DOCUMENT NO. 66SD4207
6 JANUARY 1966

FINAL REPORT

MEASUREMENT OF THERMAL CONDUCTANCE OF MULTILAYER AND OTHER INSULATION MATERIALS

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ACKNOWLEDGEMENTS

The diligent support provided by Mr. J. Ande in the execution of the major experimental program and that of Mr. R. Tanzilli on the measurement of thermal properties of the non-multilayer materials is acknowledged.

We should like to also acknowledge the assistance and cooperation of Mr. J. Poradek of the NASA Manned Spacecraft Center in the execution and guidance of this work.

SECTION 1
INTRODUCTION

This report presents the results, recommendations, and conclusions of the program, "Measurement of Thermal Conductance of Multilayer and Other Insulation Materials." The reporting period extends from October 22, 1964 to December 31, 1965.

1.1 OBJECTIVES

This program was undertaken to obtain thermal conductance data on the extravehicular spacesuit garment material. The item of prime interest was the combination of the multilayer thermal, meteoroid protection, pressure garment lay-up. Most of the investigative effort was applied to the thermal conductance evaluation of this item, while considering the many variables, such as thickness, material combinations, number of layers, etc. One of the items of investigations was a search for improvements or for simplifications of the existing material lay-up with respect to thermal performance.

The testing program on the multilayer lay-up combinations was performed on a full-time, continuing basis, since considerable time elapsed before steady-state conditions were reached on most samples.

A secondary, but nonetheless equally important effort, was applied to the determination of the thermal conductivity of items such as helmet material, shoe sole, and similar items. Since only few sample pieces were available for these tests and the possibility of variations was limited to temperature levels, the number of reported tests is relatively small.

1.2 SUMMARY OF TEST RESULTS

A total of 53 multilayer thermal insulation conductance tests for varying temperature limits, thicknesses, and lay-ups were performed on the double sample, guarded hot plate apparatus at steady-state conditions. Outside garment temperature limits were -310°F, -100°F, +200°F, and +300°F, for most cases, with the inside garment temperature at 0°F or 70°F in most cases. The suit material lay-up thickness varied from 1/8 inch to 5/16 inch.

Two basic multilayer material combinations were evaluated. The first was the current Gemini extravehicular suit lay-up consisting of seven layers of aluminized (one side only) Mylar*, separated by nonwoven Dacron*, several layers of HT-I Nylon, bladder cloth pressure layer, and a felt meteoroid protection layer. This is shown in Figure 1-1. The second lay-up was similar to the previous material combination, as shown in Figure 3-1.

It should be noted that the number and type of the multilayer insulation were variables of considerable interest in our test program. One significant result observed was the dependency of the overall thermal conductance on the material compression.

It was observed that the the substitution of aluminized polyester film for the nonwoven Dacron spacers resulted in equal or better thermal performance. Since this constitutes a system simplification, it represents an improvement.

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* Registered trademark of EI DuPont

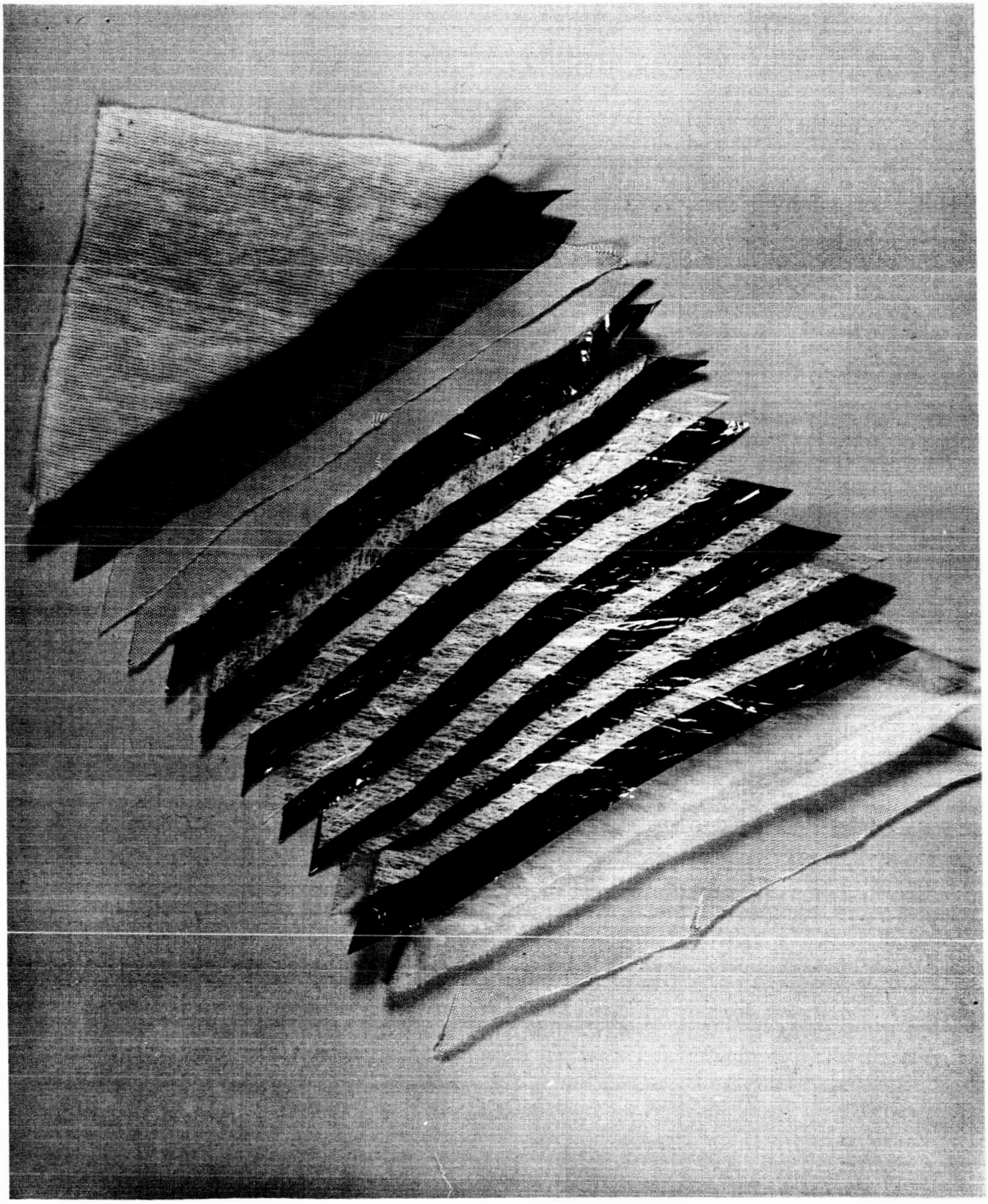


Figure 1-1. Typical Multilayer Suit Sample
Using Felt Meteoroid Layer (Series 1, 2, and 3)

The lightweight suit lay-up had a considerably lower thermal conductivity than the early version. Other results using increased numbers of aluminized polyester films or embossed film in place of wrinkled film are discussed in detail in Section 3.

It is evident from the results that additional tests are required to check on the reproducibility of many tests, with respect to a) experimental reproducibility, b) material degradation due to repeated use of some test samples over wide temperature ranges, and c) test sample batch variation. Additional tests also are required to evaluate potential simplification and improvements of the thermal insulation performance of the suit material.

SECTION 2

TEST APPARATUS AND PROCEDURES

2.1 GENERAL DESCRIPTION

Three different apparatuses were employed to measure the thermal conductivity of materials tested in this program. These instruments are: (a) multilayer insulation guarded hot plate apparatus, (b) Dynatech Model TC-2000 Guarded hot plate, and (c) Dynatech Model TC-1000 Comparator. These are described in order.

2.2 MULTILAYER GUARDED HOT PLATE APPARATUS

2.2.1 CONSTRUCTION

The device used for the largest number of tests, the guarded hot plate apparatus was built specifically for the measurement of the effective thermal conductivity of multilayer types of insulations and replaces an earlier version. The construction of this apparatus generally follows that outlined in ASTM Standard C177-45. This apparatus consists of a flat heater plate and two cold plates. Two identical samples, 14-1/4 inches square, are tested simultaneously in this apparatus to provide an average value to compensate in part for any sample inhomogeneity. A schematic view of this apparatus is shown in Figure 2-1. A photograph of the apparatus is shown in Figure 2-2. The heater plate is made in two separate sections, identified as the main heater (the actual test section) and a guard heater. Each of these two heater plates is constructed of a mica heater sandwich between two thick copper plates forming the top and bottom of the heater, providing a nearly isothermal surface. The guard heater is utilized to maintain an adiabatic boundary condition on the perimeter of the main heater. The cold plates are constructed of 3/8-inch thick copper plate to which is soldered a 1/4-inch copper tube layed out in a serpentine fashion. The various fluids used in these tests were circulated through the cold plate tubes to maintain a nearly isothermal surface.

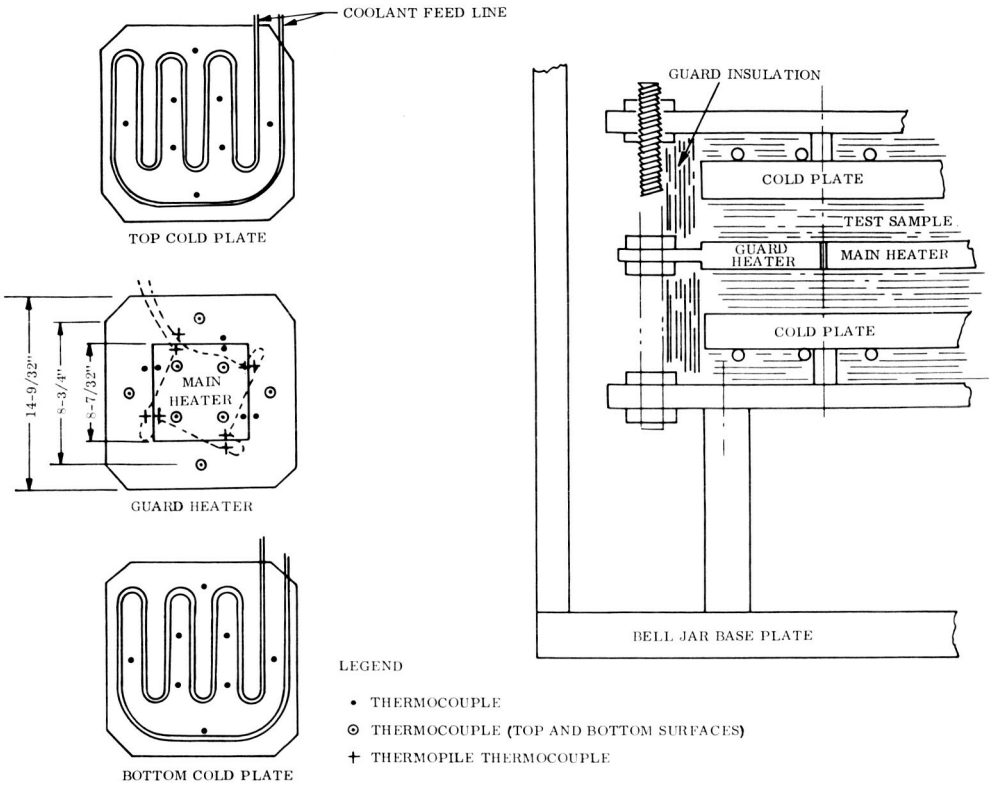


Figure 2-1. Schematic of Multilayer Insulation Test Apparatus

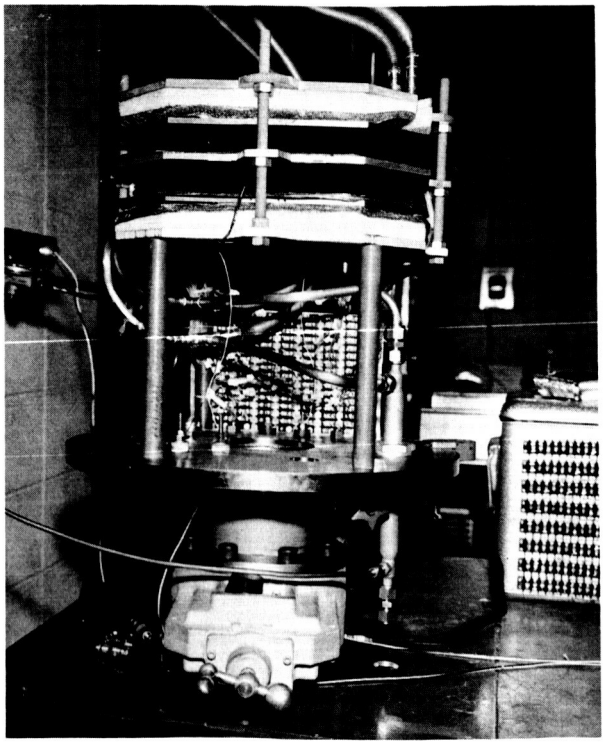


Figure 2-2. Multilayer Insulation Thermal Conductivity Apparatus

Both faces of the heater plate and the cold plates were sprayed with a flat black lacquer to reduce the radiation resistance between the plates and the multilayer assemblies. A multilayer aluminized mylar blanket is wrapped around the outer perimeter of the entire assembly, also for the purpose of providing a more nearly adiabatic boundary condition. The support structure was fabricated from Textolite, a poor thermal conductor, to reduce sources of error due to heat leaks.

2.2.2 CONTROLS

The temperature of the guard heater is slaved to that of the main heater by means of a Minneapolis-Honeywell Tel-o-set 3-mode controller. The output of a thermopile, affixed to both the main and guard heaters (see Figure 2-1) to measure the average difference in temperature between the main and guard heaters, is fed into a deviation amplifier. This signal is in turn fed into a 3-mode controller which regulates the power output of a magnetic amplifier. A precisely regulated dc power supply supplied the power to the main heater. A schematic of the guarded hot plate control system is shown in Figure 2-3. Figure 2-4 is a photograph of the overall system. This system was used to measure the thermal conductivity data for all of the multilayer assemblies and the single fiber-glass sample tested. The entire system was mounted in an 18-inch vacuum bell jar. During testing the bell jar pressure was maintained by means of a Kinney 4-inch diffusion pump with an LN_2 cold trap.

2.2.3 MEASUREMENT PROCEDURES

The heat throughput to the samples is assumed to be equal to the power input to the main heater. The power input to the main heater was obtained quite precisely by measuring the voltage drop across the main heater and the current flow across a calibrated shunt resistance placed in series with the main heater. The temperature of the heater plate was determined by averaging the measurements of eight chromel-alumel thermocouples. Similarly the temperature of each of the cold plates was obtained by averaging the measurements of four chromel-alumel thermocouples. The placement of these thermocouples is shown in Figure

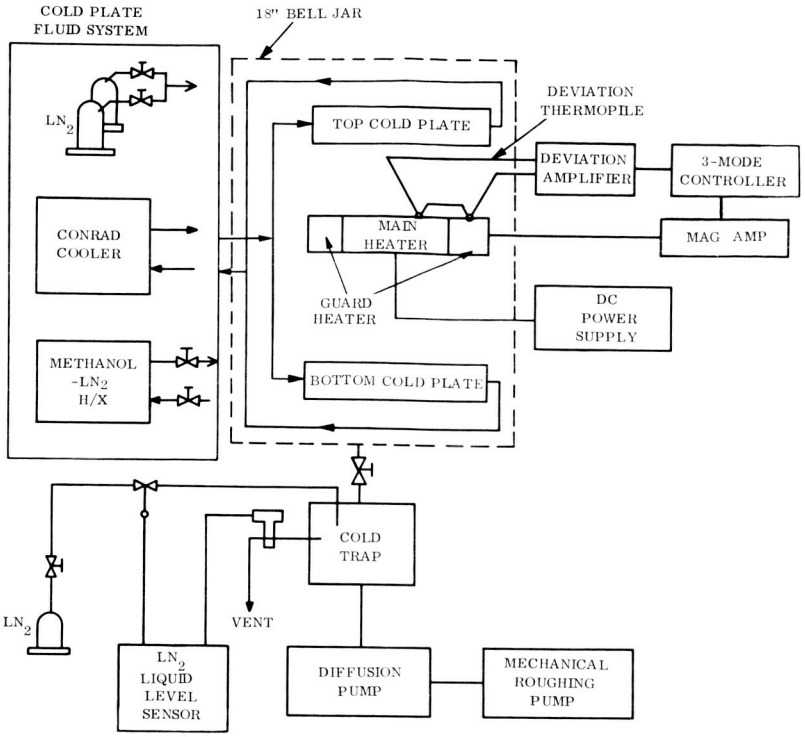


Figure 2-3. Schematic of Guarded Hot Plate Control System

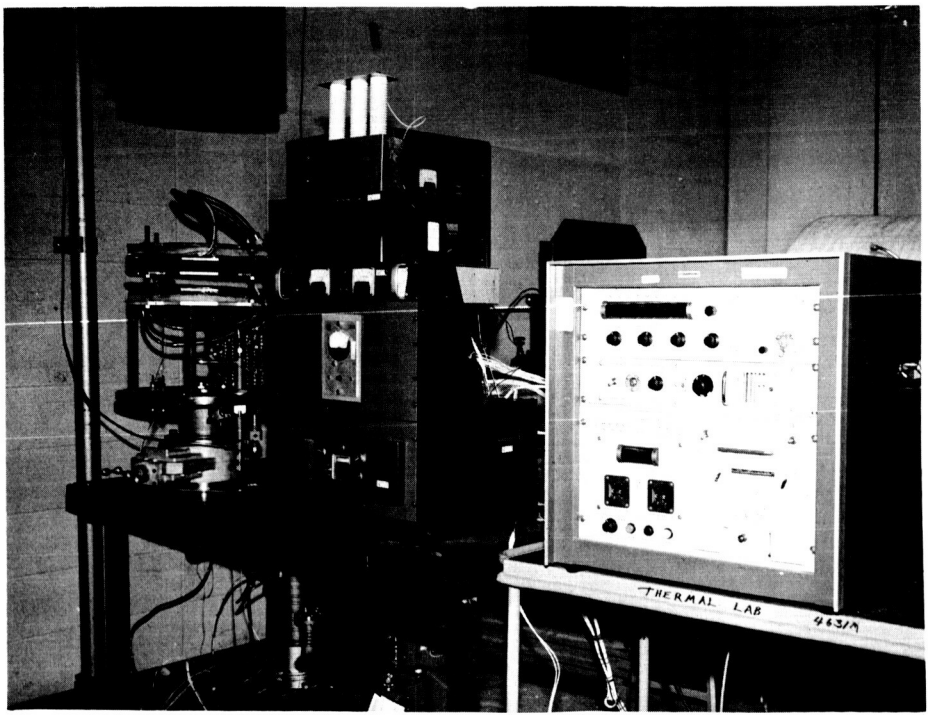


Figure 2-4. Layout of Multilayer Insulation Test Facility

2-1. The sample thickness was taken as the separation distance between the heater and cold plates and was measured by means of a set of Starrett gauge blocks at four separate locations top and bottom for each test thickness assembly. The effective thermal conductivity was taken as:

$$k_{eff} = \frac{Q\Delta X}{A\Delta T}$$

where:

Q = measured heater throughput

A = area of main heater

ΔT = temperature difference between cold and hot plates

ΔX = sample thickness

No corrections were made for heat capacity effects in the main heater.

2.3 PLEXIGLAS VISOR MATERIAL

The measurement of the plexiglas sample was made on a Dynatech Model TC-2000 guarded hot plate apparatus, which is designed on somewhat similar principles as the multilayer apparatus and which measures the absolute thermal conductivity of materials. Two identical samples are placed on either side of a flat plate circular heater assembly. This assembly consists of an inner or main heater surrounded by an outer or guard heater. The guard heater prevents radial heat losses and forces the heat generated in the main heater to flow in a unidirectional manner, through the two samples. Cooling sinks are used for heat rejection.

The operation of the apparatus is such that power is supplied through a constant voltage regulator and through an adjustable autotransformer to the main heater. The power is set by the autotransformer and measured by means of a high-accuracy watt-meter. The thermal conductivity of the sample is determined from knowledge of the heater power, the

temperature difference across the sample, the thickness of the sample, and the surface area. The guard heater surrounding the main heater and the installed sample minimizes the radial heat losses, and by running a test with the guard slightly higher in temperature than the main and then slightly lower, an extremely precise value of thermal conductivity can be found.

Figure 2-5 shows a schematic of the test arrangement for this instrument.

2.4 SHOE SOLE AND HELMET MATERIAL

The thermal conductivity of the shoe sole material and the helmet material were measured on a Dynatech Model TC-1000 Comparator, since the sample size available did not permit use of the more precise absolute guarded hot plate device.

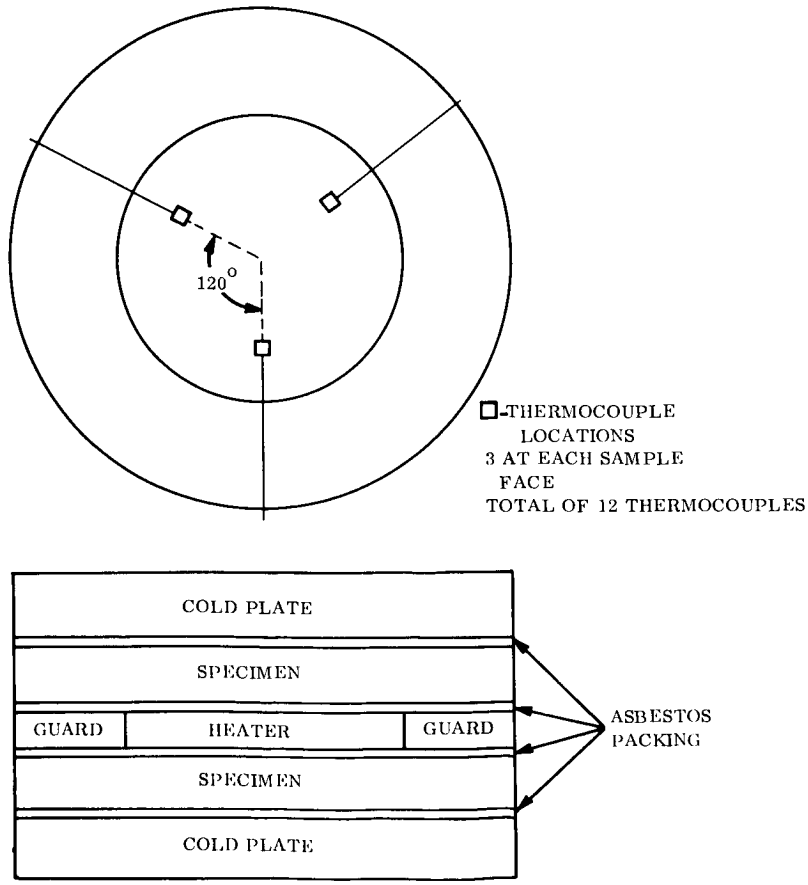


Figure 2-5. Guarded Hot Plate Test Stack

The principle of operation of the TC-1000 comparator is based upon comparing the unkown specimen's ability to conduct heat with that of heat meters of known thermal conductivity.

The apparatus consists of a power supply for supplying heater power, a water-cooled heat sink, and a test stack assembly which includes two identical heat meters between which the specimen is sandwiched. The specimen of unkown thermal conductivity is sandwiched between two identical heat meters of known thermal conductivity. The specimen and heat meters are, in turn, held between a heater and a fluid-cooled heat sink. Thus, the test section consists of a stack containing a heater, heat meter, specimen, a second heat meter, and, finally, a heat sink at the bottom of the stack.

The thermal conductivity coefficients of the specimen are determined by the following equation:

$$K_S = K_M \left(\frac{\Delta \overline{T}_M}{\Delta T_S}\right) \left(\frac{\Delta X_S}{\Delta X_M}\right)$$

where:

K_S is the specimen thermal conductivity
K_M is the heat meter thermal conductivity
ΔX_S, ΔX_M are the specimen and heat thicknesses, respectively
$\Delta \overline{T}_M$ is the average temperature drop across the heat meters
ΔT_S is the specimen temperature drop.

In the case of the two materials measured by means of the comparator, two samples of Pyroceram 9606 calibrated at the National Bureau of Standards were used as a reference standard. Figure 2-6 shows a schematic of the comparator test stack,and Figure 2-7 is a photograph of the comparator test stack.

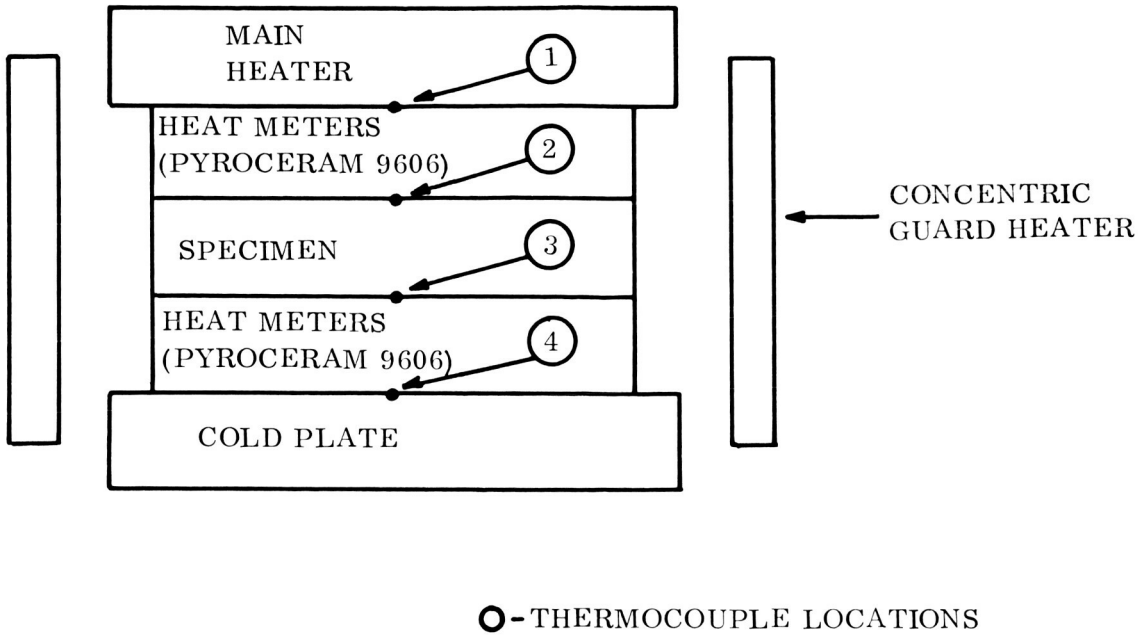


Figure 2-6. Schematic of Comparator Test Stack

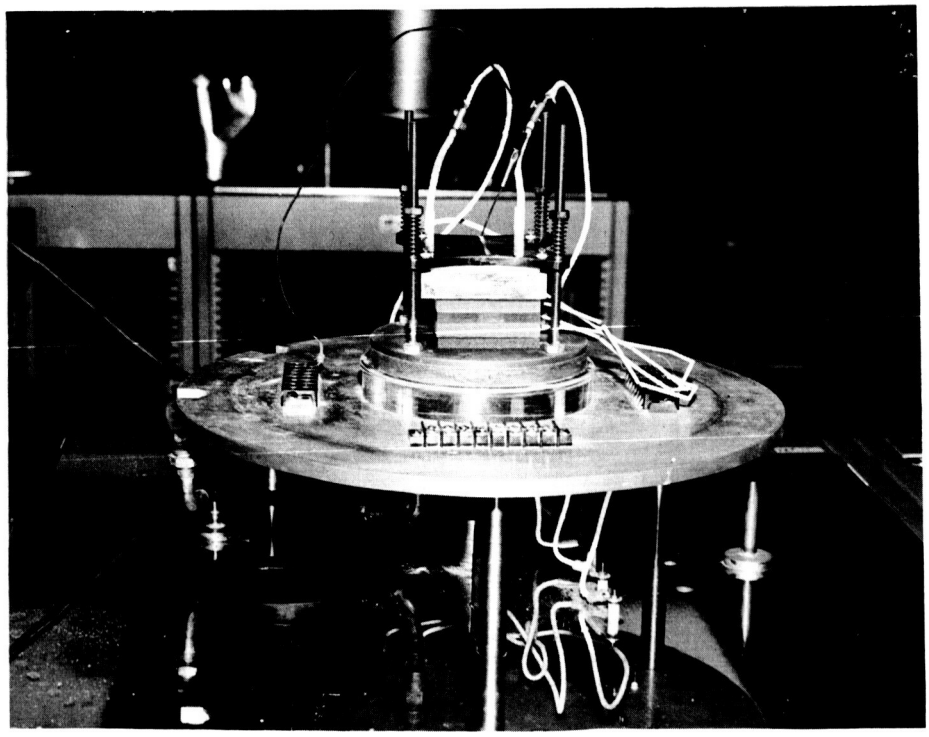


Figure 2-7. Photograph of Comparator Test Stack

2.5 COLD PLATE COOLING FLUID SOURCES

Three sources for a reference cold plate temperature were utilized: (a) Liquid N_2, (b) an LN_2-methanol heat exchanger, and (c) Conrad Cooler Model No. SB-0-0-03 were used to provide sink temperatures in the range of -310°F to +70°F. The LN_2 - methanol heat exchanger provided cold plate temperatures in the range of -150°F to -20°F. Methanol was selected as a heat transfer fluid primarily because of its low viscosity at the low operating temperatures, although its poor lubricity does create a possible pumping problem. A schematic of the LN_2-methanol heat exchanger is shown in Figure 2-8. The temperature range from -20°F to +70°F was provided by a Conrad Cooler Model SB-0-0-03.

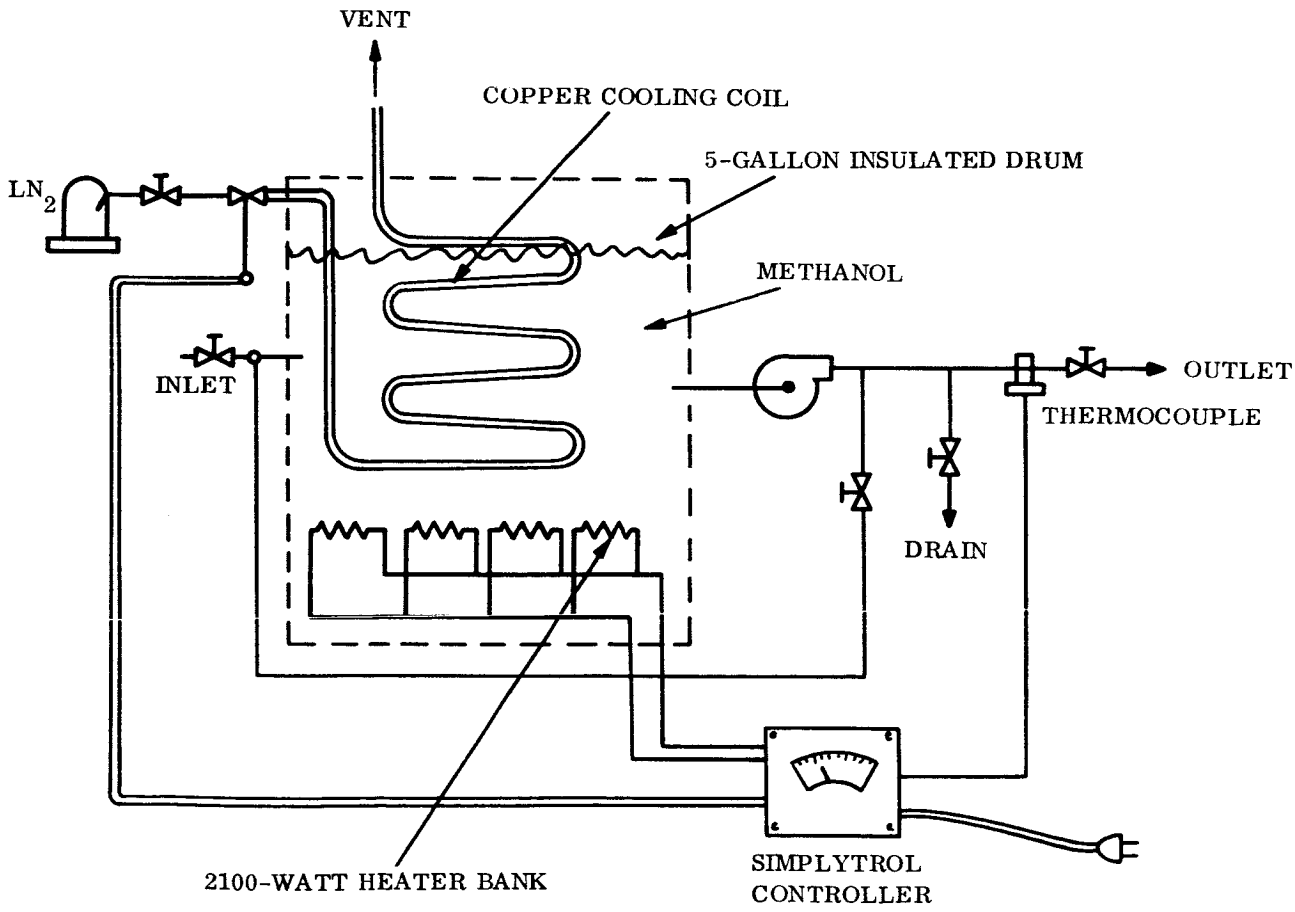


Figure 2-8. Schematic of LN_2-Methanol Heat Exchanger

2.6 TEST PROCEDURE

The general test procedure followed for all of the tests using guarded hot plates was as follows:

a. Evacuate the bell jar to approximately 10^{-4} mm Hg.

b. Start the cold plate fluid following.

c. Turn on the main heater power and, keeping the controller in the manual mode, raise or lower the main heater temperature to the specified test value.

d. The temperature difference between the main and guard heaters was then zeroed out manually and the controller was placed in the automatic mode. This procedure was found to be basically more satisfactory than operating the controller in the automatic mode, since this created problems with overshoot.

e. Several adjustments were made to the main heater power level in order to maintain the main heater temperature at or near the desired set point. The test was terminated when the rate of change of temperature was less than $0.25^{\circ}F$ over a period of 4 hours.

SECTION 3

TEST RESULTS

3.1 MULTILAYER INSULATION

Figure 3-1 gives a graphical summary of all of the test series run with the multilayer insulation assemblies. Each series consists of a different sample thickness or sample configuration. Within each series a number of tests were performed at different boundary temperatures. The temperature boundaries used in these tests were as follows: Cold plate temperature = -310°F, - 100°F, 0°F, and +70°F with the heater plate temperature set at approximately 70°F, 70°F, 200°F, and 300°F, respectively. The cotton sheeting was always located such as to be in contact with the 0°F or 70°F temperature surface. The cotton sheeting was very loosely basted to the blue nylon sheet in order to prevent the cotton cloth from curling to the point of being totally unmanageable. Table 3-1 gives a summary of the basic test data.

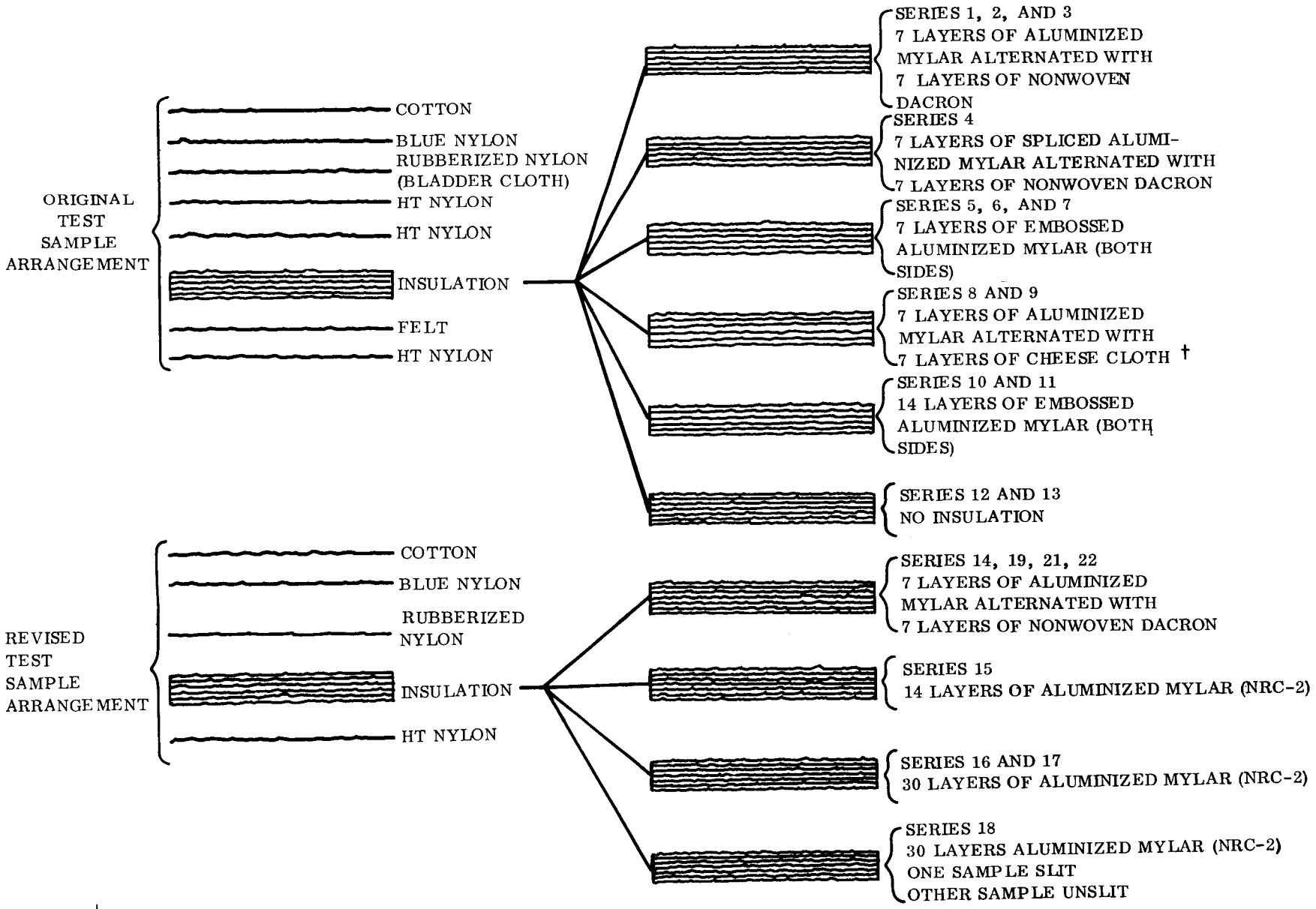
Figures 3-2 and 3-3 show some of the experimental test results in graphical form. Some of the salient conclusions reached based on the summarized test data are as follows.

3.1.1 CONCLUSIONS ON ORIGINAL TEST SAMPLE (See Figure 3-1.)

The conclusions on the original test sample are as follows:

a. Compressingof samples inevitably increased the effective thermal conductivity, leading to a 3-8 fold increase in k_{eff} depending on the temperature range.

b. Increasing the boundary temperatures increases the effective thermal conductivity, as is to be expected, demonstrating the importance of radiant heat transfer.



† GRADE 20/12 UNBLEACHED, STARCHED 100% COTTON CHEESE CLOTH.

Figure 3-1. Summary of Multilayer Test Arrangements

TABLE 3-1. SUMMARY OF FINAL TEST RESULTS

Test No.	ΔX - Sample Thickness (in.)	T_{cold} (°F)	T_{hot} (°F)	k_{eff} Btu/hr-ft °F	$k_{eff}/\Delta X$ (Btu/hr-ft^2 °F)	Q (Btu/hr)	Final Pressure (mm Hg)	Test Time (hr)
1.1	5/16	-310	+65	1.295×10^{-4}	0.00497	1.751	6×10^{-6}	55
1.2	5/16	-84	+71	2.205×10^{-4}	0.00847	1.228	4×10^{-5}	45
1.3	5/16	-1	+201	5.70×10^{-4}	0.0219	4.307	1.2×10^{-5}	31
1.4	5/16	+70	+288	1.06×10^{-3}	0.0407	8.304	2.0×10^{-5}	45
2.1	4/16	-310	+72	3.76×10^{-4}	0.0180	6.480	1×10^{-5}	77
2.2	4/16	0	+200	1.21×10^{-3}	0.0581	10.49	4.7×10^{-6}	31
2.3	4/16	+70	+300	1.935×10^{-3}	0.0929	20.09	8.4×10^{-6}	28
3.1	3/16	-310	+71	8.80×10^{-4}	0.0563	20.05	1.6×10^{-5}	77
3.2	3/16	-100	+75	1.205×10^{-3}	0.0771	12.74	8.4×10^{-6}	31
3.3	3/16	+1	+203	2.25×10^{-3}	0.144	27.36	7.1×10^{-6}	97
3.4	3/16	+70	+300	3.05×10^{-3}	0.195	42.07	9.5×10^{-6}	69
4.1	4/16	+70	+305	2.11×10^{-3}	0.101	22.36	7.4×10^{-6}	92
4.2	4/16	-310	+73	3.155×10^{-4}	0.0151	5.441	2.0×10^{-7}	52
4.3	4/16	0	+200	9.55×10^{-4}	0.0458	8.647	4.6×10^{-6}	98
5.1	5/16	-310	+77	1.77×10^{-4}	0.00680	2.467	1.1×10^{-5}	54
5.2	5/16	0	+208	5.8×10^{-3}	0.223	4.348	1.2×10^{-6}	72
5.3	5/16	+70	+301	1.07×10^{-3}	0.0411	8.928	7.0×10^{-6}	95
5.4 (1)	5/16	-310	+76	1.595×10^{-4}	0.00612	2.217	3.6×10^{-5}	73
6.1	4/16	+2	+202	1.44×10^{-3}	0.0691	12.99	8.4×10^{-6}	47
6.2	4/16	+70	+300	2.10×10^{-3}	0.101	21.80	7.0×10^{-6}	51

(1) Repeat of Test No. 5.1

TABLE 3-1. SUMMARY OF FINAL TEST RESULTS (Cont'd)

Test No.	ΔX - Sample Thickness, (in.)	T_{cold} (^oF)	T_{hot} (^oF)	k_{eff} Btu/hr-ft ^oF	$k_{eff}/\Delta X$ (Btu/hr-ft^2 ^oF)	Q (Btu/hr)	Final Pressure (mm Hg)	Test Time (hr)
6.3	4/16	-310	+75	3.525×10^{-4}	0.	6.114	2.0×10^{-5}	54
6.4 (2)	4/16	-310	70	3.805×10^{-4}	0.0183	6.512	7.4×10^{-6}	43
7.1	3/16	-310	+71	1.355×10^{-3}	0.0867	30.96	------(3)	50
7.2	3/16	+2	+200	2.515×10^{-3}	0.161	29.86	1.6×10^{-5}	47
7.3	3/16	+70	+305	3.23×10^{-3}	0.207	45.56	8×10^{-6}	68
8.1	5/16	-310	67	3.196×10^{-4}	0.0123	4.335	3.2×10^{-5}	78
8.2	5/16	70	302	1.285×10^{-3}	0.0493	10.75	8.0×10^{-6}	119
9.1	3/16	-310	72.5	1.275×10^{-3}	0.0816	29.30	5×10^{-5}	74
9.2	3/16	72	300	2.52×10^{-3}	0.161	34.51	4.7×10^{-6}	47
10.1	5/16	70	304	7.954×10^{-4}	0.0305	6.706	4×10^{-6}	141
10.2	5/16	-310	74	9.96×10^{-5}	0.00382	1.378	4×10^{-5}	50
11.1	3/16	70	300	2.496×10^{-3}	0.160	34.42	5×10^{-5}	26
11.2	3/16	-309	70	9.186×10^{-4}	0.0588	20.87	7×10^{-6}	78
12.1	3/16	-310	70	1.01×10^{-3}	0.0646	23.20	2.3×10^{-5}	78
12.2	3/16	70	300	3.16×10^{-3}	0.202	43.55	1.3×10^{-5}	29
13.1	2/16	70	301	4.71×10^{-3}	0.452	97.60	1.3×10^{-5}	48
14.1	3/16	-310	68	9.312×10^{-5}	0.00596	2.110	1.8×10^{-8}	127
14.2	3/16	70	301	5.994×10^{-4}	0.0384	8.300	2.7×10^{-5}	50
14.3 (4)	3/16	-310	68	1.736×10^{-4}	0.0111	3.933	2.0×10^{-6}	53

(2) Repeat of test No. 6.3 (3) Vacuum gauge out of order (4) Repeat of Test No. 14.1

TABLE 3-1. SUMMARY OF FINAL TEST RESULTS (Cont'd)

Test No.	ΔX - Sample Thickness, (in.)	T_{cold} (^oF)	T_{hot} (^oF)	k_{eff} Btu/hr-ft ^oF	$k_{eff}/\Delta X$ (Btu/hr-ft^2 ^oF)	Q (Btu/hr)	Final Pressure (mm Hg)	Test Time (hr)
14.4 (5)	3/16	-310	70	1.654×10^{-4}	0.0106	3.767	8.0×10^{-6}	55
15.1	3/16	-310	76	1.423×10^{-4}	0.00911	3.924	1.1×10^{-8}	97
15.2	3/16	70	305	6.327×10^{-4}	0.0405	8.913	1.6×10^{-5}	71
16.1	4/16	-310	79	3.818×10^{-5}	0.00183	0.6689	3.0×10^{-6}	48
16.2	4/16	70	297	5.774×10^{-4}	0.0277	5.903	1.9×10^{-5}	71
17.1	3/16	-310	67.5	1.544×10^{-4}	0.00988	3.493	2.2×10^{-6}	72
17.2	3/16	70	295	9.237×10^{-4}	0.0591	12.46	1.2×10^{-5}	91
18.1	4/16	-310	78	1.923×10^{-5}	0.000923	0.3361	2.3×10^{-6}	26
18.2 (6)	4/16	-310	76	1.917×10^{-5}	0.000920	0.3333	3.4×10^{-6}	67
19.1	4/16	-310	76	7.855×10^{-5}	0.00377	1.366	9×10^{-6}	67
20.1(7)	1.0	70	297	1.211×10^{-2}	0.145	30.94	1.1×10^{-6}	49
20.2	1.0	-310	68	2.068×10^{-3}	0.0248	8.801	1.5×10^{-6}	49
21.1	5/32	72	300	1.215×10^{-3}	0.0933	19.88	9.4×10^{-6}	70
22.1	7/32	71	299	3.327×10^{-4}	0.0183	3.906	8.3×10^{-6}	31

(5) Repeat of Test No. 14.1 (6) Sample slit around perimeter between main and guard heaters
(7) Owens Corning Fiberglas - 2-inch medium Fiberglas building insulation

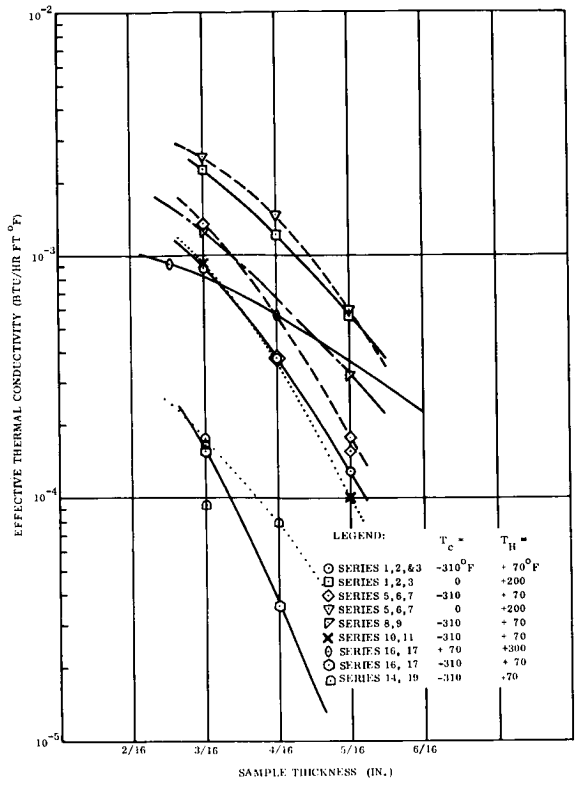


Figure 3-2. Effect of Sample Thickness on Multilayer Insulation Effective Thermal Conductivity ($T_C = -310^oF, T_H = +70^oF$; $T_C = 0^oF$, $T_H = +200^oF$)

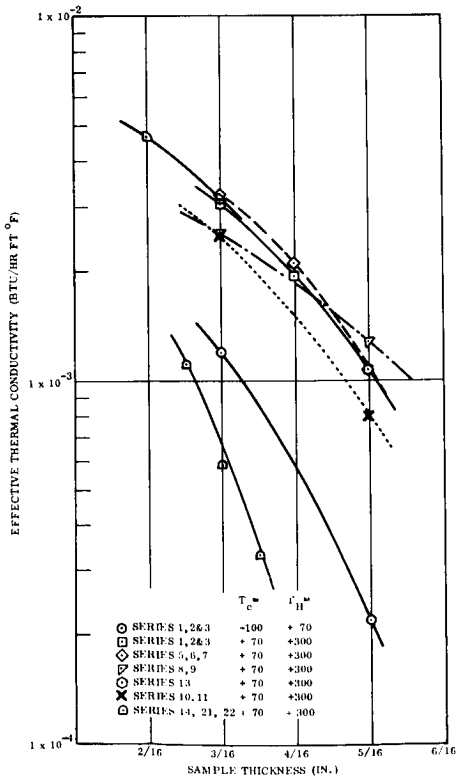


Figure 3-3. Effect of Sample Thickness on Multilayer Insulation Effective Thermal Conductivity ($T_C = -100^oF, T_H = +70^oF$; $T_C = +70^oF$, $T_H = +300^oF$)

c. Splicing insulation with tape does not cause a sufficiently large difference in insulating characteristics over unspliced insulation, outside of the estimated experimental errors; consequently, it cannot be concluded that the presence or absence of splicing makes any significant difference.

d. Embossed aluminized Mylar alone is a poorer insulator than an equivalent number of unembossed pairs of aluminized Mylar plus Dacron spacers. A difference as large as a factor of 3, depending on both sample thickness and boundary temperatures, was observed. The embossed Mylar is poorest at the lower temperature levels. The presence of the Dacron, although not an efficient radiation shield, still limits the contact-conduction through the insulation blanket.

e. Nonwoven Dacron spacer is superior to loosely woven cheesecloth by as much as a factor of 2.5. The improvement is greatest at the lower boundary temperature range.

f. Doubling the number of embossed Mylar sheets improves the insulation efficiency by as much as 50% (see Table 3-1, series 5, 6, 7, 10, 11).

g. Using as many layers of Aluminized Mylar as individual layers of aluminized Mylar and Dacron does not provide a significantly more efficient insulation.

h. The fact that series 10 and 11 are so close to that of series 1, 2, and 3 suggests the existence of an optimum number of layers lying between 7 and 14.

i. Omitting the insulation layer altogether, the remaining material still is effective as an insulator.

3.1.2 CONCLUSIONS ON REVISED TEST SAMPLE USING NEW MICROMETEOROID SHIELD (See Figure 3-1.)

a. For a given sample thickness, the revised sample arrangement is a more efficient insulation than the original arrangement. An explanation for this is given in Section 4. The improvement is as much as a factor of 5 (see Table 3-1, series 14 and 3).

b. Fourteen layers of aluminized Mylar appear to be as effective as insulation as seven layers of aluminized Mylar alternated with seven layers of nonwoven Dacron.

c. Increasing the number of sheets of aluminized Mylar to 30 layers results in a slightly poorer insulator.

Several tests were repeated as a check on basic test accuracy and reproducibility. With one exception the tests which were repeated were reproducible within 10%. No obvious reason is available to explain the poor reproducibility between tests 14.1, 14.3 and 14.4, although from the data, test No. 14.1 must be regarded as suspect.

All of the curves shown in Figures 3-2 and 3-3 have a similar slope, with the exception of the curve for test series 16 and 17, with $T_C = 70$ and $T_H = 300$.

One point in series 5, 6, and 7 is inconsistent with the other two experimental points on the basis of assuming that all of the curves should have a similar curvature. No reason for this is obvious. The result of a similar slope is consistent with the findings presented in Reference (2). This suggests a simple relationship between effective thermal conductivity and the applied load. No means of measuring applied pressure on the samples was incorporated into the test apparatus design, so it would be of interest to make a separate correlation to relate sample thickness with applied load. This might consist of merely reconstructing the various test assemblies and measuring their respective thicknesses under several measured weighted plates.

Test series 20 covers the only material listed in Table 3-1 which is not a multilayer material. This sample is a 2-inch thick material of Owens-Corning Fiberglas building insulation which was compressed to 1-inch thickness. The specifications based on 1-inch thick material are:

density	= $1.072\ lb/ft^3$	based on 1-inch thick mat
solid fraction	= 0.304	based on 1-inch thick mat
mean fiber diameter	= 0.00024 in.	

The estimated experimental accuracy of the data reported is ±15%

3.2 PLEXIGLAS VISOR MATERIAL

A tabular summary of the thermal conductivity of the plexiglas sample is given in Table 3-2.

The plexiglas thermal conductivity versus temperature is shown graphically in Figure 3-4. The plexiglas results show good agreement with published data.

TABLE 3.2. PLEXIGLAS THERMAL CONDUCTIVITY

Sample Mean Temperature (^oF)	ΔT (^oF)	k (Btu/ft hr^oF)
-290	63	0.069
-304	43	0.067
-89	27	0.081
-79	34.5	0.084
13	15.7	0.088
20	24.6	0.088
120	31.0	0.093
114	23.9	0.091

3.3 HELMET MATERIAL

The measured data for the helmet material (a Fiberglas-epoxy laminate) is in Table 3-3..

TABLE 3-3. THERMAL CONDUCTIVITY OF HELMET MATERIAL

Sample Mean Temperature (^{o}F)	Δ T (^{o}F)	k(Btu/ft-hr^{o}F)
167	83	0.168
82	20	0.151
-73.5	17	0.143
-254.5	55	0.144

A plot of this data is given in Figure 3-5.

3.4 SHOE SOLE MATERIAL

The thermal conductivity of the shoe sole material is tabulated in Table 3-4.

TABLE 3-4. THERMAL CONDUCTIVITY OF SHOE SOLE MATERIAL

Sample Mean Temperature (^{o}F)	Δ T (^{o}F)	k (Btu/ft-hr^{0}F)
-108	239	0.123
-12	162	0.125
+18	80	0.128
+55	122	0.126
+115	66	0.117
+133	91	0.125
+142	90	0.128

This data is shown plotted in Figure 3-6.

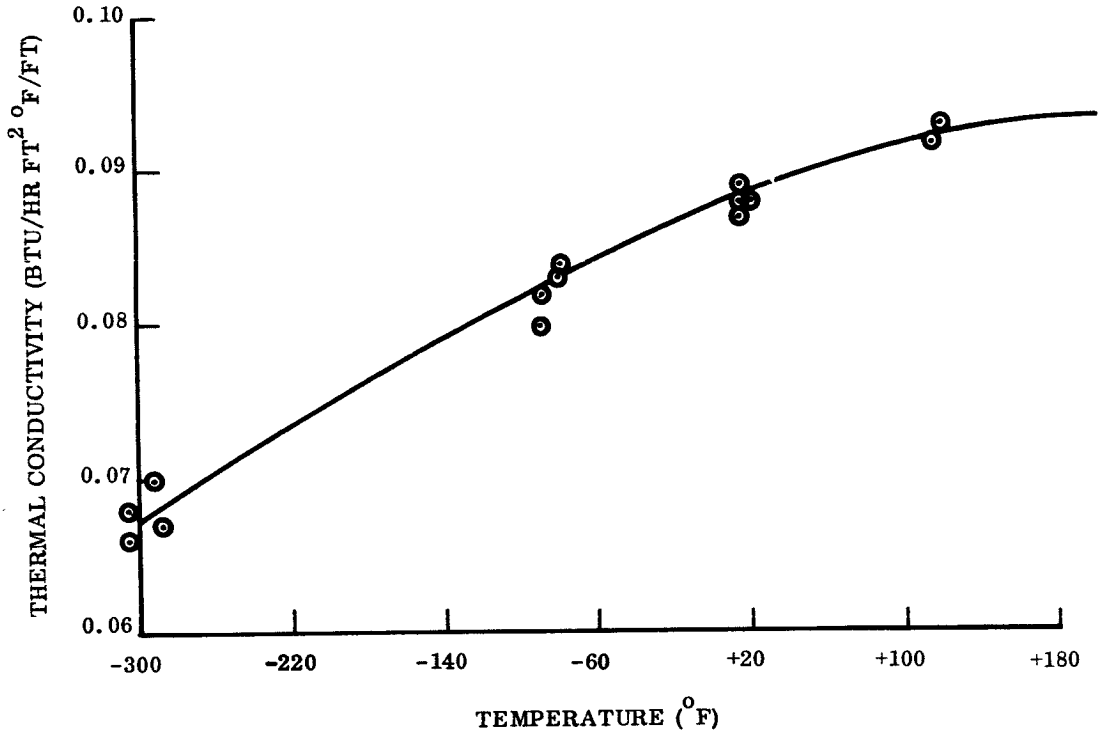


Figure 3-4. Thermal Conductivity of Plexiglas (Visor)

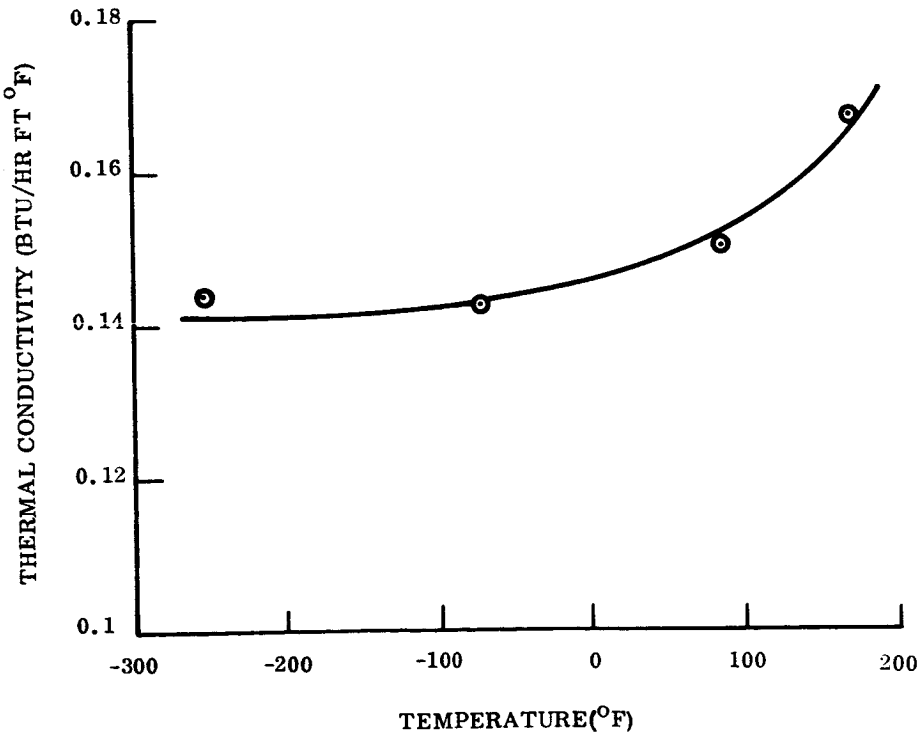


Figure 3-5. Thermal Conductivity of Helmet Material

SECTION 4

DATA ANALYSIS

4.1 INTRODUCTION

The experimental data obtained in the reported program illustrates several salient characteristics of multilayer insulation systems. Multilayer insulations are in general quite sensitive to the application of mechanical load. This is amply demonstrated in the test results of this program. In addition some of the test results suggest the existence of an optimum bulk density. Reference 1 discusses this effect in some detail. On the basis of conduction heat transfer alone, the thermal conductivity of multilayer insulation should increase monotonically as the bulk density decreases. However, it has been observed (Ref. 1,2) that the thermal conductivity first decreases with an increase in bulk density and then increases. This suggests that another mechanism of heat transfer, namely radiation, contributes significantly to the overall heat transfer. The explanation for this phenomenon of a minimum thermal conductivity is a simple one. Initially, radiation heat transfer is controlling. As additional layers of material are added to increase the bulk density of the insulation, the radiation resistance increases so that the effective thermal conductivity actually decreases. As more layers are added, a point is reached where contact conductance becomes more significant until a bulk density is achieved beyond which contact conductance is controlling and consequently the apparent thermal conductivity increases. This is a partial explanation for why Test series 10 and 11, for example, are a better insulation than series 1, 2 and 3 and also why series 16 and 17 are not better than series 14, 19, 21 and 22 (see Table 3-1).

Reference 2 raises some other rather interesting conclusions which have a bearing on the current test program. It was concluded that the configuration (whether or not the aluminized Mylar is embossed) appears to have no effect on the apparent thermal conductivity. Moreover, it was found that the application and subsequent release of mechanical loading appeared to improve the insulating properties of the multilayer insulation. Since all of the tests were not run in order of increasing or decreasing mechanical load, this effect, if applicable

to the test arrangements in this program, would have some bearing on the question of basic test accuracy and reproducibility. In some of the tests the samples were completely disassembled and then reconstructed so that presumably this effect would not be present.

4.2 THEORY

A significant body of literature (Ref. 3, 4, 5, 6, and 7) has been generated to theoretically explain the basic characteristics of multilayer insulation. Reference 3 gives a very lucid discussion as to the basic exploration behind the efficiency of multilayer vacuum insulation.

The kinetic theory of gases provides a means to understand the methods of energy transfer between parallel plates or surfaces with the enclosed gas at a very low pressure, i.e., a rarefied gas. When the mean free path of a gas molecule is much greater than the distance separating the boundaries or, as in our case, the material layers across which heat is to be transferred, then intermolecular collisions are much less frequent than are collisions with these boundaries. For this case the thermal conductivity of the gas, if one can still call it this, becomes negligible. Thus the apparent thermal conductivity of the multilayer assembly will decrease with decreasing gaseous pressure until it levels off at a value consistent with radiation and contact conductance effects. The data presented in References 8, 9, and 10, illustrate this phenomena. From this data it is evident that below an ambient pressure of about 10^{-5} mm Hg, pressure effects are no longer of any significance. There are, however, some qualifications to this statement; these will be discussed in Section 5.

4.3 DATA CORRELATIONS

Reference 3 discusses the lack of separability of the various heat transfer mechanisms present in multilayer insulation and the interdependence of radiation and conduction heat transfers. Several attempts have been made, however, to attempt to develop a separable solution to the problem of heat transfer in multilayer insulation (Ref. 6 and 7). A solution

of the form:

$$Q = K_1 (T_h - T_c) + K_2 (\sigma T_h^4 - \sigma T_c^4)$$

was fitted to some of the data, unfortunately, without particular success. A summary of the derived coefficients are given in Table 4-1. The manner of obtaining the coefficients is given in Appendix C.

The lack of consistency within the constants calculated for the proposed equation, suggests that another form for the equation may be more accurate. The so-called constants are undoubtedly themselves functions of temperature.

TABLE 4-1. DATA CORRELATION ANALYSIS

Test No.	$(T_h - T_c)$ °F	$(\sigma T_h^4 - \sigma T_c^4)$ Btu/hr-ft^2	Q (Btu/hr)	K_1	K_2
1.1	375	129.3	1.751		
1.2	155	102.0	1.228	-3.499×10^{-3}	2.179×10^{-2}
1.3	202	251.1	4.307		
1.4	218	401.4	8.304		
2.1	382	136.4	6.48		
2.2	200	248.5	10.90	5.605×10^{-3}	4.54×10^{-2}
2.3	230	436.6	20.09		
3.1	381	135.4	20.05		
3.2	175	112.6	12.74	2.2×10^{-2}	8.568×10^{-2}
3.3	203	255.8	27.36		
3.4	230	436.6	42.07		
4.1	235	451.8	22.36		
4.2	383	137.4	5.441	-5.038×10^{-3}	4.934×10^{-2}
4.3	200	248.5	8.647		
5.1	387	141.6	2.467	-1.542×10^{-3}	2.028×10^{-2}
5.2	208	264.6	4.348		
5.3	231	439.6	8.928		
5.4	386	140.6	2.217		
6.1	200	241.1	13.00	-2.496×10^{-3}	5.224×10^{-2}
6.2	230	436.6	21.80		
6.3	385	139.5	6.114		

TABLE 4-1. DATA CORRELATION ANALYSIS (Cont'd)

Test No.	$(T_h - T_c)$ ^oF	$(\sigma T_h^4 - \sigma T_c^4)$ Btu/hr-ft^2	Q (Btu/hr)	K_1	K_2
7.1	381	135.4	30.96		
7.2	198	247.1	29.86	5.602	7.246
7.3	235	452.8	45.56	$x10^{-2}$	$x10^{-2}$
8.1	377	131.3	4.335	3.69 x	2.242
8.2	232	442.6	10.78	10^{-3}	$x10^{-2}$
10.1	232	449.7	6.706	-2.082	1.599x
10.2	379.5	135.6	1.378	$x10^{-3}$	10^{-2}
11.1	229.5	435.3	34.42	3.189	6.226
11.2	384.0	138.5	20.87	$x10^{-2}$	$x10^{-2}$
12.1	384	138.5	23.2	3.017x	8.385
12.2	230	436.6	43.55	10^{-2}	$x10^{-2}$
9.1	382.5	137.4	29.30	5.946	4.772x
9.2	230	436.6	34.51	$x10^{-2}$	10^{-2}

SECTION 5

ERROR ANALYSIS

5.1 SOURCES OF ERROR

Some of the basic sources of error can be readily identified and assessed; in the case of others, additional experimentation is required to solve the problem of test accuracy. The major sources of error are:

a. Heater power measurement.

b. Cold plate and heater plate temperature measurement.

c. Sample thickness.

d. Basic inhomogeneity of materials.
   1. Coating thickness
   2. Mylar thickness
   3. Dacron spacer uniformity

e. Lateral heat flow within sample due to mismatch in temperature between main heater and guard heater.

f. Lateral heat flow within sample due to a nonadiabatic boundary measurement.

g. The system has not reached a steady state condition.

h. Internal pressure effects due to outgassing of materials.

The first five of these errors are somewhat amenable to analysis; the last three must be determined by physical measurements.

5.2 PHYSICAL MEASUREMENTS

The heater power measurements are obtained by measuring the applied voltage on the main heater with a Cimron recording digital voltmeter (Model No. 6410) and the current by measuring voltage drop across a calibrated manganin shunt resistance placed in series with the main heater. The stated accuracy of the voltmeter in the operating range used in these tests is $\pm$ 0.05% of full scale. In the case of the main heater voltage, this is a maximum error of $\pm$ 0.006 v and in the case of the shunt voltage this is a maximum error of $\pm$ 0.006 mv. The shunt resistance was measured on a GE Double Bridge (Cat. No. 9069199G-1) with a stated accuracy of $\pm$ 0.00004 ohms. From the above, the estimated accuracy of the power measurements is $\pm$ 2%.

Both the heater plate and cold plate temperatures were measured with precision grade chromel-alumel thermocouples. The estimated accuracy of measurement of the temperature difference is $\pm$ 1%. Sample thickness is the most imprecise measurement with an estimated accuracy of $\pm$ 10% at thicknesses greater than 1/4 inch.

A limited number of samples have been tested, making estimates of the effect of material inhomogeneities impossible to assess, although it is known that nonuniform aluminizing and nonuniform fiber size and weave for the spacer materials are a major source of discrepancy.

5.3 TEMPERATURE CONTROLLER ERROR

The fifth identified source of error has received some comment in other references. References 11 and 12 both allude to the problem of lateral heat flow in multilayer insulation. This problem is compounded by the severe anisotrophy of this material. In order to analytically define the problem of a mismatch in temperature between the main heater and the guard heater several simplifying assumptions have been made:

a. The insulation is treated as anisotropic with two effective thermal conductivities, k_x and k_y in the x and y directions, respectively.

b. The assumed temperature distribution on the top face of the insulation is shown in Figure 5-1.

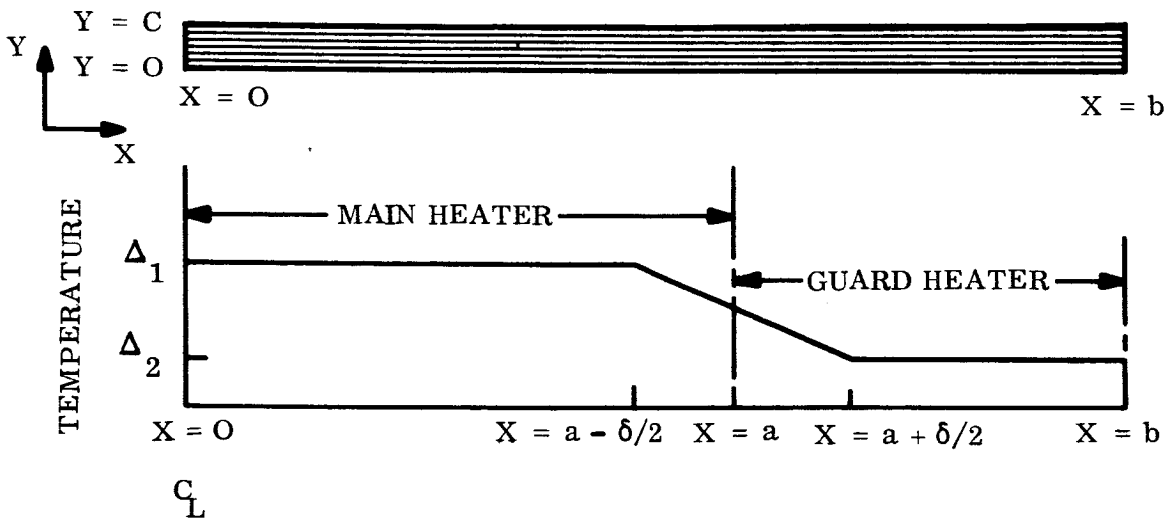


Figure 5-1. Insulation Temperature Distribution

The error in the measurement of heat flow through the main portion of the insulation is:

$$\text{Error (\%)} = 100 \times \left[\frac{-\int_0^a k_y \left.\frac{\partial T}{\partial y}\right|_{y=0} dx}{\int_0^a k_y \left.\frac{\partial T}{\partial y}\right|_{y=0} dx - \int_0^c k_x \left.\frac{\partial T}{\partial x}\right|_{x=a} dy} \right]$$

$$\text{Error (\%)} = \frac{100}{\left[1 + \dfrac{\dfrac{\pi\alpha}{2}\left(\dfrac{a}{c}\right)\left[\Delta_1\left(\dfrac{a}{b}\right) + \Delta_2\left(1 - \dfrac{a}{b}\right)\right] + \sum\limits_{n=1}^{\infty} \dfrac{2(\Delta_1 - \Delta_2)}{n^2 \pi \delta} \dfrac{\sin^2 \dfrac{n\pi a}{b} \sin \dfrac{n\pi\delta}{2b}}{\sinh \dfrac{n\pi c}{\alpha b}}}{\dfrac{\dfrac{2b}{\delta n^2 \pi}(\Delta_1 - \Delta_2) \sin^2 \dfrac{n\pi a}{b} \sin \dfrac{n\pi\delta}{2b}\left[\cosh \dfrac{n\pi c}{\alpha b} - 1\right]}{\sinh \dfrac{n\pi c}{\alpha b}}}\right]}$$

The complete derivation of this is presented in Appendix B. Figures 5-2 to 5-5 give a graphical presentation of the above equations for several values of the above parameter. The following example illustrates the order of magnitude of these effects.

Assume 60 layers aluminized Mylar (1/4 mil) in 1/2 inch.

Take ky = 2×10^{-5} Btu/hr-ft ^{o}F

k_{eff} = 1.55 Btu/hr-ft ^{o}F (based on 2 layers of aluminum (2 μ in. thick) in series with Mylar (k = 0.09 Btu/hr-ft ^{o}F)

Actual material thickness = 0.015 in.

fraction of sample thickness

occupied by material = f = 0.03.

The lateral heat conduction is taken as:

$$Q_{lateral} = k_{eff} \frac{f A \Delta T}{\Delta x} + 4 \epsilon A \sigma \overline{T}^3 \Delta T = k_x \frac{A \Delta T}{\Delta x}$$

so $k_x = k_{eff} \times f + 4 \epsilon \sigma \overline{T}^3 \Delta x$

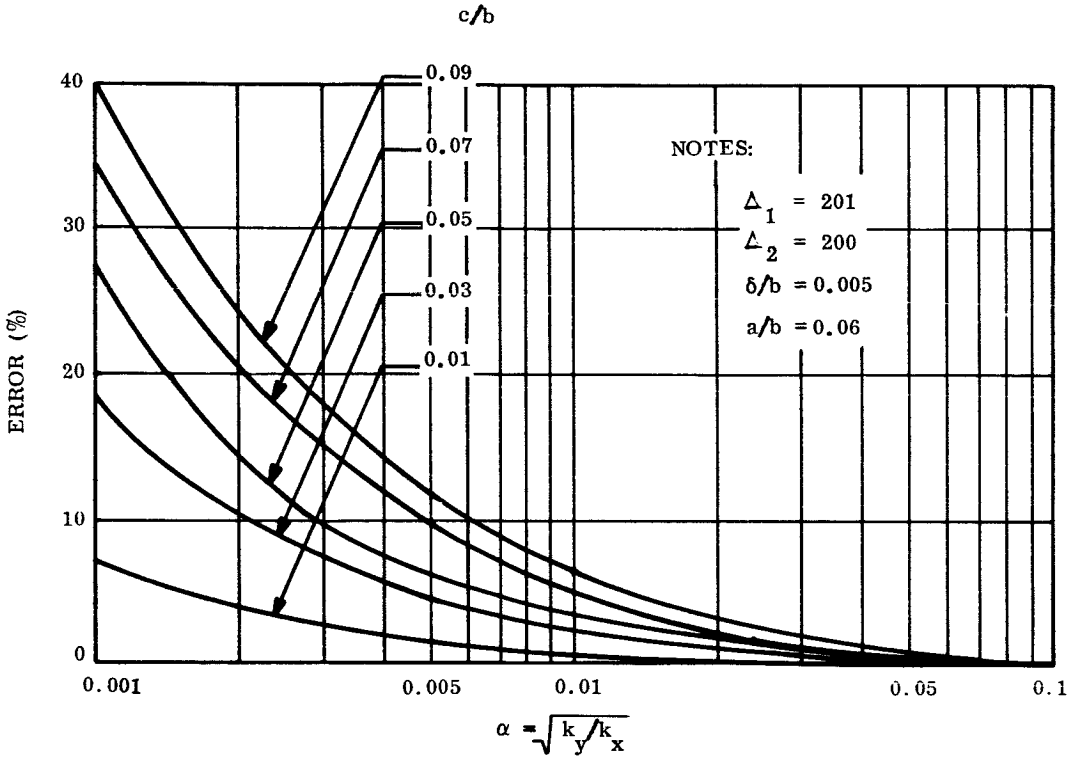


Figure 5-2. Error Versus Thermal Conductivity Ratio (Δ_1 = 201, Δ_2 = 200, δ/b = 0.005, a/b = 0.6)

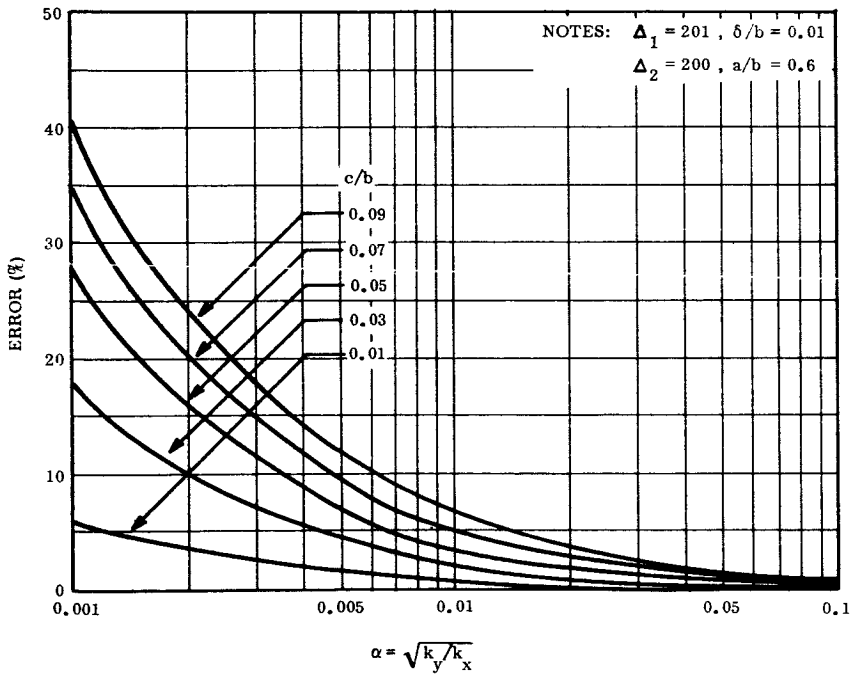


Figure 5-3. Error Versus Thermal Conductivity Ratio (Δ_1 = 201, Δ_2 = 200, δ/b = 0.01, a/b = 0.6)

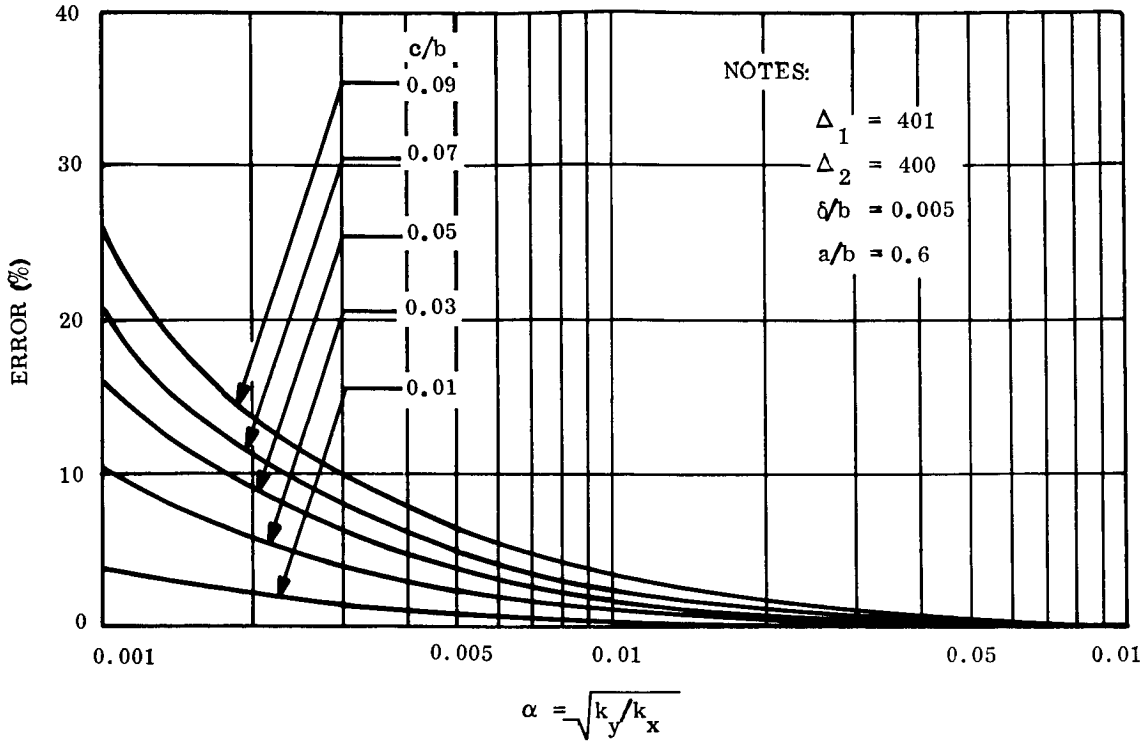


Figure 5-4. Error Versus Thermal Conductivity Ratio (Δ_1 = 401, Δ_2 = 400, δ/b = 0.005, a/b = 0.6)

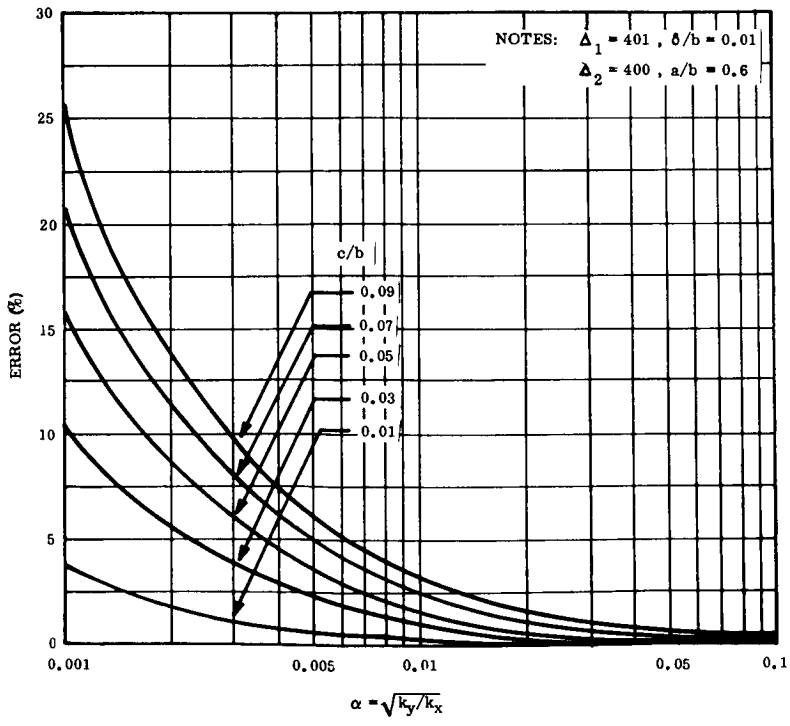


Figure 5-5. Error Versus Thermal Conductivity Ratio (Δ_1 = 401, Δ_2 = 400, δ/b = 0.01, a/b = 0.6)

Take $\epsilon = 1$ (black body)

$T = 100^{o}F = 560^{o}R$

$\Delta x = 1/16$ in. $= 0.0625$ in. $= 0.00521$ ft

Then $k_x = 1.55 \times 0.03 + 4 \times 1 \times 0.3 \times 0.00521$

$= 0.0465$ to $0.0062 = 0.0527$

so

$$\alpha = \frac{ky}{kx} = \sqrt{\frac{2x10^{-5}}{0.0527}} = 0.0195$$

Hence from Figure 5-2, the error is 2.2% (c/b = 0.5/7=0.07). The fact that the error is as small as it is even for a $1^{o}F$ mismatch in temperature is perhaps a surprising result; however, the low thermal conductivity of the Mylar is the controlling reason for this. One other note might be made of the fact that it is possible to achieve a relatively steady mismatch in temperature between the main heater and guard heater with the current test arrangement. This situation arises from the fact that it is possible to have the reset rate of a value low enough to have a permanent temperature offset. Since the output of the magnetic amplifier does not go to zero, the proportional band setting may not be able to correct this situation.

5.4 EFFECT OF NONADIABATIC BOUNDARY

In the previous discussion an adiabatic boundary condition was assumed. Reference 7 shows experimental data to demonstrate that a nonadiabatic boundary can be highly significant. Past experience suggests that an adiabatic test condition may not exist in fact. The present multilayer test apparatus is the second such apparatus to have been constructed. The first apparatus was essentially the identical configuration except that it incorporated a 1-inch-wide guard heater in place of the 3-inch-wide guard heater in the present design. Using the earlier test rig, the thermal conductivity of a blanket composed of 60 layers of aluminized Mylar 1/2 inch thick was measured to be 7×10^{-5} Btu/hr-ft ^{o}F for boundary temperatures of +70 and $-310^{o}F$. The present apparatus gave a value of 2×10^{-5} Btu/hr-ft ^{o}F for the same insulation blanket. These results were observed even though in each

case a blanket of aluminized mylar was wrapped around the perimeter of the test apparatus to provide an adiabatic boundary. The value measured in the current rig is, however, consistent with values obtained from other sources.

5.5 EFFECT OF SLITTING THE INSULATION

All of the tests with one exception were run with the multilayer blanket in one integral piece. One test was made to determine the difference, if any, in test accuracy between a continuous test sample and one where the insulation was slit around the perimeter between the guard and main heaters. Ostensibly the purpose of slitting the insulation is to provide a more nearly adiabatic boundary temperature. This will result in either of two effects:

a. Overlapping edges from an extremely fine slit will produce short circuiting.

b. Radiant interchange between the hot and cold portions of the sample will result from leaving an actual gap.

The second effect is discussed in Reference 12. This latter arrangement is probably the very poorest choice. As an example, consider a sample 1/2-inch thick with a slit 1/64 inch wide extending around the full perimeter of the main heater. The effective gap width δ_{eff} is from Reference 12:

$$\frac{\delta_{eff}}{d} = \left(\frac{2}{\epsilon} - 1\right) n\, f\left(\frac{\delta}{d}\right)$$

where

$$f\left(\frac{\delta}{d}\right) = \sqrt{1 + \frac{\delta^2}{d^2}} \left(\frac{1}{3} - \frac{2}{3}\frac{\delta^2}{d^2}\right) + \left(\frac{2}{3}\frac{\delta^3}{d^3} - \frac{1}{3}\right) + \frac{\delta^2}{d^2} \ln\left(\frac{1 + \sqrt{1 + \frac{\delta^2}{d^2}}}{\delta/d}\right)$$

where d = sample thickness = 1/2 inch

n = number of layers

ϵ = emittance of insulating sheet

Take $n = 60$

$\epsilon = 0.06$

Then $\delta_{eff}/d = 7.5$

so that for a perimeter of 35 inches the effective gap area is $\frac{7.5 \times 35}{144} = 1.81\ ft^2$, or since the heat transfer area of the main sample is $8\ 7/32 \times 8\ 7/32 \approx 1\ ft^2$, the presence of a gap represents an error of 180% in the measurement of heat flow through the sample.

5.6 TIME TO REACH TEMPERATURE EQUILIBRIUM

The time to reach temperature equilibrium has been assessed (Ref. 13) in order to verify the criteria used in terminating individual tests. This analysis is based on two assumptions: (a) a constant thermal conductivity through the insulation (the validity of the assumption is borne out by Reference 14); and (b) a step change in one of the boundary temperatures, maintaining the other boundary at a fixed value. Considering the above assumptions, it can be shown that if the heat flow is measured at the surface where the temperature is kept constant, the ratio of the instantaneous heat flow to the value at time (t) = ∞ is:

$$\frac{q_t}{q_\infty} = 1 + 2 \sum_{n=1}^{\infty} \cos n\pi\, e^{-K \frac{n^2 \pi^2 t}{\ell^2}}$$

where t = time

ℓ = sample thickness

K = thermal diffusivity

If the heat flow is measured at the surface where the step change in temperature occurs, then the above ratio becomes:

$$\frac{q_t}{q_\infty} = 1 + 2 \sum_{n=1}^{\infty} e^{-\frac{K n^2 \pi^2 t}{\ell^2}}$$

As an example, if a 1/2-inch sample with a thermal diffusivity of $2 \times 10^{-5} \frac{ft^2}{hr}$ is considered, the time to reach 99% of equilibrium for a 1/2-inch sample is 46.6 hours. This justifies the somewhat lengthy duration of the tests, since taking the transient data and correcting it for heat capacity effects is felt to be of somewhat dubious accuracy.

5.7 PRESSURE EQUILIBRIUM

An equilibrium condition is based on achieving both temperature and pressure equilibrium. The question of pressure equilibrium is the more difficult one to evaluate either analytically or experimentally. Reference 15 presents one attempt at a solution to the problem of time to reach pressure equilibrium. The present theory is inadequate to solve this problem, primarily because of the lack of a complete theory to account for outgassing effects. From data published in Reference 16, the rate of outgassing from an aluminized surface can produce a significant pressure gradient within a multilayer insulation blanket. Since no specific provision was made in the apparatus to vent the samples, the presence of gas could represent a potential source of error, although no specific evidence in the test results exists to demonstrate this. No technique exists at present for measuring the entrapped gas pressure within a multilayer insulation blanket. The presence of outgassing was partially illustrated by the fact that the bell jar pressure was significantly higher for the elevated temperature tests than that for the tests run at liquid nitrogen temperatures. Of course the outgassing effect is somewhat masked by the fact that the liquid nitrogen promotes cryo-pumping.

SECTION 6

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APPENDIX A
MULTILAYER INSULATION TEST RESULTS

APPENDIX A

MULTILAYER INSULATION TEST RESULTS

A computer program has been written to process all of the test data and to plot this data automatically. The first three tests have been excluded from this compilation on account of incomplete test data. One fact which is interesting to note is that the effective thermal conductivity of the multilayer insulation reached an equilibrium value considerably before the temperatures reached what was considered a proper equilibrium condition. Some of the testing was extended on account of difficulties with maintaining a constant liquid nitrogen temperature and periodic irregularities in the operation of the Conrad cooler.

The past experience with the multilayer insulation testing has resulted in the following conclusions with regard to improving both the test accuracy and reducing test time.

a. Instead of adjusting the main heater temperature by trial and error, it is preferable to regulate the main heater temperature thermostatically and to consider an equilibrium condition on the basis of the power reaching a steady-state value. The curves shown in this appendix amply demonstrate that considerable test time was lost with adjusting the power level by trial and error.

b. Some very limited data shows that the temperature gradients through the insulation are quite nearly linear. This being the case, it would be advisable to revise the general test procedure to:

   1. Pump the system down.
   2. Purge the system with a noncondensable gas; then start the cold plate fluid flowing.
   3. After the desired boundary temperatures have been established, backfill the chamber with a noncondensable gas maintain the chamber at an elevated pressure until a linear or near-linear temperature gradient is established, at which point the chamber should be

re-evacuated and the system can then be allowed to come to a proper equilibrium. The advantage of the increased pressure is of course the very much increased effective thermal conductivity resulting in a relatively short time to establish a linear temperature gradient.

