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STRUCTURAL EVALUATION OF CANDIDATE SPACE SHUTTLE THERMAL PROTECTION SYSTEMS

Lockheed Missiles & Space Company, Inc.
A Subsidiary of Lockheed Aircraft Corporation
Space Systems Division
Sunnyvale, California

26 June 1972

Prepared for

NASA — LANGLEY RESEARCH CENTER
Hampton, Virginia 23665

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FINAL REPORT FOR STRUCTURAL EVALUATION OF CANDIDATE SPACE SHUTTLE THERMAL PROTECTION SYSTEMS

CONTRACT NAS 1-11153

Prepared by:

A. Bruce Burns
Project Leader

Approved by:

G. L. Alexander
Asst. Chief Technology Engineer

J. F. Milton
Vice President and General Manager
Space Shuttle Program Division

LOCKHEED MISSILES & SPACE COMPANY

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Section 1
INTRODUCTION

The development of an efficient and economical Space Shuttle vehicle is highly dependent upon the development of a lightweight reusable thermal protection system (TPS). Radiative heat shield systems have been identified as one of the candidate systems which may be capable of meeting the groundrules of 100 mission life with low refurbishment costs and high operational frequency. The feasibility of using such heat shields has been demonstrated analytically. However, demonstration of flight performance capability requires a proper aerodynamic environment to determine overall structural integrity, flutter resistance, extent of hot gas flow in joints and resultant internal heating, and to identify any unforeseen problems that can occur only in the flight environment. To obtain some of the needed test data, the LMSC designed and fabricated a full scale TPS assembly for subsequent tests in the Langley Mach 7-8 ft High Temperature Structures Tunnel.

The following two deliverable items were designed, fabricated, and shipped to the Langley Research Center:

- One 42.5 by 60-in. instrumented assembly for test in the Langley Mach 7, 8-ft, High Temperature Structures Tunnel
- One 22 by 22-in. panel for vibration testing

These test articles consist of metallic substrates with upper surfaces covered with LMSC's all-silica, reusable, surface insulation material for thermal protection systems (TPS). This material, called LI-1500, is processed in the form of tiles. The external surfaces of the tiles are provided with the 0042 coating system, which consists of a borosilicate coating with a silicon carbide emittance agent and impregnation with a hydrophobic agent. Finished tiles with this coating, identified as LI-1542 tiles, are attached to the metal substrate by bonding with RTV-560 adhesive.

This final report presents supporting data and documentation for the test articles. Mr. L. R. Hunt, Structures and Dynamics Division, Thermal Structures Branch, Thermal Protection Section, has been the LaRC Technical Representative for this contract, having replaced Mr. C. P. Shore in January 1972.

Section 2
DESIGN AND ANALYSIS

2.1 DESIGN APPROACH

The two test articles utilize the subpanel approach to the application of reusable surface insulation to the Space Shuttle vehicle. The LI-1542 tiles are attached to a metallic subpanel that is designed to carry only differential pressures across the external wall of the vehicle. The subpanel is supported by internal frames which are an integral part of the vehicle framing system. Structural panels carrying in-plane compression, tension, and shear are attached to the bottom flange of the internal frames.

The vibration test article consists of one subpanel with LI-1542 tiles. Studies conducted at LMSC (Refs. 1 and 2) show that beryllium is the most efficient material for subpanel construction based on thermo-structural optimization techniques. Therefore, this material has been specified for the subpanel for the vibration test article as well as for two identical subpanels in the wind tunnel test assembly. The latter assembly also provides for a simulation of internal frames and primary structure. Titanium has been selected for the internal frames based on the thermal environment and the low thermal conductivity of titanium. An aluminum base plate is used to close the bottom of the test assembly and to simulate primary structure. The two subpanels with LI-1542 tiles do not fill the test cavity; a fairing consisting of titanium plate covered with LI-1542 tiles surrounds the actual test section.

The wind tunnel test assembly is designed to be shipped completely assembled for installation on top of the structural steel cross-beams which exist in the test cavity.

2.2 MATERIAL PROPERTIES/STRUCTURAL INFORMATION.

Current design properties for the LI-1542 material system are presented in Ref. 2, together with substantiating test data. A summary table from this reference is reproduced here as Table 1. Of significance in Table 1 are the data for LI-1500 thermal

Table 1

LI-1500 INSULATION SYSTEM DESIGN PROPERTIES

(ROOM TEMPERATURE UNLESS OTHERWISE NOTED)

PROPERTY (ULTIMATE)	LI-1500		RTV-560 BOND	LI-0042 COATING
	STRONG DIRECTION	WEAK DIRECTION		
TENSION (PSI)	70	15	800	>2000
TENSILE MODULUS (PSI)	60,000	6,000	300	$<9.1 \times 10^6$*
COMPRESSION (PSI)	150	40	-	>2000
COMPRESSION MODULUS (PSI)	50,000	5,000	-	$<9.1 \times 10^6$*
SHEAR (PSI)	40	25	400	-
SHEAR MODULUS (PSI)	20,000	4,000	100	$<3.7 \times 10^6$
	PARALLEL TO FIBER	PERPENDICULAR TO FIBER		
THERMAL EXPANSION (IN./IN./°F)	3.0×10^{-7}	3.0×10^{-7}	1.14×10^{-4}	2.0×10^{-7}**
HEAT CAPACITY (BTU/LB-°F) (RT) (2000°F)	0.15 0.32	0.15 0.32	0.30 -	-
THERMAL CONDUCTIVITY (BTU-IN./FT^2-HR-°F) ~1 ATMOSPHERE (RT) (2000°F)	0.58	0.35 1.56	2.16 -	6.5 14.2
THERMAL CONDUCTIVITY (BTU IN./FT^2 HR-°F) ~ VACUUM (RT) (2000°F)	0.31	0.17 0.67	-	6.5 14.2
EMITTANCE (RT) (2000°F)	- -	- -	- -	0.89 0.93

* LATEST TEST DATA INDICATE MODULUS VALUES OF APPROXIMATELY 1.9×10^6 PSI

** LATEST TEST DATA INDICATE THERMAL EXPANSION COEFFICIENT OF APPROXIMATELY 4.0×10^{-7} IN./IN./°F conductivity, which show a much lower thermal conductivity in vacuum than at one atmosphere. Reference 2 also presents the methods of modeling and analysis for the prediction and evaluation of thermo-structural behavior of a similar LI-1542-covered beryllium subpanel configuration.

Mechanical properties for beryllium cross-rolled sheet, as well as initial compression buckling data, are listed in the table below. Physical properties have been taken from MIL-HDBK-5B and from Ref. 3. In summary, the mechanical and physical properties of beryllium cross-rolled sheet are:

		Room Temperature	$600^{o}F$
F_{TU}	(psi)	70,000	51,000
F_{TY}	(psi)	50,000	40,000
F_{CY}	(psi)	55,000	43,000
E	(psi)	42,500,000	37,000,000
υ		0.0625	–
e	(% in 2 inch)	5	–
α	(in./in./F)	6.5×10^{-6}	8.1×10^{-6}
K	(Btu/[hr-ft^2-F/FT])	104	82
C	(Btu/lb F)	0.445	0.615

Tensile properties and elongation at room temperature noted above conform to the requirements of military specification MIL-B-8964 and Lockheed specification LAC-07-4008A. Material for this program was procured to the latter specification.

The titanium specified for this program was annealed Ti-6Al-4V to specification MIL-T-9046F. Properties of this material are presented in MIL-HDBK-5B.

2.3 LOADS/TRAJECTORY DATA

The design loads for the test articles are identical to those specified by NASA/MSC for Contract NAS9-12083 (see Ref. 2). A summary of these loads for vehicle Area 2 (the forward portion of the wing lower surface) is presented in Fig. 1. This vehicle location is subjected to higher differential pressures and higher maximum surface temperatures than the aft portion of the wing lower surface shown as Area 1 on the figure.

It may be seen that maximum collapse and burst differential pressures occur during ascent when the maximum surface temperature is less than 200°F. During post-entry cruise maneuvers, differential panel pressures peak at values which are roughly half the values attained during ascent. At this time, the maximum surface temperature has cooled to approximately 100°F, but the internal vehicle temperature is rising toward the arbitrary maximum of 300°F established for aluminum primary structure. This maximum is reached after the vehicle has come to a dead stop. Note that the maximum surface temperature is reached when there is relatively low differential pressure across the shell wall.

Plots of collapse and burst differential pressure versus time for both ascent and entry, as taken from the NASA/MSC requirements for Contract NAS9-12083, are presented in Figs. 2 and 3, respectively. These plots, as well as data in Fig. 1, show a significantly longer time for entry from 400,000 feet than is currently contemplated; for example, see Fig. 4. This figure has been reproduced from Ref. 4 and presents lower centerline surface temperature and heating rate data for the 040A Orbiter. Maximum temperatures in the region of interest remain at approximately 2300°F; time from 400,000 ft., however, is reduced to 2000 sec. Based on this more current information, the recommended test pulse for the wind tunnel test assembly that simulates entry spans 2000 sec, as noted elsewhere in this report, and the data of Figs. 2 and 3 are suitably modified in the test pulse to be compatible.

Design sound pressure levels for the test articles are presented in Fig. 5, as taken from the NASA/MSC requirements for Contract NAS9-12083. Maximum SPLs occur during ascent, at launch and separation, for relatively short time intervals. A lower SPL is experienced during entry, but over a substantially longer period of time.

OPERATION	ELAPSED TIME	DIFFERENTIAL PRESSURE (LIMIT) (PSI) COLLAPSE	BURST	SPL (dB)	MAXIMUM SURFACE TEMPERATURE (°F)	MAXIMUM ALUMINUM BACKFACE TEMPERATURE (AMBIENT) (°F)
LAUNCH	—	—	—	160		R.T.
ASCENT	60 SEC 67 SEC 75 SEC	+4.0 — +1.8	-3.0 — -1.9	150 161 155	≈200	R.T. R.T. R.T.
ENTRY	10 MIN 25-45 MIN	+0.1 +1.5	-0.0 -0.5	- 141	2300 1850-400	-150 <300
POST - ENTRY CRUISE	45-60 MIN	+2.0	-0.5	124	≈100	< 300
LANDING	60 MIN	+0.5	-0.5	124	≈100	< 300
DEAD STOP	> 60 MIN	—	—		≈100	300

- PLUS PRESSURE IS COLLAPSE (VENTING ALLOWANCE INCLUDED)
- FACTOR-OF-SAFETY BETWEEN LIMIT AND ULTIMATE IS 1.5

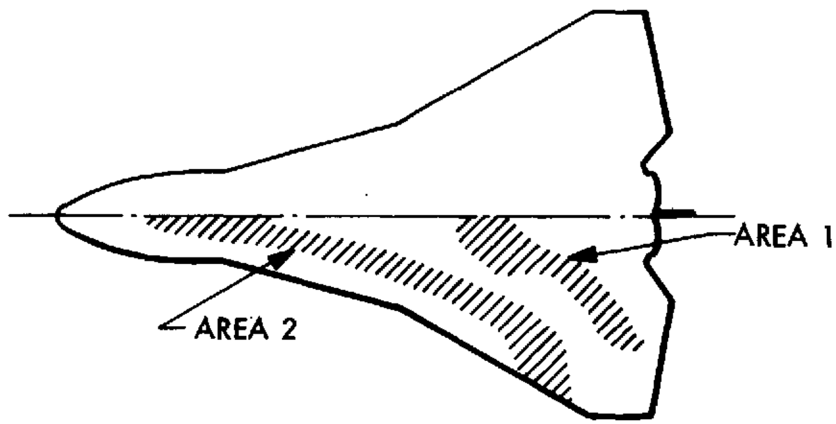


Fig. 1 Summary of Area 2 Orbiter Shell Design Conditions

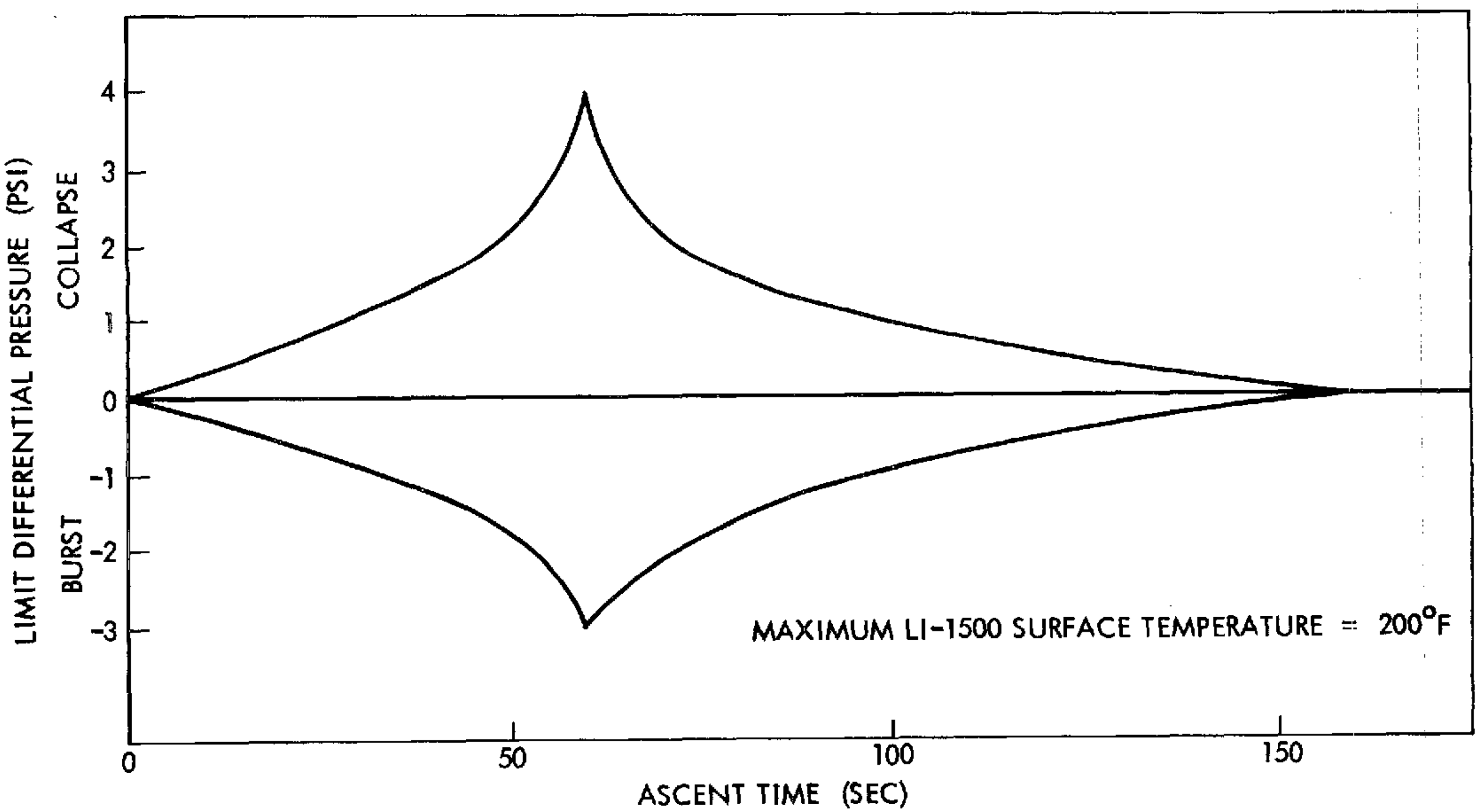


Fig. 2 Limit Differential Panel Pressures During Ascent

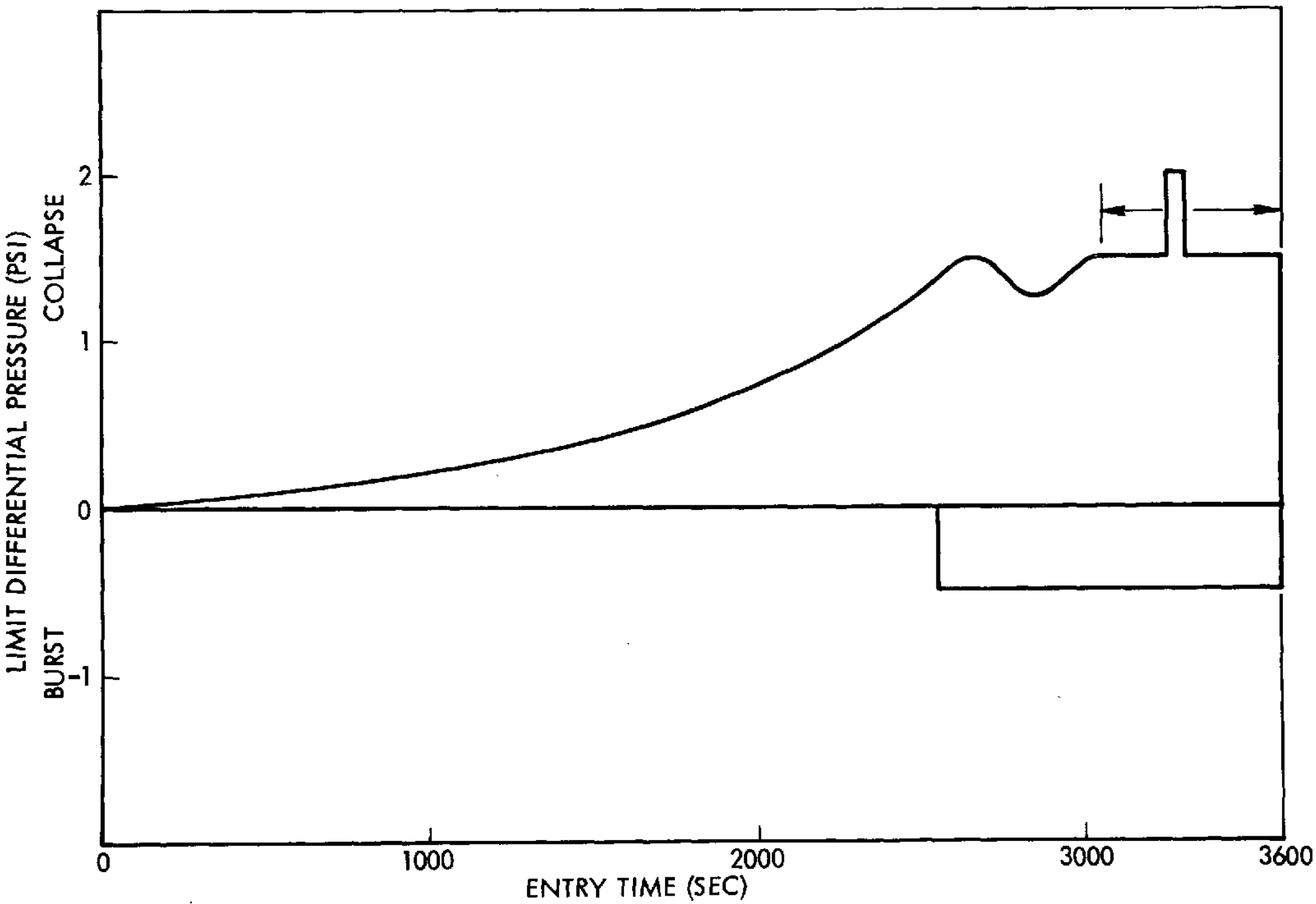


Fig. 3 Limit Differential Panel Pressures During Entry

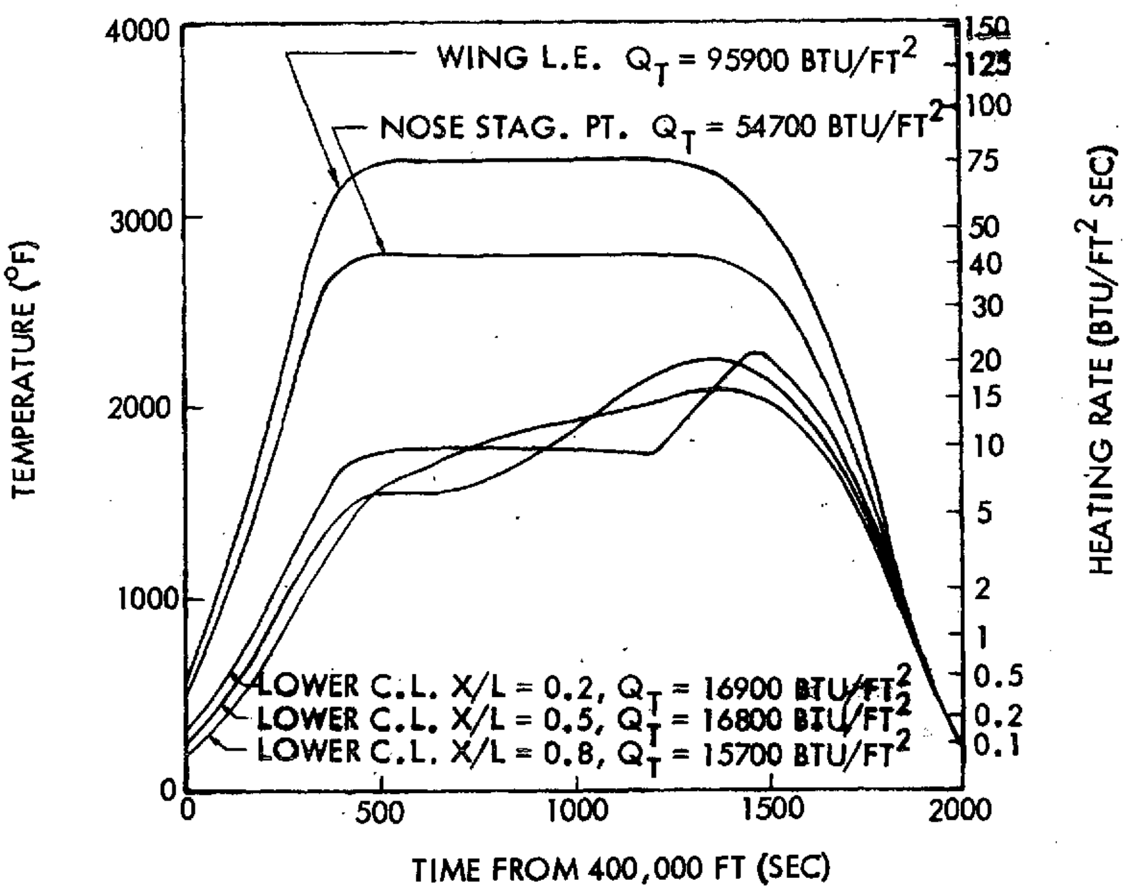


Fig. 4 O40A Orbiter Surface Temperature and Heating Rate Histories Based on Trajectory RE-230

