUR MIN SEC MSEC	TIMEEXPT SEC
99	CTC18-247	NONE	5	-5.27	17.27	26.00	3.117	0 16 33 657	35.71

M	PT PSIA	TI DEG R	T DEG R	P PSIA	Q PSIA	V FT/SEC	RHO LBM/FT3	MU LBF-SEC/FT2	RE FT-1	ITT BTU/LBM	CP BTU/LBM-DEG-R
3.93	97.72	1895.7	486.7	6.683E-01	7.22	4247.9	3.706E-03	3.557E-07	1.376E+06	4.771E+02	2.396E-01

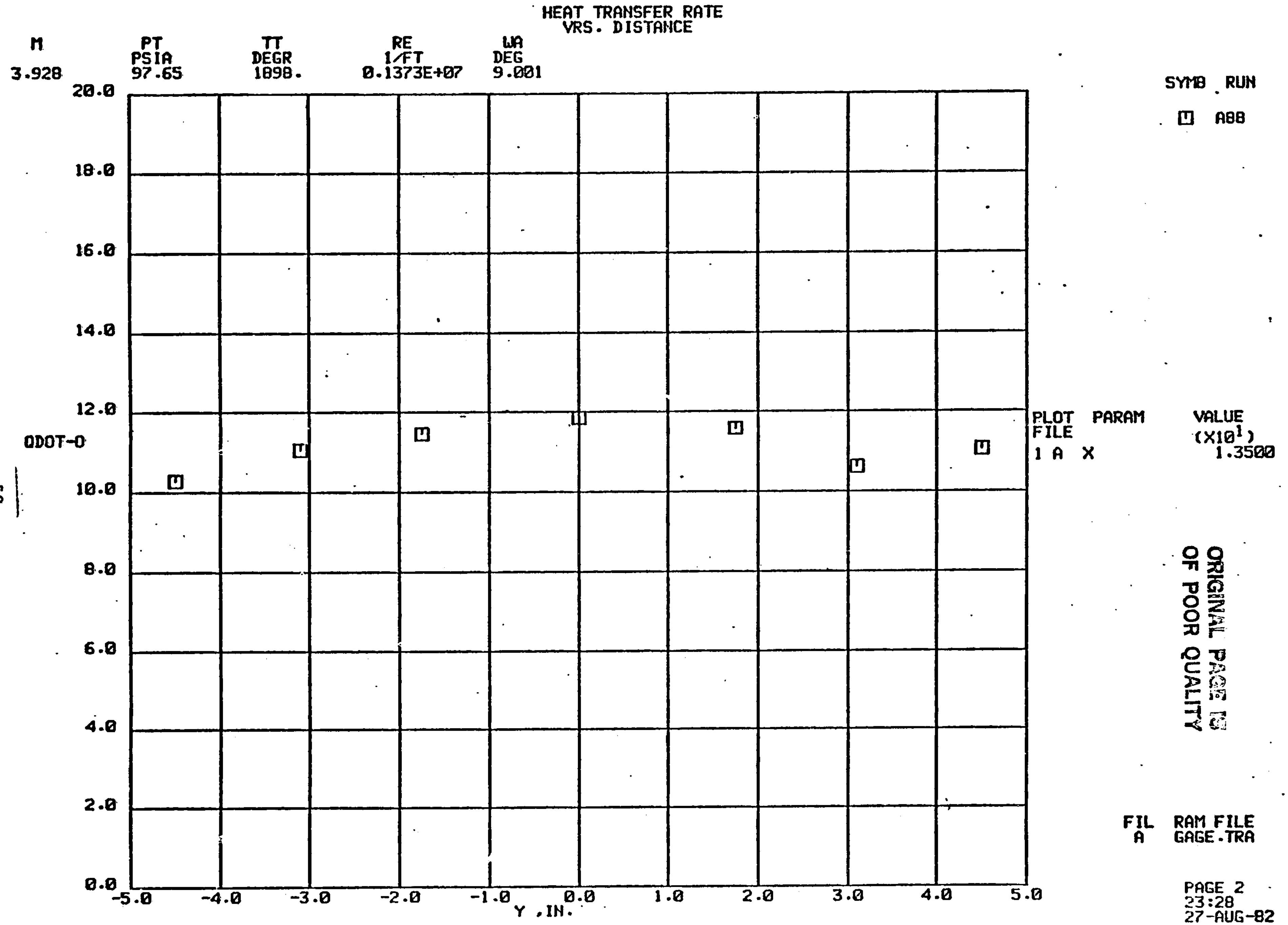
WEDGE GARDON GAGE DATA

GAGE	X (IN)	Y (IN)	TGE (DEG R)	TW (DEG R)	QDOT (BTU/FT2-SEC)	H(TT) (BTU/FT2-SEC-R)	QDOT-0 (BTU/FT2-SEC)	ST	STREX.2
1	7.50	0.00	910.6	966.1	11.89	1.279E-02	1.837E+01	3.392E-03	5.216E-02
2	9.00	0.00	878.4	933.1	12.06	1.253E-02	1.800E+01	3.323E-03	5.300E-02
3	10.50	0.00	846.8	903.5	12.53	1.263E-02	1.813E+01	3.348E-03	5.506E-02
4	12.00	0.00	820.7	872.6	12.46	1.218E-02	1.749E+01	3.229E-03	5.455E-02