FIGURE 1.A

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 3.1
SAMPLE THICKNESS (IN.) 0.1875
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 71.0
COLD PLATE (DEG F)- 308.0

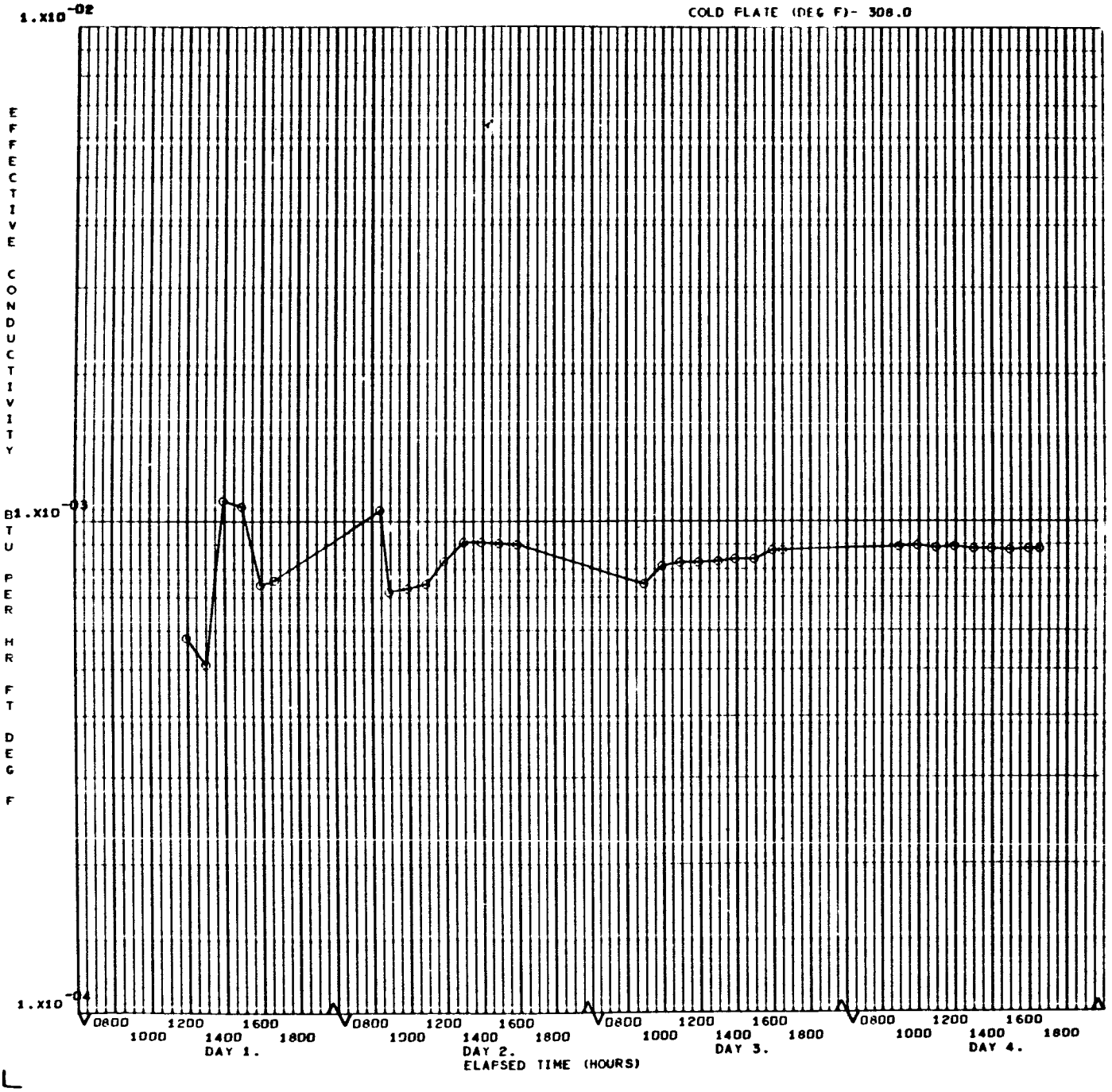


FIGURE 1.B

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 3.1
SAMPLE THICKNESS (IN.) 0.1875
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 71.0
COLD PLATE (DEG-F)- 308.0

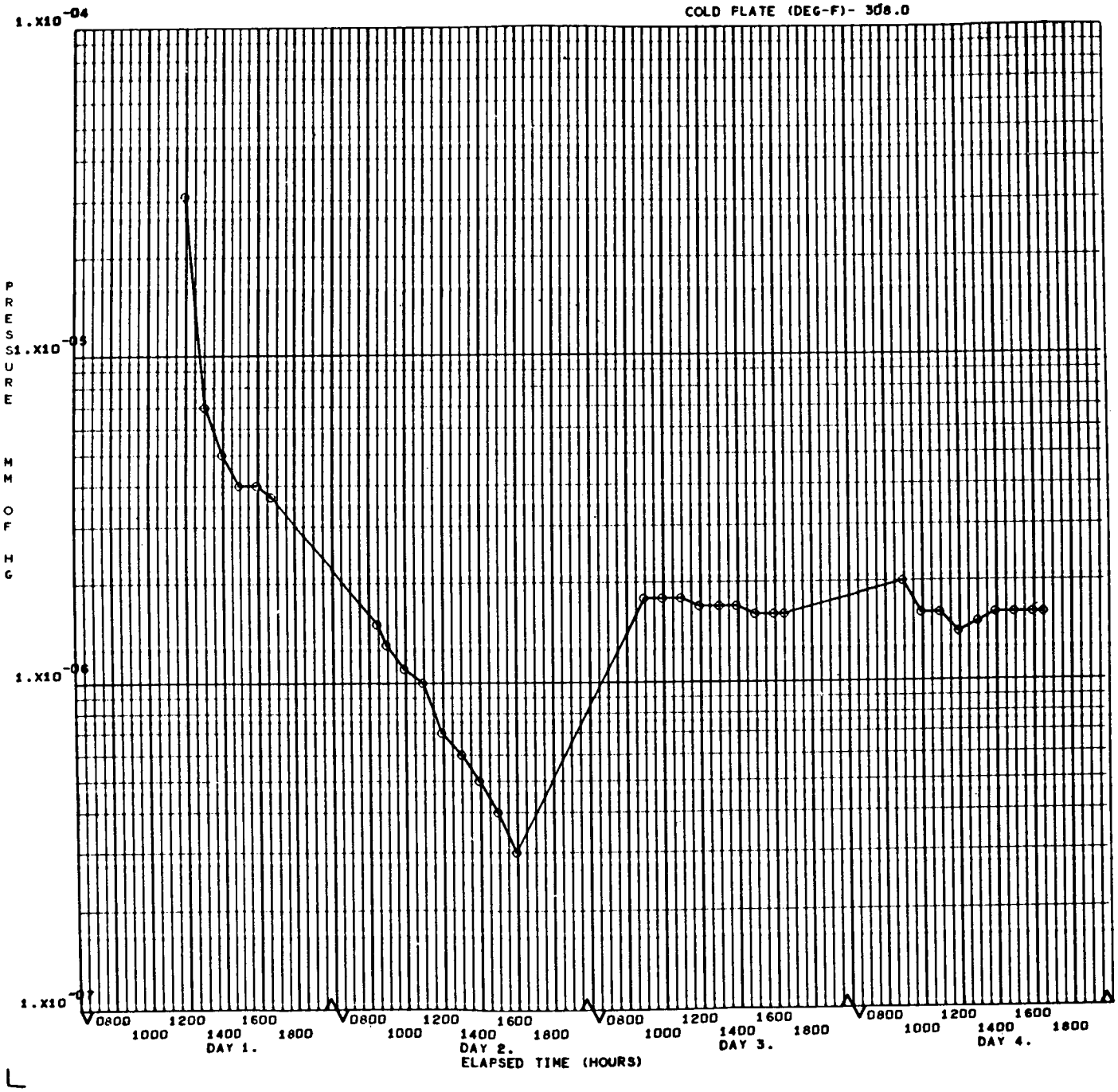


FIGURE 1.C

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 3.1
SAMPLE THICKNESS (IN.) 0.1875
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 71.0
COLD PLATE (DEG-F)- 308.0

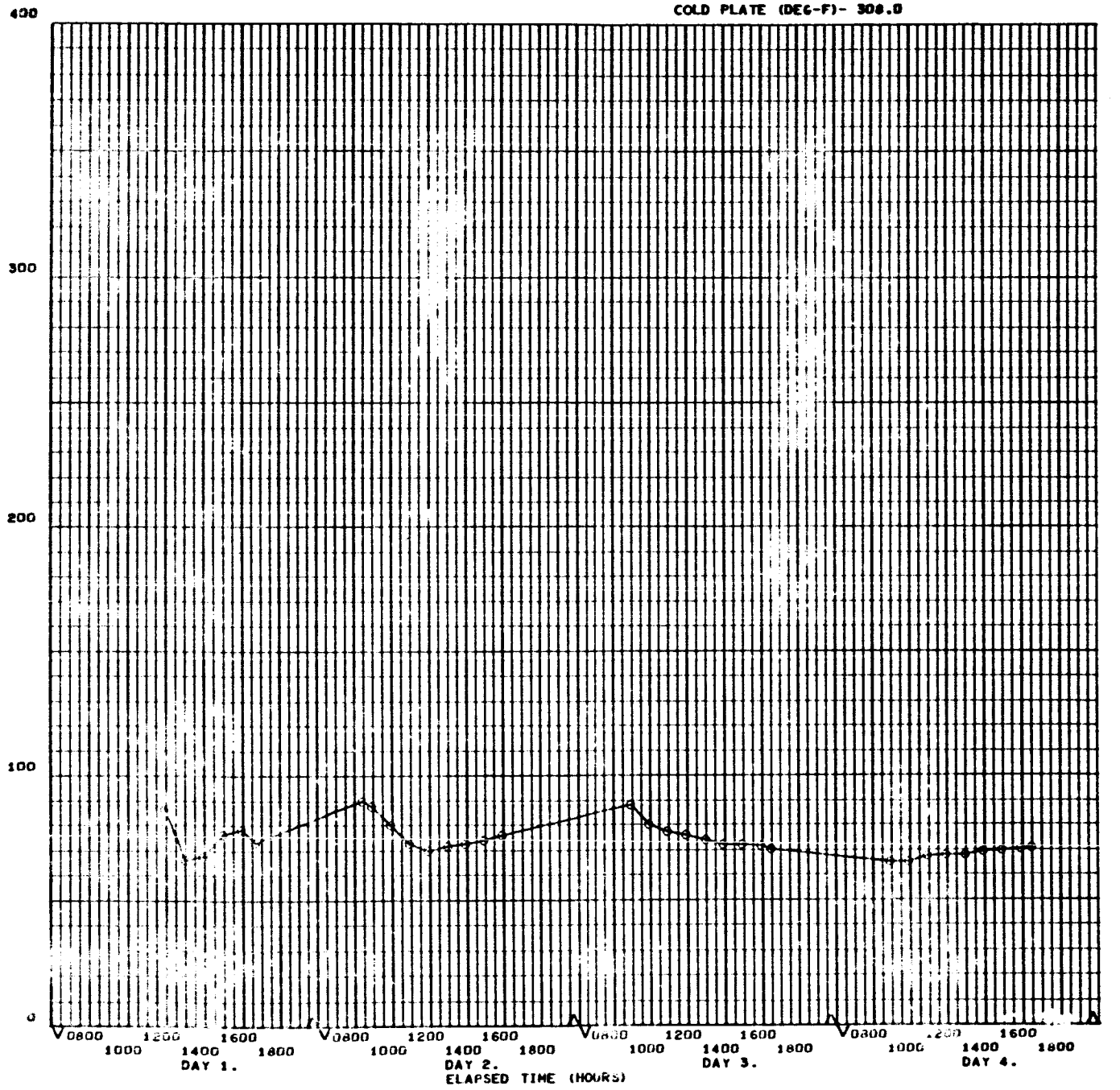


FIGURE 1.D

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 3.1
SAMPLE THICKNESS (IN.) 0.1875
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 71.0
COLD PLATE (DEG-F)- 308.0

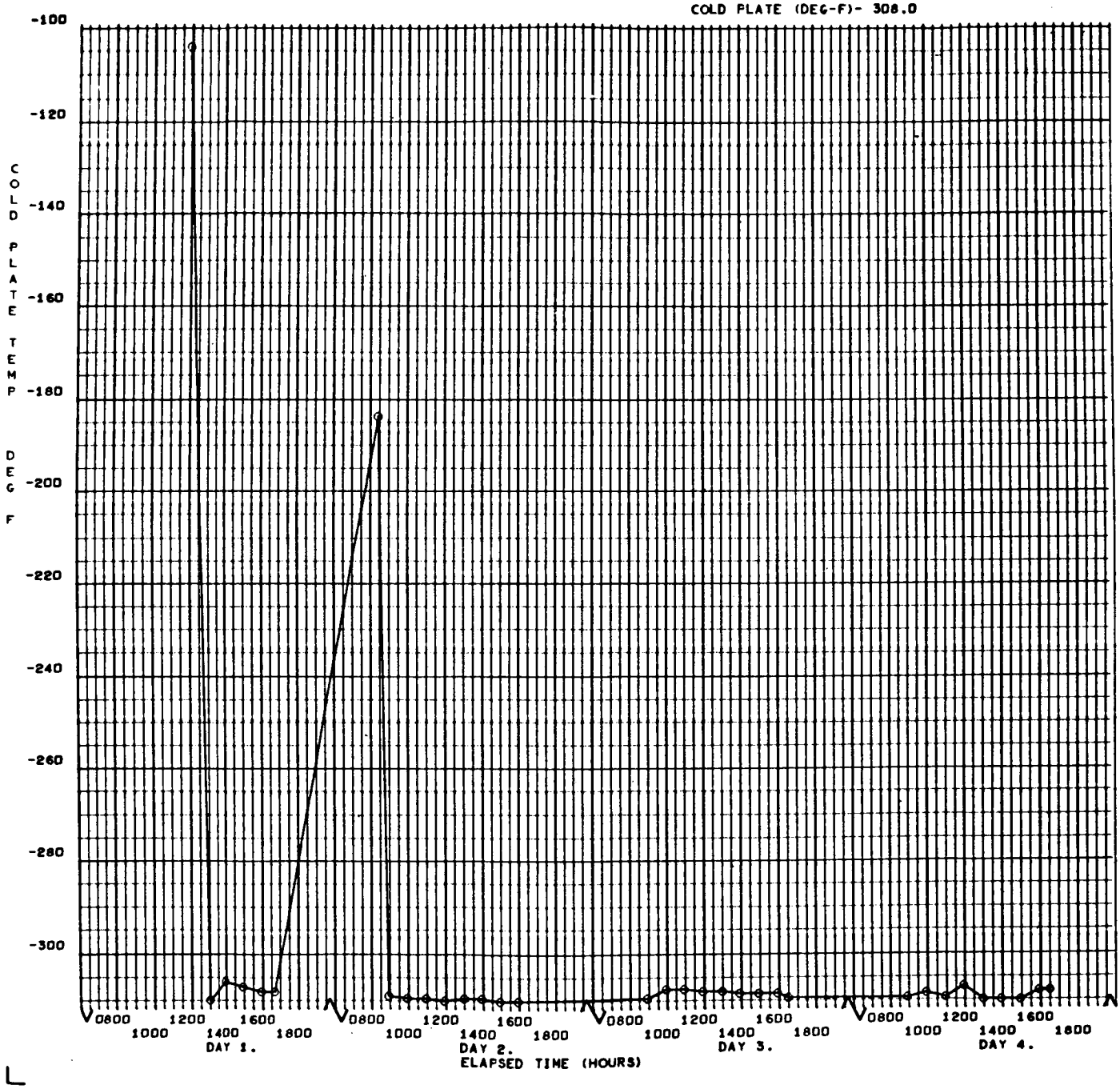


FIGURE 1.E

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 3.1
SAMPLE THICKNESS (IN.) 0.1875
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 71.0
COLD PLATE (DEG-F)- 308.0

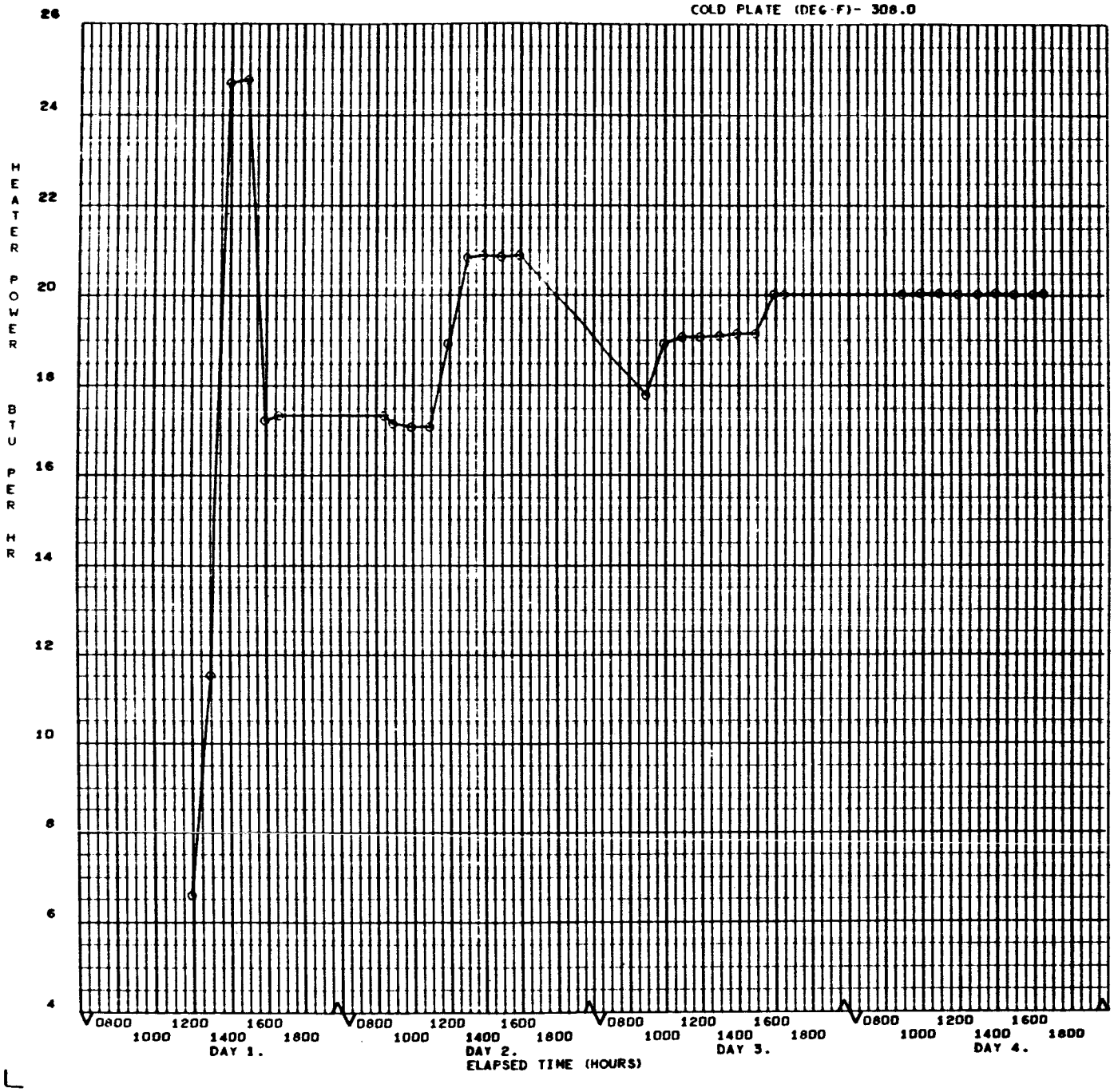


FIGURE 2.A

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 3.2
SAMPLE THICKNESS (IN.) 0.1875
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 75.5
COLD PLATE (DEG-F)- 99.5

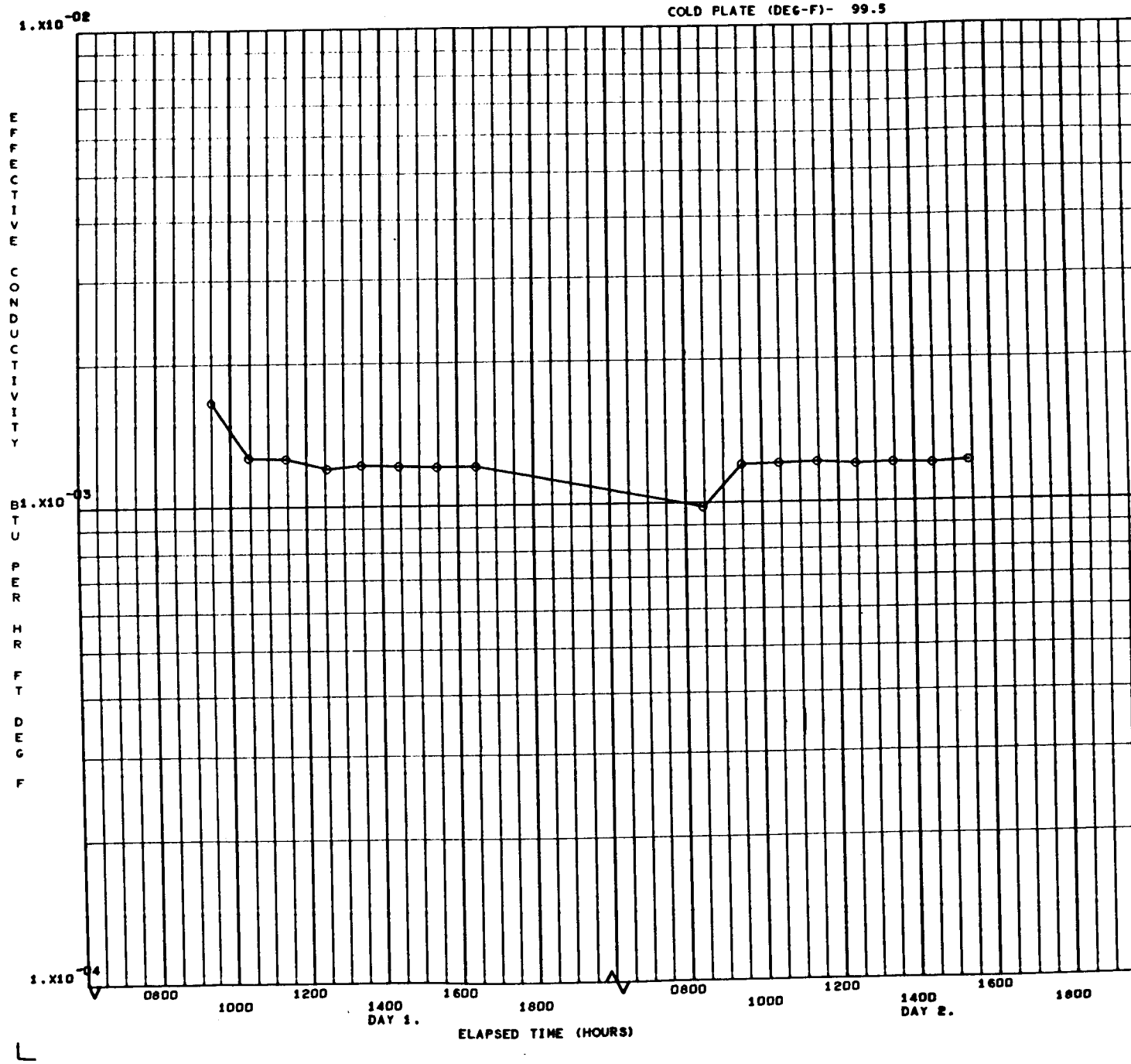


FIGURE 2.B

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 3.2
SAMPLE THICKNESS (IN.) 0.1875
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 75.5
COLD PLATE (DEG-F)- 99.5

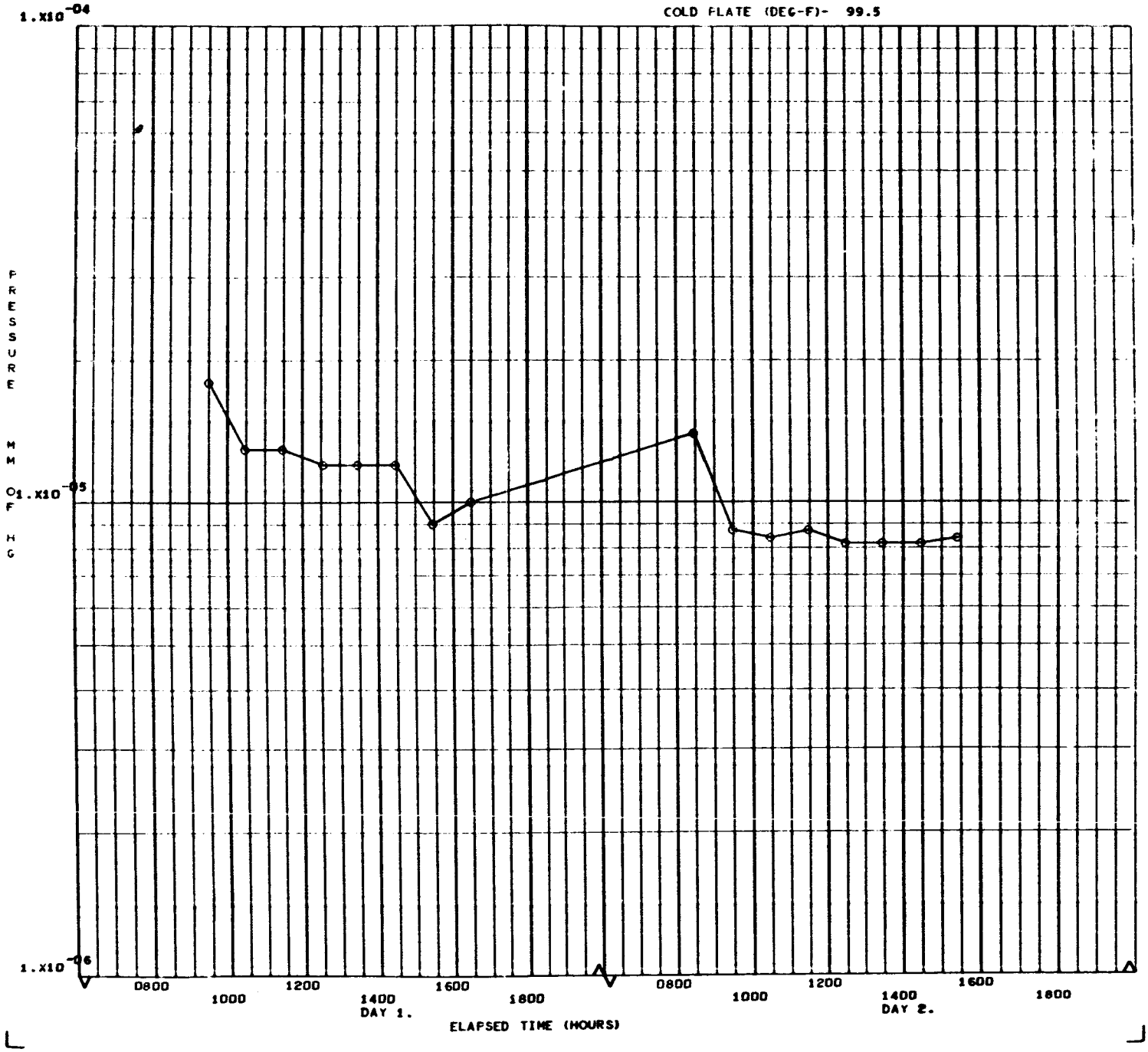


FIGURE 2.C

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 3.2
SAMPLE THICKNESS (IN.) 0.1875
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 75.5
COLD PLATE (DEG-F)- 99.5

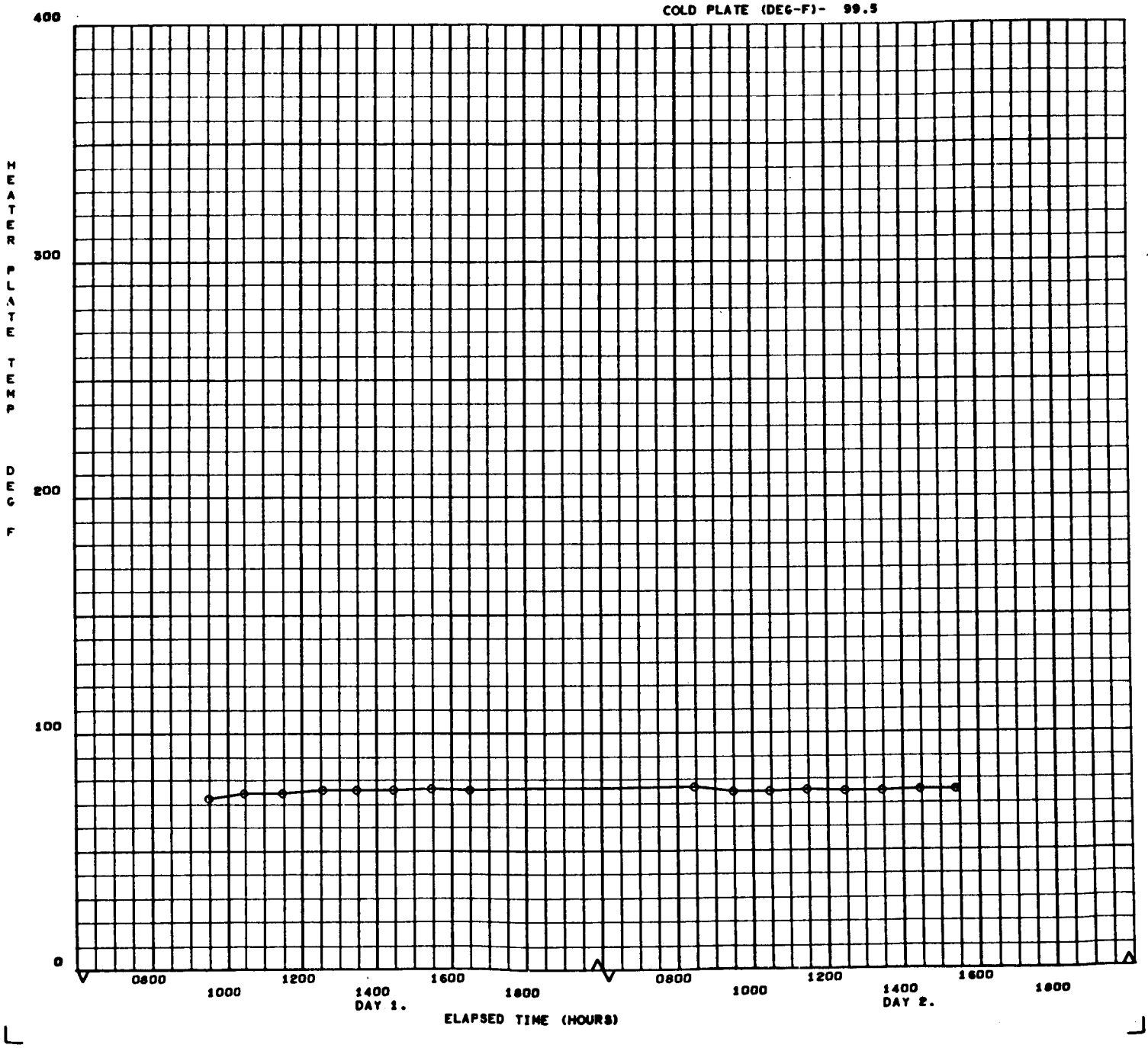


FIGURE 2.D

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 3.2
SAMPLE THICKNESS (IN.) 0.1875
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 75.5
COLD PLATE (DEG-F)- 99.5

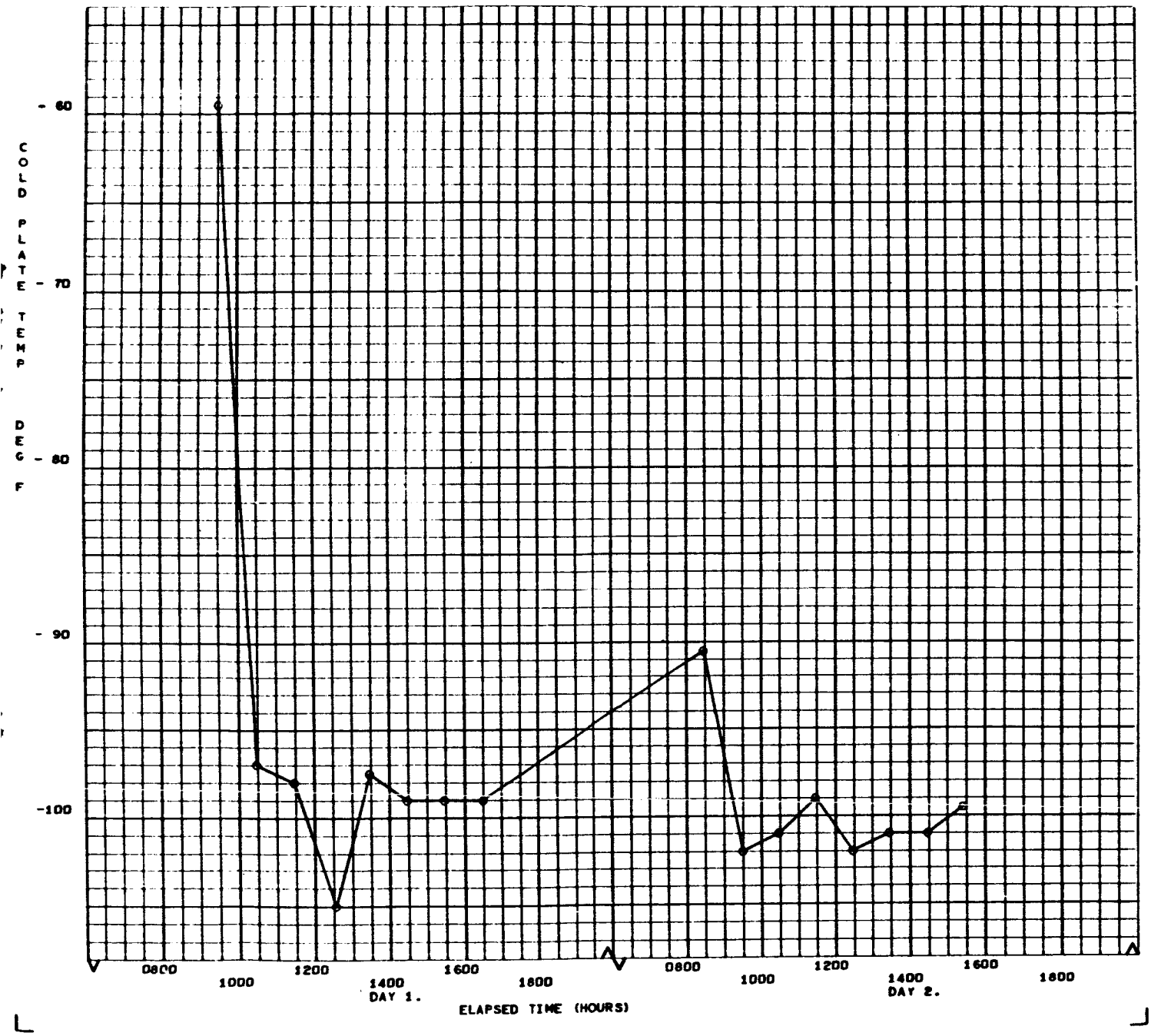


FIGURE 2.E

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 3.2
SAMPLE THICKNESS (IN.) 0.1875
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 75.5
COLD PLATE (DEG-F)- 99.5

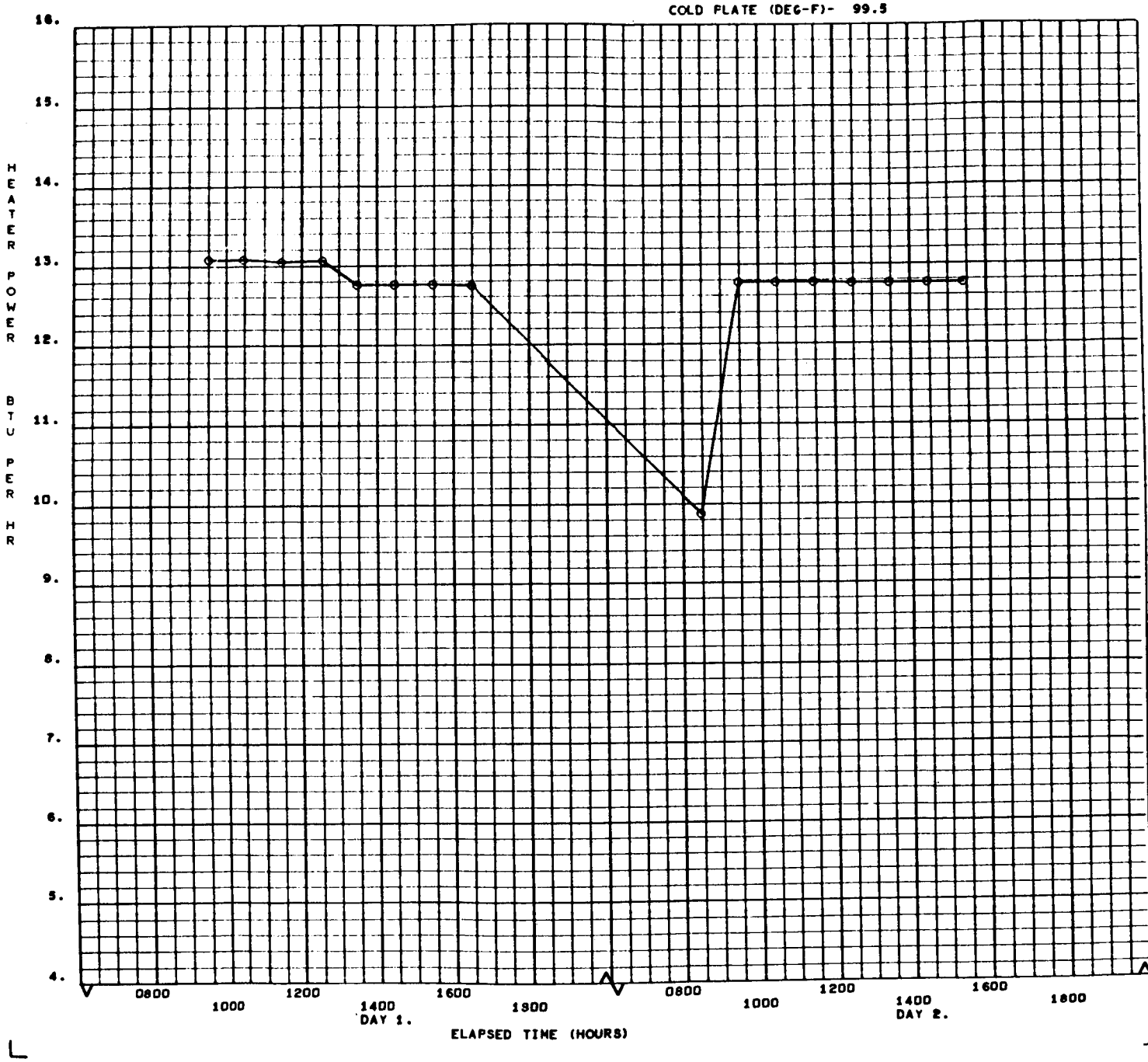


FIGURE 3.A

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 1.3
SAMPLE THICKNESS (IN.) 0.3125
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 201.5
COLD PLATE (DEG-F)- 1.0

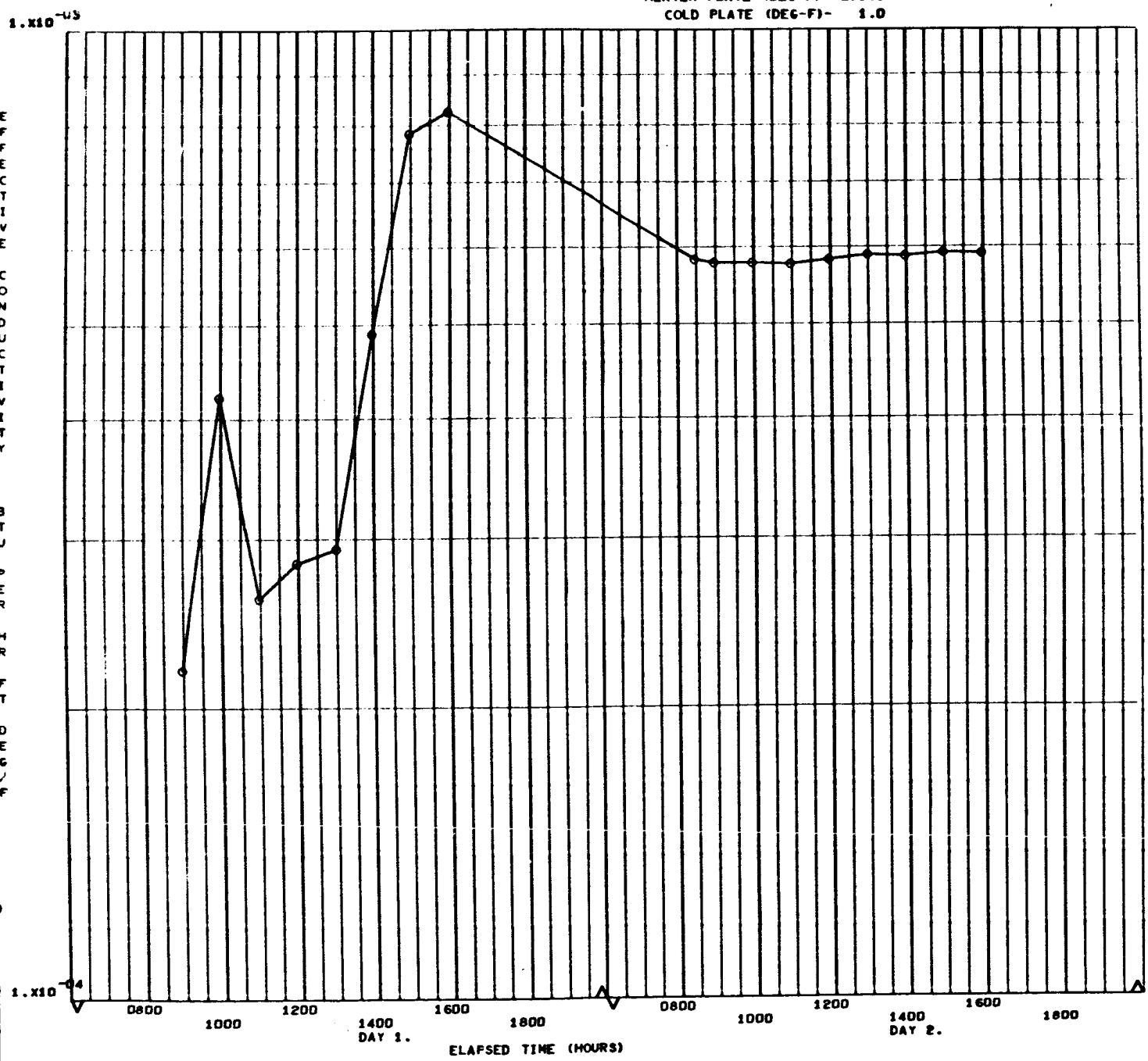


FIGURE 3.8

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 1.3
SAMPLE THICKNESS (IN.) 0.3125
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 201.5
COLD PLATE (DEG-F)- 1.0

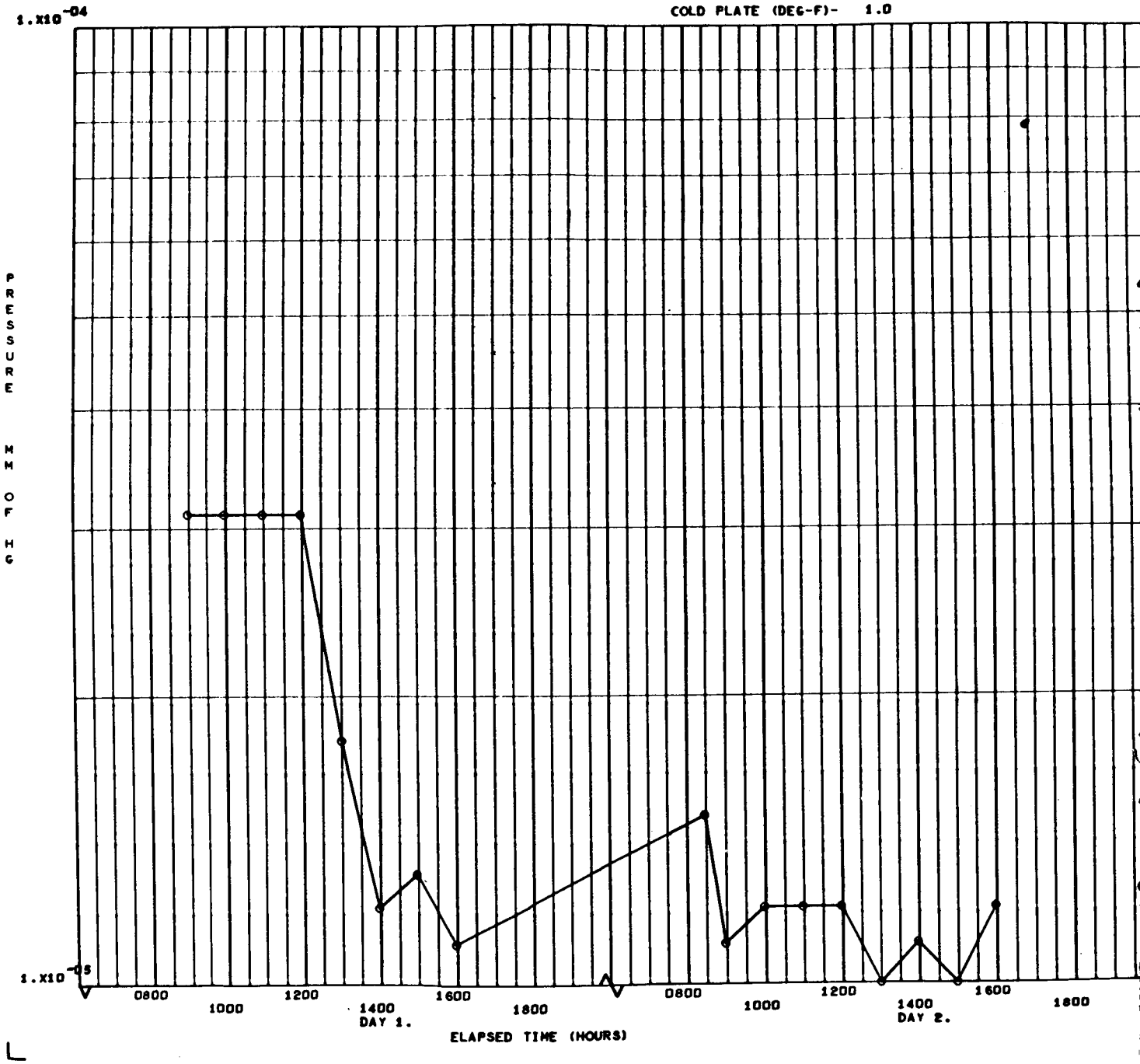


FIGURE 3.C

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 1.3
SAMPLE THICKNESS (IN.) 0.3125
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 201.5
COLD PLATE (DEG-F)- 1.0

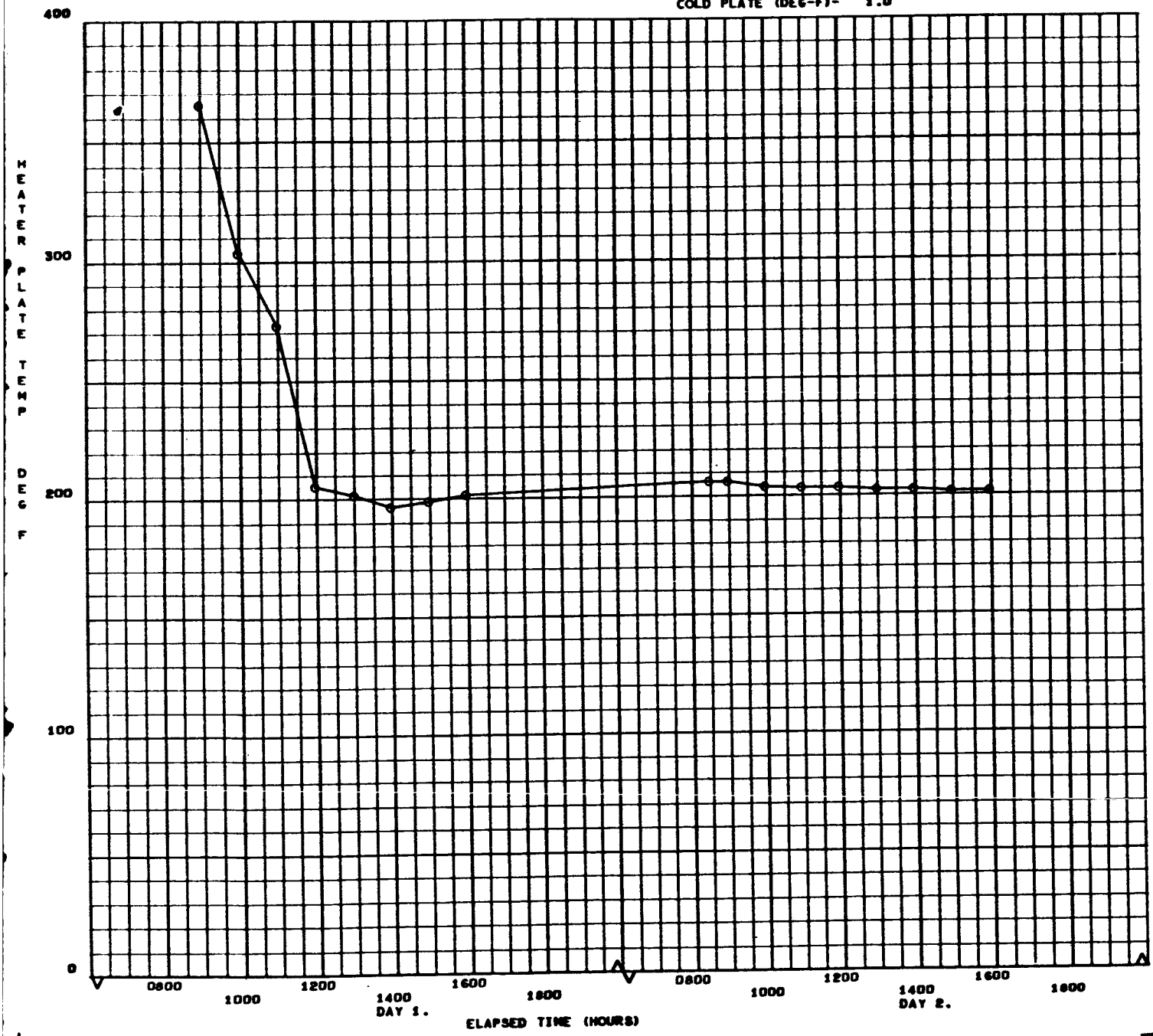


FIGURE 3.D

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 1.3
SAMPLE THICKNESS (IN.) 0.3125
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 201.5
COLD PLATE (DEG-F)- 1.0

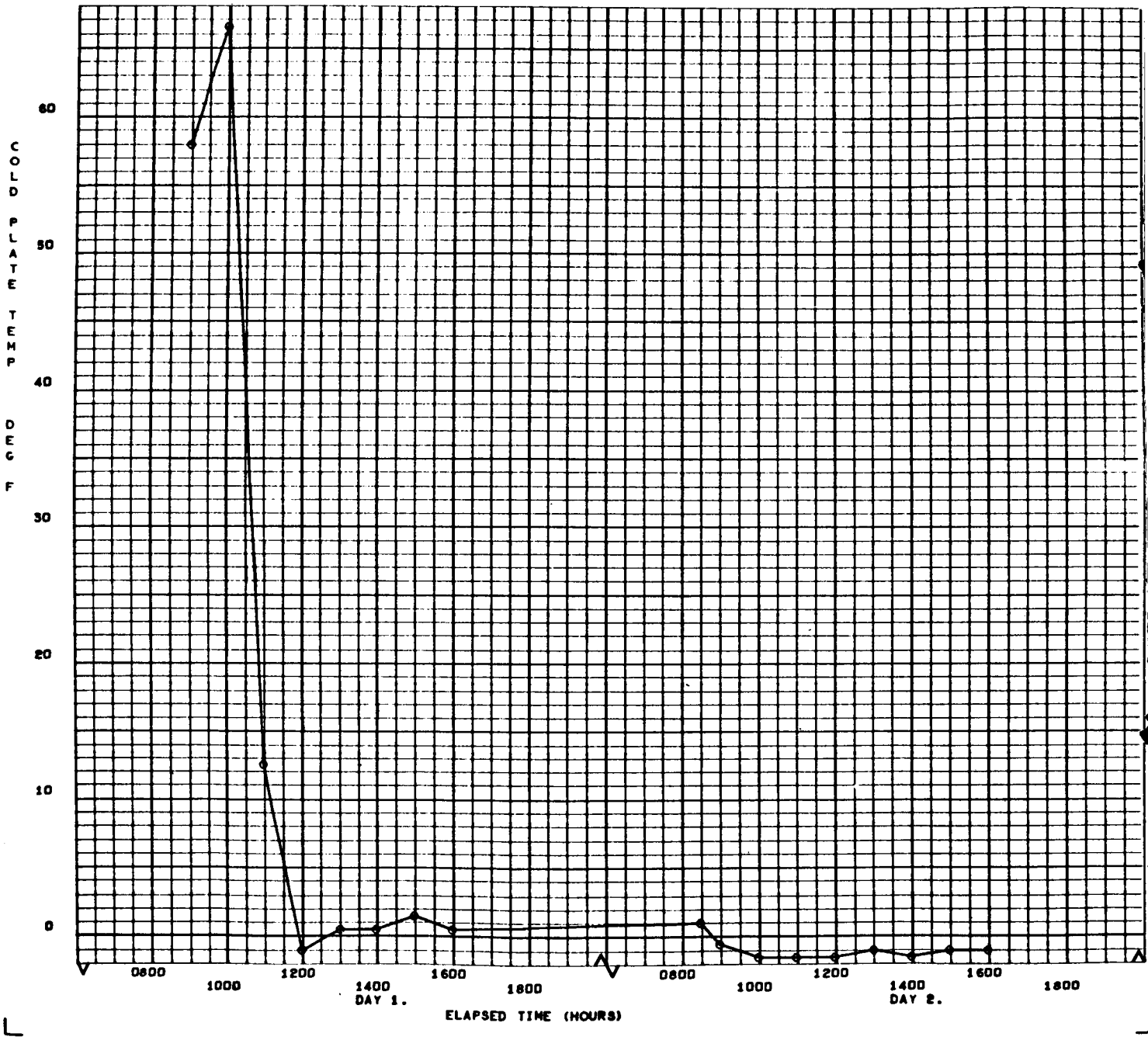


FIGURE 3.E

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 1.3
SAMPLE THICKNESS (IN.) 0.3125
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 201.5
COLD PLATE (DEG-F)- 1.0

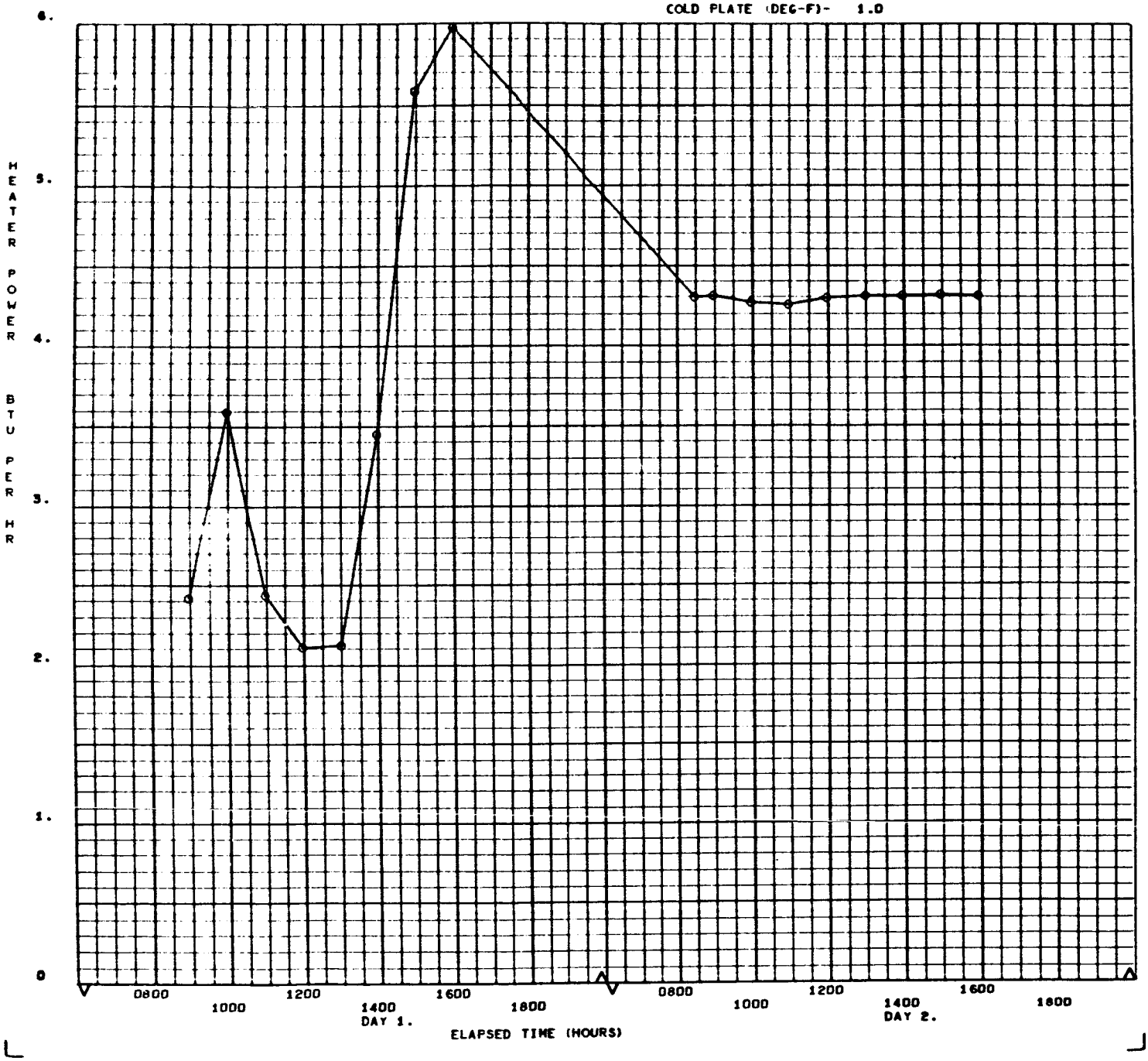


FIGURE 4.A

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 1.4
SAMPLE THICKNESS (IN.) 0.3125
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 287.5
COLD PLATE (DEG-F) 70.5

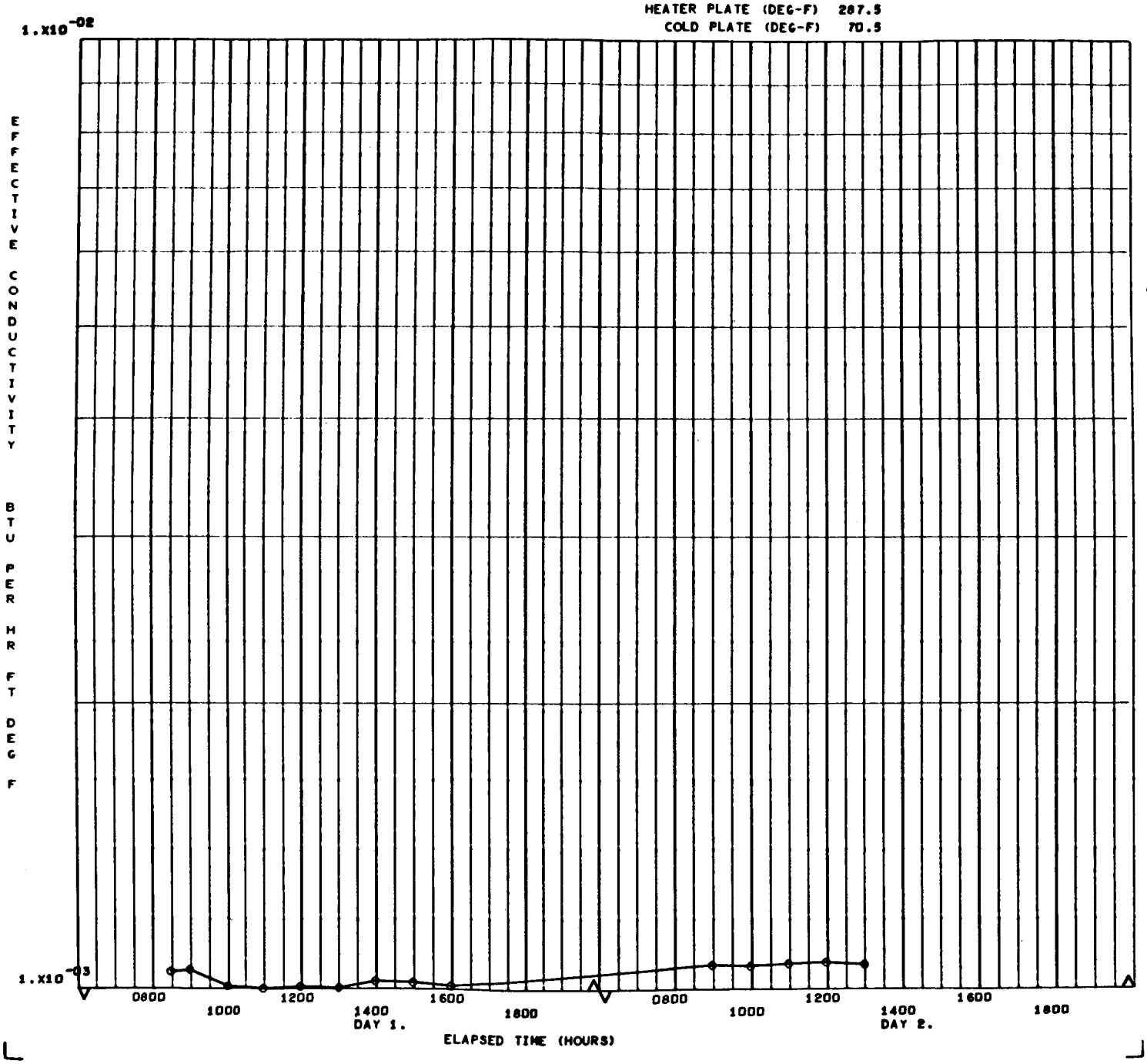


FIGURE 4.8

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 1.4
SAMPLE THICKNESS (IN.) 0.3125
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 287.5
COLD PLATE (DEG-F) 70.5

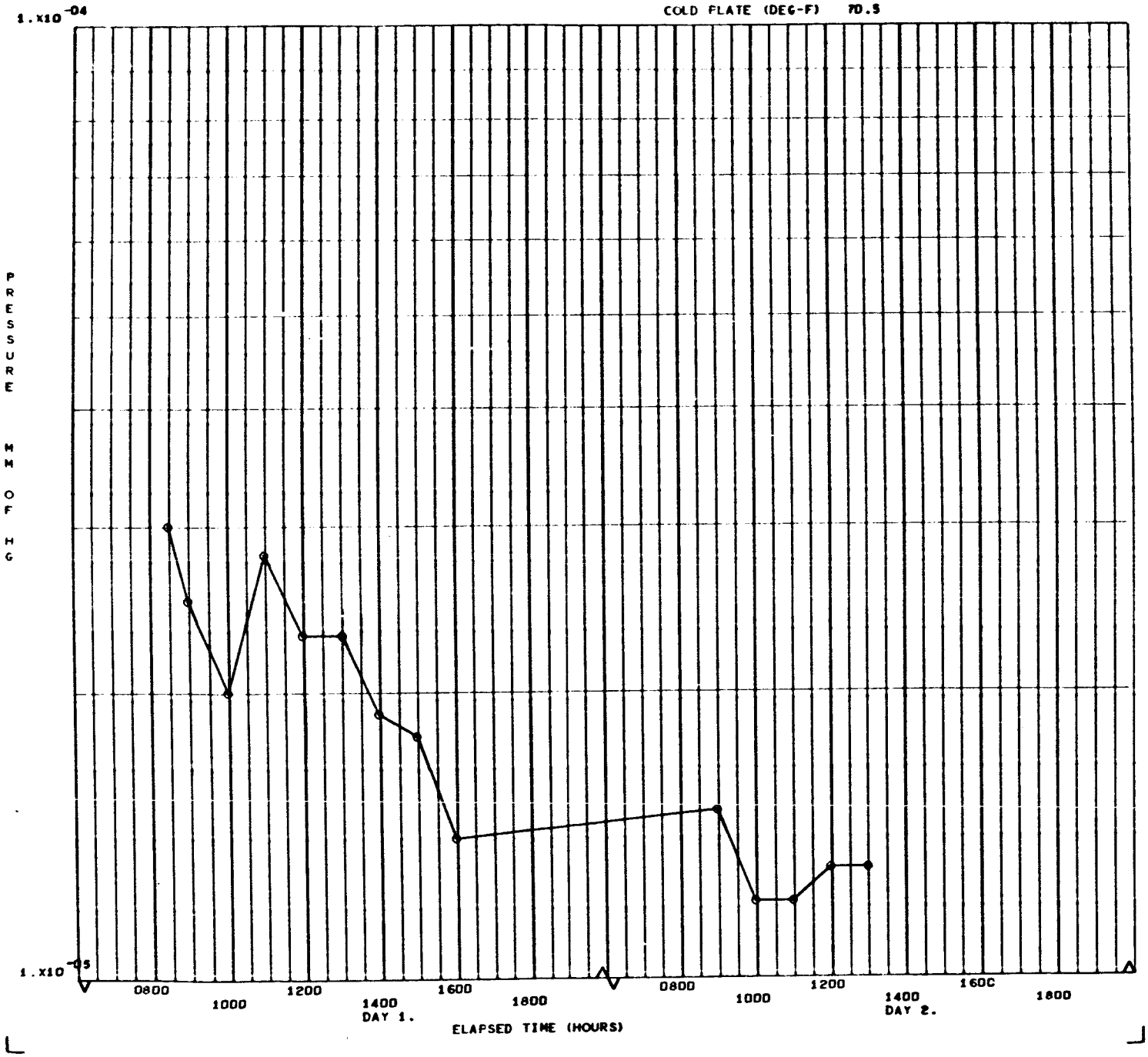


FIGURE 4.C

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 1.4
SAMPLE THICKNESS (IN.) 0.3125
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 287.5
COLD PLATE (DEG-F) 70.5

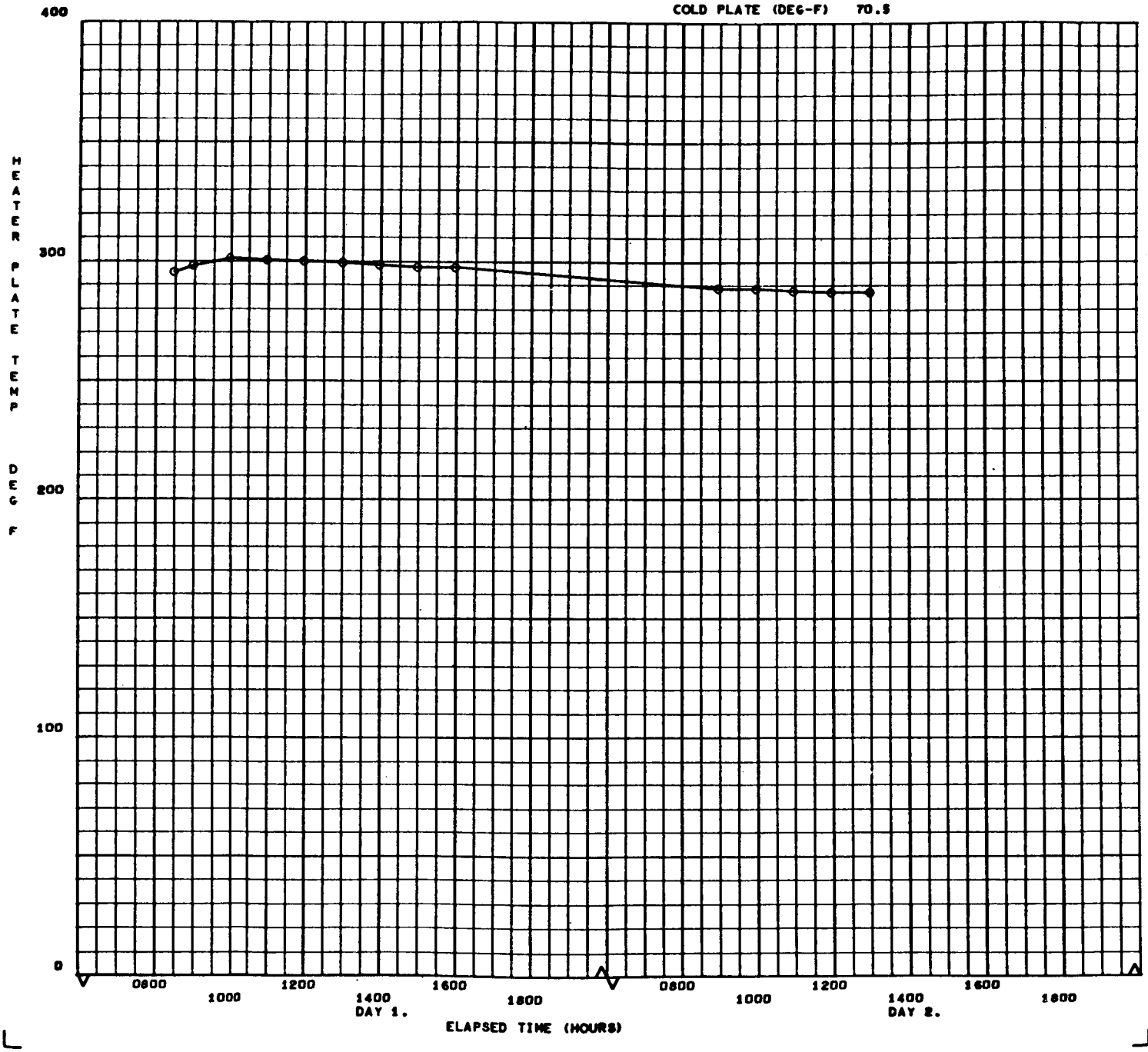


FIGURE 4.D

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 1.4
SAMPLE THICKNESS (IN.) 0.3125
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 207.5
COLD PLATE (DEG-F) 70.5

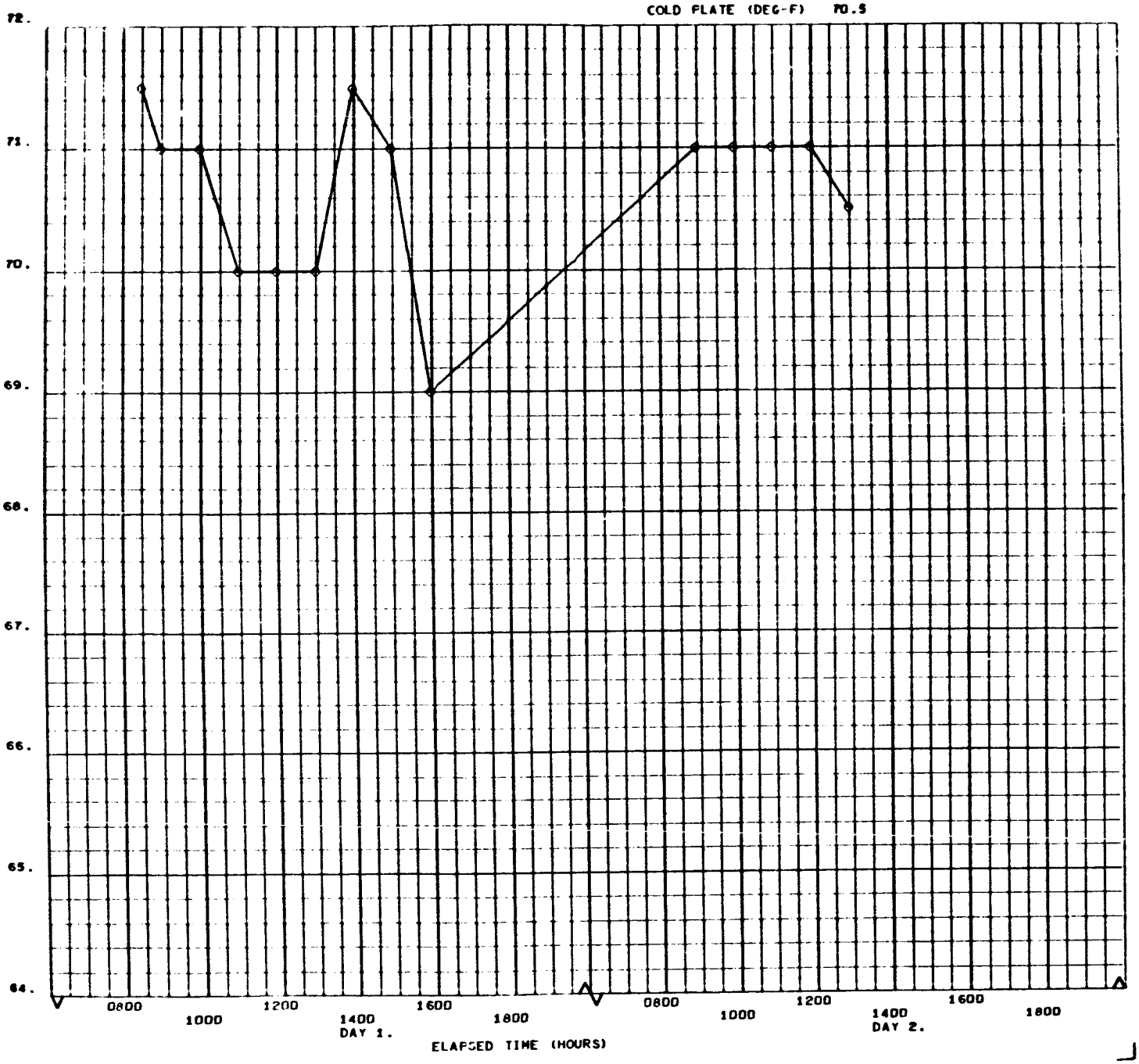


FIGURE 4.E

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 1.4
SAMPLE THICKNESS (IN.) 0.3125
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 287.5
COLD PLATE (DEG-F) 70.5

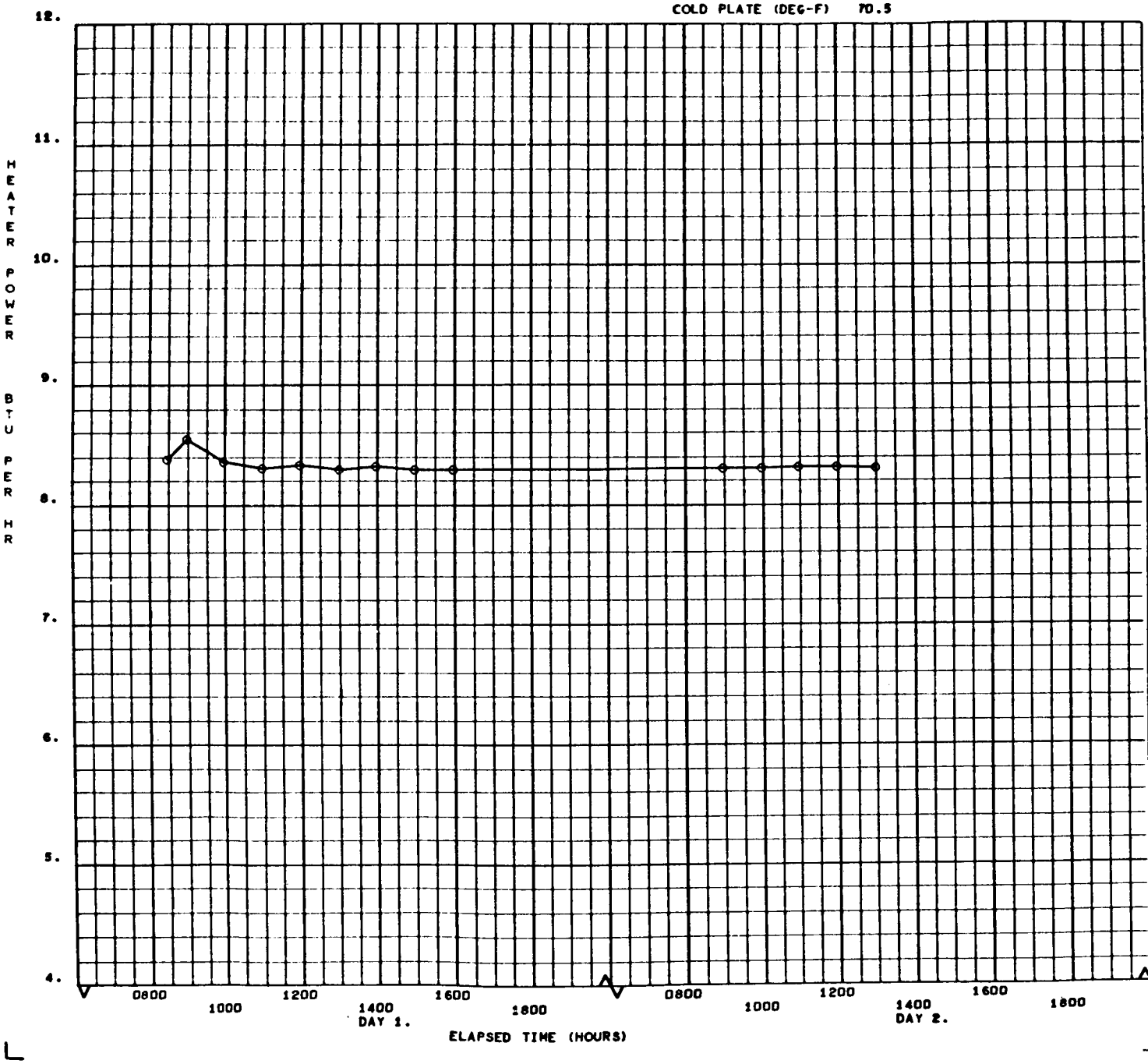


FIGURE 5.A

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 2.2
SAMPLE THICKNESS (IN.) 0.2500
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 200.5
COLD PLATE (DEG-F) 0.0

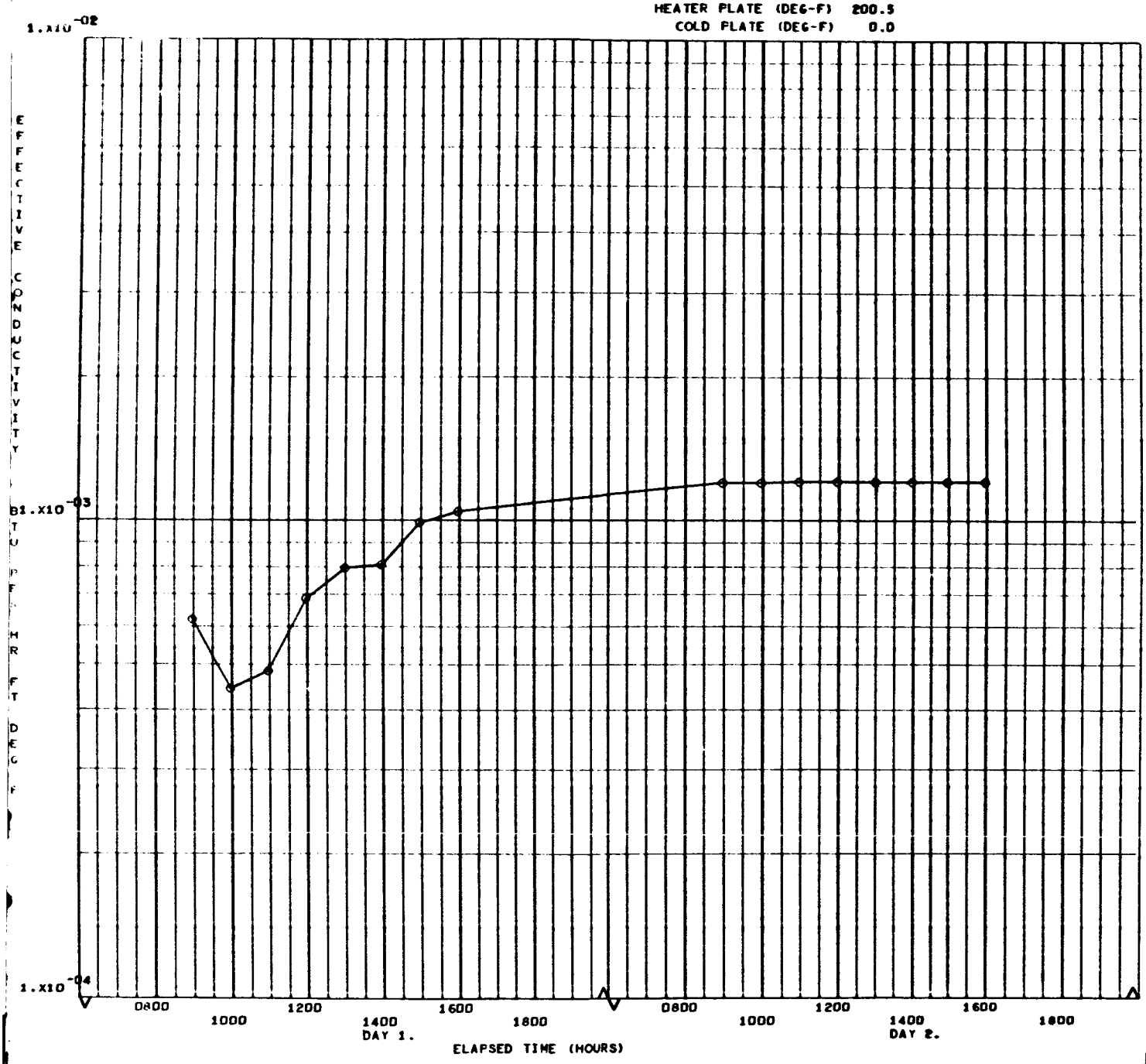


FIGURE 5.B

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 2.2
SAMPLE THICKNESS (IN.) 0.2500
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 200.5
COLD PLATE (DEG-F) 0.0

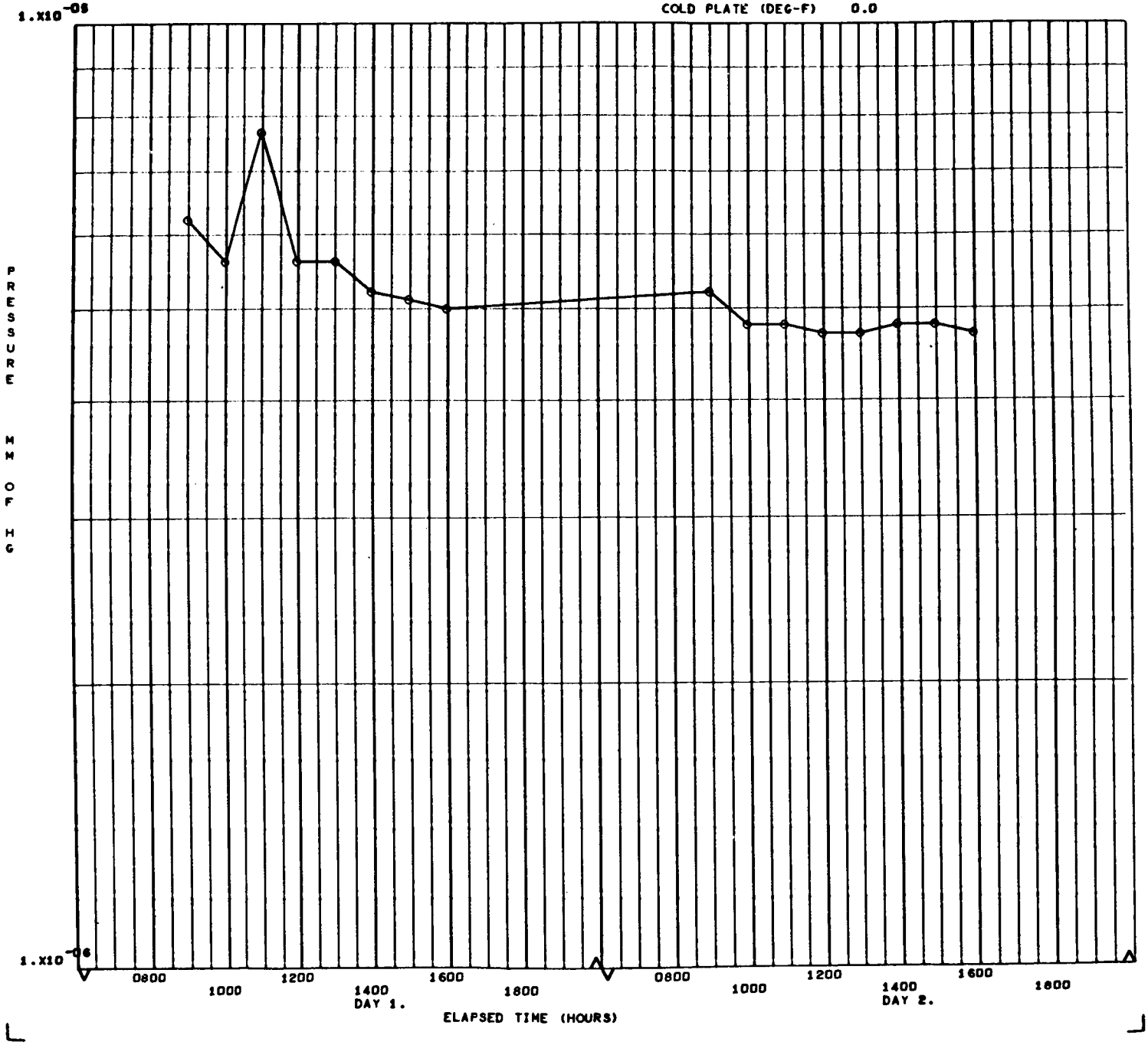


FIGURE 5.C

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 2.2
SAMPLE THICKNESS (IN.) 0.2500
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 200.5
COLD PLATE (DEG-F) 0.0

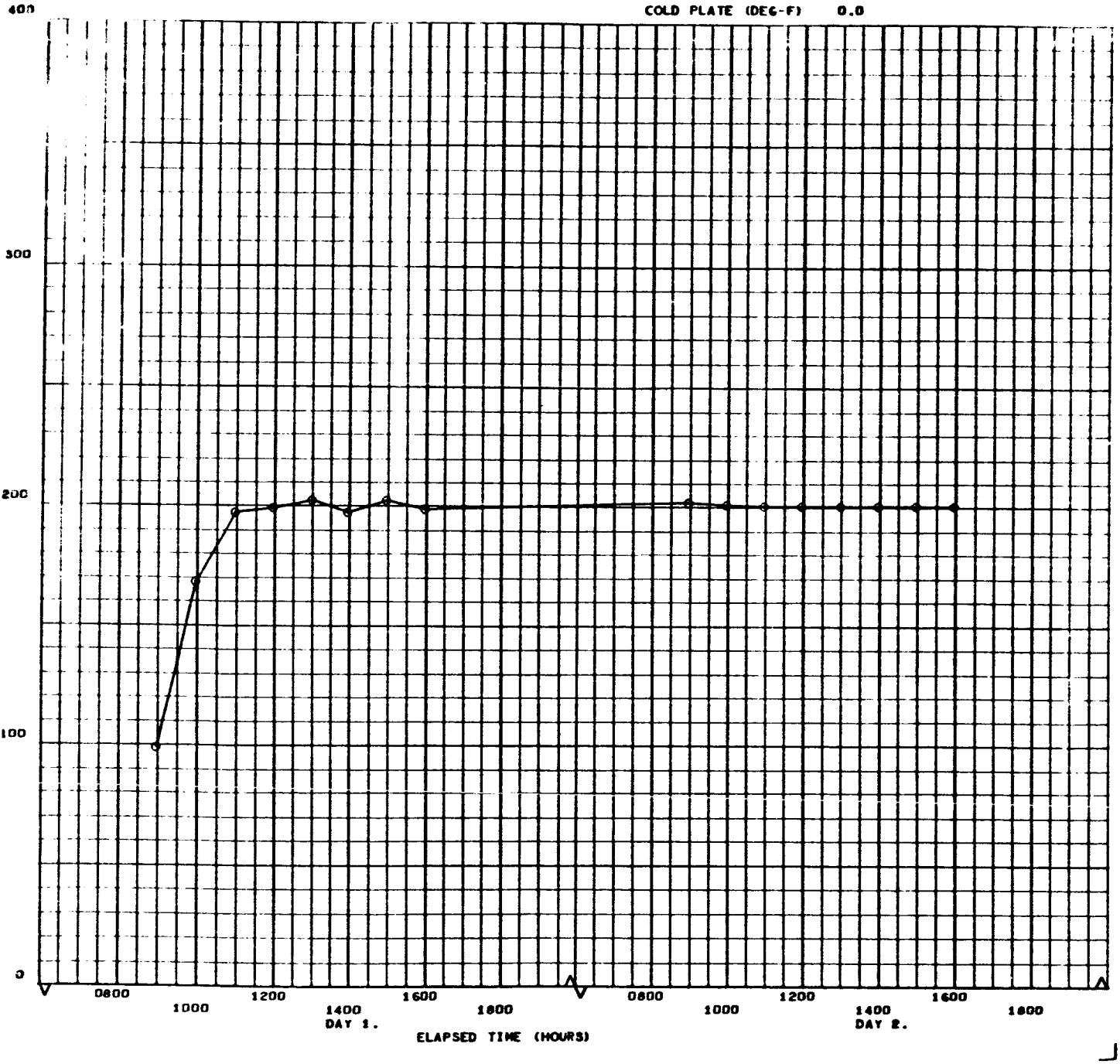


FIGURE 5.D

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 2.2
SAMPLE THICKNESS (IN.) 0.2500
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 200.5
COLD PLATE (DEG-F) 0.0