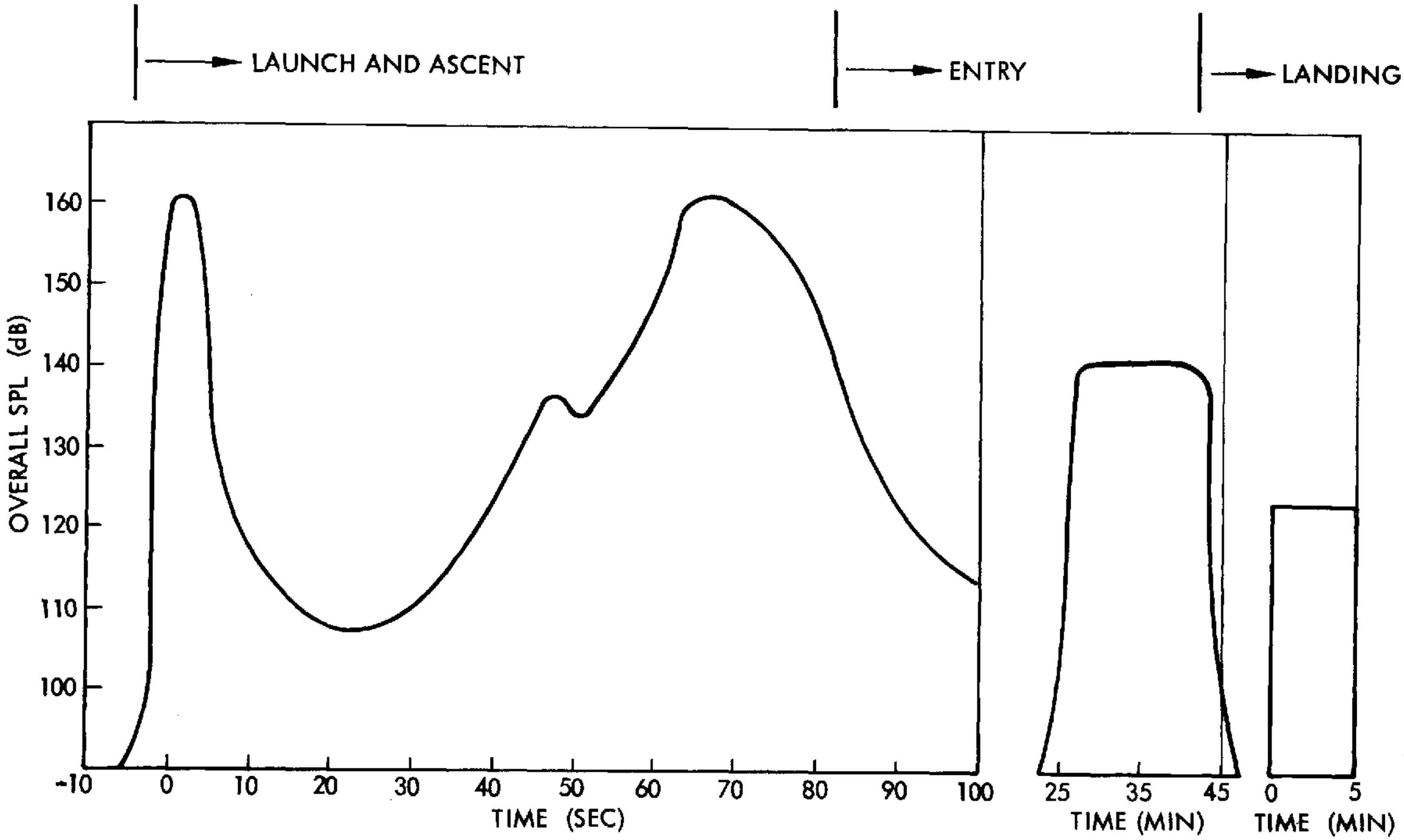


Fig. 5 Overall SPS Versus Time – Typical Orbiter Mission

2.4 SUMMARY OF MARGINS OF SAFETY

The beryllium subpanels have been thermo-structurally optimized for ascent loads (6 psi ultimate collapse pressure and 4.5 psi ultimate burst pressure at room temperature). In sizing the subpanels, the heat sink capacity of beryllium has been taken into account, and weight tradeoff studies between beryllium and LI-1500 have been conducted. These studies show that the optimum LI-1542-covered beryllium subpanel requires somewhat greater affective thickness than that required for strength alone. Therefore, the margins of safety for the subpanel are generally high at room temperature, and may be shown to be positive at 600°F for the same loads:

Part	Mode	MS at R. T.	MS at 600°F
Edge Angles	Comp. Buckling	0.87	0.56
Skin	Bending	High	High
End Frames	Comp. Buckling	High	High
Rivets	Shear	0.60	0.31
Skin	Inter-Rivet Buckling	High	High
Interior Frames	Flange Comp. Buckling	0.51	0.19
Interior Frames	Skin Side Comp. Buckling	0.21	0.02
Interior Frames	Tension	0.52	0.11

The LI-1542 material system has not been analyzed specifically for this program because analyses for almost identical design conditions have been performed previously for Contract NAS9-12083. A summary of these calculations is reproduced from Ref. 2 as Table 2. Note that the tile length for the present program is somewhat smaller (11 in. versus 12 in.); thus, stresses in the tiles should be somewhat lower. Note also that the maximum backface temperatures expected in the test articles are less than the 550 and 600°F values cited in Table 2 (see Section 4, Test Plan). Nevertheless, the stresses developed from these differentials, as shown in Table 2, do not exceed the material allowables.

Margins of safety for the titanium fairing and channels are as follows:

Part	Mode	MS at R. T.
Fairing	bending	high
Channels	flange bending	0.32
	section bending	high

Table 2

MAXIMUM STRESSES FOR BERYLLIUM FLIGHT PANEL NO. 1
ORBITER FUSELAGE AREA 2 (CONTRACT NAS 9-12083)

COATING THICK = 0.010 IN. LI-1500 THICK = 1.224 IN. RTV-560 THICK = 0.090 IN. TILE LENGTH = 12 IN.

LOADING CONDITIONS		PRESSURE (PSI) AXIAL LOAD	6.75 COLLAPSE 0	3 COLLAPSE * 0	1.5 BURST * 0	0 * 0
TEMPERATURE		SURFACE (°F)	75	100	100	75
		BACKFACE (°F)	75	550	550	600
MAXIMUM STRESSES (PSI)	LI-1500	PRIN. TEN.	35	60	64	64
		PRIN. COMP.	- 17	- 32	- 25	- 31
		SHEAR	8	12	12	14
		LONG.	35	60	64	64
		NORMAL TEN.	3	5	12	9
		NORMAL COMP.	- 13	- 6	- 5	- 4
	RTV-560	PRIN. TEN.	5	11	19	16
		PRIN. COMP.	- 17	- 17	- 17	- 17
		SHEAR	4	10	10	11
		LONG.	- 7	- 14	- 13	- 13
		PEEL	3	6	14	10
	COATING	PRIN. TEN.	0	6	1283	598
		PRIN. COMP.	-2207	-310	0	- 86

MATERIAL PROPERTIES	E (PSI)	G (PSI)	μ	α (IN./IN./F°)
COATING	9.1×10^6	3.9×10^6	0.17	0.2×10^{-6}
LI-1500	60,000 (L), 6,000 (T)	4150	0.3	0.3×10^{-6}
RTV-560	300 (RT) - 200 (500°-600°F)	100 (RT) - 67 (500°-600°F)	0.5	115.0×10^{-6}
SUBSTRATE	42×10^6 (RT) - 37.2×10^6 (600°F)	20×10^6 (RT) - 18.8×10^6 (600°F)	0.1	5.15×10^{-6} (RT) 7.7×10^{-6} (600°F)

* EXCEPT FOR COATING STRESS ALL VALUES CORRESPOND TO PANEL EXPANSION IN DIRECTION PERPENDICULAR TO STIFFENERS

A check of the steel support beams mounted in the LaRC test cavity yields a margin of 0.25 for section bending under the applied load.

2.5 WEIGHT DATA

A complete breakdown of the weight of the vibration test article is as follows:

	Weight (lb)	
Beryllium Subpanel	3.47	
Titanium Support Frame	2.16	
Bolts, Shims	0.32	
Metallic Substrate		5.95
LI-1542 Tiles (22 by 22 in. Area)	5.30	
FI-600 Filler Strips	0.08	
RTV-560 Bond	2.53	
LI-1542 Material System		7.91
Total Vibration Test Article Weight		13.86

Note that four LI-1542 tiles are bonded to this particular test article. These nominally 11 by 11 by 1.25 in. tiles have measured densities of 16.1, 16.7, 15.3 and 15.1 lb/cu ft. Also, the average measured bondline thickness is 0.097 in., compared to a calculated bondline thickness of 0.083 in. based on the manufacturers published density for RTV-560 of 90.5 lb/cu ft.

A complete breakdown of the weight of the wind tunnel test assembly is as follows:

	Weight (lb)	
Forward Beryllium Subpanel	3.54	
LI-1542 Tiles (23 by 23 in. Area)	6.54	
FI-600 Filler Strips (23 by 23 in. Area)	0.16	
RTV-560 Bond	2.53*	
Forward Panel Weight		12.77

*Calculated

Section 3
FABRICATION

The following drawings were released to Manufacturing for fabrication of the test articles:

- SKW 100511C, dated 21 Jan. 1972, Thermal Test Panel, NASA Langley
- SKW 100512B, Sheets 1 through 4, dated 24 Jan. 1972, TPS-Langley Test Assembly and Details

The vibration test article was called out as a -503 assembly on drawing SKW 100511C. The complete package of drawings was required to fabricate the wind tunnel test assembly.

Some minor modifications were authorized during the course of fabrication which are not shown on the above-noted drawings. These changes, together with several drafting errors, have been identified in a set of red-lined prints which accompany this report.

Following fabrication of the beryllium subpanel for the vibration test article, it was mutually agreed with the LaRC Technical Representative to furnish a titanium support frame to which the beryllium subpanel would be attached. An overall height limitation of 1.0 in. was placed on this frame so that the height of the vibration test article would not exceed an overall height restraint imposed by the test fixture. Details of the support frame do not appear on the drawings because this requirement developed after the drawings had been released. The frame was fabricated from sketches supplied by the Program Office, copies of which are included in this report as Appendix A.

Figures 6 through 15 show the test articles during various stages of manufacture. Figures 6 and 7 present views of one of the completed beryllium subpanels, while the completed vibration test article may be seen in Fig. 8. The remaining figures show details of the wind tunnel test assembly. Figures 9 and 10 illustrate the titanium substructure and fairing; one of the beryllium subpanels is shown in place in Fig. 11. A view of the completed metallic structure with the initial layer of RTV-560 applied is presented in

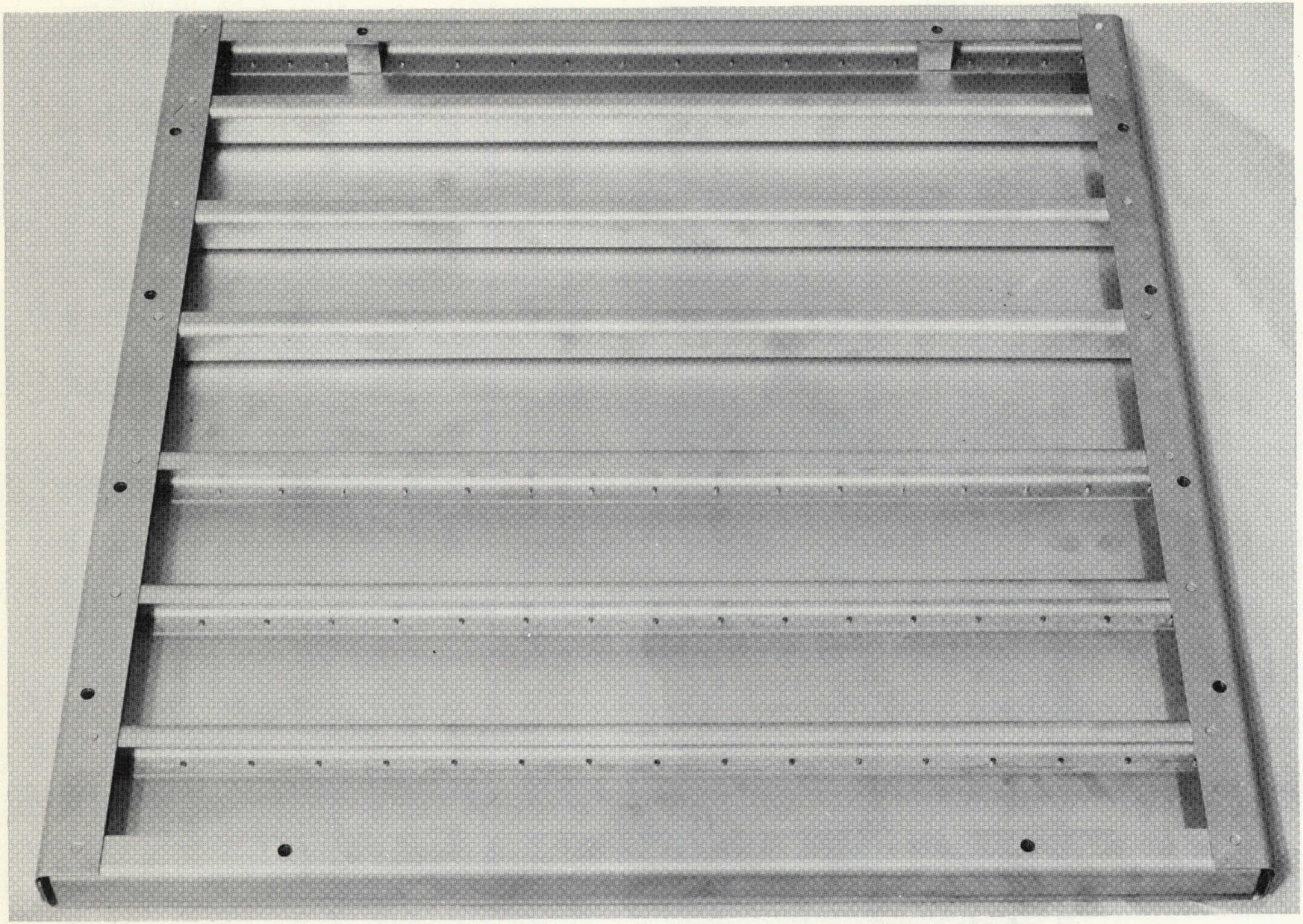


Fig. 6 Bottom View of Beryllium Subpanel
(Note beryllium spacer blocks at top of photo)