5	13.50	4.50	800.8	861.1	12.17	1.176E-02	1.689E+01	3.119E-03	5.394E-02
6	13.50	3.10	805.9	862.2	11.09	1.073E-02	1.541E+01	2.844E-03	4.919E-02
7	13.50	1.75	799.1	870.5	12.54	1.223E-02	1.756E+01	3.242E-03	5.607E-02
8	13.50	0.00	800.9	854.3	12.93	1.242E-02	1.783E+01	3.292E-03	5.694E-02
9	13.50	-1.75	800.5	848.0	12.18	1.163E-02	1.670E+01	3.083E-03	5.333E-02
10	13.50	-3.10	796.5	875.2	12.37	1.212E-02	1.740E+01	3.213E-03	5.558E-02
11	13.50	-4.50	793.9	843.1	11.25	1.069E-02	1.535E+01	2.834E-03	4.901E-02

RUN 99

a. Gardon Gage Data

Sample 1. Heat Transfer Data



NASA/MM ET TPS MATERIALS TEST

b. Heat Transfer Rate vs Y on Centerline
Sample 1. Continued

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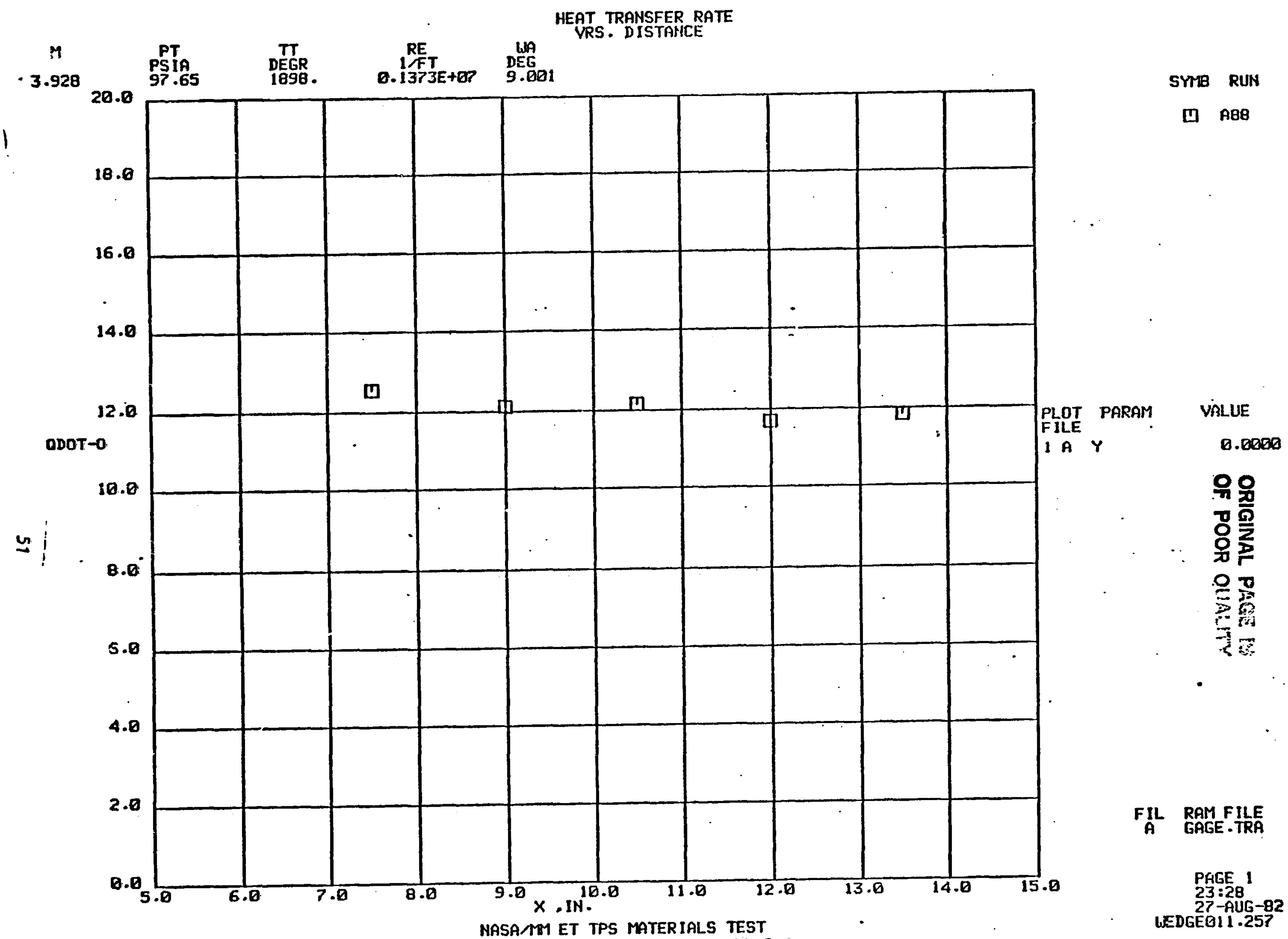