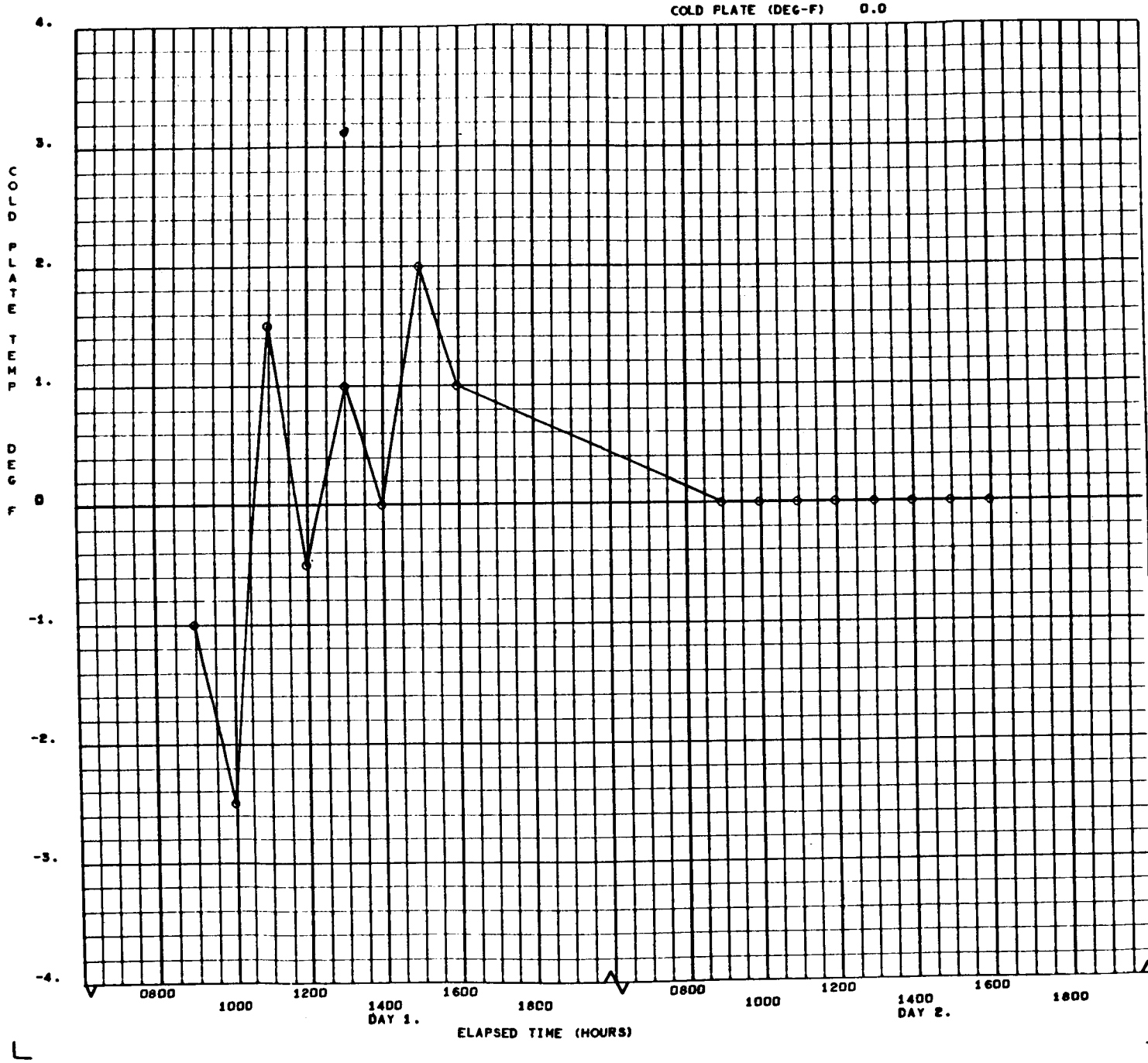


FIGURE 5.E

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 2.2
SAMPLE THICKNESS (IN.) 0.2500
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 200.5
COLD PLATE (DEG-F) 0.0

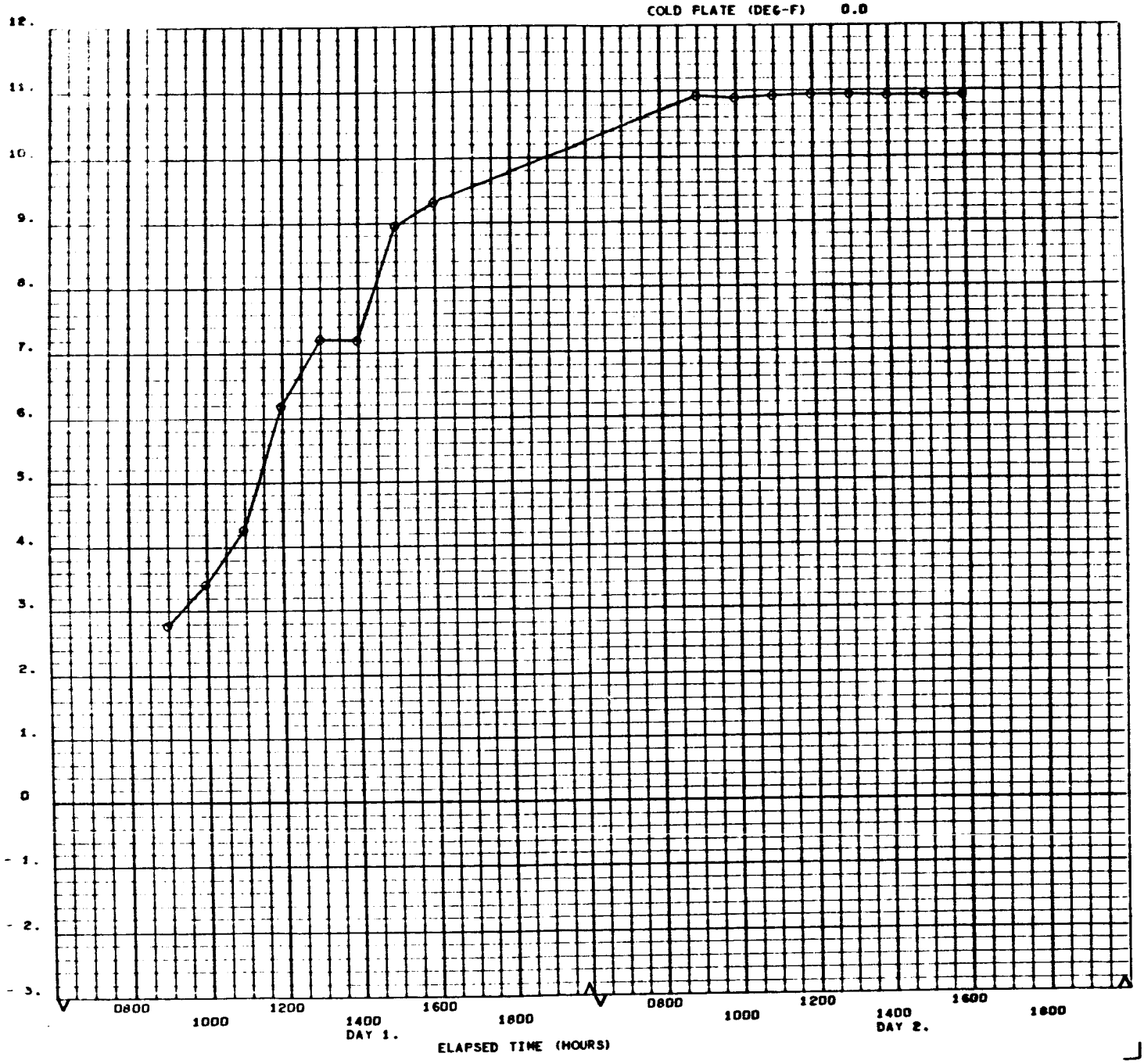


FIGURE 6.A

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 2.3
SAMPLE THICKNESS (IN.) 0.2500
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 300.0
COLD PLATE (DEG-F) 70.5

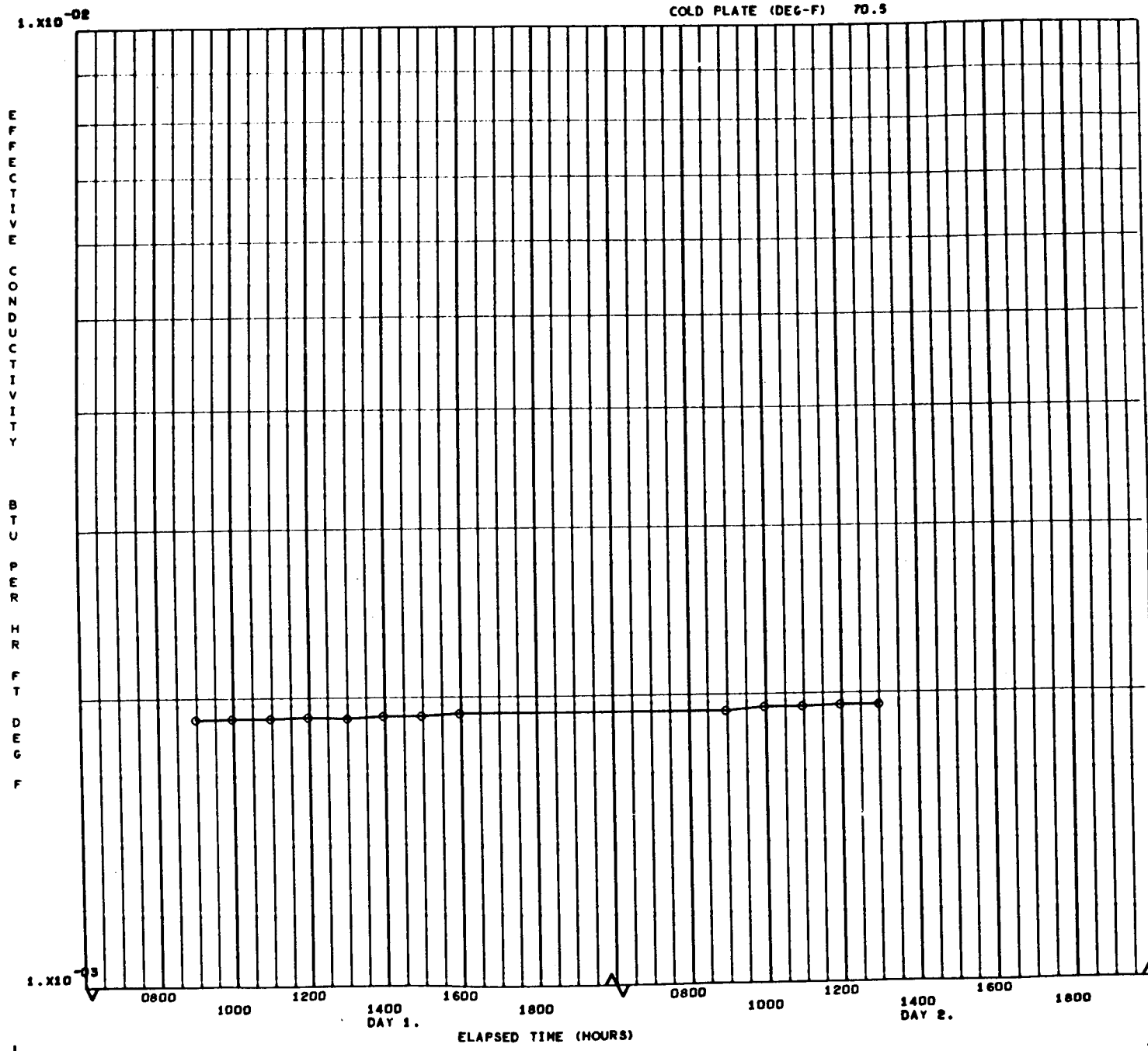


FIGURE 6.B

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 2.3
SAMPLE THICKNESS (IN.) 0.2500
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 300.0
COLD PLATE (DEG-F) 70.5

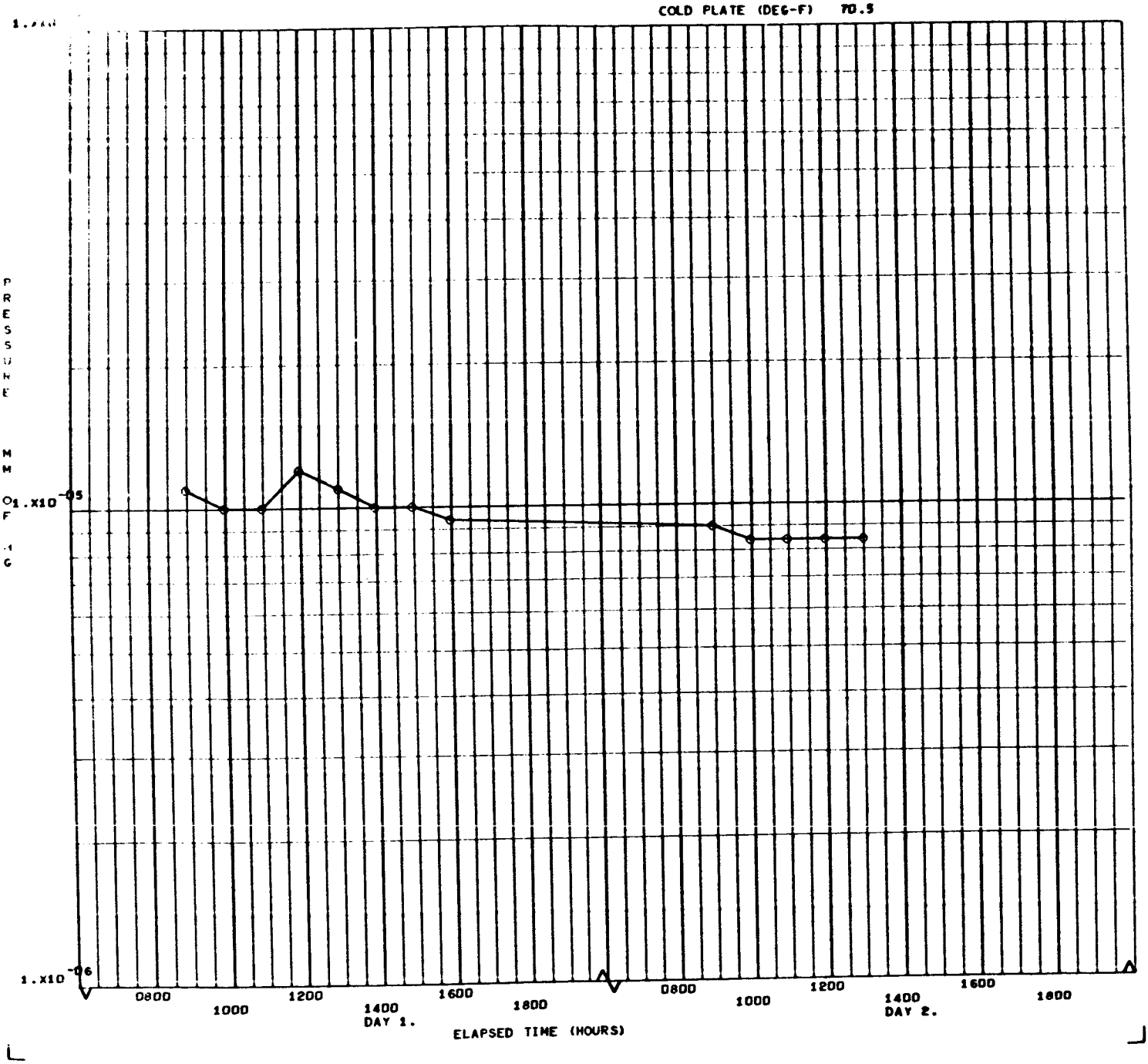


FIGURE 6.C

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 2.3
SAMPLE THICKNESS (IN.) 0.2500
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 300.0
COLD PLATE (DEG-F) 70.5

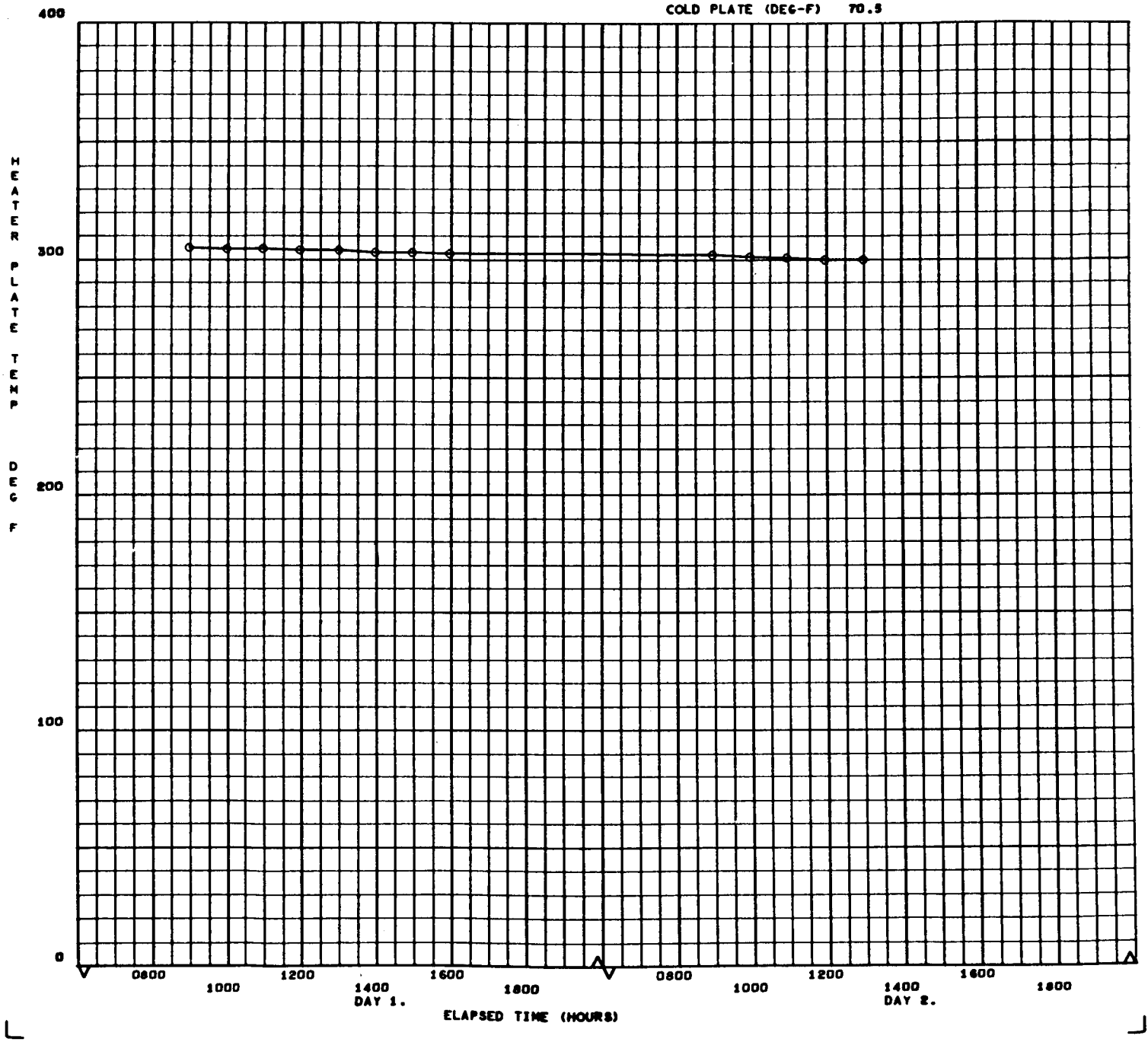


FIGURE 6.D

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 2.3
SAMPLE THICKNESS (IN.) 0.2500
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 300.0
COLD PLATE (DEG-F) 70.5

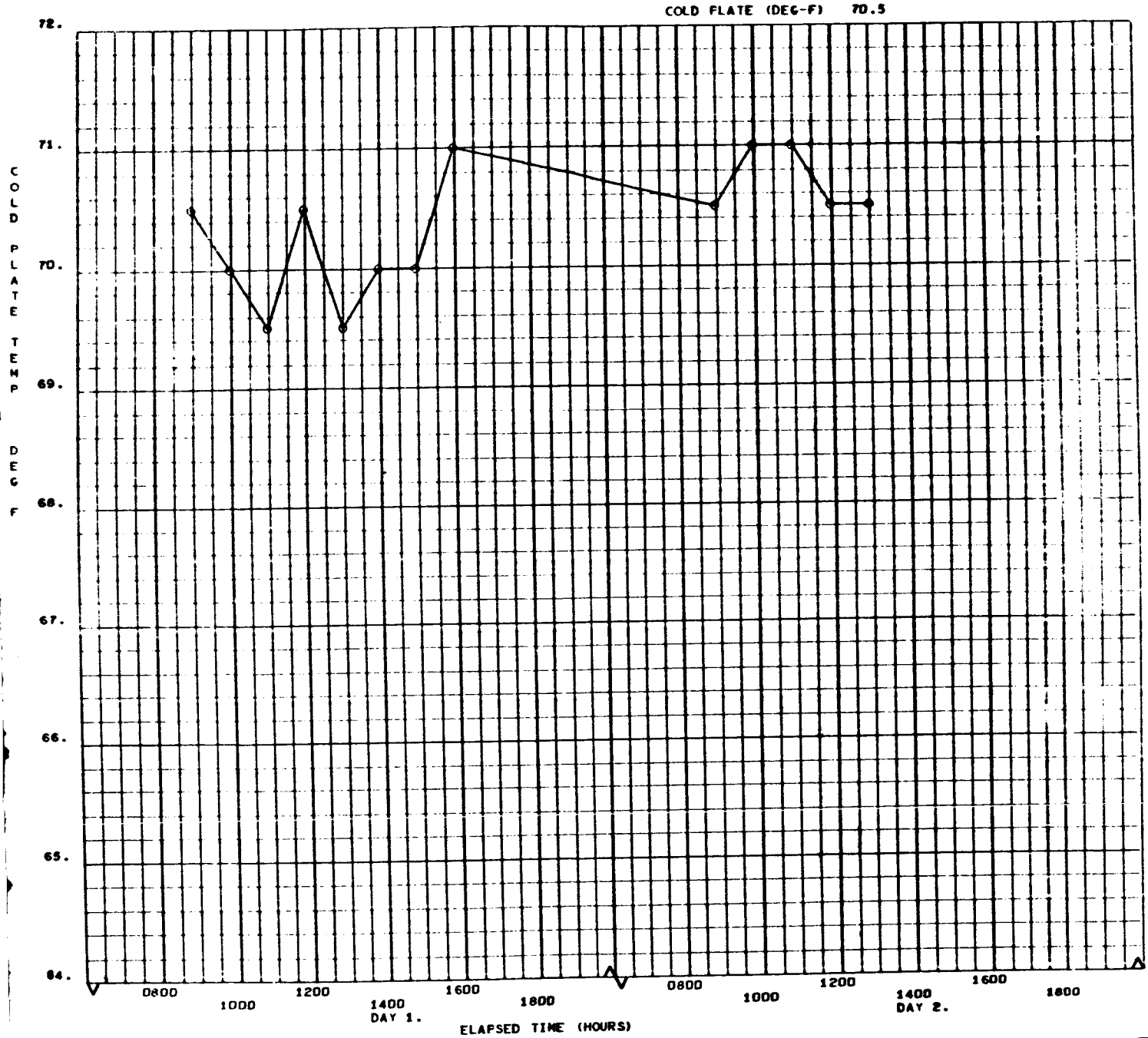


FIGURE 6.E

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 2.3
SAMPLE THICKNESS (IN.) 0.2500
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 300.0
COLD PLATE (DEG-F) 70.5

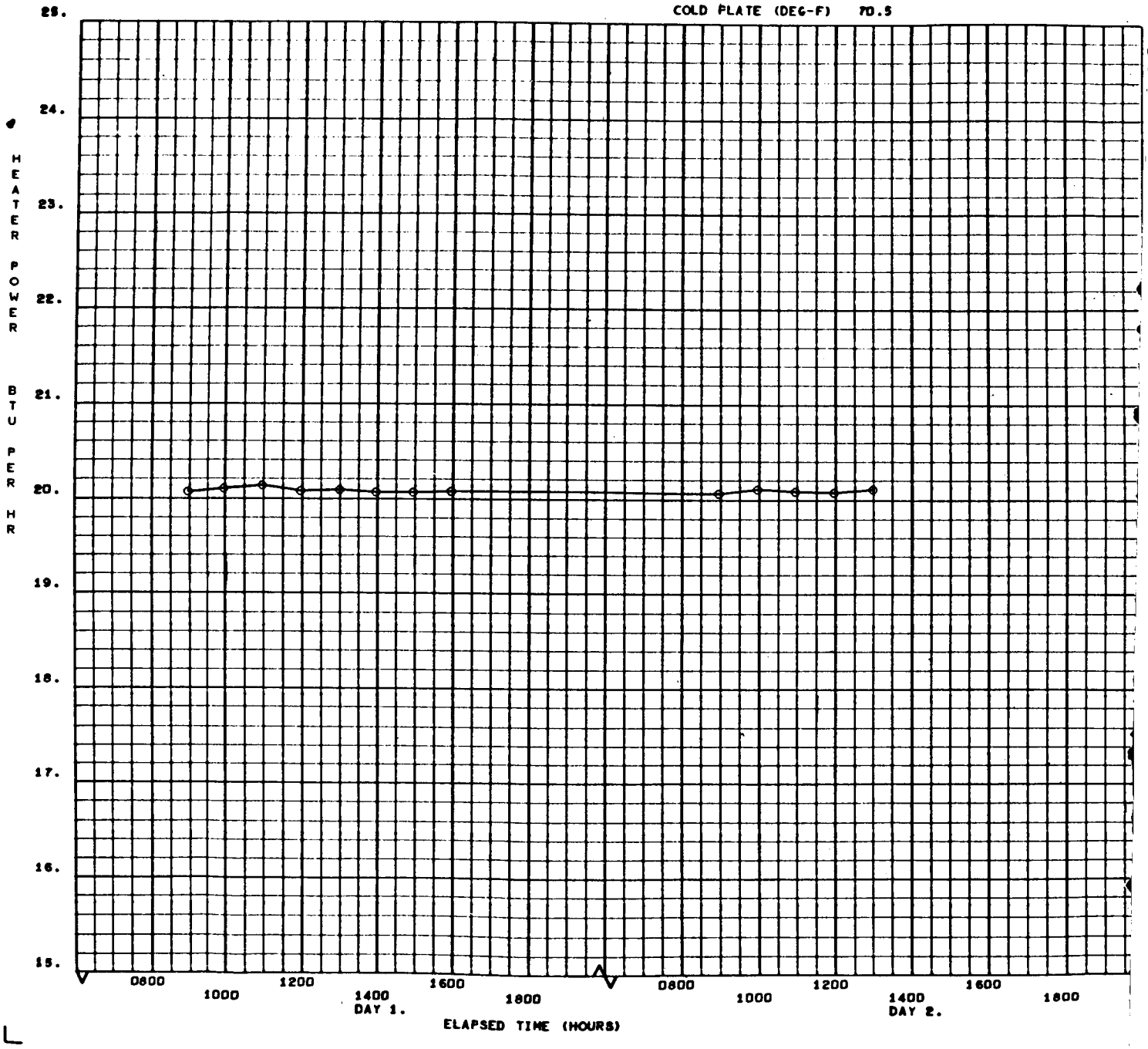


FIGURE 7.A

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 3.3
SAMPLE THICKNESS (IN.) 0.1875
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 203.5
COLD PLATE (DEG-F) 1.0

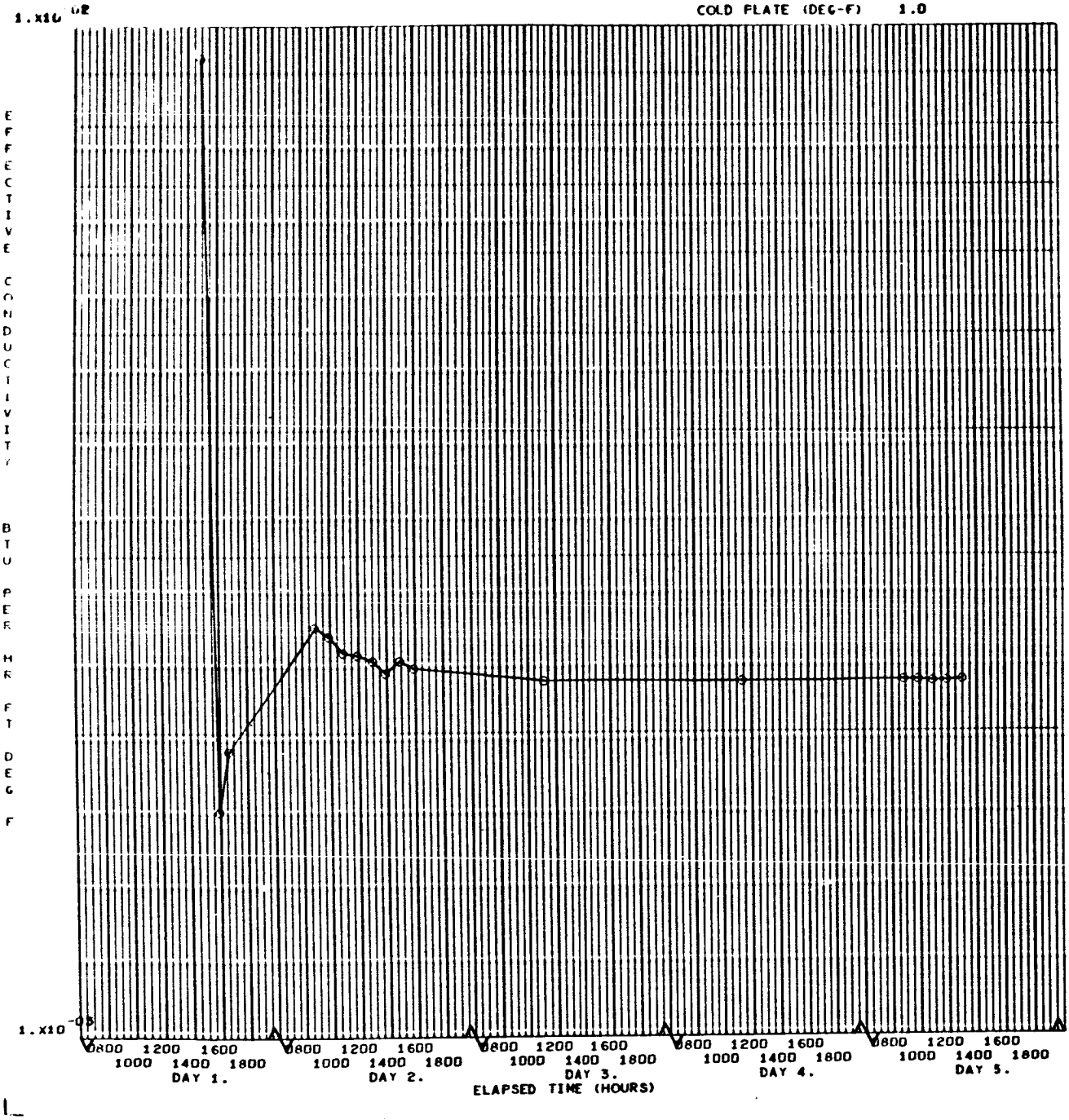


FIGURE 7.8

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 3.3
SAMPLE THICKNESS (IN.) 0.1875
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 203.5
COLD PLATE (DEG-F) 1.0

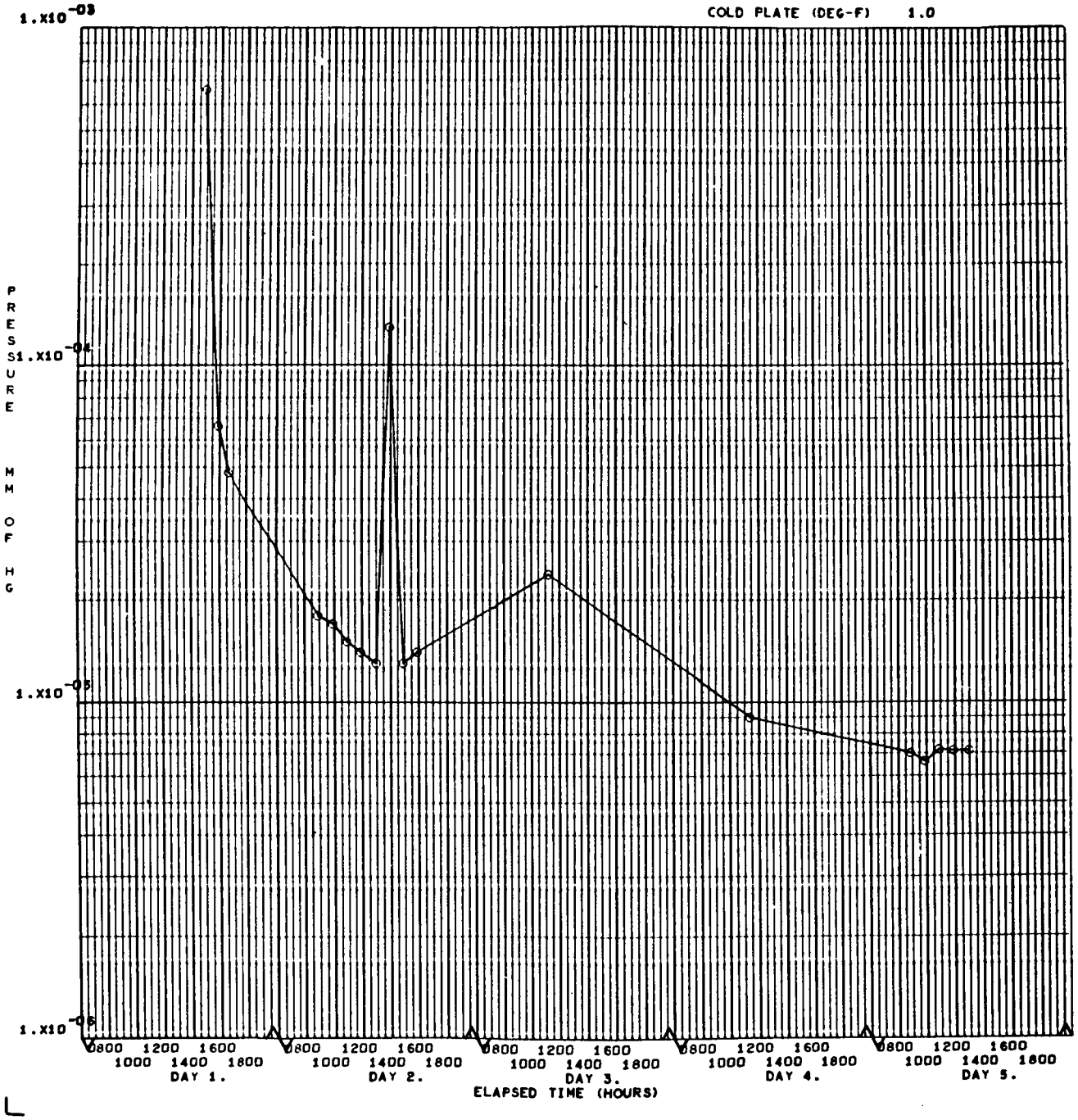


FIGURE 7.C

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 3.3
SAMPLE THICKNESS (IN) 0.1875
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 203.5
COLD PLATE (DEG-F) 1.0

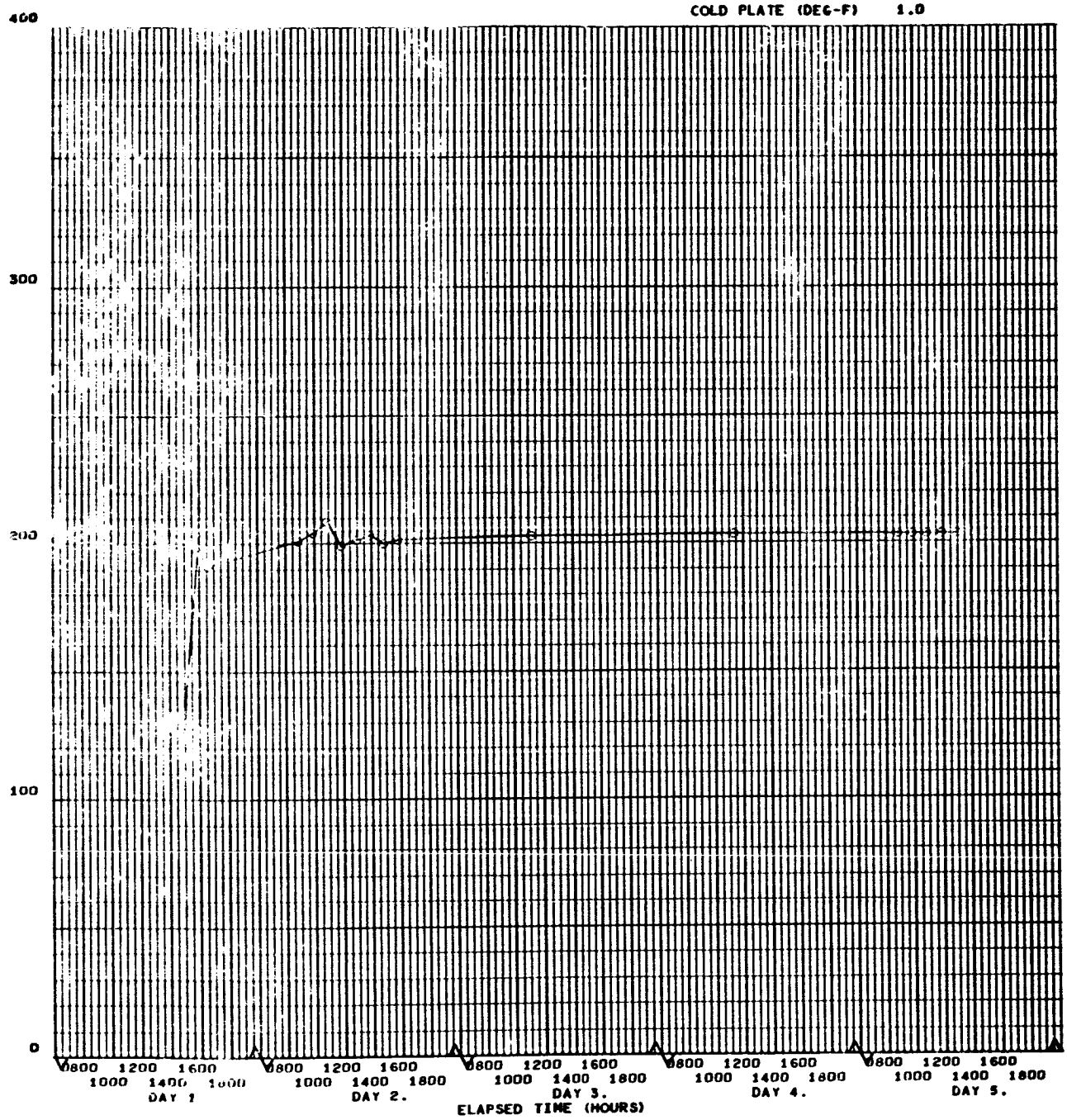


FIGURE 7.D

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 3.3
SAMPLE THICKNESS (IN.) 0.1875
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 203.5
COLD PLATE (DEG-F) 1.0

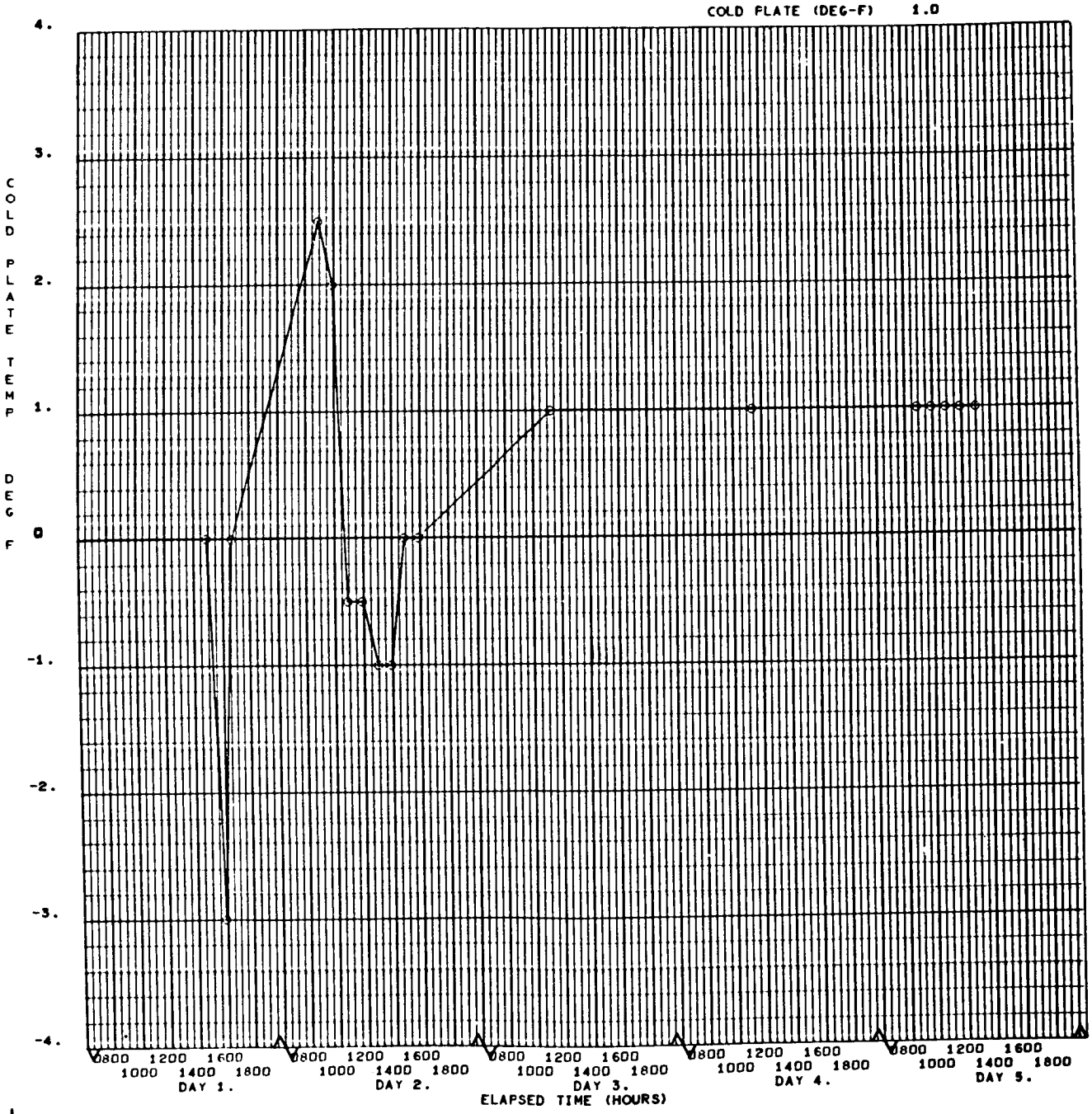


FIGURE 7.E

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 3.3
SAMPLE THICKNESS (IN.) 0.1875
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 203.5
COLD PLATE (DEG-F) 1.0

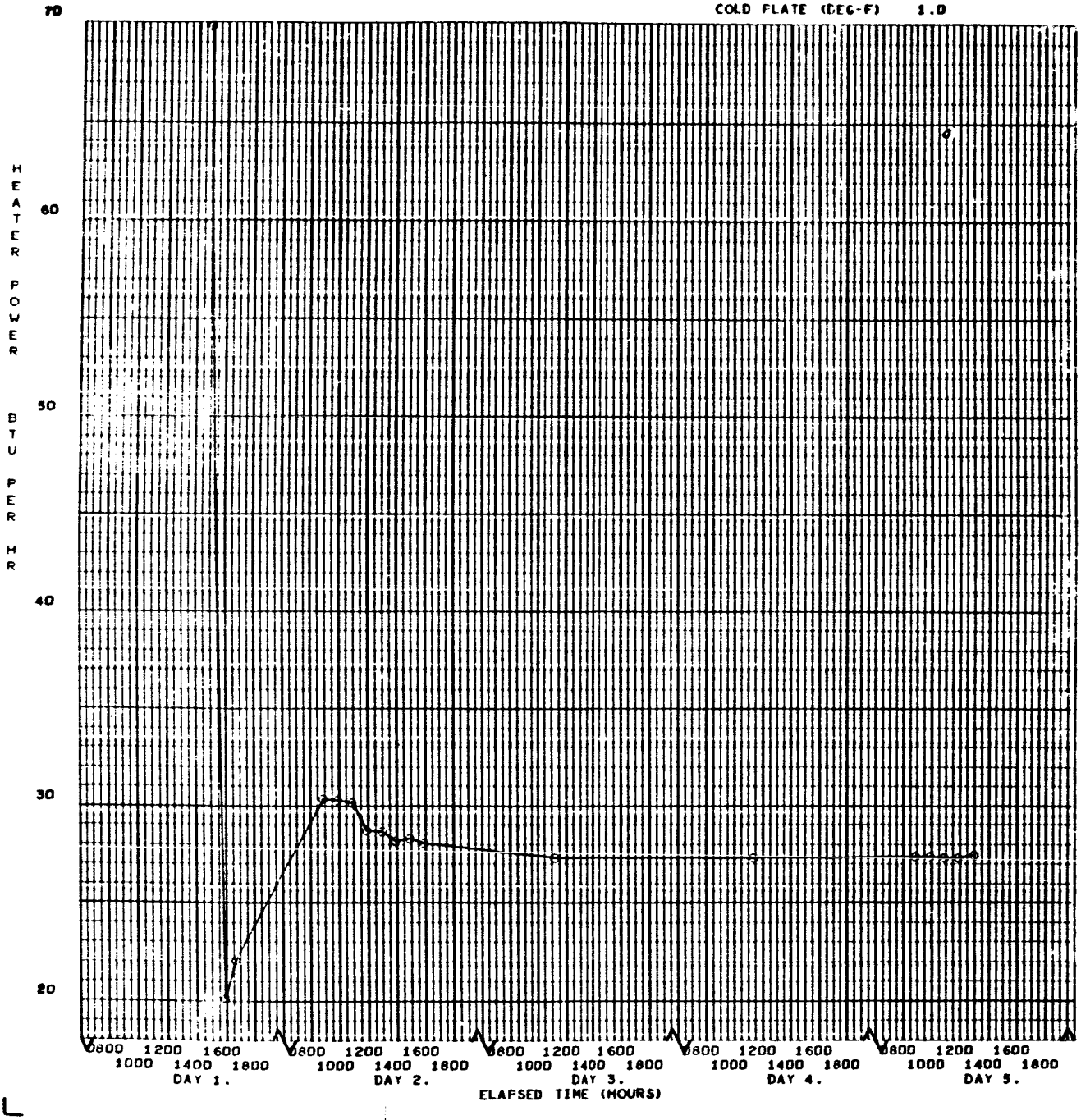


FIGURE 8.A

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 3.4
SAMPLE THICKNESS (IN.) 0.1875
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 301.0
COLD PLATE (DEG-F) 69.5

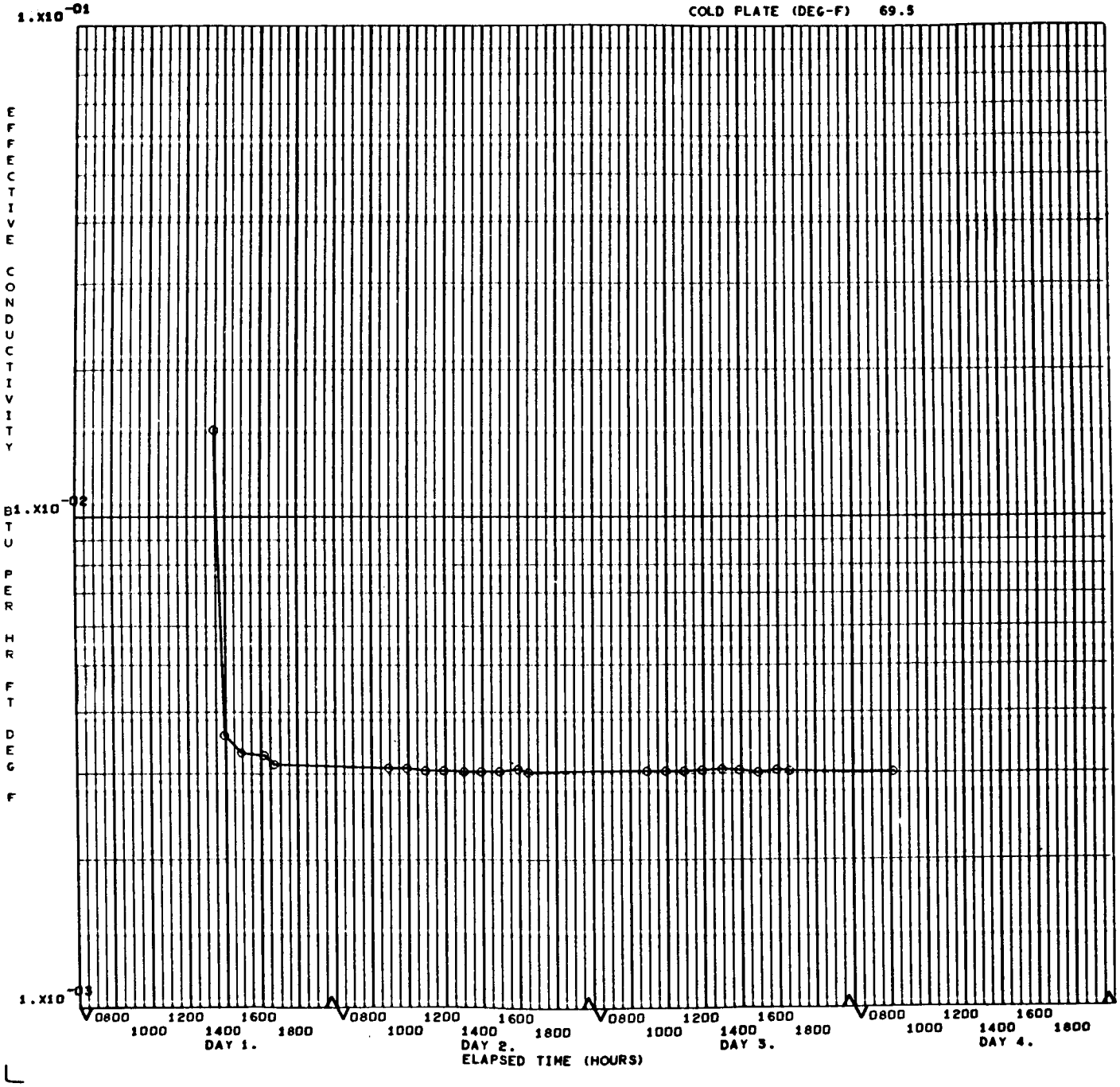


FIGURE 8.B

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 3.4
SAMPLE THICKNESS (IN.) 0.1875
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 301.0
COLD PLATE (DEG-F) 69.5

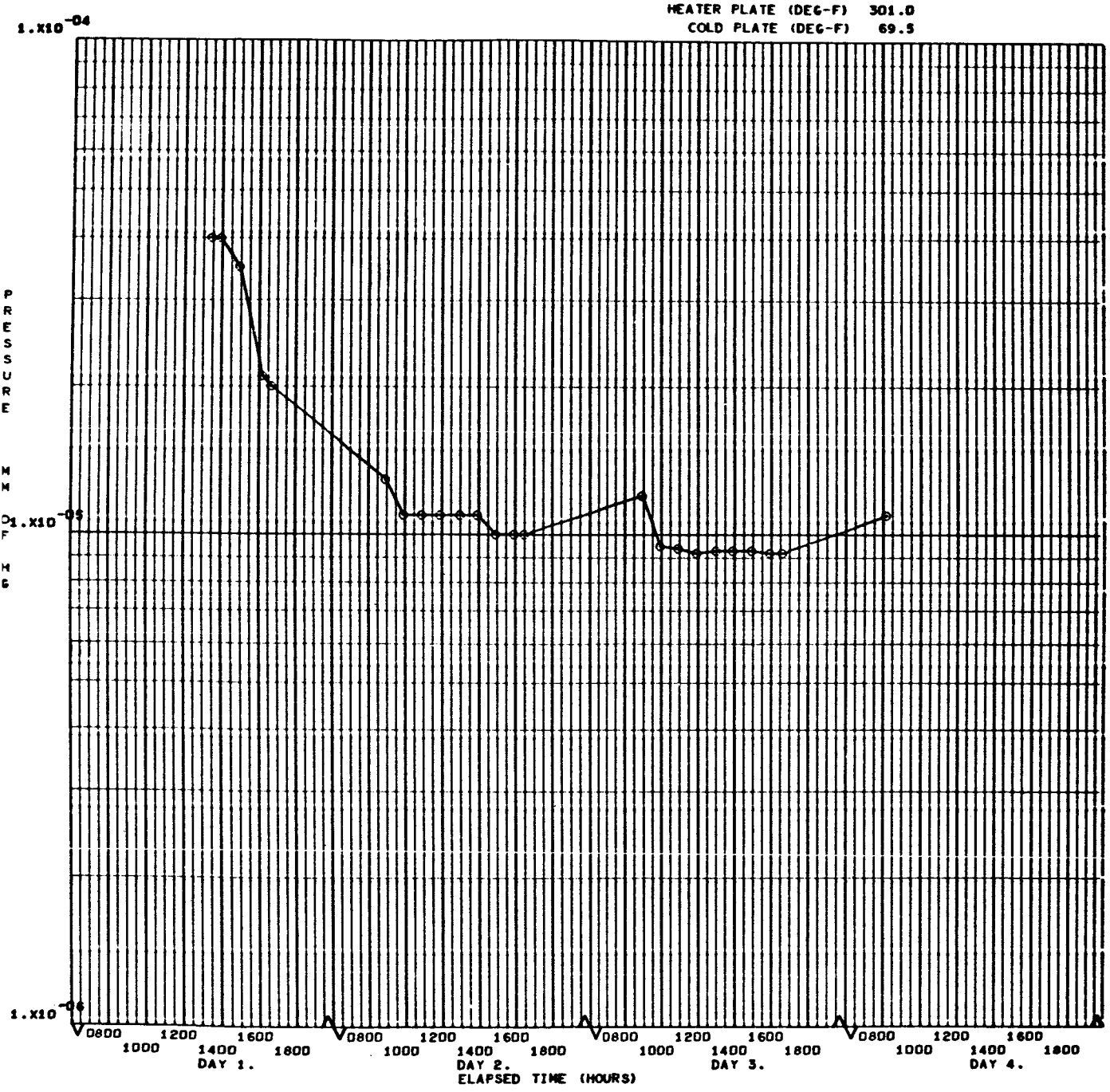


FIGURE 8.C

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 3.4
SAMPLE THICKNESS (IN.) 0.1875
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 301.0
COLD PLATE (DEG-F) 69.5

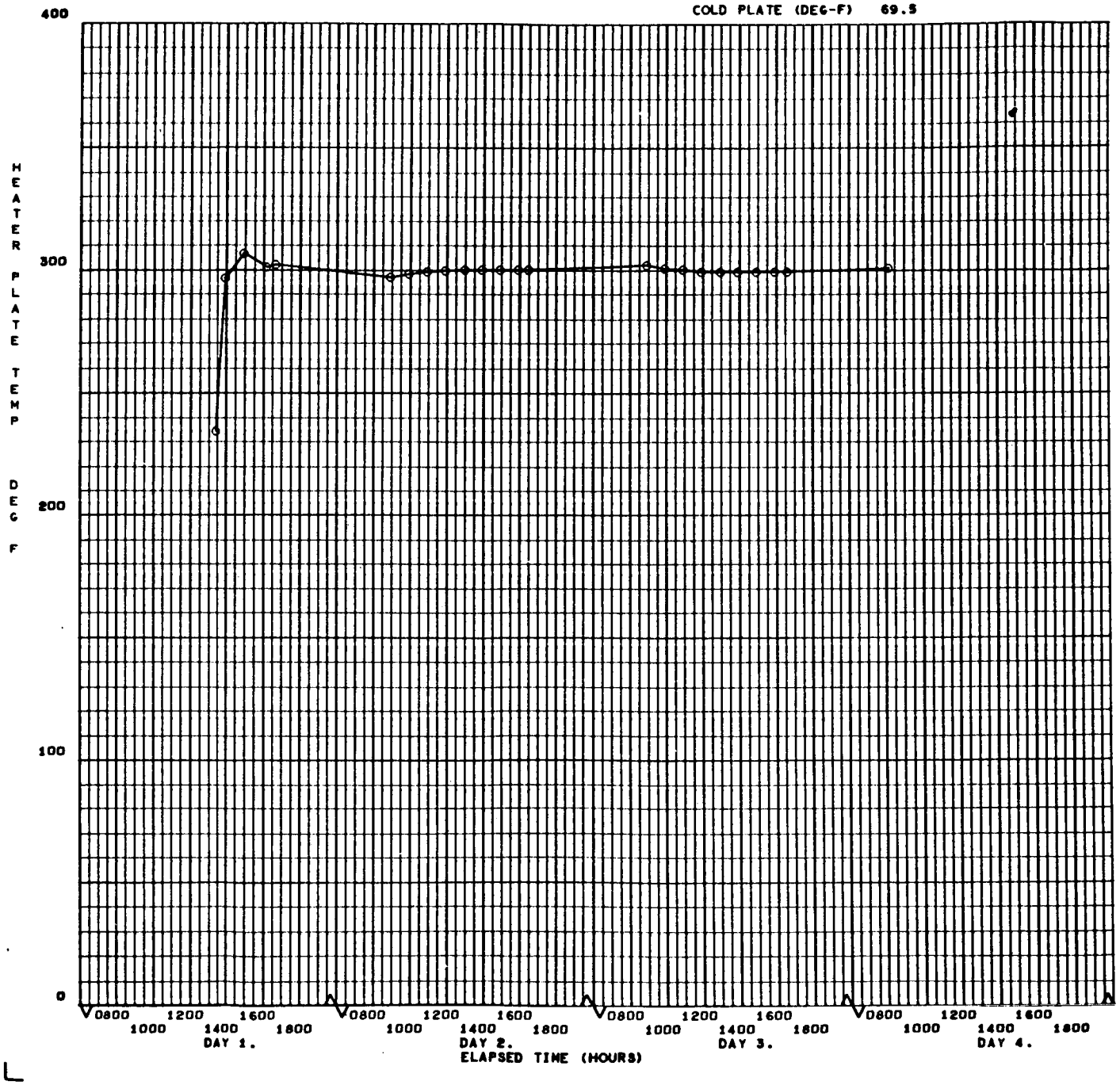


FIGURE 8.D

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 3.4
SAMPLE THICKNESS (IN.) 0.1875
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 301.0
COLD PLATE (DEG-F) 69.5

FIGURE 8.E

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 3.4
SAMPLE THICKNESS (IN.) 0.1875
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 301.0
COLD PLATE (DEG-F) 69.5

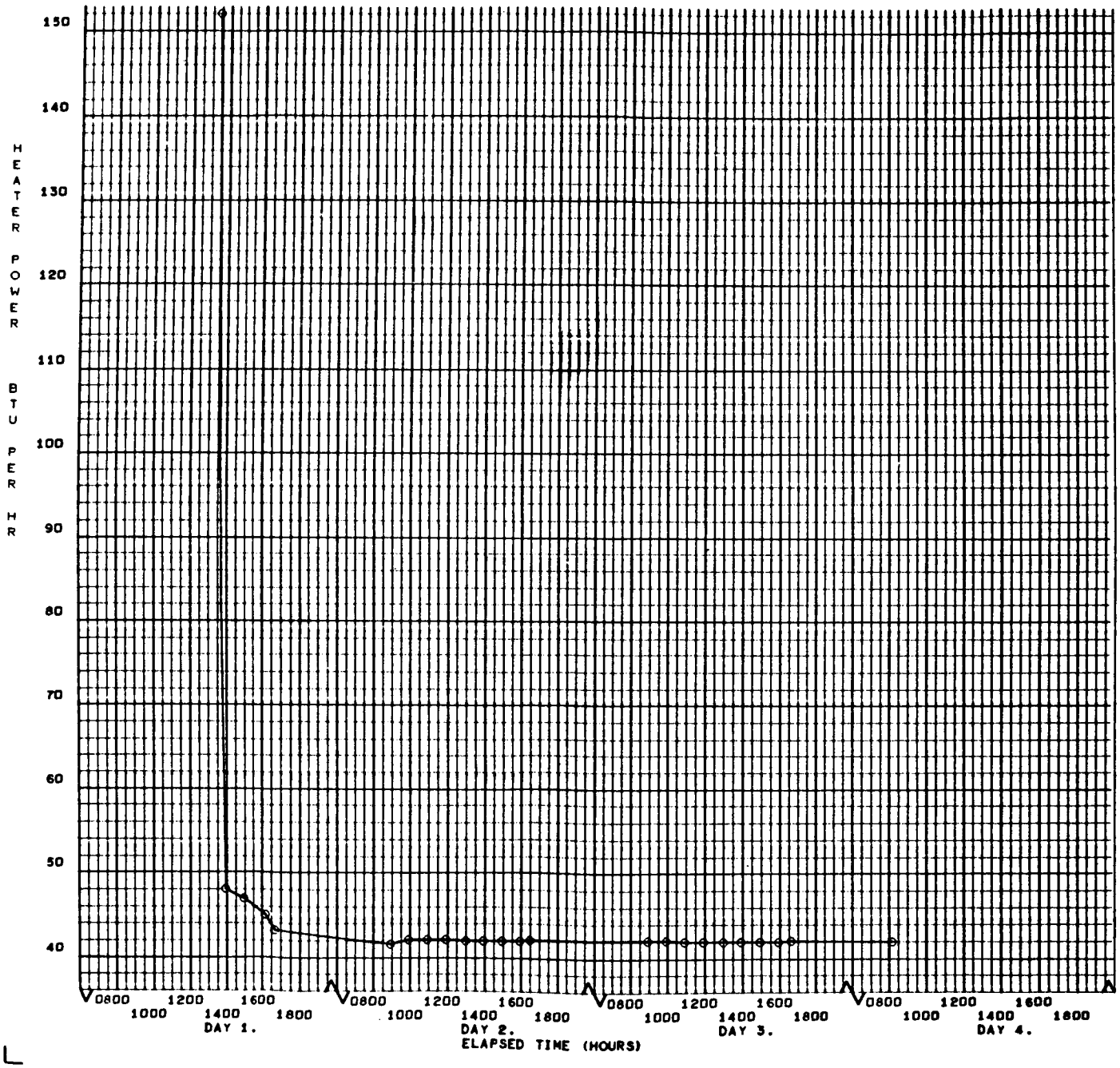


FIGURE 9.A

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 4.1
SAMPLE THICKNESS (IN.) 0.2500
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 304.5
COLD PLATE (DEG-F) 71.0

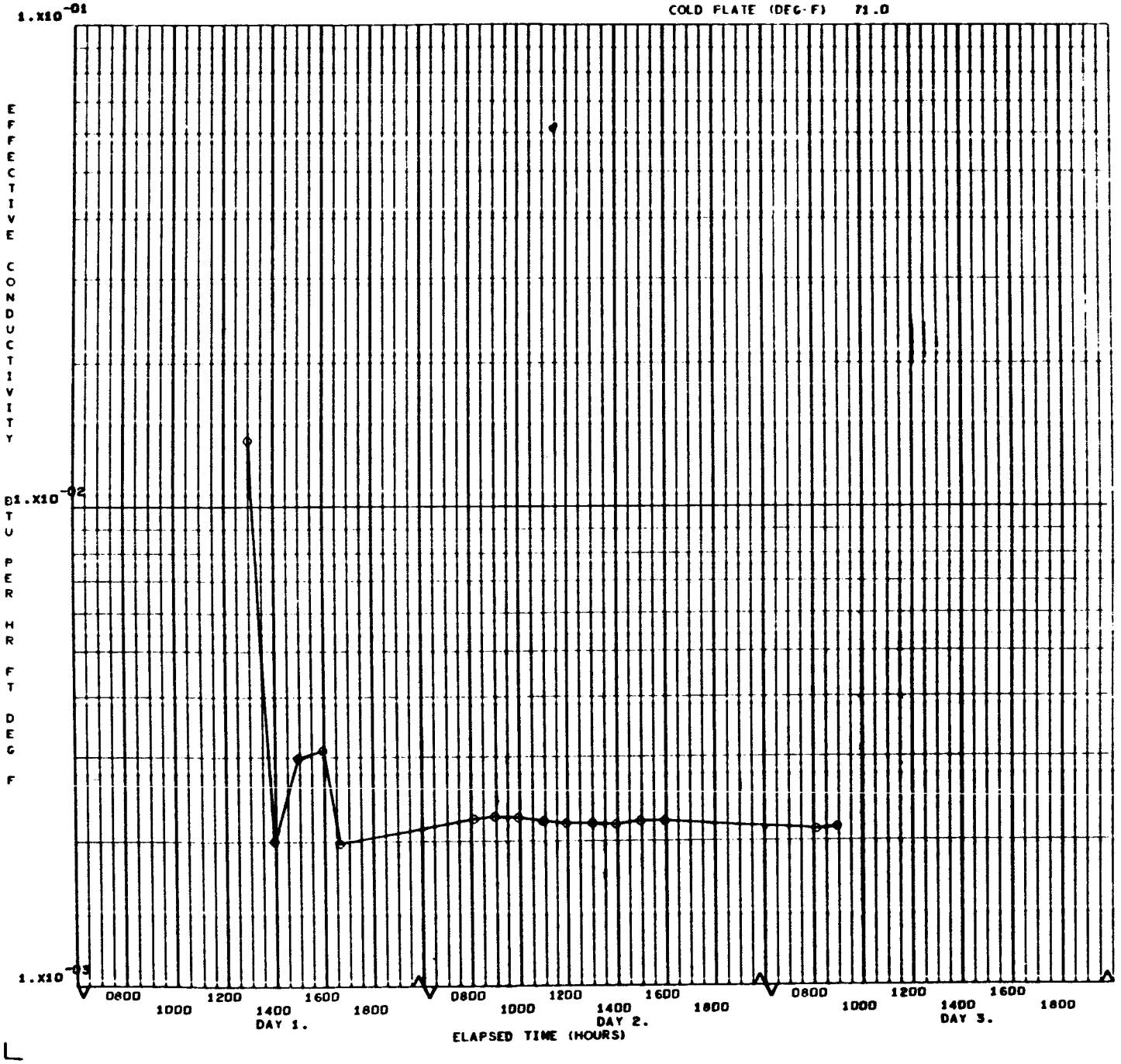


FIGURE 9.B

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 4.1
SAMPLE THICKNESS (IN.) 0.2500
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 304.5
COLD PLATE (DEG-F) 71.0

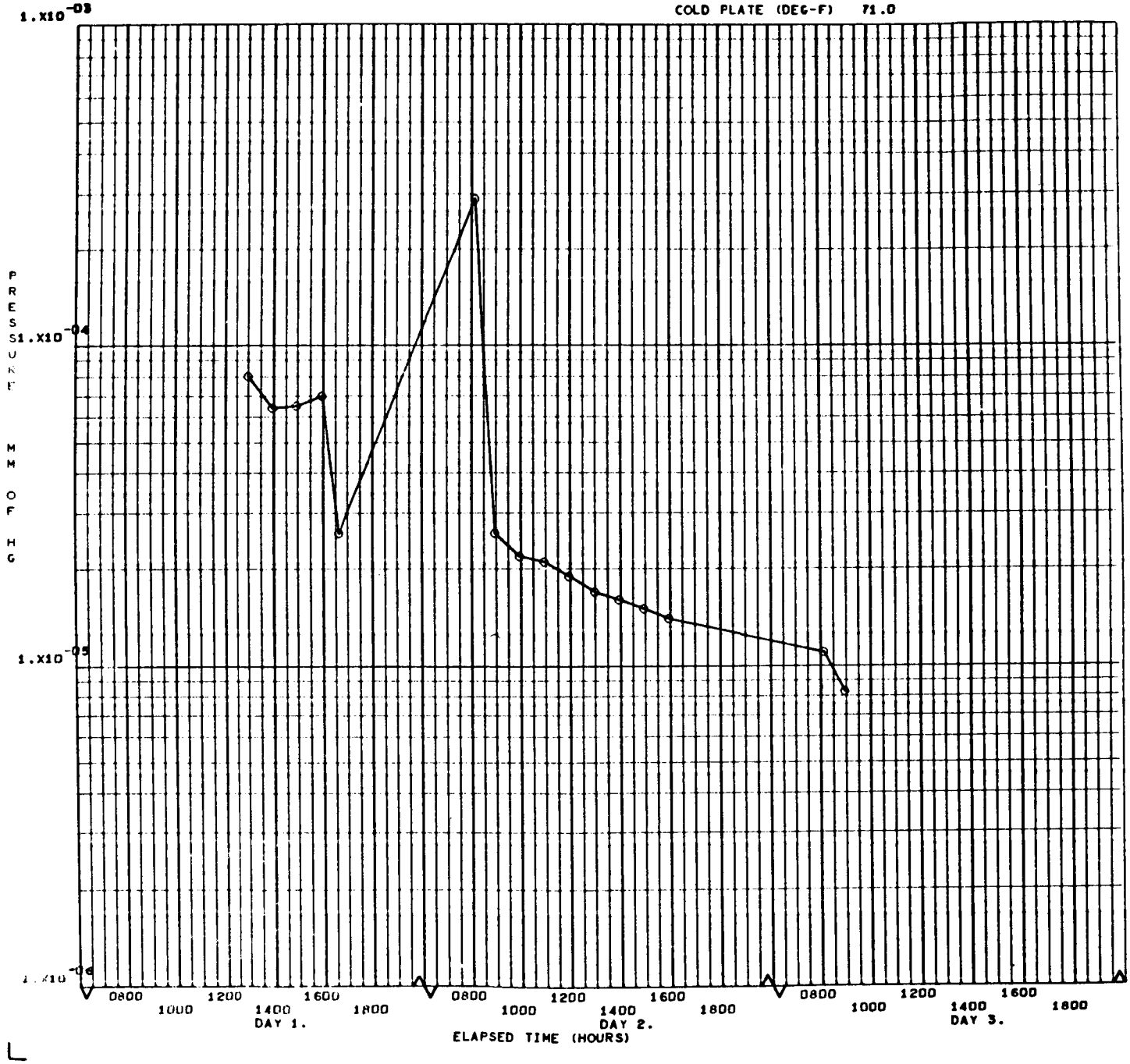


FIGURE 9.C

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 4.1
SAMPLE THICKNESS (IN.) 0.2500
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 304.5
COLD PLATE (DEG-F) 71.0

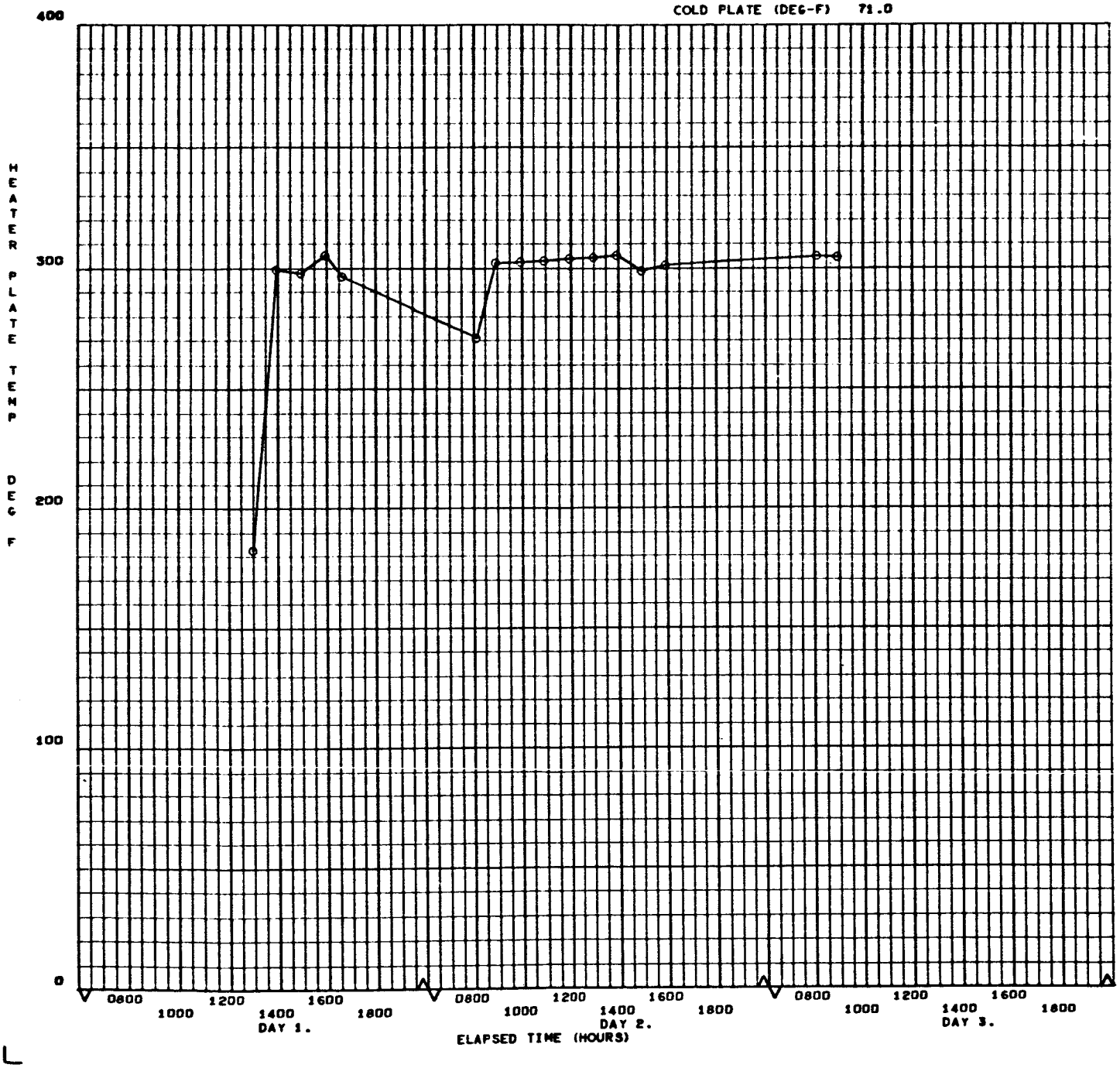


FIGURE 9.D

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 4.1
SAMPLE THICKNESS (IN.) 0.2500
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 304.5
COLD PLATE (DEG-F) 71.0

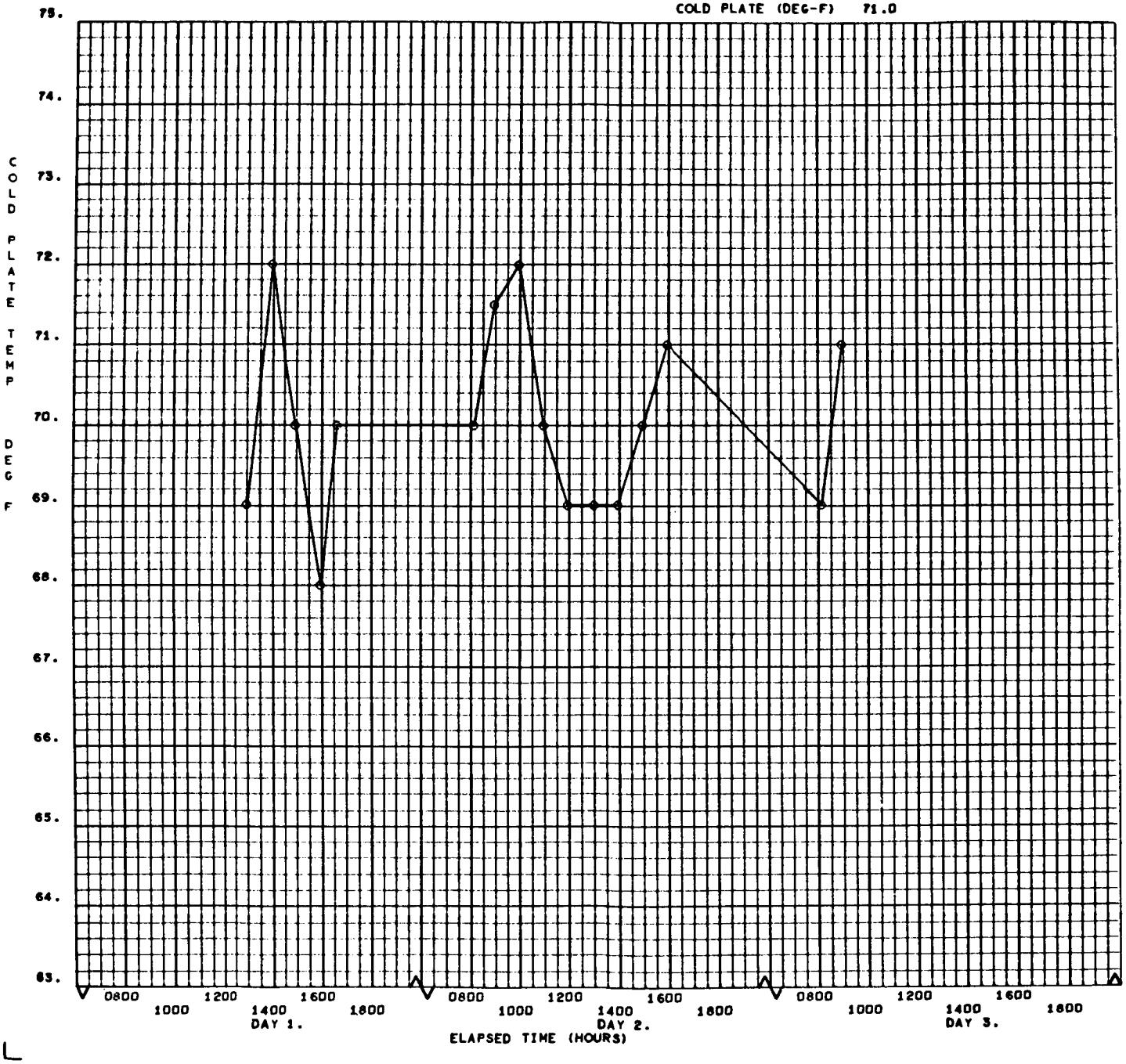


FIGURE 9.E

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 4.1
SAMPLE THICKNESS (IN.) 0.2500
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 304.5
COLD PLATE (DEG-F) 71.0

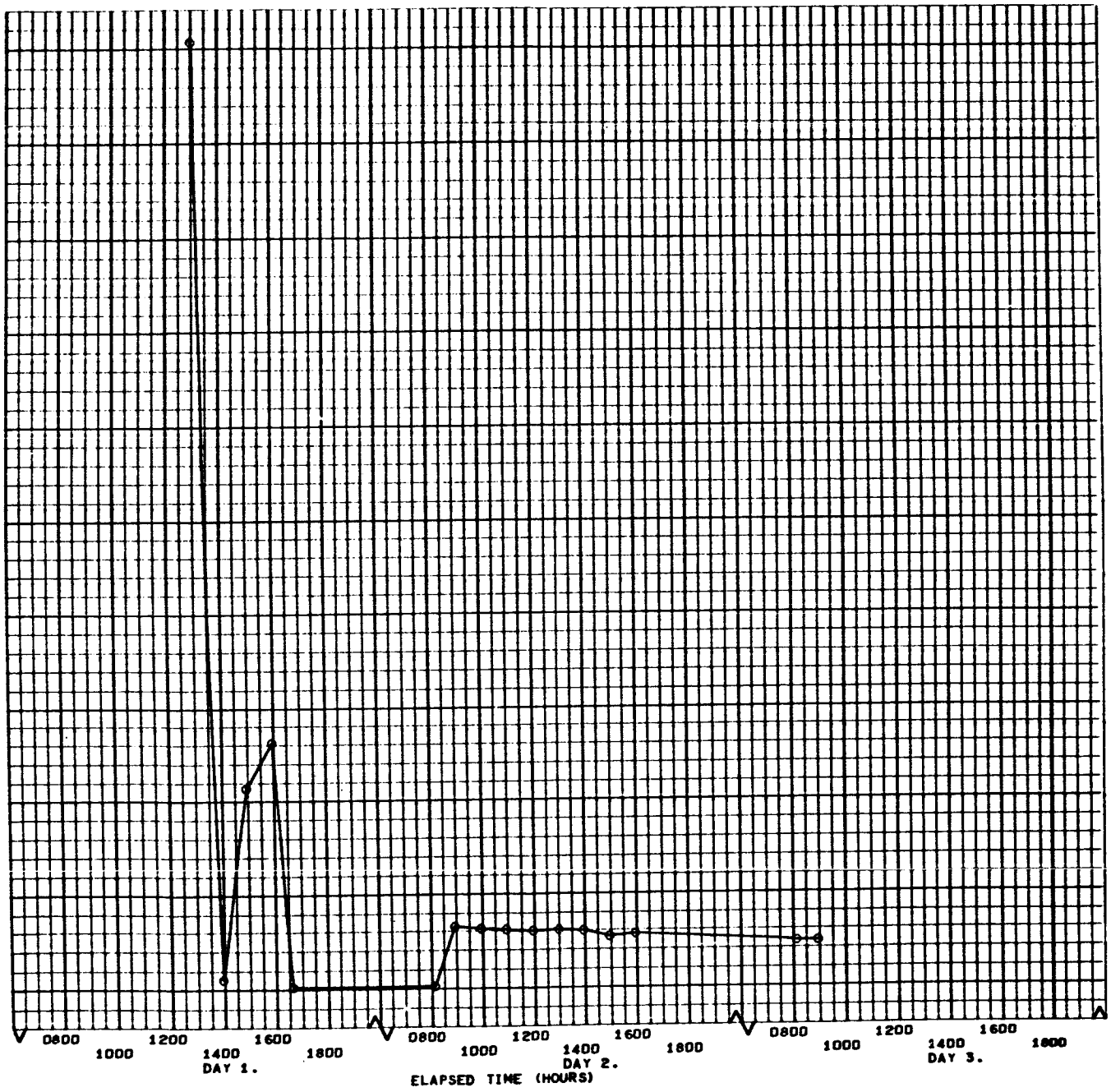


FIGURE 10.A

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 4.2
SAMPLE THICKNESS (IN.) 0.2500
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 71.0
COLD PLATE (DEG-F)- 310.0

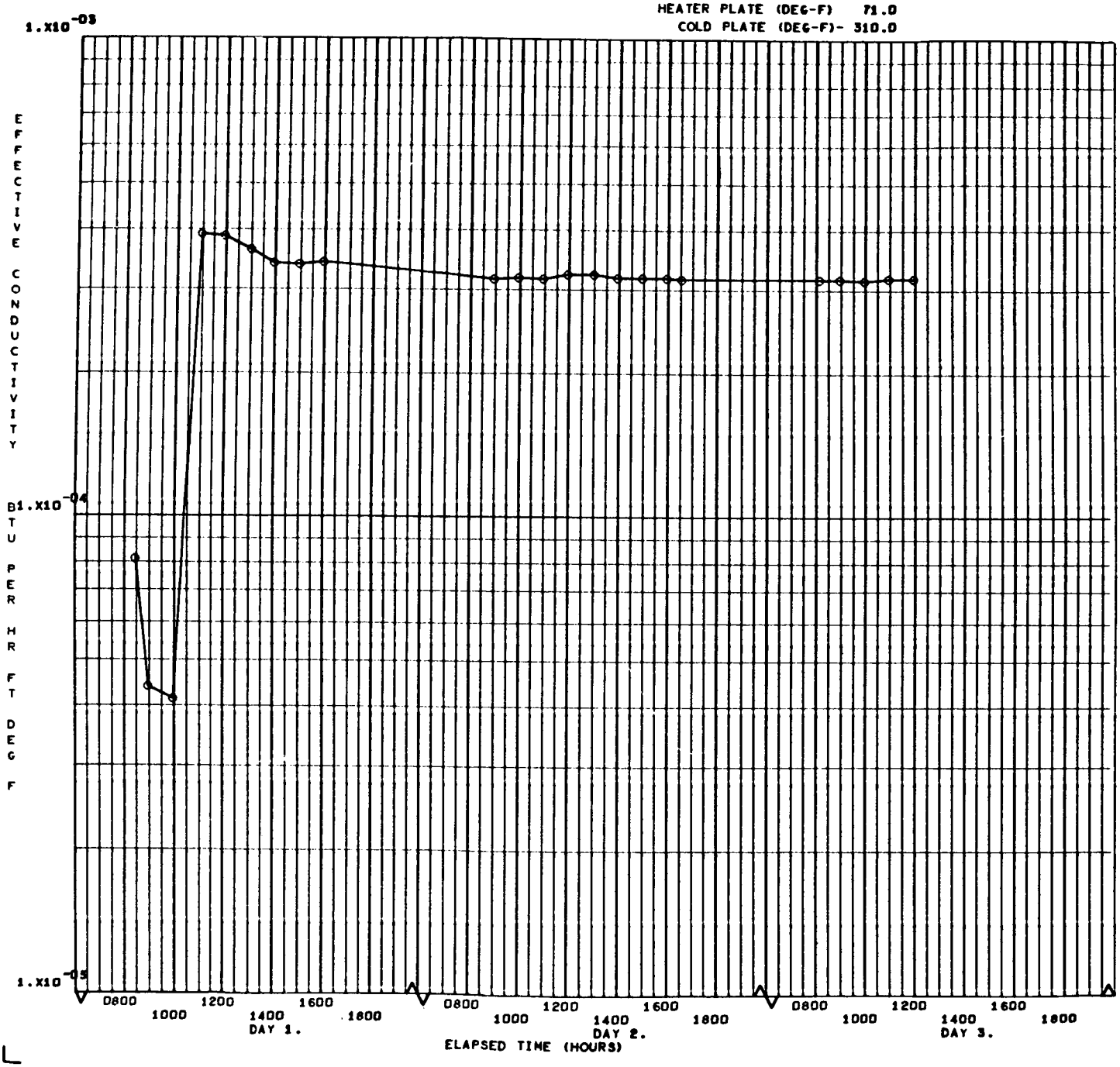


FIGURE 10.B

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 4.2
SAMPLE THICKNESS (IN.) 0.2500
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 71.0
COLD PLATE (DEG-F)- 310.0

FIGURE 10.C

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 4.2
SAMPLE THICKNESS (IN.) 0.2500
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 71.0
COLD PLATE (DEG-F)- 310.0

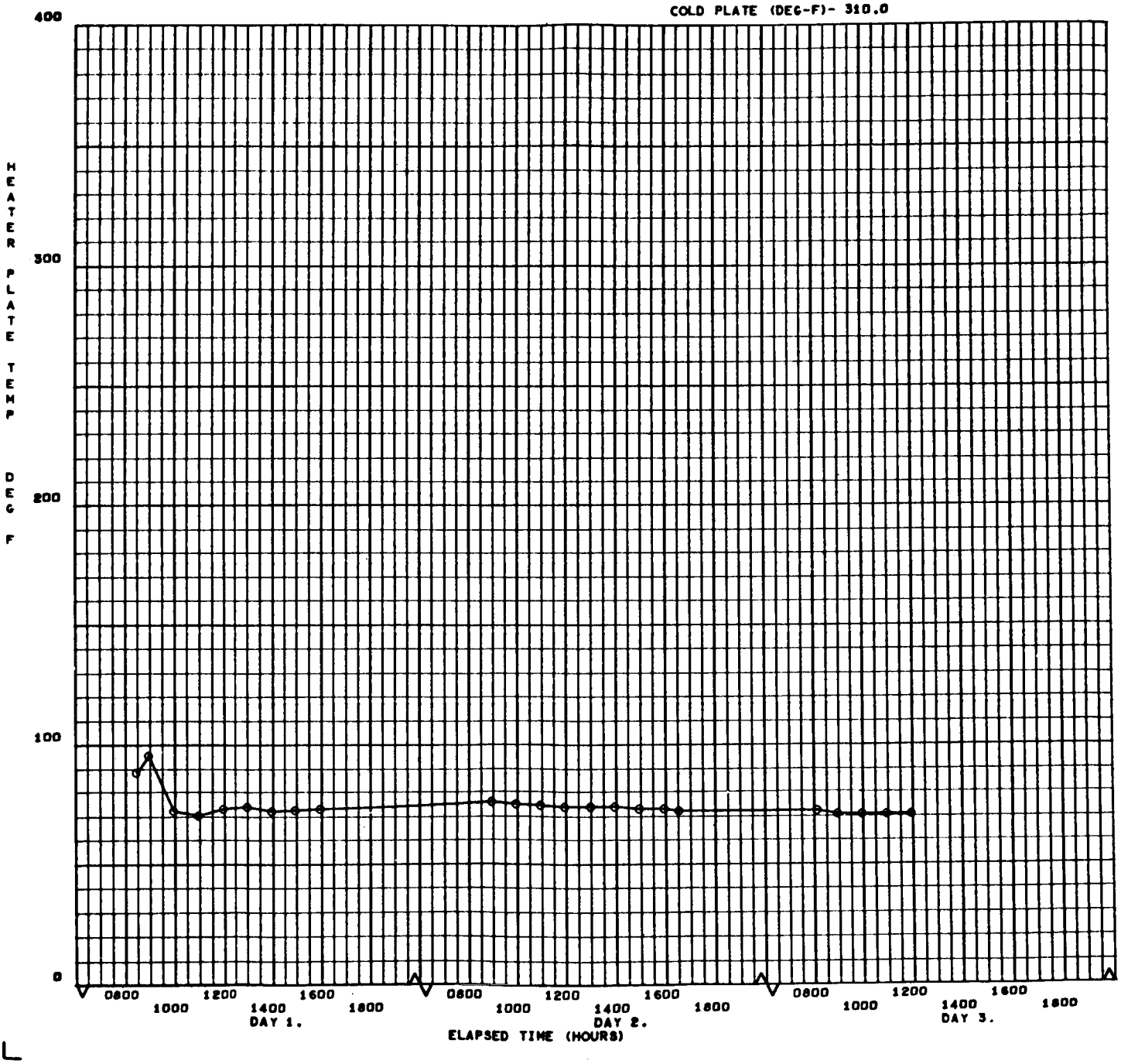


FIGURE 10.D

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 4.2
SAMPLE THICKNESS (IN.) 0.2500
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 71.0
COLD PLATE (DEG-F)- 310.0