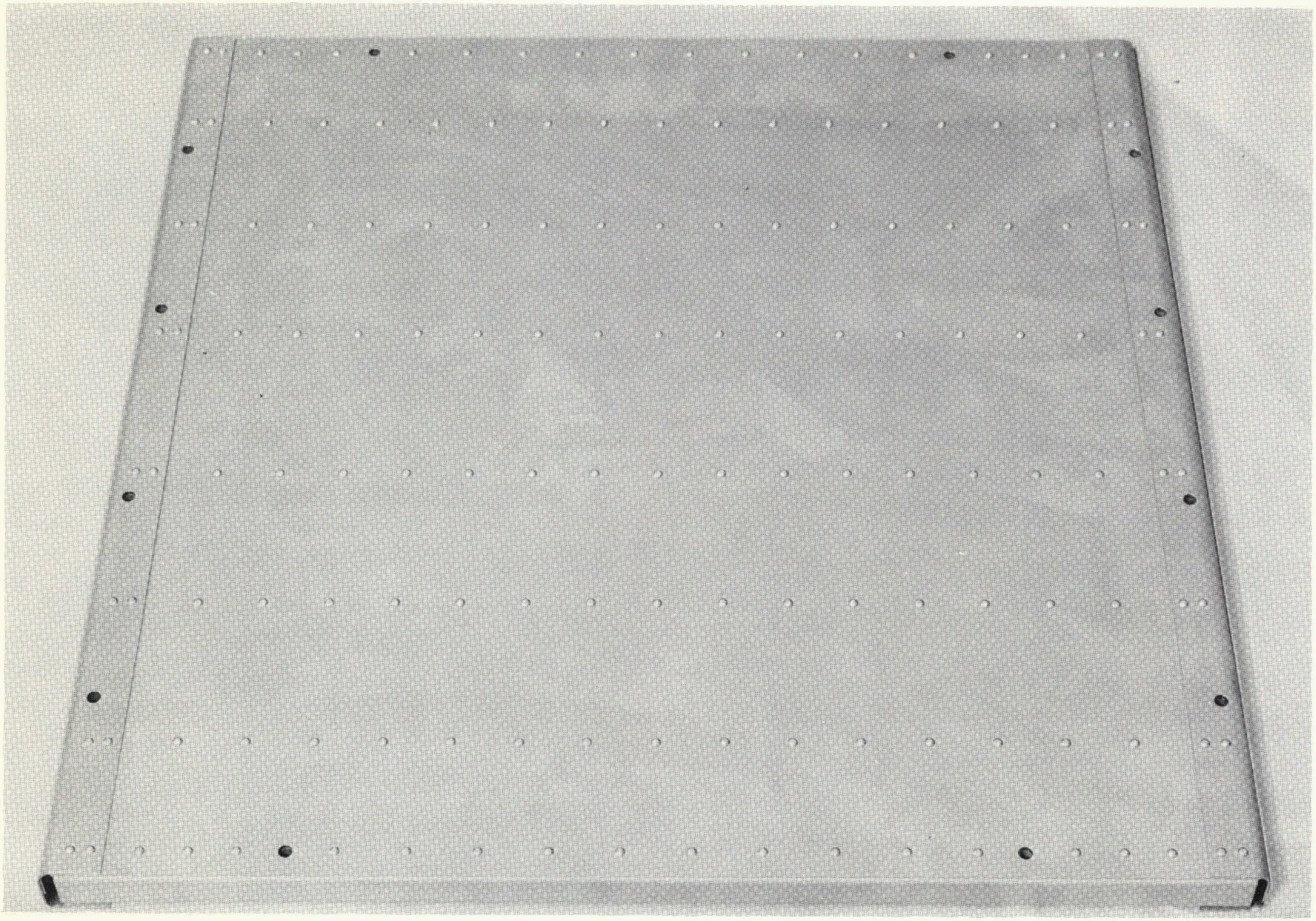


Fig. 7 Top View of Beryllium Subpanel

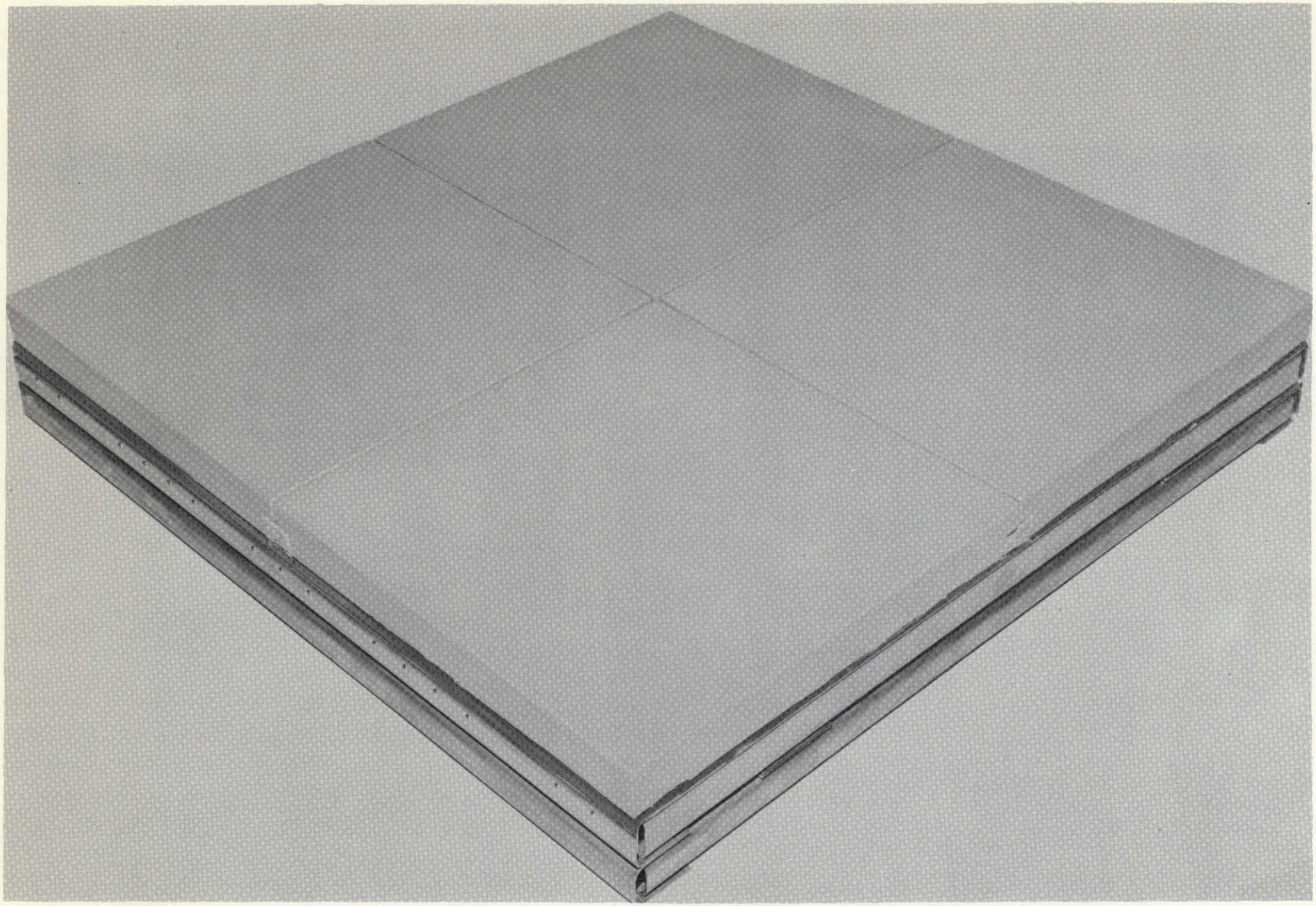


Fig. 8 Completed Vibration Test Article: LI-1542 Tiles Bonded to Beryllium Subpanel; Subpanel Bolted to Titanium Support Frame (Note FI-600 filler strips at panel centerlines)

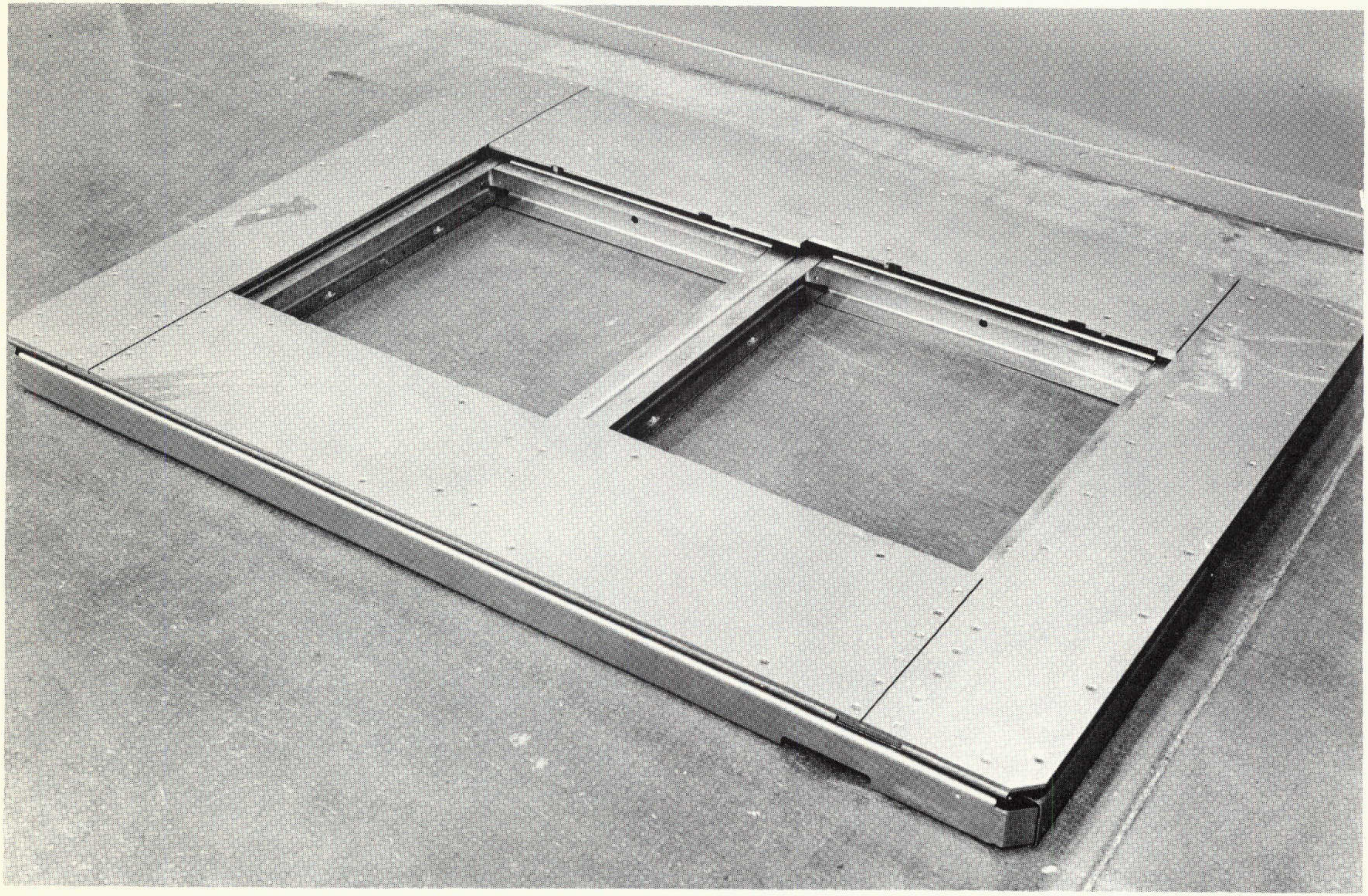


Fig. 9 Top View of Titanium Substructure and Fairing for Wind Tunnel Test Assembly

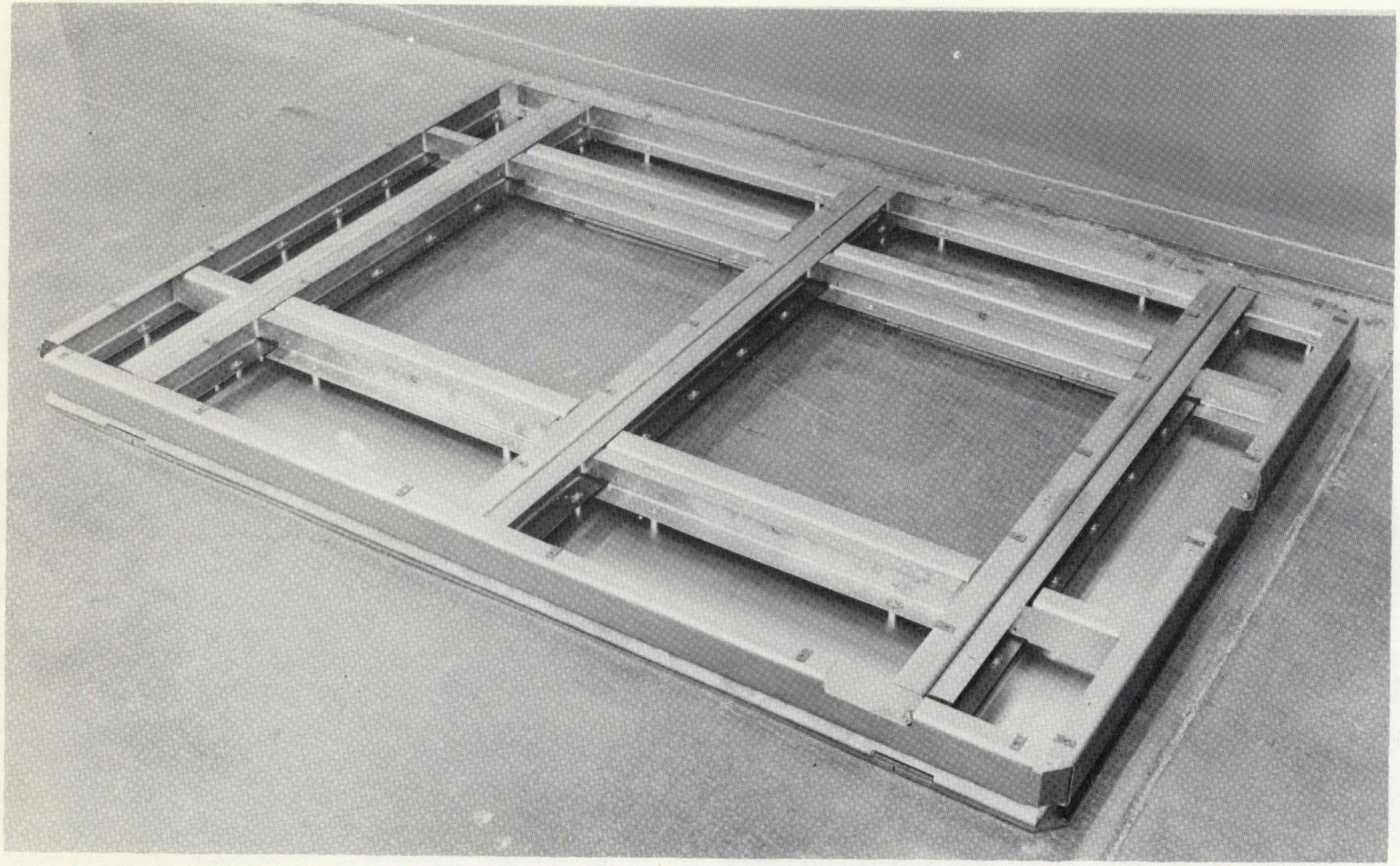


Fig. 10 Bottom View of Titanium Substructure and Fairing for Wind Tunnel Test Assembly

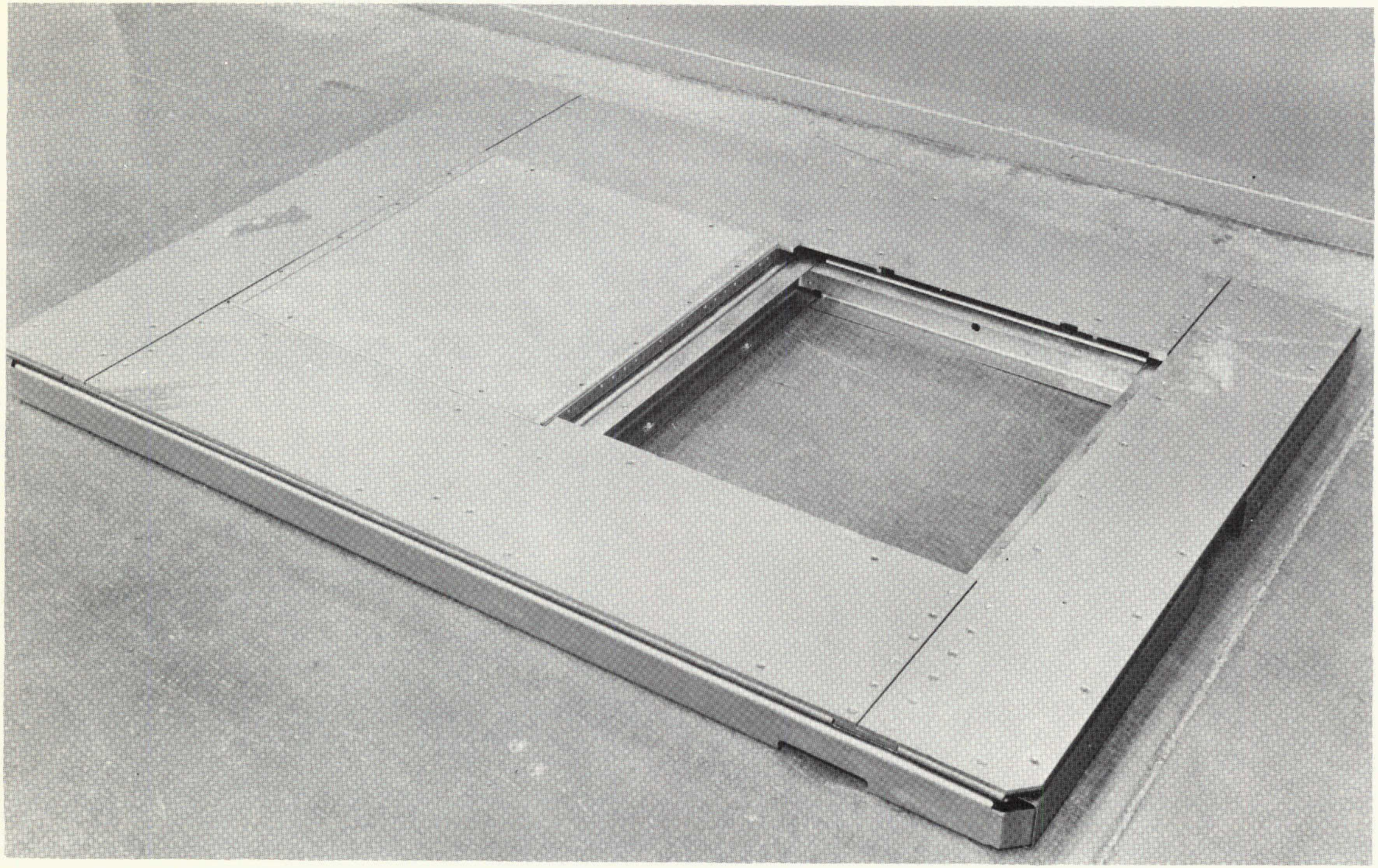


Fig. 11 Top View of Titanium Substructure and Fairing for Wind Tunnel Test Assembly With Forward Beryllium Subpanel in Place

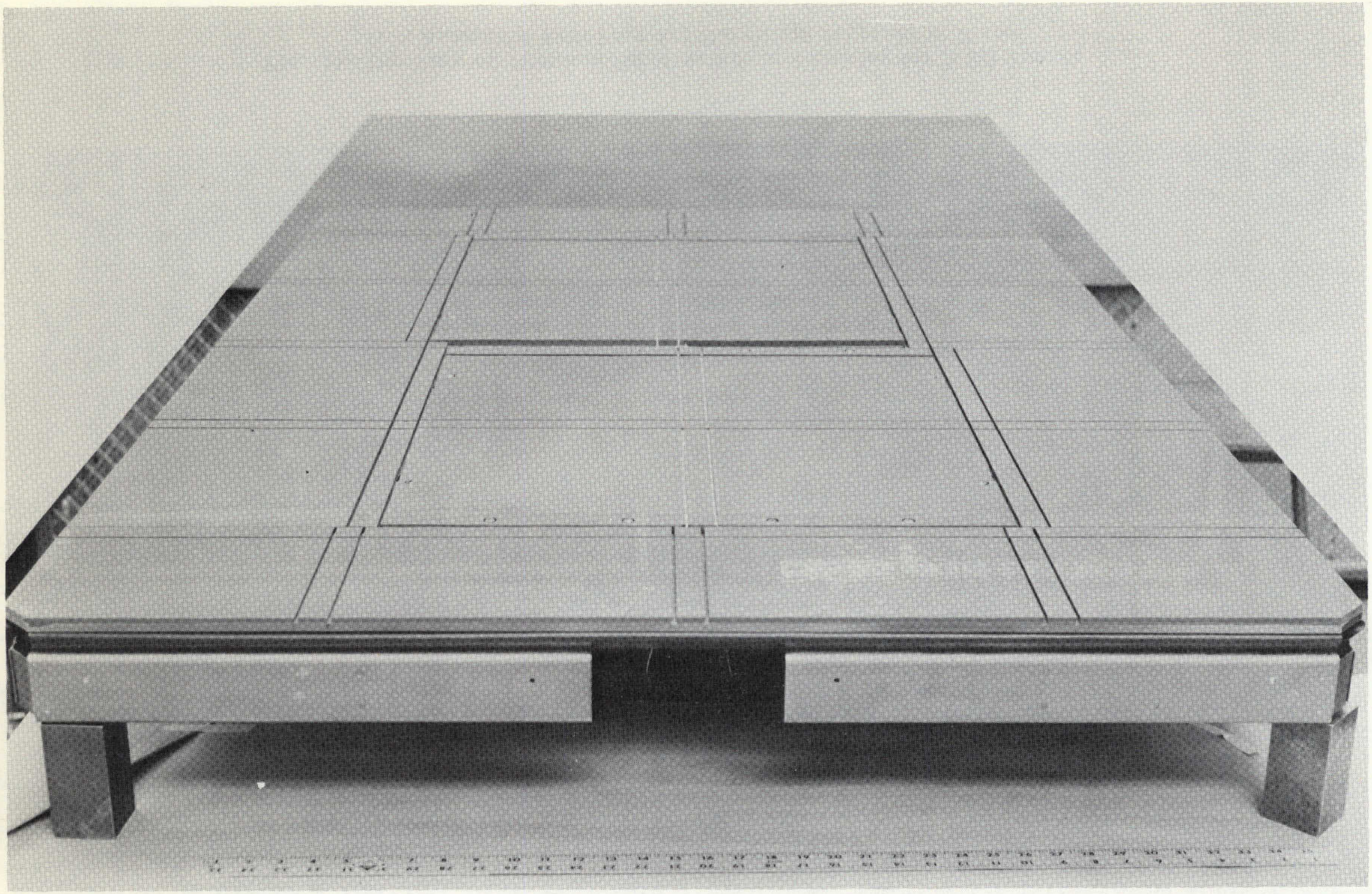


Fig. 12 View of Wind Tunnel Test Assembly With Initial Layer of RTV-560 Bond Applied Over Entire Upper Surface of Beryllium Subpanels and Titanium Fairing (Note discontinuities in bond layer at FI-600 filler strip locations to reduce stresses in LI-1542 tiles)