c. Heat Transfer Rate vs Y, X = 13.5 in.
Sample 1, Continued

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ARVIN/CALSPAN FIELD SERVICES, INC.
AEDC DIVISION
VON KARMAN GAS DYNAMICS FACILITY
ARNOLD AIR FORCE STATION, TENNESSEE
NASA/MM OF TPS MATERIALS TEST

DATE COMPUTED 24-MAY-82
TIME COMPUTED 13:23:52
DATE RECORDED 12-APR-82
TIME RECORDED 23:18: 6
PROJECT NUMBER V C 1P

ORIGINAL PAGE IS
OF POOR QUALITY

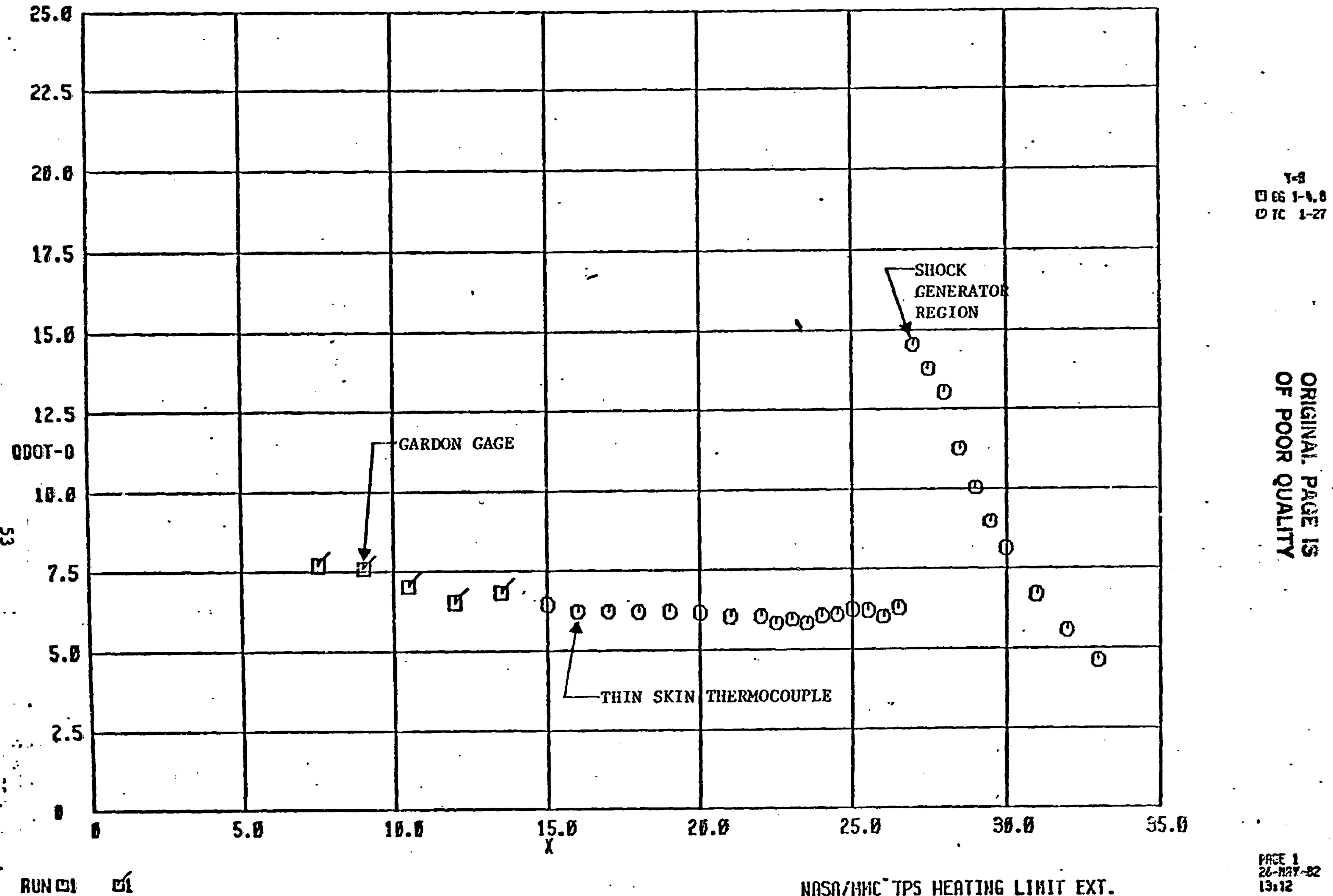
RUN	SAMPLE	PROTUB	ALPHI DEG	WA DEG	CR IN	SGA DEG
1	SHOCK CAL	NONE	11.12	0.88	0.00	5