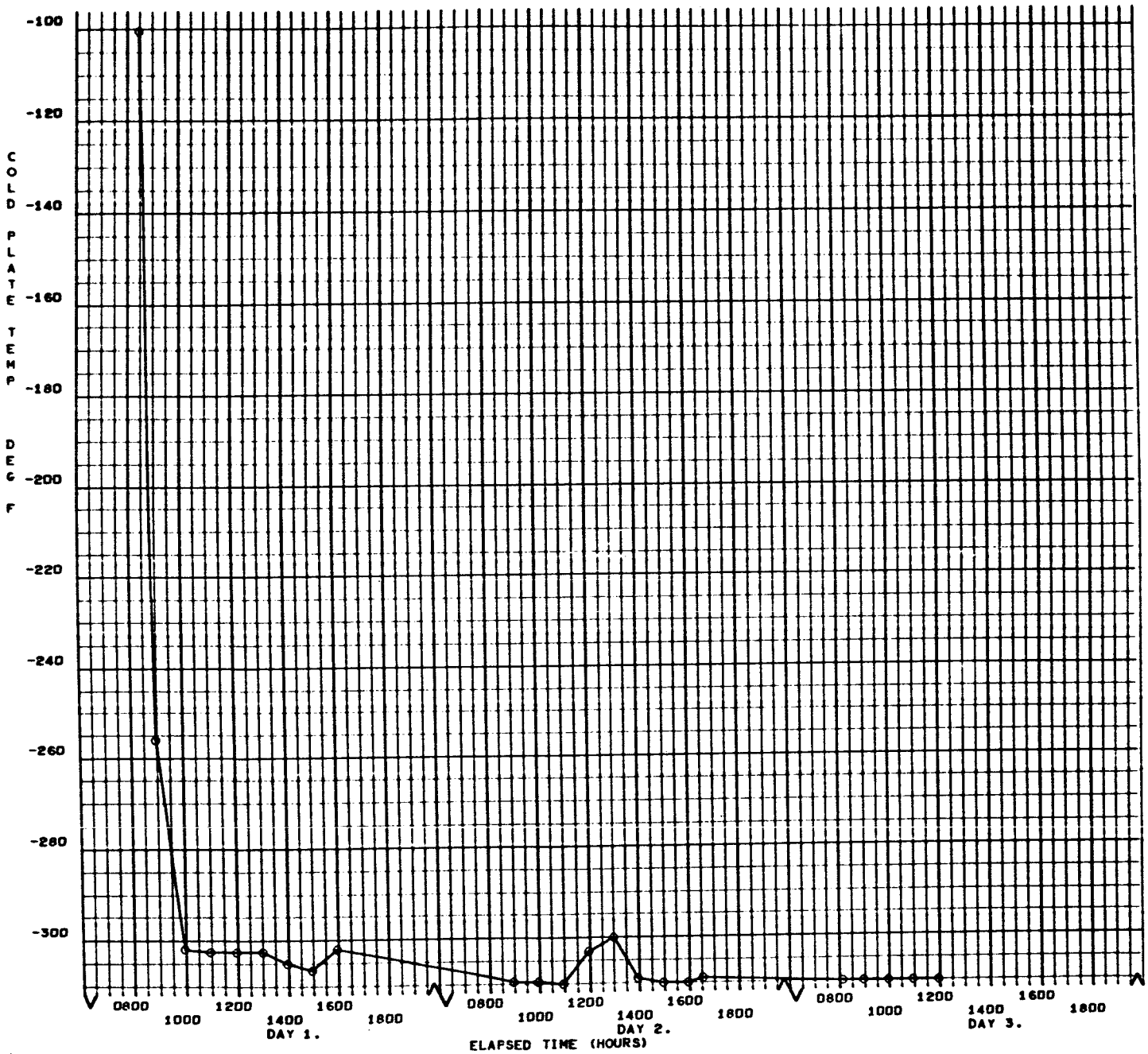


FIGURE 10.E

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 4.2
SAMPLE THICKNESS (IN.) 0.2500
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 71.0
COLD PLATE (DEG-F)- 310.0

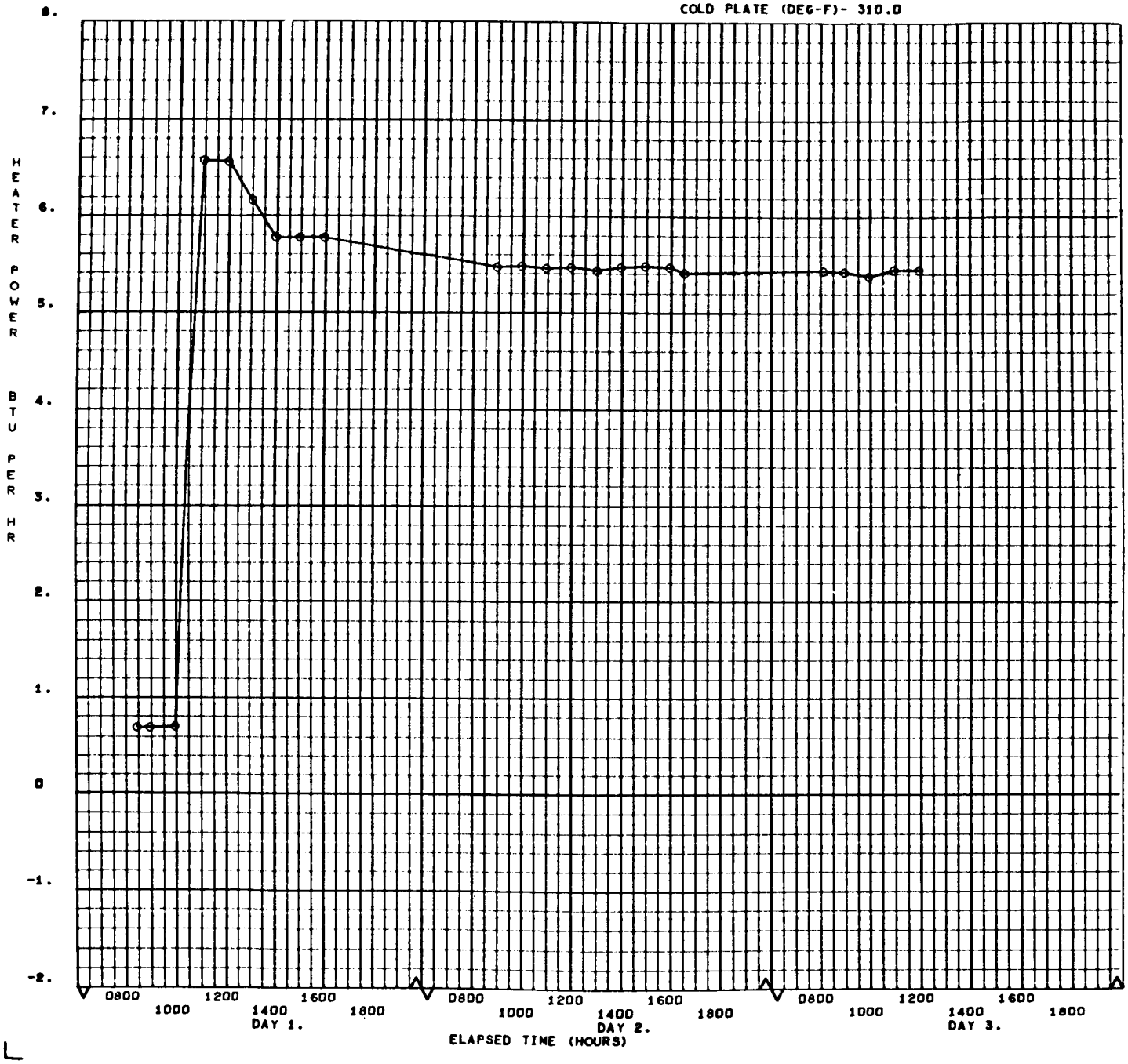


FIGURE 11.A

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 4.3
SAMPLE THICKNESS (IN.) 0.2500
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 201.0
COLD PLATE (DEG-F) 1.0

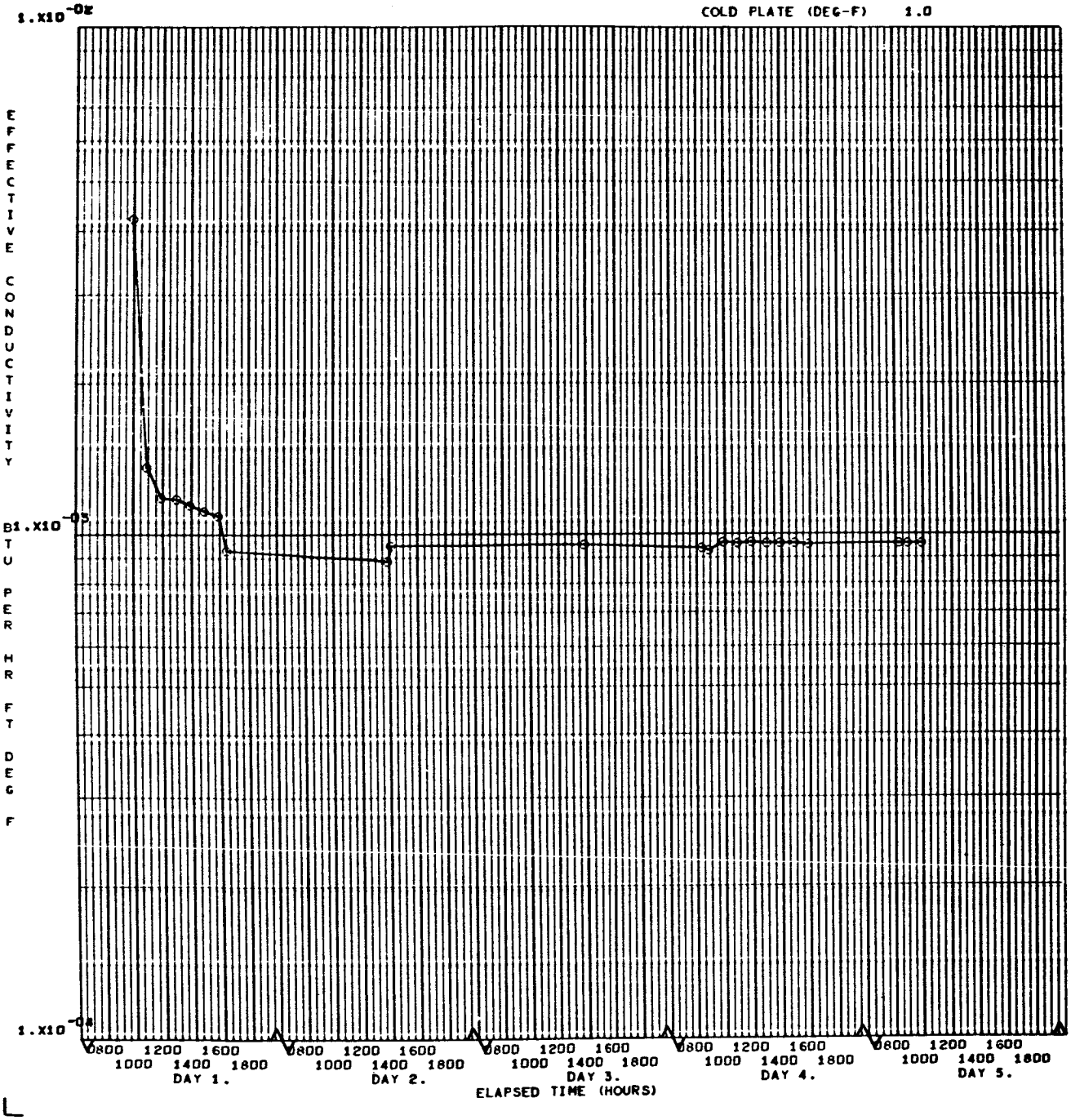


FIGURE 11.B

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 4.3
SAMPLE THICKNESS (IN.) 0.2500
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 201.0
COLD PLATE (DEG-F) 1.0

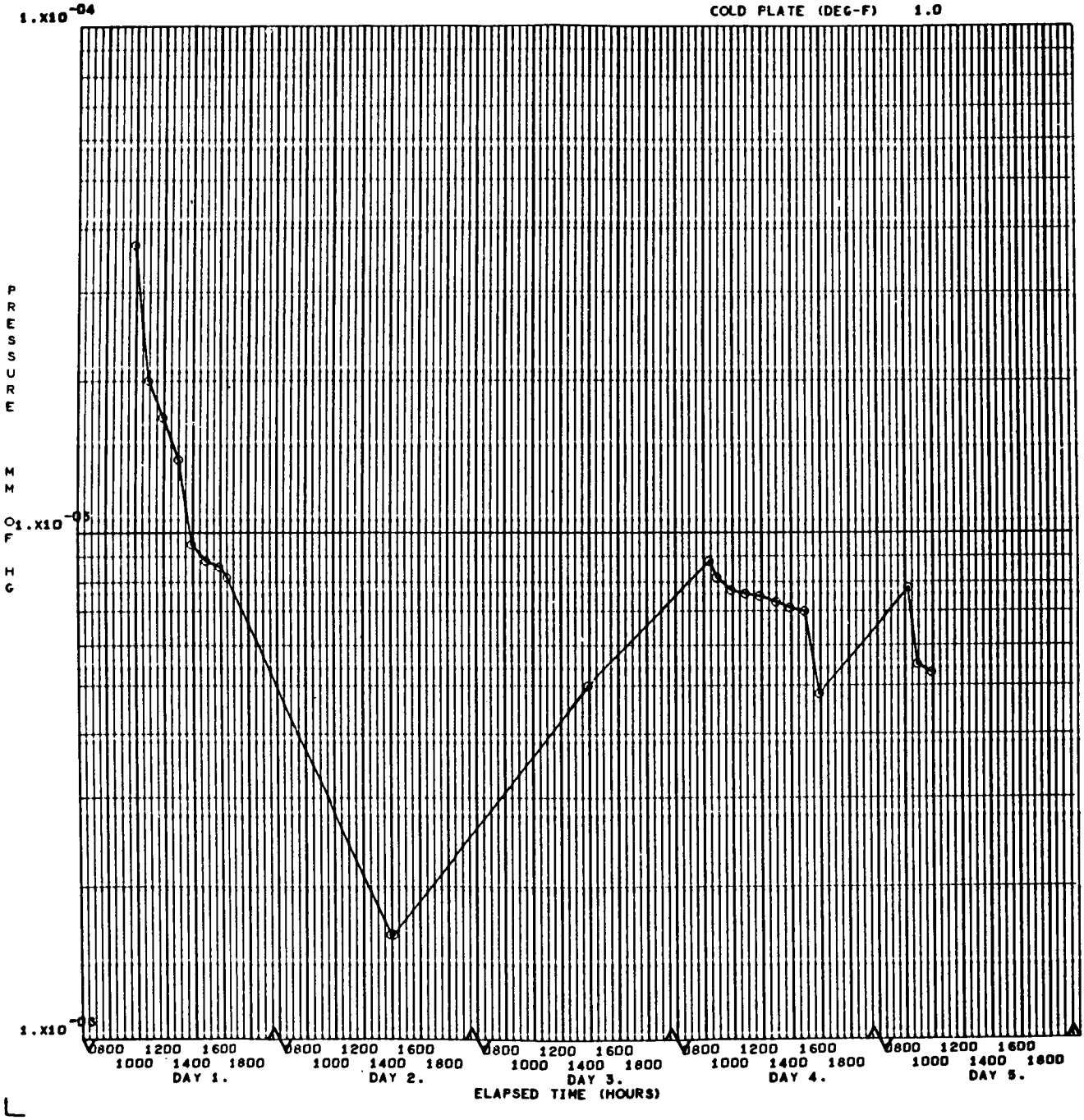


FIGURE 11.C

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 4.3
SAMPLE THICKNESS (IN.) 0.2500
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 201.0
COLD PLATE (DEG-F) 1.0

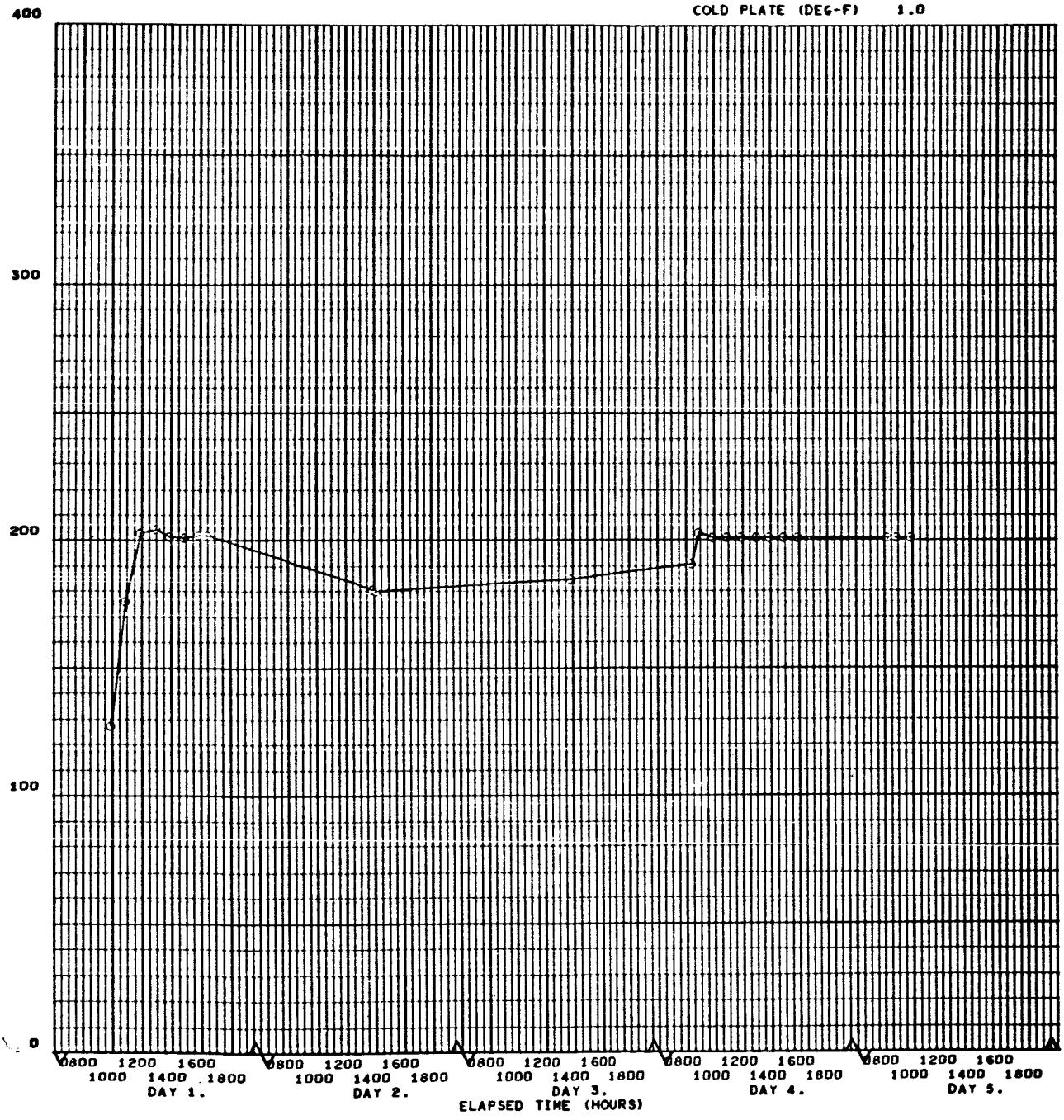


FIGURE 11.D

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 4.3
SAMPLE THICKNESS (IN.) 0.2500
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 201.0
COLD PLATE (DEG-F) 1.0

FIGURE 11.E

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 4.3
SAMPLE THICKNESS (IN.) 0.2500
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 201.0
COLD PLATE (DEG-F) 1.0

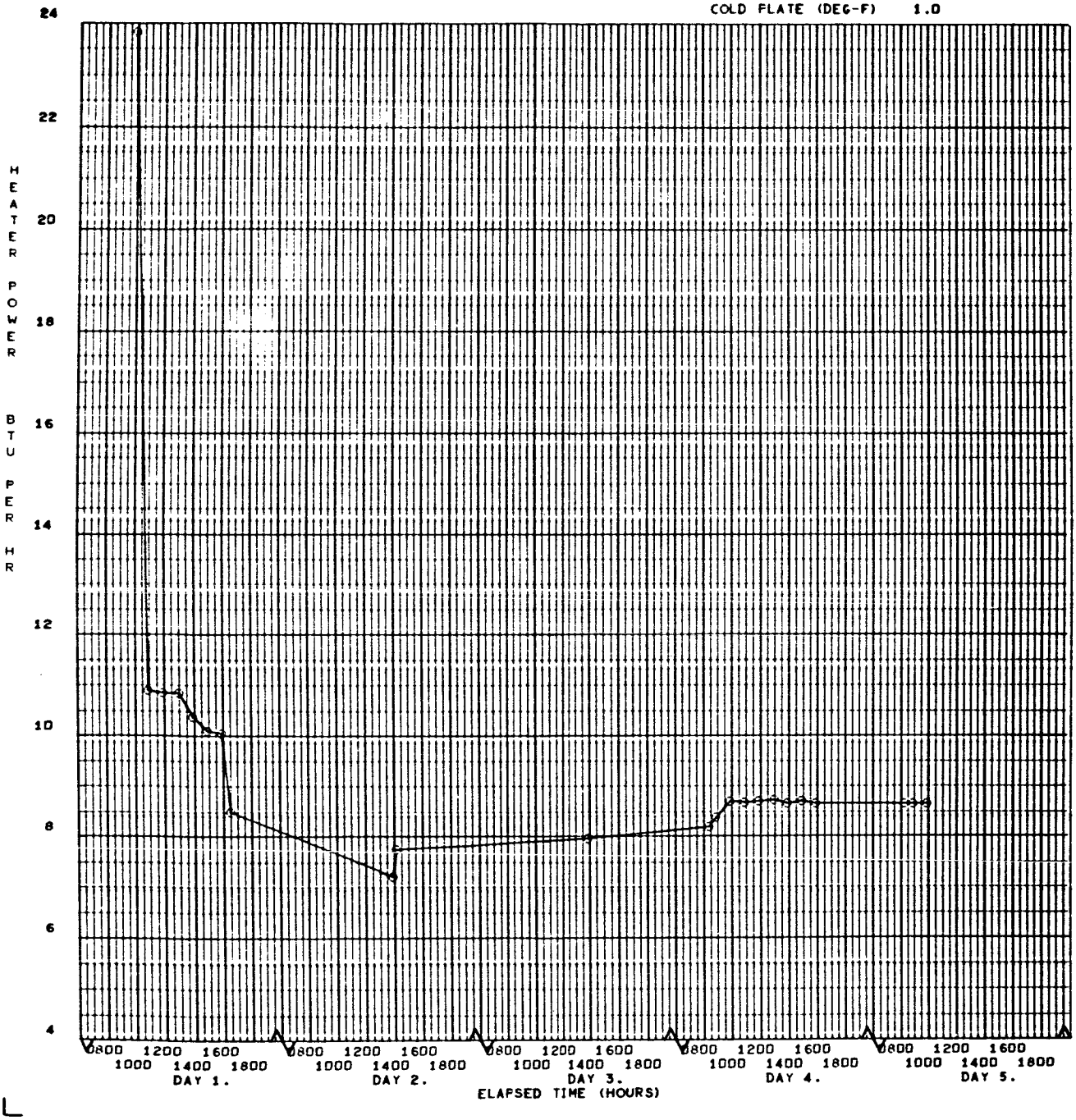


FIGURE 12.A

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 5,1
SAMPLE THICKNESS (IN.) 0.3125
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 77.0
COLD PLATE (DEG-F)- 310.0

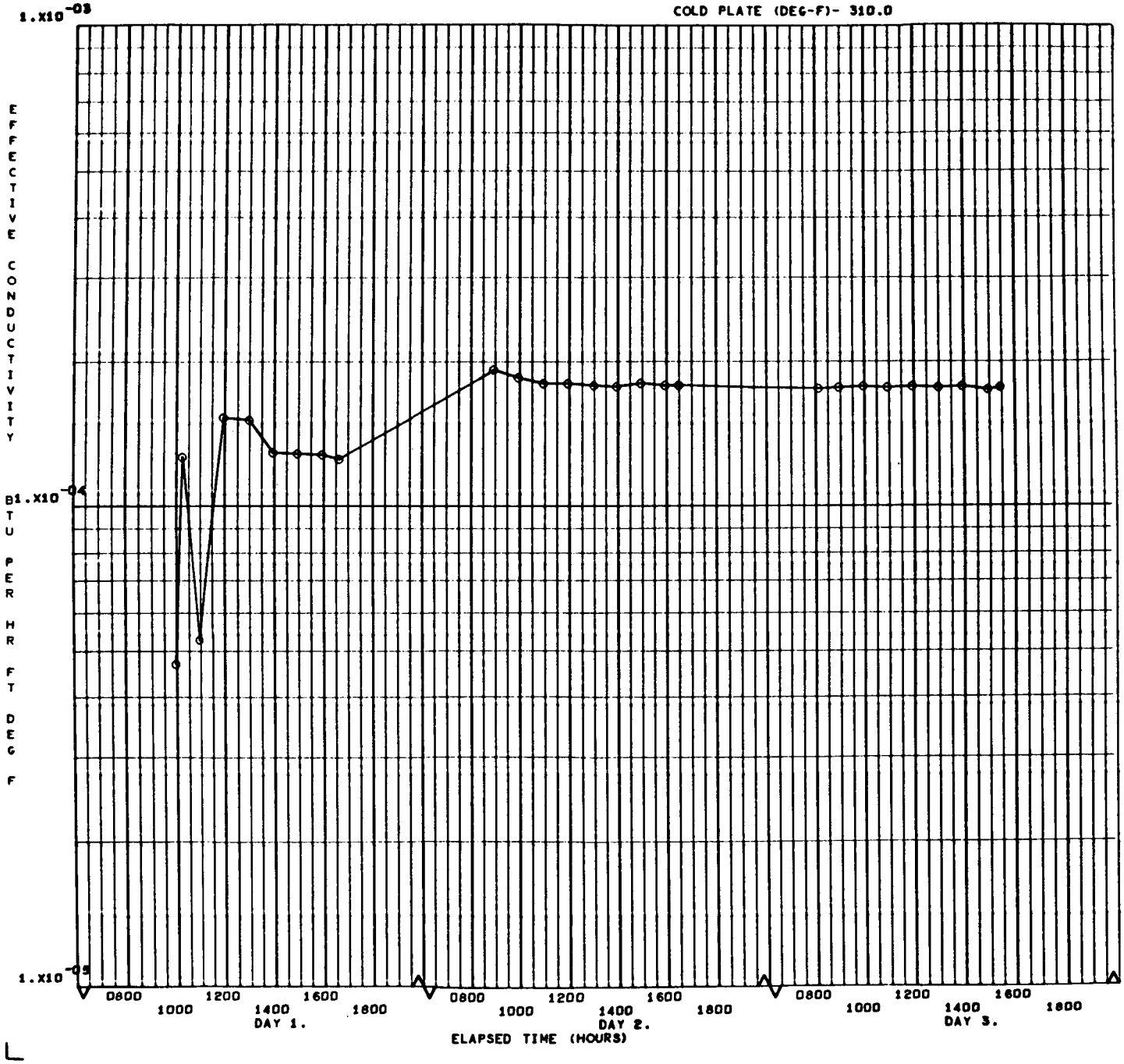


FIGURE 12.B

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 5.1
SAMPLE THICKNESS (IN.) 0.3125
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 77.0
COLD PLATE (DEG-F)- 310.0

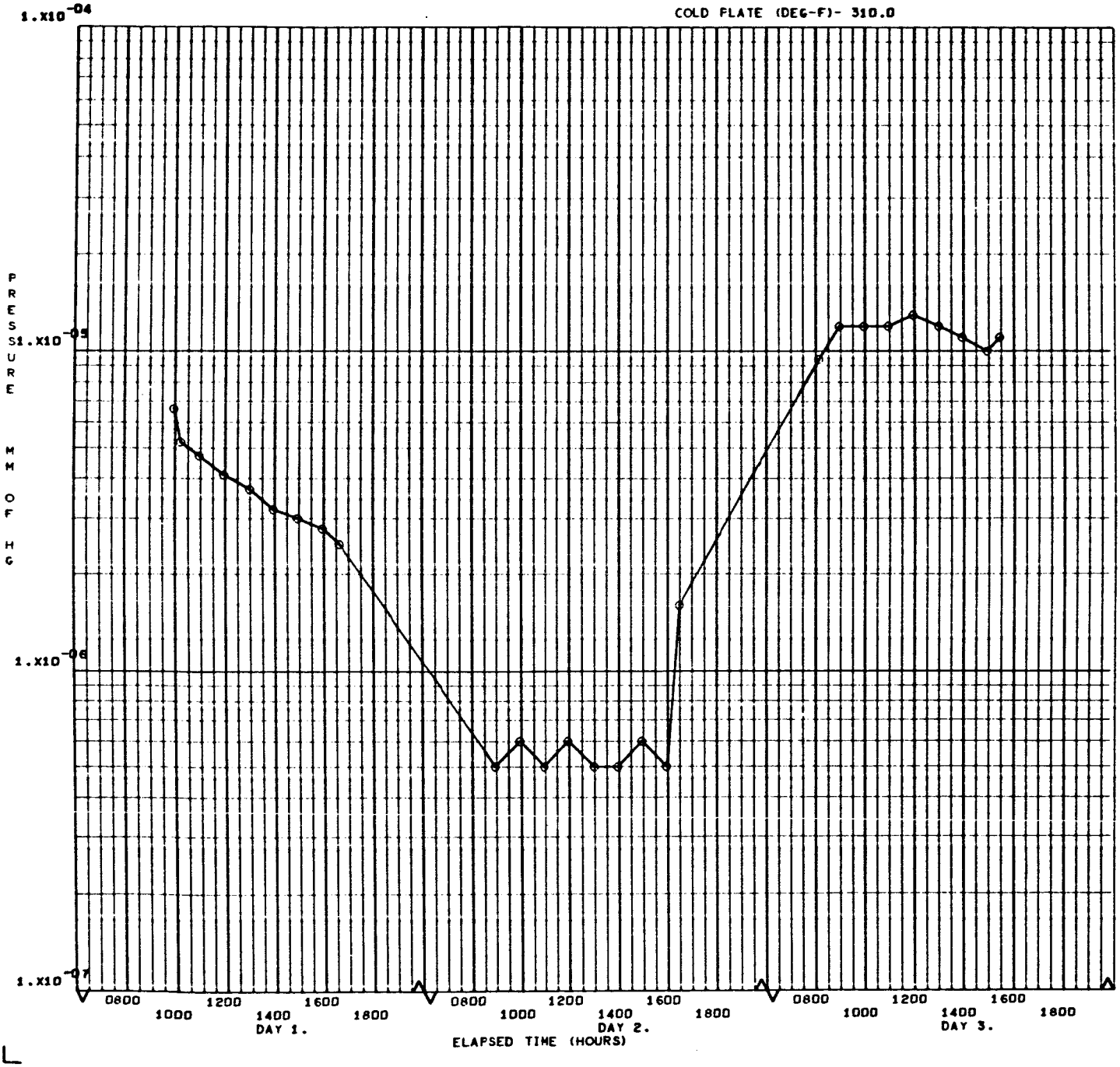


FIGURE 12.C

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 5.1
SAMPLE THICKNESS (IN.) 0.3125
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 77.0
COLD PLATE (DEG-F)- 310.0

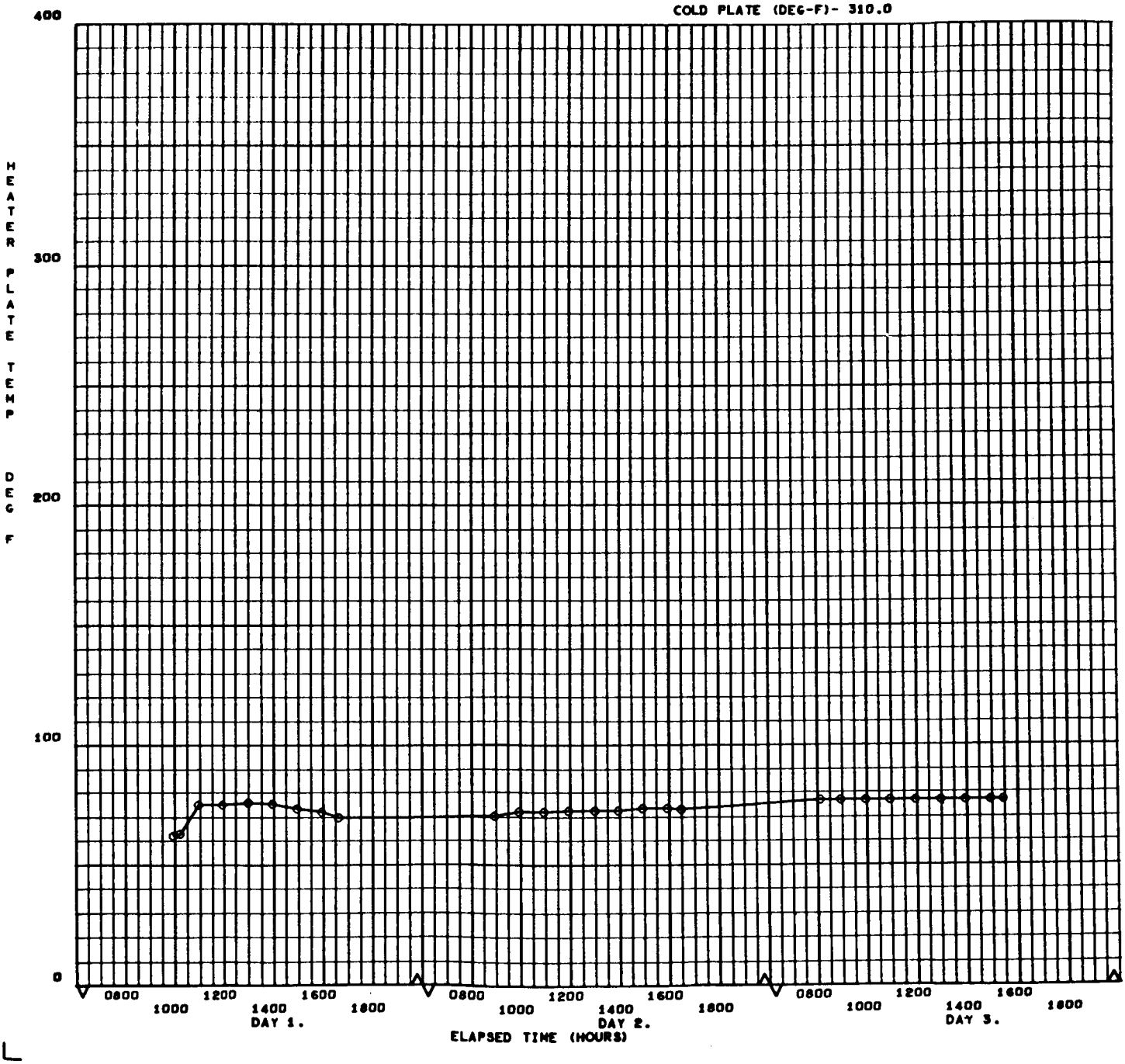


FIGURE 12.D

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 5.1
SAMPLE THICKNESS (IN.) 0.3125
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 77.0
COLD PLATE (DEG-F)- 310.0

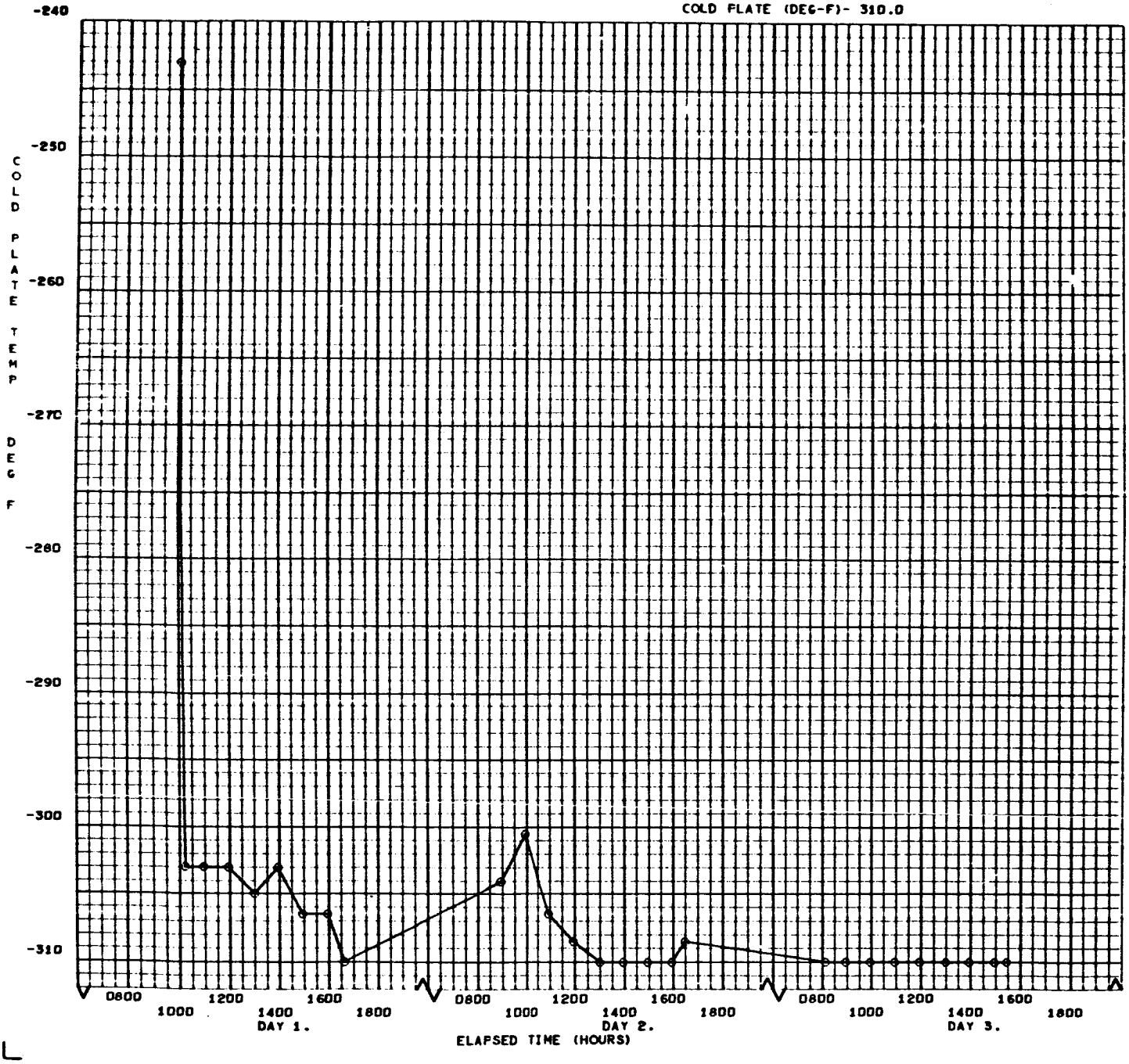


FIGURE 12.E

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 5.1
SAMPLE THICKNESS (IN.) 0.3125
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 77.0
COLD PLATE (DEG-F)- 310.0

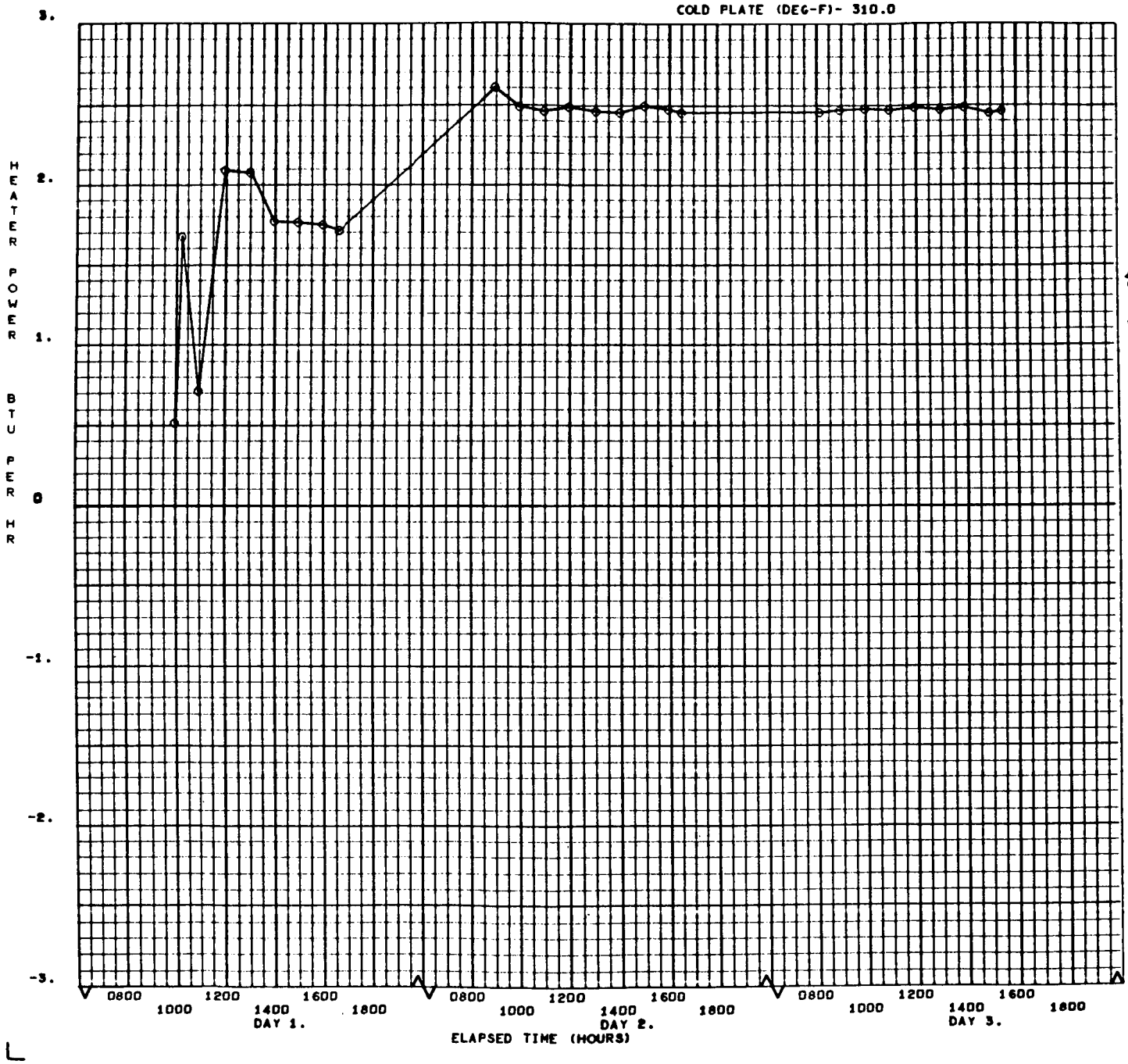


FIGURE 13.A

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 5.2
SAMPLE THICKNESS (IN.) 0.3125
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 208.5
COLD PLATE (DEG-F) 0.0

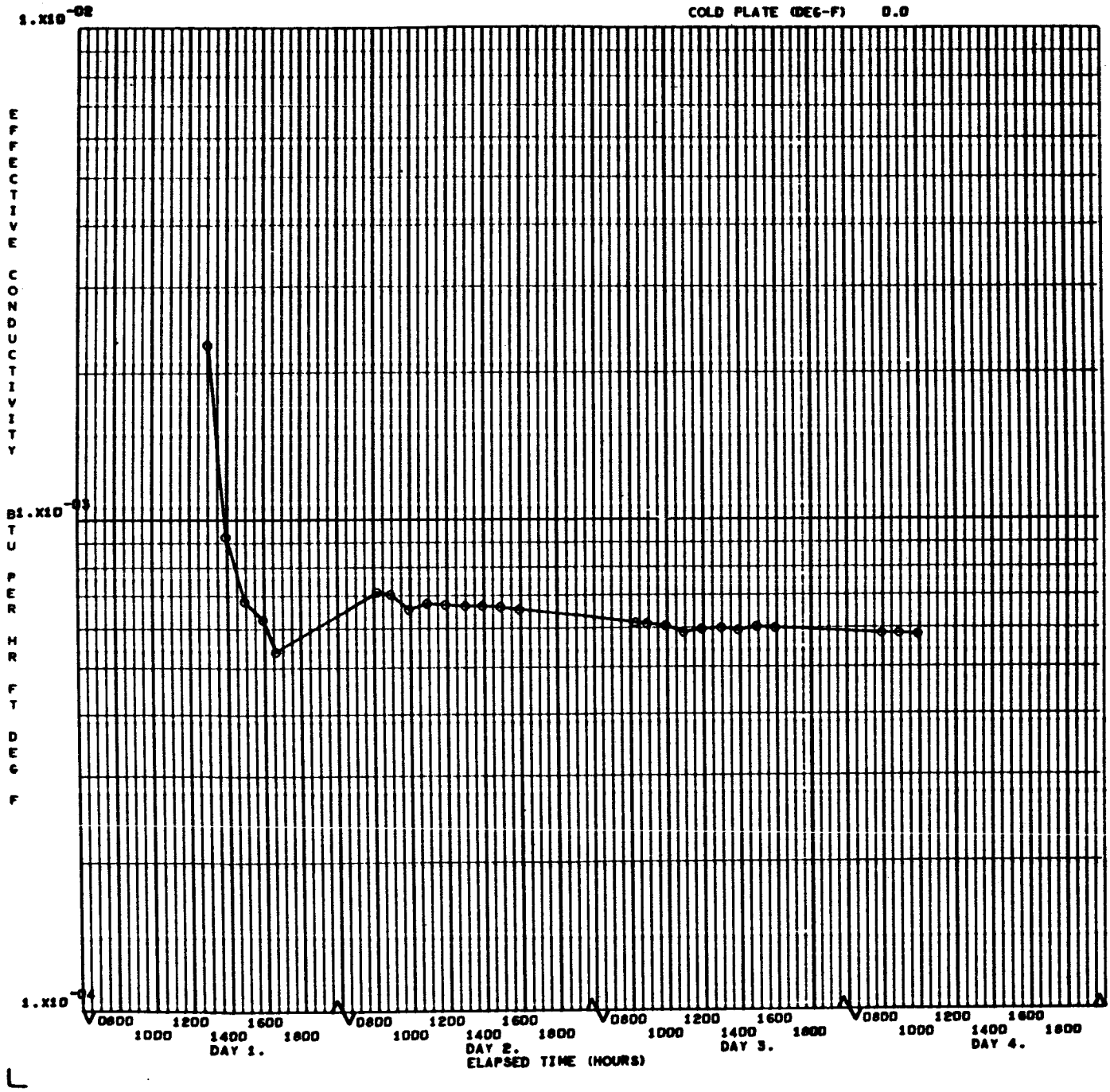


FIGURE 13.B

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 5.2
SAMPLE THICKNESS (IN.) 0.3125
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 208.5
COLD PLATE (DEG-F) 0.0

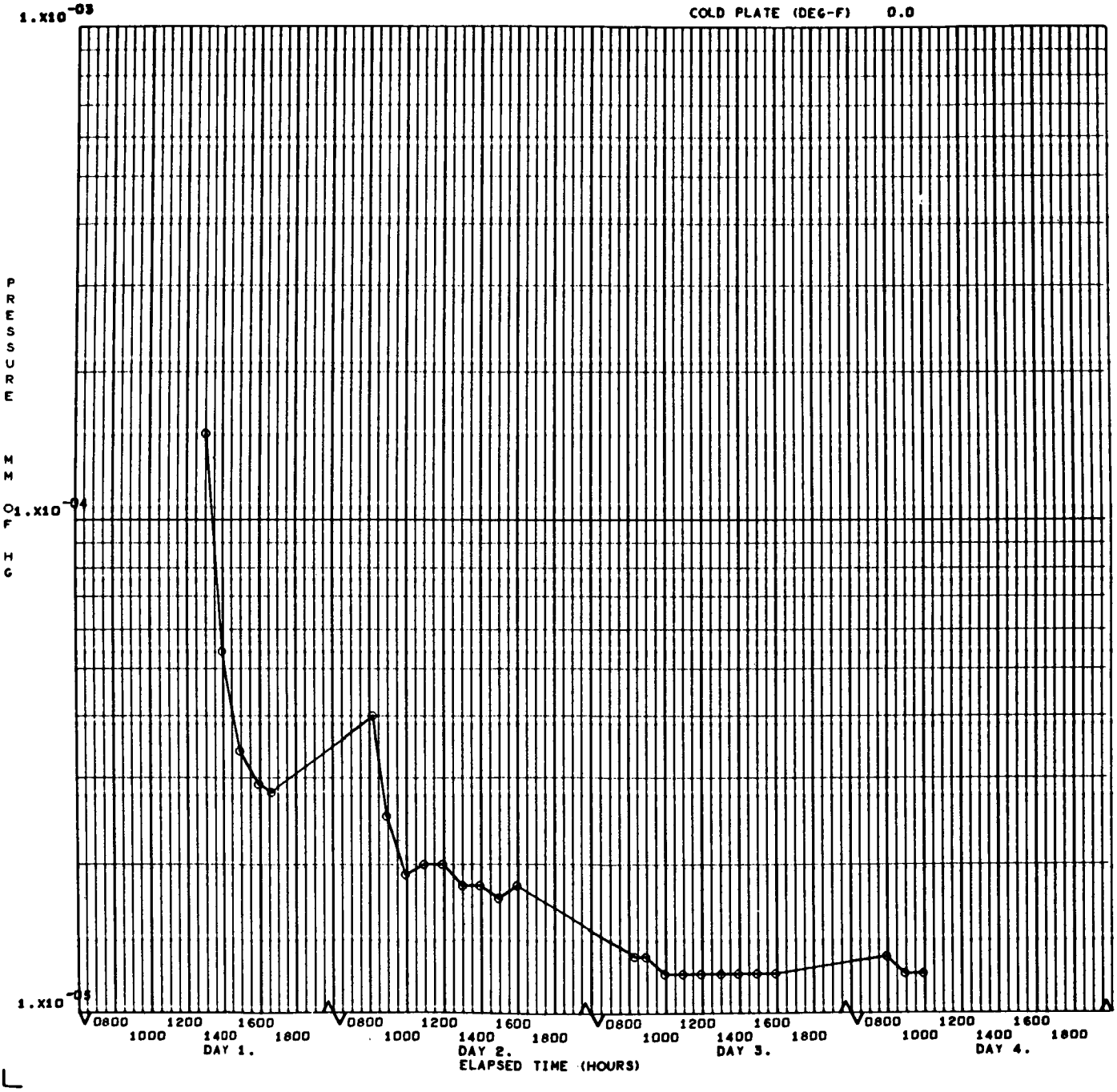


FIGURE 13.C

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 5.2
SAMPLE THICKNESS (IN.) 0.3125
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 208.5
COLD PLATE (DEG-F) 0.0

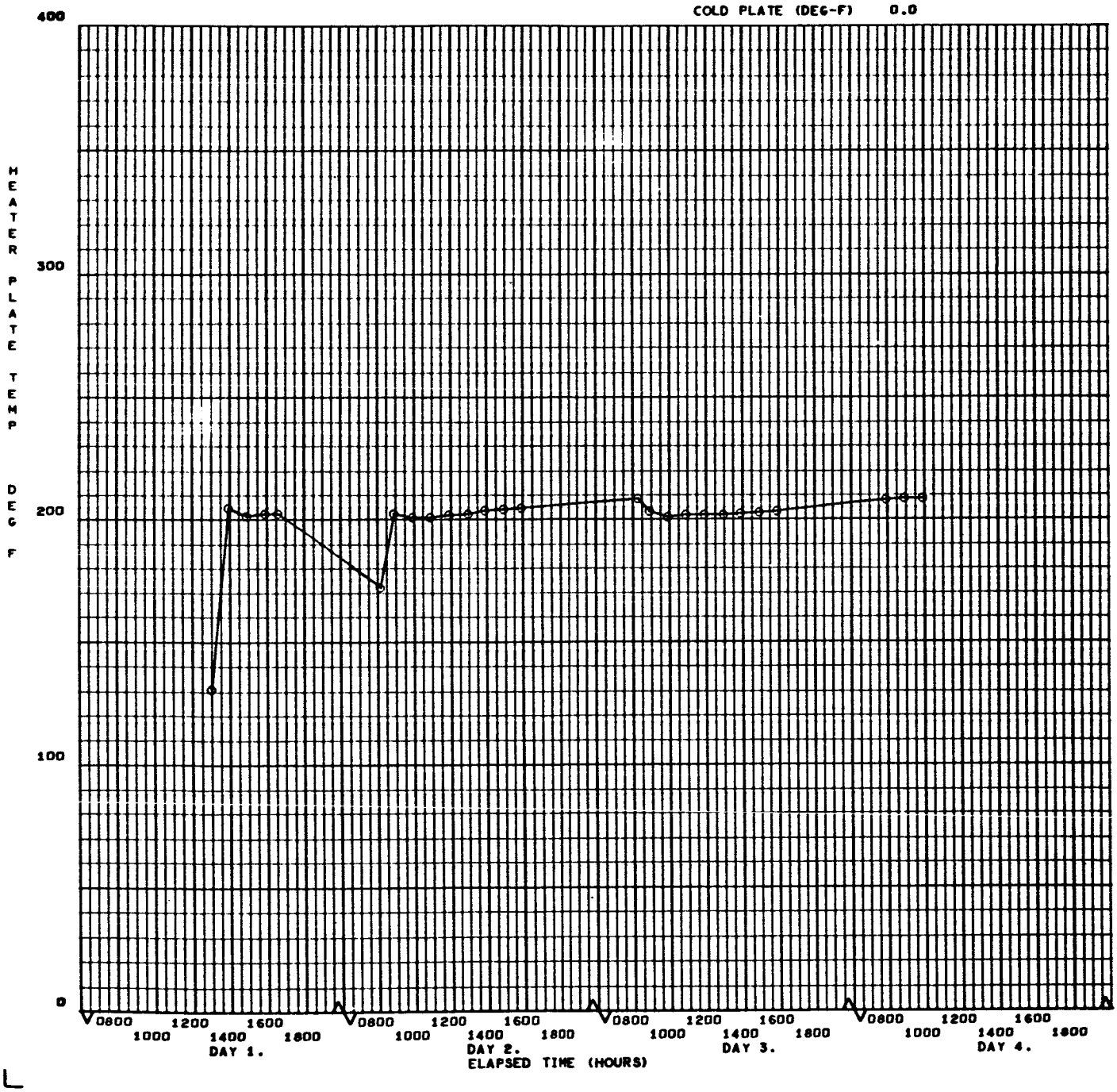


FIGURE 13.D

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 5.2
SAMPLE THICKNESS (IN.) 0.3125
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 208.5
COLD PLATE (DEG-F) 0.0

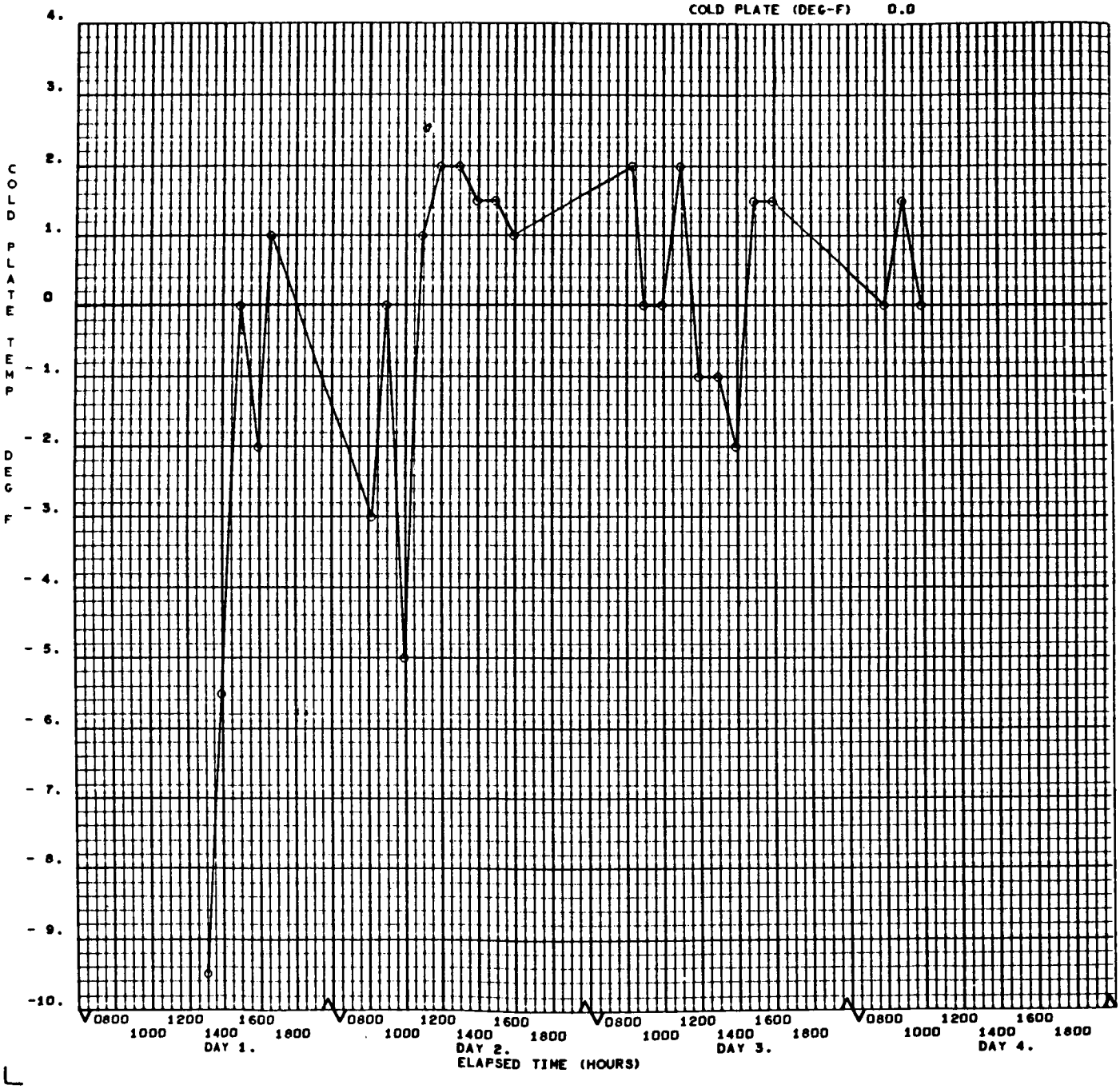


FIGURE 13.E

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 5.2
SAMPLE THICKNESS (IN.) 0.3125
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 208.5
COLD PLATE (DEG-F) 0.0

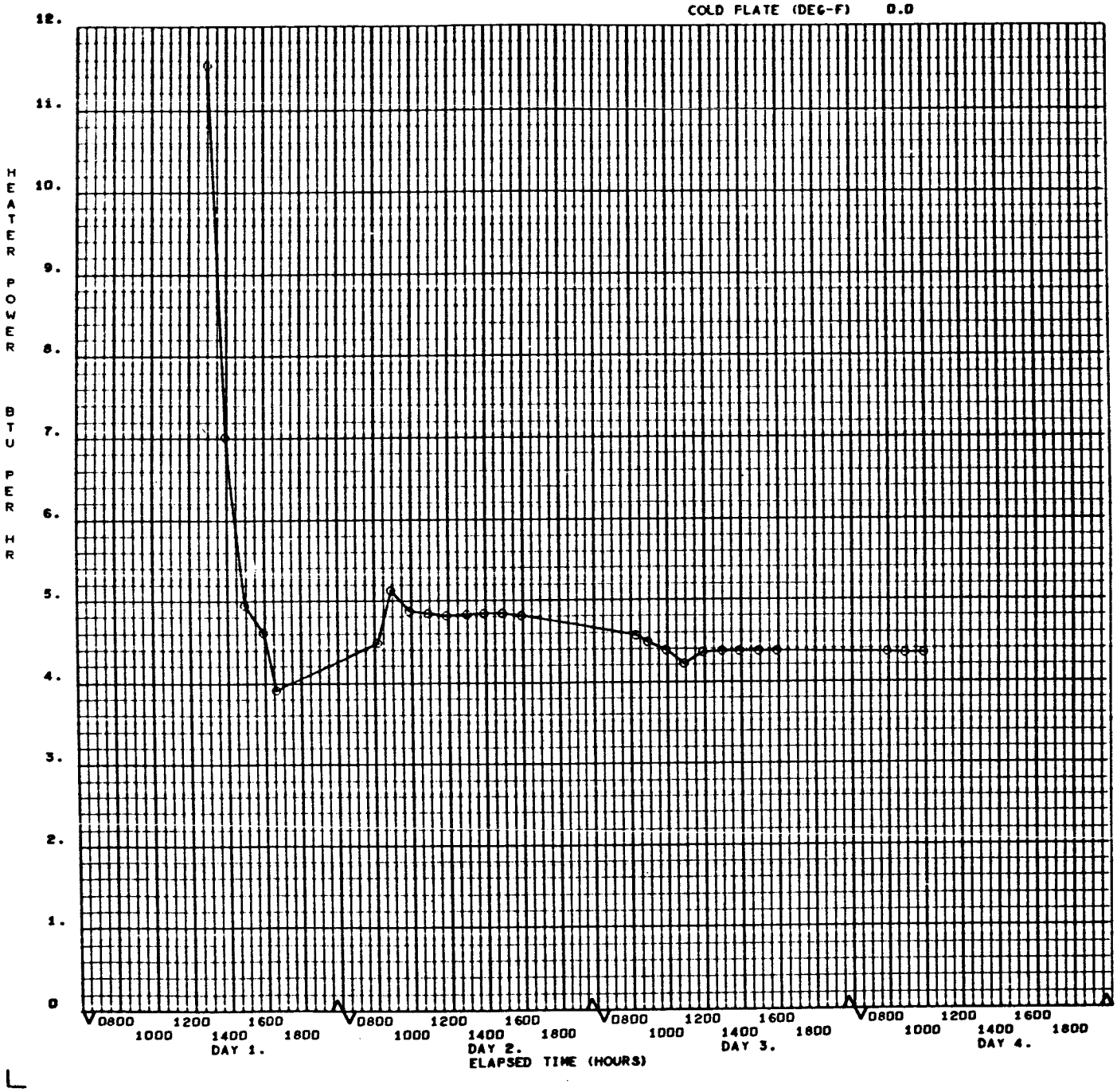


FIGURE 14.A

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 5.3
SAMPLE THICKNESS (IN.) 0.3125
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 301.5
COLD PLATE (DEG-F) 69.0

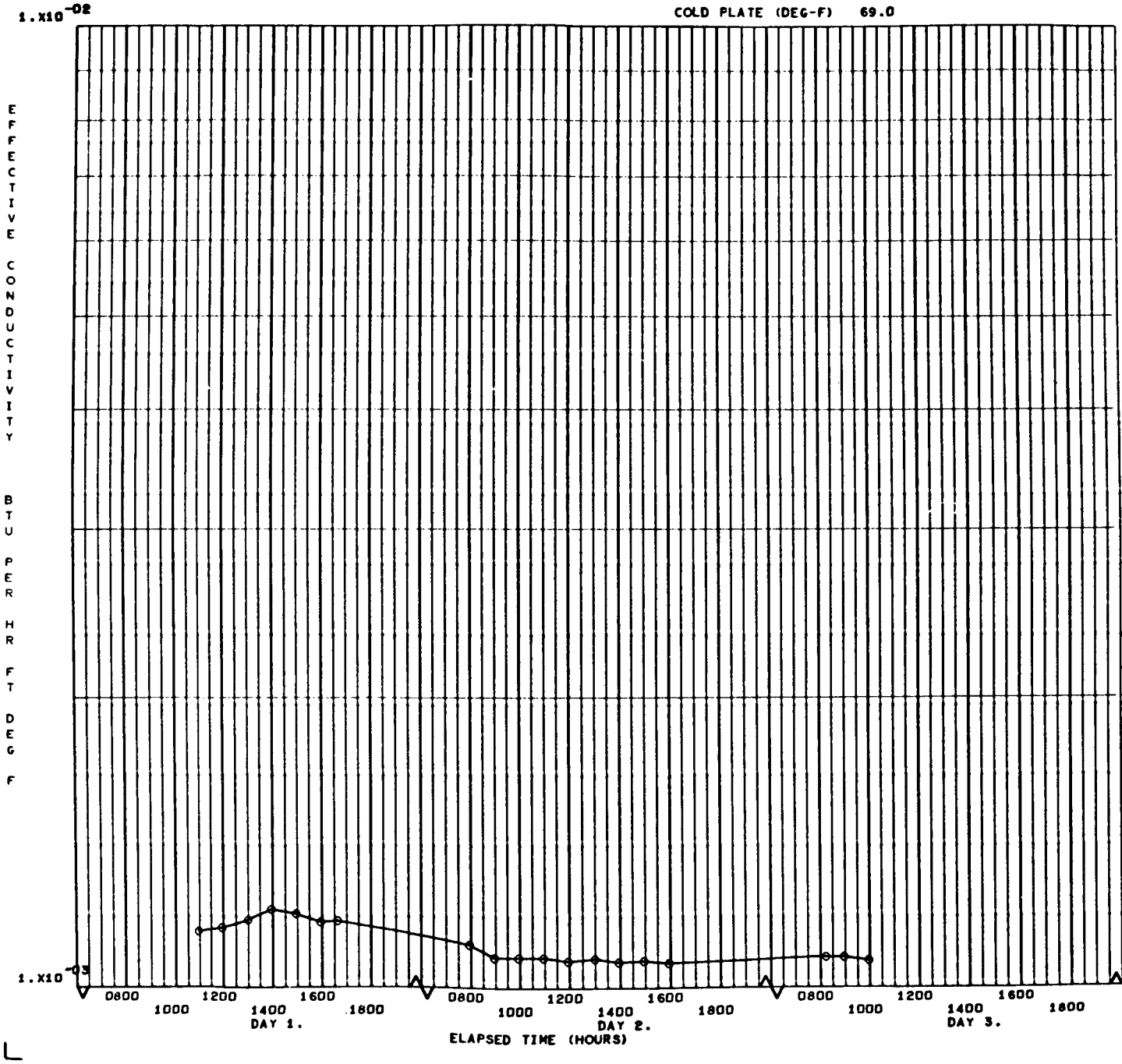


FIGURE 14.B

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 5.3
SAMPLE THICKNESS (IN.) 0.3125
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 301.5
COLD PLATE (DEG-F) 69.0

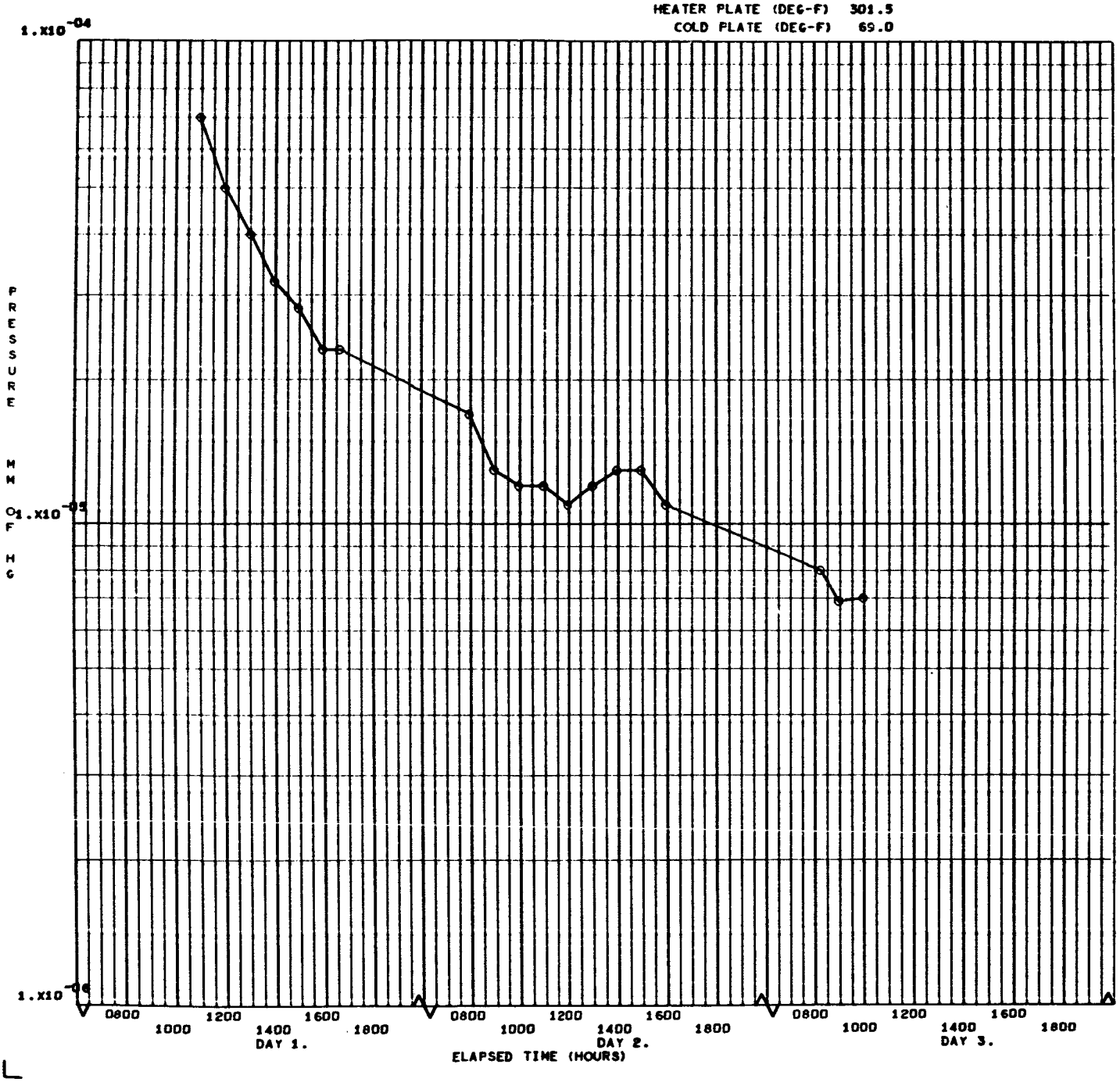


FIGURE 14.C

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 5.3
SAMPLE THICKNESS (IN.) 0.3125
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 301.5
COLD PLATE (DEG-F) 69.0

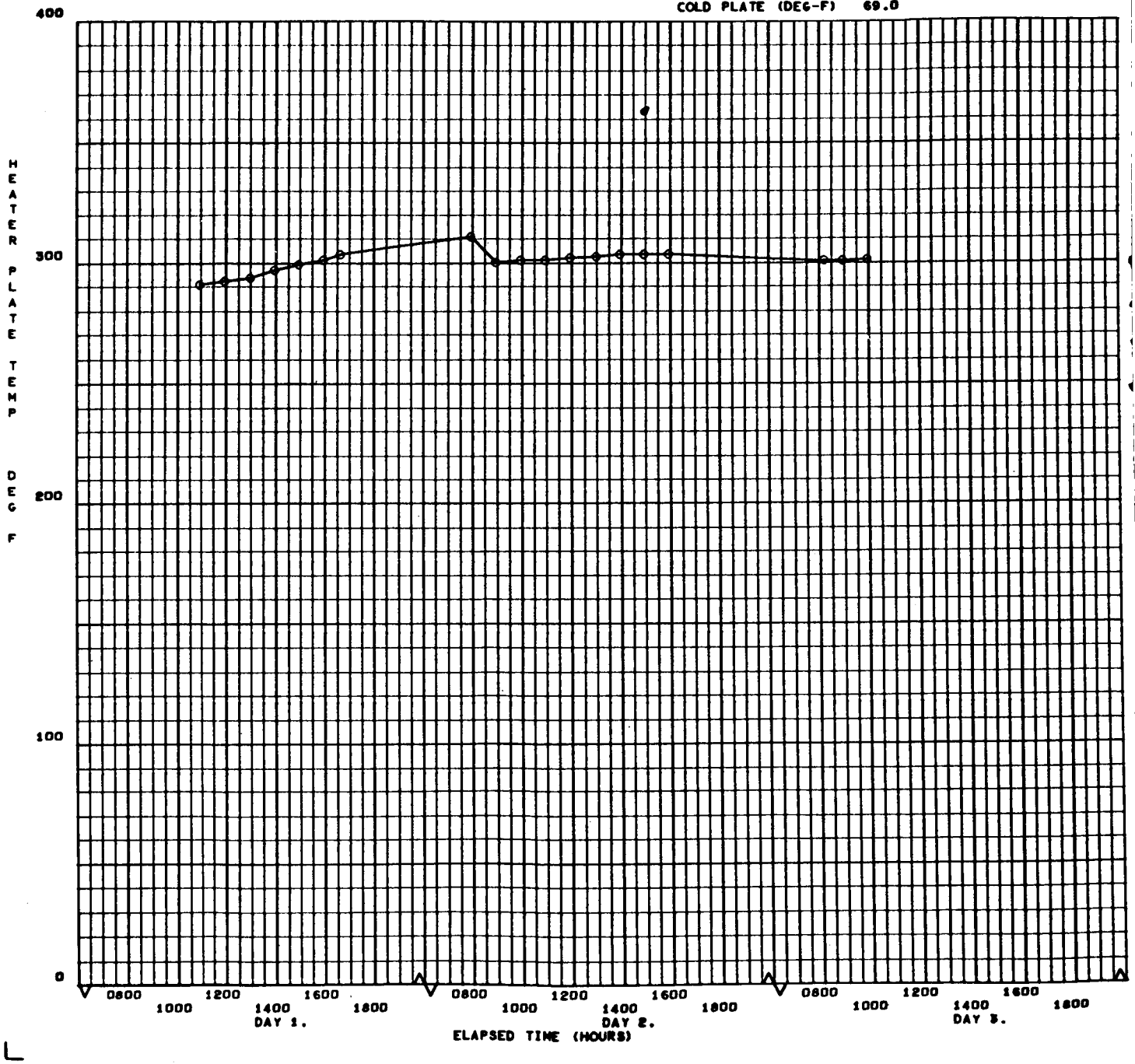


FIGURE 14.D

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 5.3
SAMPLE THICKNESS (IN.) 0.3125
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 301.5
COLD PLATE (DEG-F) 69.0

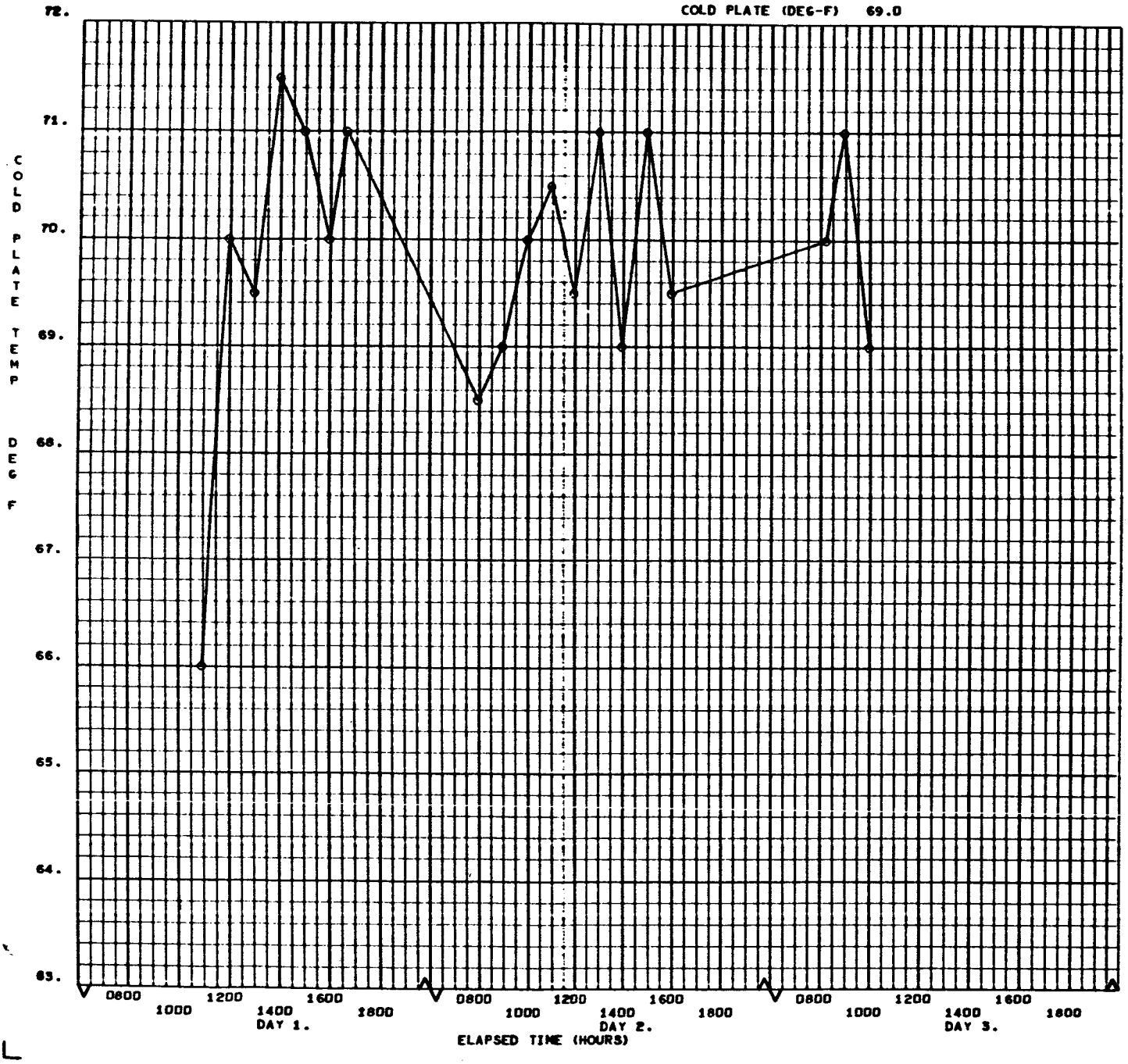


FIGURE 14.E

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 5.3
SAMPLE THICKNESS (IN.) 0.3125
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 301.5
COLD PLATE (DEG-F) 69.0

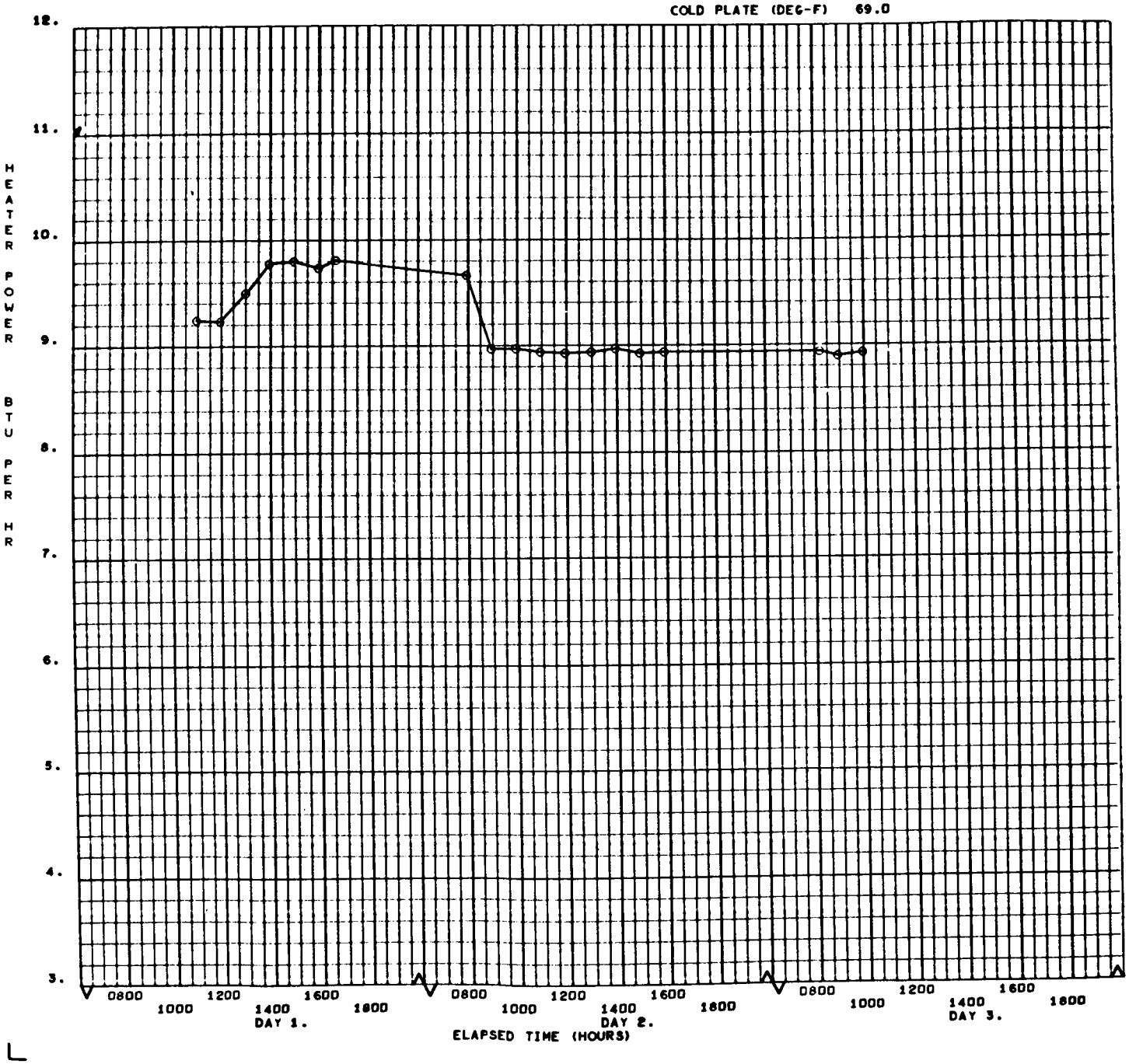


FIGURE 15.A

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 6.1
SAMPLE THICKNESS (IN.) 0.2500
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 202.0
COLD PLATE (DEG-F) 2.0

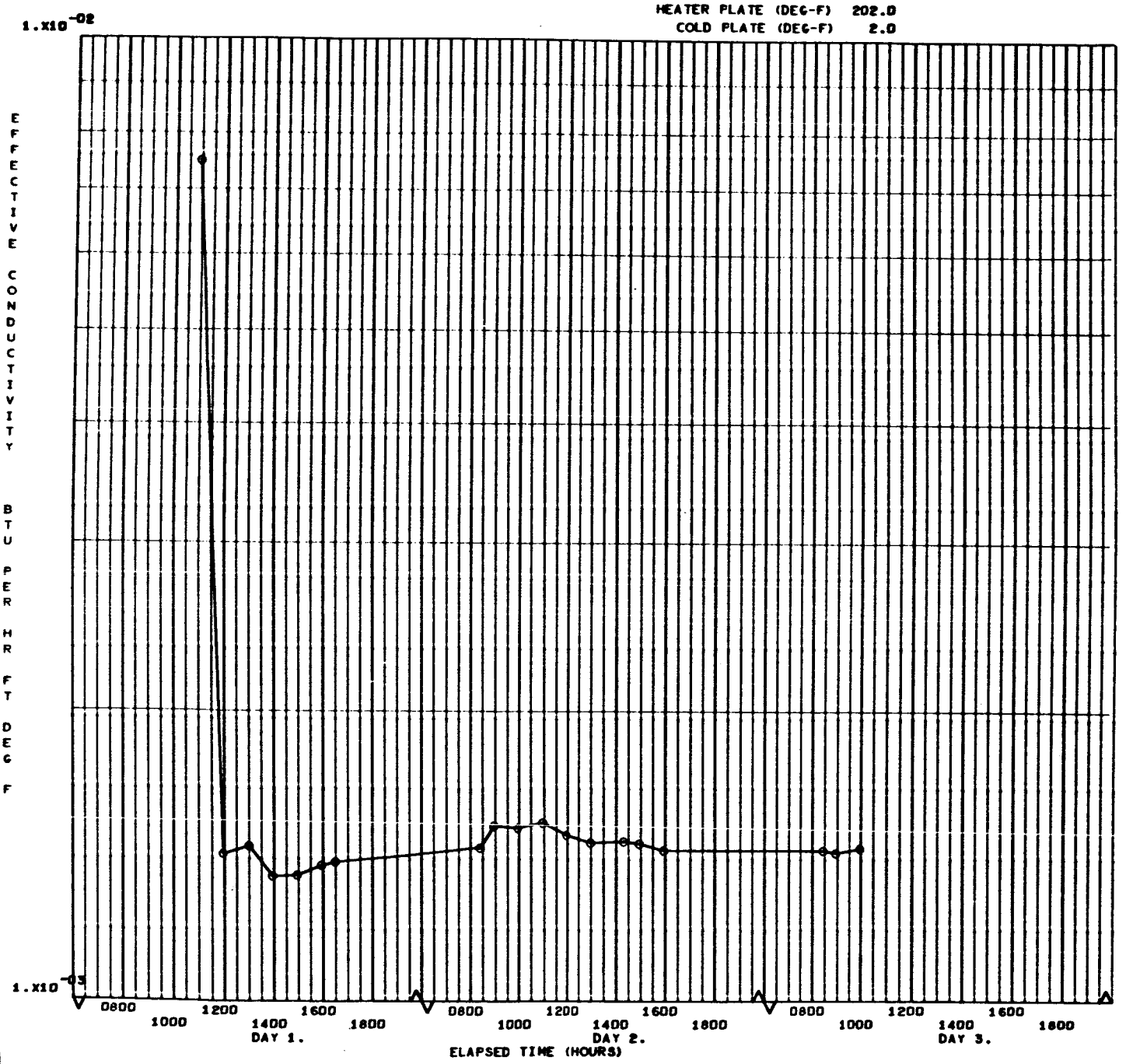


FIGURE 15.B

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 6.1
SAMPLE THICKNESS (IN.) 0.2500
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 202.0
COLD PLATE (DEG-F) 2.0

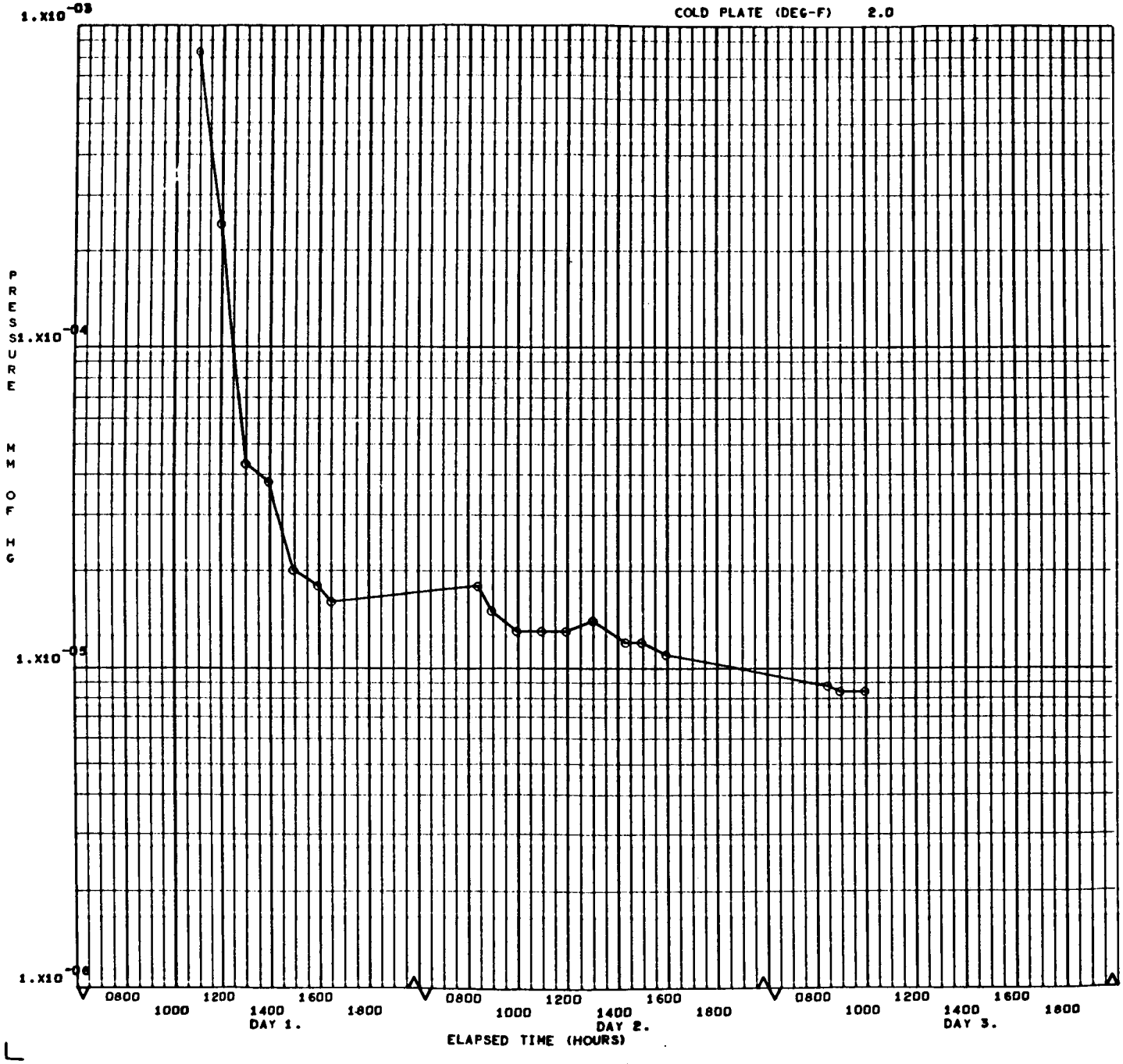


FIGURE 15.C

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 6.1
SAMPLE THICKNESS (IN.) 0.2500
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 202.0
COLD PLATE (DEG-F) 2.0