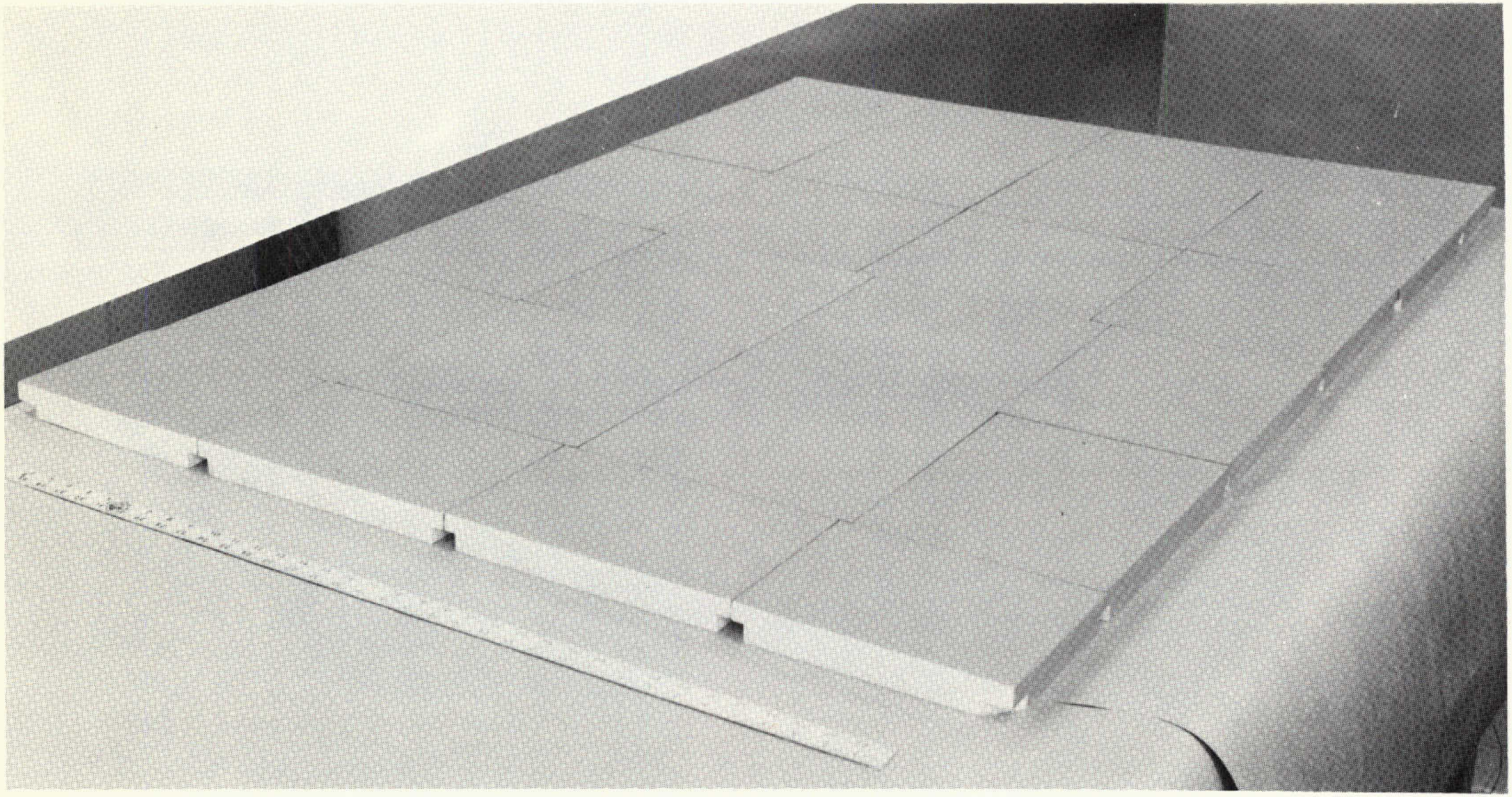


Fig. 13 Array of LI-1542 Tiles for Wind Tunnel Test Assembly Prior to Bonding

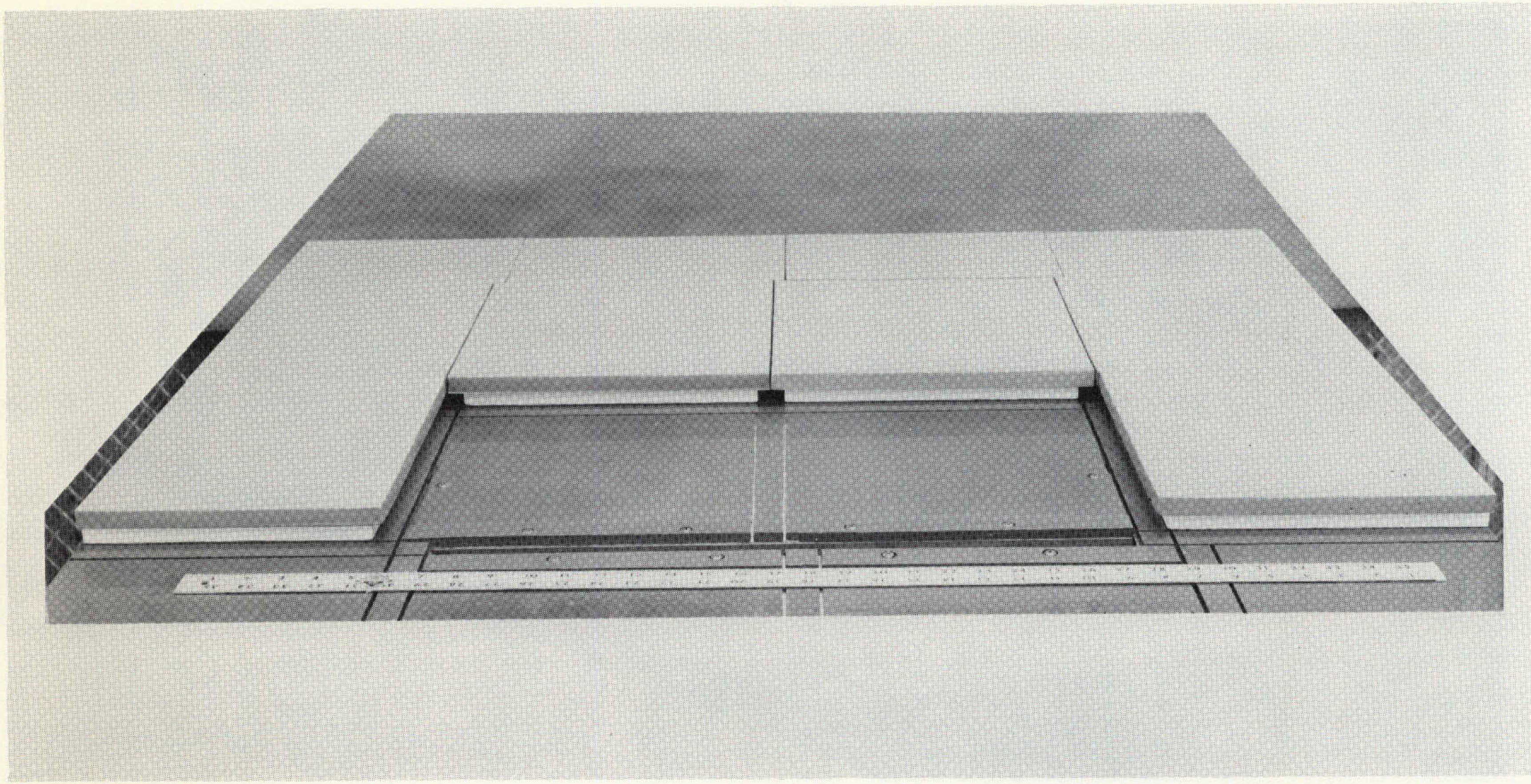


Fig. 14 View of Forward Top Surface of Wind Tunnel Test Assembly With LI-1542 Tiles Positioned (but not bonded) in Place (Note position of tiles with respect to discontinuities in initial RTV-560 bond layer)

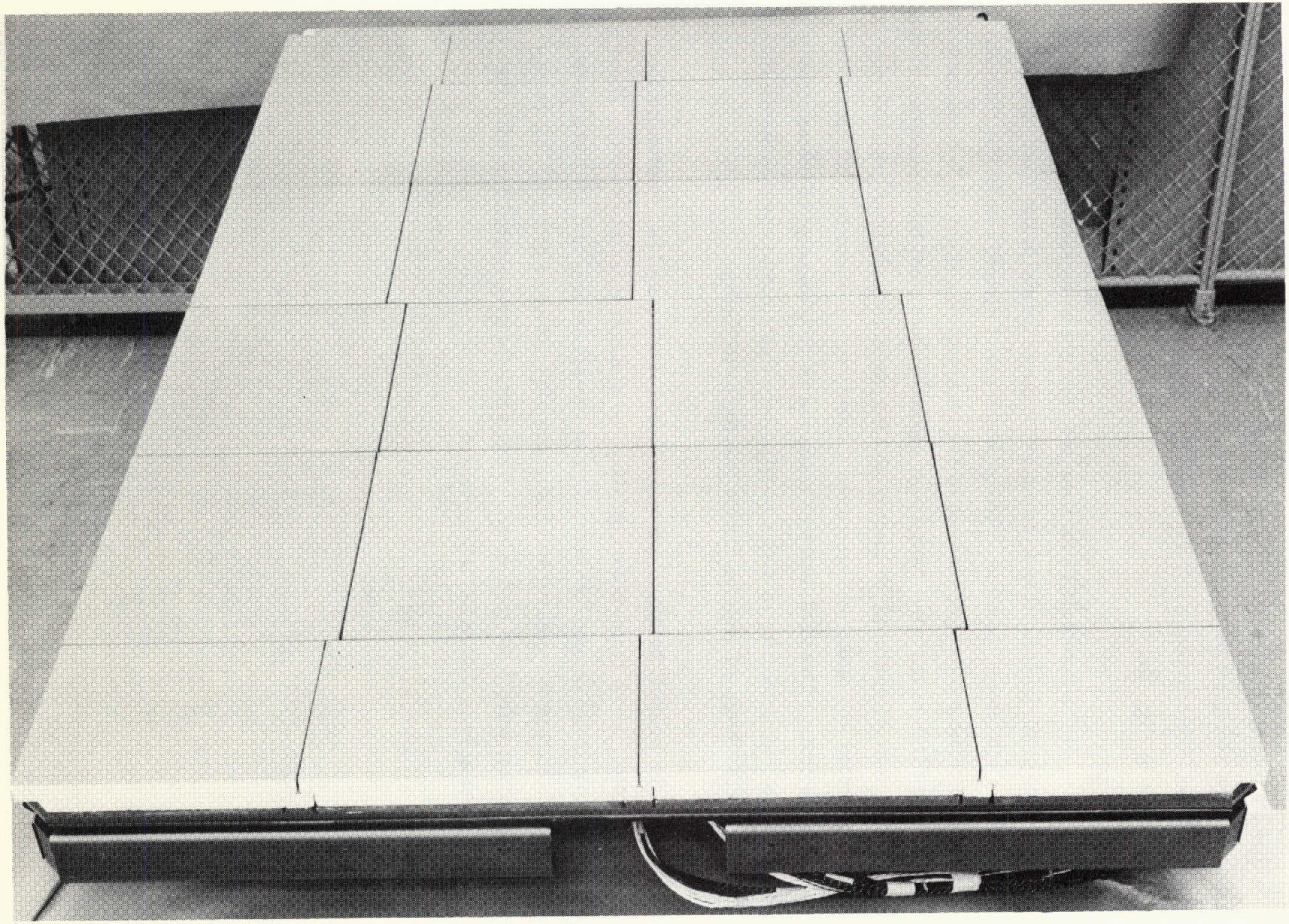


Fig. 15 Aft View of Completed Wind Tunnel Test Assembly
Prior to Attachment of Aluminum Base Plate

Fig. 12, while the array of LI-1542 tiles for the wind tunnel test assembly may be seen in Fig. 13. Figure 14 shows the forward portion of the top of the wind tunnel test assembly with LI-1542 tiles in place but not bonded. The completed wind tunnel test assembly is shown in Fig. 15.

An X-ray inspection of the completed vibration test article was conducted and films are available in the Program Office. These films show minor voids in the tiles and the bond which are not considered serious. Areas of the panel directly over the titanium support frame cannot be monitored because of the poor transmission of X-rays through titanium. Similar films of the wind tunnel test assembly were not taken because of the presence of the 1/4-m. titanium plate fairing and the titanium substructure. X-ray films would not reveal any detail in these areas, which cover about two-thirds of the surface of the assembly. The decision was made not to risk damage to the assembly by moving it to the X-ray facility in order to film only those clear areas beneath the beryllium subpanels which, of course, are transparent to X-rays.

Measurements of the overall height of the wind tunnel test assembly, (including the aluminum base plate), were taken before crating the assembly for shipment. These measurements were taken around the periphery of the assembly, and all were between 4.98 and 5.00 in., except for measurements at the aft starboard corner. Measurements at this location were 5.00 to 5.03 in. These values are compatible with the 5.0-in. height available in the LaRC test cavity.

	Weight (lb)	
Aft Beryllium Subpanel	3.51	
LI-1542 Tiles (23 by 23 in. Area)	5.78	
FI-600 Filler Strips (23 by 23 in. Area)	0.16	
RTV-560 Bond	2.53*	
Aft Panel Weight		11.98
Titanium Fairing	72.13	
LI-1542 Tiles	15.88	
FI-600 Filler Strips	0.42	
RTV-560 Bond	19.14*	
Fairing Weight		107.57
Titanium Substructure and Seals		27.44
Aluminum Base Plate		8.10
Bolts, Spacers, Shims		3.06
Instrumentation		4.58
Total Wind Tunnel Test Assembly Weight		175.50

Densities of the individual tiles are presented in Table 3. In this table, the tile identifications are those used during prooessing, and they do not necessarily agree with the tile numbering system shown on Sheet 4 of Drawing SKW 100512B.

Conversions in the numbering system are presented for the eight 11.5 by 11.5 by 1.25 in. tiles, which were bonded to the two beryllium subpanels.

*Calculated

Table 3

DENSITIES OF TILES IN WIND TUNNEL TEST ASSEMBLY

LI-1542 Tile Size (in.)	Tile Process No.	Tile Dwg No.	Tile Density (lb/cu ft)
11.5 by 11.5 by 1.25	-1	I	17.0
11.5 by 11.5 by 1.25	-2	II	17.7
11.5 by 11.5 by 1.25	-3	III	18.2
11.5 by 11.5 by 1.25	-4	VI	15.2
11.5 by 11.5 by 1.25	-5	V	15.1
11.5 by 11.5 by 1.25	-6	IV	15.3
11.5 by 11.5 by 1.25	-7	VII	14.6
11.5 by 11.5 by 1.25	-14	VIII	15.4
9.7 by 6.9 by 1.25	-15		14.3
9.7 by 6.9 by 1.25	-26		16.7
9.7 by 6.9 by 1.25	-18		16.3
9.7 by 6.9 by 1.25	-25		16.1
11.5 by 10 by 1.25	-13		16.7
11.5 by 10 by 1.25	-8		13.8
11.5 by 10 by 1.25	-12		16.9
11.5 by 10 by 1.25	-19		14.4
11.5 by 9.2 by 1.25	-20		15.2
11.5 by 9.2 by 1.25	-11		14.4
11.5 by 9.2 by 1.25	-21		15.8
11.5 by 9.2 by 1.25	-10		14.5
11.5 by 6.9 by 1.25	-23		14.9
11.5 by 6.9 by 1.25	-24		14.8
11.5 by 6.9 by 1.25	-17		14.1
11.5 by 6.9 by 1.25	-16		16.4

Section 4
INSTRUMENTATION

Thermocouples and strain gages were installed in the wind tunnel test assembly according to drawing SKJ 205025, Sheets 1 and 2, dated 20 January 1972, "Instrumentation Installation, TPS-Langley Test Assembly." As with the manufacturing drawings, some minor modifications were authorized between drawing release and installation of the instrumentation, and these changes/additions have been identified on red-lined prints, which accompany this report. The principal addition is a table cross-referencing the connector identification number with identification numbers for the thermocouples and strain gages. This information is presented here in Table 4, which also gives the connector pin hookups and the location of the individual thermocouples and strain gages. Note that cable leads from the thermocouples and strain gages were routed to the rear of the assembly and then combined into a single bundle. The length of the bundled cables from the rear edge of the assembly to the connectors is approximately 8-1/2 feet.

Thermocouples 1-48 are installed in the eight LI-1500 tiles in the test section (over the beryllium subpanels). Each tile carries between four and seven thermocouples. Note that thermocouples along the sides of each tile and in the corners are positioned to be within 1/8 in. of the edge of the tile. Lead wires are laid in grooves cut in the bottom of the tile and held in place with RTV-560 adhesive bond. The grooves lead to the center of the outboard edge of each tile. In general, the thermocouples were installed with leads which reached just beyond the edge of the tile; after the adhesive bond had set up, the required cable length was joined to these leads. This approach resulted in instrumented tiles that could be bonded relatively easily; the cable was threaded through slots in the titanium fairing, and the instrumented tile was laid in place.

Continuity in the instrumentation was checked at several stages. After the bonding operation, two open thermocouples were found: Nos. 19 and 37. Number 19 is the surface thermocouple in tile II, while Number 37 is the center thermocouple in a

Table 4

CONNECTOR IDENTIFICATION TABLE

Connector	T/C No.	Location* (LI-1500 Tile No.)	A	B	C	D
1	1	I	+	-		
	2	I			+	-
2	3	III	+	-		
	4	I			+	-
3	5	I	+	-		
	6	I			+	-
4	7	I	+	-		
	8	I			+	-
5	9	III	+	-		
	10	III			+	-
6	11	III	+	-		
	12	III			+	-
7	13	III	+	-		
	14	III			+	-
8	15	II	+	-		
	16	II			+	-
9	17	IV	+	-		
	18	II			+	-
10	19	II	+	-		
	20	IV			+	-
11	21	IV	+	-		
	22	IV			+	-
12	23	V	+	-		
	24	V			+	-
13	25	VII	+	-		
	26	VII			+	-
14	27	V	+	-		
	28	V			+	-
15	29	VII	+	-		
	30	VII			+	-
16	31	VII	+	-		
	32	V			+	-

Table 4 (Cont.)

Connector	T/C No.	Location* (LI-1500 Tile No.)	A	B	C	D
17	33	V	+	-		
	34	VII			+	-
18	35	VI	+	-		
	36	VI			+	-
19	37	VI	+	-		
	38	VI			+	-
20	39	VI	+	-		
	40	VIII			+	-
21	41	VIII	+	-		
	42	VIII			+	-
22	43	VIII	+	-		
	44	VIII			+	-
23	45	VIII	+	-		
	46	VI			+	-
24	47	VI	+	-		
	48	VIII			+	-
25	59	TITANIUM CHANNELS (MAX. TEMP. = $425^{o}F$)	+	-		
	60				+	-
26	61		+	-		
	62				+	-
27	63		+	-		
	64				+	-
28	65		+	-		
	66				+	-
29	67		+	-		
	68				+	-
30	69		+	-		
	70				+	-
31	71		+	-		
	72				+	-
32	73		+	-		
	74				+	-
33	75		+	-		
	76				+	-

Table 4 (Cont.)

Connector	T/C No.	Location* (LI-1500 Tile No.)	A	B	C	D
34	77	Aluminum	+	-		
	78	Base Plate			+	-
35	79	With S/G's on Beryllium Panels	+	-		
	80				+	-
36	81		+	-		
	82				+	-
37	83		+	-		
	84				+	-
38	85		+	-		
	86				+	-
39	87		+	-		
	88				+	-
	S/G No.					
40	49	Beryllium Panels	+		-	O/P
41	50		+		-	O/P
42	51		+		-	O/P
43	52		+		-	O/P
44	53		+		-	O/P
45	54		+		-	O/P
46	55		+		-	O/P
47	56		+		-	O/P
48	57		+		-	O/P
49	58		+		-	O/P

*Ref. Dwg. SKJ 205025, Sheet 1

3-thermocouple plug in tile VI. These could not be repaired. It was felt that the problem was in the cable juncture mentioned previously. Attempts were made to inspect the suspect junctures, but these attempts were abandoned when it became apparent that the junctures were virtually inaccessible and there was substantial risk of damage to the other junctures for cables leading into the tile.

The elevated temperature strain gages on the beryllium subpanels have been installed using a high-temperature cement which was cured at 525°F. The temperature of each gage will be monitored by a separate thermocouple, as noted in Table 4. The strain gages are installed in a half-bridge configuration as shown by the solid lines in Fig. 16. The dashed lines, showing resistors which complete the Wheatstone bridge represent portions of the instrumentation to be supplied by LaRC.

In the arrangement of Fig. 16, one gage is the active gage, mounted on the actual structure, while the other gage is a dummy gage, usually mounted on an unstressed piece of the same material in close proximity to the active gage. Thus, both gages

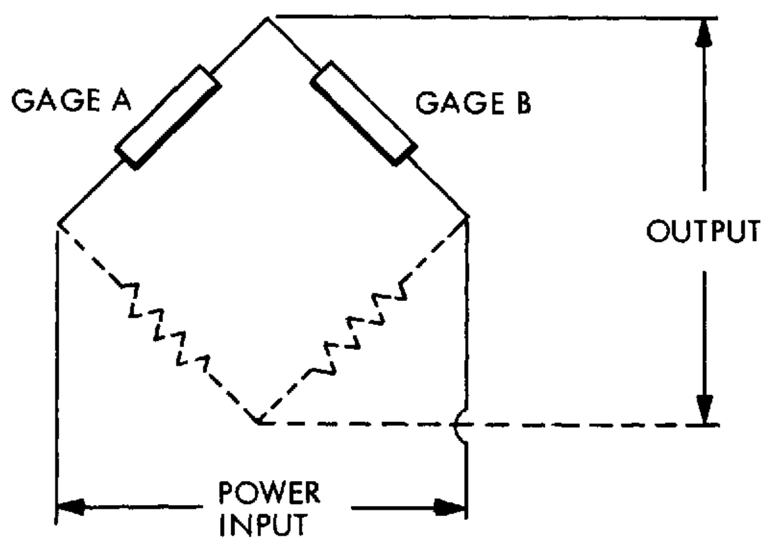


Fig. 16 Strain Gage Installation Schematic

are subjected to the same temperature, and the thermal strain in the dummy gage can be subtracted automatically from the active gage strain with the result that temperature-compensated mechanical strains are obtained from the active gage.