M	PT PSIA	TT DEG R	T DEG R	P PSIA	Q PSIA	V FT/SEC	RHO LBM/FT3	MU LBF-SEC/FT2	RE FT-1	ITT BTU/LBM
4.00	97.07	1904.7	475.9	6.021E-01	6.74	4277.9	3.414E-03	3.494E-07	1.299E+06	4.795E+02

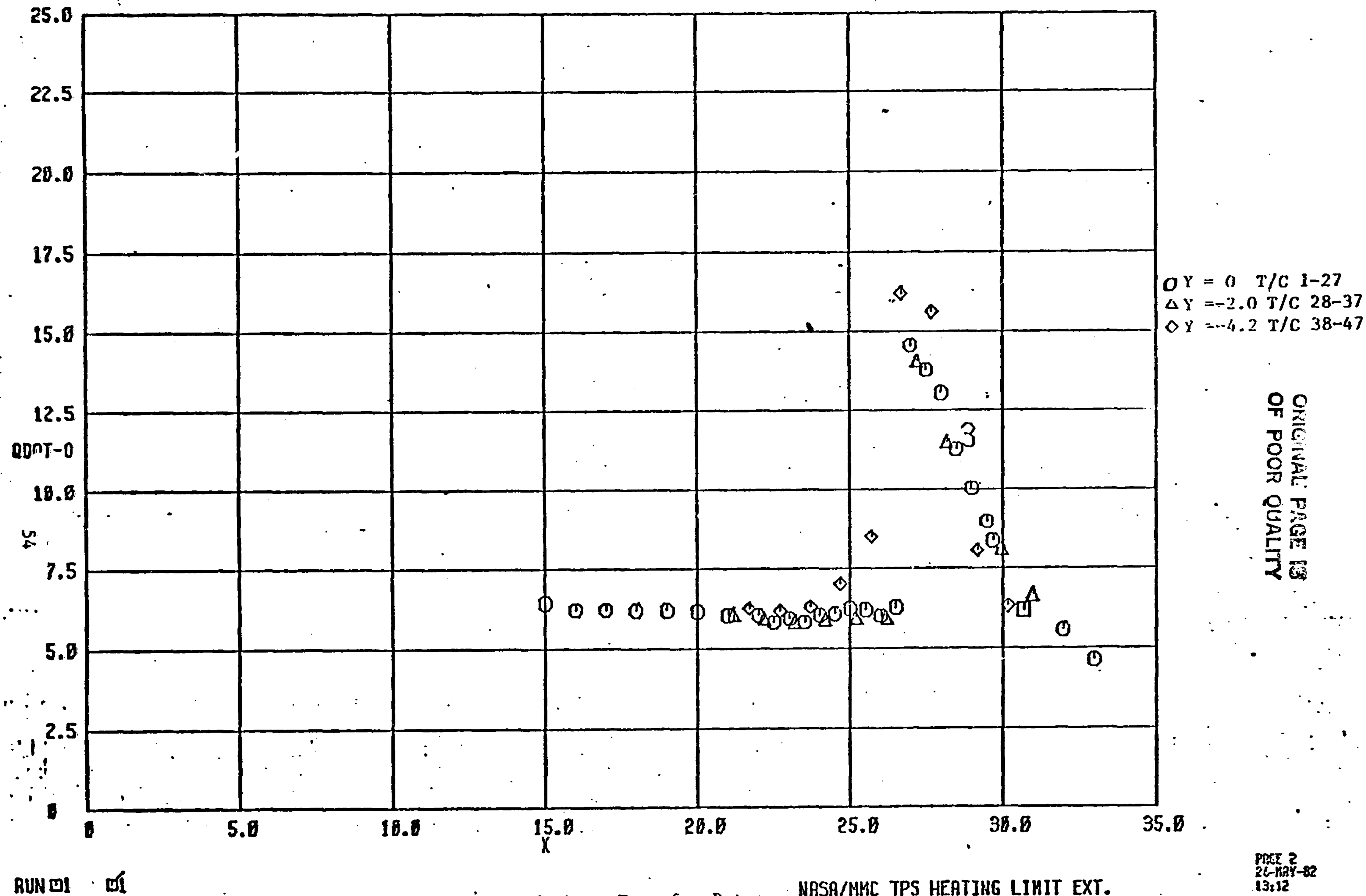
T/C	X (IN.)	Y (IN.)	TW (DEG R)	QDOT (BTU/FT2-SEC)	H(TT) (BTU/FT2-SEC-R)	QDOT-O (BTU/FT2-SEC)	THICK (IN.)	ST	STREX.2
1	15.000	0.000	567.3	5.9663	4.461E-03	6.4452	0.062	1.1890E-03	2.0764E-02
2	16.000	0.000	568.4	5.7659	4.315E-03	6.2334	0.062	1.1499E-03	2.0342E-02
3	17.000	0.000	568.7	5.7661	4.316E-03	6.2352	0.062	1.1502E-03	2.0596E-02
4	18.000	0.000	569.0	5.7438	4.300E-03	6.2126	0.062	1.1460E-03	2.0756E-02
5	19.000	0.000	570.0	5.7361	4.298E-03	6.2089	0.062	1.1453E-03	2.0969E-02
6	20.000	0.000	571.1	5.6910	4.267E-03	6.1649	0.062	1.1371E-03	2.1034E-02
7	21.000	0.000	571.8	5.5800	4.186E-03	6.0478	0.062	1.1155E-03	2.0836E-02
8	22.000	0.000	572.3	5.5794	4.188E-03	6.0496	0.062	1.1158E-03	2.1036E-02
9	22.500	0.000	571.9	5.3807	4.037E-03	5.8324	0.062	1.0757E-03	2.0373E-02
10	23.000	0.000	572.4	5.4762	4.110E-03	5.9382	0.062	1.0952E-03	2.0833E-02
11	23.500	0.000	571.5	5.3733	4.030E-03	5.8226	0.062	1.0740E-03	2.0517E-02
12	24.000	0.000	572.9	5.5719	4.184E-03	6.0443	0.062	1.1148E-03	2.1386E-02
13	24.500	0.000	573.2	5.6162	4.218E-03	6.0939	0.062	1.1239E-03	2.1650E-02
14	25.000	0.000	573.6	5.7489	4.319E-03	5.2395	0.062	1.1507E-03	2.2257E-02
15	25.500	0.000	574.1	5.7190	4.298E-03	6.2093	0.062	1.1451E-03	2.2236E-02
16	26.000	0.000	572.5	5.5500	4.166E-03	6.0186	0.062	1.1100E-03	2.1639E-02
17	26.500	0.000	580.9	5.7525	4.346E-03	6.2779	0.062	1.1573E-03	2.2647E-02