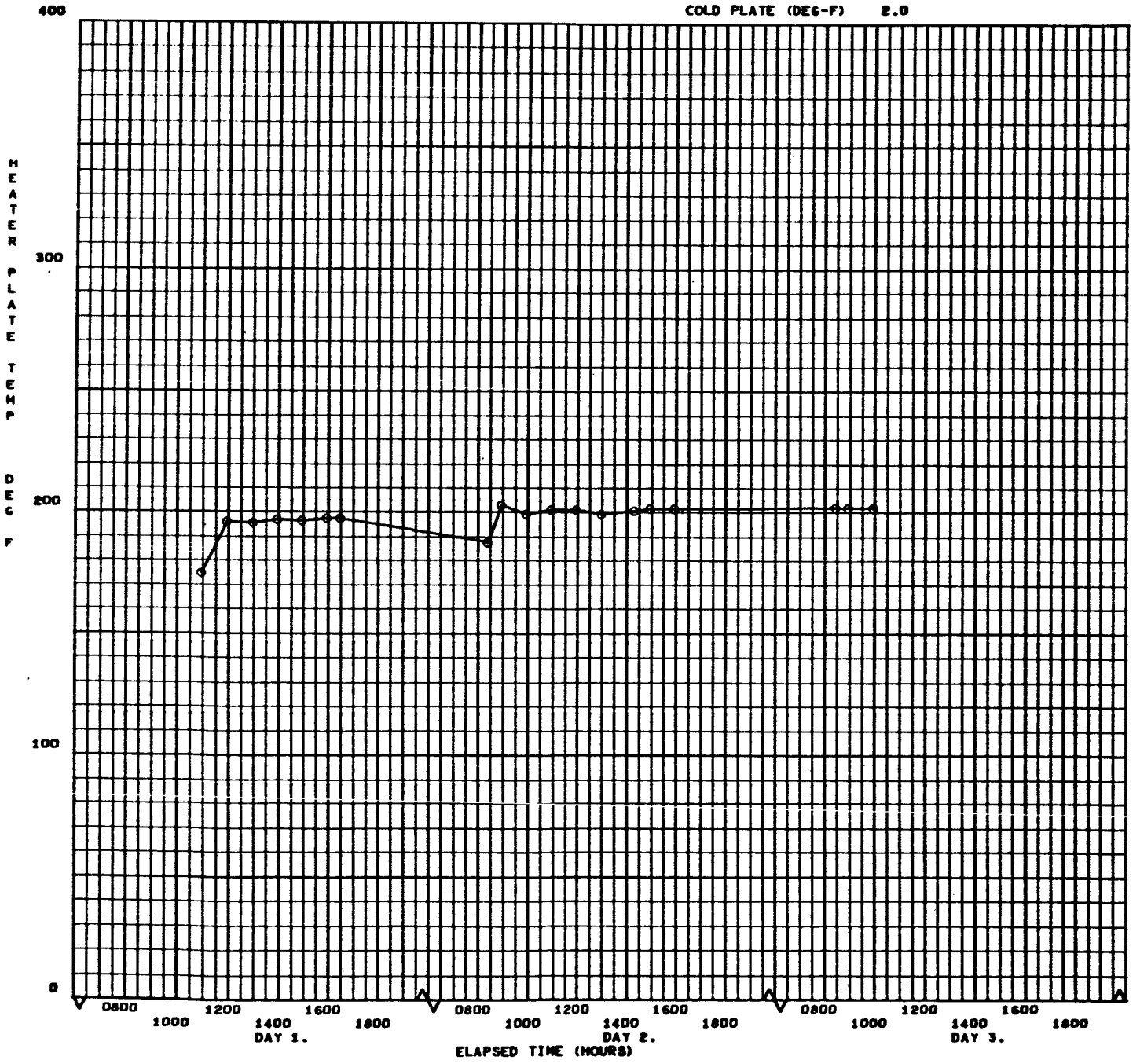


FIGURE 15.D

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 6.1
SAMPLE THICKNESS (IN.) 0.2500
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 202.0
COLD PLATE (DEG-F) 2.0

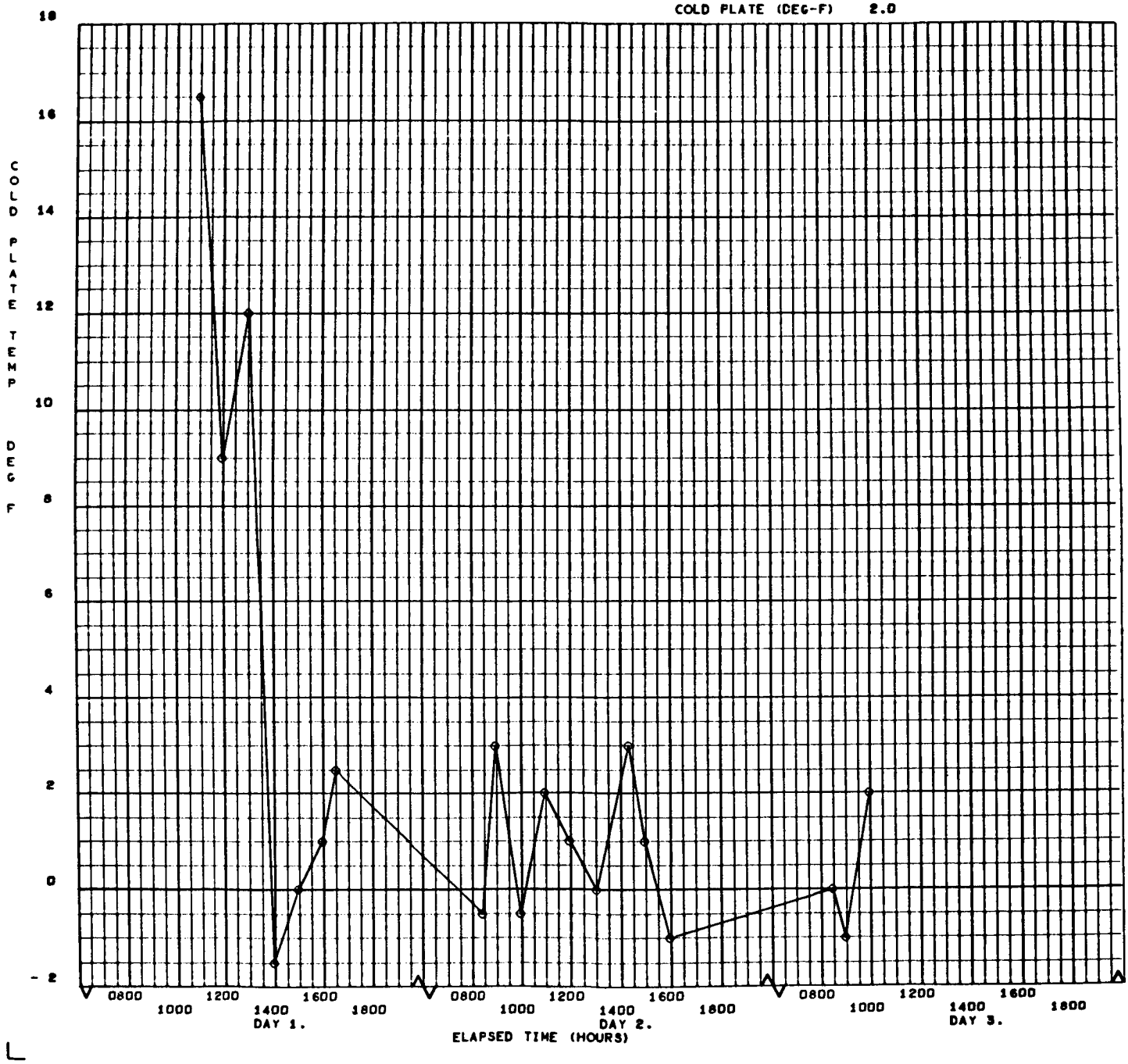


FIGURE 15.E

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 6.1
SAMPLE THICKNESS (IN.) 0.2500
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 202.0
COLD PLATE (DEG-F) 2.0

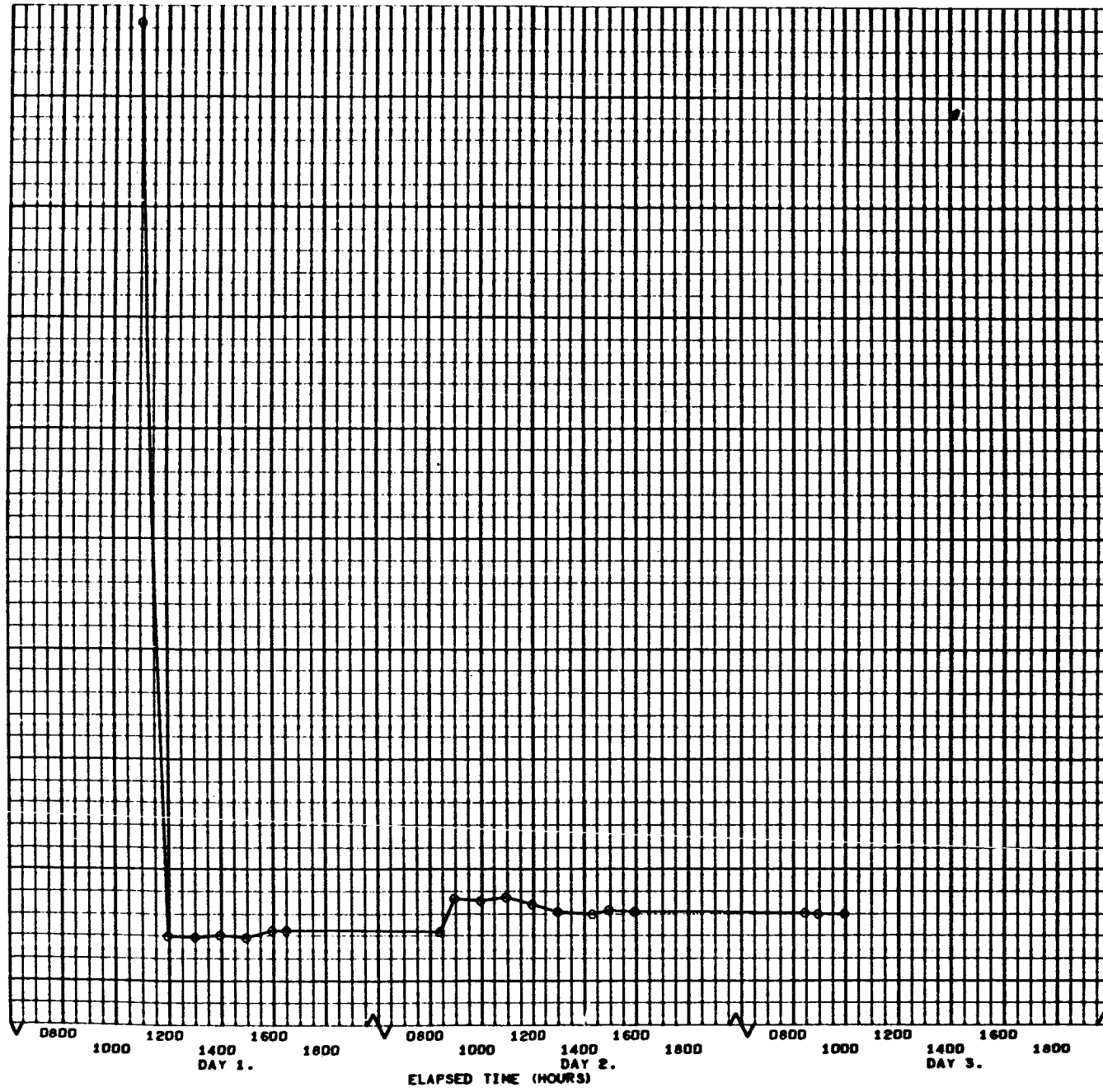


FIGURE 16.A

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 6.2
SAMPLE THICKNESS (IN.) 0.2500
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 300.0
COLD PLATE (DEG-F) 70.5

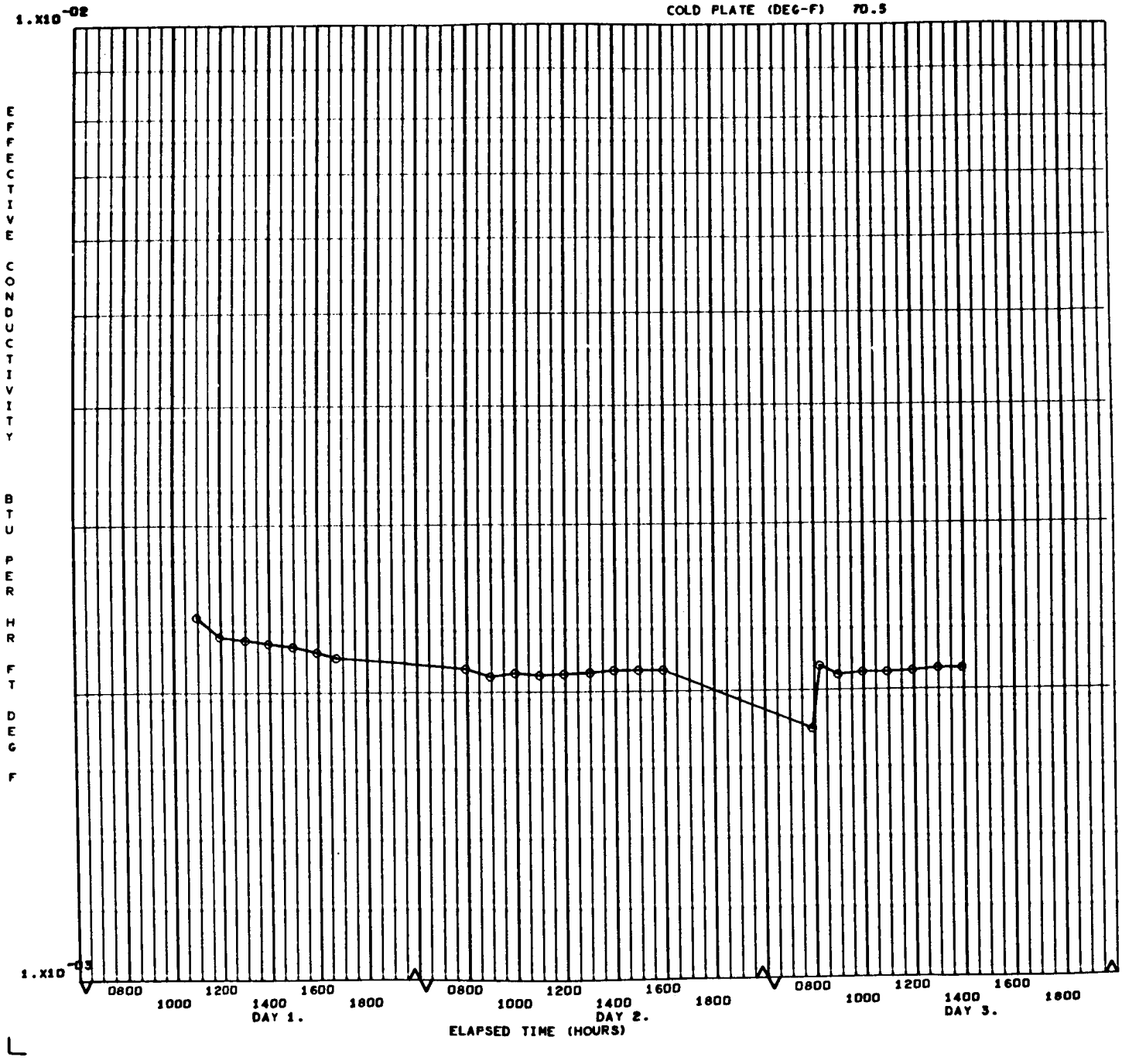


FIGURE 16.B

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 6.2
SAMPLE THICKNESS (IN.) 0.2500
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 300.0
COLD PLATE (DEG-F) 70.5

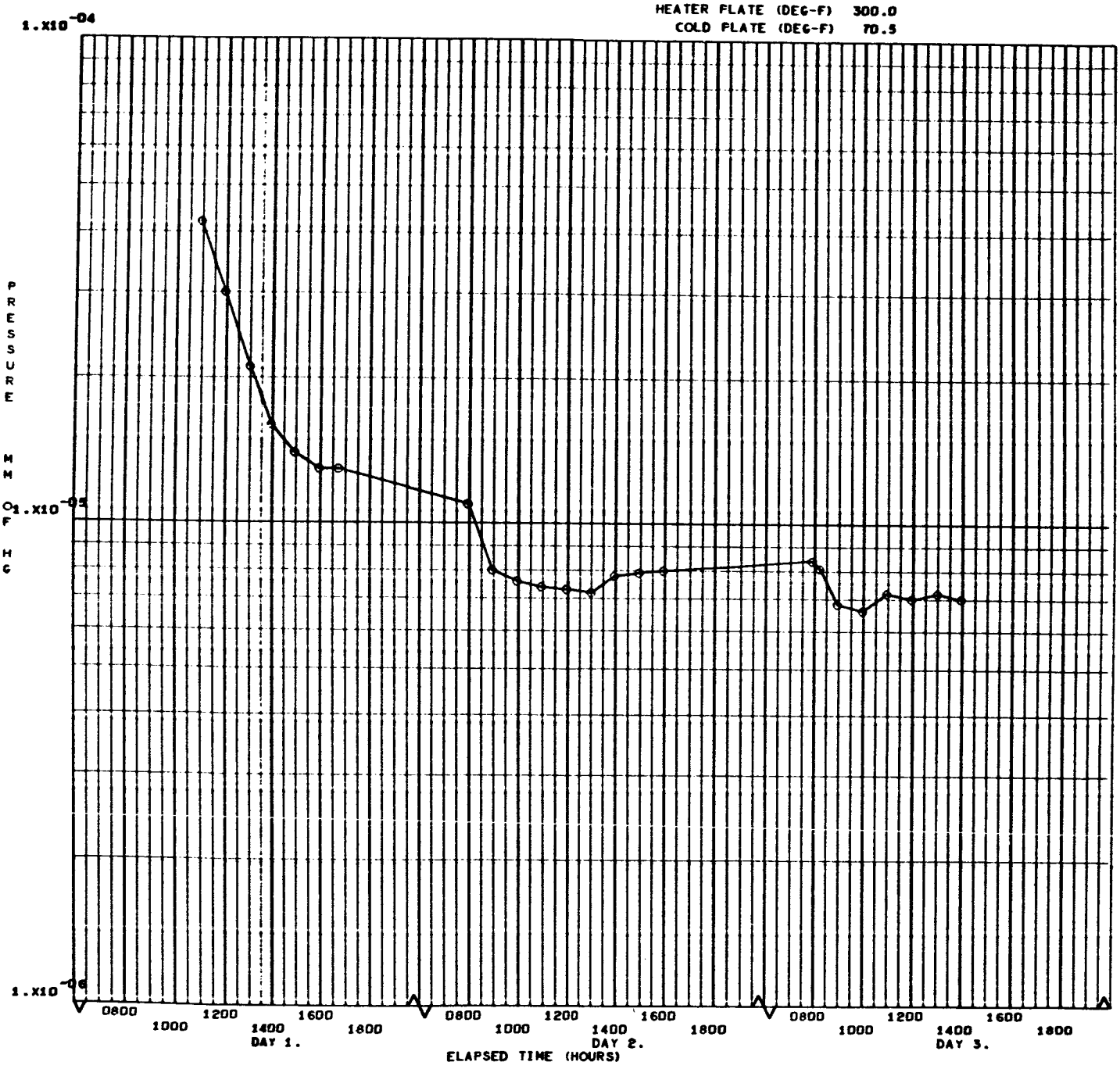


FIGURE 16.C

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 6.2
SAMPLE THICKNESS (IN.) 0.2500
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 300.0
COLD PLATE (DEG-F) 70.5

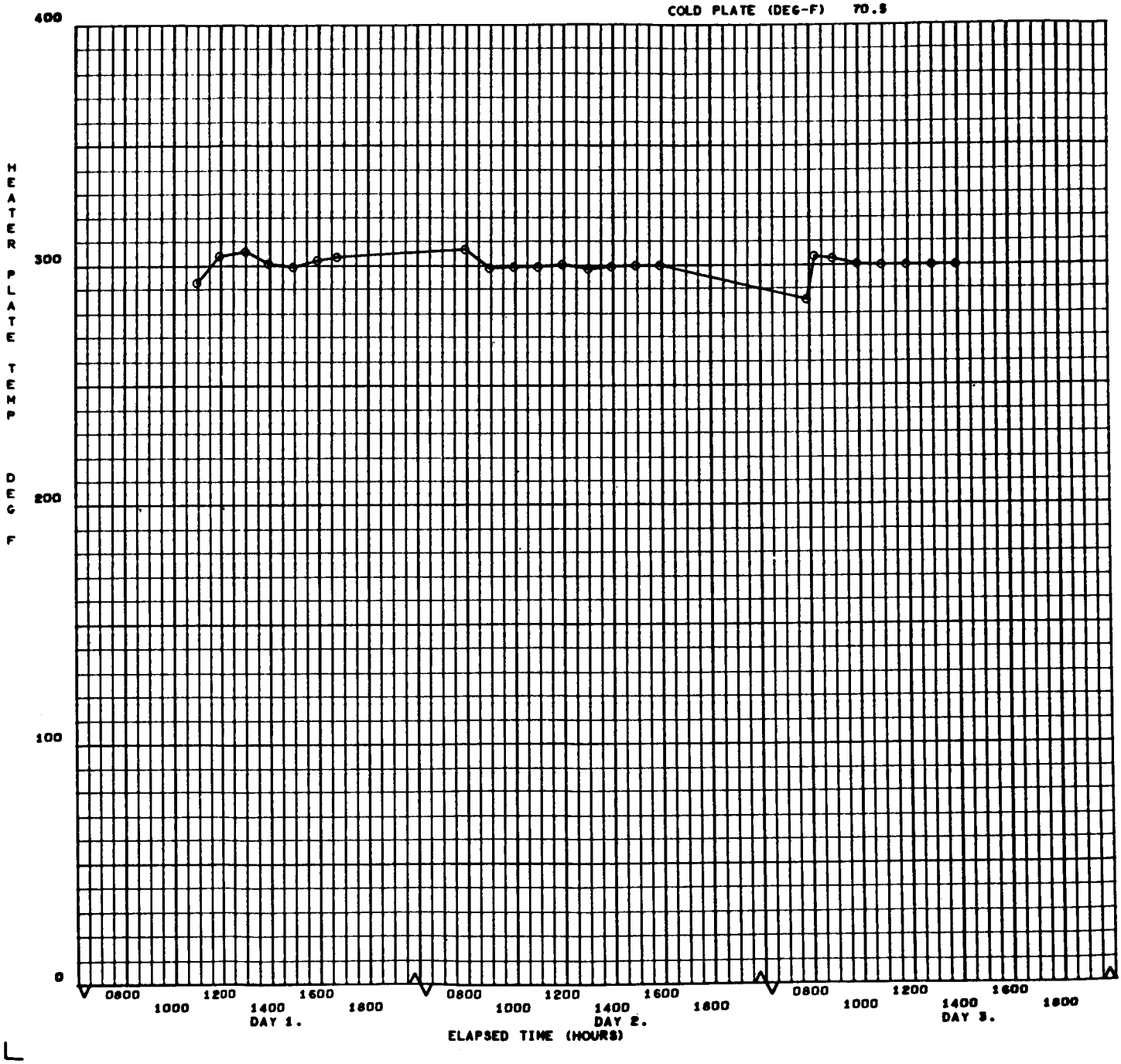


FIGURE 16.D

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 6.2
SAMPLE THICKNESS (IN.) 0.2500
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 300.0
COLD PLATE (DEG-F) 70.5

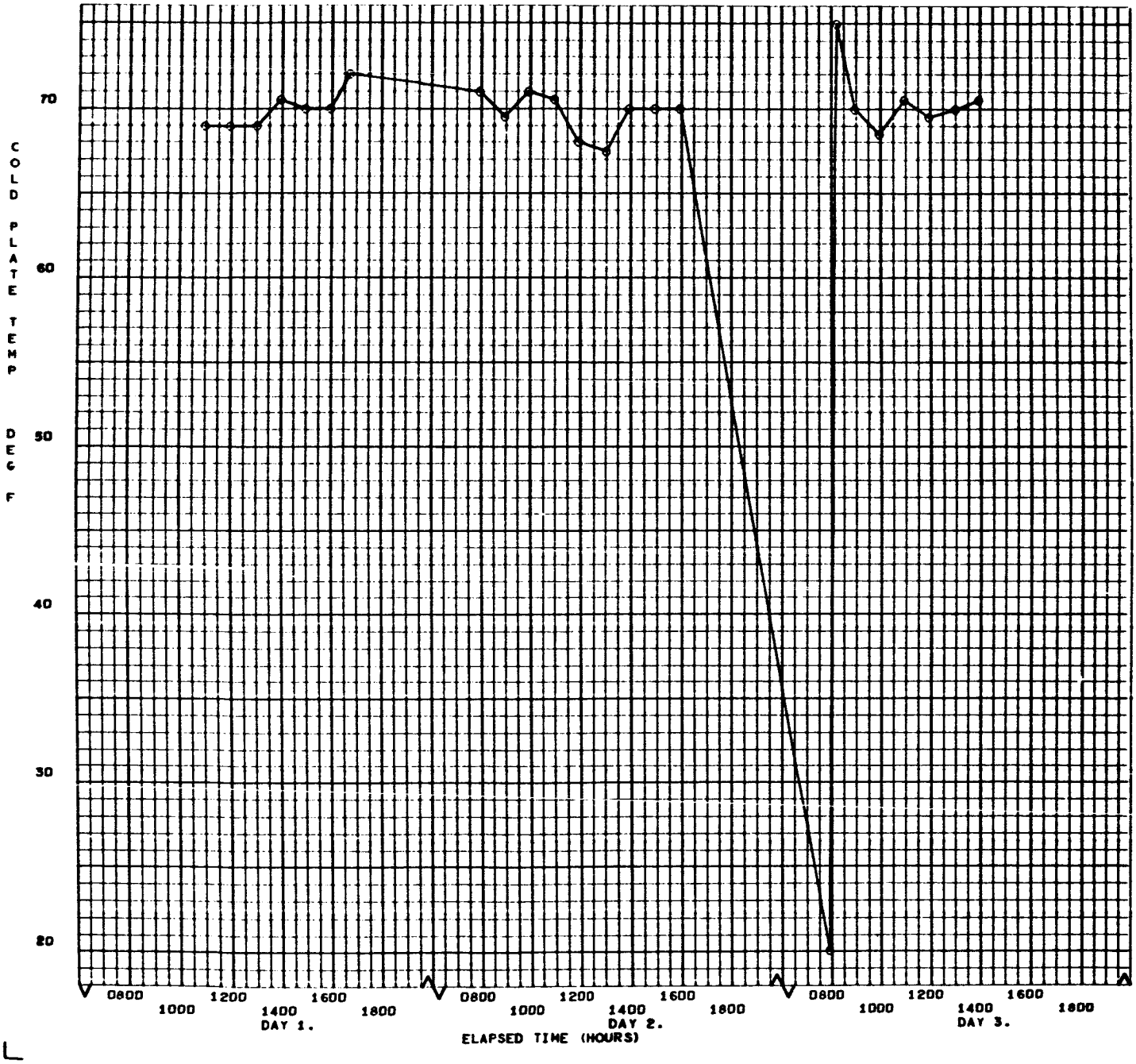


FIGURE 16.E

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 6.2
SAMPLE THICKNESS (IN.) 0.2500
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 300.0
COLD PLATE (DEG-F) 70.5

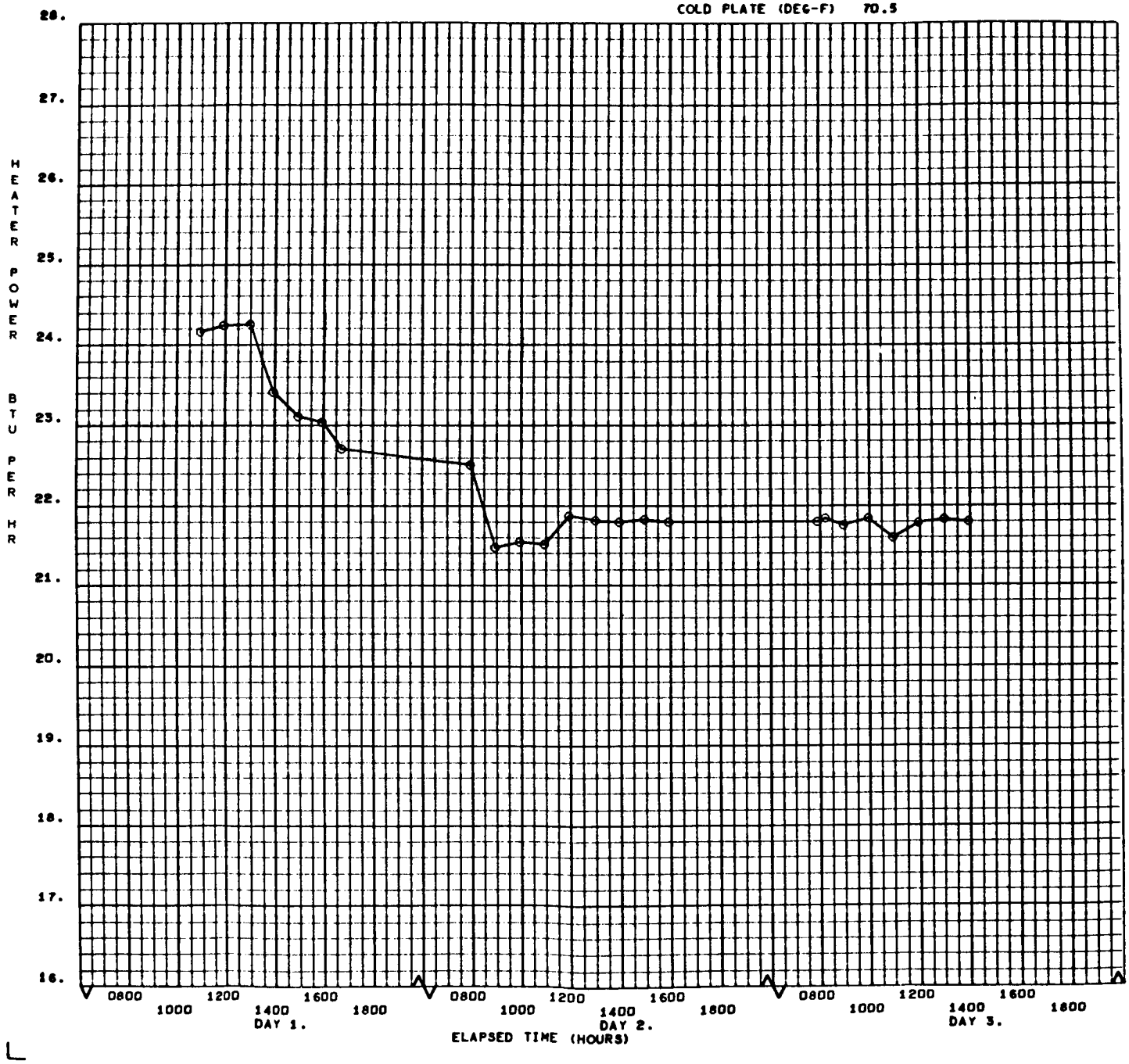


FIGURE 17.A

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 6.3
SAMPLE THICKNESS (IN.) 0.2500
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 75.0
COLD PLATE (DEG-F)- 310.0

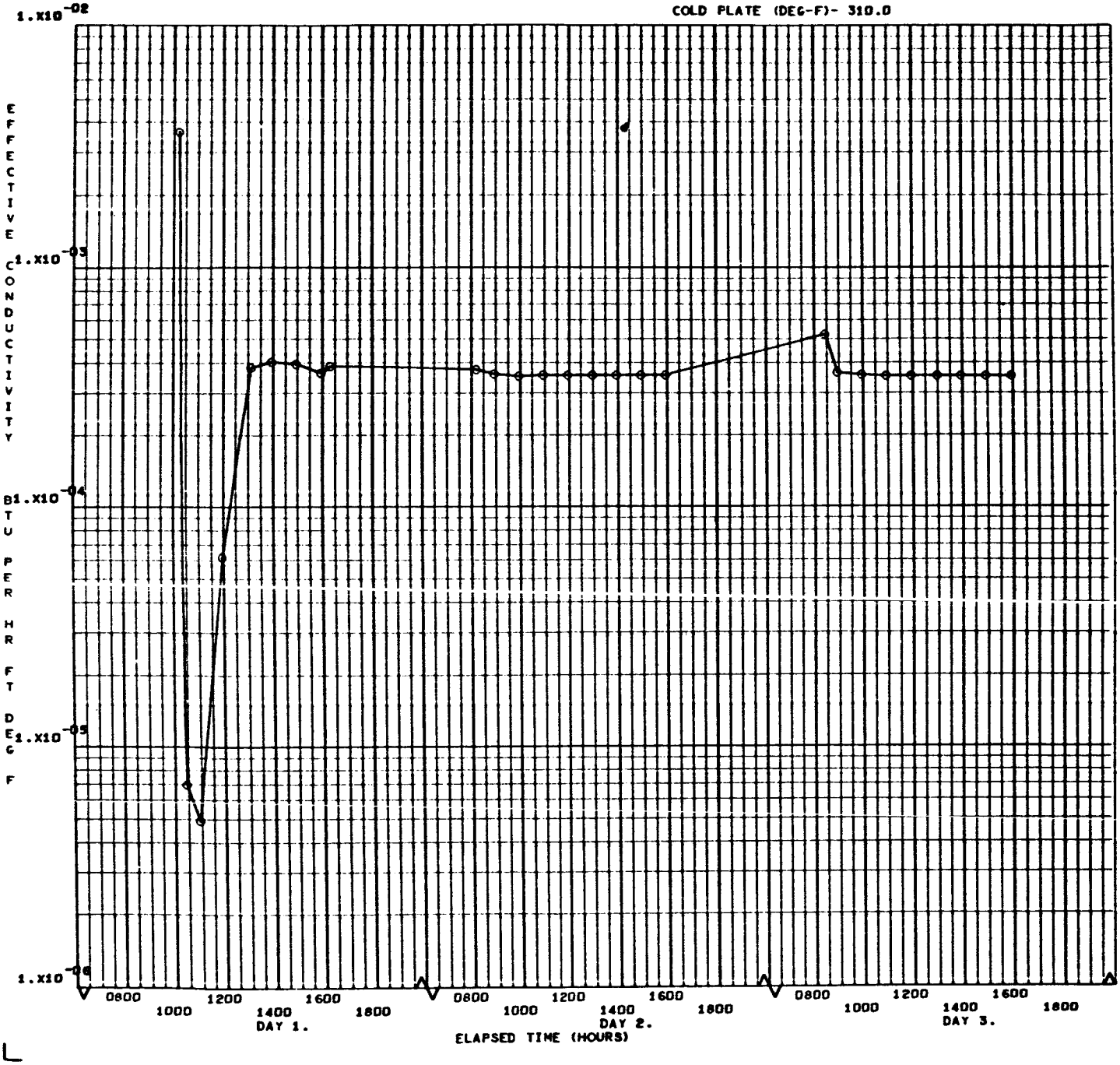


FIGURE 17.B

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 6.3
SAMPLE THICKNESS (IN.) 0.2500
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 75.0
COLD PLATE (DEG-F)- 310.0

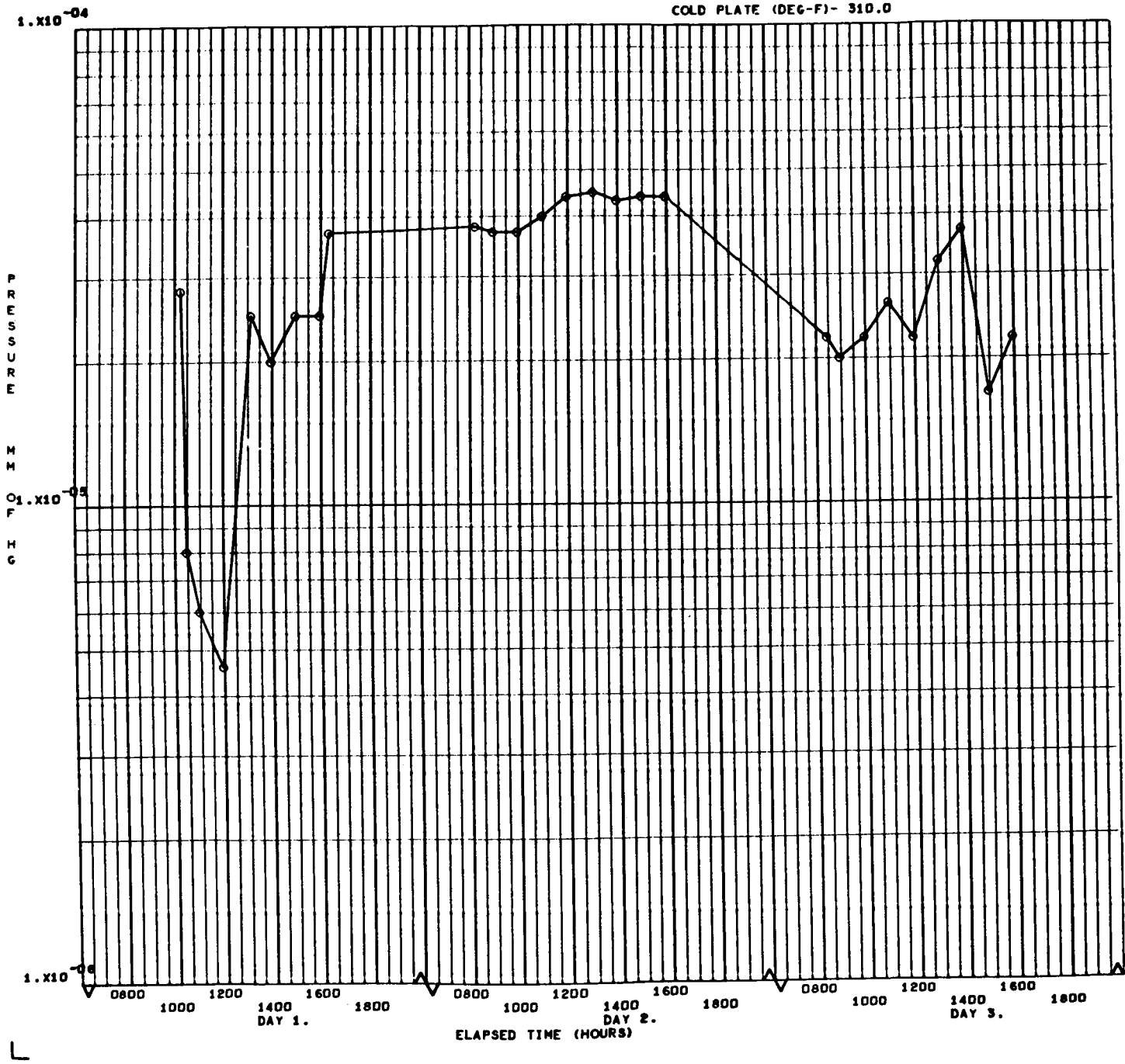


FIGURE 17.C

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 6.3
SAMPLE THICKNESS (IN.) 0.2500
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 75.0
COLD PLATE (DEG-F)- 310.0

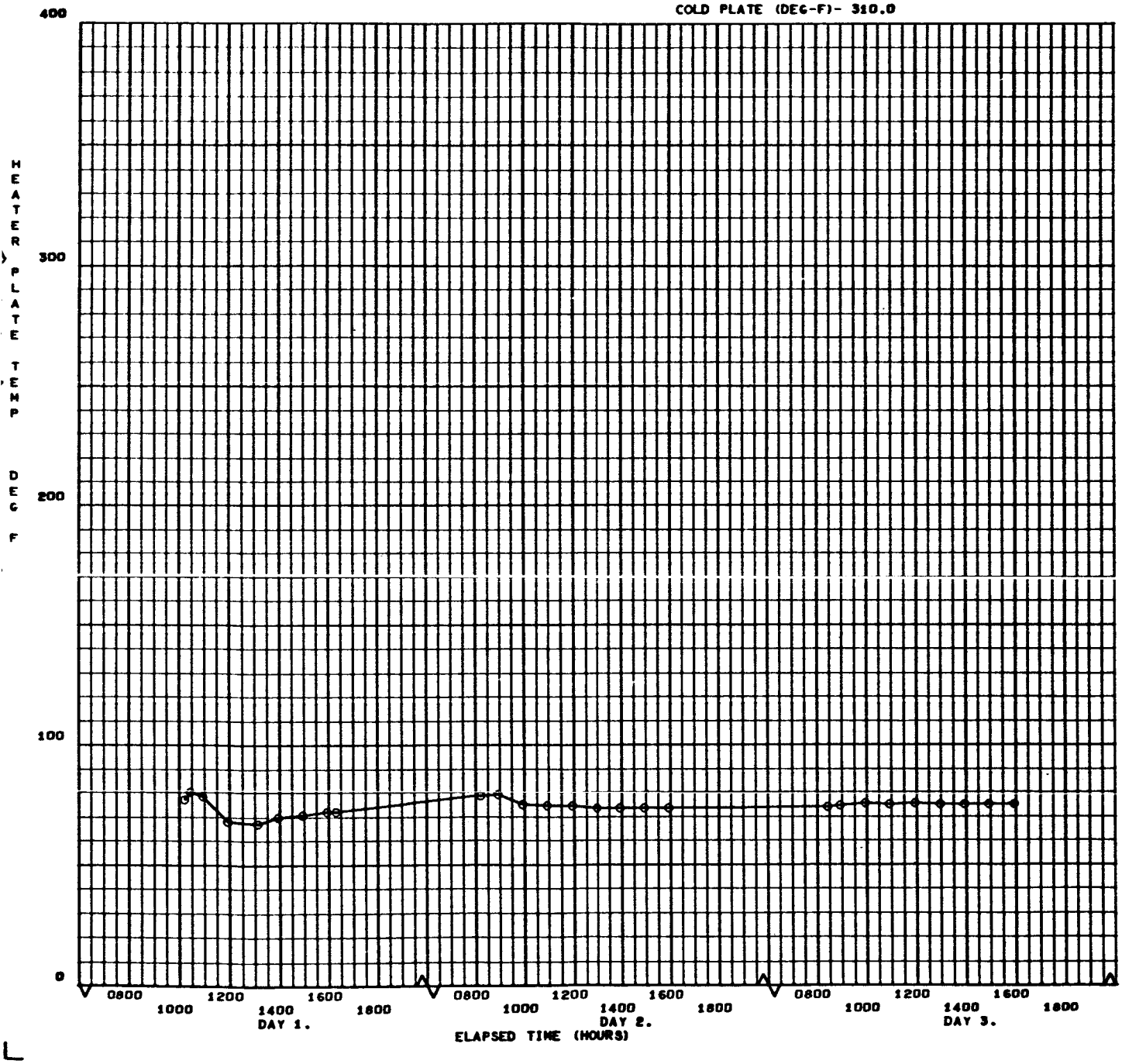


FIGURE 17.D

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 6.3
SAMPLE THICKNESS (IN.) 0.2500
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 75.0
COLD PLATE (DEG-F)- 310.0

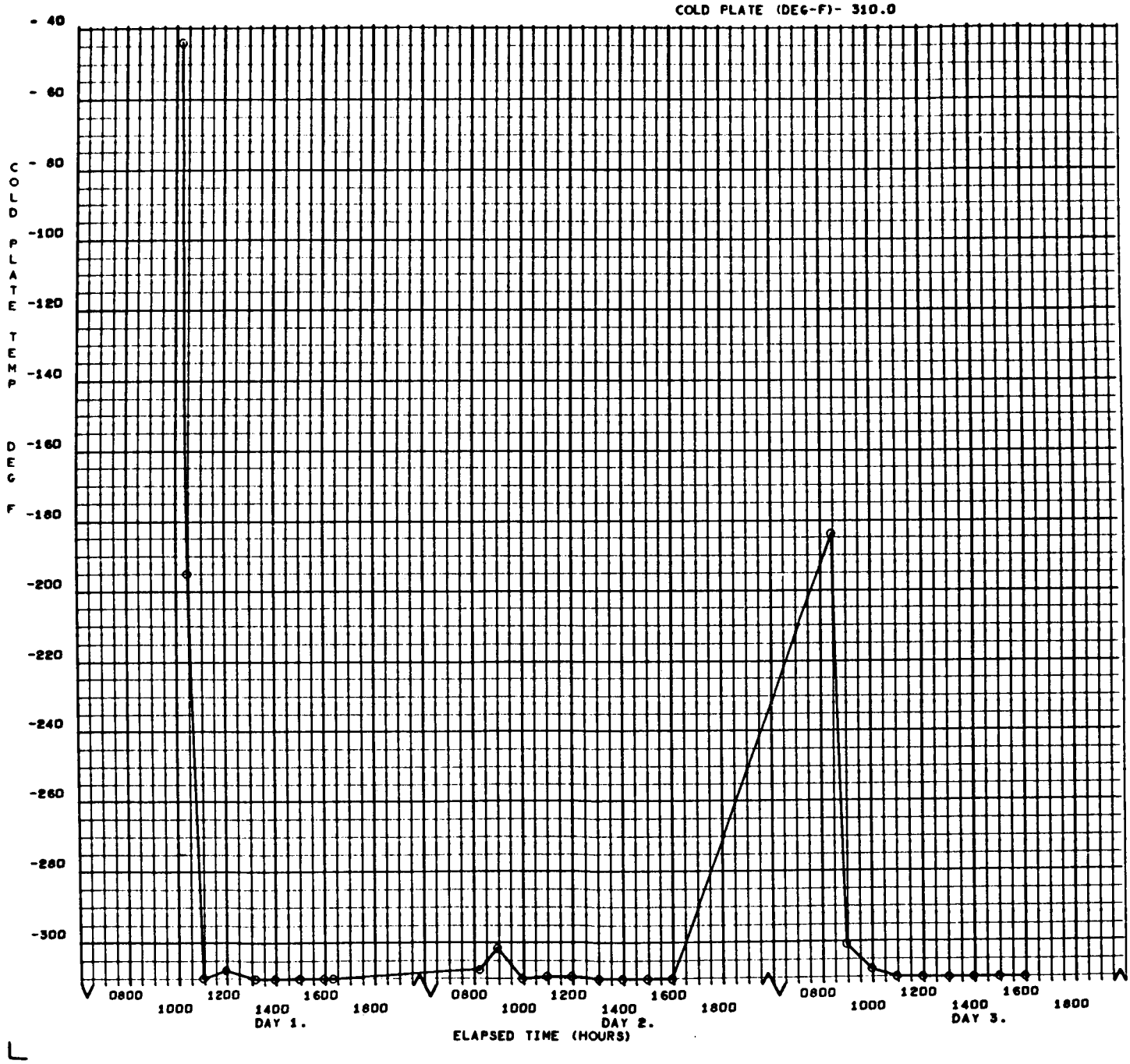


FIGURE 17.E

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 6.3
SAMPLE THICKNESS (IN.) 0.2500
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 75.0
COLD PLATE (DEG-F)- 310.0

FIGURE 18.A

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 7.1
SAMPLE THICKNESS (IN.) 0.1875
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 71.0
COLD PLATE (DEG-F)- 309.5

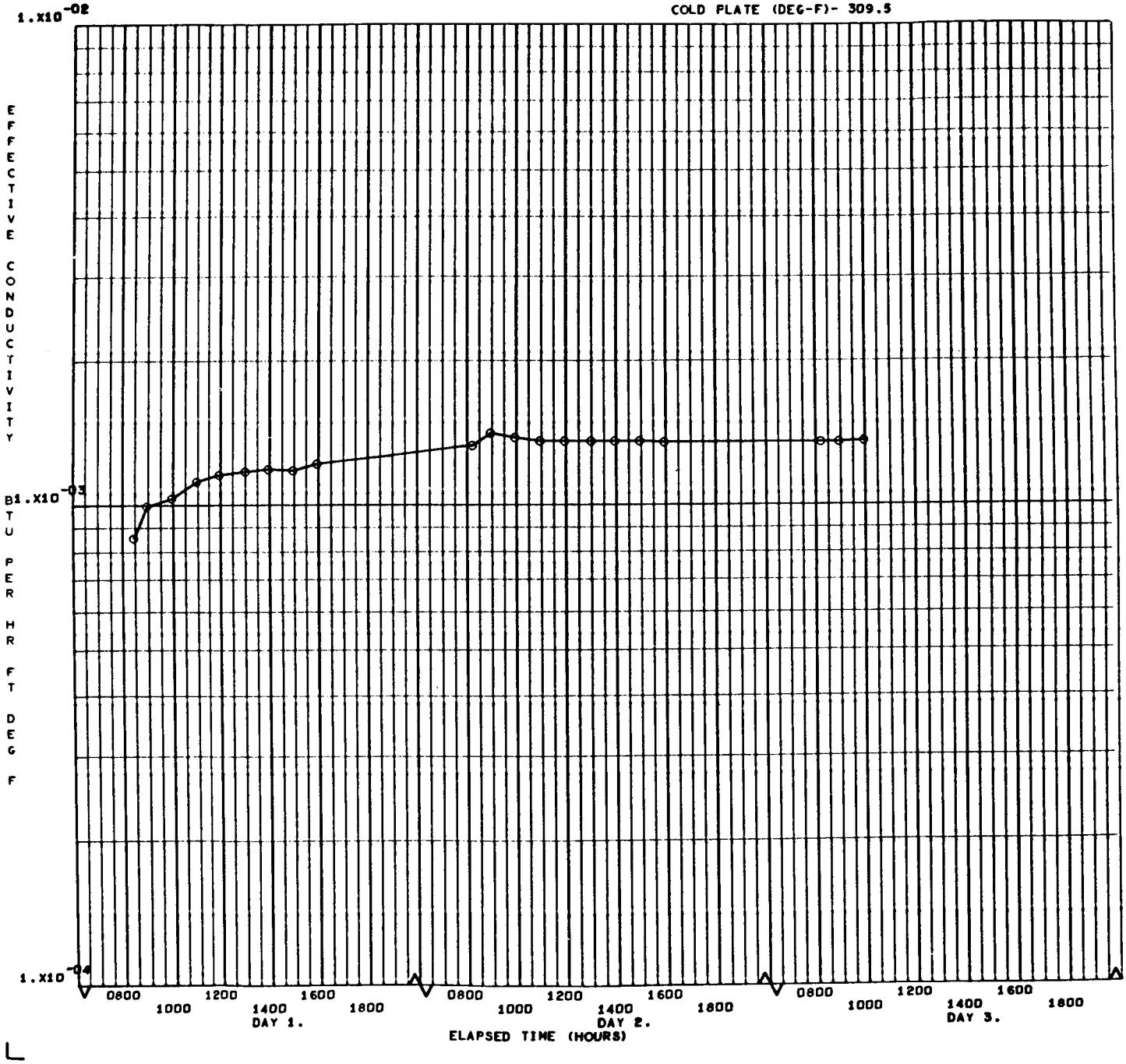


FIGURE 18.B

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 7.1
SAMPLE THICKNESS (IN.) 0.1875
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 71.0
COLD PLATE (DEG-F)- 309.5

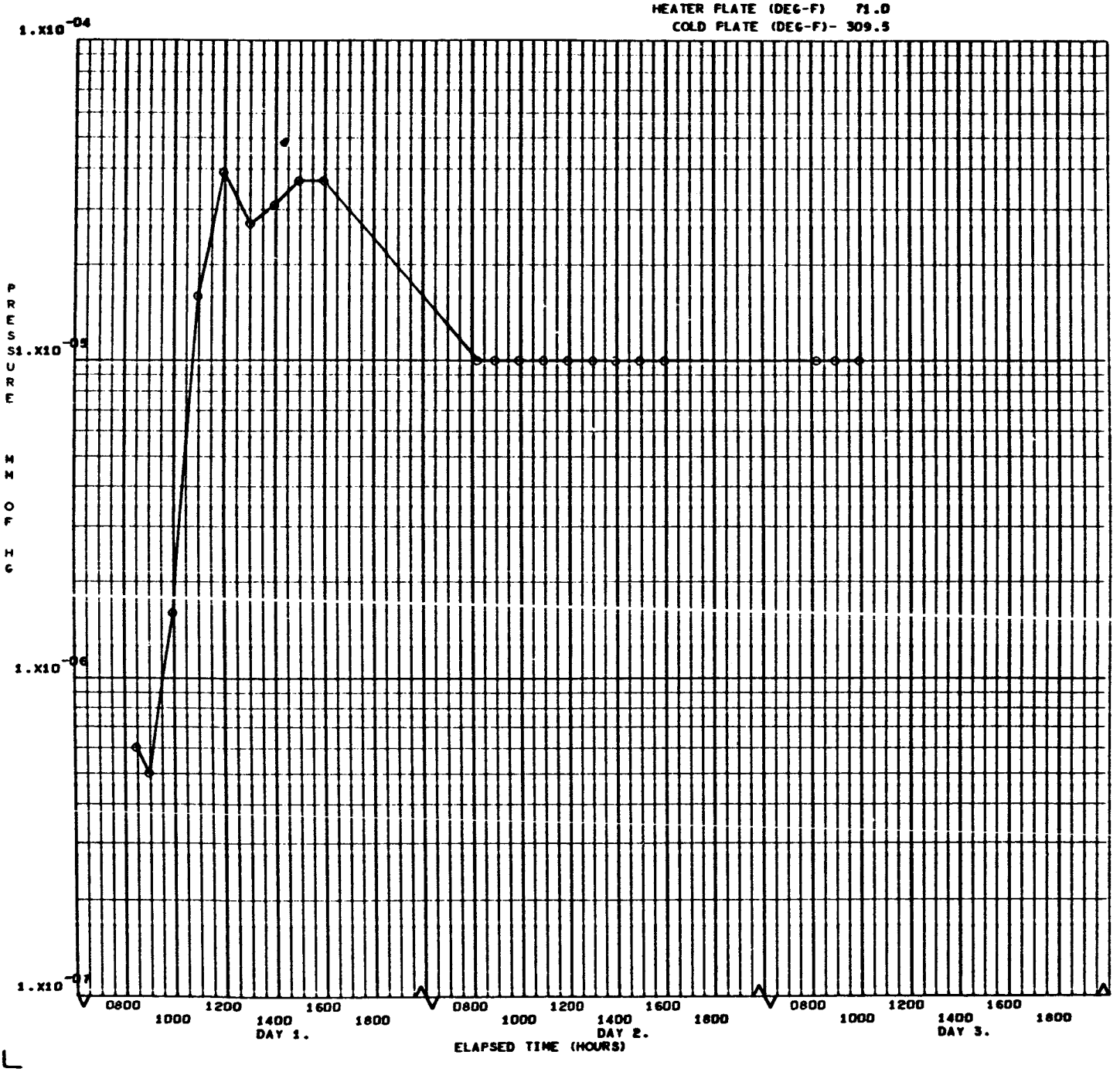


FIGURE 10.C

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 7.1
SAMPLE THICKNESS (IN.) 0.1875
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 71.0
COLD PLATE (DEG-F)- 309.5

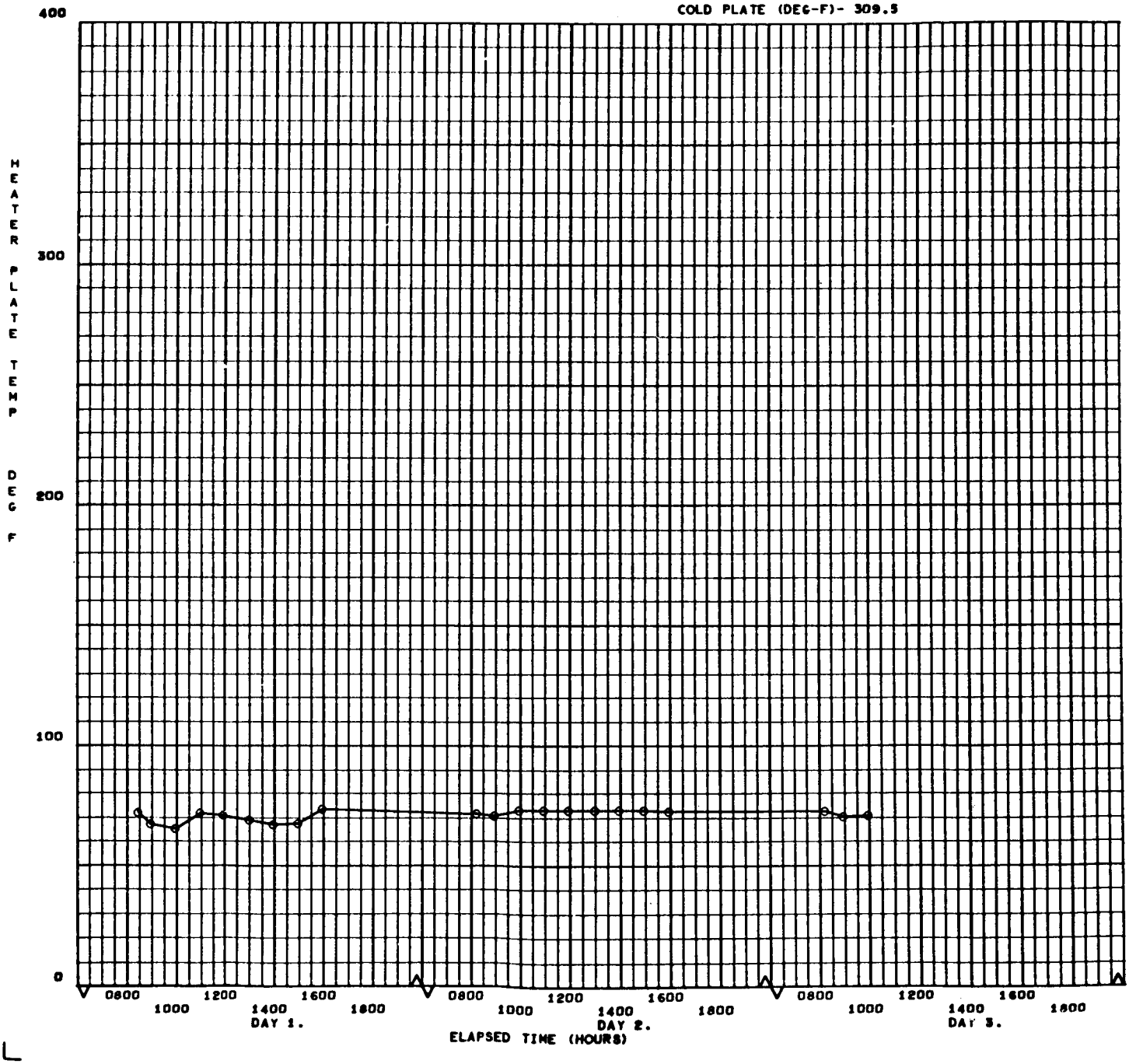


FIGURE 18.D

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 7.1
SAMPLE THICKNESS (IN.) 0.1875
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 71.0
COLD PLATE (DEG-F)- 309.5

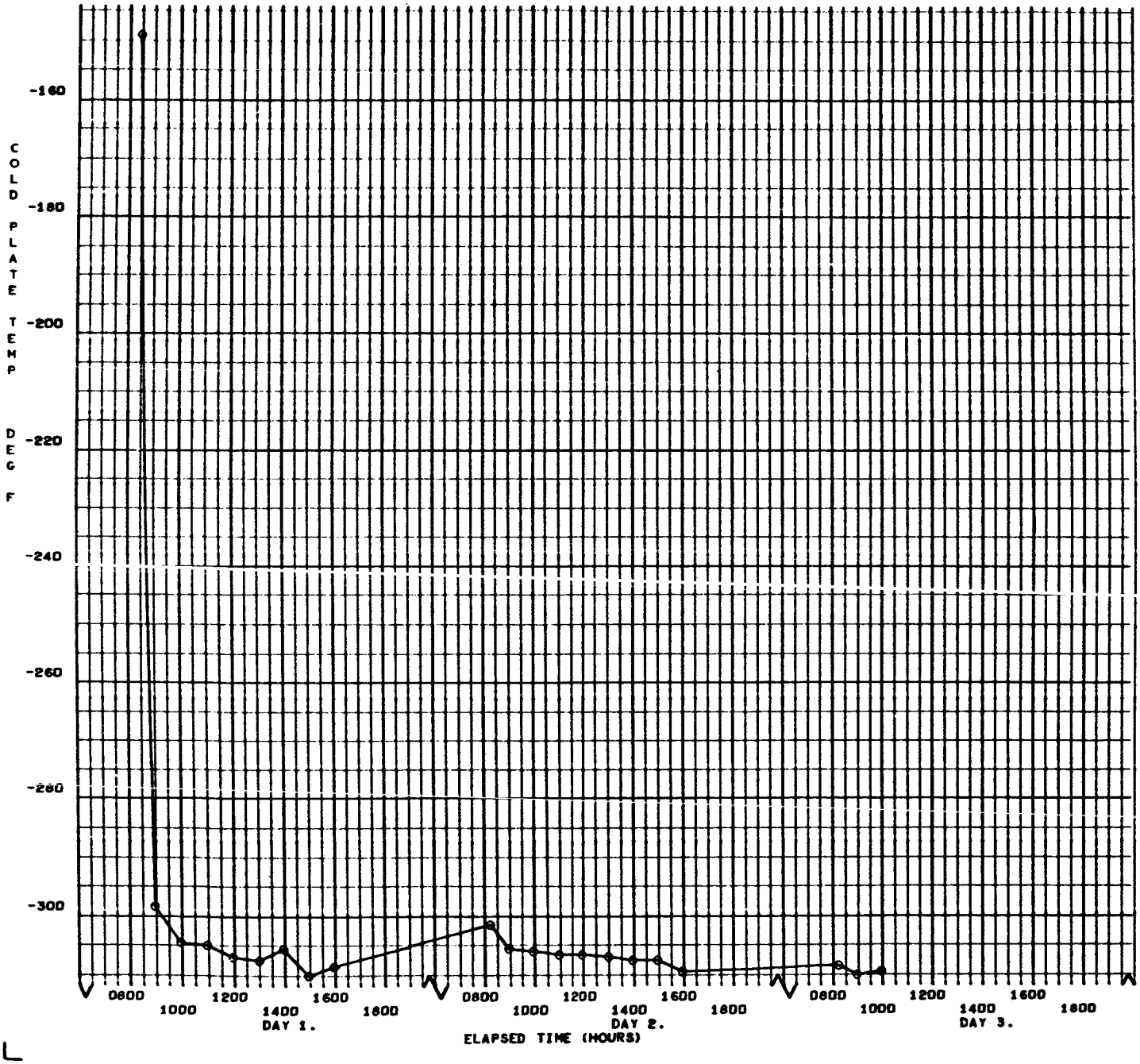


FIGURE 18.E

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 7.1
SAMPLE THICKNESS (IN.) 0.1875
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 71.0
COLD PLATE (DEG-F)- 309.5

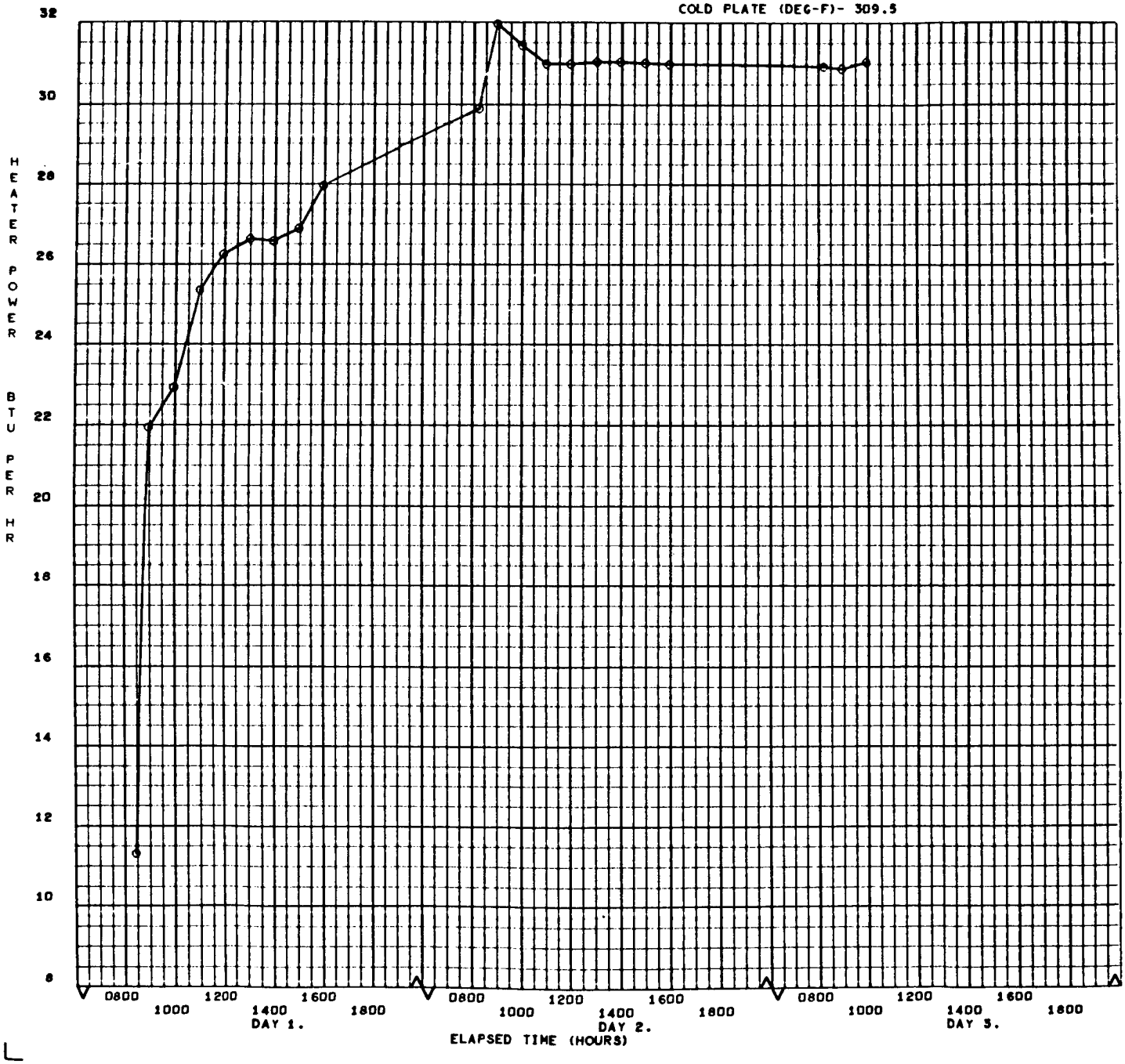


FIGURE 19.A

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 7.2
SAMPLE THICKNESS (IN.) 0.1875
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 204.5
COLD PLATE (DEG-F) 0.0

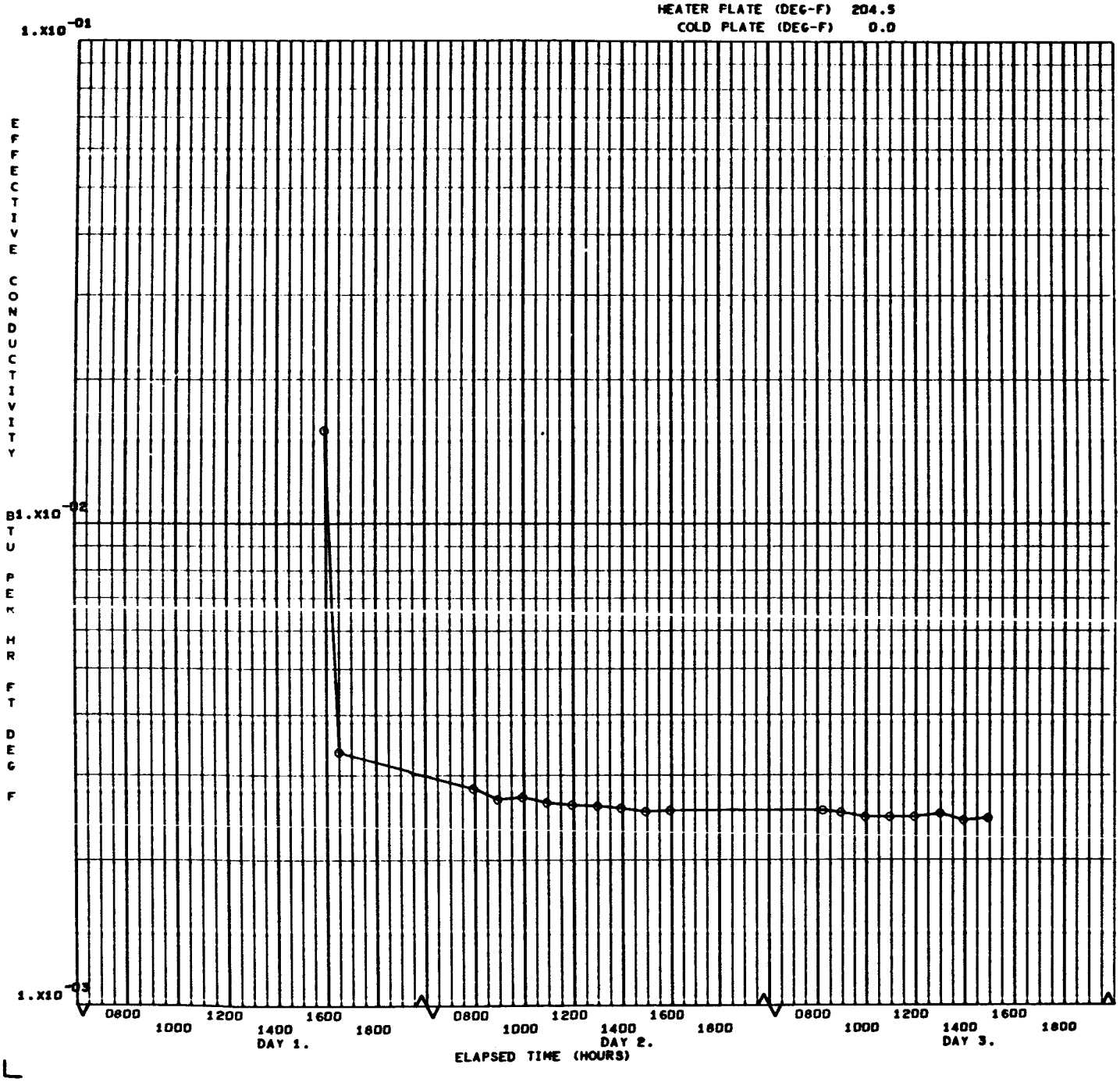


FIGURE 19.8

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 7.2
SAMPLE THICKNESS (IN.) 0.1875
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 204.5
COLD PLATE (DEG-F) 0.0

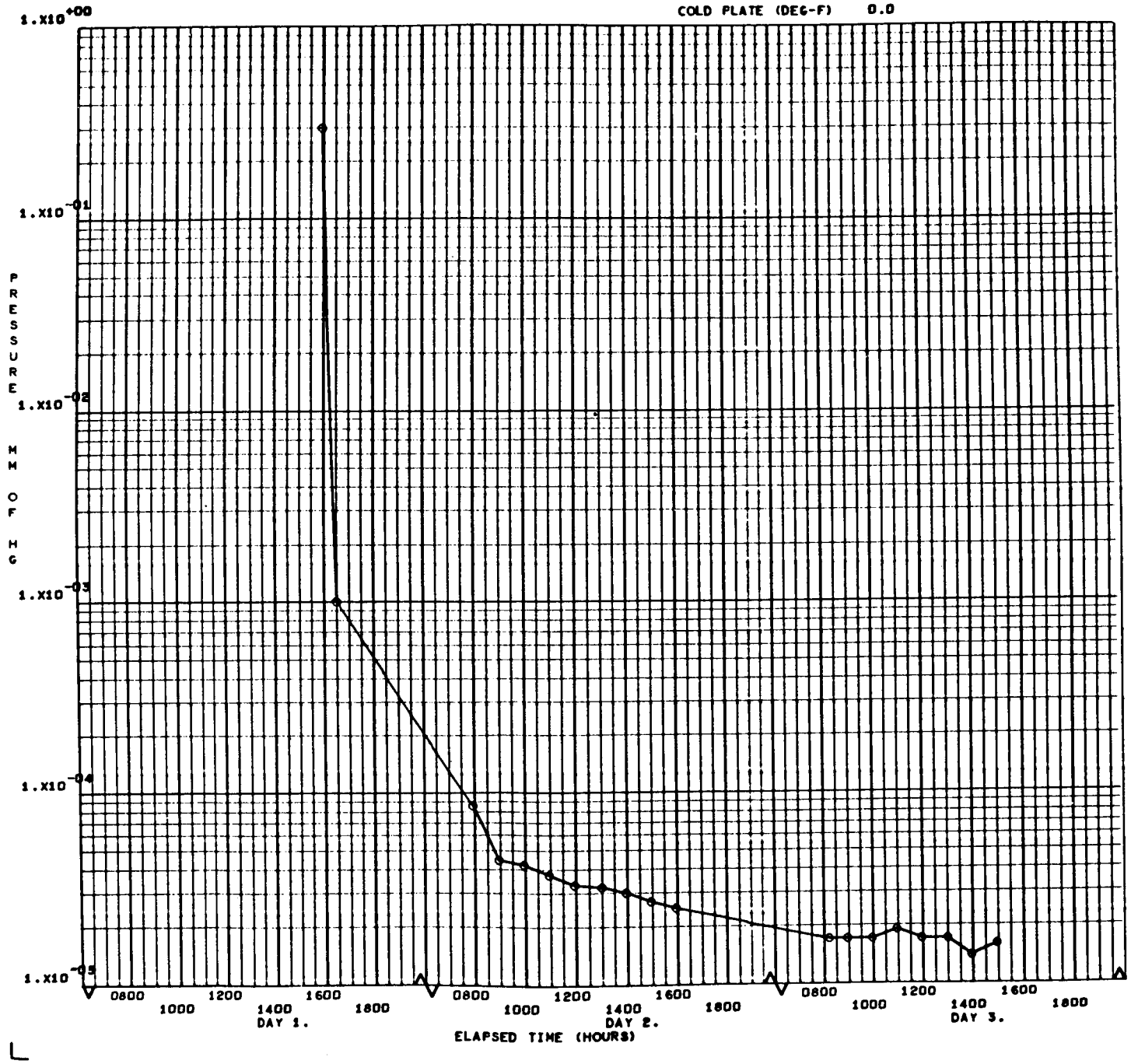


FIGURE 19.C

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 7.2
SAMPLE THICKNESS (IN.) 0.1075
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 204.5
COLD PLATE (DEG-F) 0.0

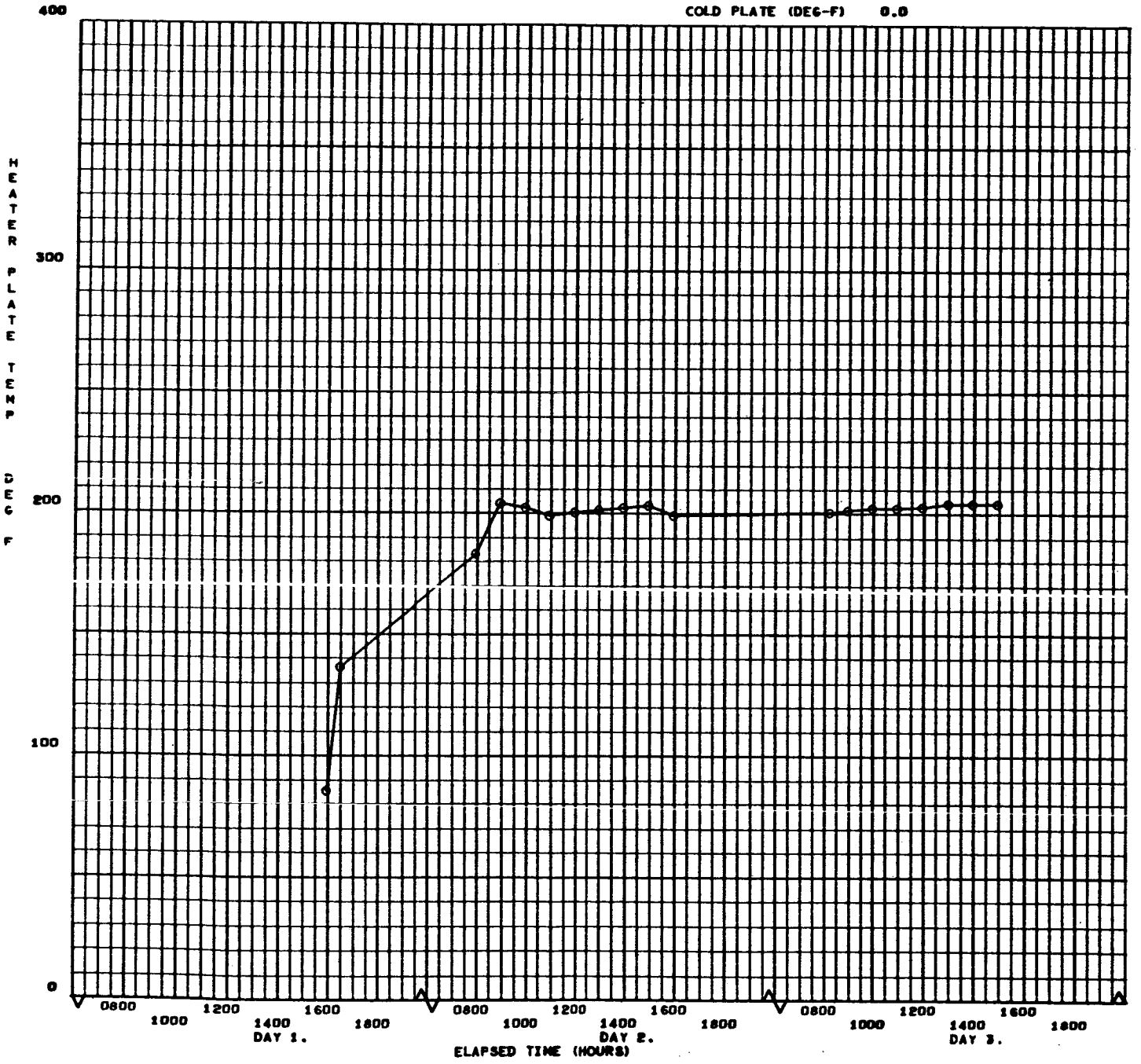


FIGURE 19.D

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 7.2
SAMPLE THICKNESS (IN.) 0.1875
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 204.5
COLD PLATE (DEG-F) 0.0

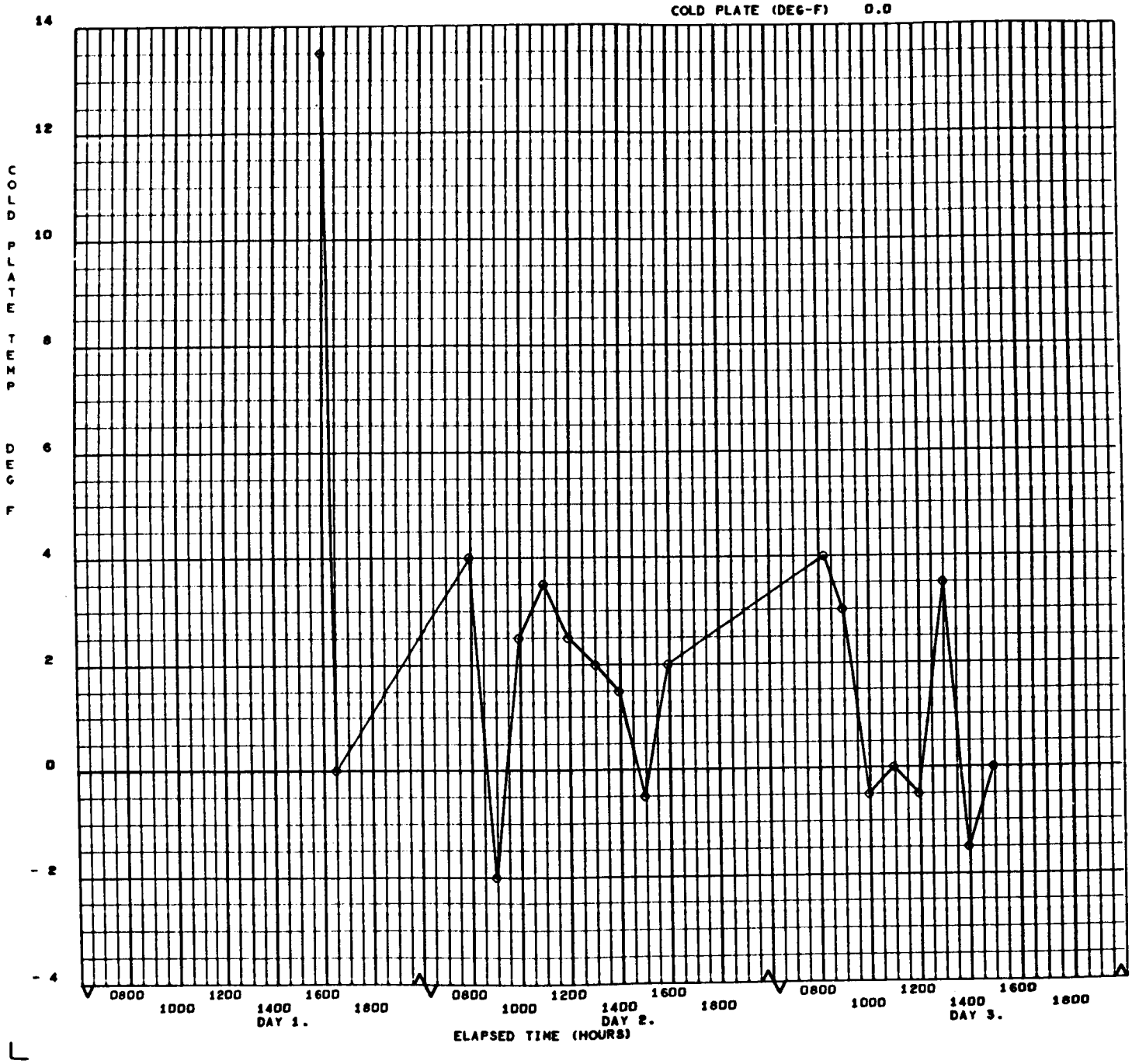


FIGURE 19.E

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 7.2
SAMPLE THICKNESS (IN.) 0.1875
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 204.5
COLD PLATE (DEG-F) 0.0

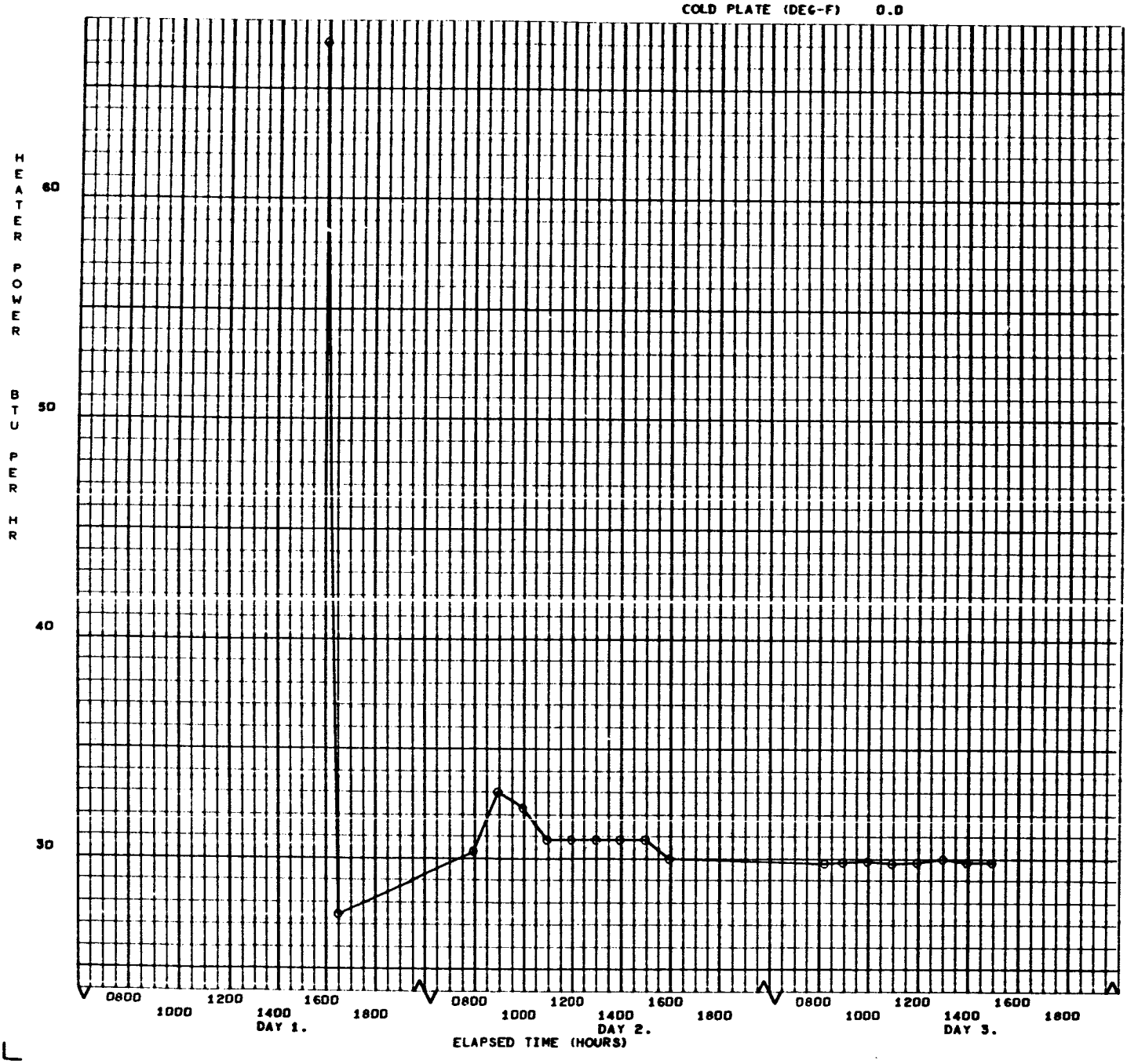


FIGURE 20.A

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 7.3
SAMPLE THICKNESS (IN.) 0.1875
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 306.5
COLD PLATE (DEG-F) 70.0

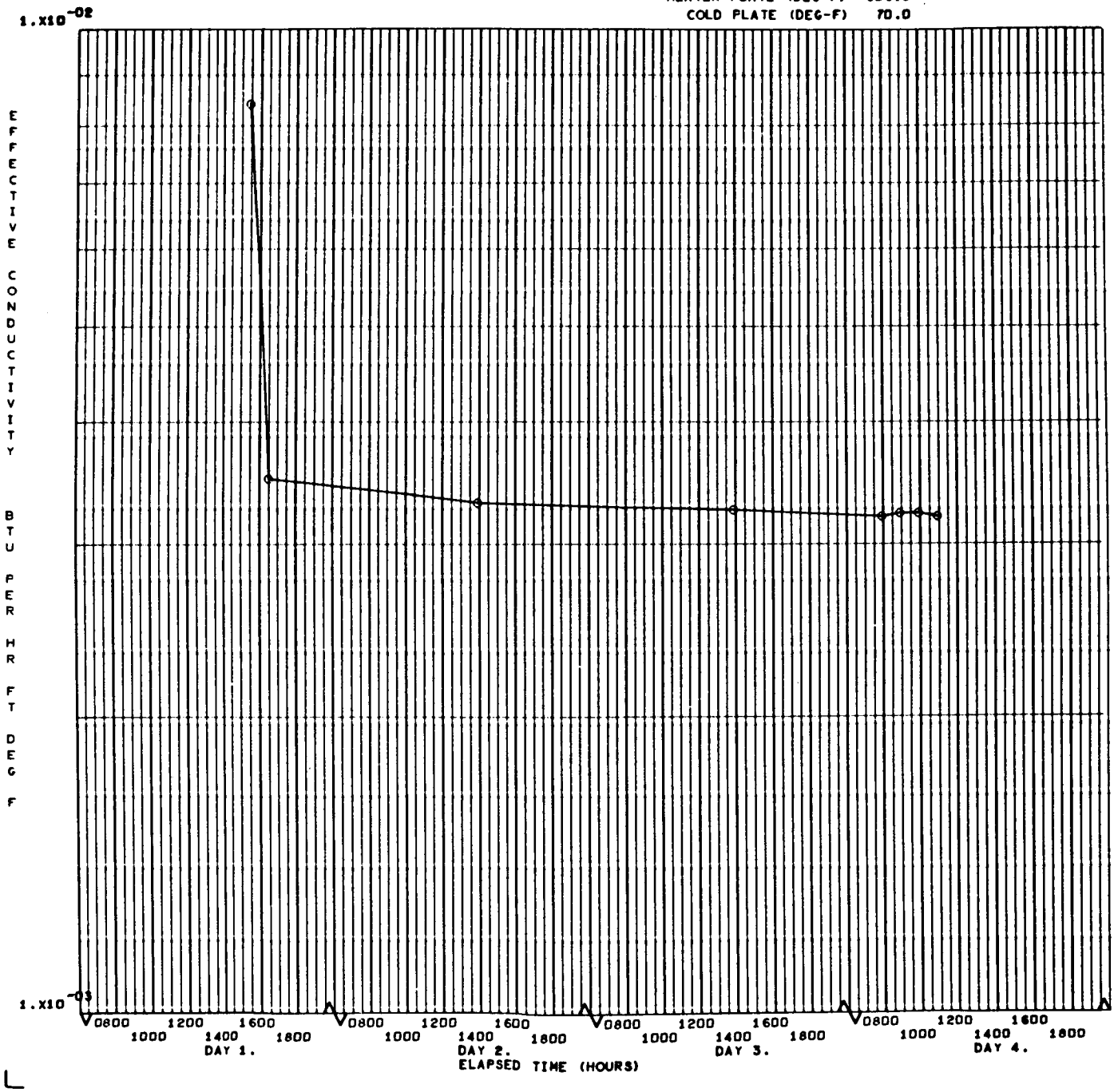


FIGURE 20.B

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 7.3
SAMPLE THICKNESS (IN.) 0.1875
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 306.5
COLD PLATE (DEG-F) 70.0