There is some difficulty in placing a dummy gage on a piece of material so that it experiences the same temperature as the active gage, while experiencing zero mechanical stress. In the present case, the dummy gages were placed on the same surface perpendicular to the active gages. This ensures that both the active and dummy gages are subjected to the same temperature but it involves the risk of possible mechanical straining of the dummy gages.

Mechanical straining in the dummy gage direction on the outstanding flanges of the channel stiffeners will be negligible. For those gages mounted on the beryllium panel skin between stiffeners, analysis has been performed which shows that the maximum (bending) stress in the transverse direction is 150 psi, while the maximum stress in the longitudinal direction is 11,700 psi at the centerline of the panel and 8800 psi at the quarter-point of the panel. These stresses are all based on a collapse pressure of 6 psi (ult.).

Beam theory has been used, and the stiffening effect of the LI-1500 and bond line has been considered in the transverse direction. A weak direction compressive modulus of 5000 psi of LI-1500 was employed in these calculations; use of the strong direction modulus, or any increase in the weak direction modulus, will decrease the 150 psi maximum stress in the transverse direction noted above. In summary, some mechanical straining of the dummy gages mounted on the beryllium panel skin will occur, but it will be small and the error involved probably is no greater than the temperature error in dummy gages mounted on an unstressed piece of the same material. Note that the same conclusions do not necessarily hold for all loading conditions. Studies made for Contract NAS9-12083 (Ref. 2) revealed transverse strains higher than longitudinal strains for the case of tiles with 100°F outer surfaces and 500°F inner surfaces (touchdown condition), in combination with a 1.5 psi burst pressure. However, the maximum stresses are substantially lower than 150 psi in both directions in this case.

Predictions of readings of the strain gages mounted on the beryllium subpanels are presented in Fig. 17; likewise, predictions of beryllium panel deflections are given in Fig. 18. Predictions for a range of burst and collapse pressures are given at room temperature and at 475°F. All strains in Fig. 17 are based on an elastic beryllium modulus. Actually, some plasticity will be experienced by gage No. 57 under a 6 psi collapse pressure, but it will be minor; i.e., the prediction here is slightly low. Note that the deflections anticipated are rather low, being less than 0.08 in. under a 6-psi collapse pressure.

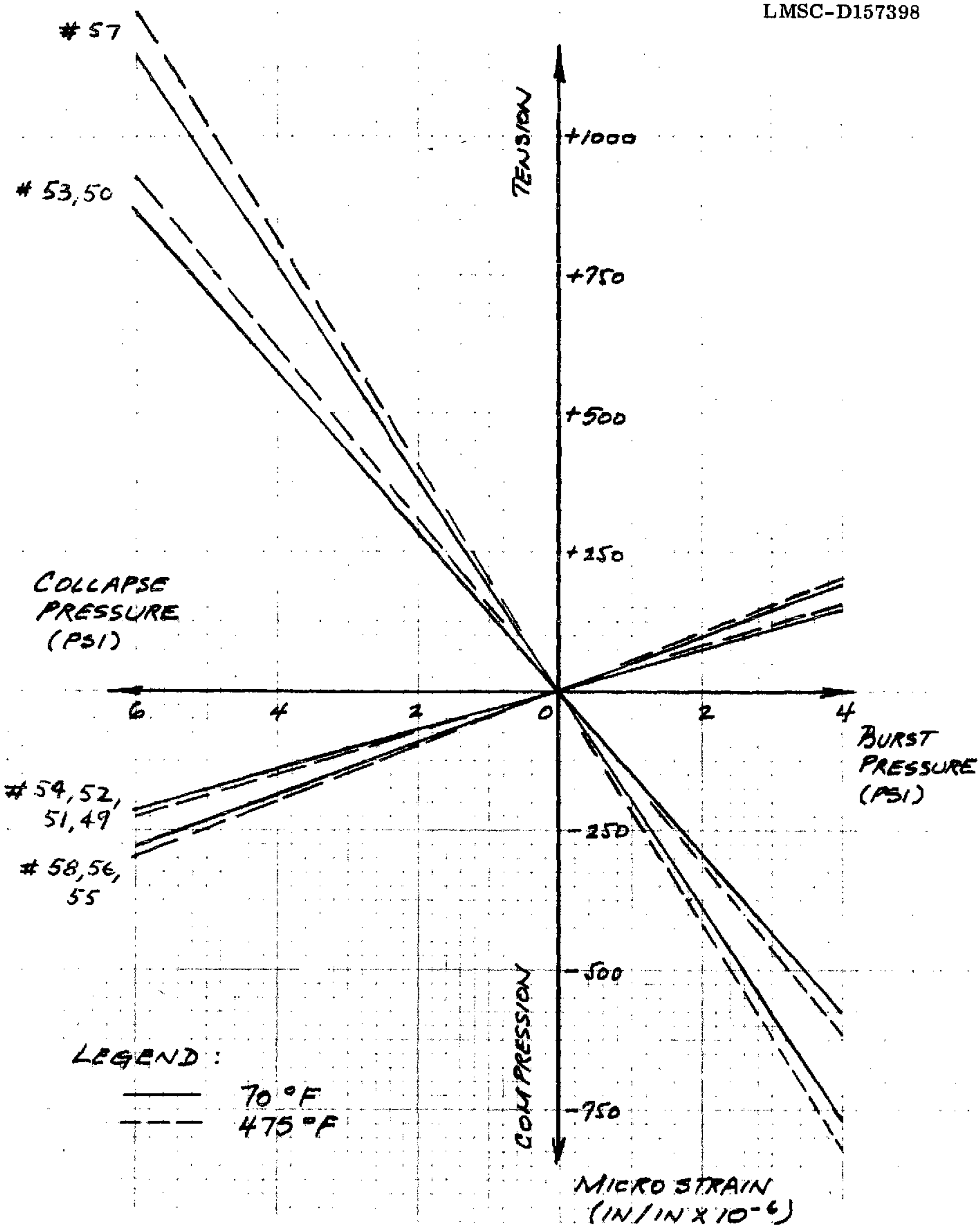


Fig. 17 Strain Gage Reading Predictions for LMSC Wind Tunnel Test Assembly

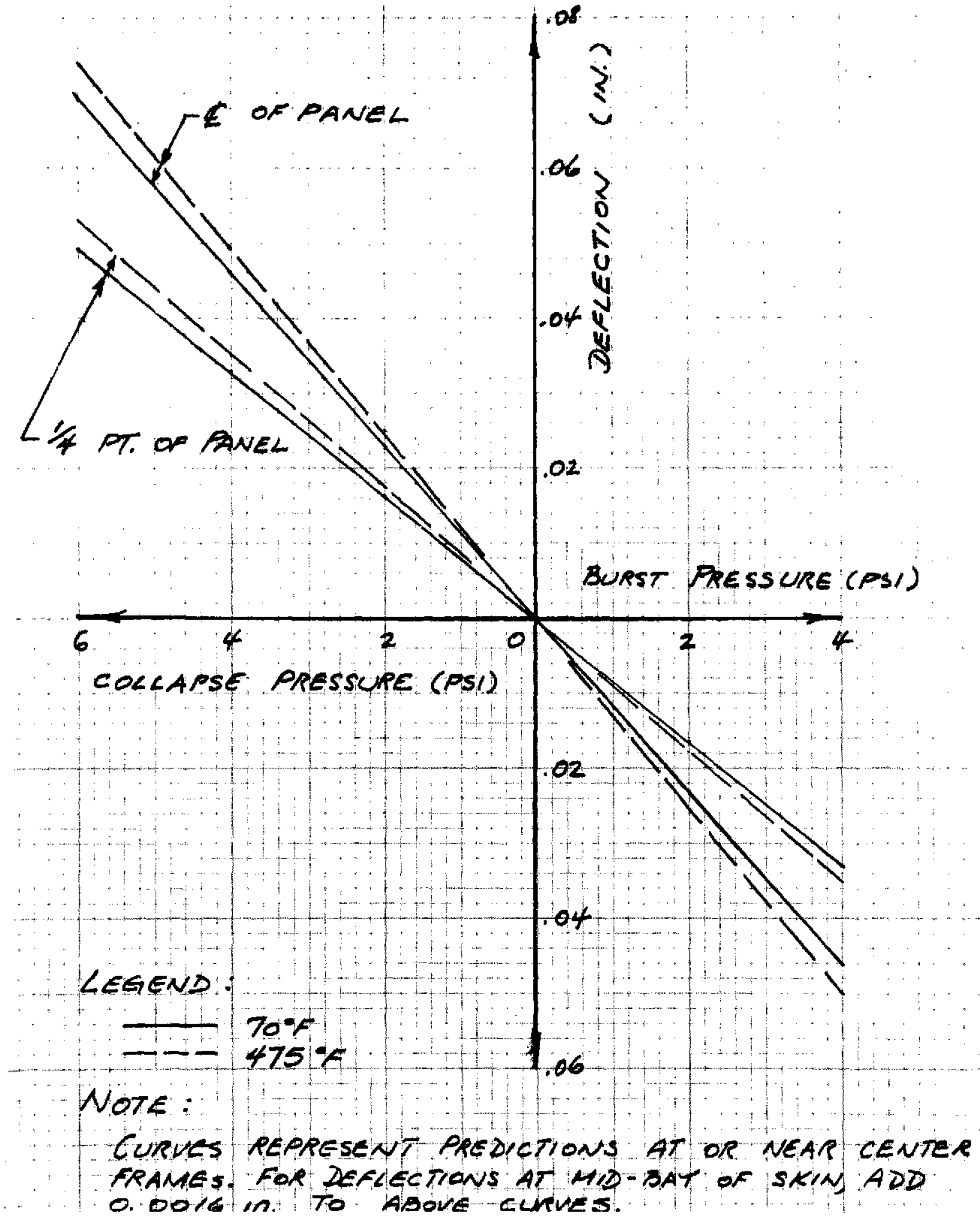


Fig. 18 Beryllium Panel Deflection Predictions for LMSC Wind Tunnel Test Assembly (Contract NAS1-11153)

Section 5
REFERENCES

1. "Final Report for Development of a Rigidized, Surface Insulative Thermal Protection System for Shuttle Orbiter," Contract NAS 9-11222, LMSC-A984200, 16 February 1971, NASA CR-114958.

2. "Final Report: Space Shuttle Thermal Protection System Development," Volumes I and II, Contract NAS 9-12083, LMSC-D152738, 17 January 1972. Volume I — NASA CR-115582, Volume II — NASA CR-115583.

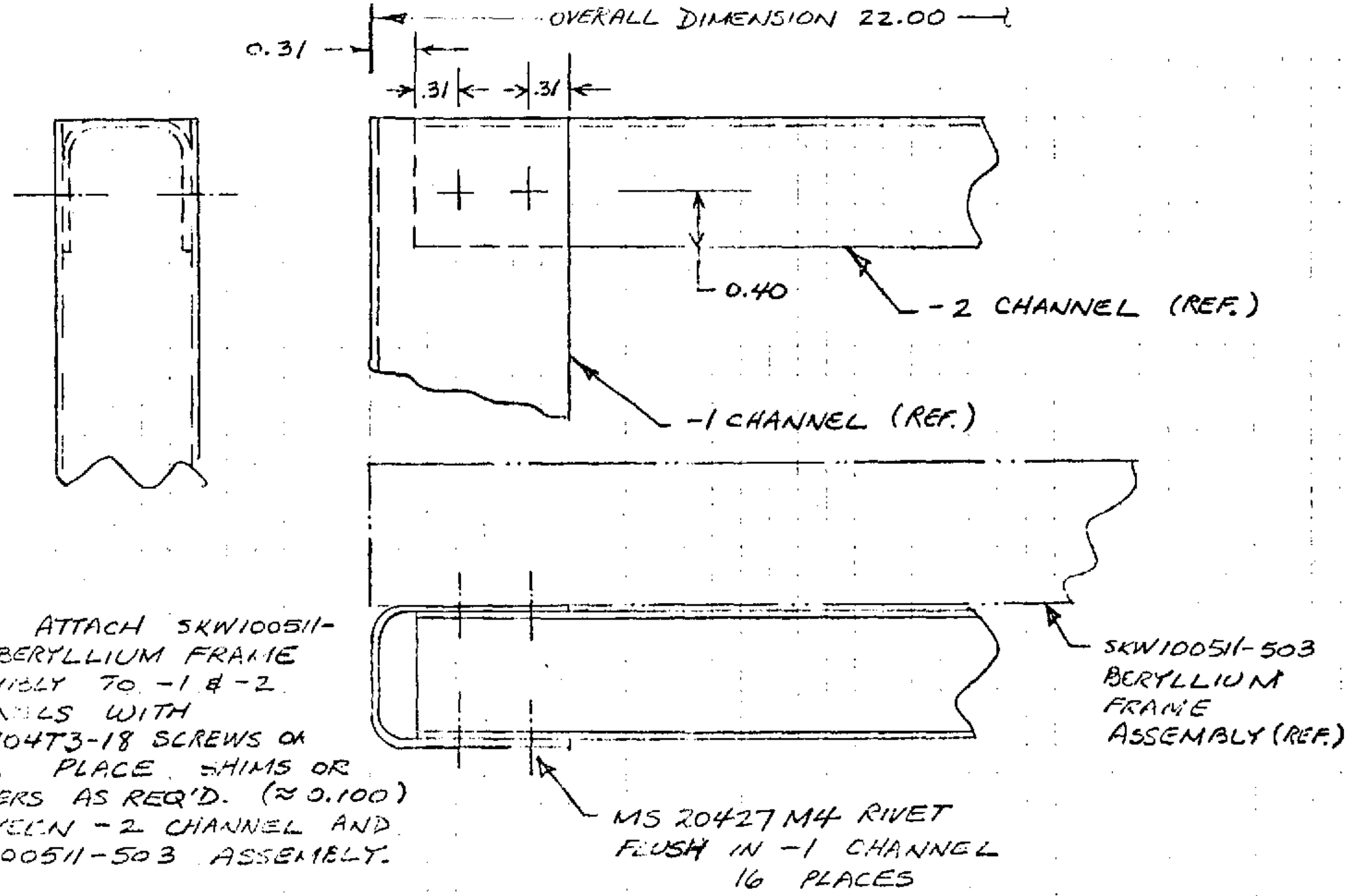
3. "Strength, Efficiency and Design Data for Beryllium Structures," ASD TR-61-692, Contract AF33(616)-6905, February 1962.

4. "Final Report: Alternate Concepts Study Extension, Vol. II: Concept Analysis and Definition, Part I: 040A System", Contract NAS 8-26362, LMSC-A995931, 15 November 1971. NASA CR-123962.

Appendix A

TITANIUM SUPPORT FRAME DETAILS FOR VIBRATION TEST ARTICLE

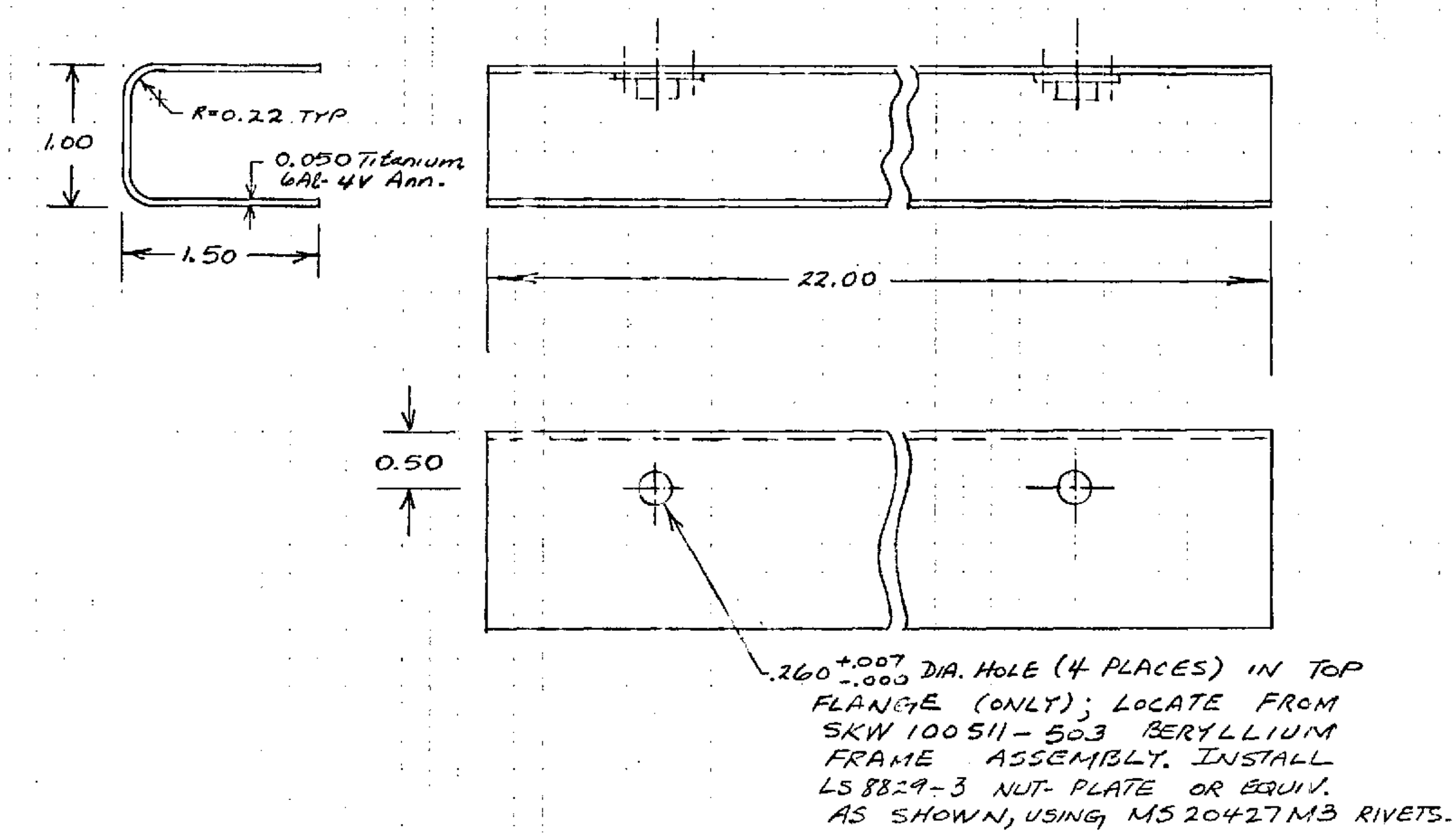
TITANIUM SUPPORT FRAME (1 REQ'D.) FOR BERYLLIUM FRAME ASSEMBLY



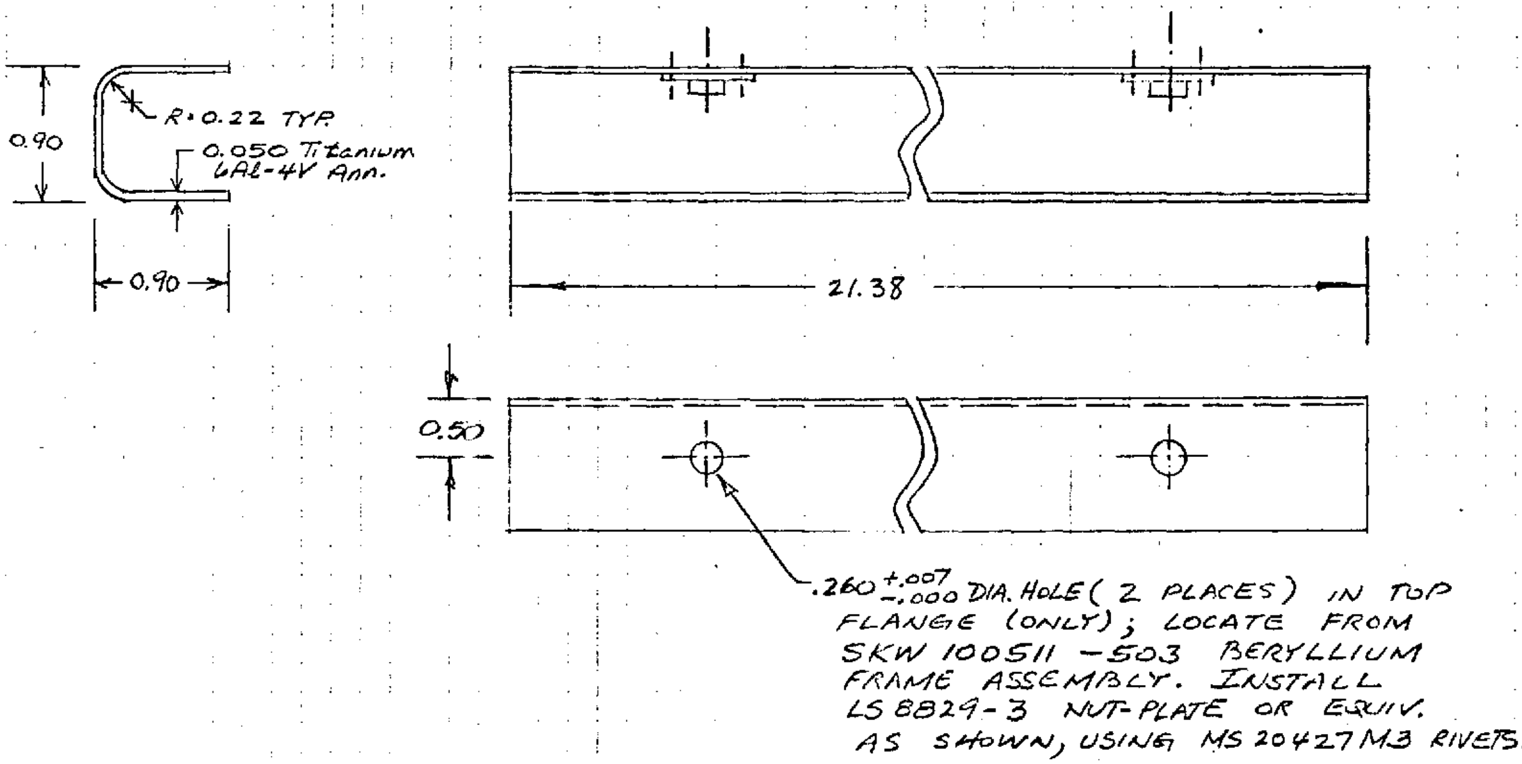
NOTE: ATTACH SKW100511-503 BERYLLIUM FRAME ASSEMBLY TO -1 & -2 CHANNELS WITH LS8704T3-18 SCREWS OR EQUIV. PLACE SHIMS OR WASHERS AS REQ'D. (≈ 0.100) BETWEEN -2 CHANNEL AND SKW100511-503 ASSEMBLY.