18	27.000	0.000	602.2	13.1288	1.008E-02	14.5621	0.062	2.6816E-03	5.2670E-02
19	27.500	0.000	599.5	12.4666	9.552E-03	13.7990	0.062	2.5414E-03	5.0101E-02
20	28.000	0.000	595.5	11.8350	9.040E-03	13.0595	0.062	2.4057E-03	4.7597E-02
21	28.500	0.000	587.1	10.2992	7.817E-03	11.2924	0.062	2.0811E-03	4.1321E-02
22	29.000	0.000	582.9	9.1958	6.957E-03	10.0507	0.062	1.8527E-03	3.6914E-02
23	29.500	0.000	578.1	8.2403	6.212E-03	8.9743	0.062	1.6547E-03	3.3081E-02
24	30.000	0.000	574.3	7.4825	5.624E-03	8.1255	0.062	1.4985E-03	3.0059E-02
25	31.000	0.000	567.3	6.1879	4.627E-03	6.6844	0.062	1.2332E-03	2.4906E-02
26	32.000	0.000	560.6	5.1871	3.859E-03	5.5754	0.062	1.0289E-03	2.0909E-02
27	33.000	0.000	558.2	4.3017	3.195E-03	4.6155	0.062	8.5190E-04	1.7416E-02
28	21.200	-2.000	571.2	5.6096	4.207E-03	6.0773	0.062	1.1209E-03	2.0977E-02
29	22.200	-2.000	571.9	5.4766	4.109E-03	5.9364	0.062	1.0919E-03	2.0680E-02
30	23.200	-2.000	572.4	5.3950	4.050E-03	5.8503	0.062	1.0790E-03	2.0560E-02
31	24.200	-2.000	573.4	5.4610	4.102E-03	5.9261	0.062	1.0929E-03	2.1002E-02
32	25.200	-2.000	574.2	5.4977	4.132E-03	5.9698	0.062	1.1009E-03	2.1328E-02
33	26.200	-2.000	574.1	5.4979	4.132E-03	5.9694	0.062	1.1009E-03	2.1493E-02
34	27.200	-2.000	600.5	12.6947	9.734E-03	14.0628	0.062	2.5899E-03	5.0934E-02
35	28.200	-2.000	592.9	10.4581	7.973E-03	11.5179	0.062	2.1220E-03	4.2044E-02
36	29.200	-2.000	578.4	7.4066	5.584E-03	8.0676	0.062	1.4875E-03	2.9676E-02
37	30.200	-2.000	569.7	5.8469	4.380E-03	6.3273	0.062	1.1671E-03	2.3444E-02
38	21.700	-4.200	573.6	5.7815	4.344E-03	6.2750	0.063	1.1573E-03	2.1758E-02