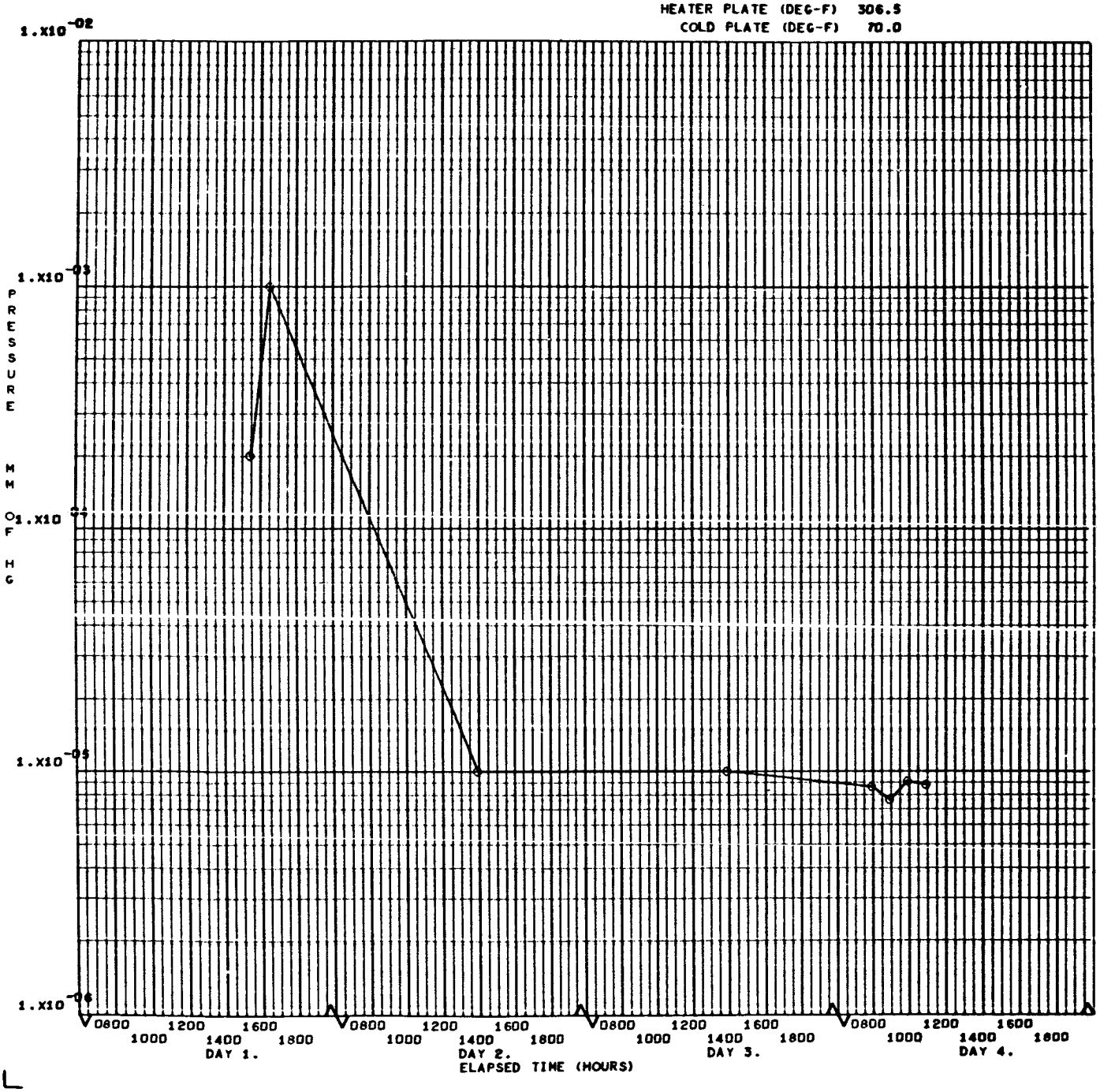


FIGURE 20.C

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 7.3
SAMPLE THICKNESS (IN.) 0.1875
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 306.5
COLD PLATE (DEG-F) 70.0

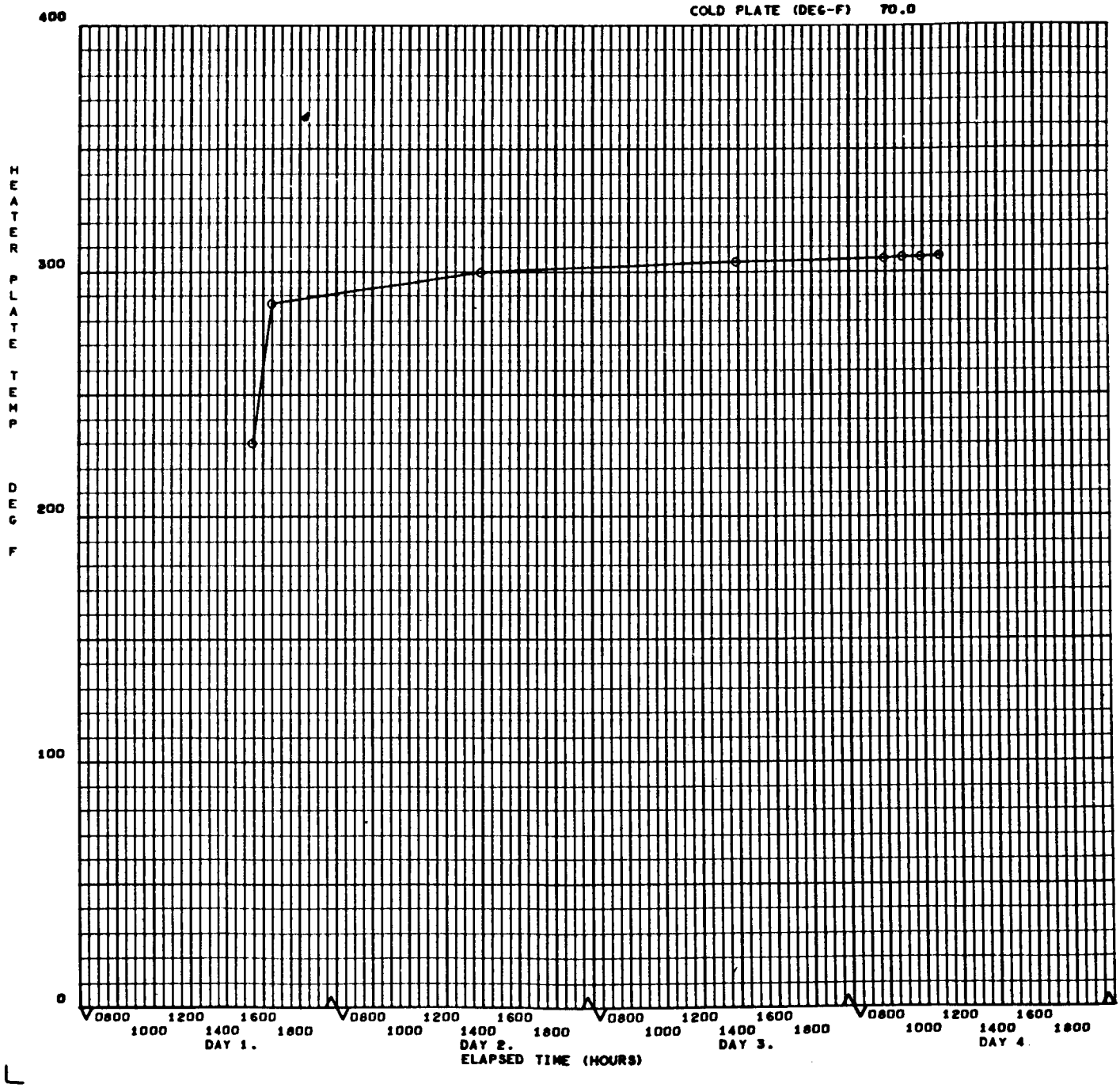


FIGURE 20.D

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 7.3
SAMPLE THICKNESS (IN.) 0.1875
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 306.5
COLD PLATE (DEG-F) 70.0

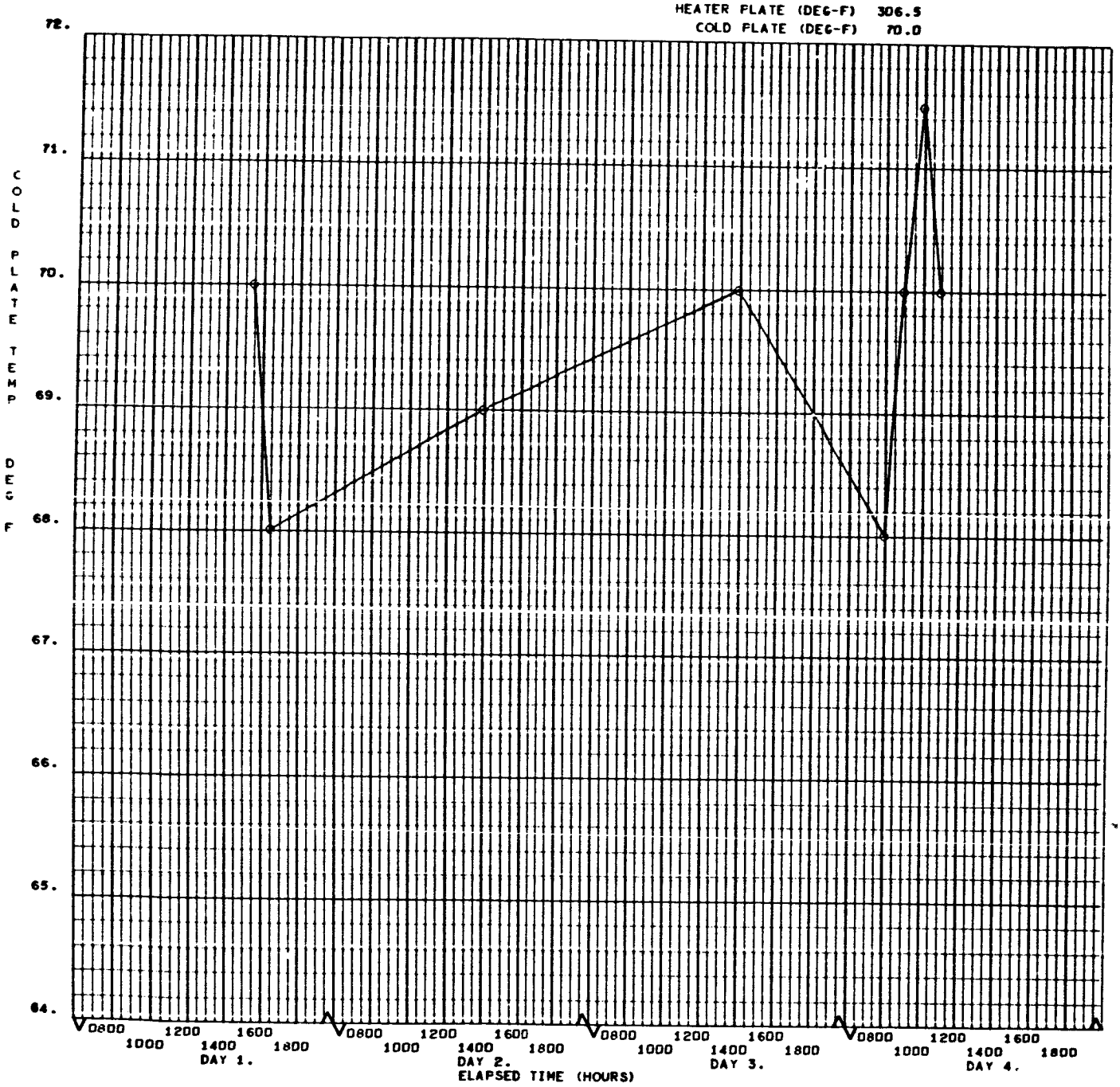


FIGURE 20.E

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 7.3
SAMPLE THICKNESS (IN.) 0.1875
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 306.5
COLD PLATE (DEG-F) 70.0

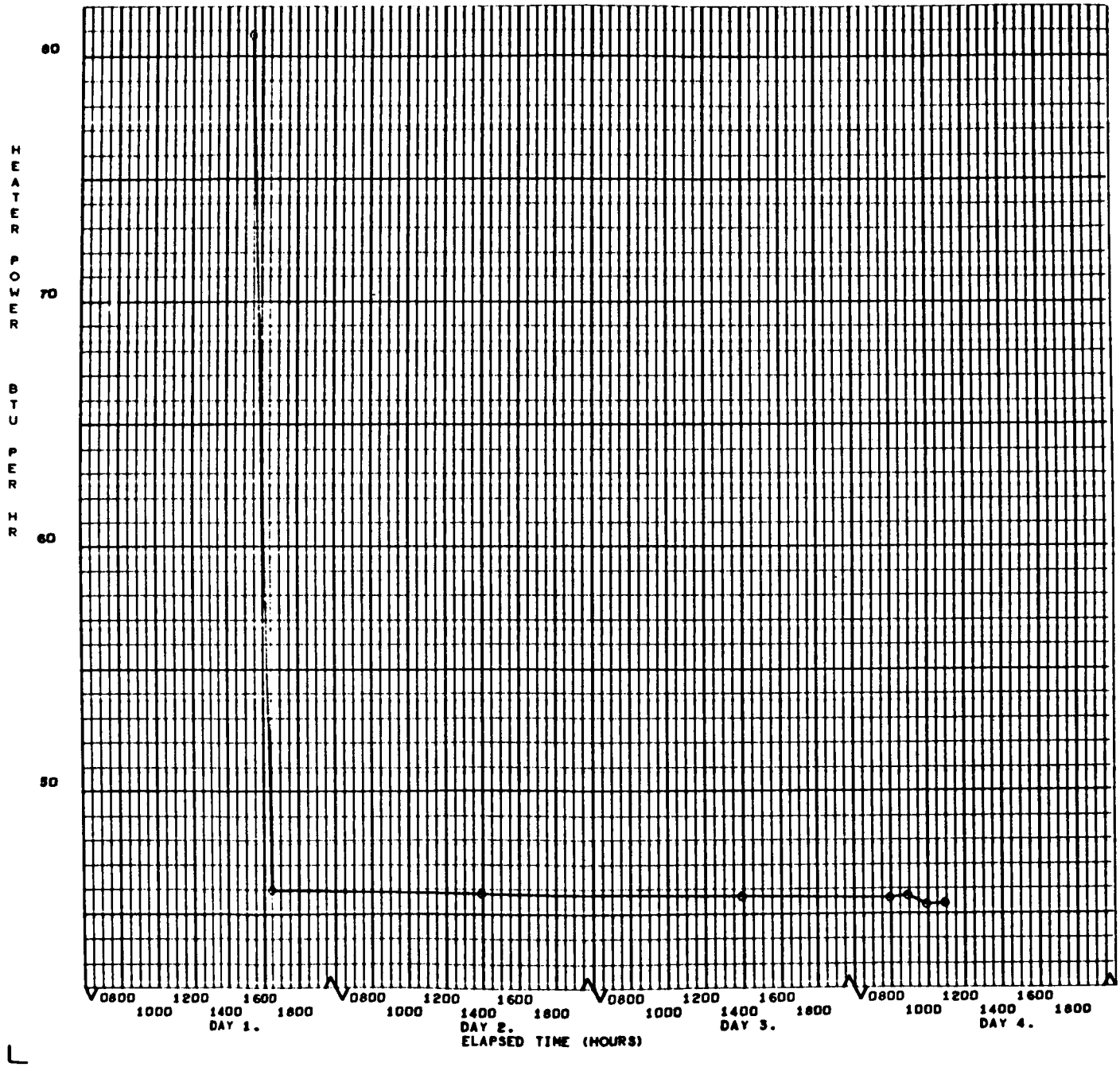


FIGURE 21.A

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 5.4
SAMPLE THICKNESS (IN.) 0.3125
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 76.5
COLD PLATE (DEG-F)- 310.0

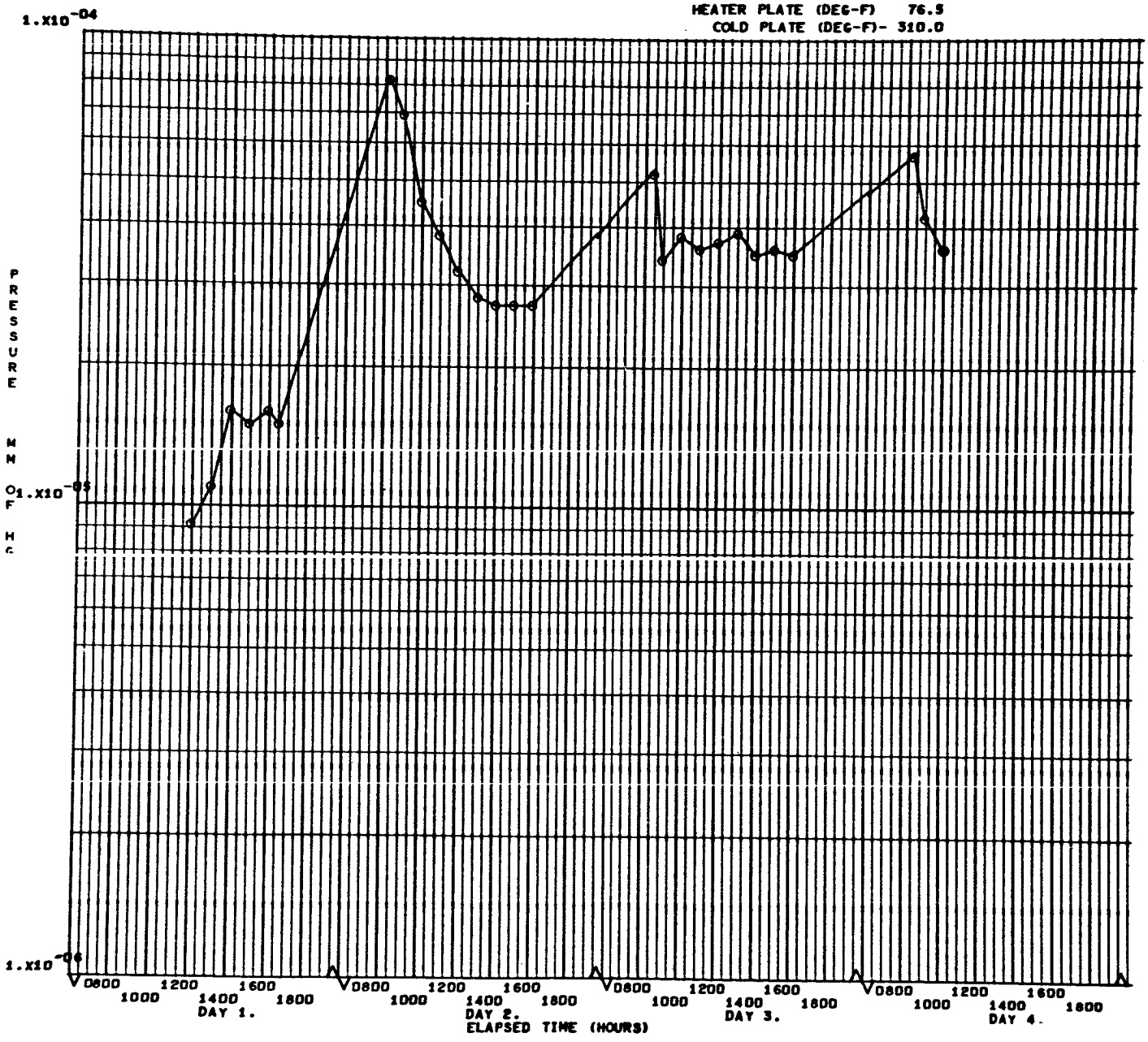


FIGURE 21.B

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 5.4
SAMPLE THICKNESS (IN.) 0.3125
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 76.5
COLD PLATE (DEG-F)- 310.0

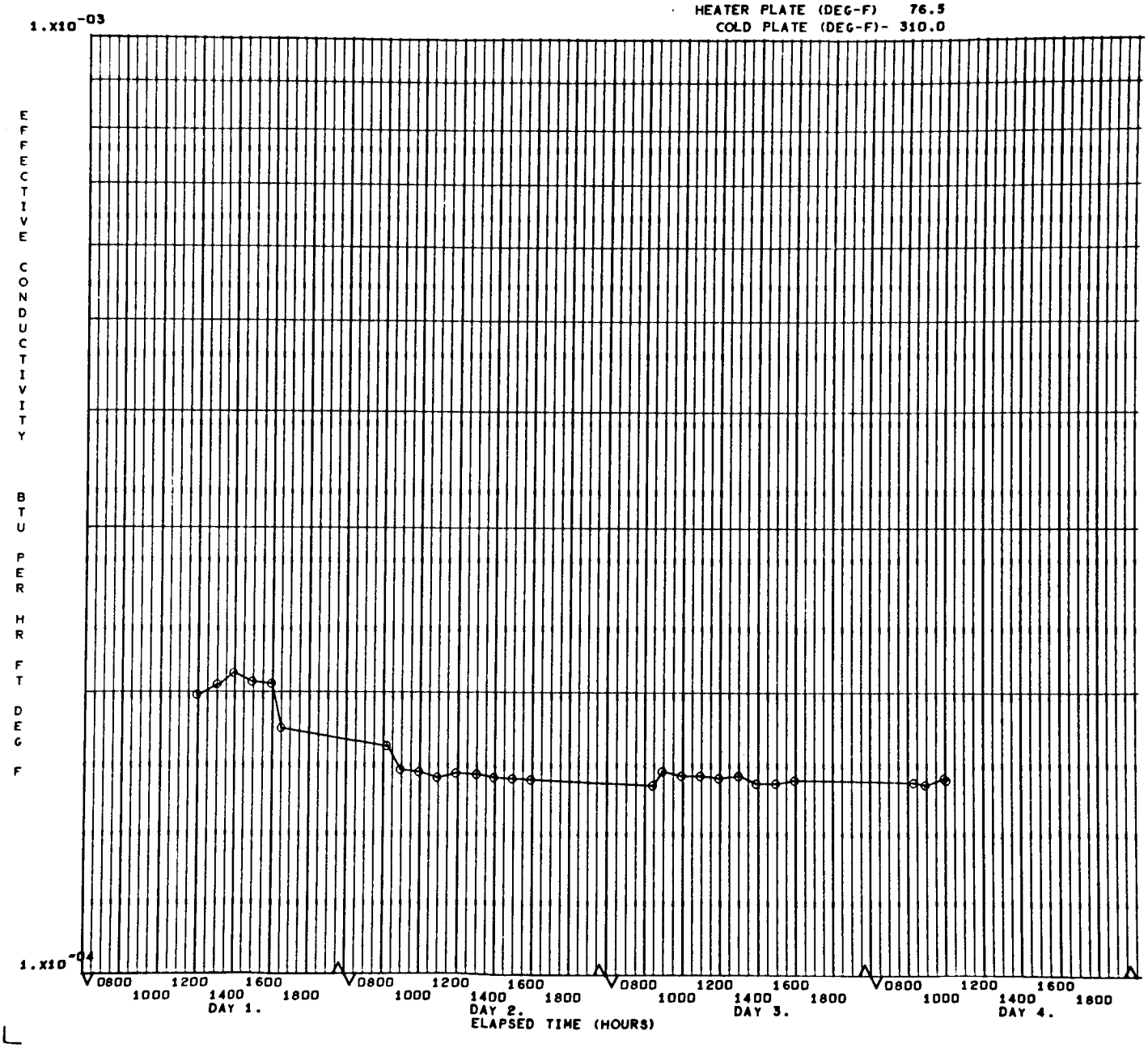


FIGURE 21.C

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 5.4
SAMPLE THICKNESS (IN.) 0.3125
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 76.5
COLD PLATE (DEG-F)- 310.0

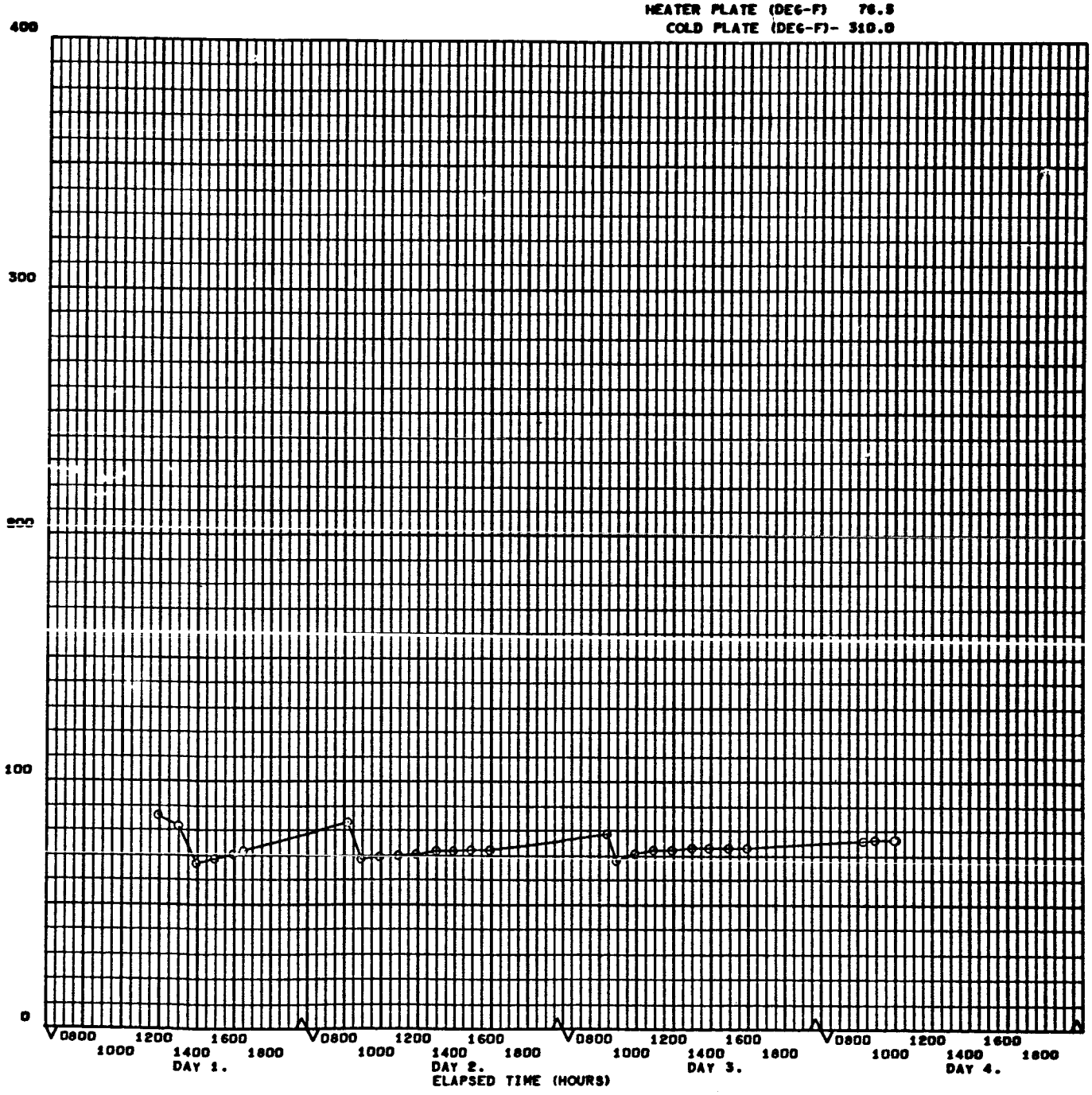


FIGURE 21.D

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 5.4
SAMPLE THICKNESS (IN.) 0.3125
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 76.5
COLD PLATE (DEG-F)- 310.0

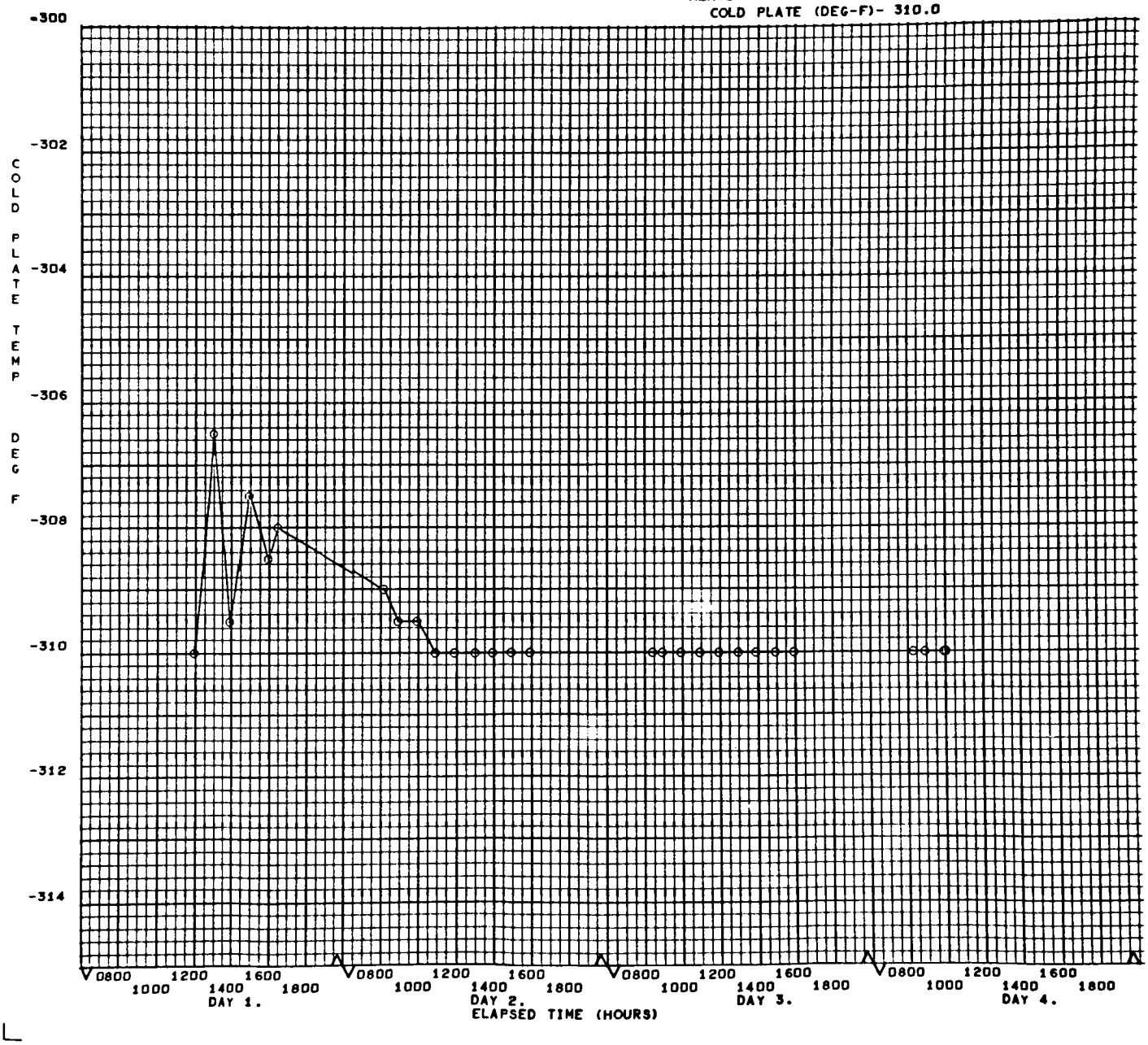


FIGURE 21.E

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 5.4
SAMPLE THICKNESS (IN.) 0.3125
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 76.5
COLD PLATE (DEG-F)- 310.0

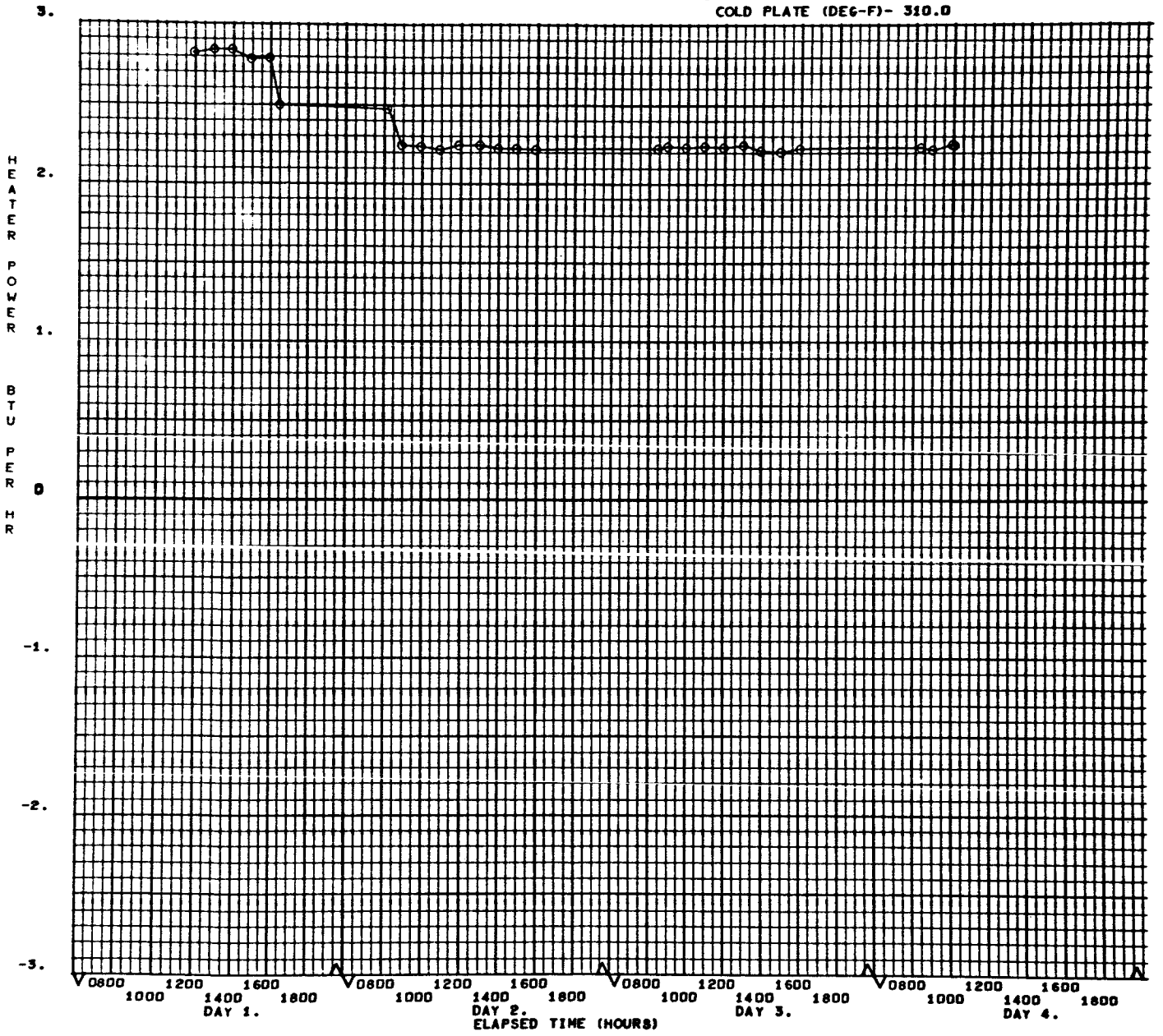


FIGURE 22.A

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 8.1
SAMPLE THICKNESS (IN.) 0.3125
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 67.0
COLD PLATE (DEG-F)- 310.0

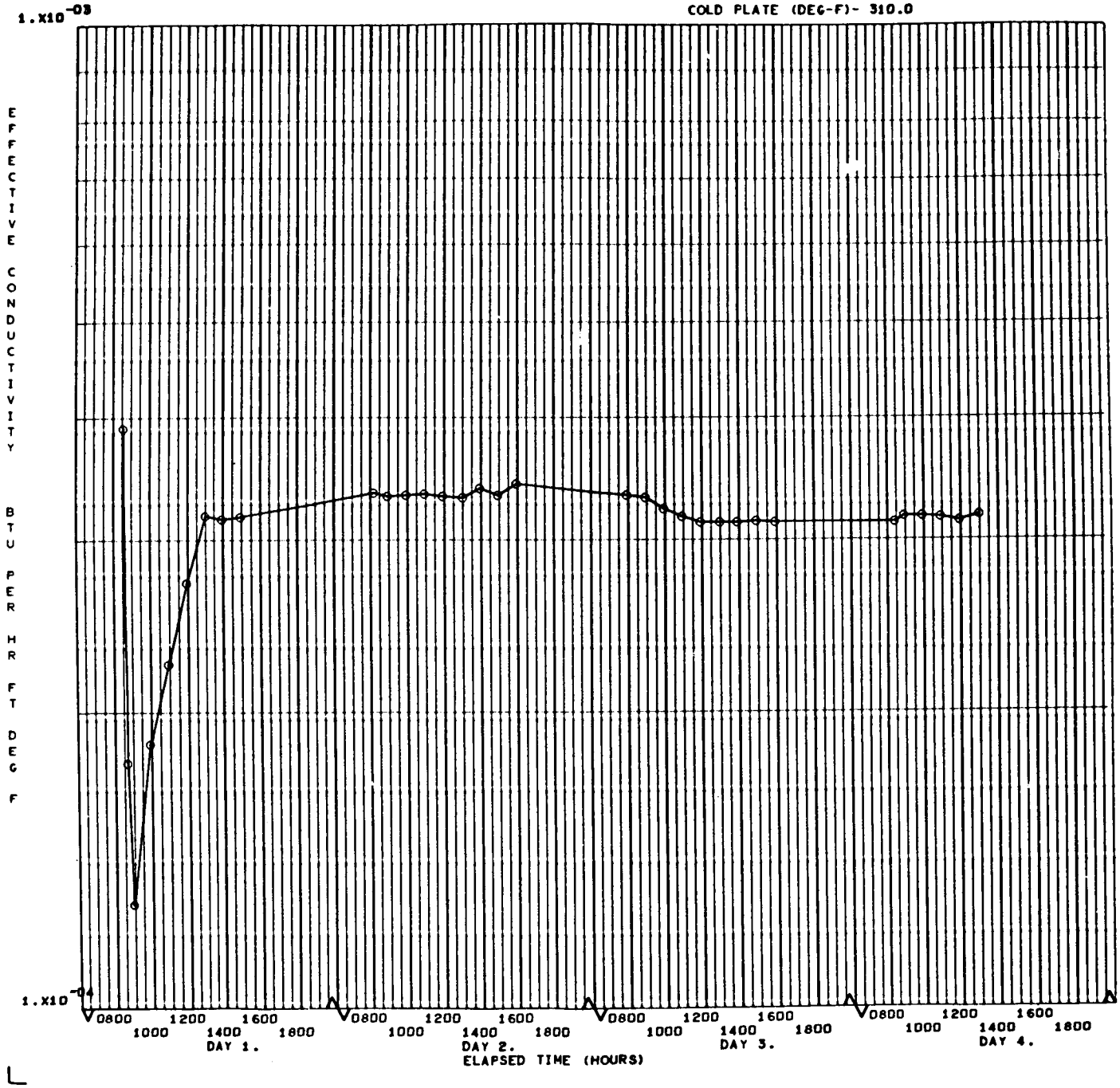


FIGURE 22.B

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 8.1
SAMPLE THICKNESS (IN.) 0.3125
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 67.0
COLD PLATE (DEG-F)- 310.0

FIGURE 22.C

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 8.1
SAMPLE THICKNESS (IN.) 0.3125
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 67.0
COLD PLATE (DEG-F)- 310.0

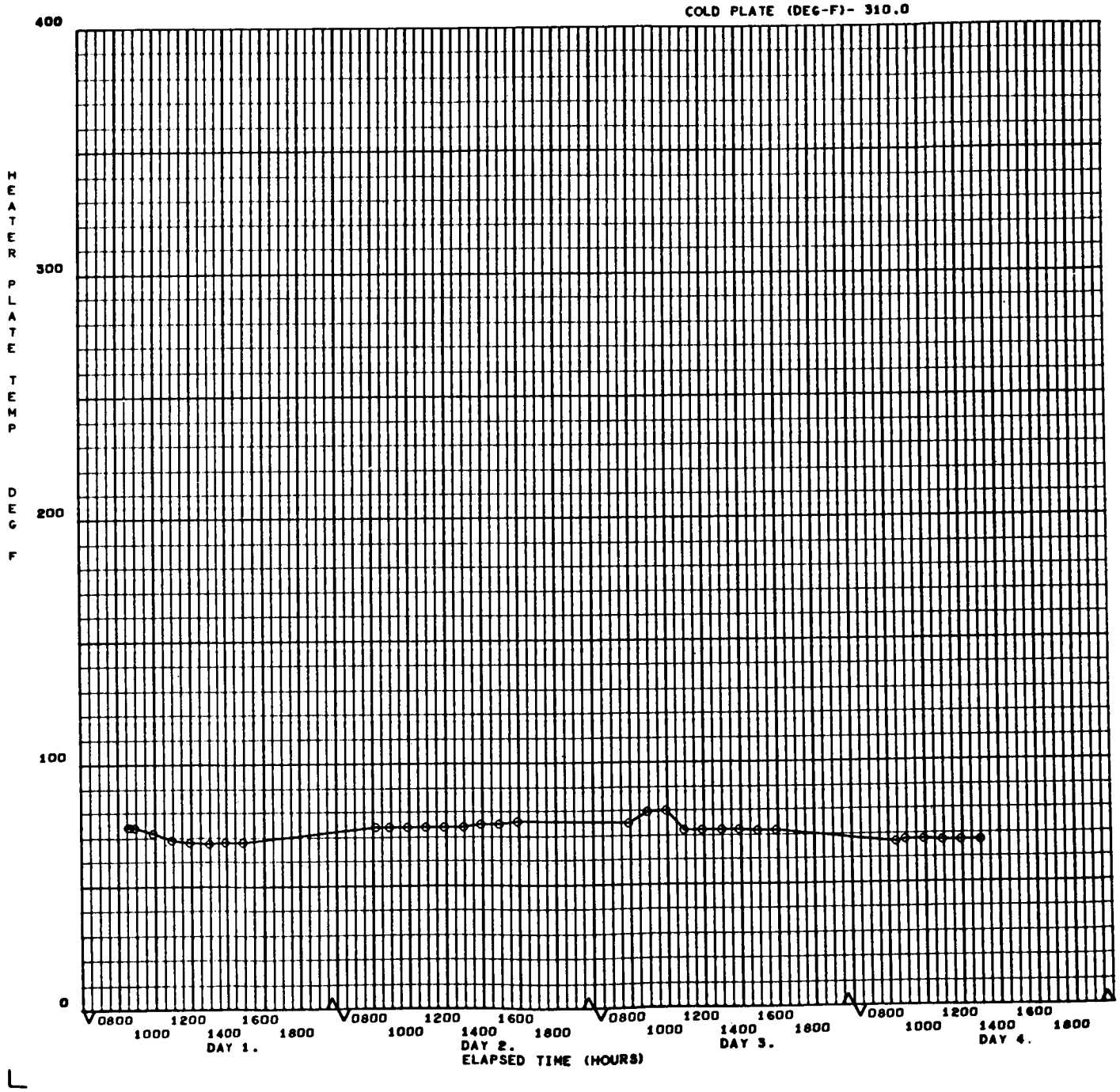


FIGURE 22.D

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 8.1
SAMPLE THICKNESS (IN.) 0.3125
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 67.0
COLD PLATE (DEG-F)- 310.0

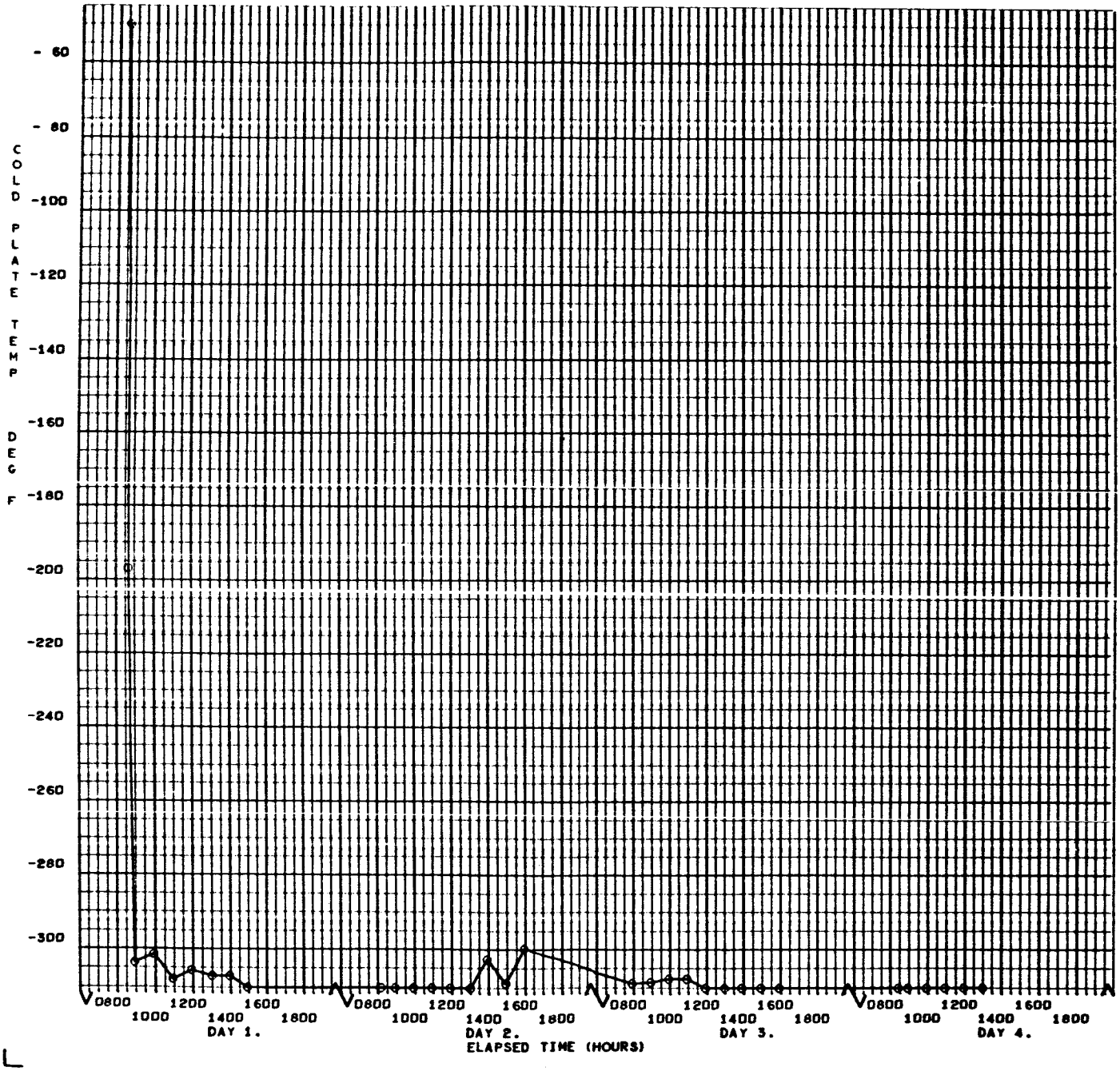


FIGURE 22.E

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 8.1
SAMPLE THICKNESS (IN.) 0.3125
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 67.0
COLD PLATE (DEG-F)- 310.0

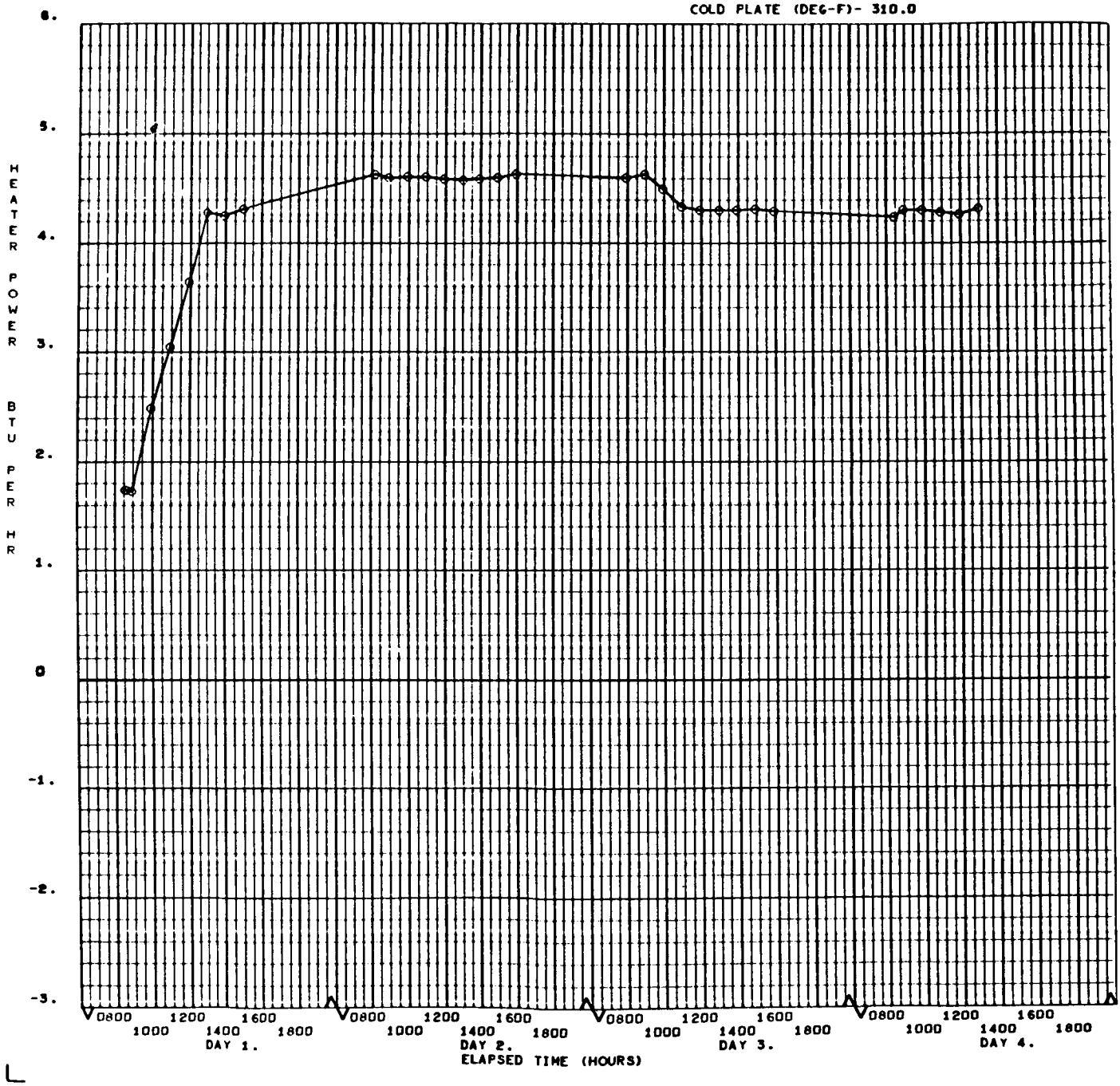


FIGURE 23.A

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 9.1
SAMPLE THICKNESS (IN.) 0.1875
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 73.0
COLD PLATE (DEG-F)- 310.0

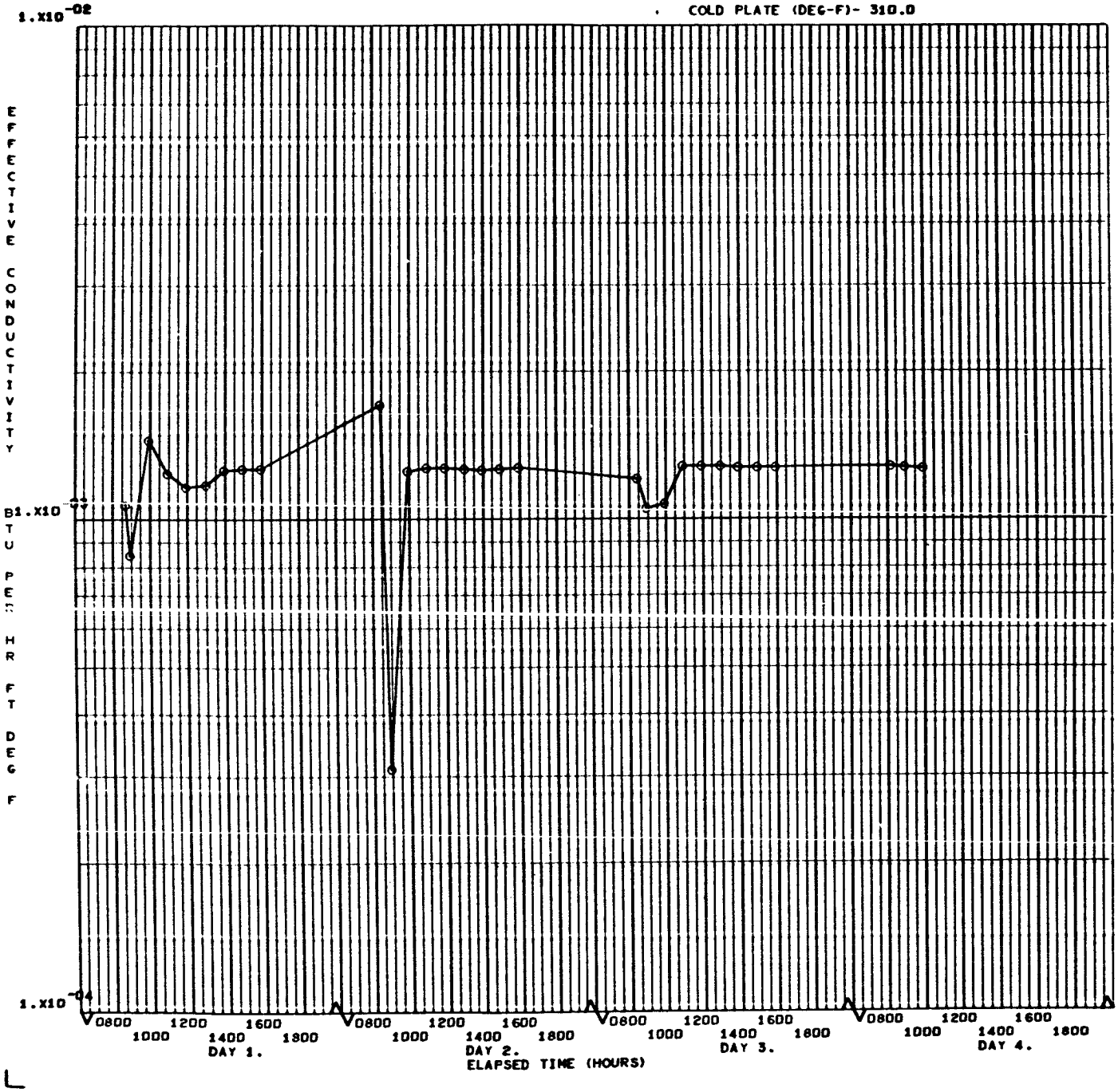


FIGURE 23.B

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 9.1
SAMPLE THICKNESS (IN.) 0.1875
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 73.0
COLD PLATE (DEG-F)- 310.0

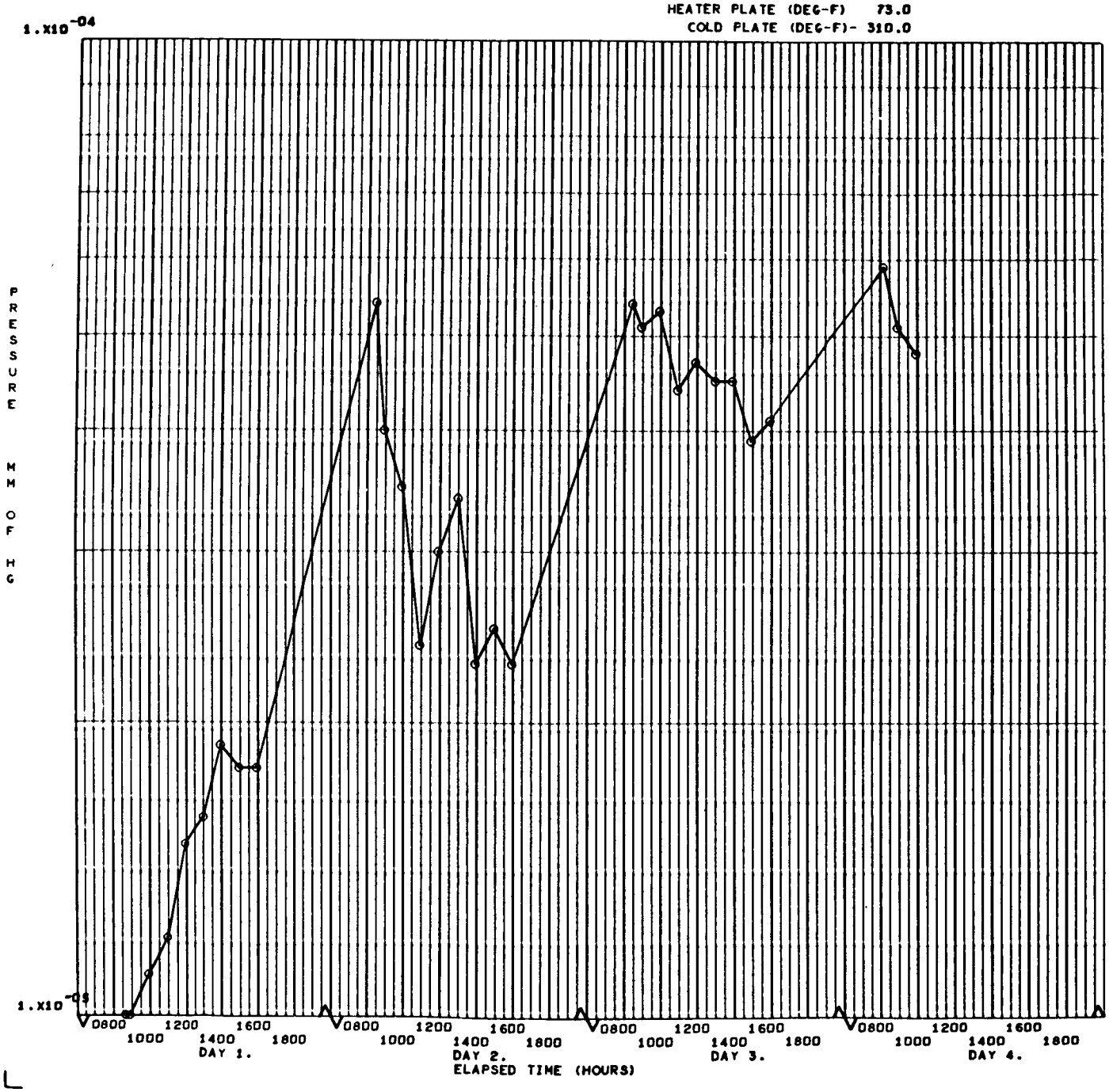


FIGURE 23.C

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 9.1
SAMPLE THICKNESS (IN.) 0.1875
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 73.0
COLD PLATE (DEG-F)- 310.0

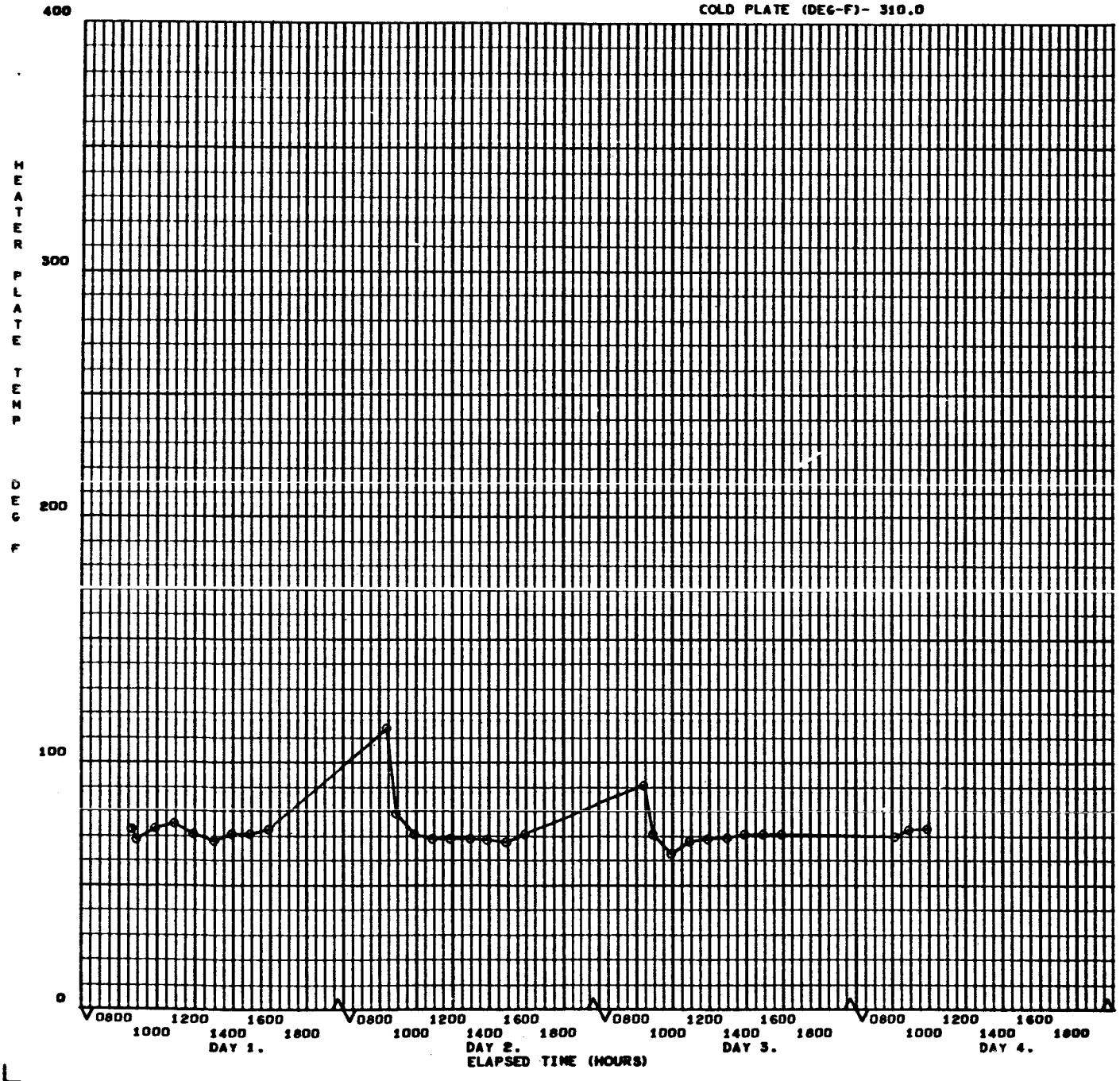


FIGURE 23.D

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 9.1
SAMPLE THICKNESS (IN.) 0.1875
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 73.0
COLD PLATE (DEG-F)- 310.0

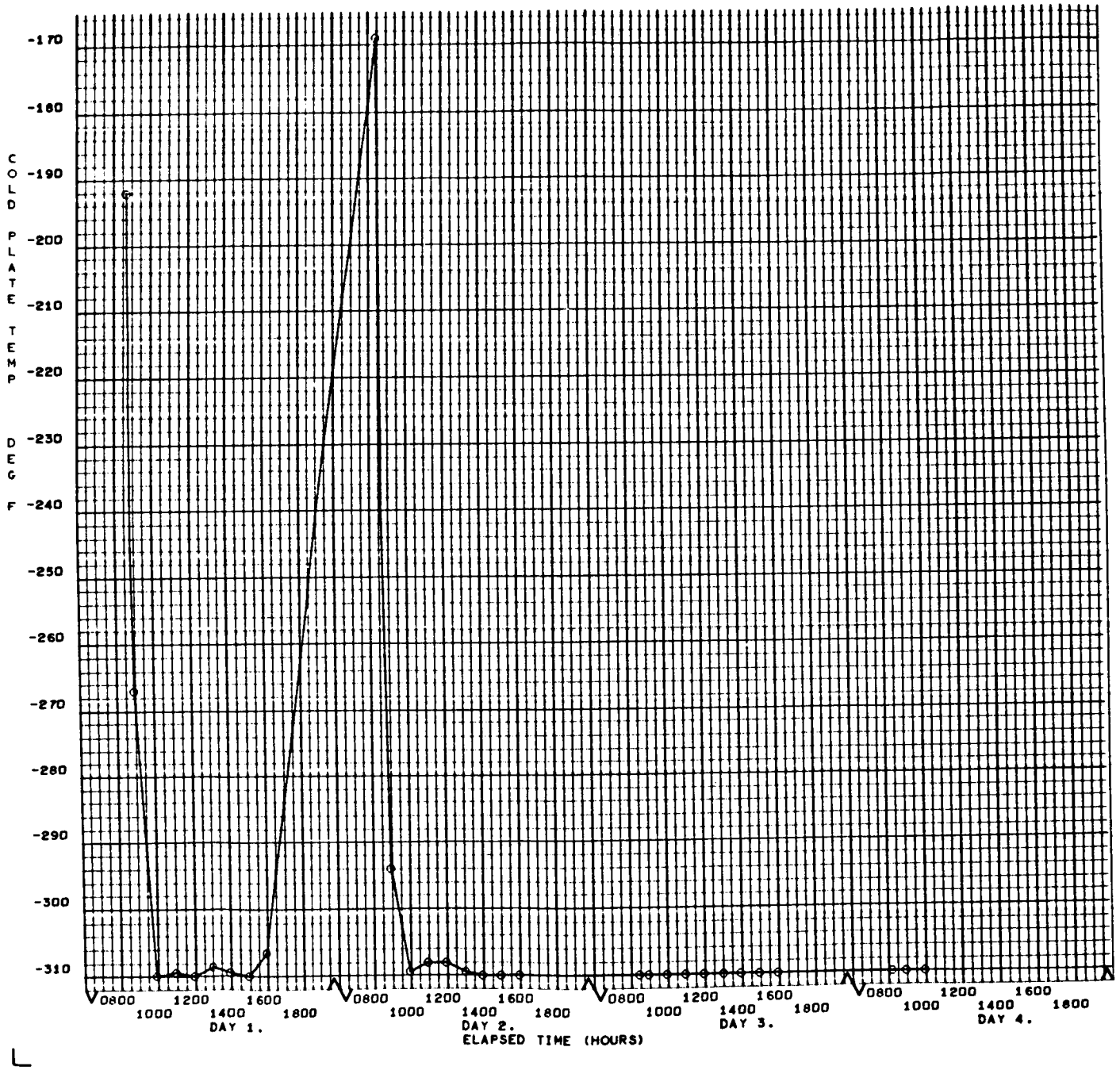


FIGURE 24.A

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 8.2
SAMPLE THICKNESS (IN.) 0.3125
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 302.0
COLD PLATE (DEG-F) 70.0

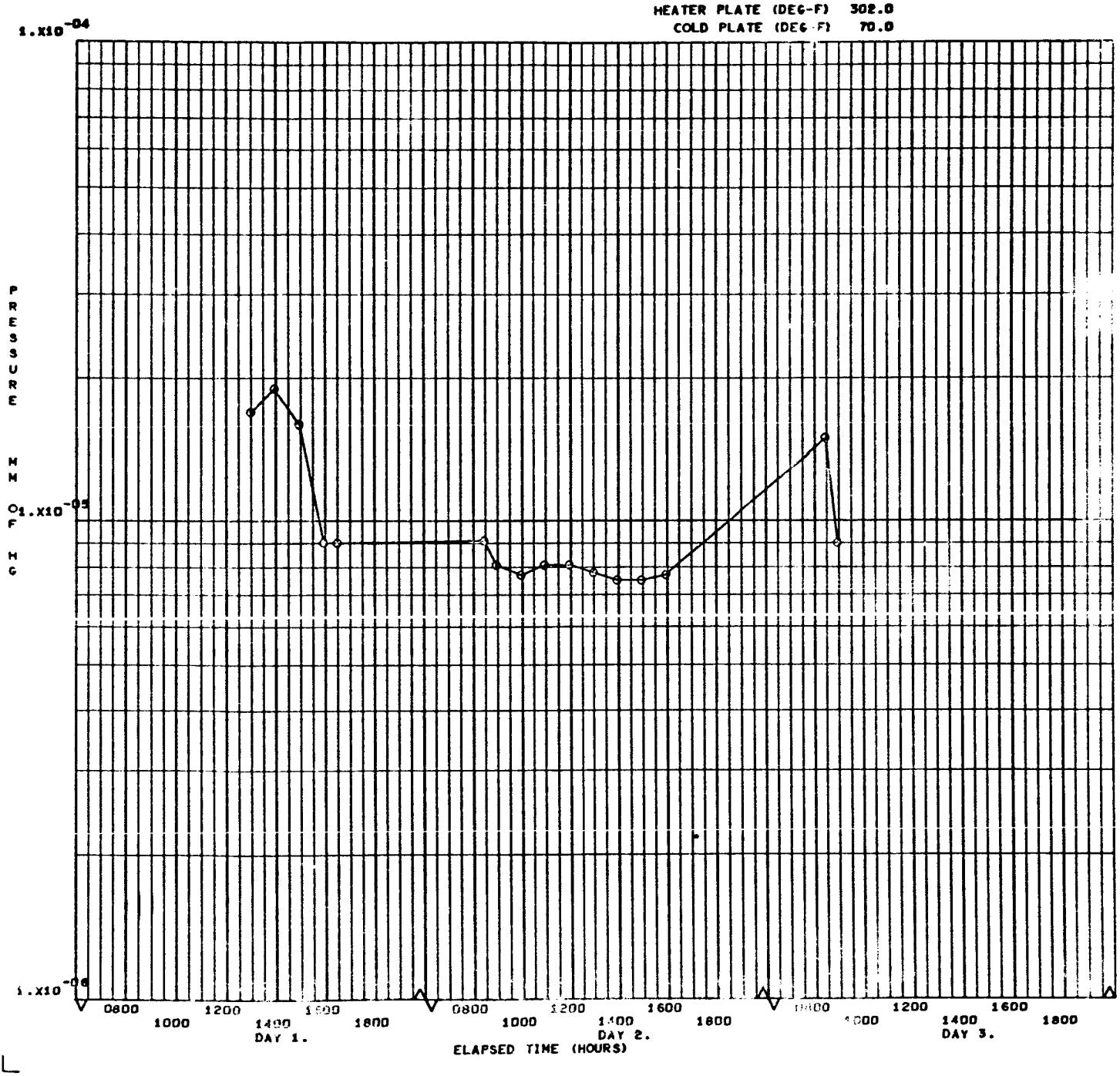


FIGURE 23.E

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 9.1
SAMPLE THICKNESS (IN.) 0.1875
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 73.0
COLD PLATE (DEG-F)- 310.0

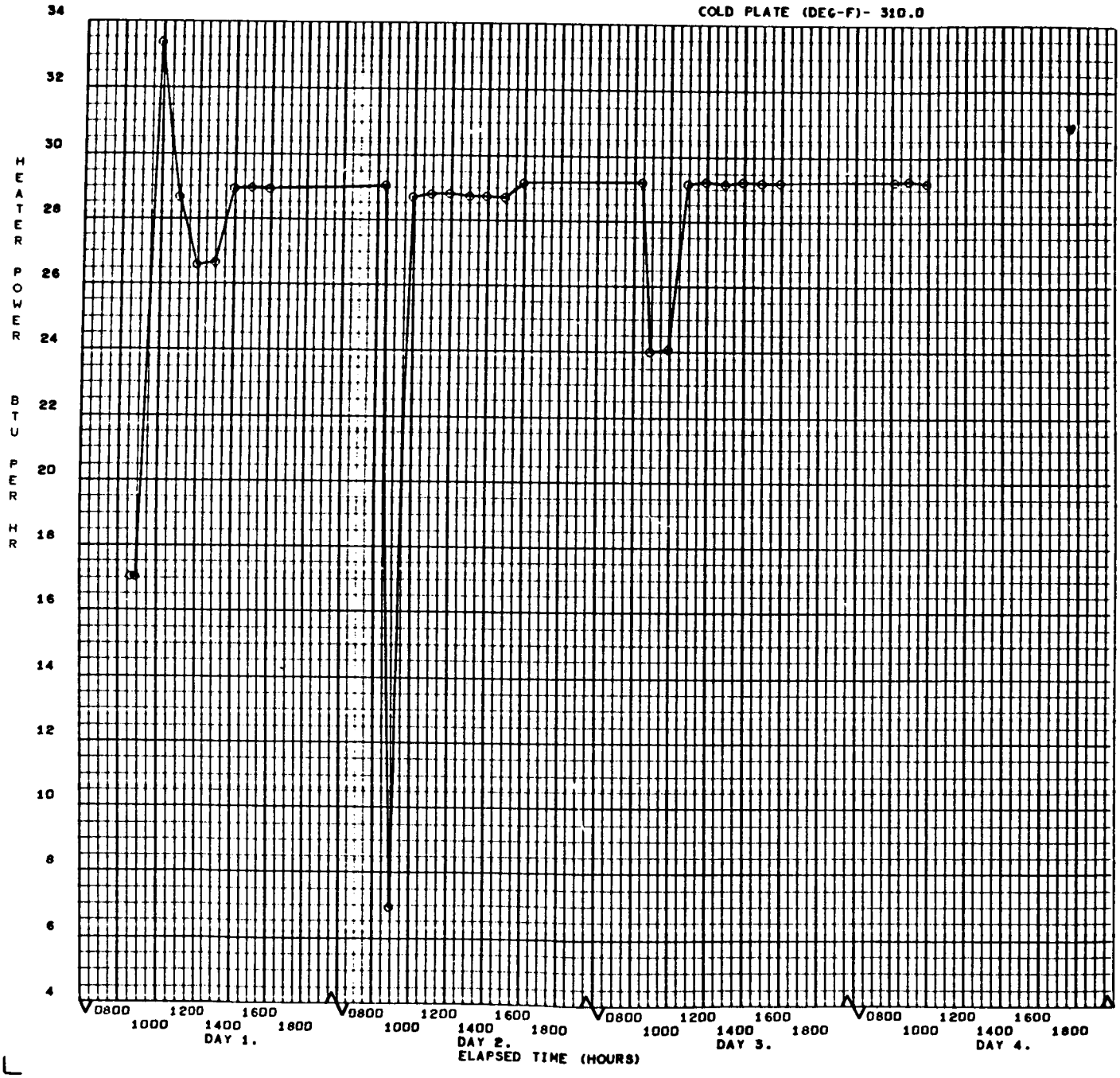


FIGURE 24.B

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 8.2
SAMPLE THICKNESS (IN.) 0.3125
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 302.0
COLD PLATE (DEG-F) 70.0

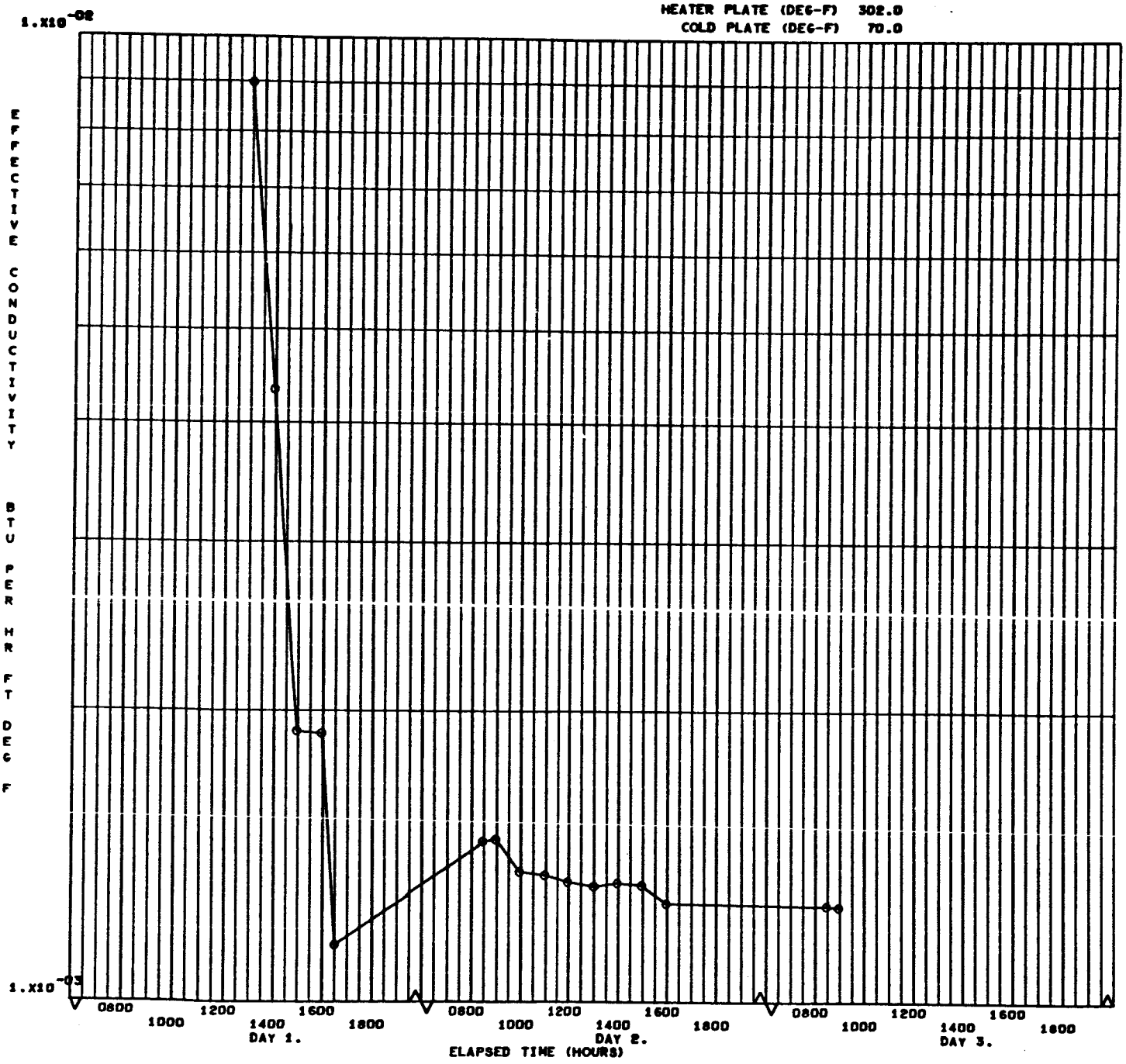


FIGURE 24.C

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 8.2
SAMPLE THICKNESS (IN.) 0.3125
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 302.0
COLD PLATE (DEG-F) 70.0

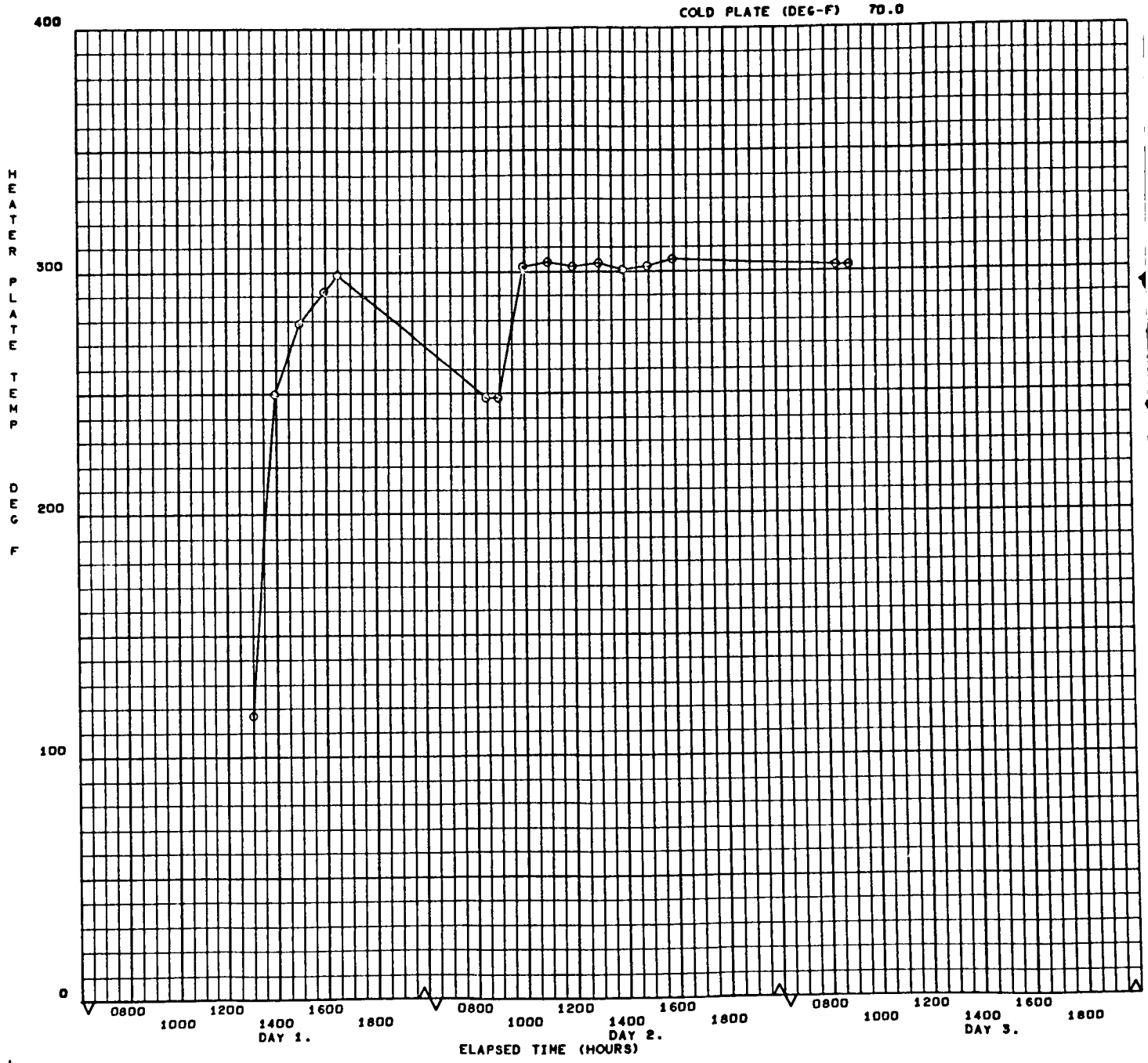


FIGURE 24.D

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 8.2
SAMPLE THICKNESS (IN.) 0.3125
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 302.0
COLD PLATE (DEG-F) 70.0

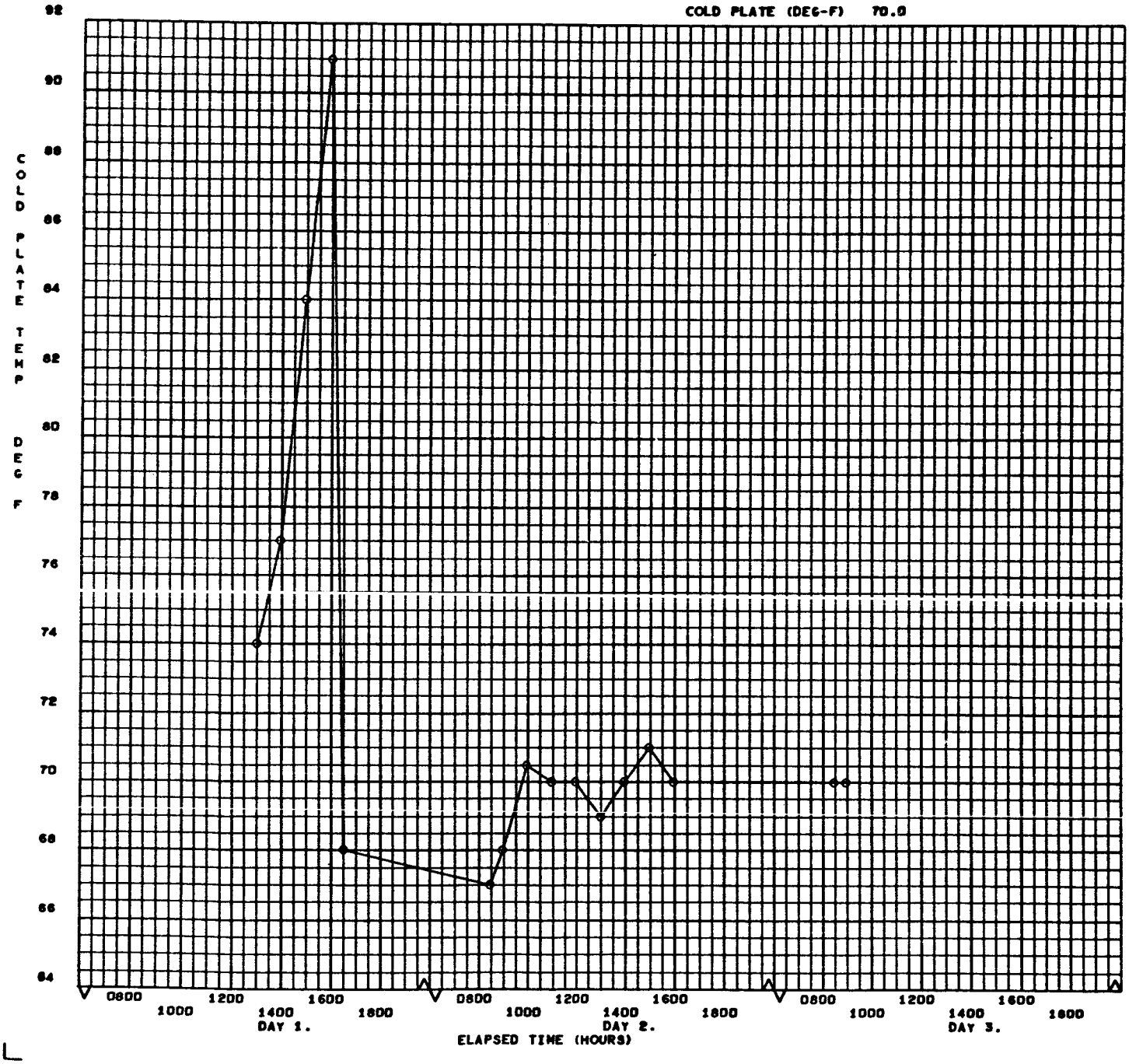


FIGURE 24.E

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 8.2
SAMPLE THICKNESS (IN.) 0.3125
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 302.0
COLD PLATE (DEG-F) 70.0

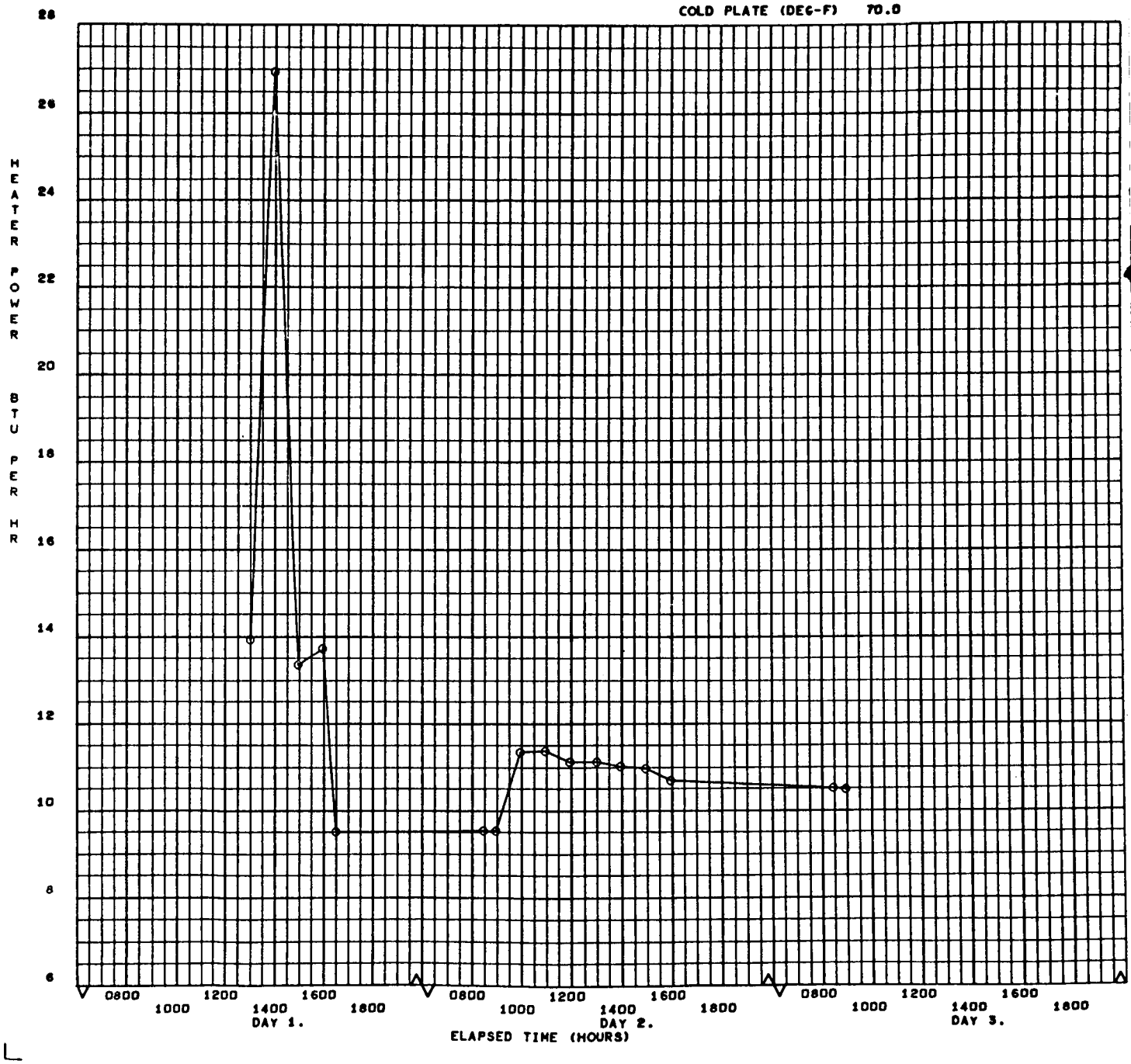


FIGURE 25.A

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 9.2
SAMPLE THICKNESS (IN.) 0.1875
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 300.0
COLD PLATE (DEG-F) 70.5