TYPICAL SUPPORT FRAME JOINT

CONTRACT NAS1-11153



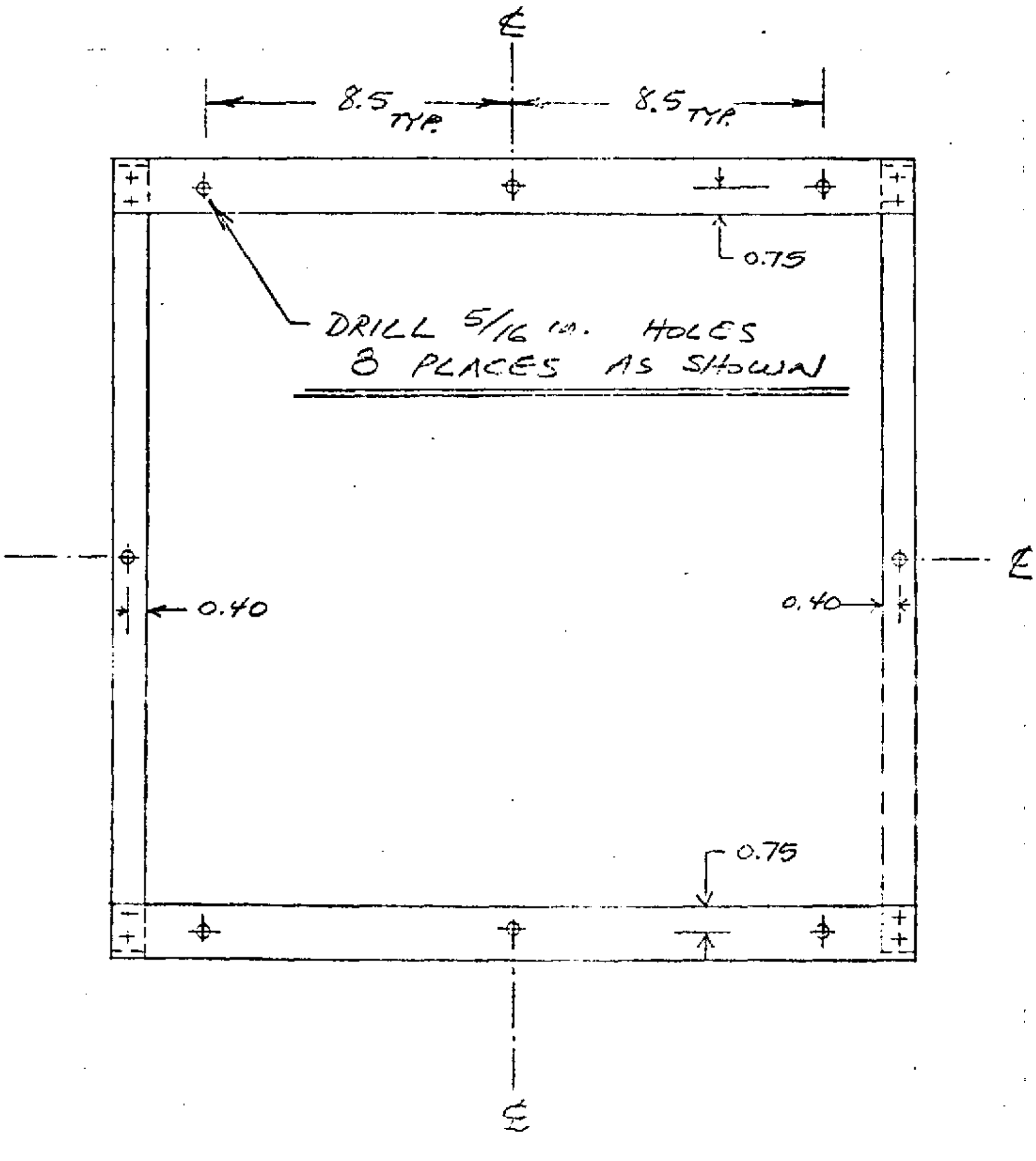
-1 CHANNEL (2 REQ'D)



-2 CHANNEL (2 REQ'D.)

TITANIUM SUPPORT FRAME
ATTACH HOLES LOC.

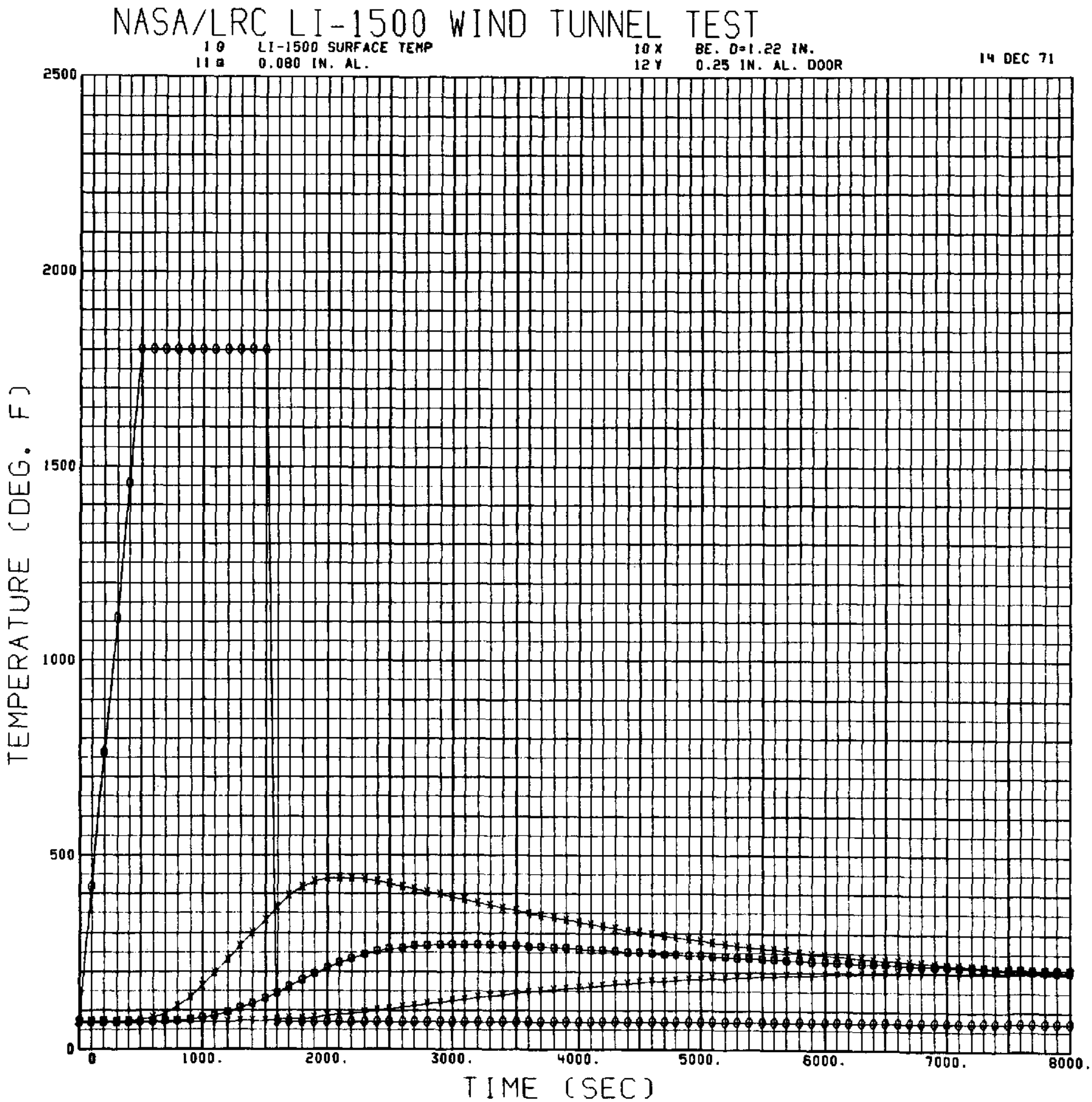
VIEW LOOKING UP AT BOTTOM SIDE



Appendix B

COMPUTERIZED PREDICTIONS OF THERMAL DISTRIBUTIONS THROUGH THE DEPTH OF THE WIND TUNNEL TEST ASSEMBLY AS A FUNCTION OF TIME FOR SELECTED SURFACE TEMPERATURE PROFILES

CONTENTS FOR APPENDIX B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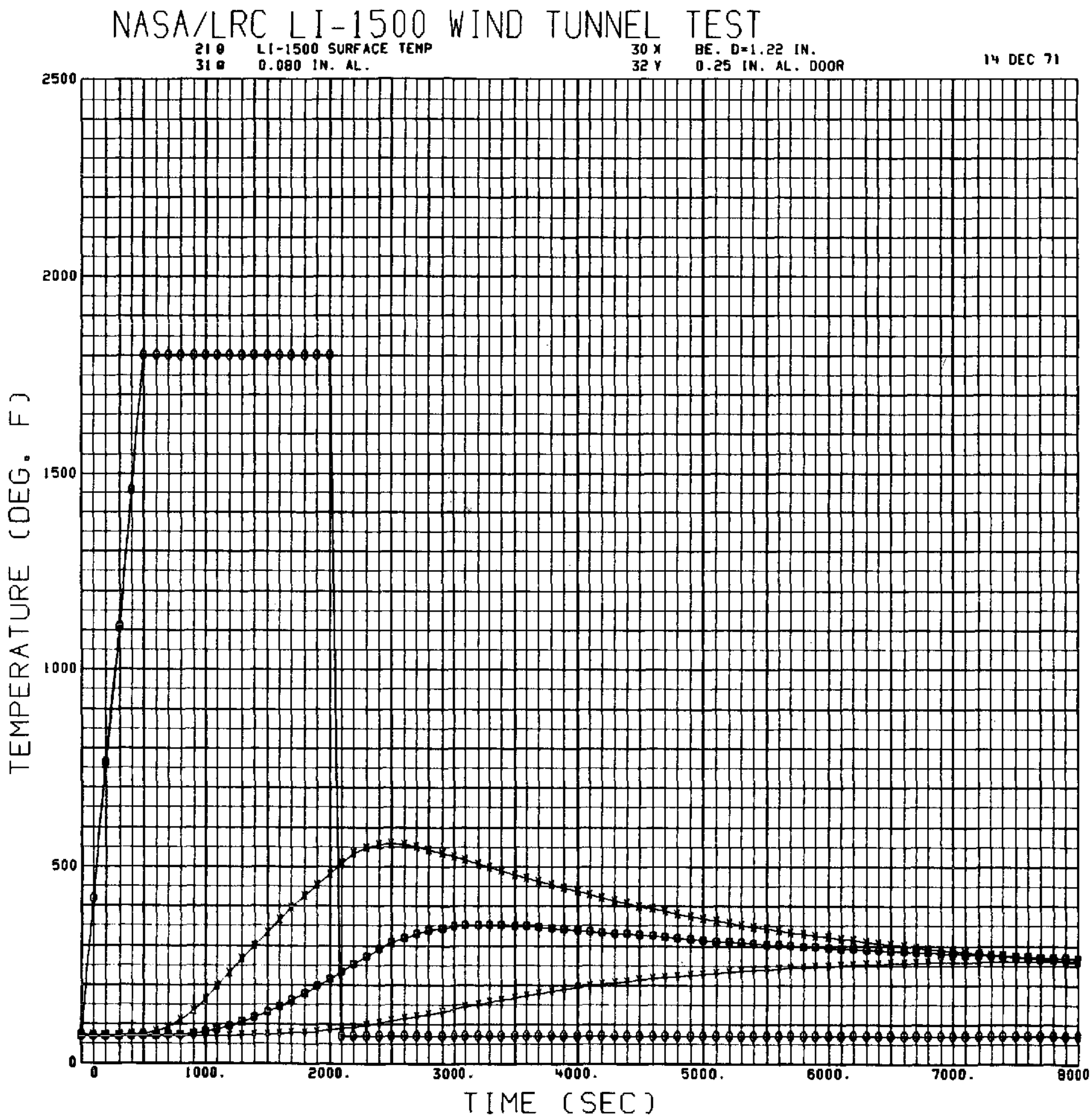
1 ⊖ LI-1500 SURFACE TEMP
11 ⊠ 0.080 IN. AL.
10 X BE. D=1.22 IN.
12 Y 0.25 IN. AL. DOOR
14 DEC 71
2500
2000
1500
1000
500
0
TEMPERATURE (DEG. F)
0
1000.
2000.
3000.
4000.
5000.
6000.
7000.
8000.
TIME (SEC)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31 0.080 IN. AL.
30 BE. D=1.22 IN.
32 0.25 IN. AL. DOOR
14 DEC 71
2500
2000
1500
1000
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0
TEMPERATURE (DEG. F)
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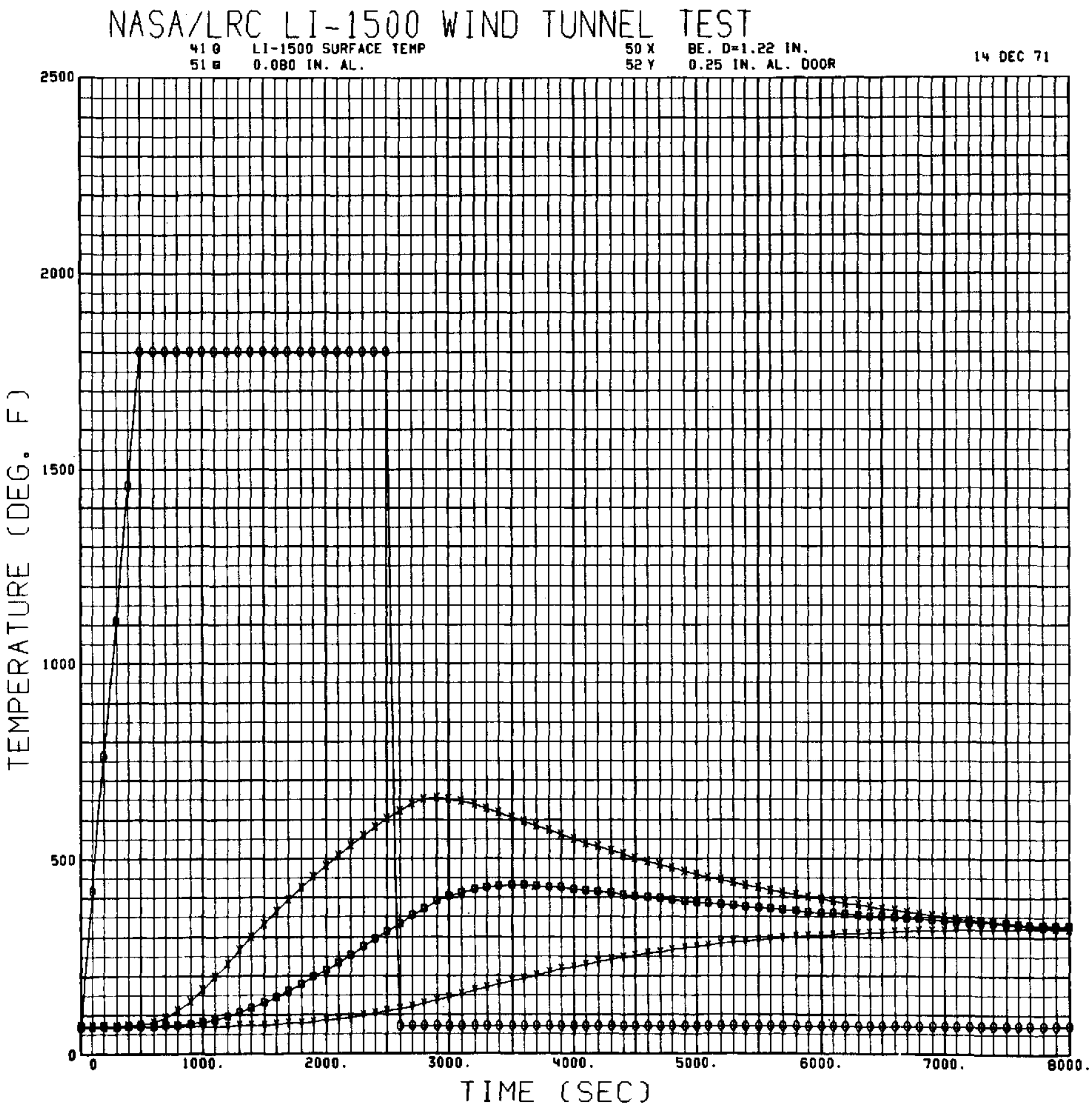
7000.
8000.
TIME (SEC)