d. Thin Skin Data

Sample 1. Continued



e. Heat Transfer Rate on Centerline
Sample 1. Continued



f. Thin Skin Heat Transfer Rates
Sample 1. Concluded

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PAGE 1

DATE COMPUTED 28-AUG-82
TIME COMPUTED 00:16:46
DATE RECORDED 28-AUG-82
TIME RECORDED 0:16:23
PROJECT NUMBER V--C-1P

RUN	SAMPLE	PROTUB.	SGA DEG	ALPHI DEG	KA DEG	CR IN	TIMEINJ SEC	TIMECL HOUR MIN SEC MSEC	TIMEEXPT SEC
99	CIC18-247	NONE	5	-5.27	17.27	26.00	3.117	0 16 33 657	35.71

M	PI PSIA	TI DEG R	T DEG R	P PSIA	Q PSIA	V FT/SEC	RHO LBM/FT3	MU LBF-SEC/FT2	RE FT-1	ITT BTU/LBM	CP BTU/LBM-DEG-R
3.93	97.72	1895.7	486.7	6.683E-01	7.22	4247.9	3.706E-03	3.557E-07	1.376E+06	4.771E+02	2.396E-01

CAMERA	PIC NO.	TIME SEC	TIMEEXP SEC	TP DEG R
TOP	1	0.20		681.8
DS	1	0.20		681.8
TOP	2	3.65	1.90	681.5
DS	2	3.65	1.90	681.5
SEG	1	5.29	3.54	681.5
TOP	3	7.27	5.52	681.7
DS	3	7.27	5.52	681.7
TOP	4	10.93	9.18	681.7
DS	4	10.93	9.18	681.7
TOP	5	14.61	12.86	682.0
DS	5	14.61	12.86	682.0
TOP	6	18.29	16.54	682.0
DS	6	18.29	16.54	682.0
TOP	7	21.96	20.21	682.1
DS	7	21.96	20.21	682.1
DS	8	25.64	23.89	682.2
TOP	8	25.65	23.90	682.5
TOP	9	29.32	27.57	682.3
DS	9	29.32	27.57	682.3
TOP	10	32.97	31.22	682.4
DS	10	32.97	31.22	682.4
TOP	11	36.60	34.85	682.4
DS	11	36.60	34.85	682.4
		35.71	MODEL HAS LEFT CENTERLINE	

RUN 99

Sample 2. Photographic Data