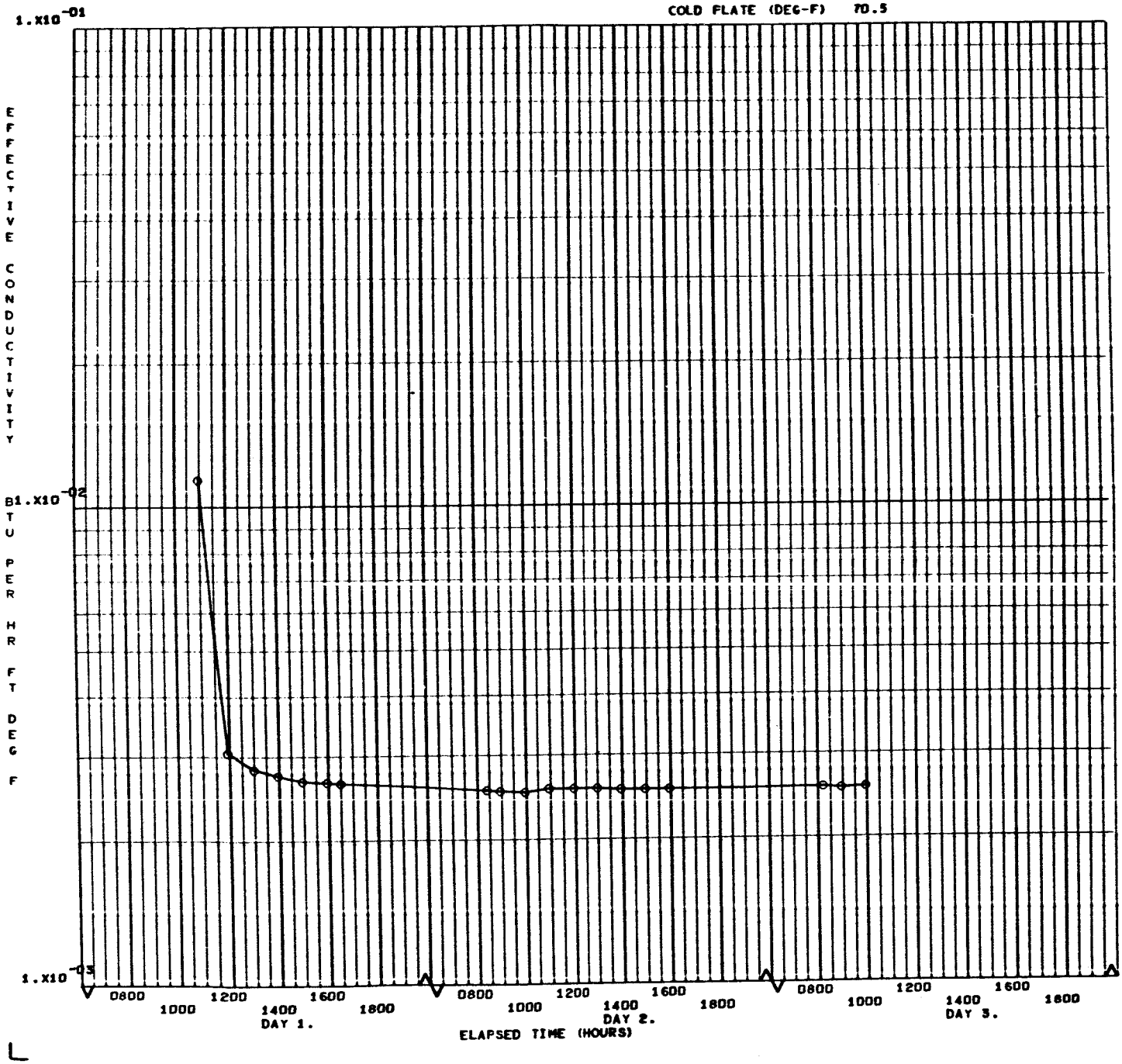


FIGURE 25.B

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 9.2
SAMPLE THICKNESS (IN.) 0.1875
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 300.0
COLD PLATE (DEG-F) 70.5

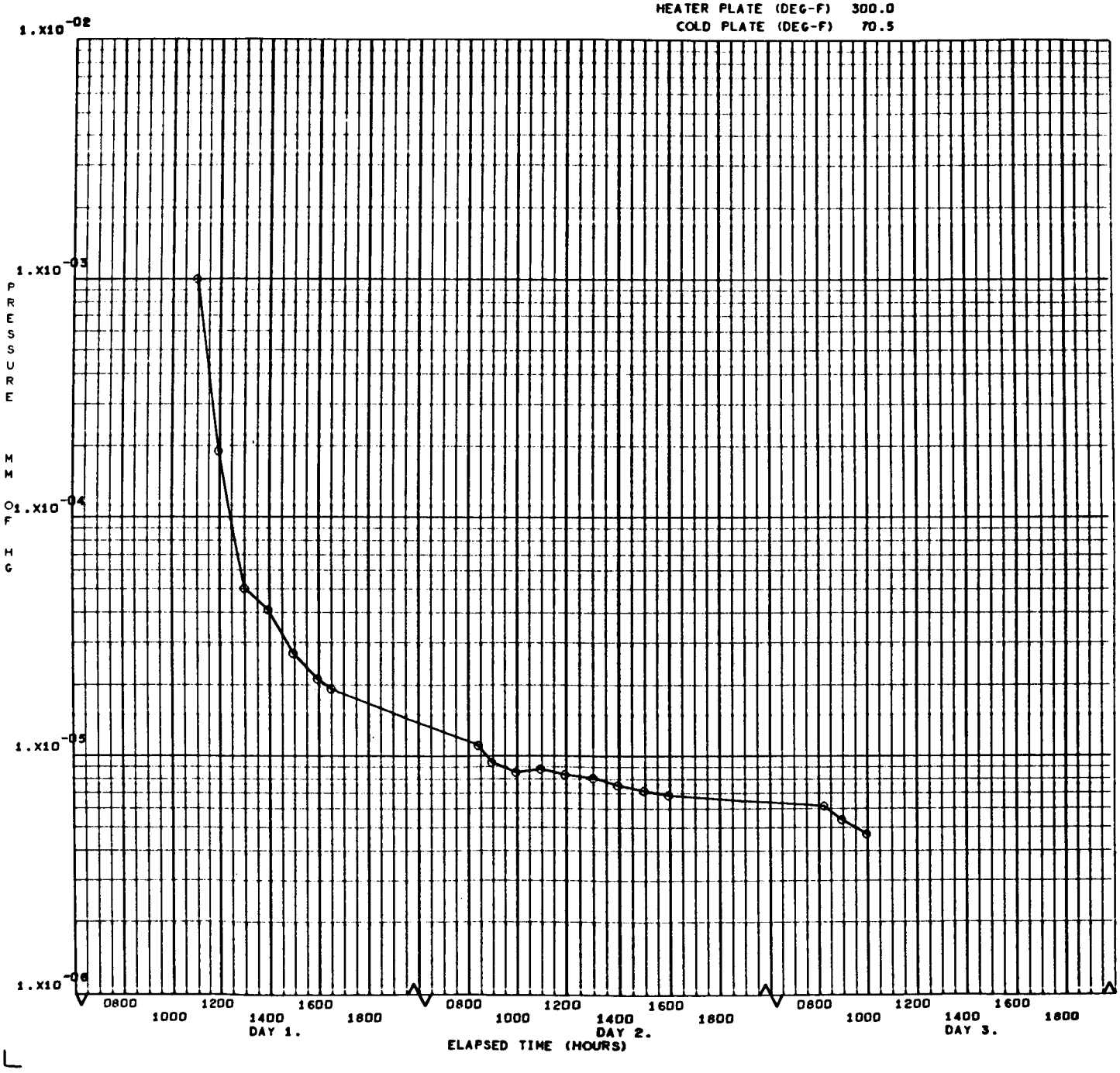


FIGURE 29.C

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 9.2
SAMPLE THICKNESS (IN.) 0.1875
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 300.0
COLD PLATE (DEG-F) 70.5

FIGURE 25.D

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 9.2
SAMPLE THICKNESS (IN.) 0.1875
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 300.0
COLD PLATE (DEG-F) 70.5

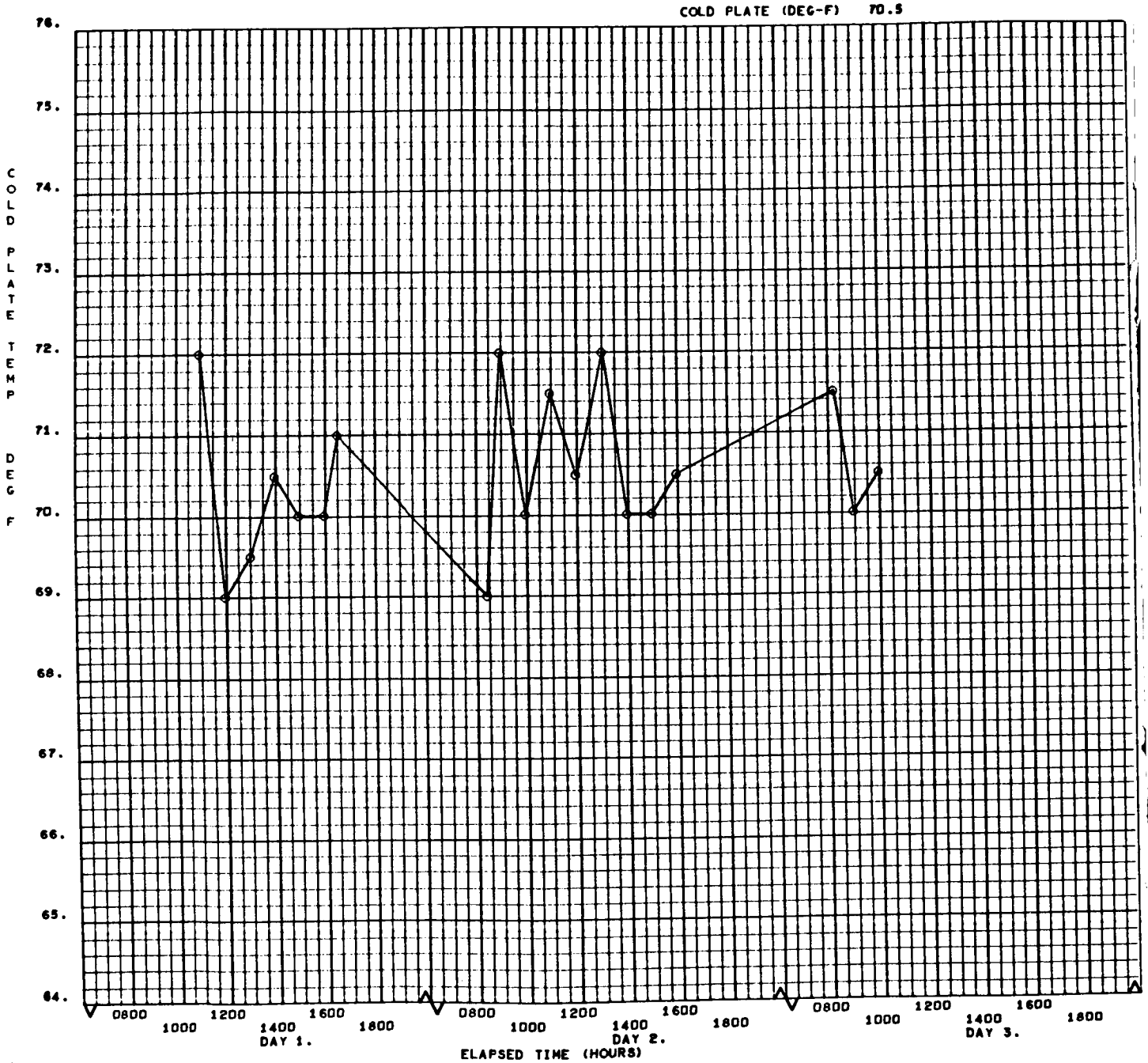


FIGURE 25.E

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 9.2
SAMPLE THICKNESS (IN.) 0.1875
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 300.0
COLD PLATE (DEG-F) 70.5

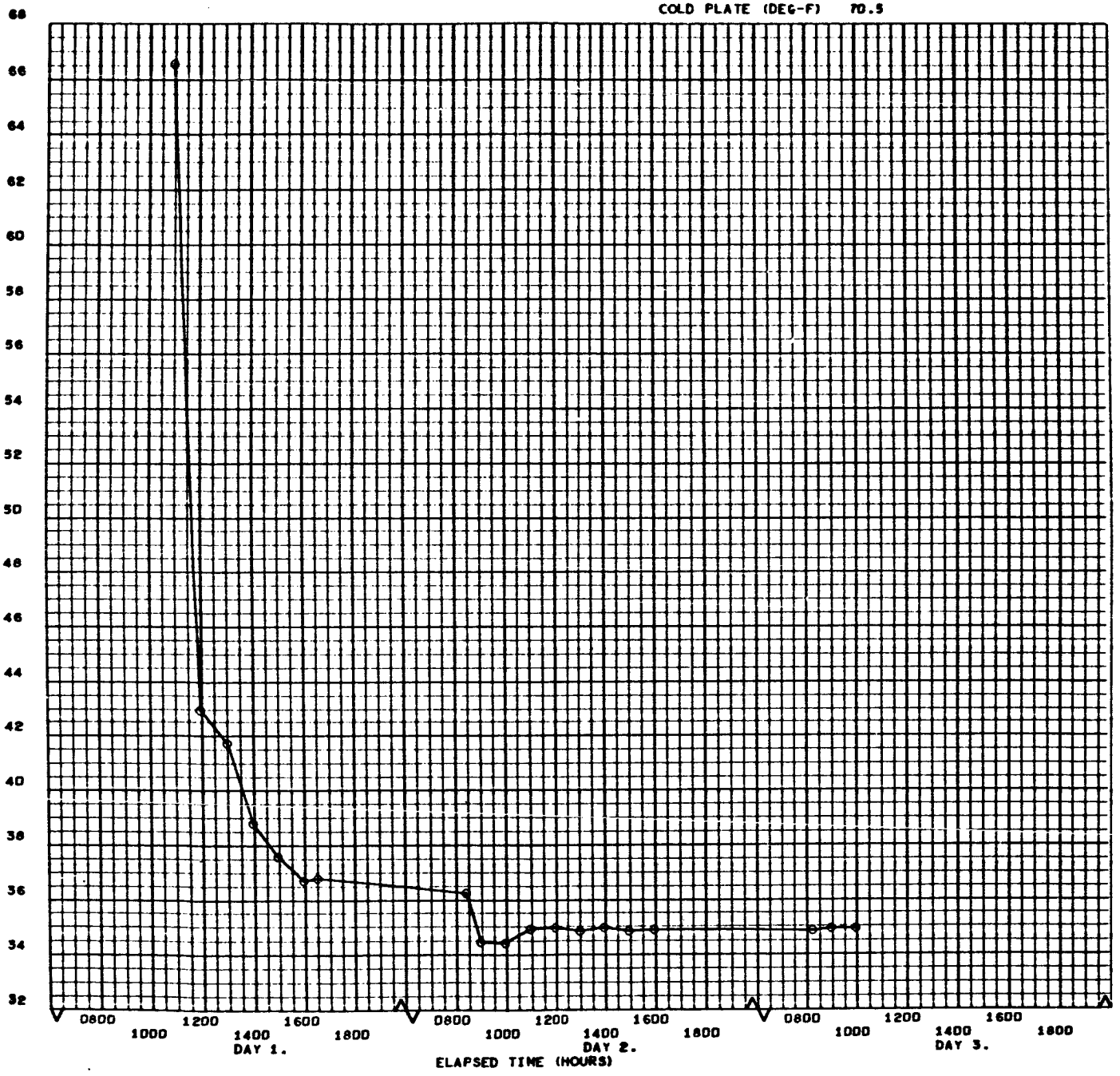


FIGURE 26.A

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 10.2
SAMPLE THICKNESS (IN.) 0.3125
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 74.0
COLD PLATE (DEG-F)- 310.0

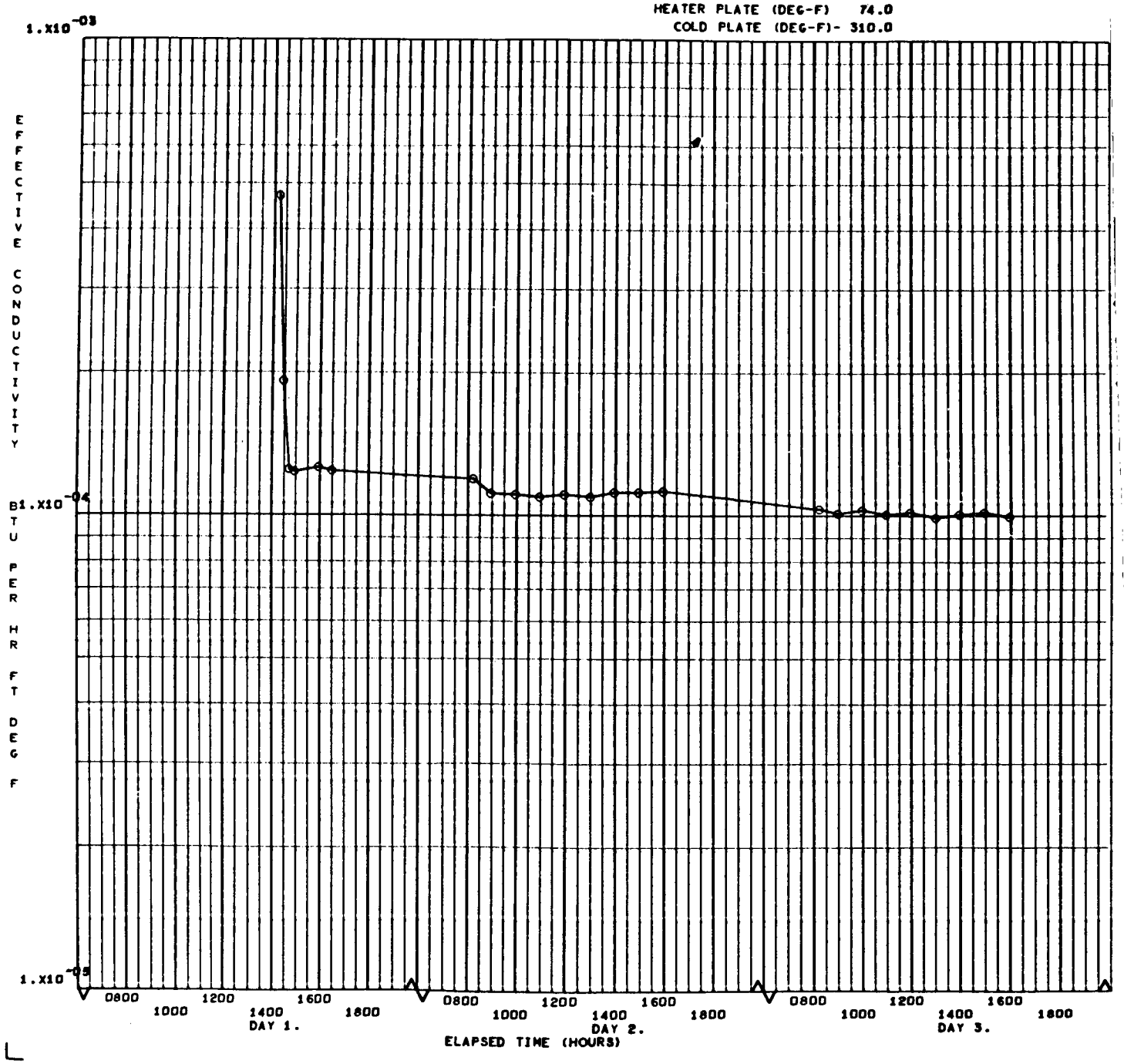


FIGURE 26.B

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 10.2
SAMPLE THICKNESS (IN.) 0.3125
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 74.0
COLD PLATE (DEG-F)- 310.0

FIGURE 26.C

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 10.2
SAMPLE THICKNESS (IN.) 0.3125
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 74.0
COLD PLATE (DEG-F)- 310.0

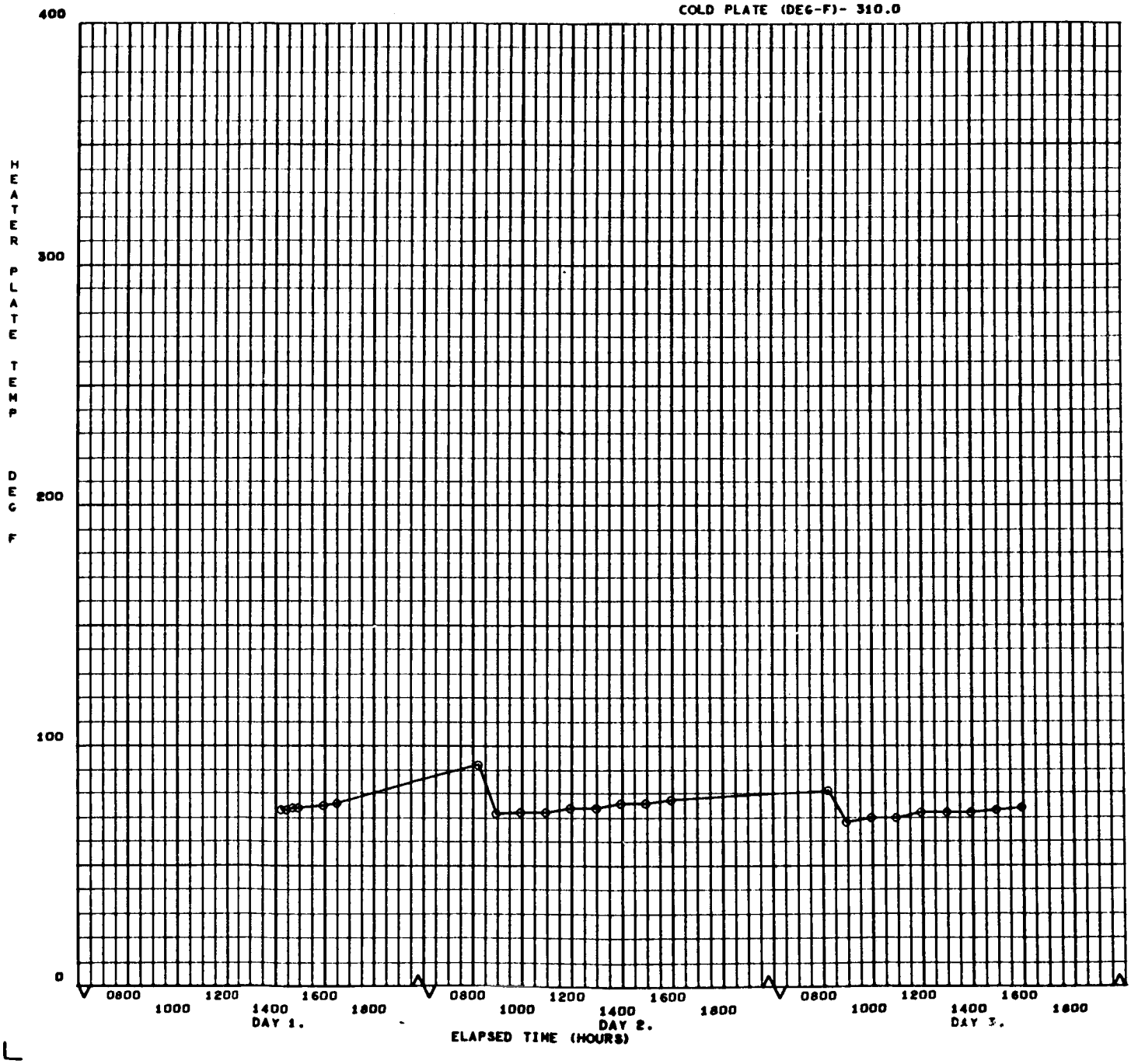


FIGURE 26.D

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 10.2
SAMPLE THICKNESS (IN.) 0.3125
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 74.0
COLD PLATE (DEG-F)- 310.0

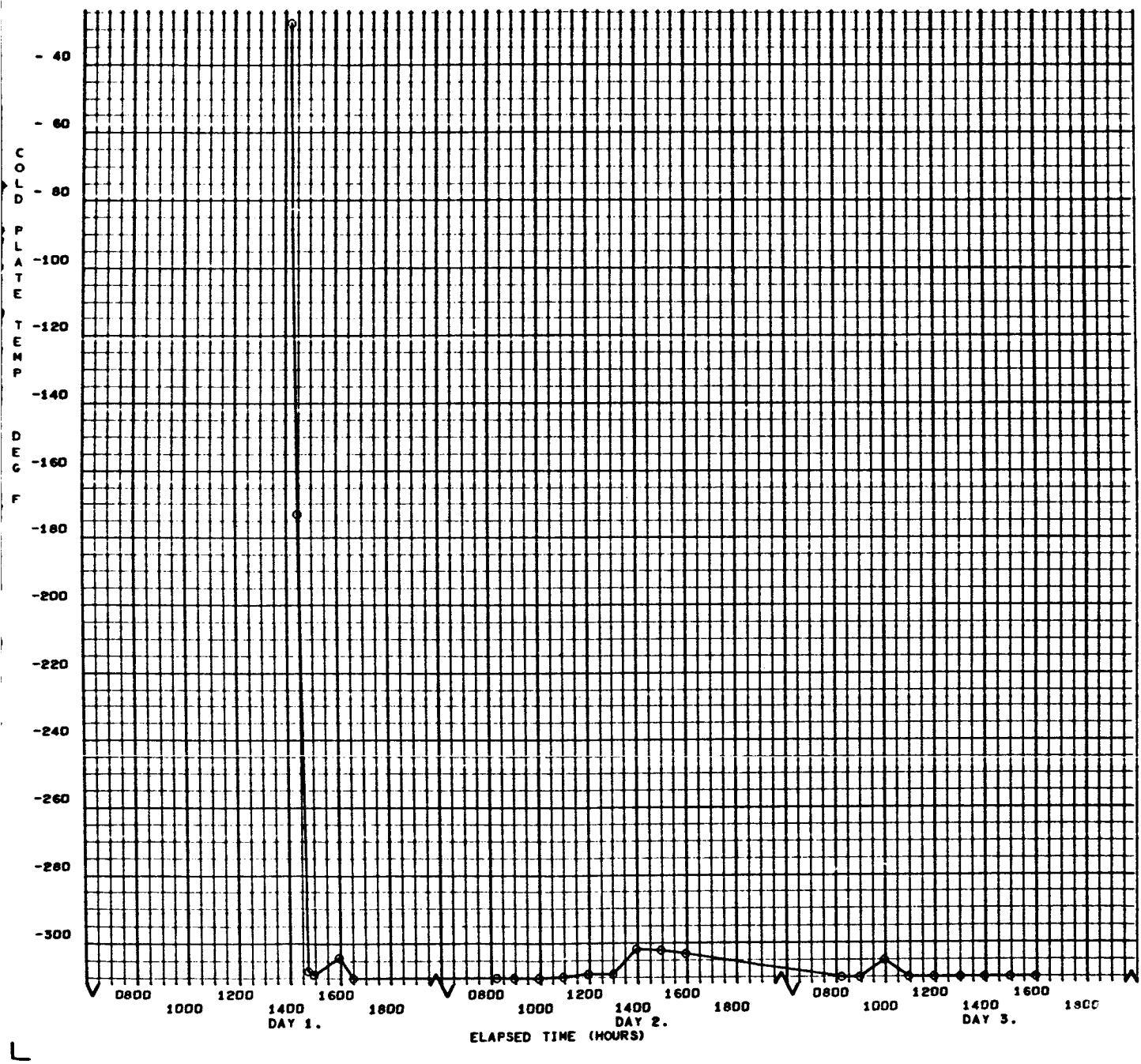


FIGURE 26.E

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 10.2
SAMPLE THICKNESS (IN.) 0.3125
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 74.0
COLD PLATE (DEG-F)- 310.0

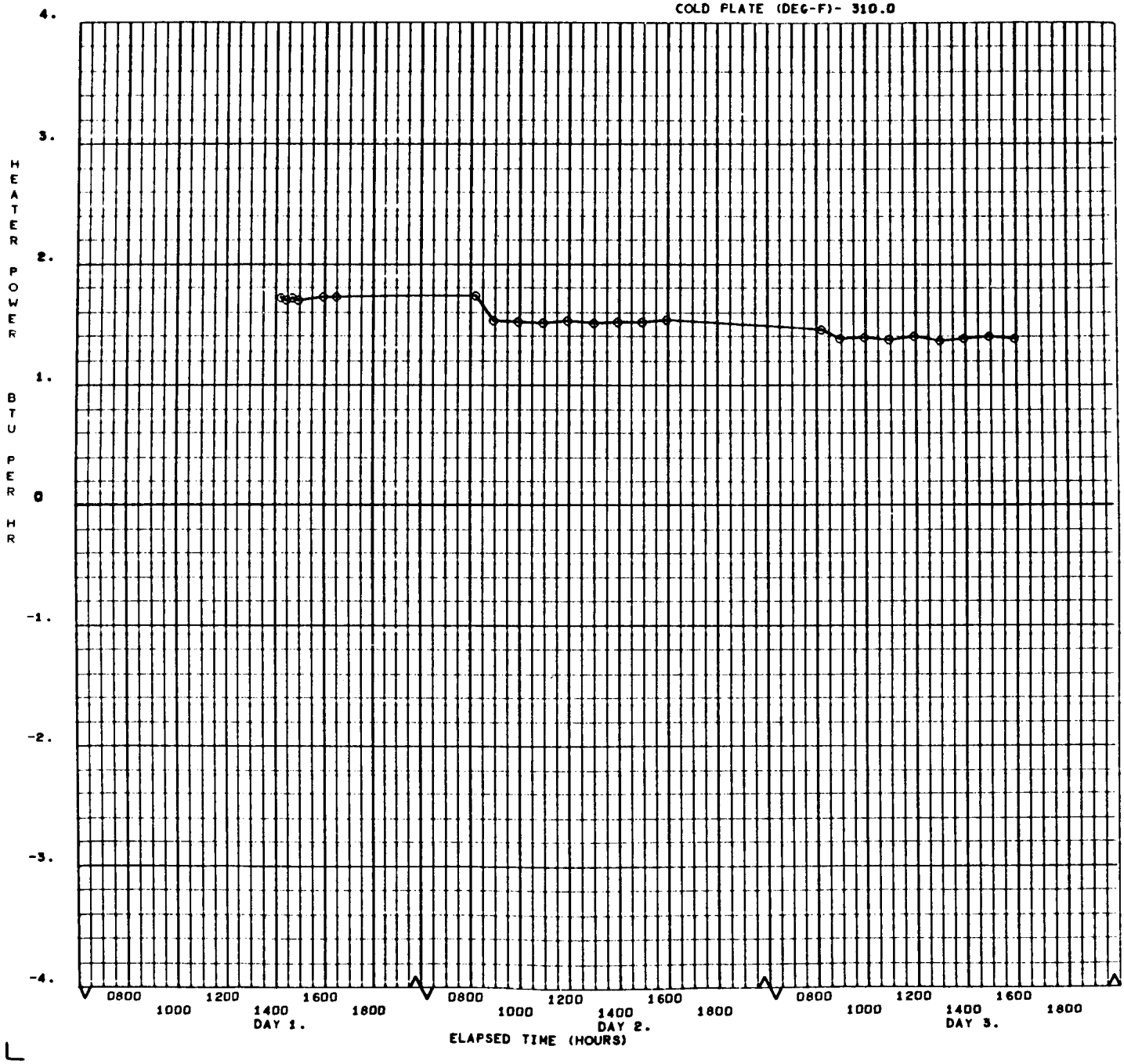


FIGURE 27.A

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 11.2
SAMPLE THICKNESS (IN.) 0.1875
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 70.0
COLD PLATE (DEG-F)- 310.0

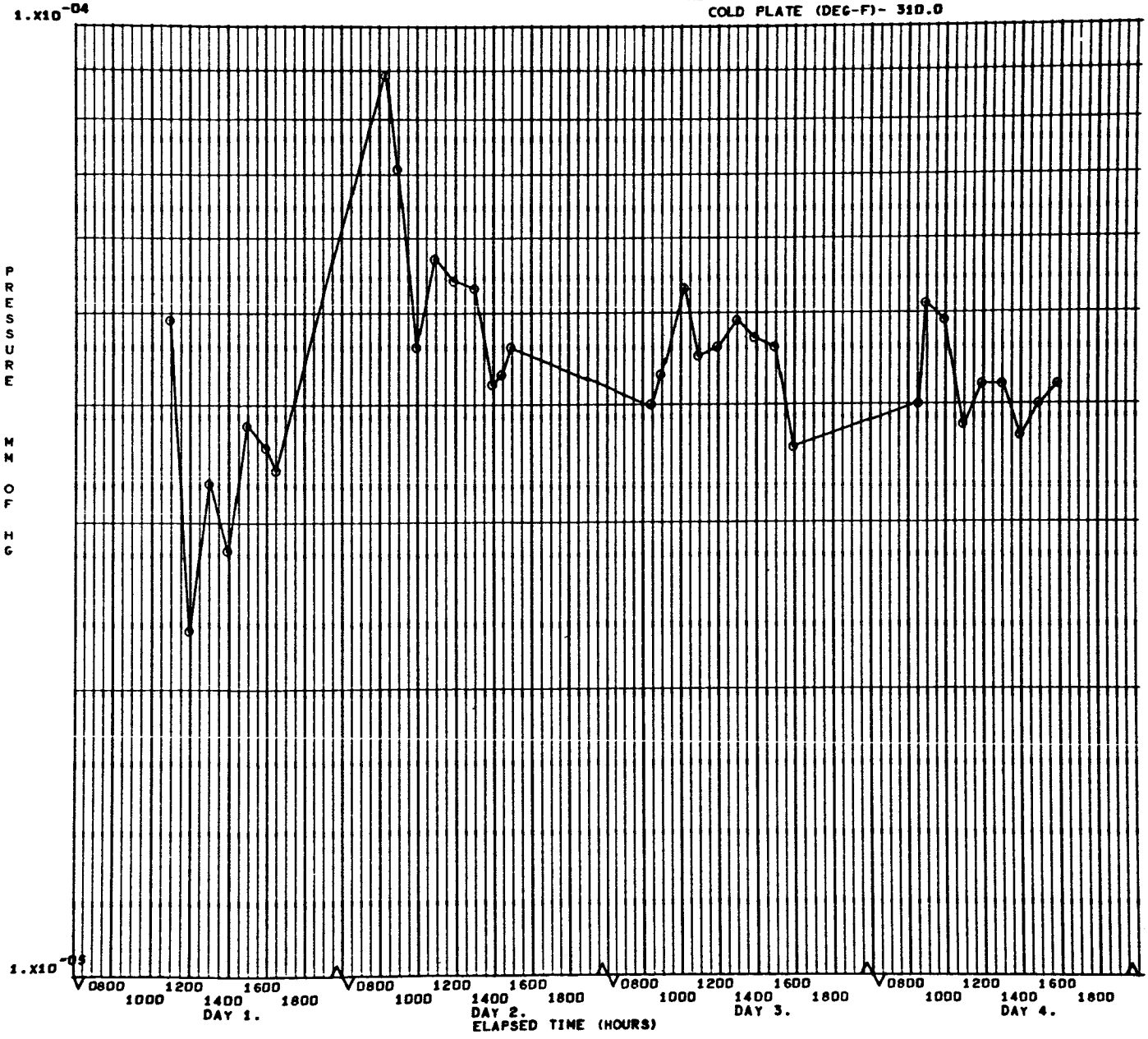


FIGURE 27.B

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 11.2
SAMPLE THICKNESS (IN.) 0.1875
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 70.0
COLD PLATE (DEG-F)- 310.0

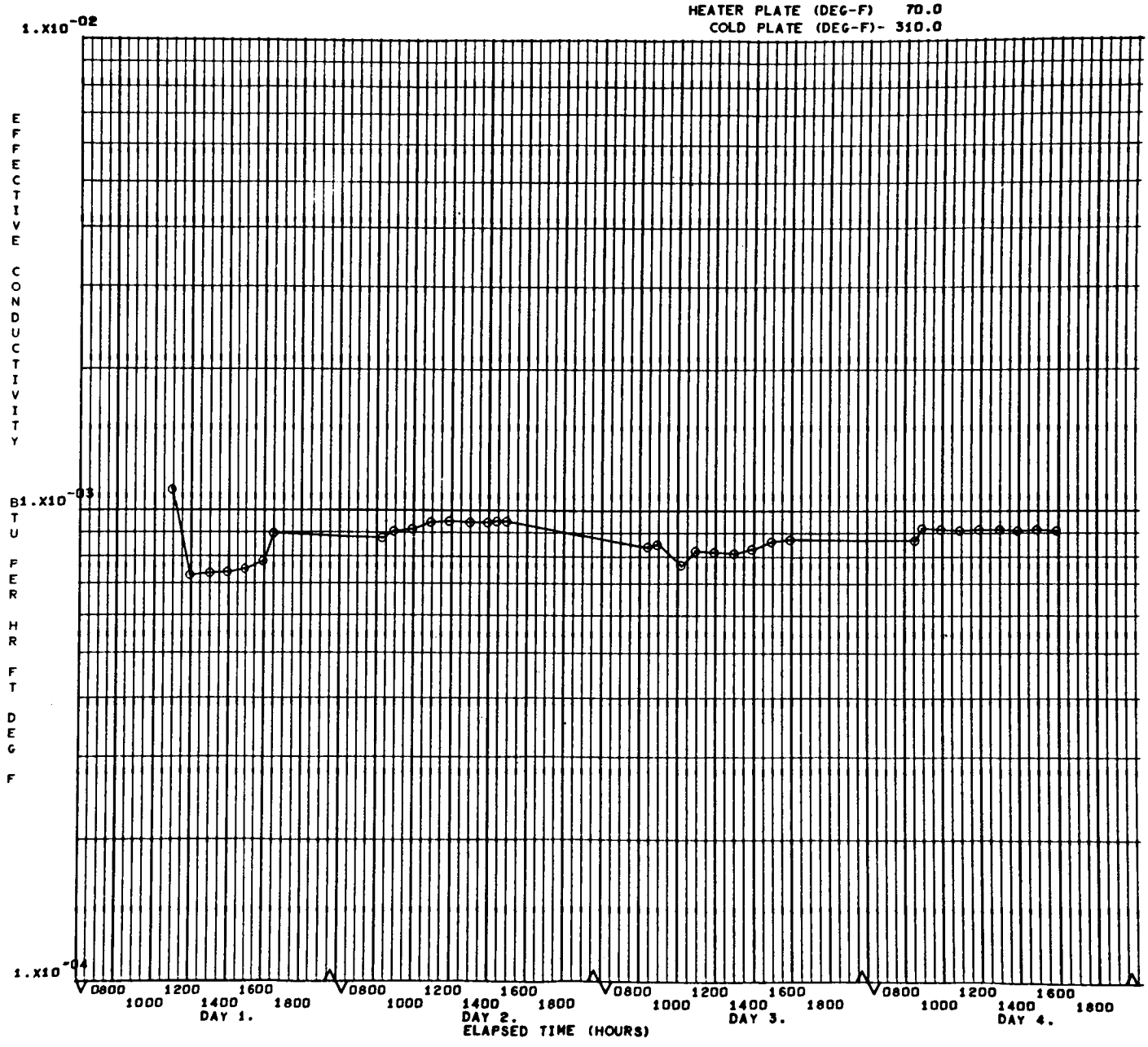


FIGURE 27.C

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 11.2
SAMPLE THICKNESS (IN.) 0.1875
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 70.0
COLD PLATE (DEG-F)- 310.0

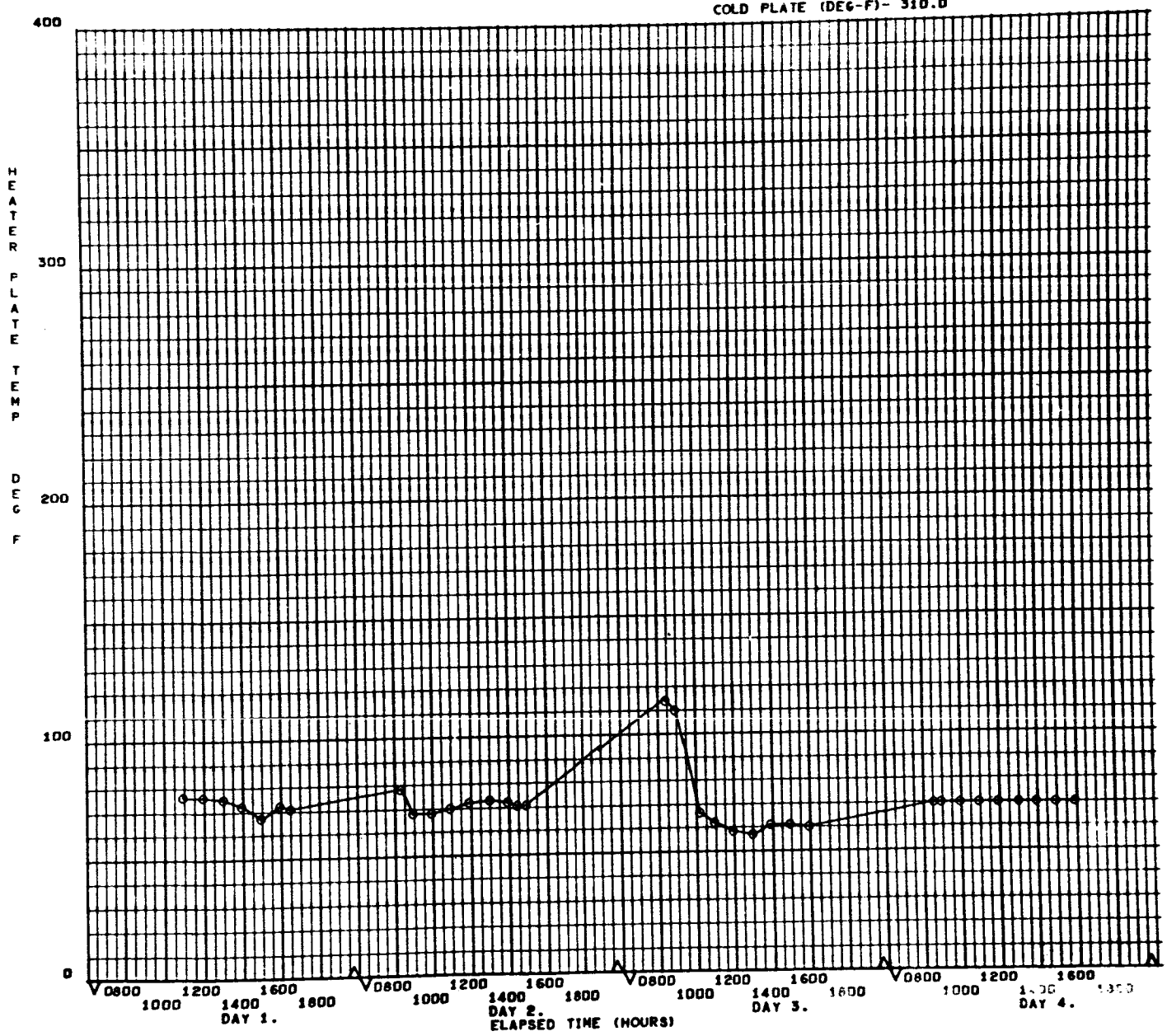


FIGURE 27.D

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 11.2
SAMPLE THICKNESS (IN.) 0.1875
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 70.0
COLD PLATE (DEG-F)- 310.0

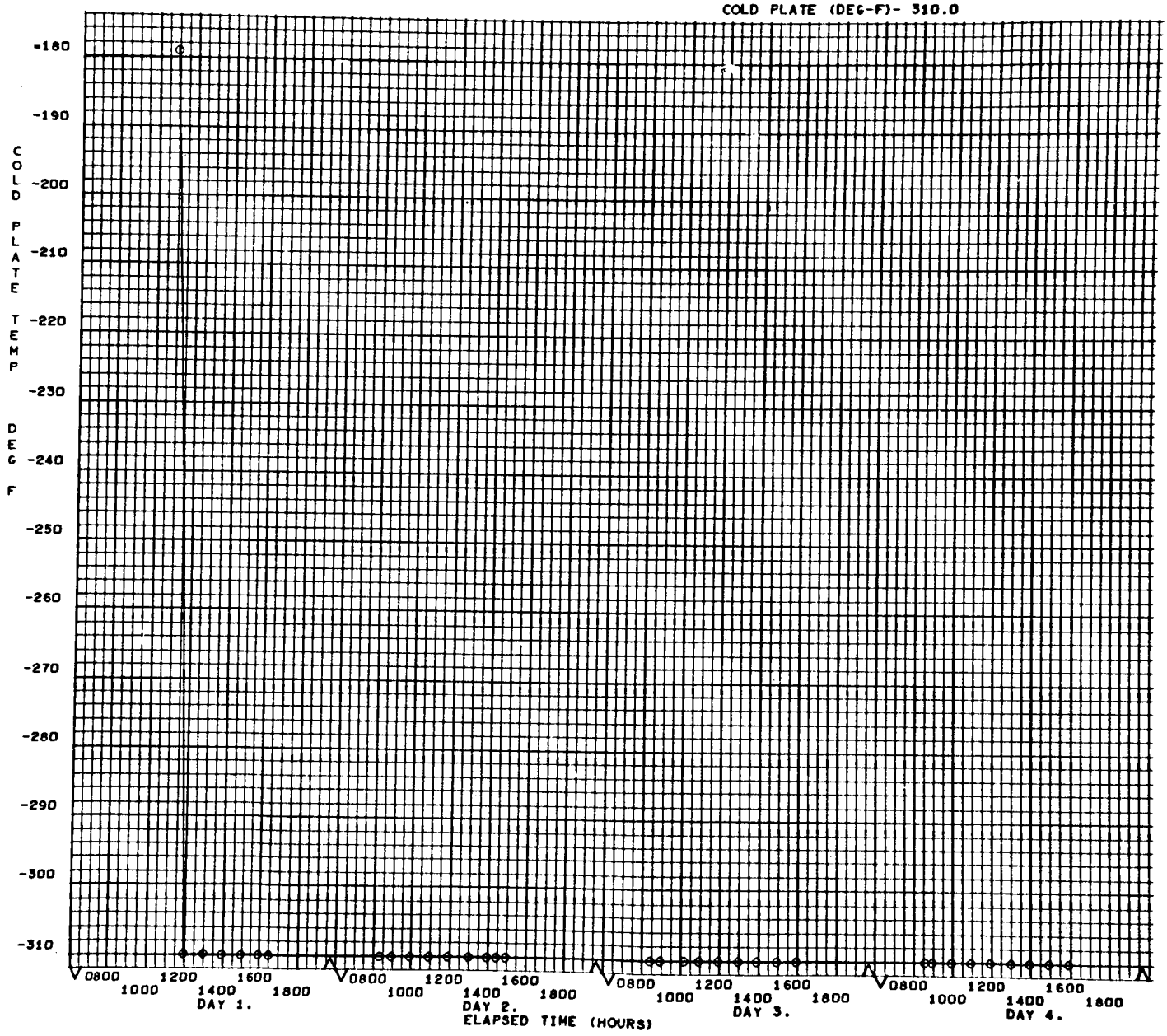


FIGURE 27.E

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 11.2
SAMPLE THICKNESS (IN.) 0.1875
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 70.0
COLD PLATE (DEG-F)- 310.0

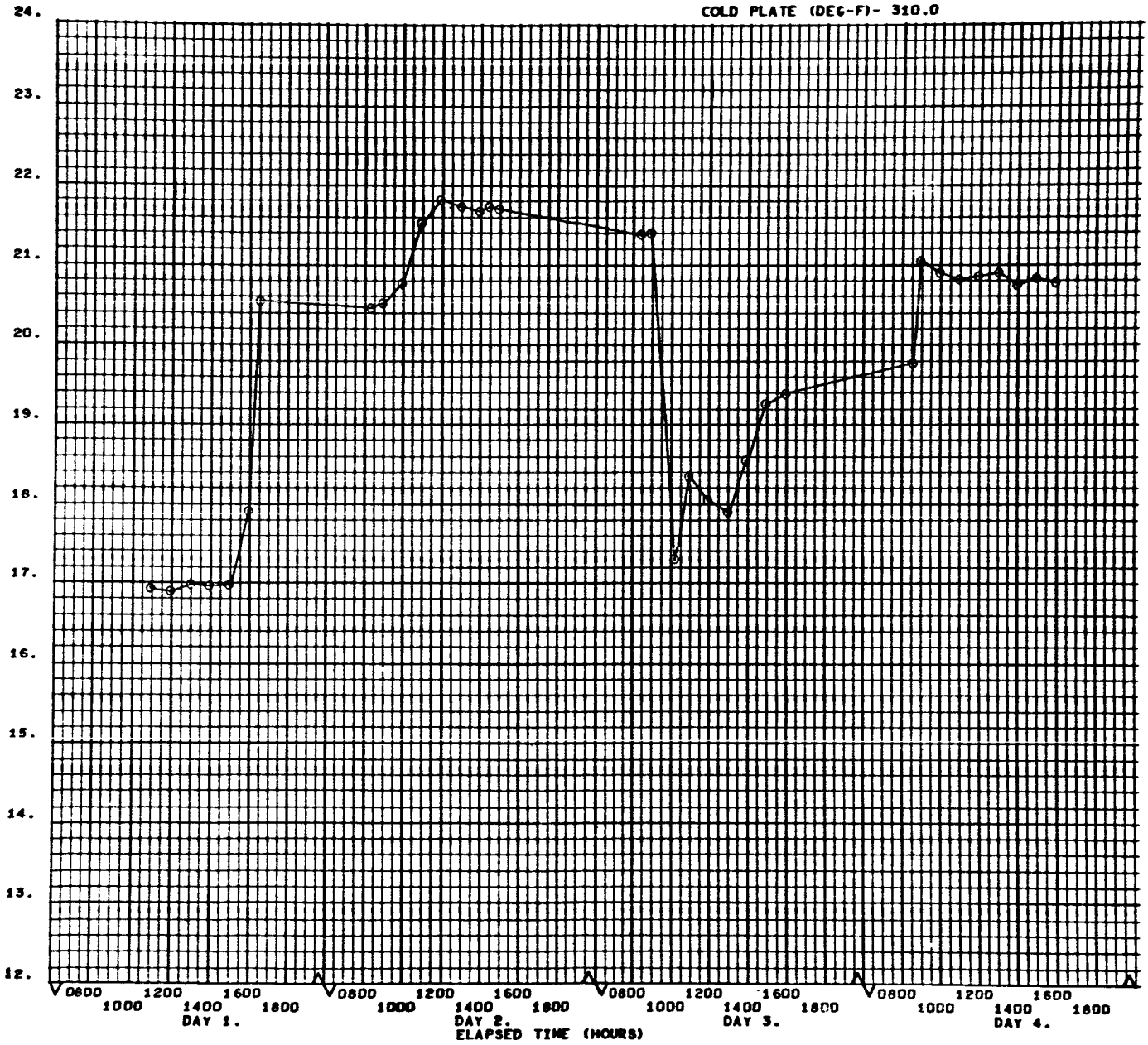


FIGURE 28.A

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 10.1
SAMPLE THICKNESS (IN.) 0.3125
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 306.5
COLD PLATE (DEG-F) 70.0

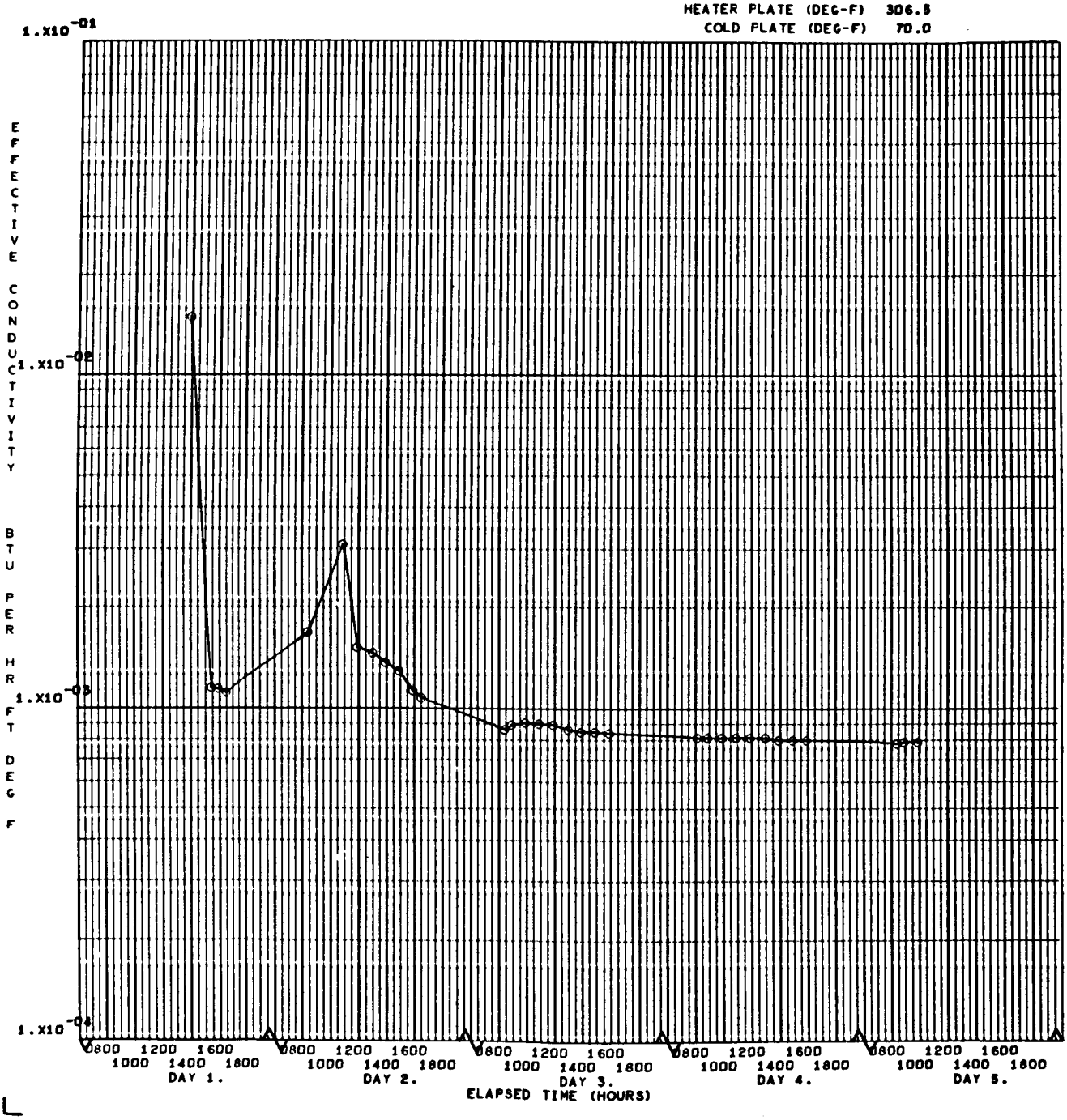


FIGURE 28.B

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 10.1
SAMPLE THICKNESS (IN.) 0.3125
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 306.5
COLD PLATE (DEG-F) 70.0

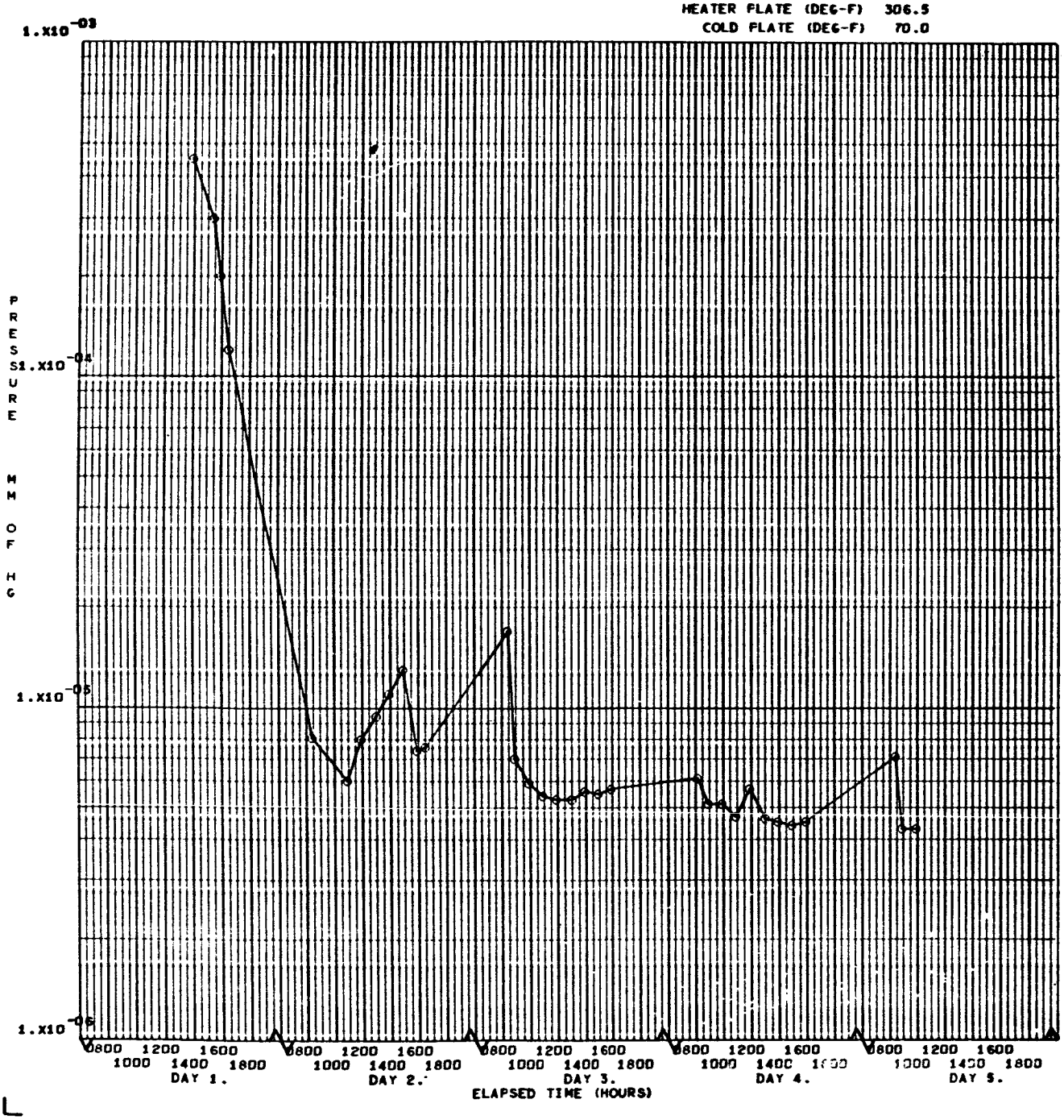


FIGURE 28.C

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 10.1
SAMPLE THICKNESS (IN.) 0.3125
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 306.5
COLD PLATE (DEG-F) 70.0

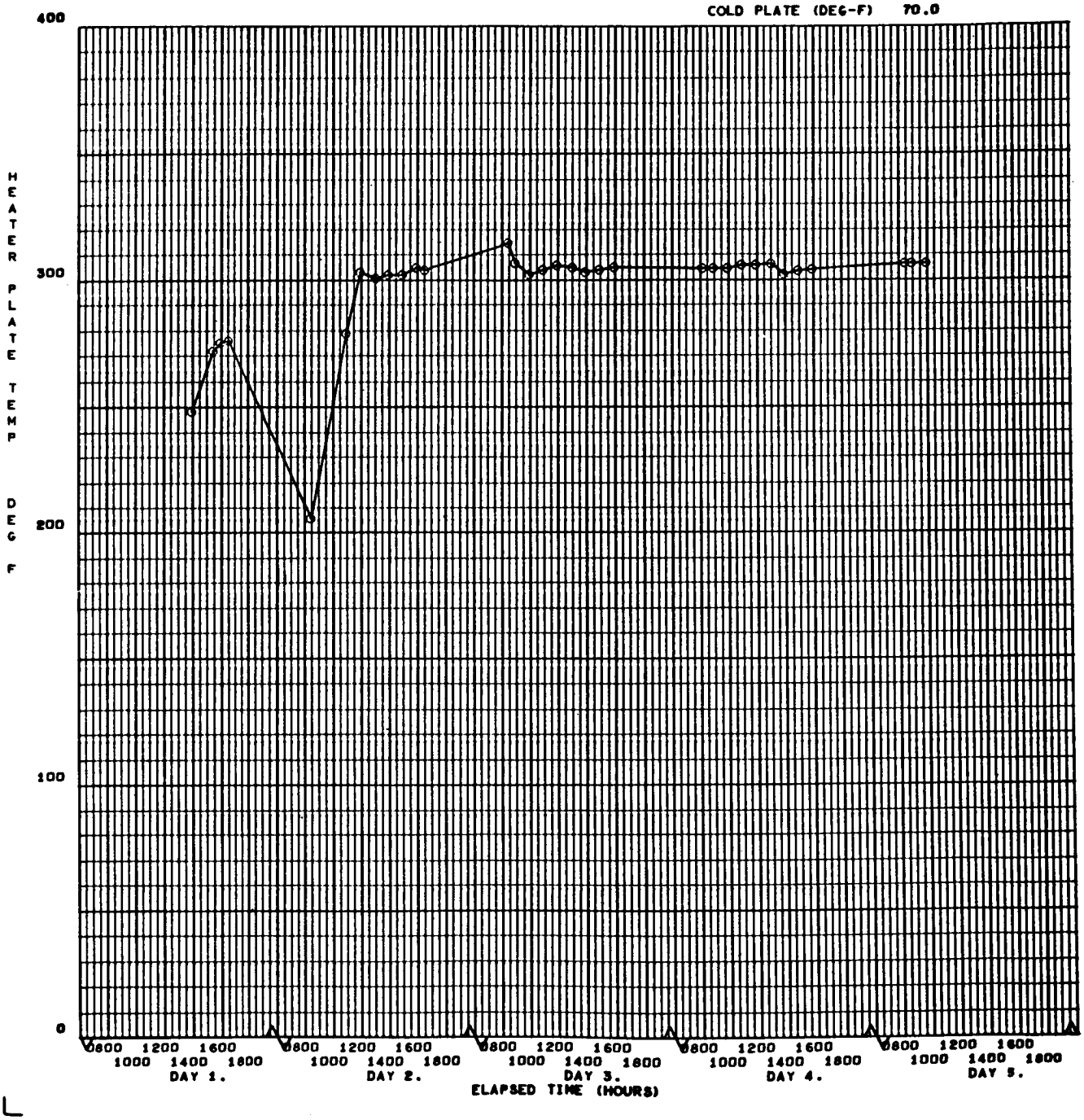


FIGURE 28.D

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 10.1
SAMPLE THICKNESS (IN.) 0.3125
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 306.5
COLD PLATE (DEG-F) 70.0

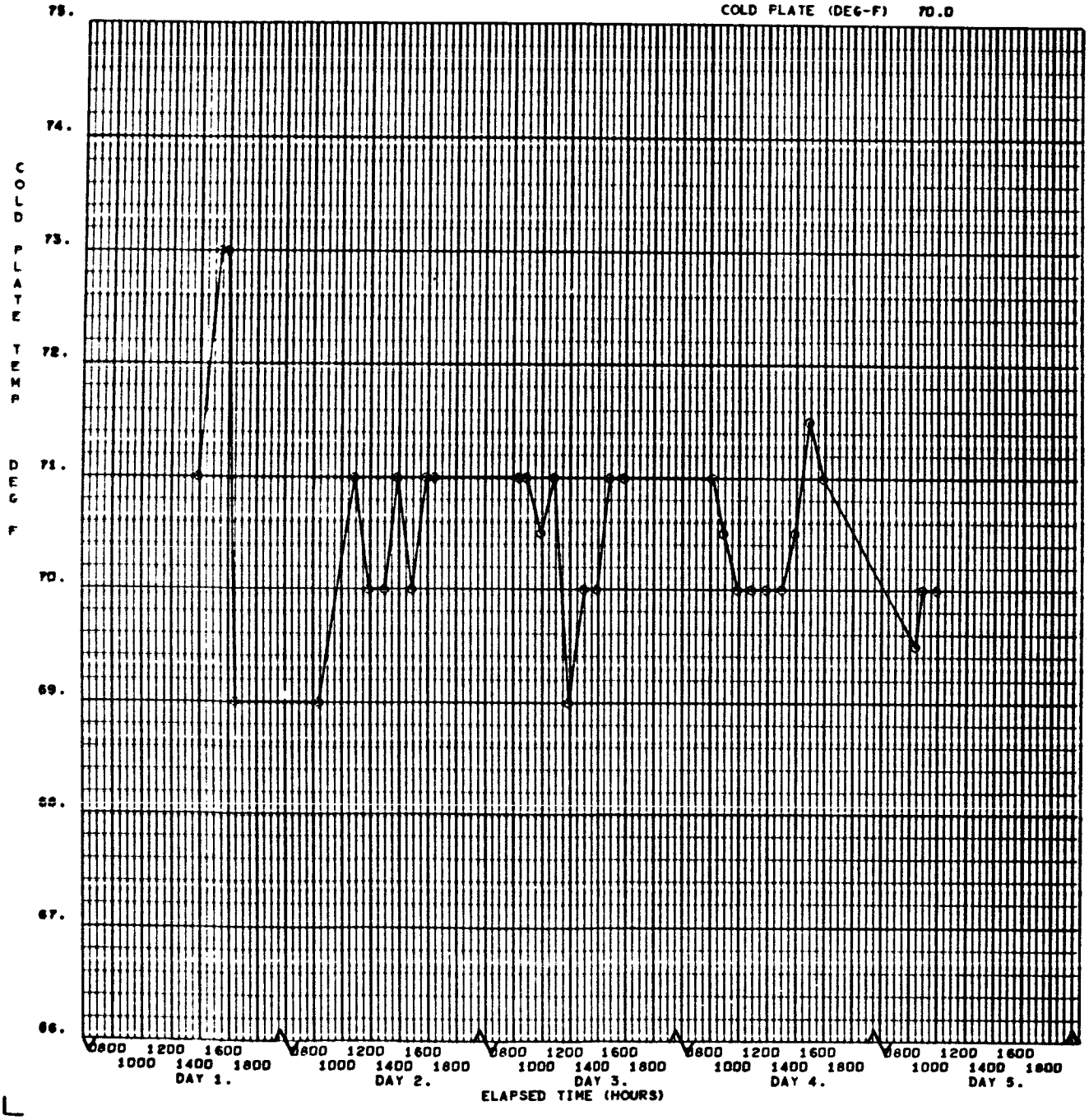


FIGURE 28.E

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 10.1
SAMPLE THICKNESS (IN.) 0.3125
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 306.5
COLD PLATE (DEG-F) 70.0

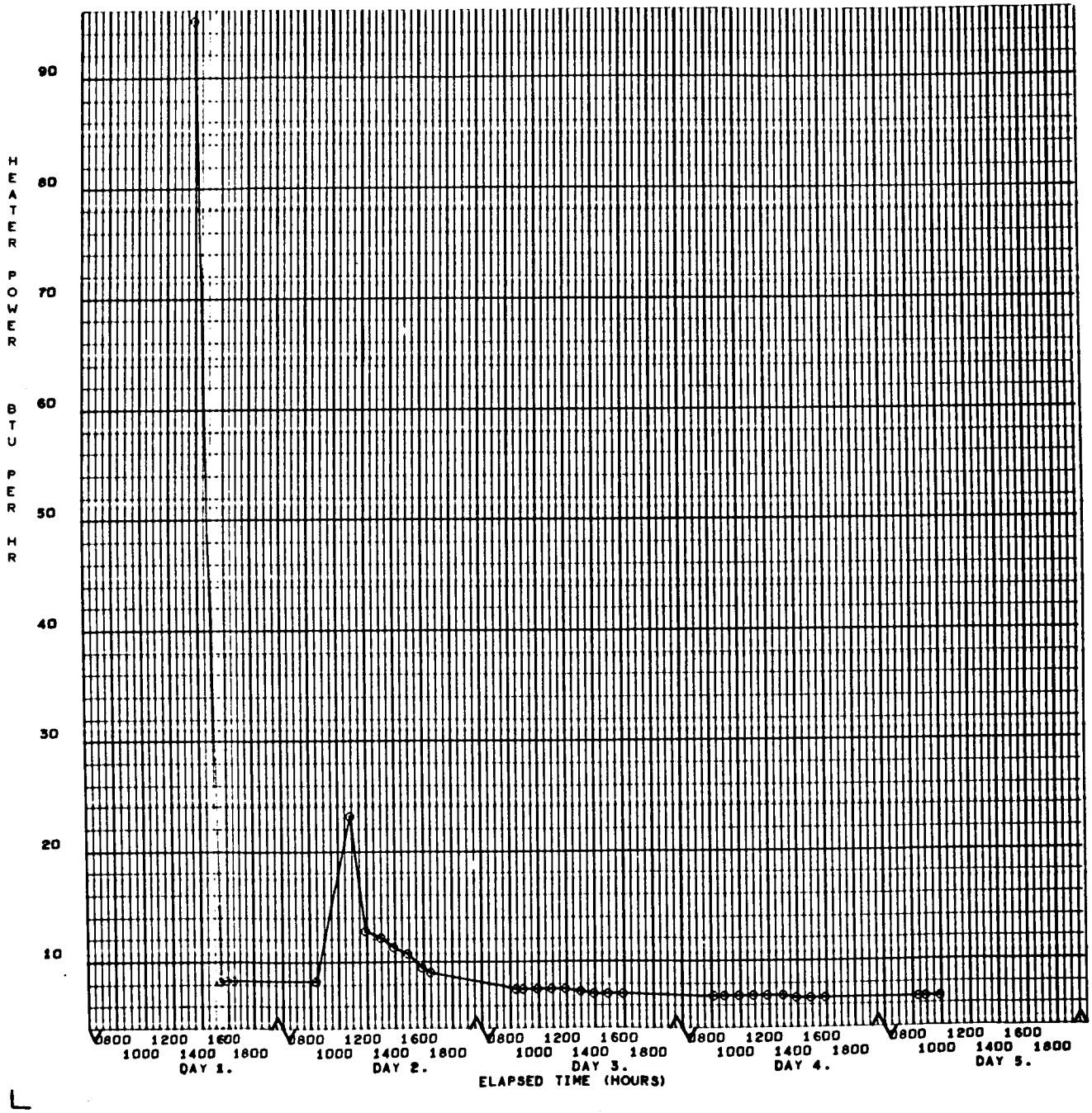


FIGURE 29.A

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 12.1
SAMPLE THICKNESS (IN.) 0.1875
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 73.5
COLD PLATE (DEG-F)- 310.0

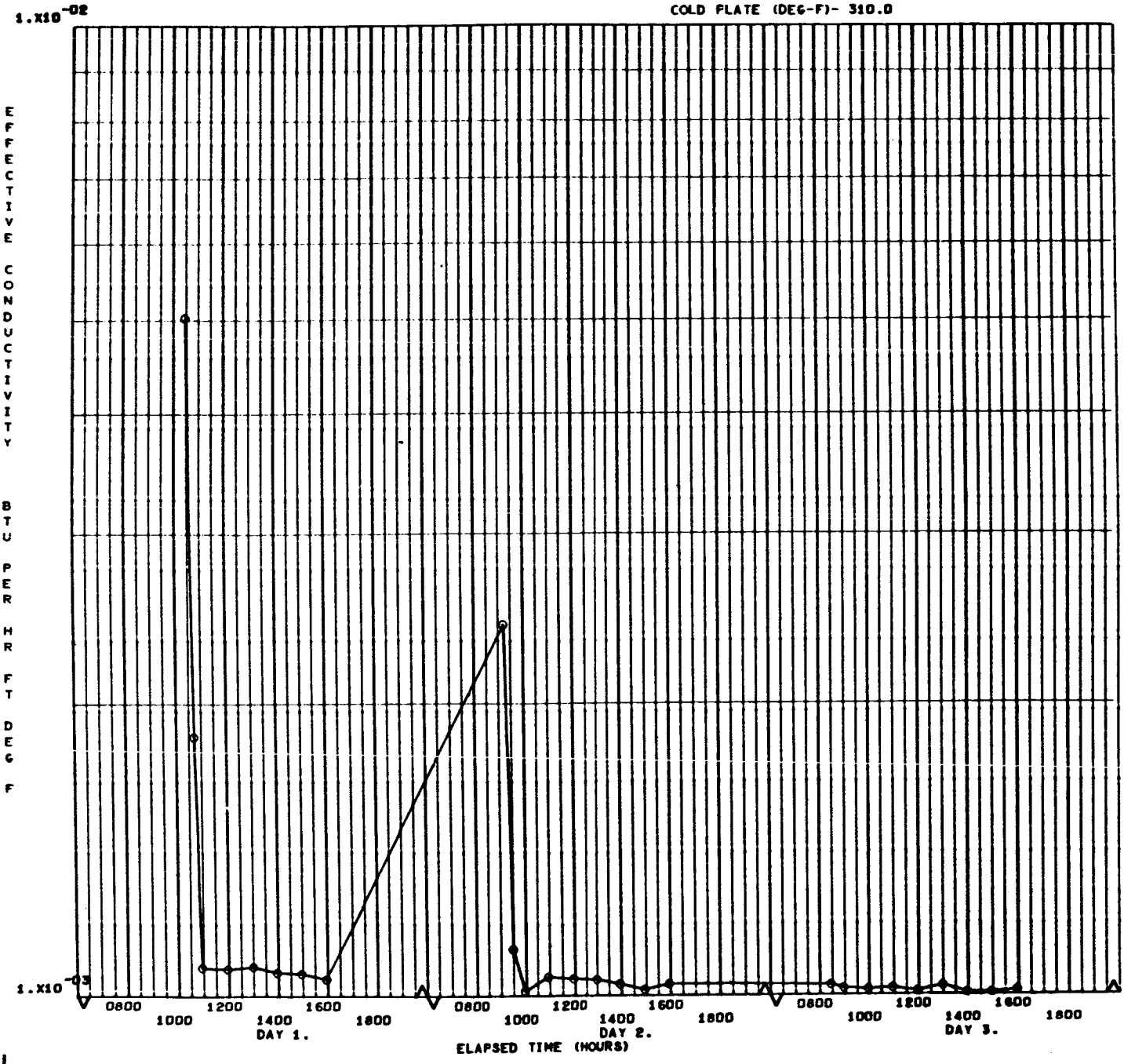


FIGURE 29.B

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 12.1
SAMPLE THICKNESS (IN.) 0.1875
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 73.5
COLD PLATE (DEG-F)- 310.0

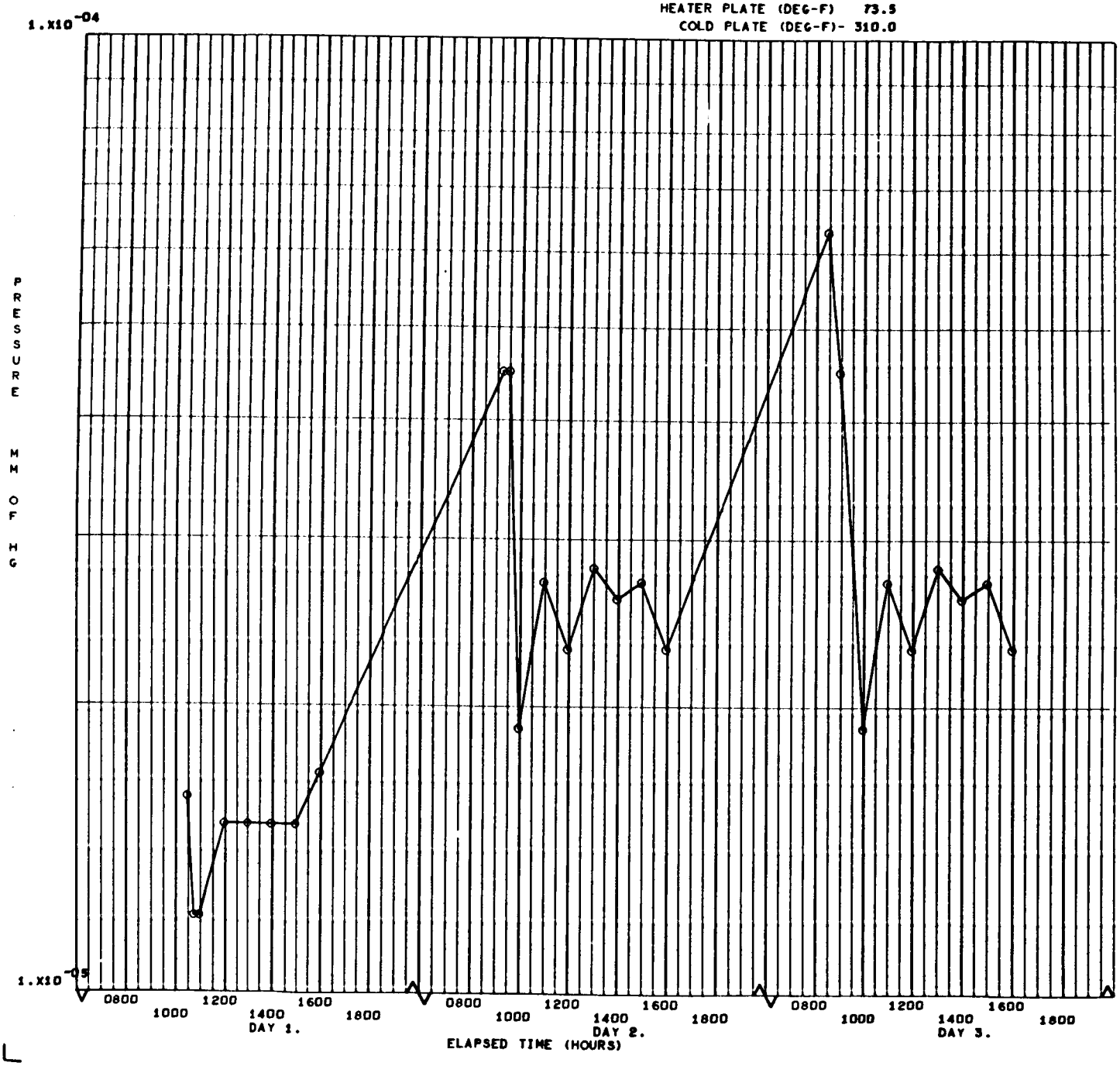


FIGURE 29.C

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 12.1
SAMPLE THICKNESS (IN.) 0.1875
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 73.5
COLD PLATE (DEG-F)- 310.0

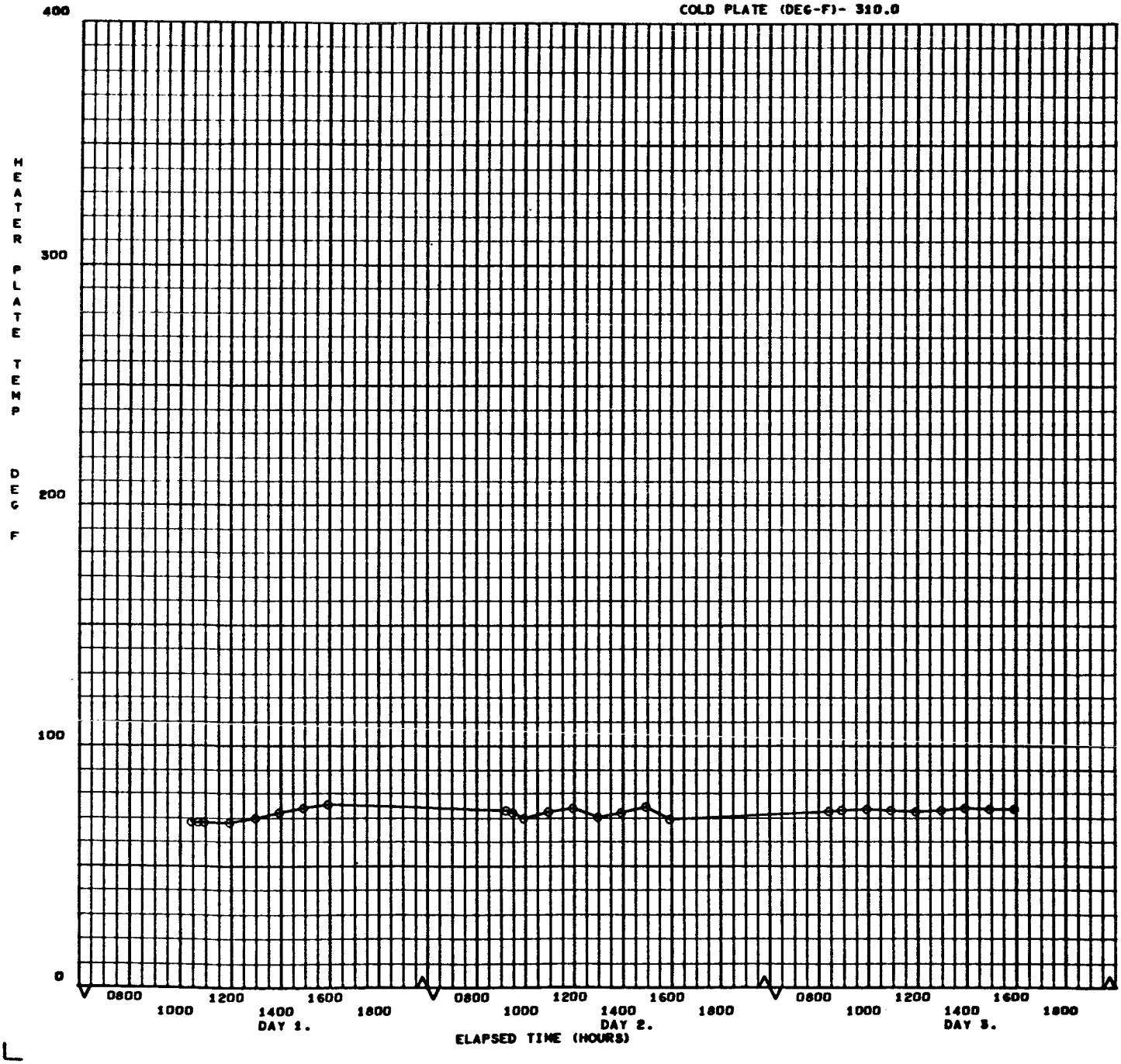


FIGURE 29.D

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 12.1
SAMPLE THICKNESS (IN.) 0.1875
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 73.5
COLD PLATE (DEG-F)- 310.0

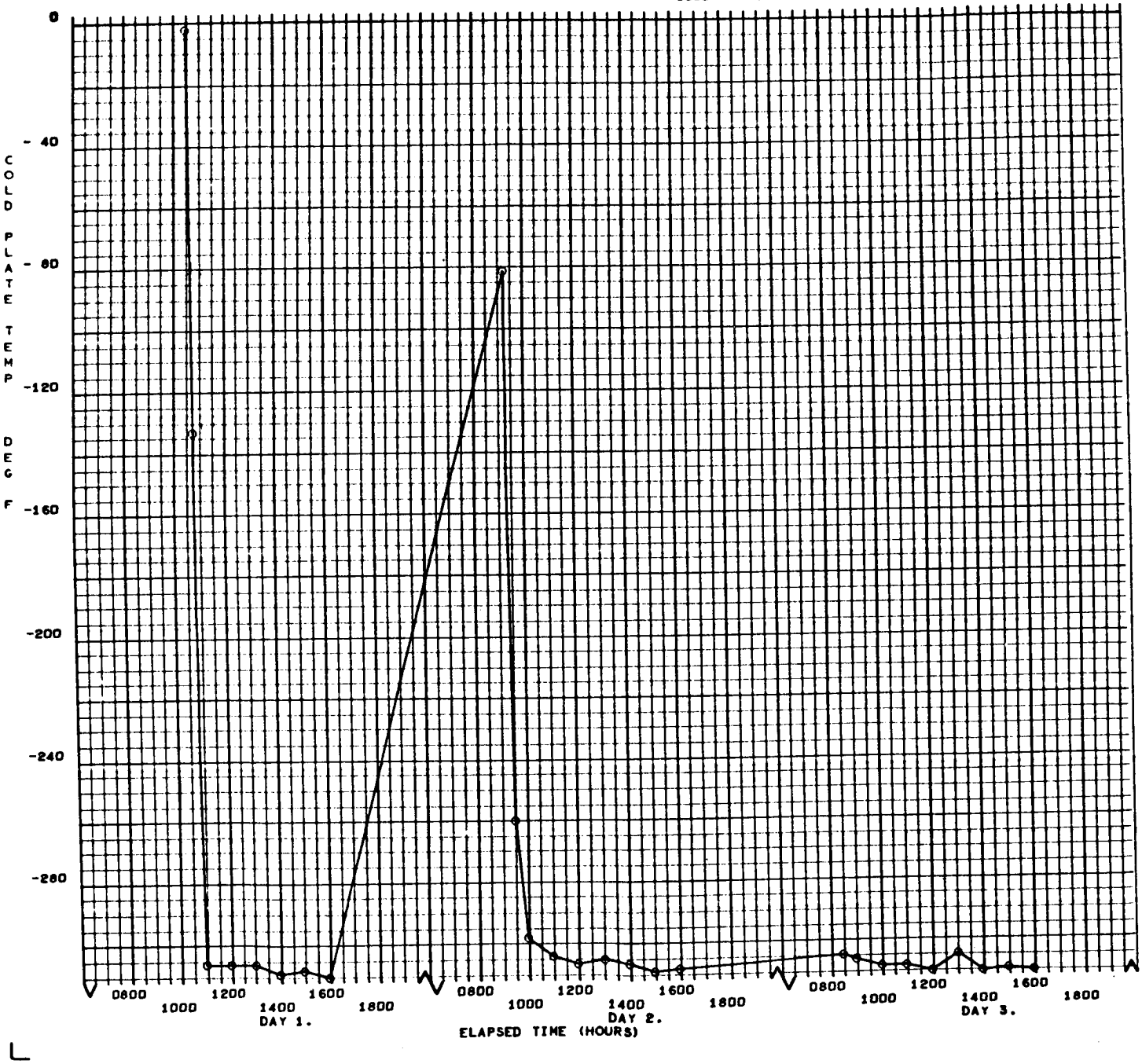


FIGURE 29.E

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 12.1
SAMPLE THICKNESS (IN.) 0.1875
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 73.5
COLD PLATE (DEG-F)- 310.0

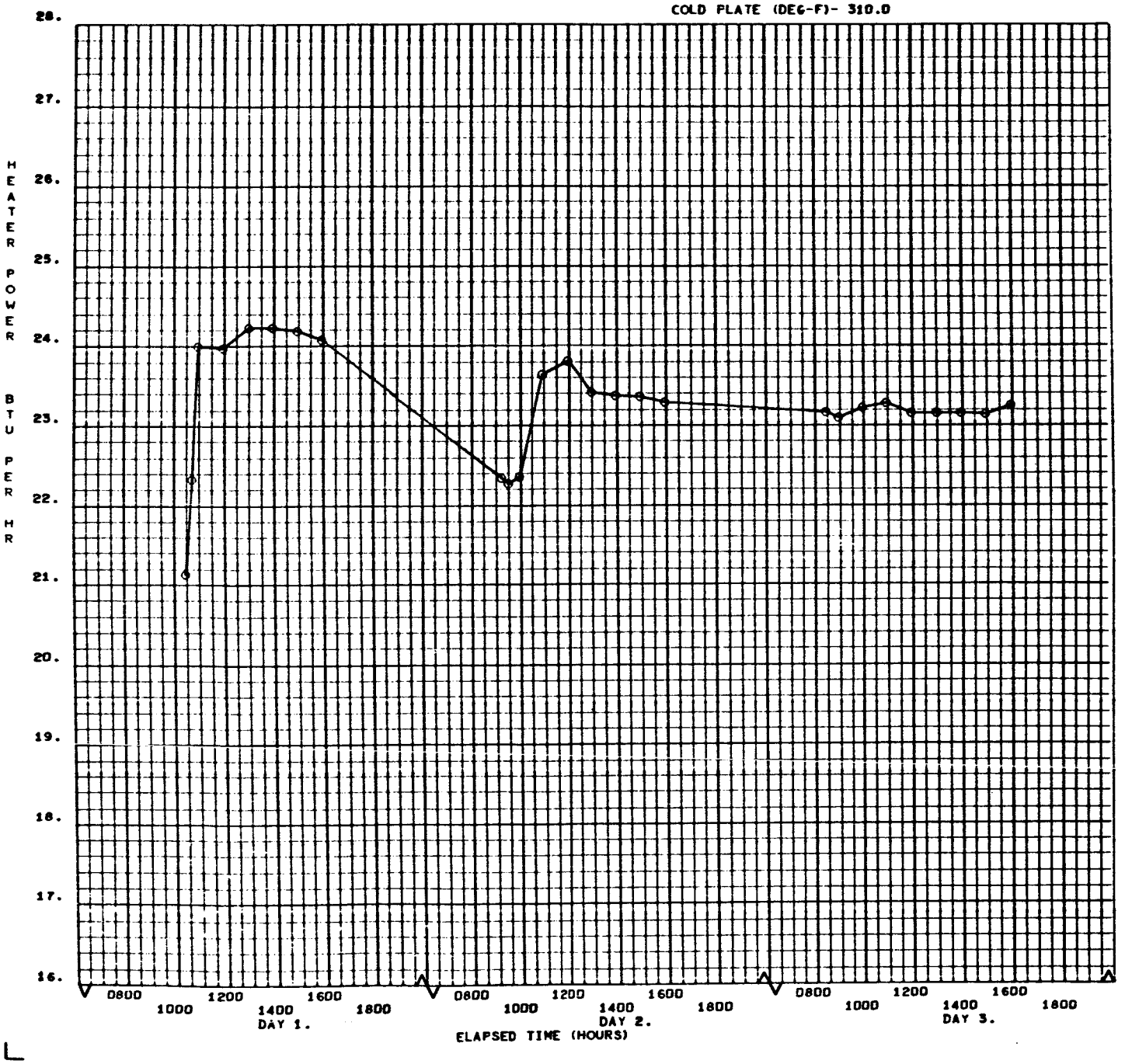


FIGURE 30.A

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 12.2
SAMPLE THICKNESS (IN.) 0.1875
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 300.5
COLD PLATE (DEG-F) 69.5