NASA/LRC LI-1500 WIND TUNNEL TEST
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50 X BE. D=1.22 IN.
52 Y 0.25 IN. AL. DOOR
14 DEC 71
TEMPERATURE (DEG. F)
0
500
1000
1500
2000
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2000.
3000.
4000.
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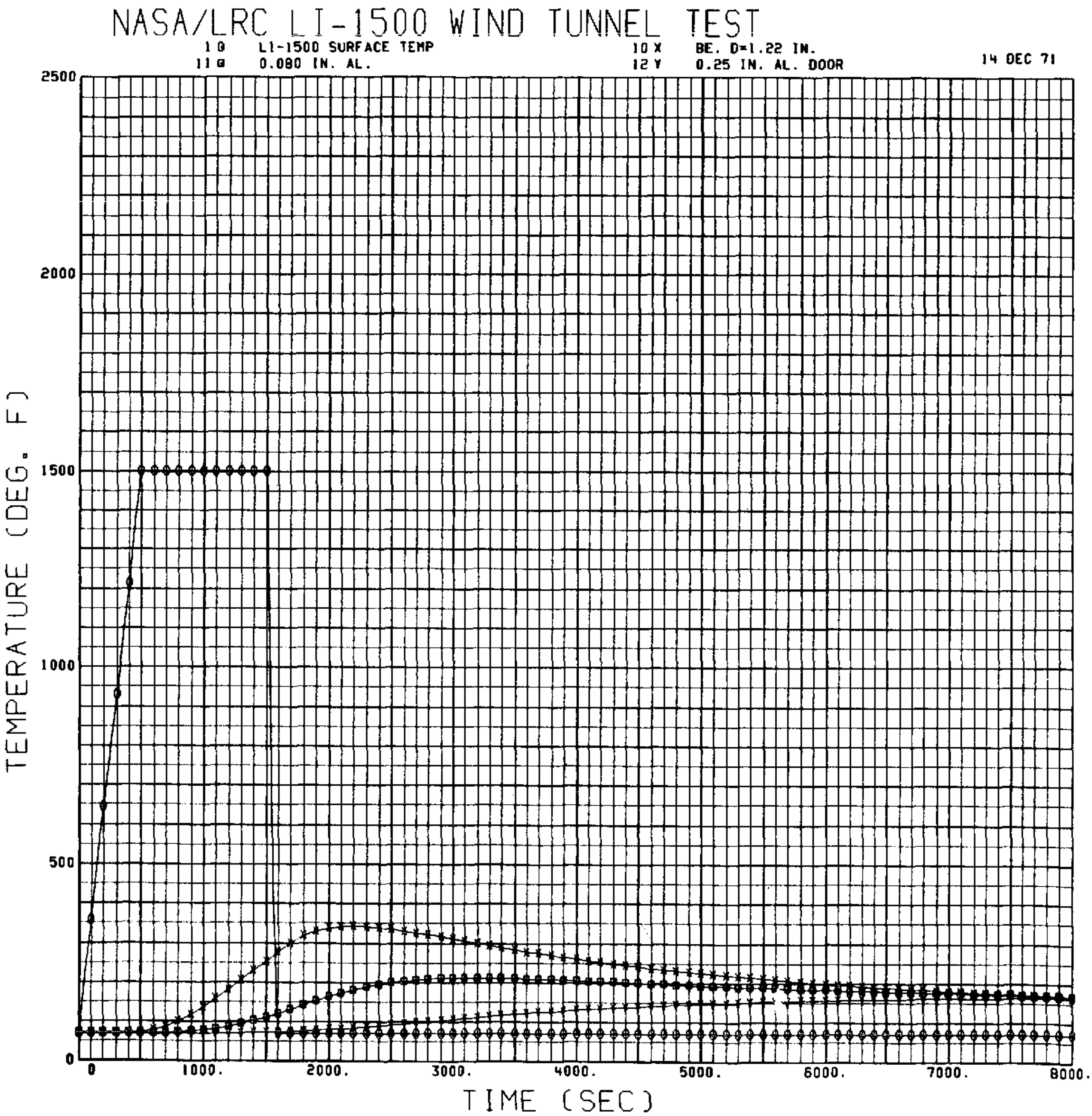
7000.
8000.
TIME (SEC)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10 X BE. D=1.22 IN.
12 Y 0.25 IN. AL. DOOR
14 DEC 71
2500
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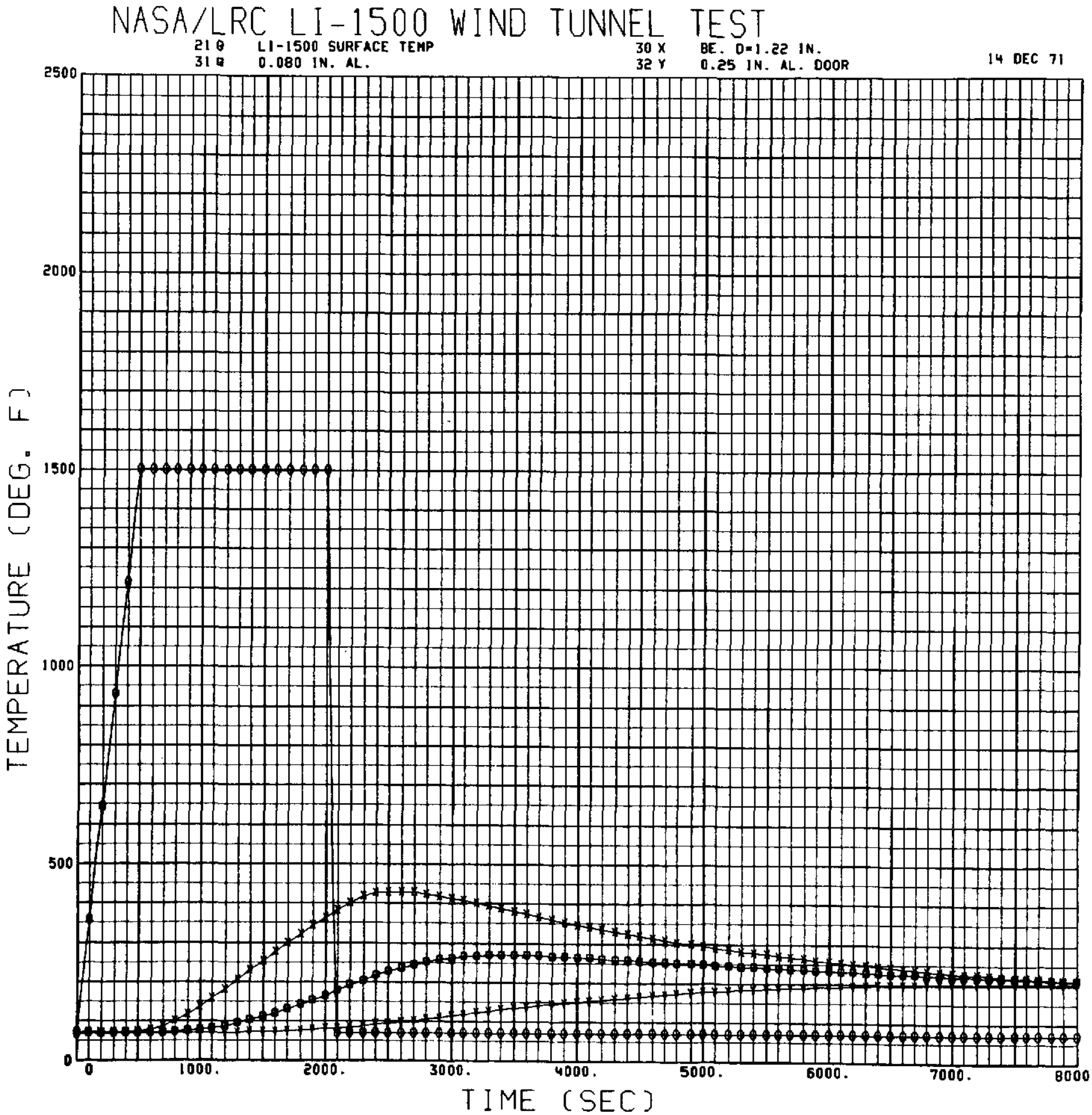
TEMPERATURE (DEG. F)
TIME (SEC)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31 ⊕ 0.080 IN. AL.
30 X BE. D=1.22 IN.
32 Y 0.25 IN. AL. DOOR
14 DEC 71
2500
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1500
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TEMPERATURE (DEG. F)
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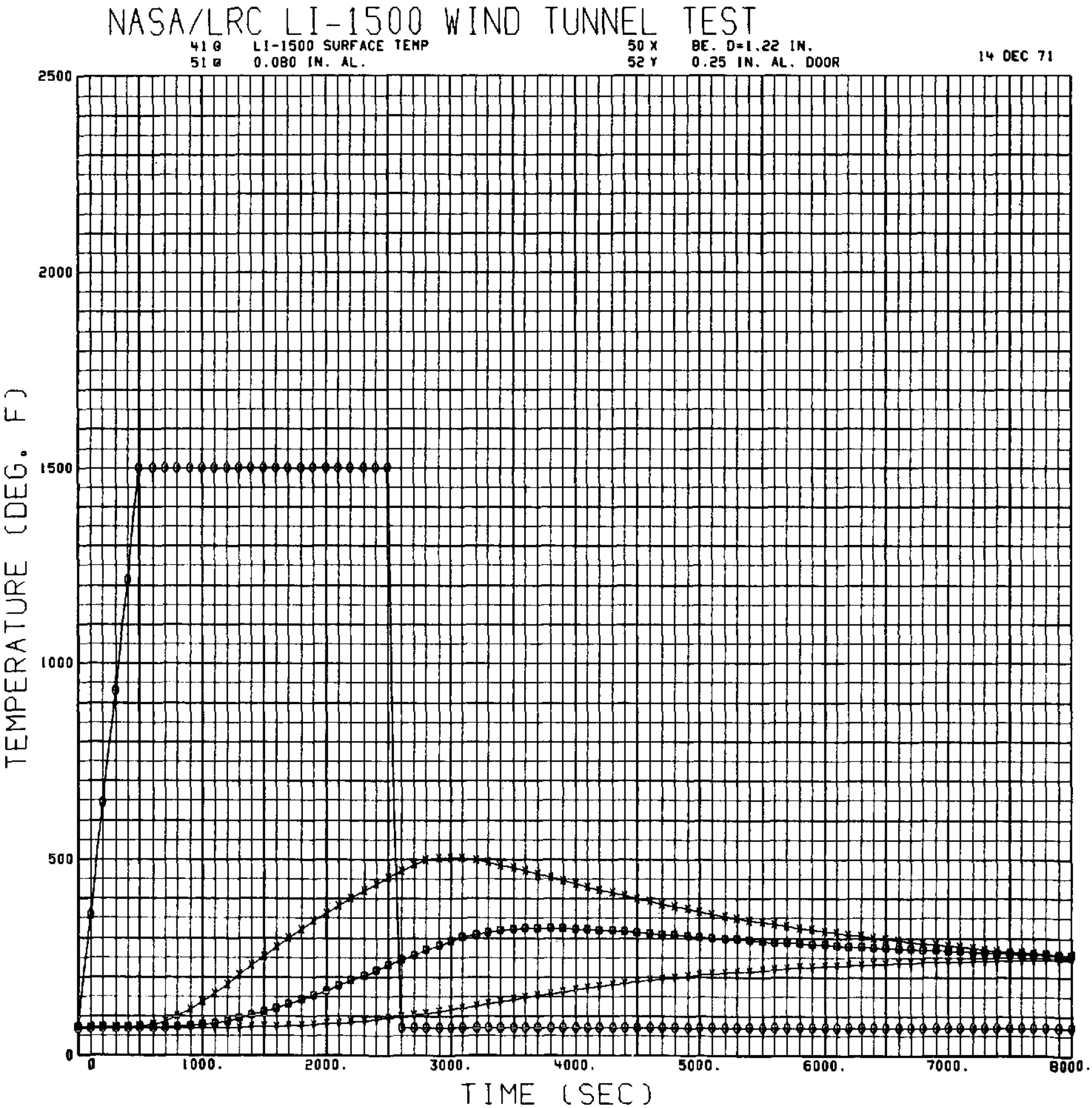
TIME (SEC)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52 Y 0.25 IN. AL. DOOR
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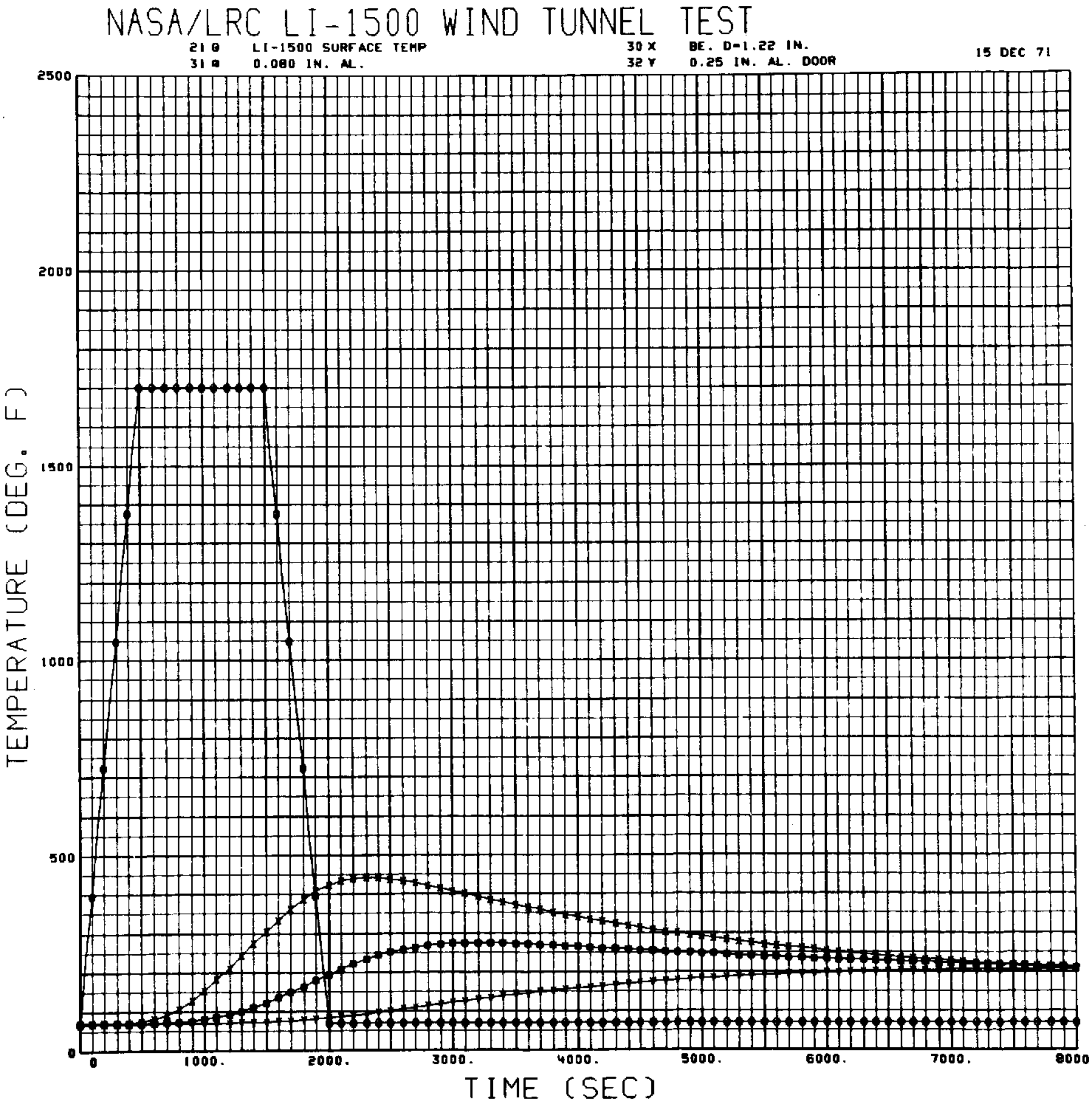
TIME (SEC)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32 Y 0.25 IN. AL. DOOR
15 DEC 71
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TEMPERATURE (DEG. F)
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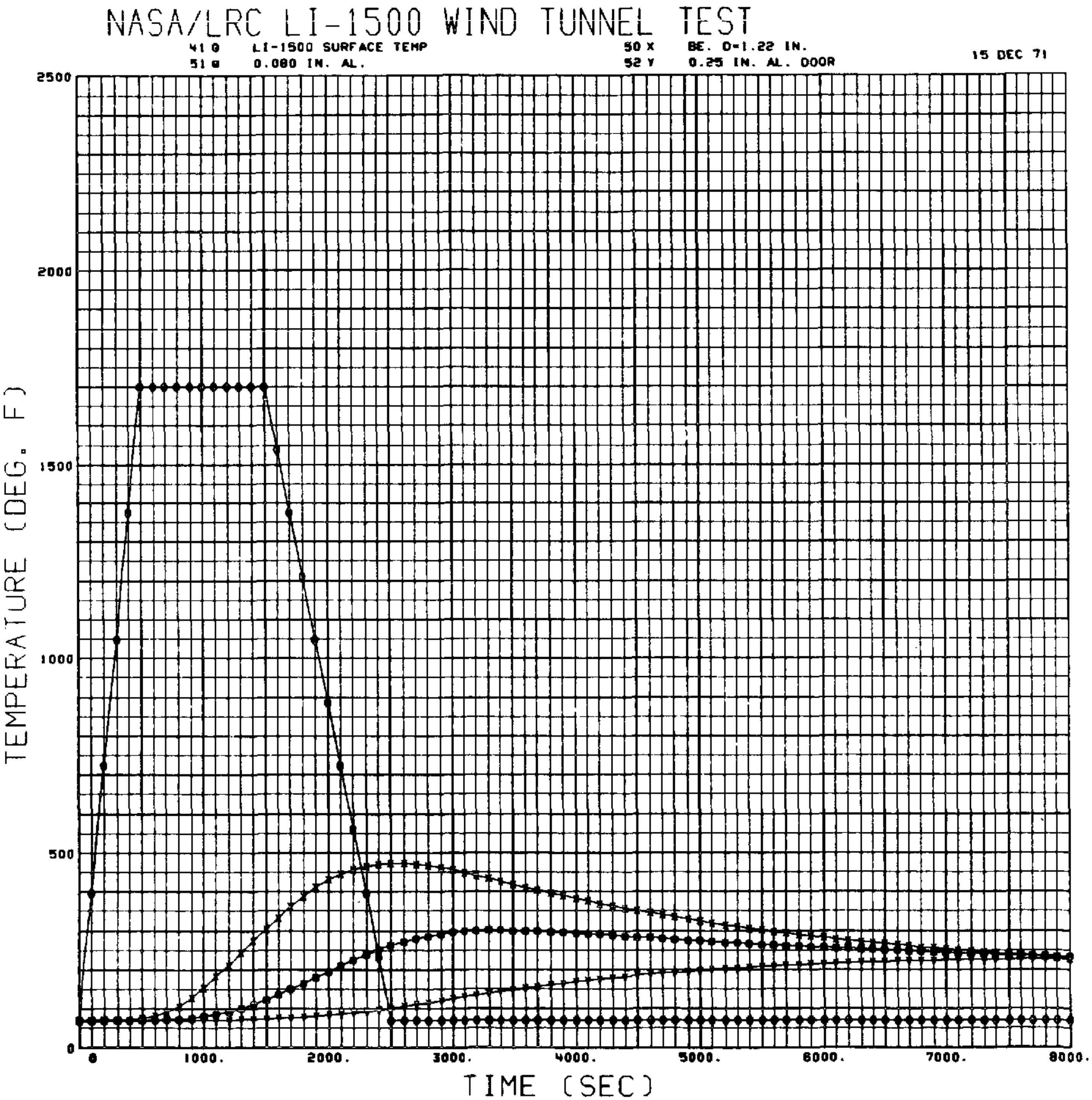
TIME (SEC)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52 Y 0.25 IN. AL. DOOR
15 DEC 71
TEMPERATURE (DEG. F)
2500
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TIME (SEC)
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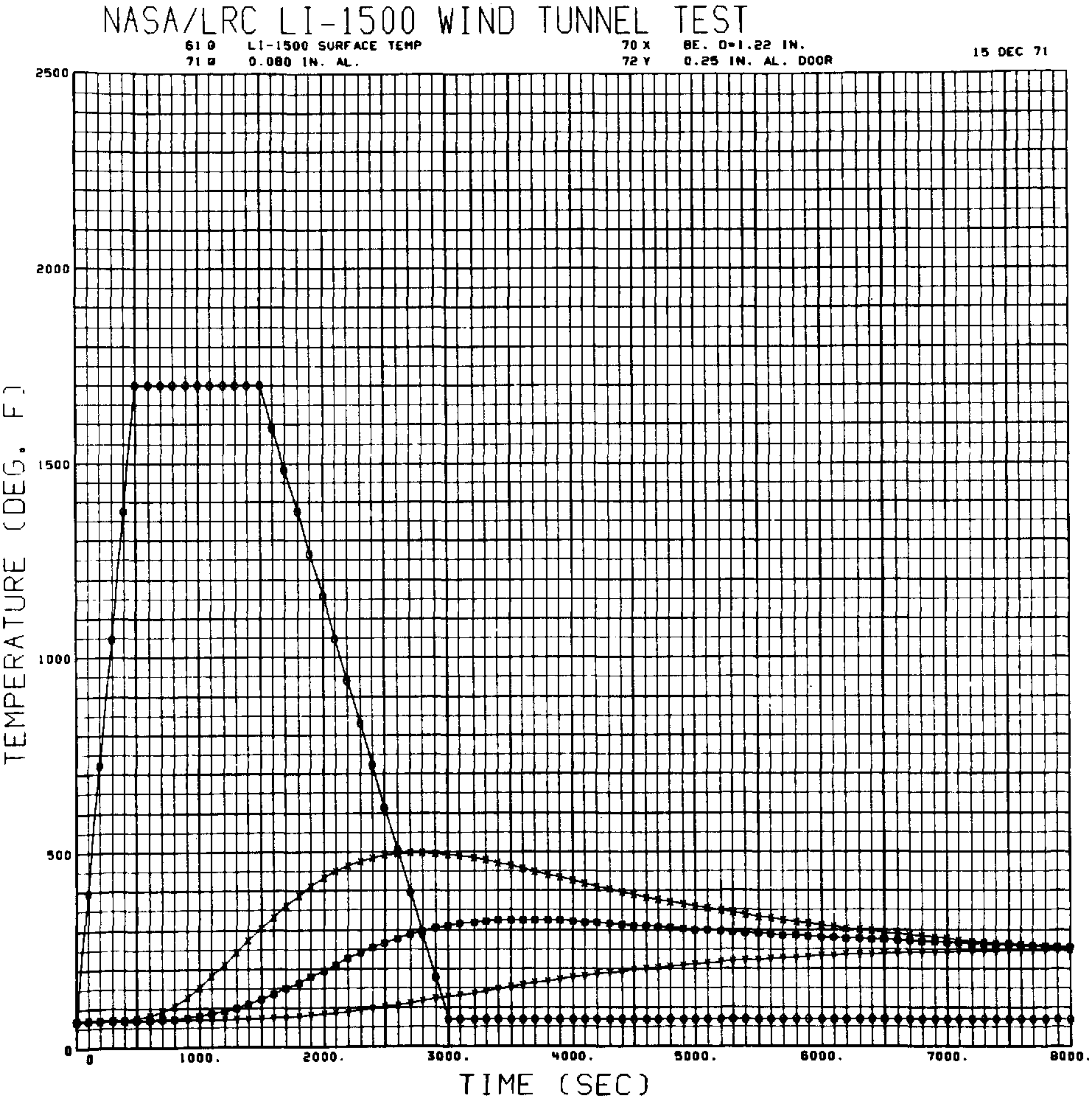
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72 Y 0.25 IN. AL. DOOR
15 DEC 71
TEMPERATURE (DEG. F)
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2000
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0
TIME (SEC)
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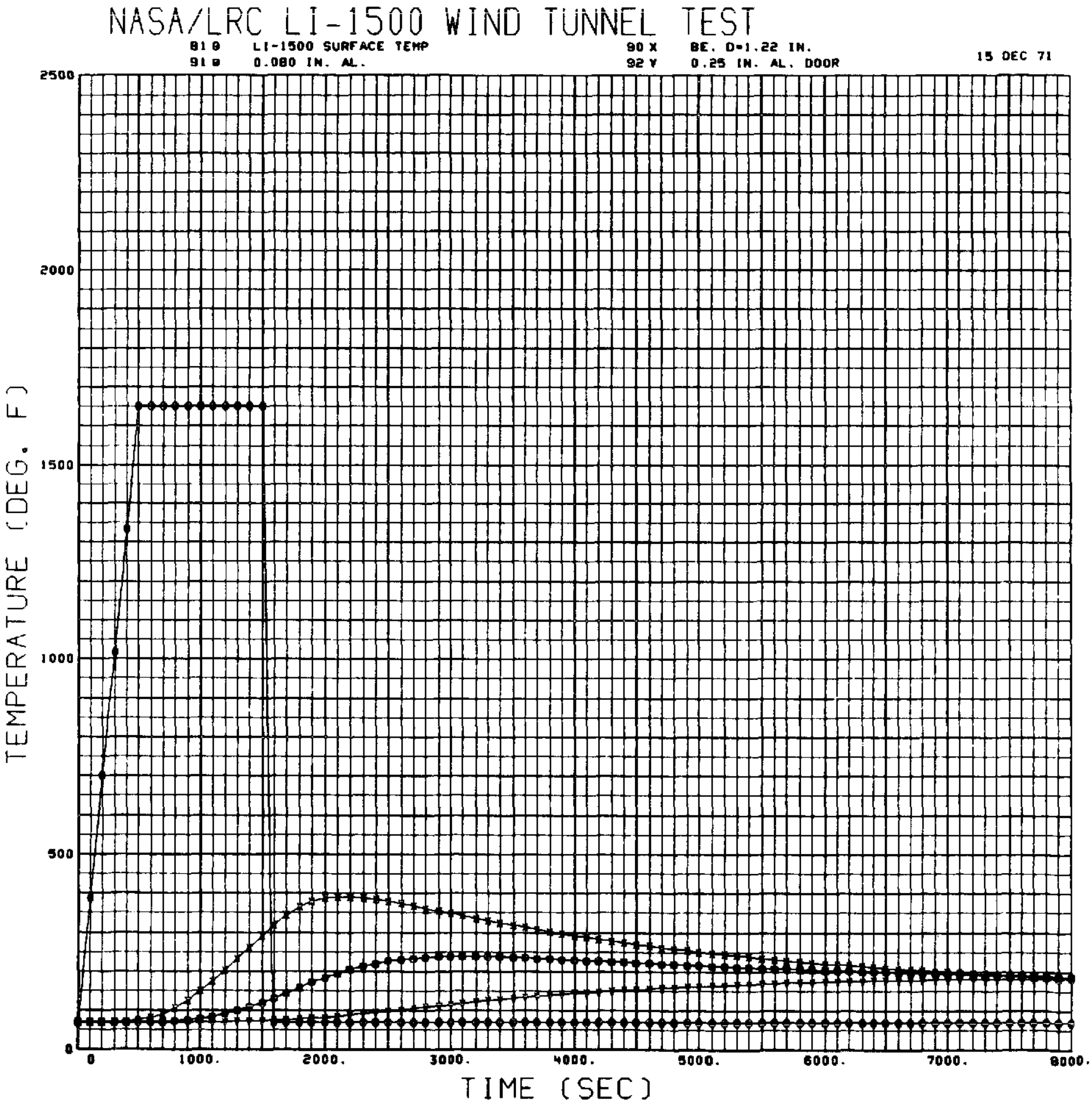
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92 Y 0.25 IN. AL. DOOR
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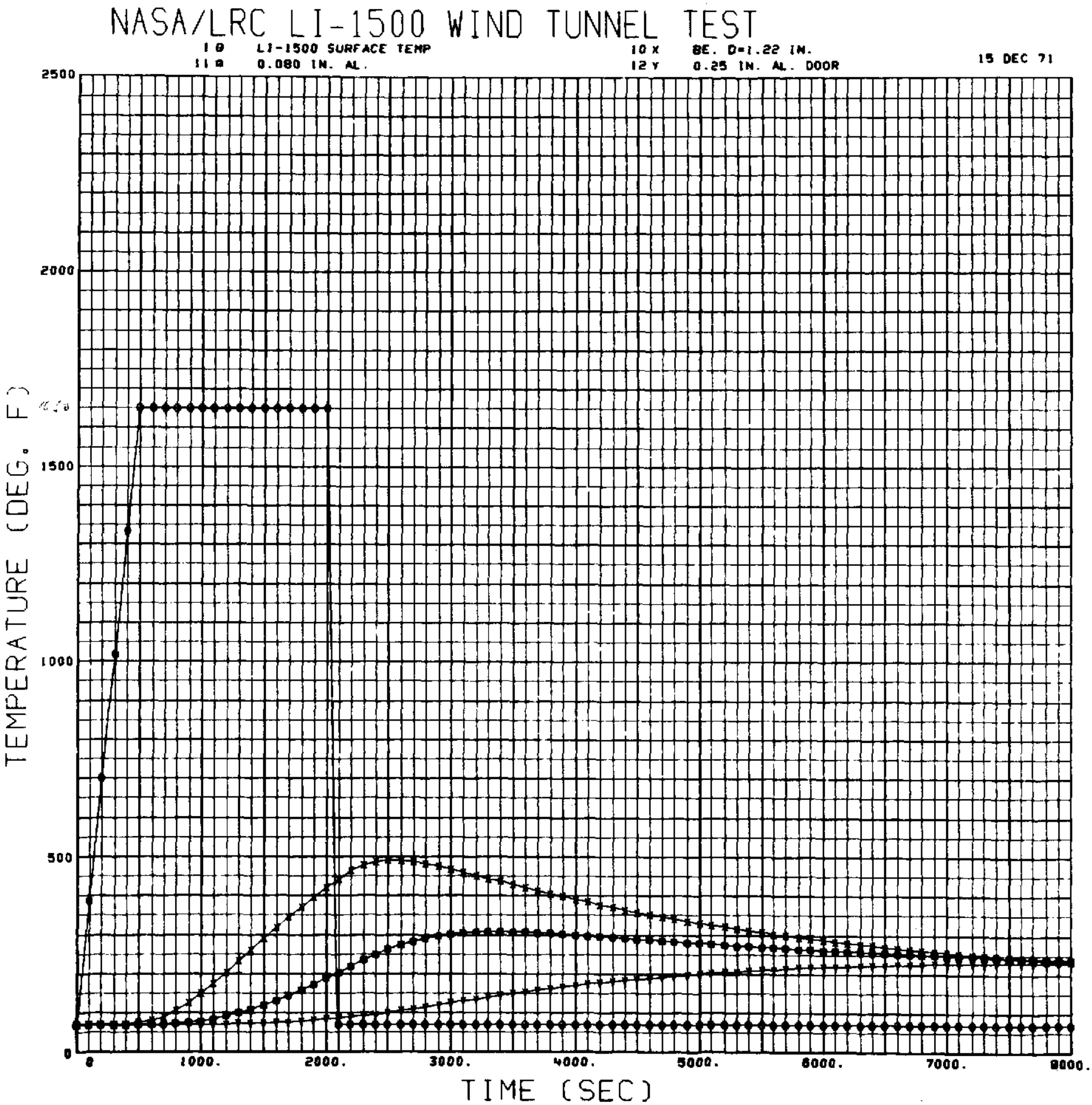
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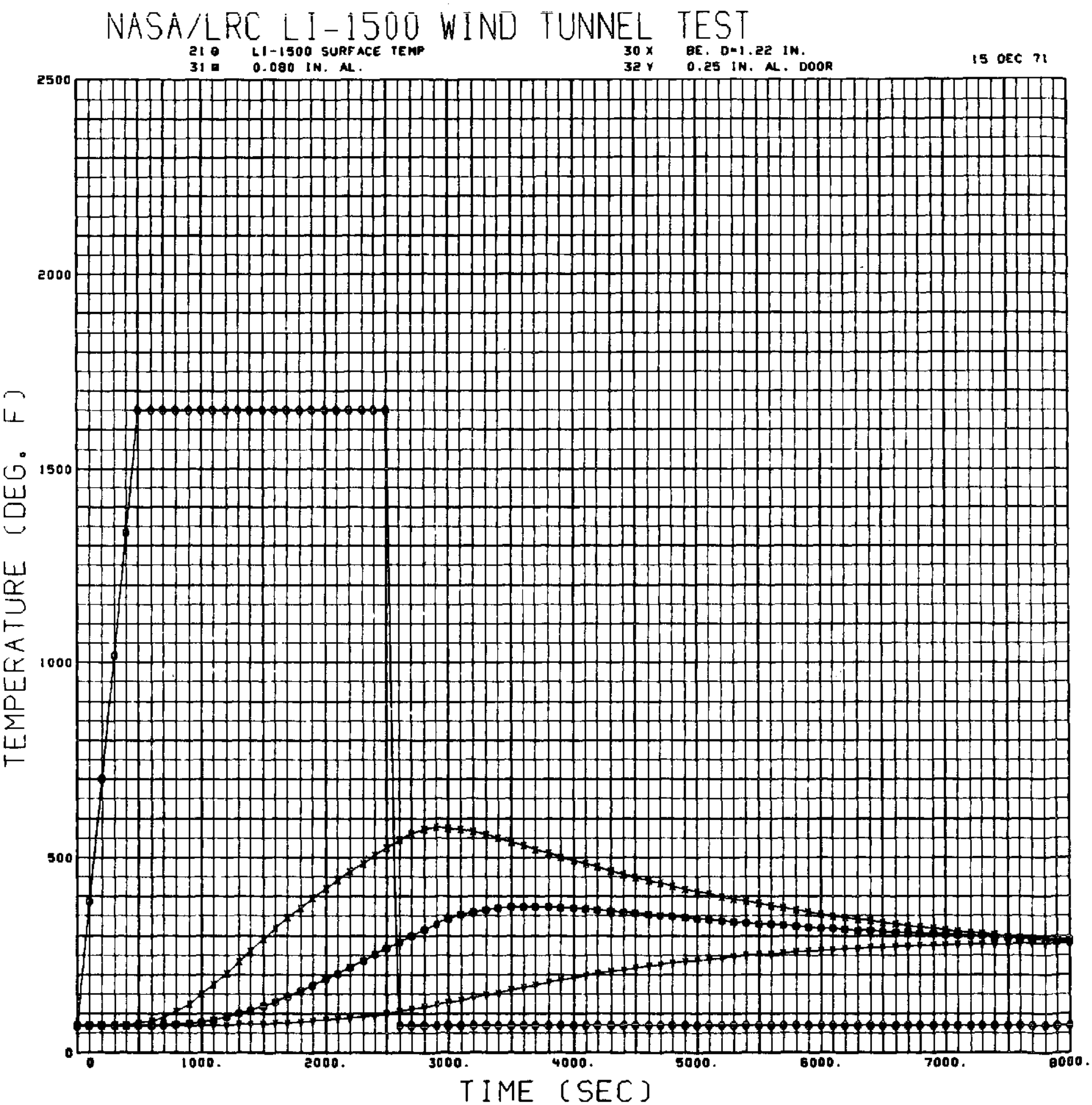
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15 DEC 71
TEMPERATURE (DEG. F)
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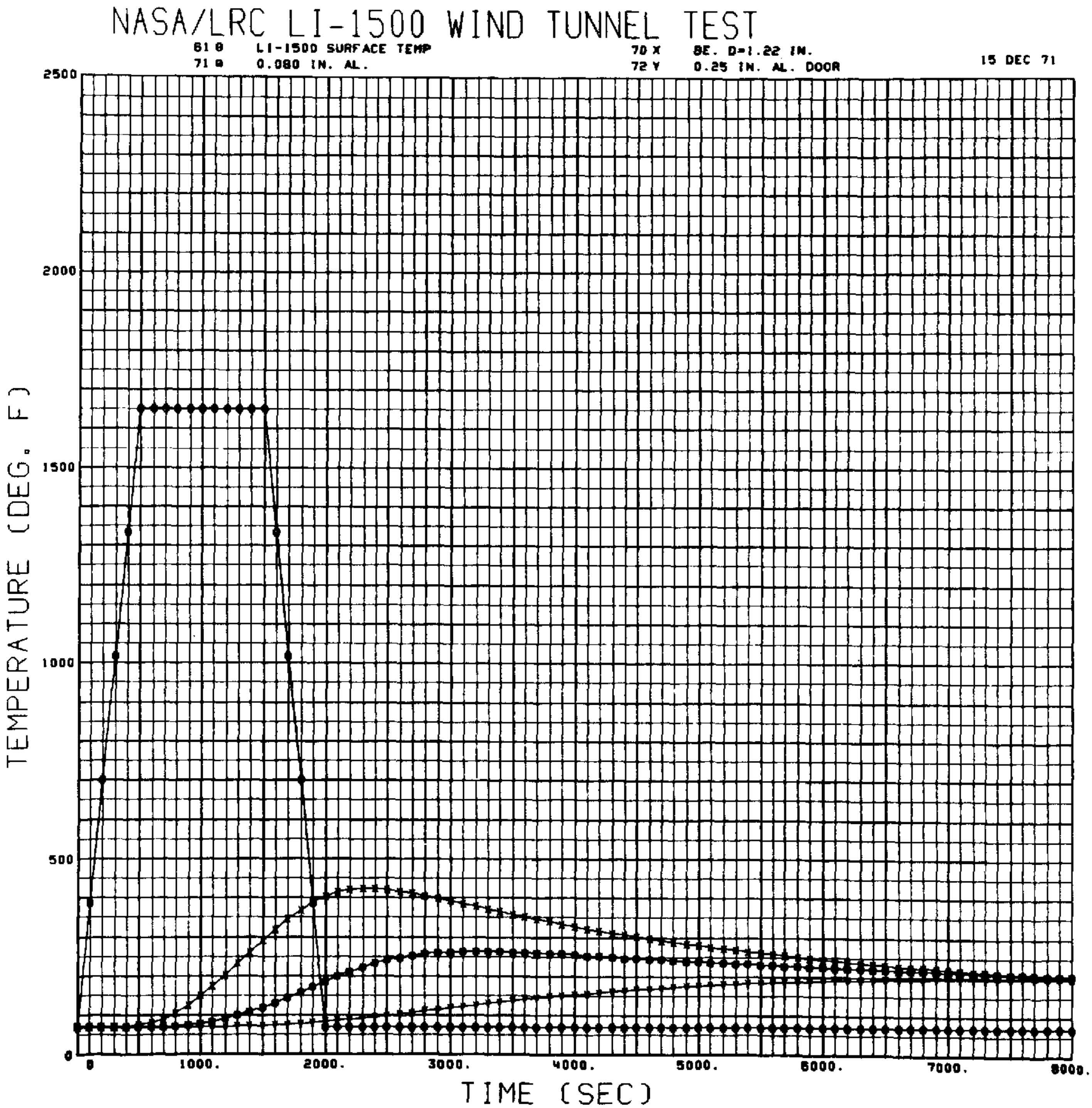

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15 DEC 71
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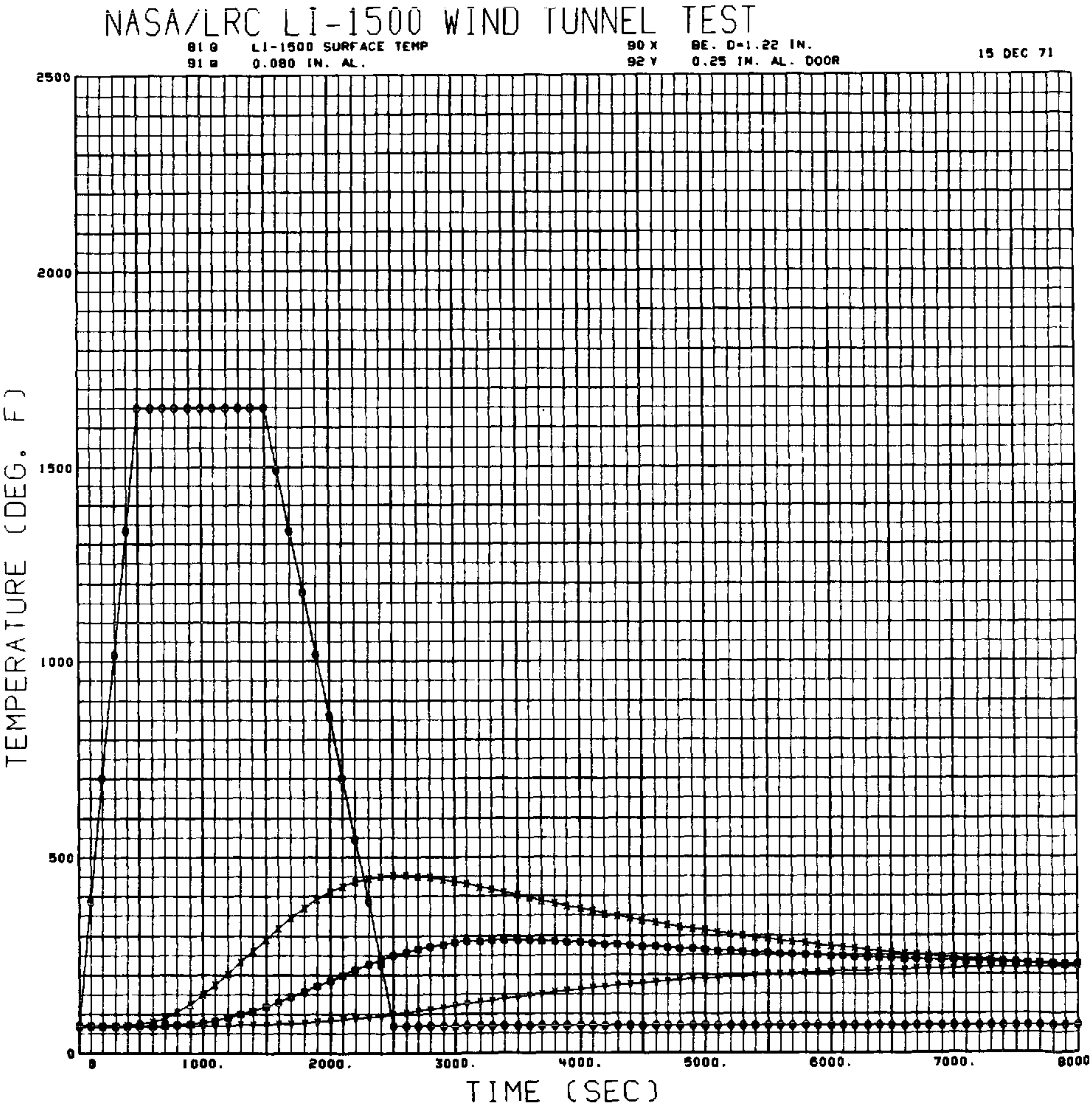

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92 Y 0.25 IN. AL. DOOR
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6000.
7000.
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TIME (SEC)