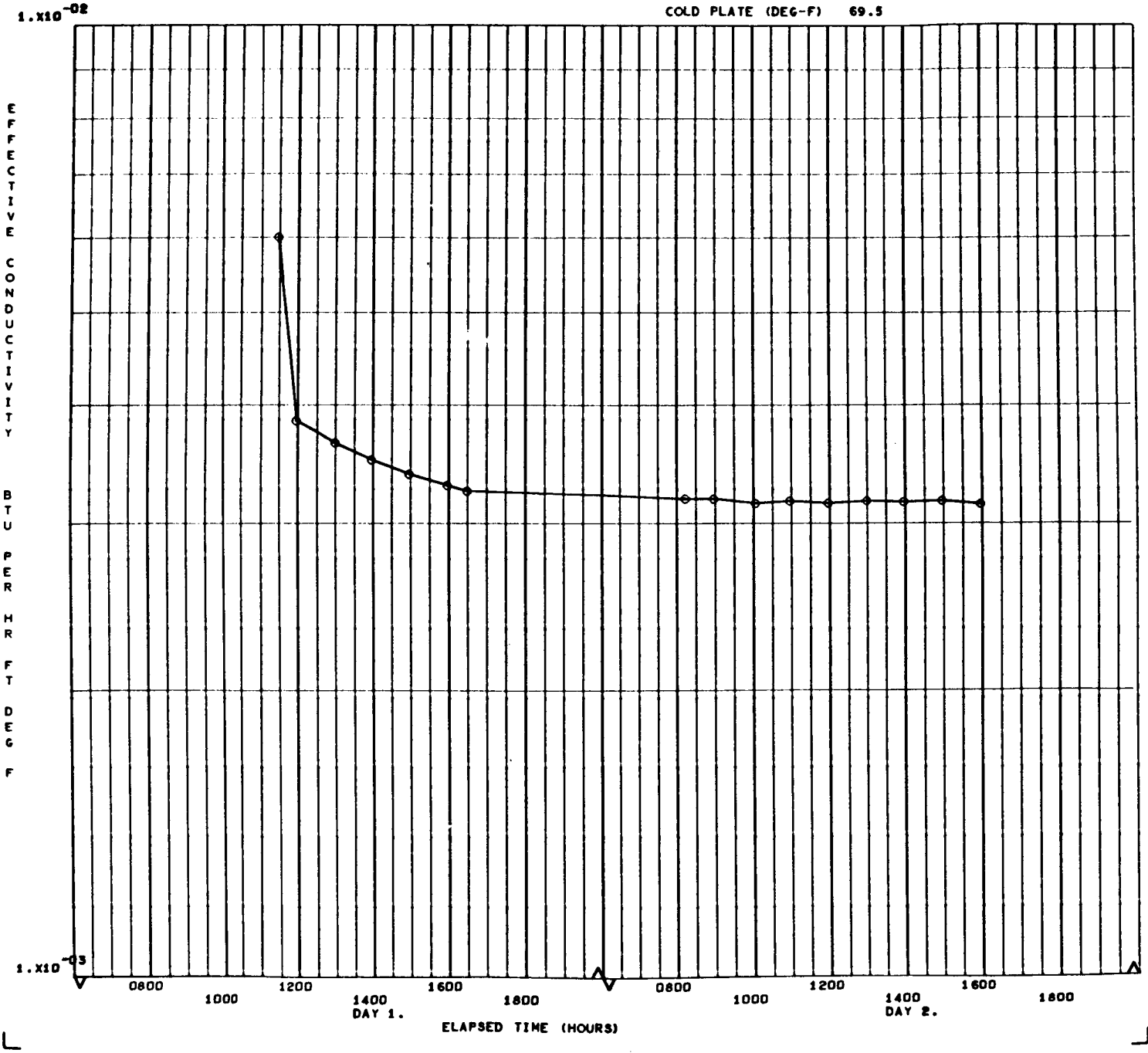


FIGURE 30.B

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 12.2
SAMPLE THICKNESS (IN.) 0.1875
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 300.5
COLD PLATE (DEG-F) 69.5

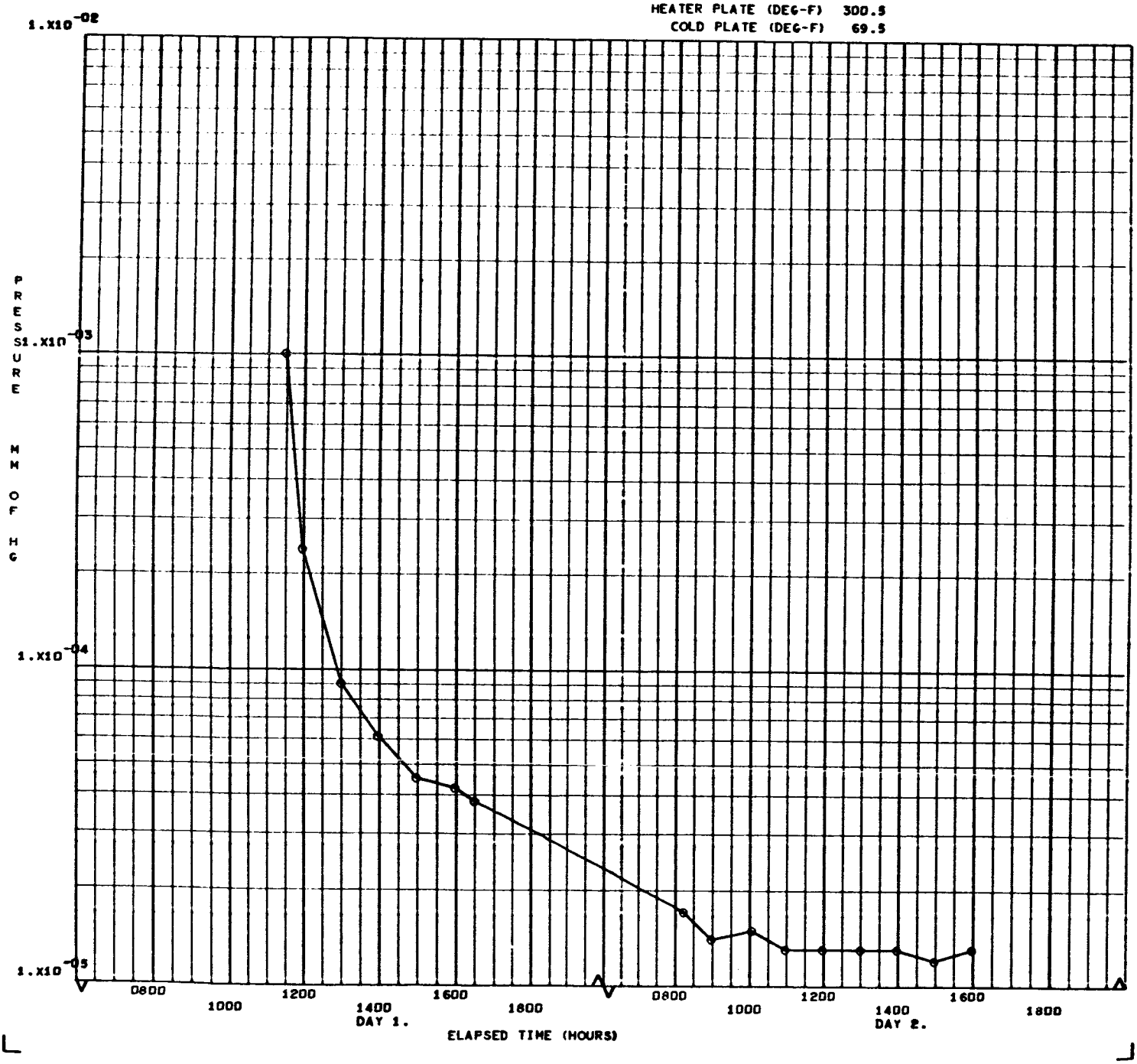


FIGURE 30.C

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 12.2
SAMPLE THICKNESS (IN.) 0.1875
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 300.5
COLD PLATE (DEG-F) 69.5

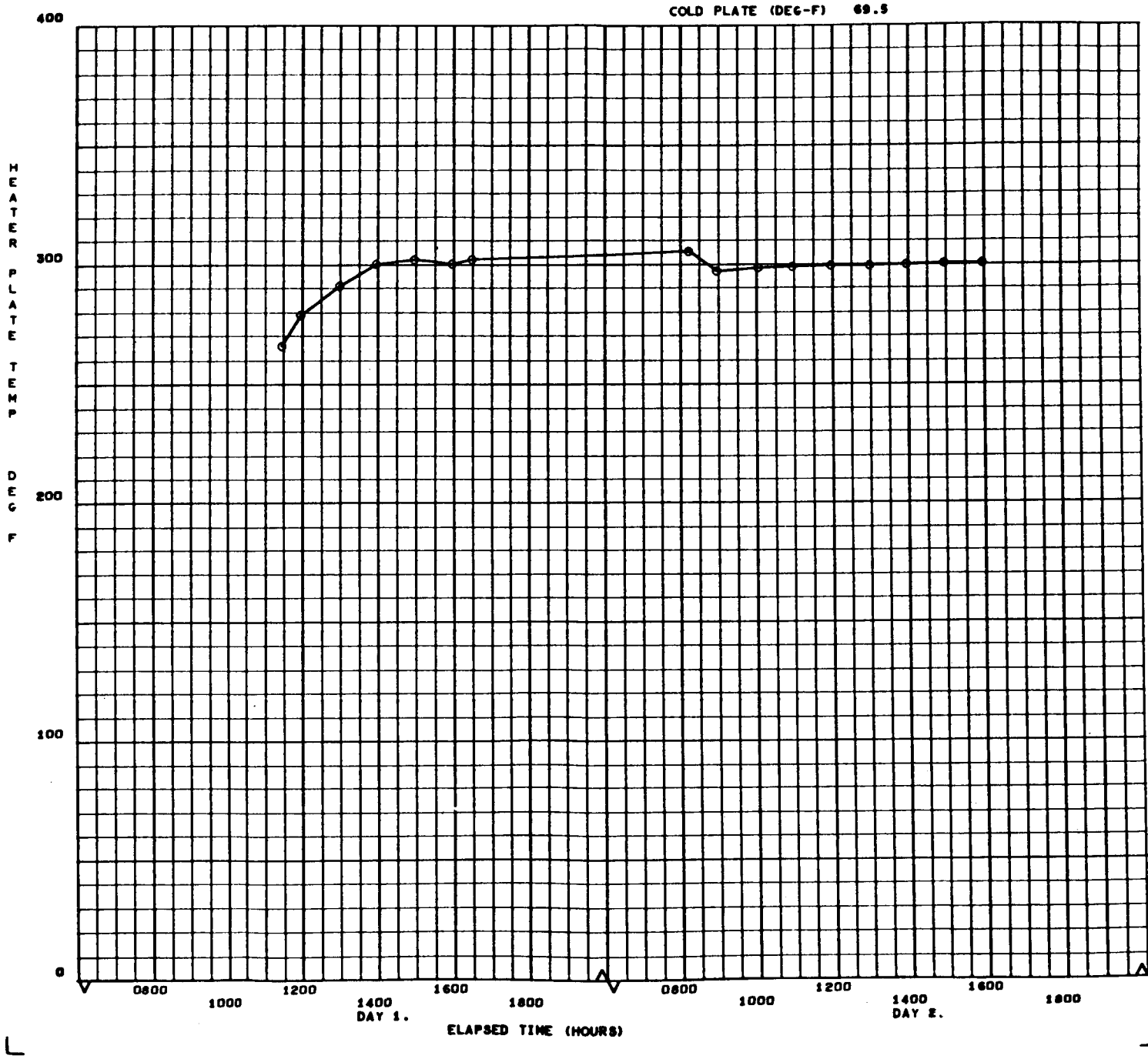


FIGURE 30.D

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 12.2
SAMPLE THICKNESS (IN.) 0.1875
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 300.5
COLD PLATE (DEG-F) 69.5

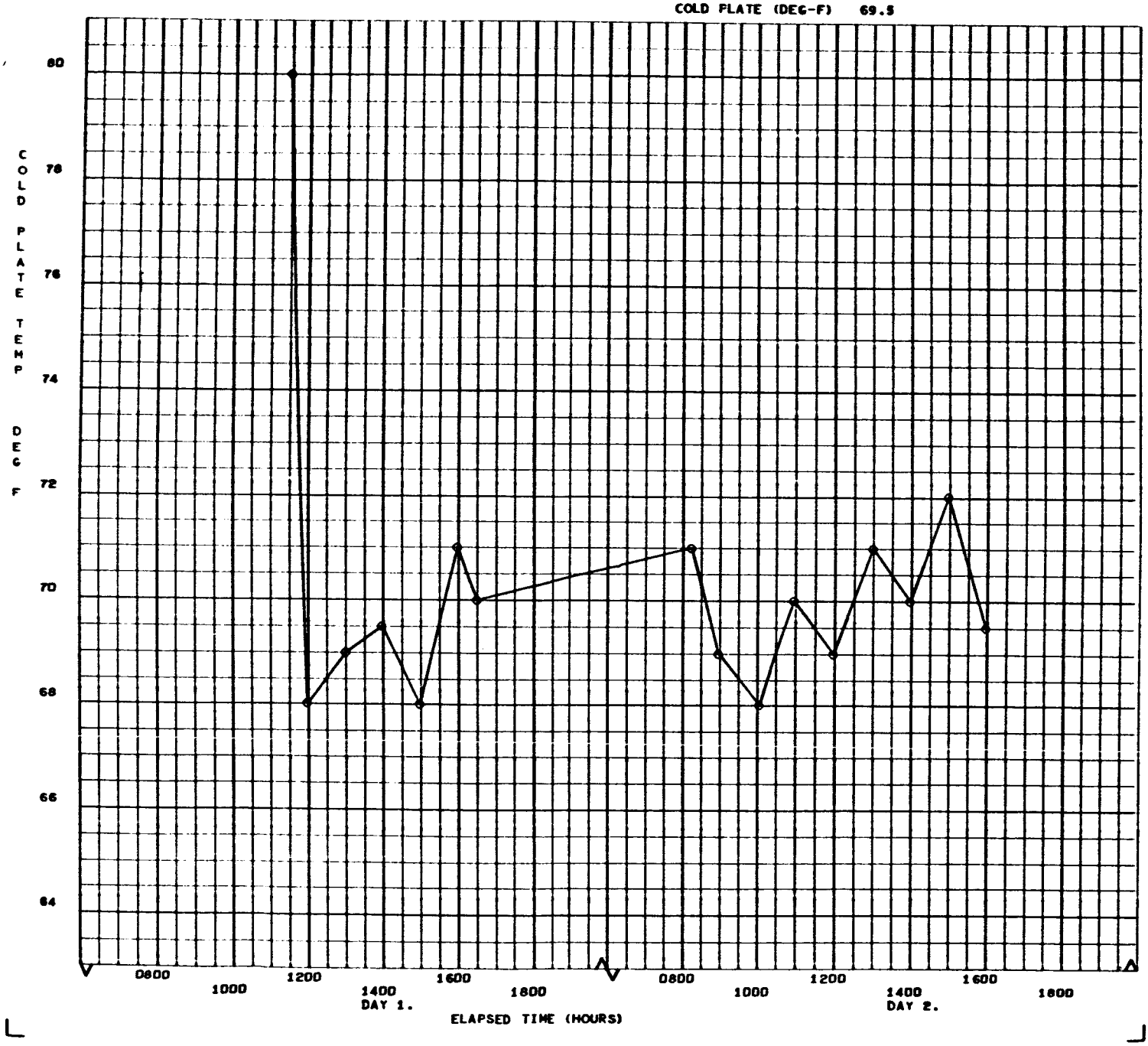


FIGURE 30.E

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 12.2
SAMPLE THICKNESS (IN.) 0.1875
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 300.5
COLD PLATE (DEG-F) 69.5

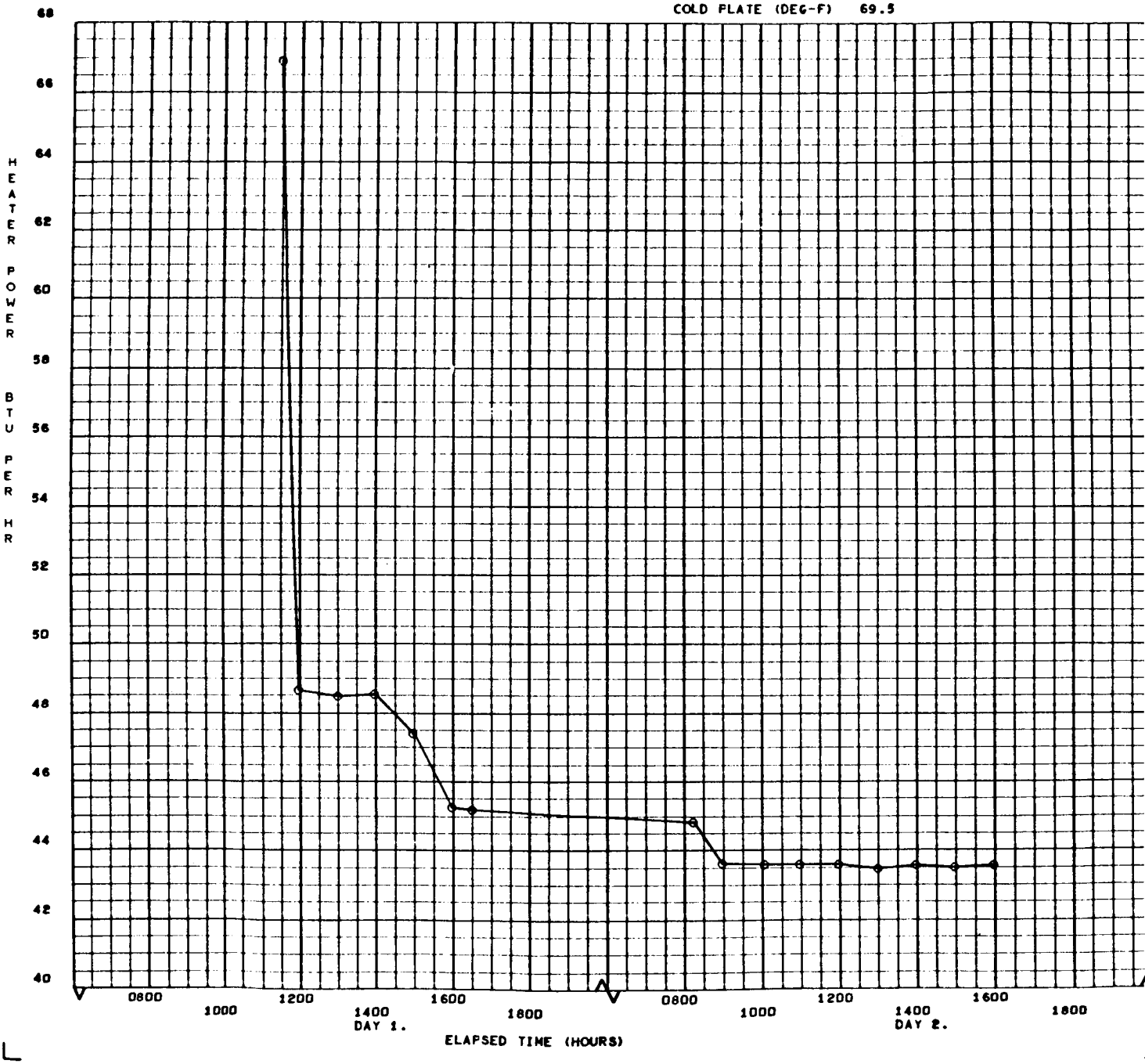


FIGURE 31.A

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 13.1
SAMPLE THICKNESS (IN.) 0.1250
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 301.0
COLD PLATE (DEG-F) 69.5

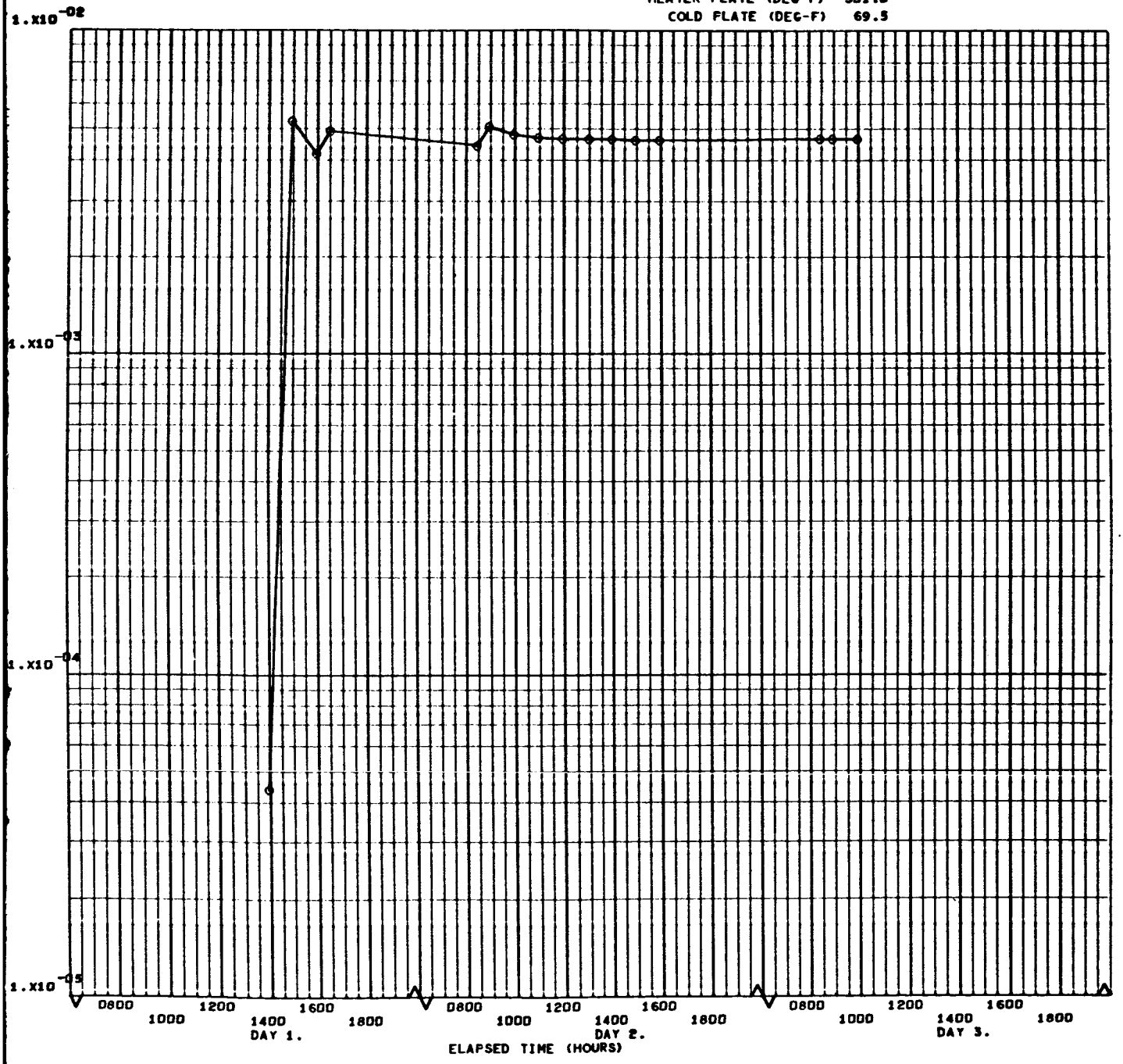


FIGURE 31.B

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 13.1
SAMPLE THICKNESS (IN.) 0.1250
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 301.0
COLD PLATE (DEG-F) 69.5

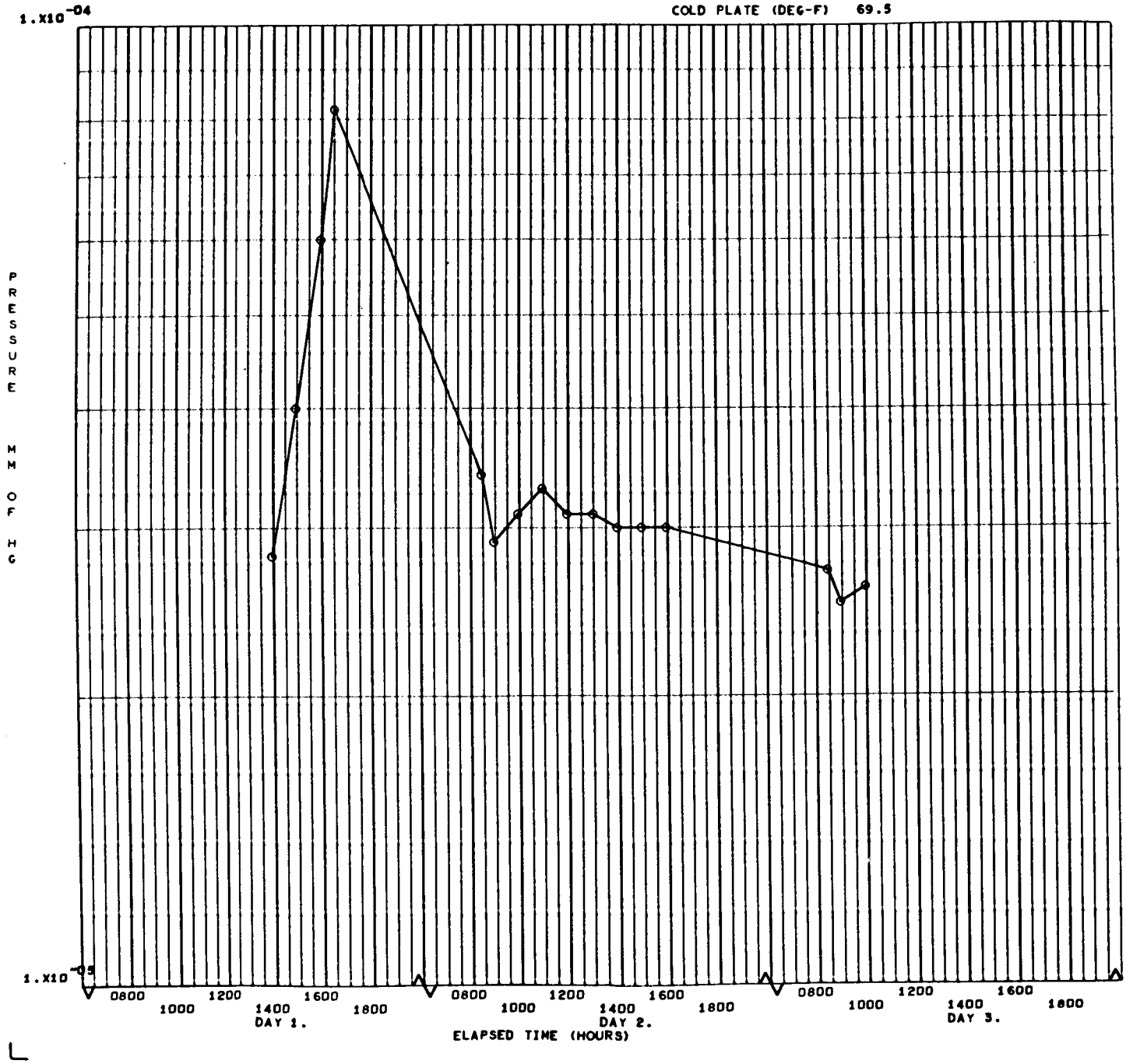


FIGURE 31.C

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 13.1
SAMPLE THICKNESS (IN.) 0.1250
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 301.0
COLD PLATE (DEG-F) 69.5

FIGURE 31.D

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 13.1
SAMPLE THICKNESS (IN.) 0.1250
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 301.0
COLD PLATE (DEG-F) 69.5

FIGURE 31.E

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 13.1
SAMPLE THICKNESS (IN.) 0.1250
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 301.0
COLD PLATE (DEG-F) 69.5

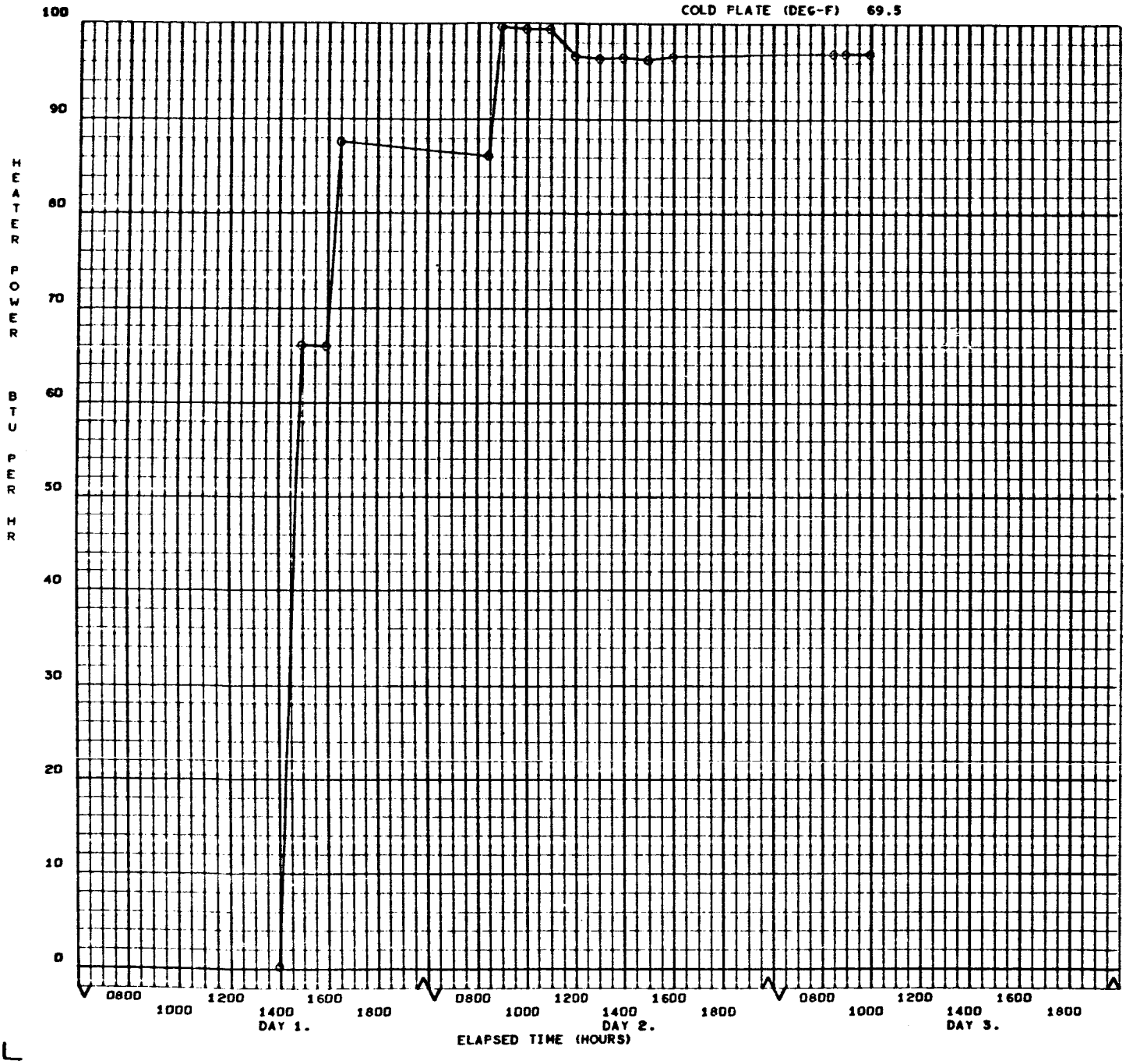


FIGURE 32.A

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 14.1
SAMPLE THICKNESS (IN.) 0.1875
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 68.0
COLD PLATE (DEG-F)- 310.0

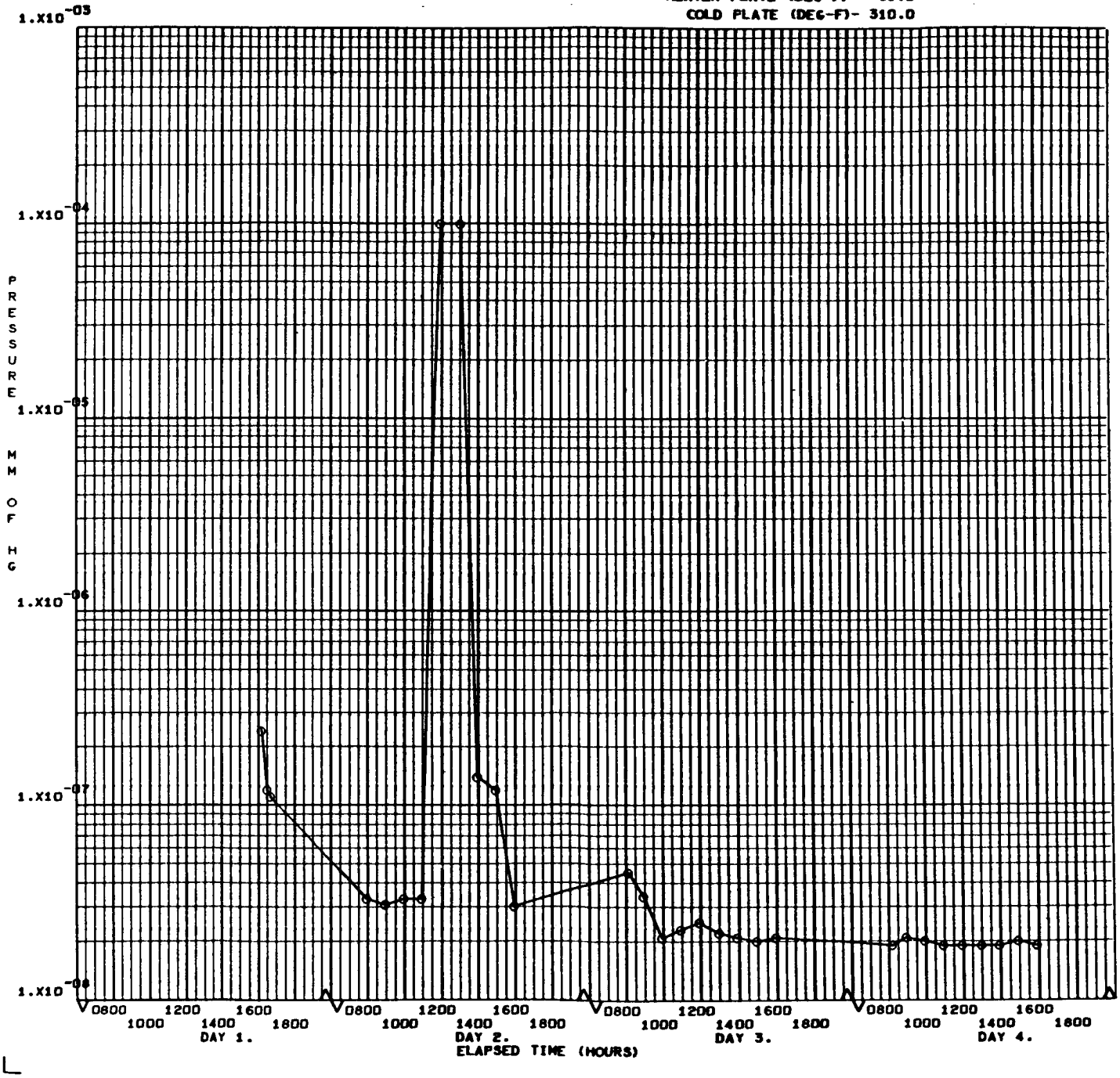


FIGURE 32.B

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 14.1
SAMPLE THICKNESS (IN.) 0.1875
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 68.0
COLD PLATE (DEG-F)- 310.0

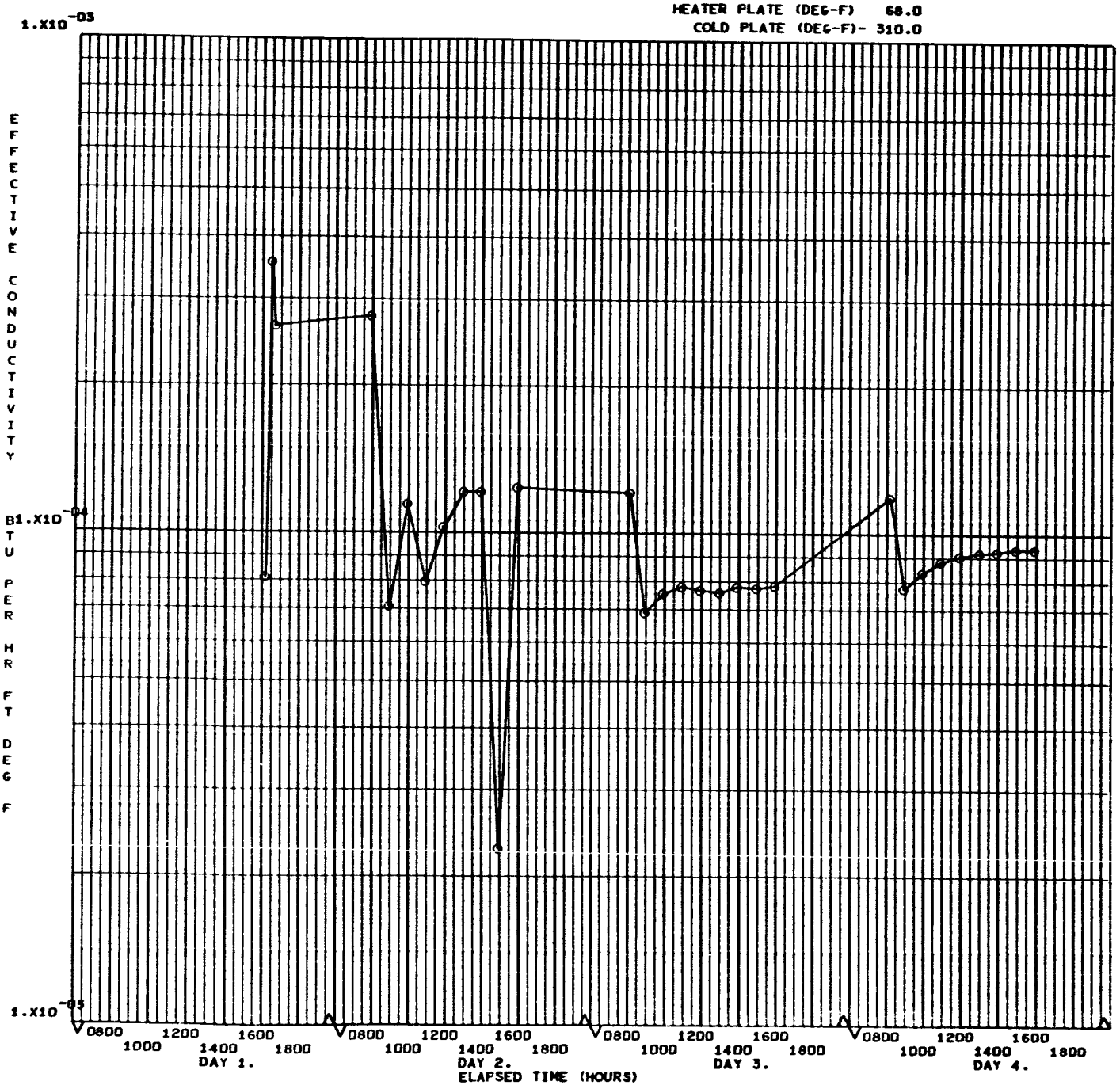


FIGURE 32.C

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 14.1
SAMPLE THICKNESS (IN.) 0.1875
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 68.0
COLD PLATE (DEG-F)- 310.0

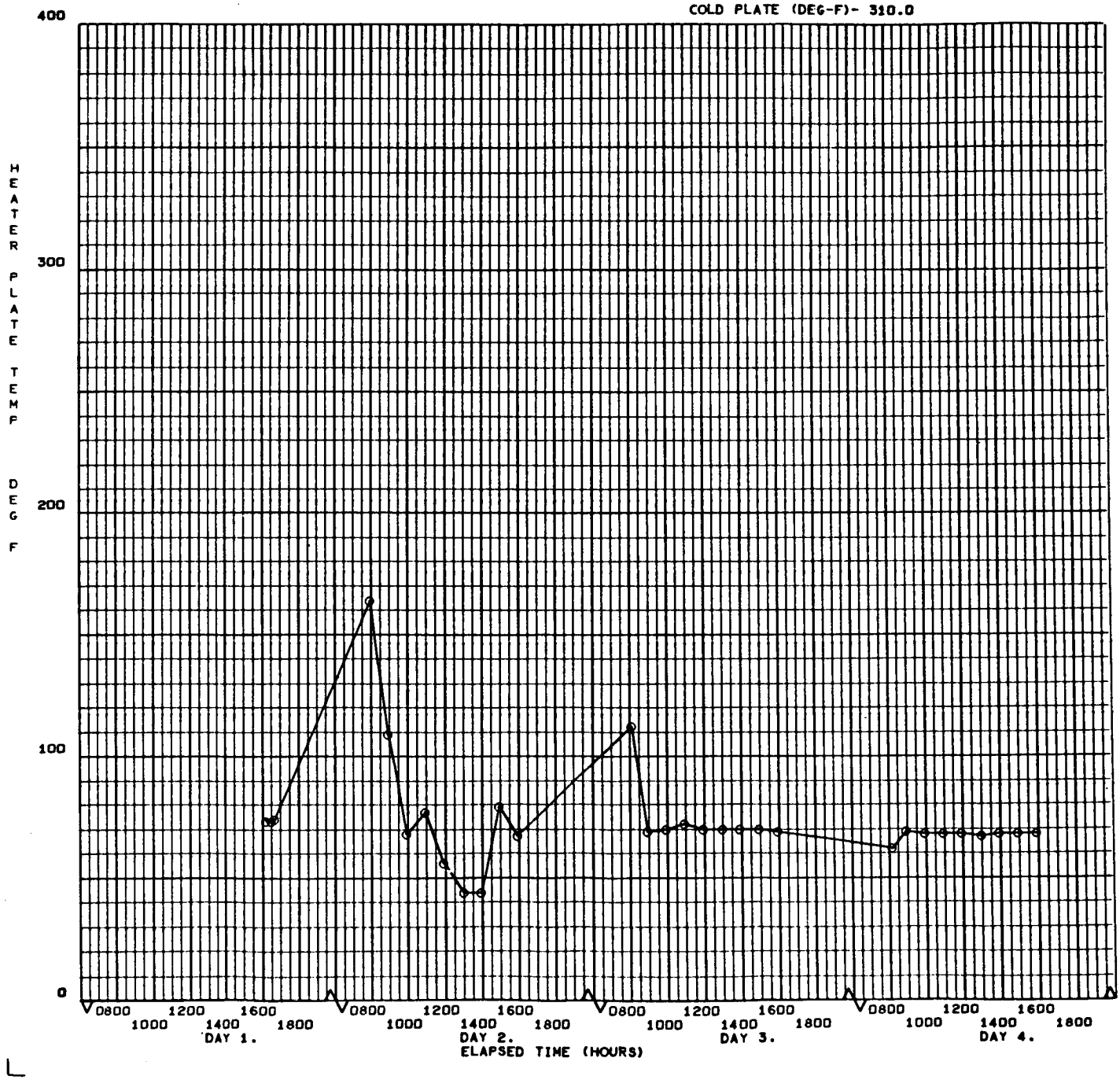


FIGURE 32.D

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 14.1
SAMPLE THICKNESS (IN.) 0.1875
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 68.0
COLD PLATE (DEG-F)- 310.0

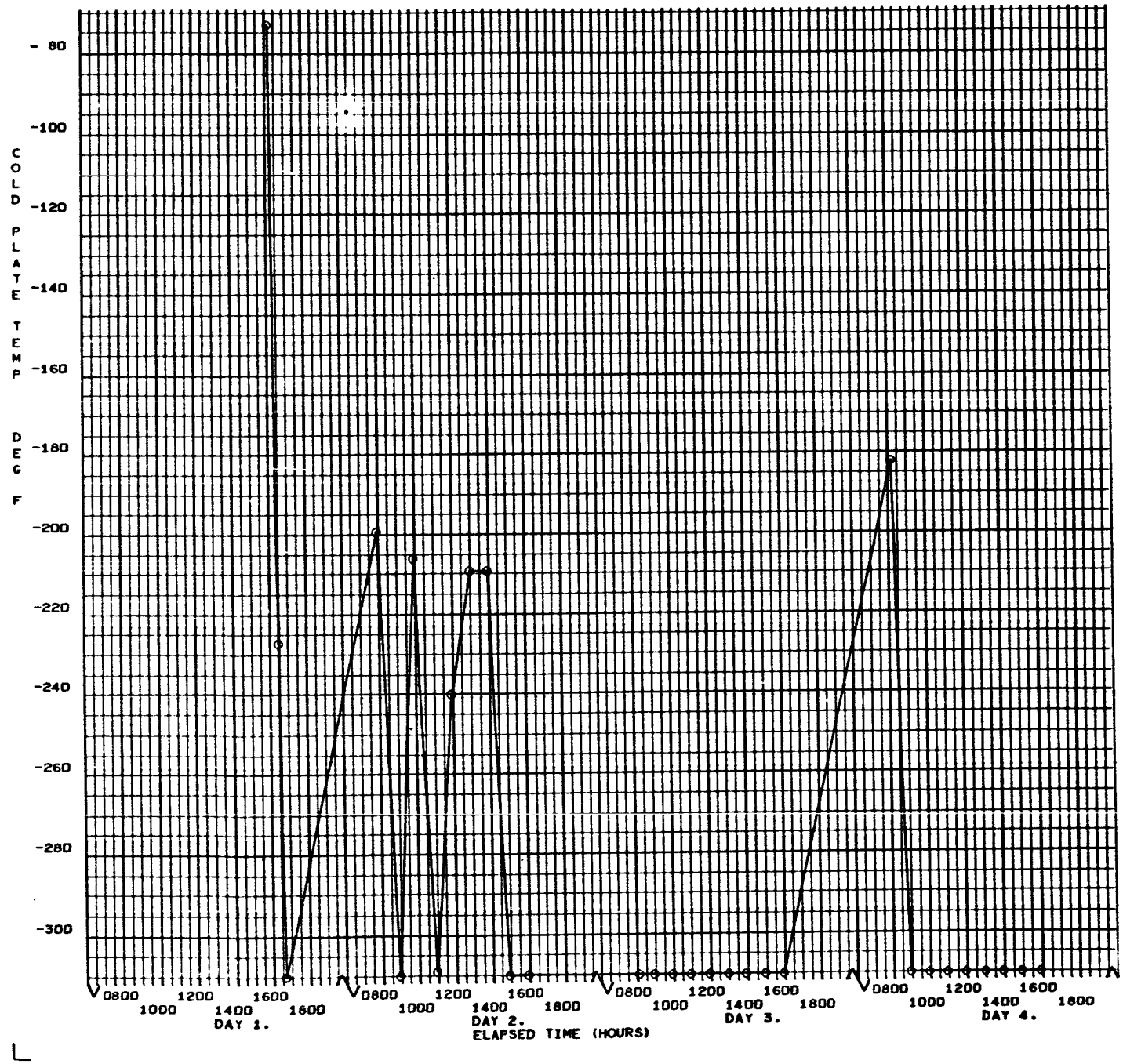


FIGURE 32.E

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 14.1
SAMPLE THICKNESS (IN.) 0.1875
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 68.0
COLD PLATE (DEG-F)- 310.0

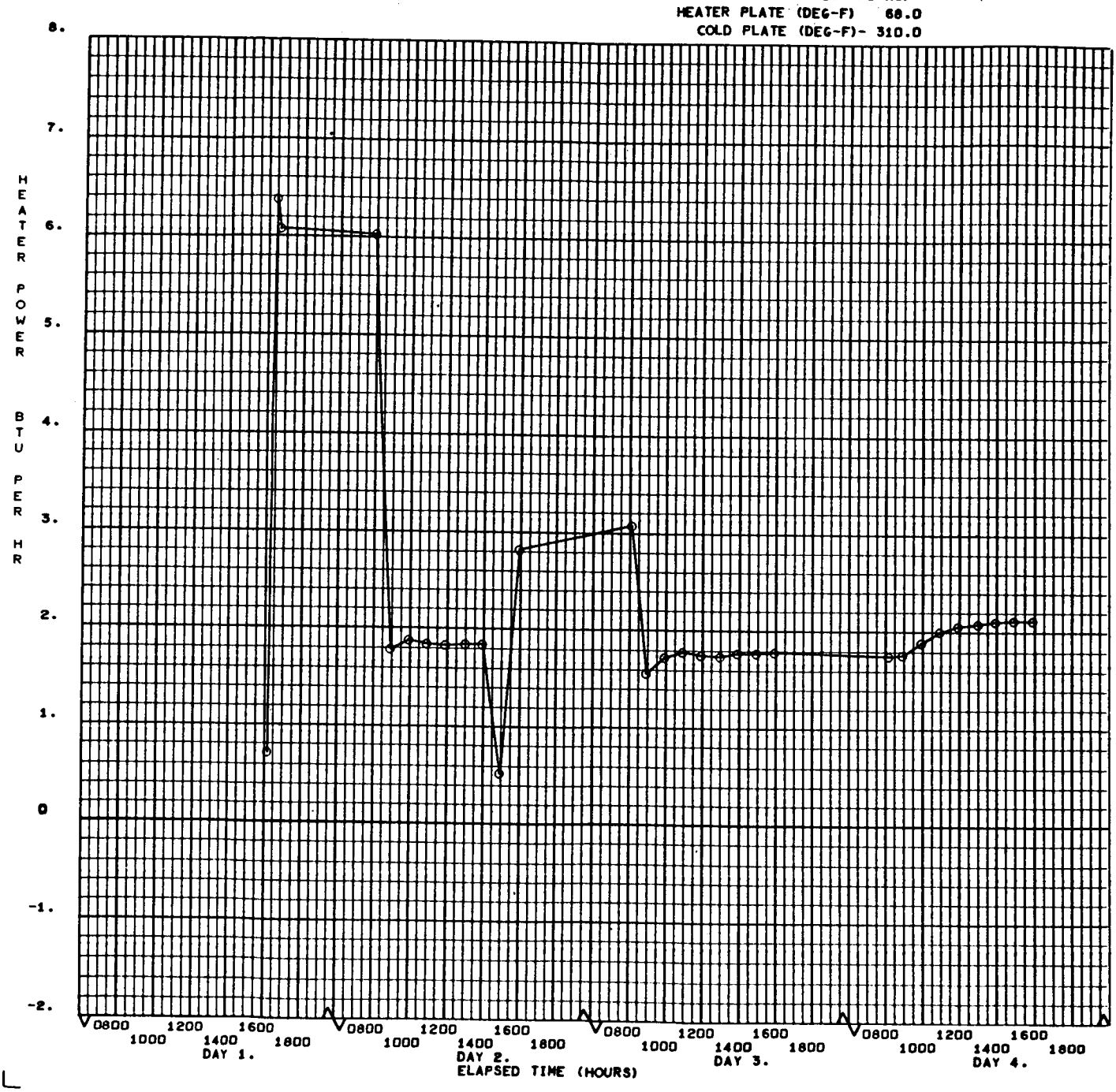


FIGURE 33.A

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 14.2
SAMPLE THICKNESS (IN.) 0.1875
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 300.0
COLD PLATE (DEG-F) 70.0

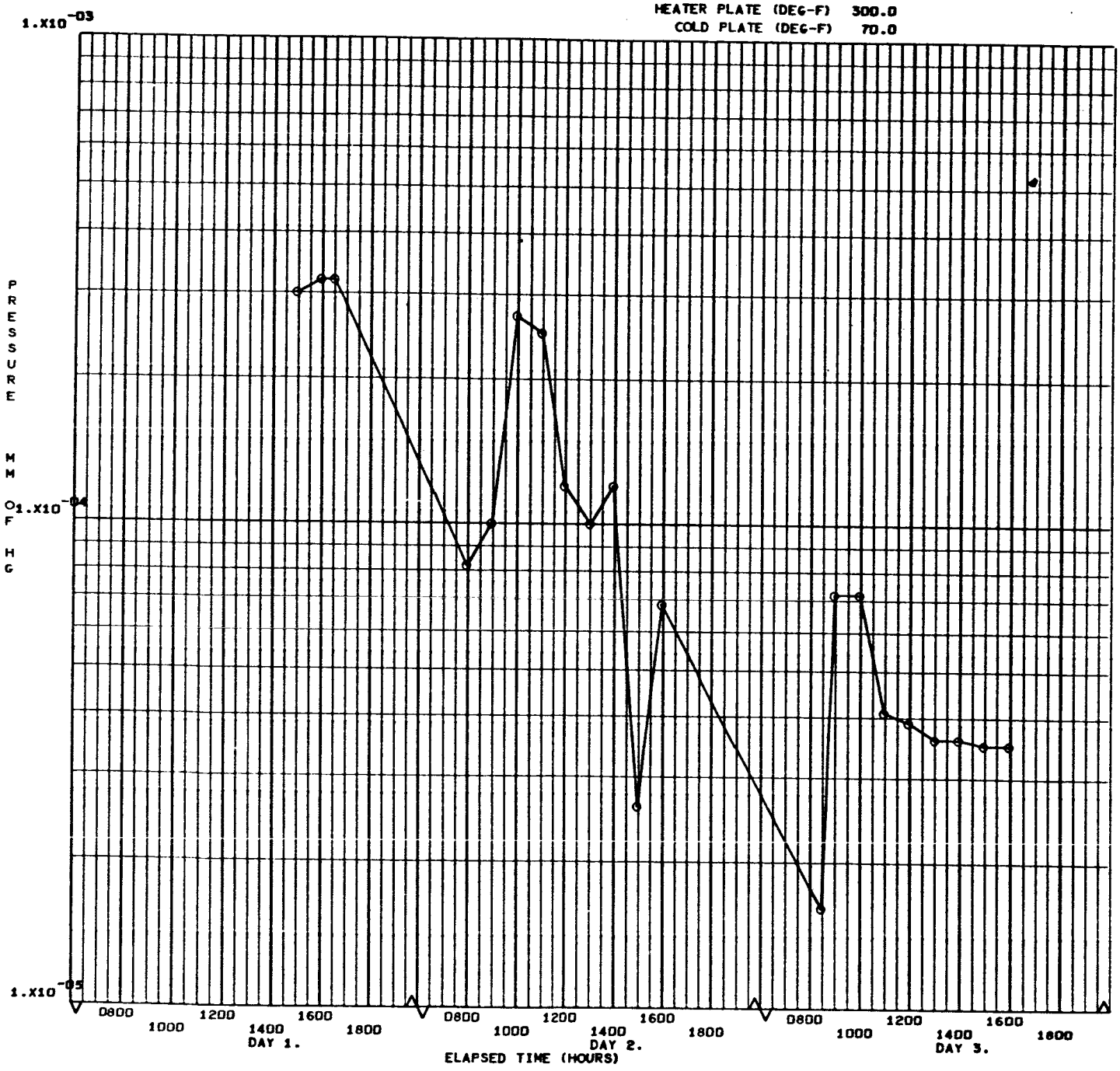


FIGURE 33.B

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 14.2
SAMPLE THICKNESS (IN.) 0.1875
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 300.0
COLD PLATE (DEG-F) 70.0

FIGURE 33.C

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 14.2
SAMPLE THICKNESS (IN.) 0.1875
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 300.0
COLD PLATE (DEG-F) 70.0

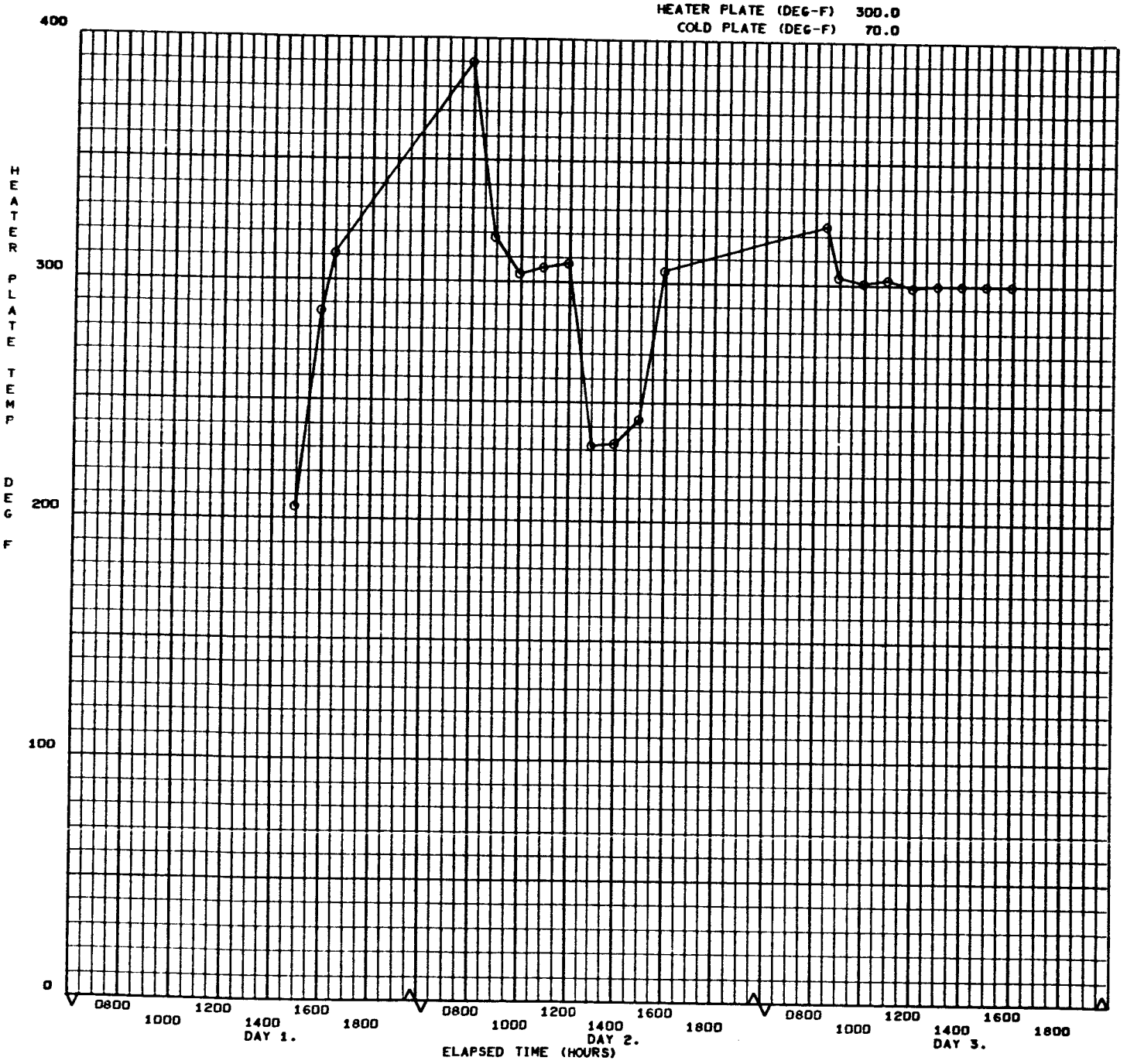


FIGURE 33.D

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 14.2
SAMPLE THICKNESS (IN.) 0.1875
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 300.0
COLD PLATE (DEG-F) 70.0

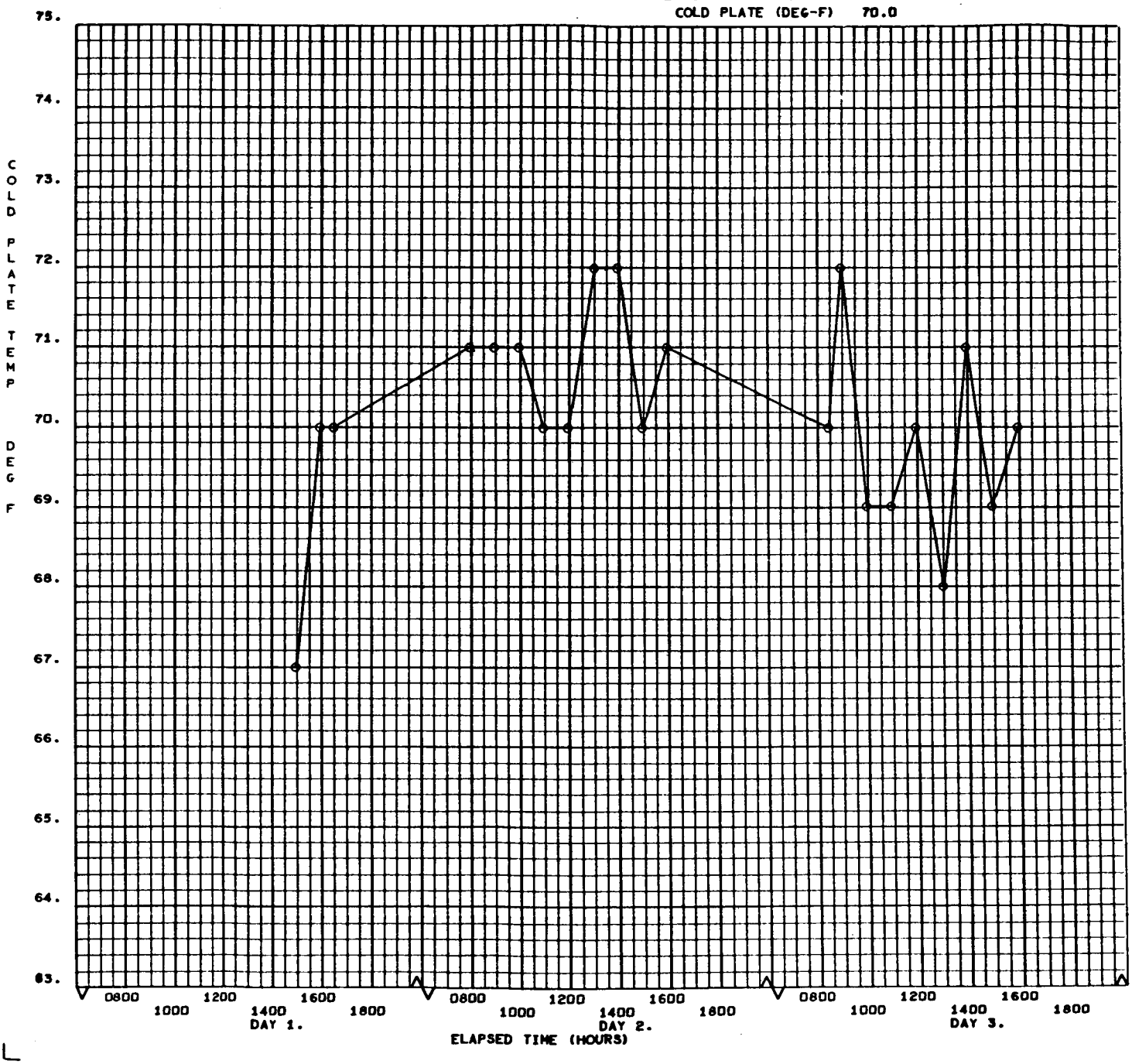


FIGURE 33.E

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 14.2
SAMPLE THICKNESS (IN.) 0.1875
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 300.0
COLD PLATE (DEG-F) 70.0

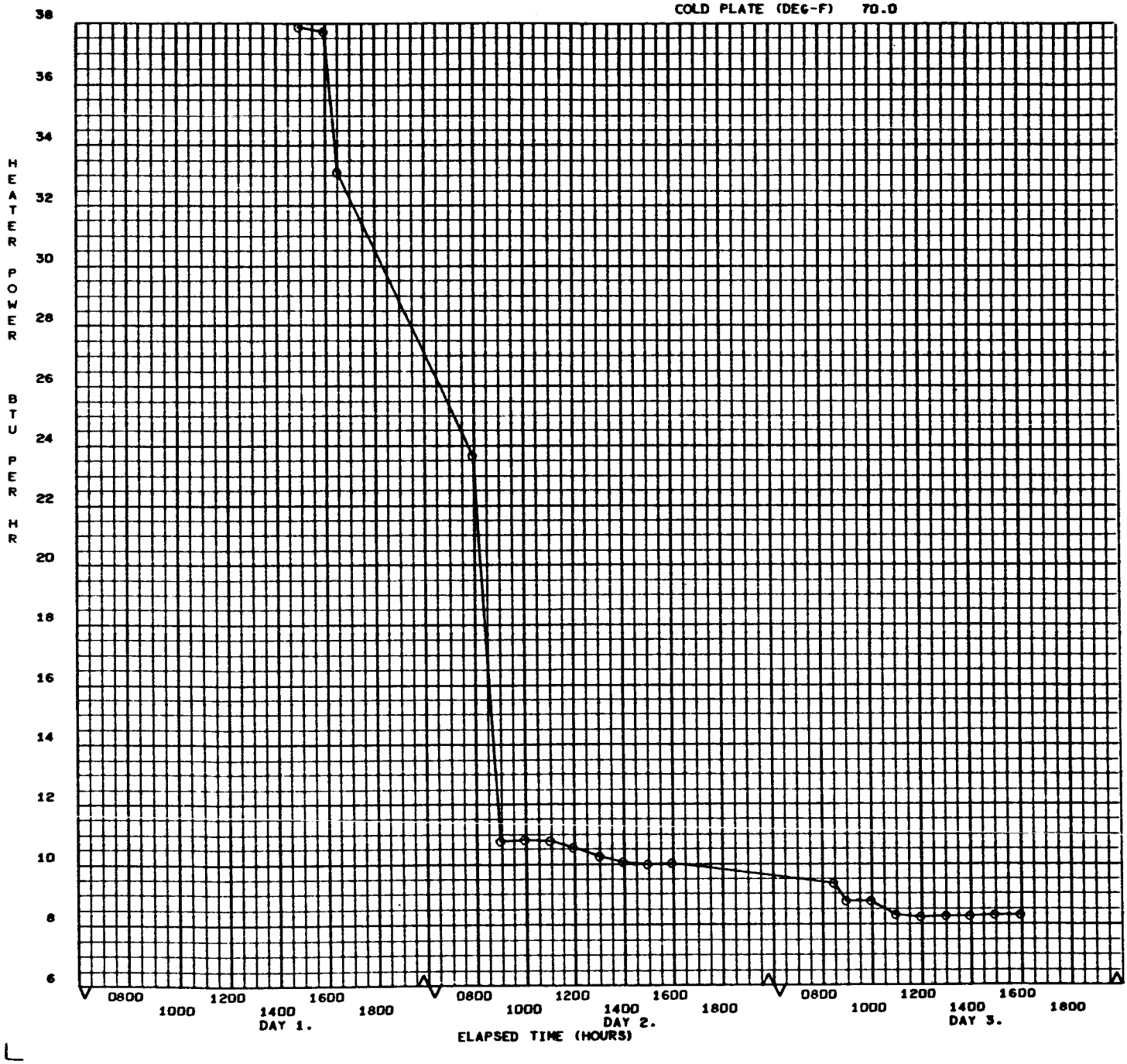


FIGURE 34.A

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 15.1
SAMPLE THICKNESS (IN.) 0.1875
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 76.0
COLD PLATE (DEG-F)- 310.0

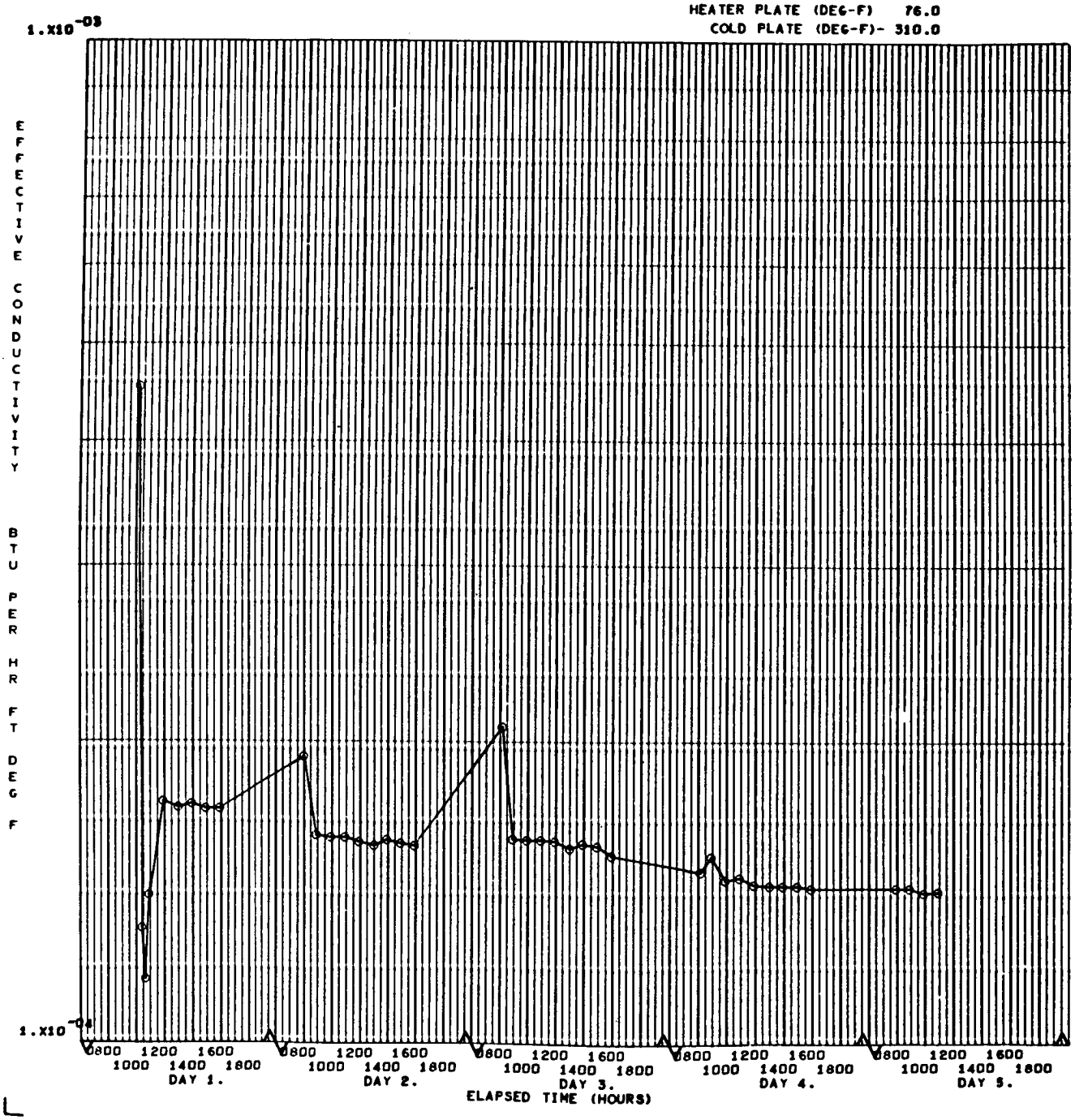


FIGURE 34.B

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 15.1
SAMPLE THICKNESS (IN.) 0.1875
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 76.0
COLD PLATE (DEG-F)- 310.0

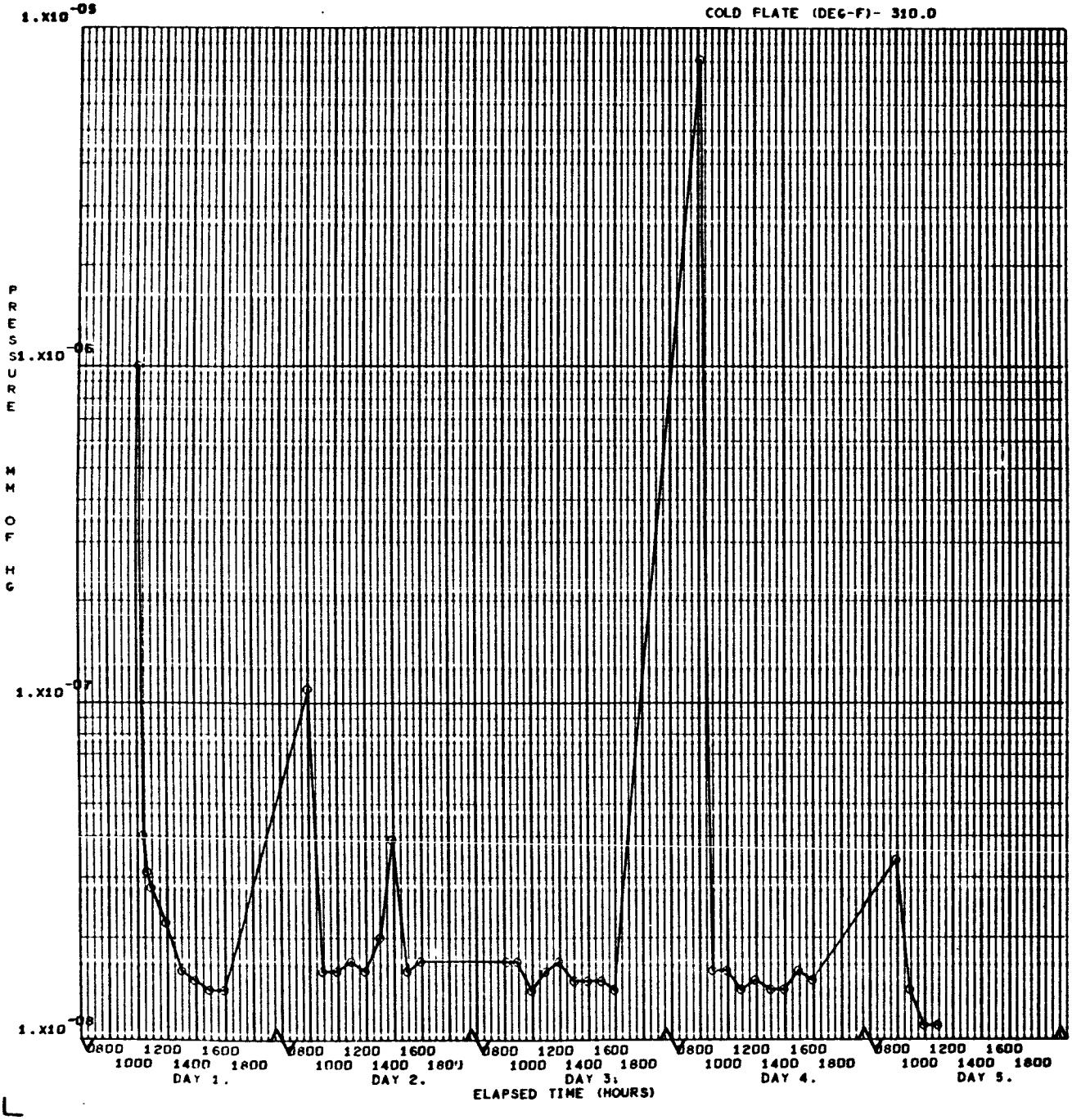


FIGURE 34.C

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 15.1
SAMPLE THICKNESS (IN.) 0.1875
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 76.0
COLD PLATE (DEG-F)- 310.0

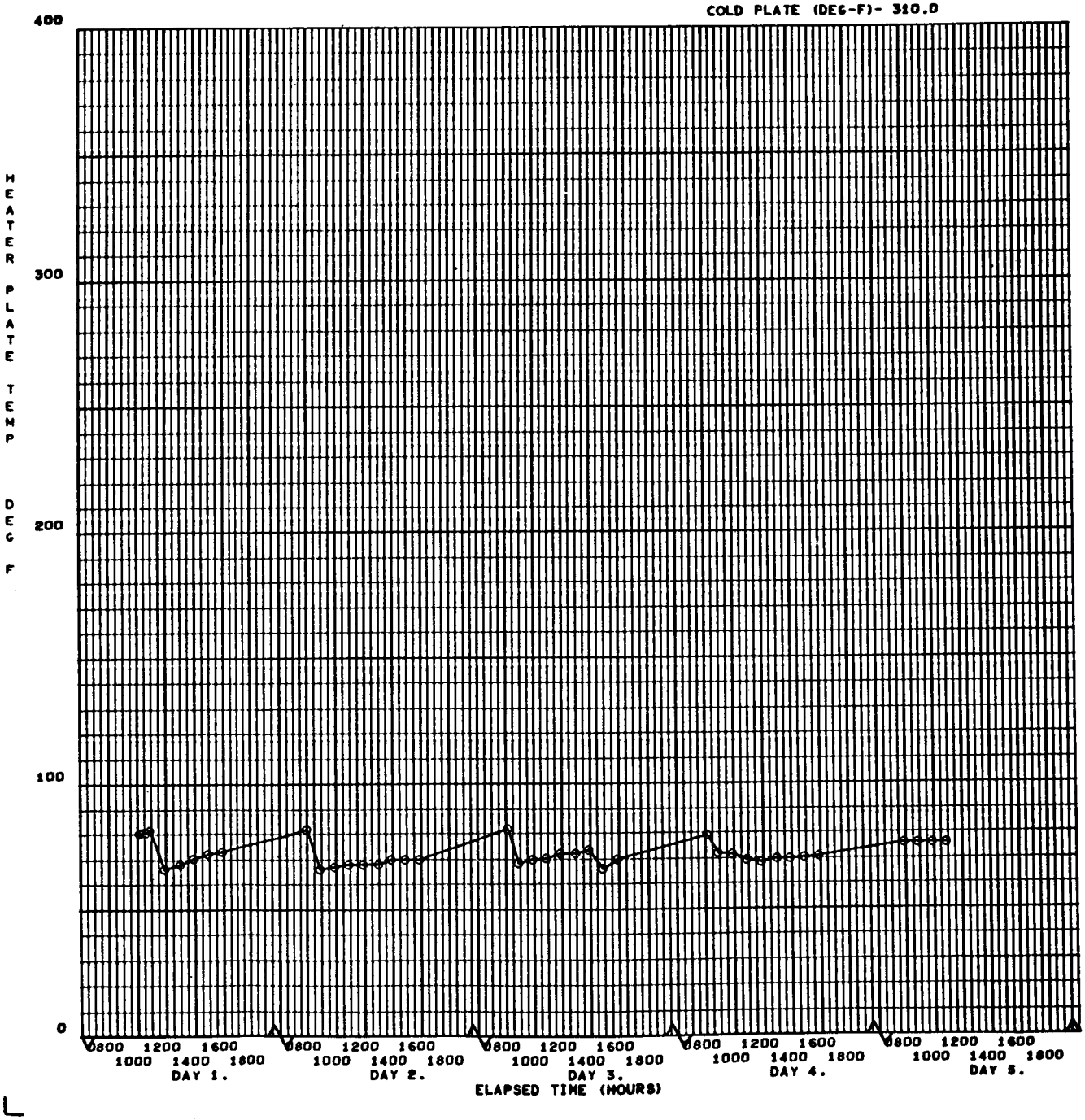


FIGURE 34.D

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 15.1
SAMPLE THICKNESS (IN.) 0.1875
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 76.0
COLD PLATE (DEG-F)- 310.0

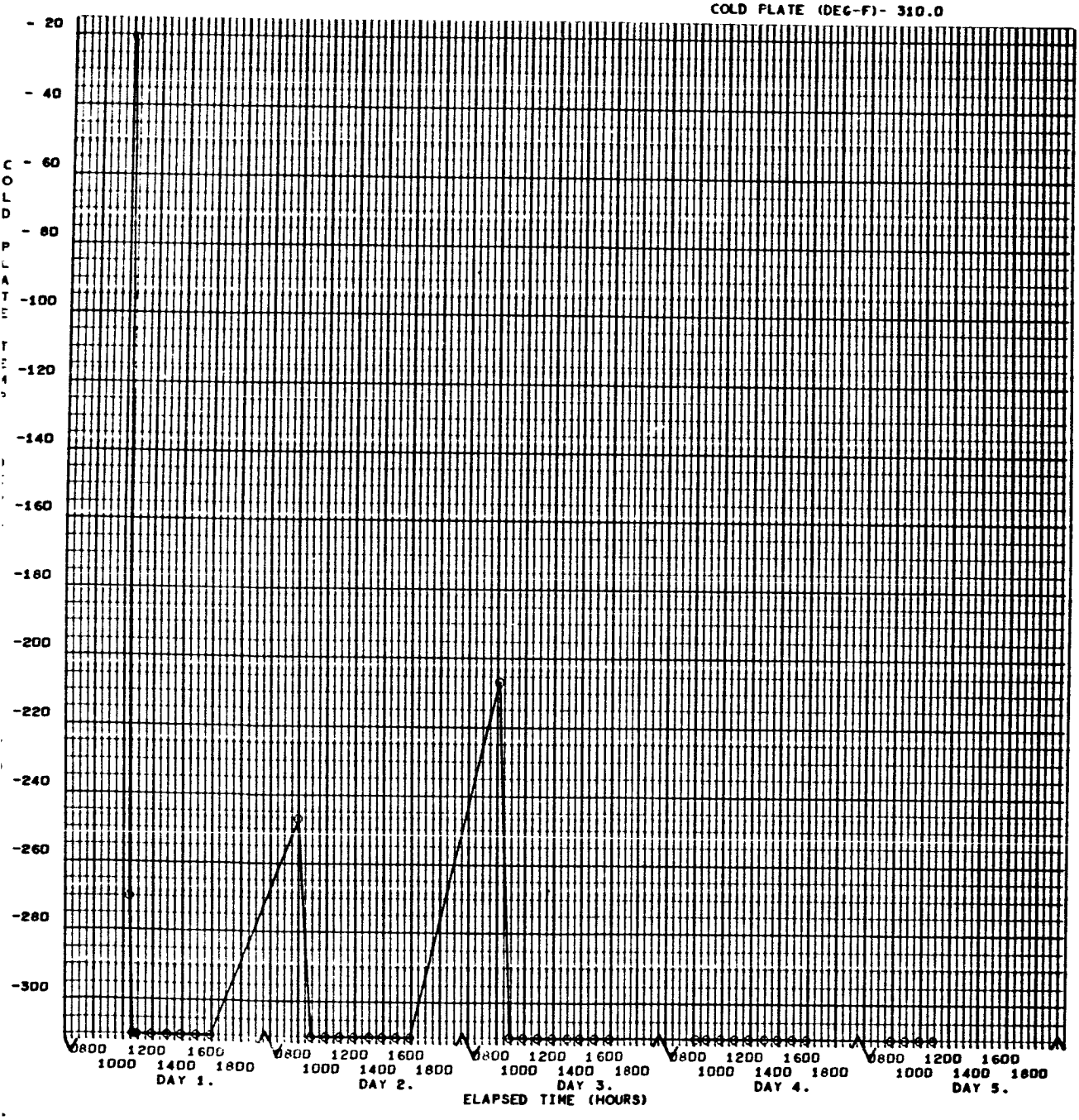


FIGURE 34.E

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 15.1
SAMPLE THICKNESS (IN.) 0.1875
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 76.0
COLD PLATE (DEG-F)- 310.0

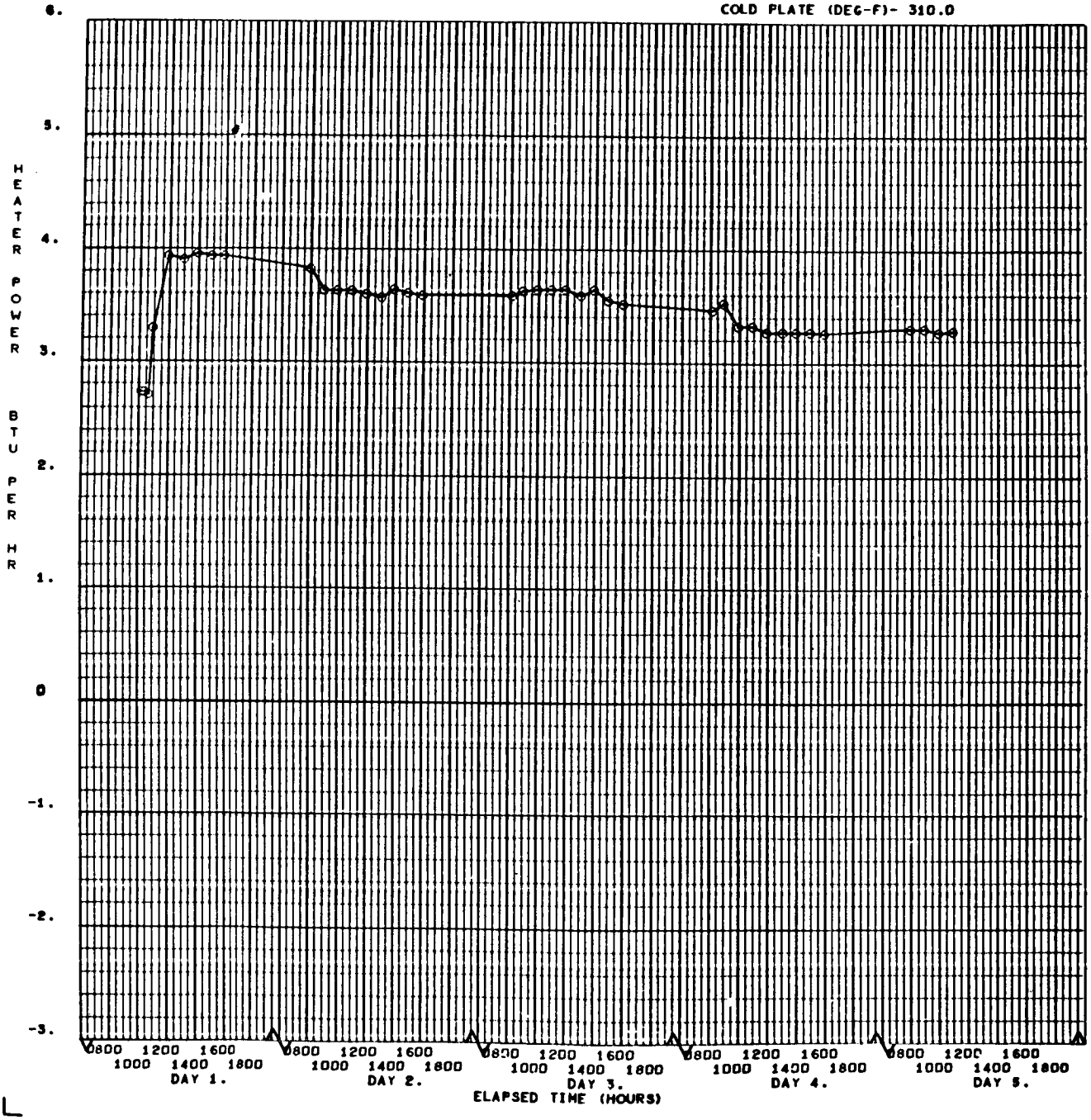


FIGURE 35.A

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 15.2
SAMPLE THICKNESS (IN.) 0.1875
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 305.0
COLD PLATE (DEG-F) 69.5

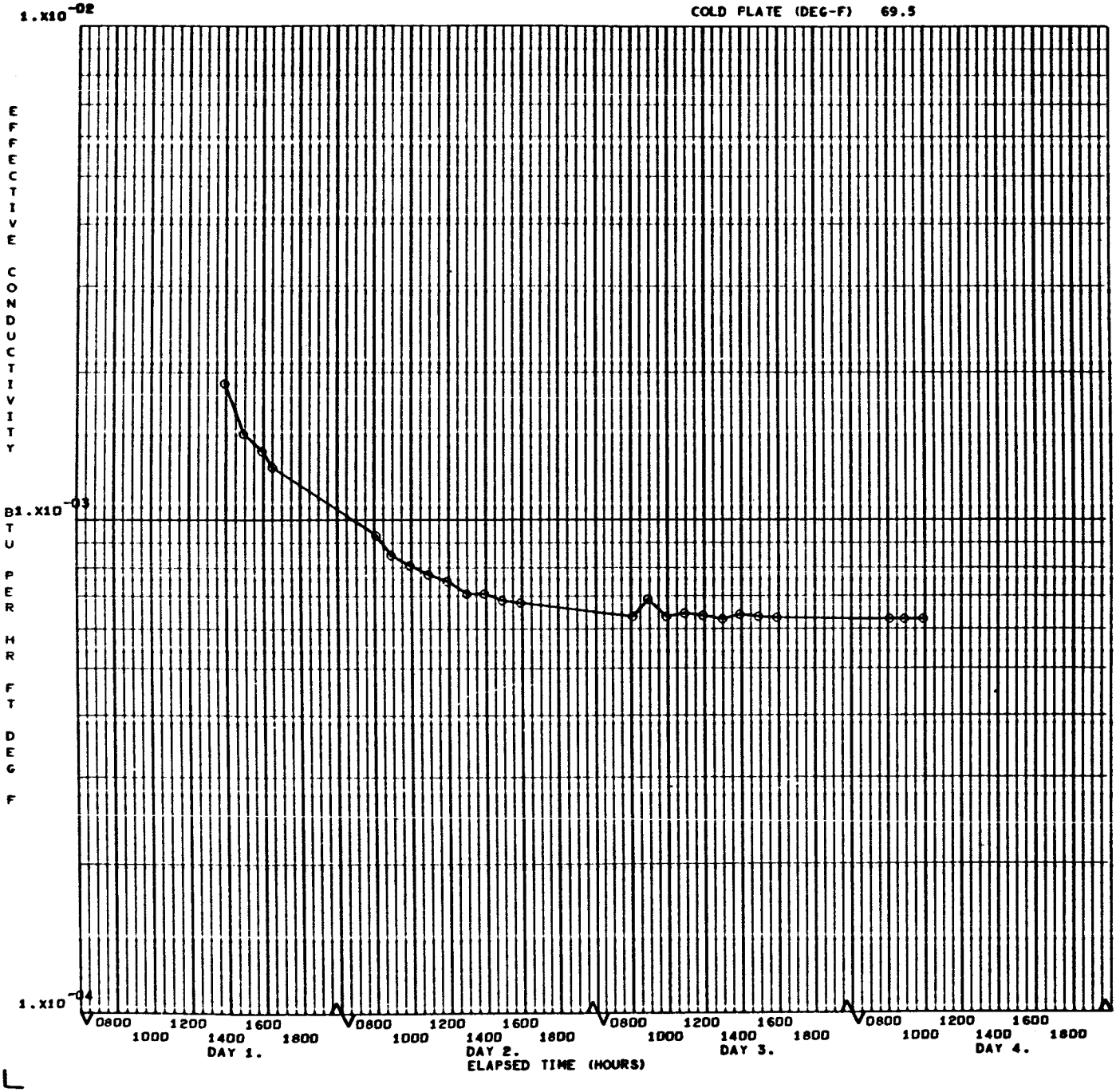


FIGURE 35.B

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 15.2
SAMPLE THICKNESS (IN.) 0.1875
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 305.0
COLD PLATE (DEG-F) 69.5

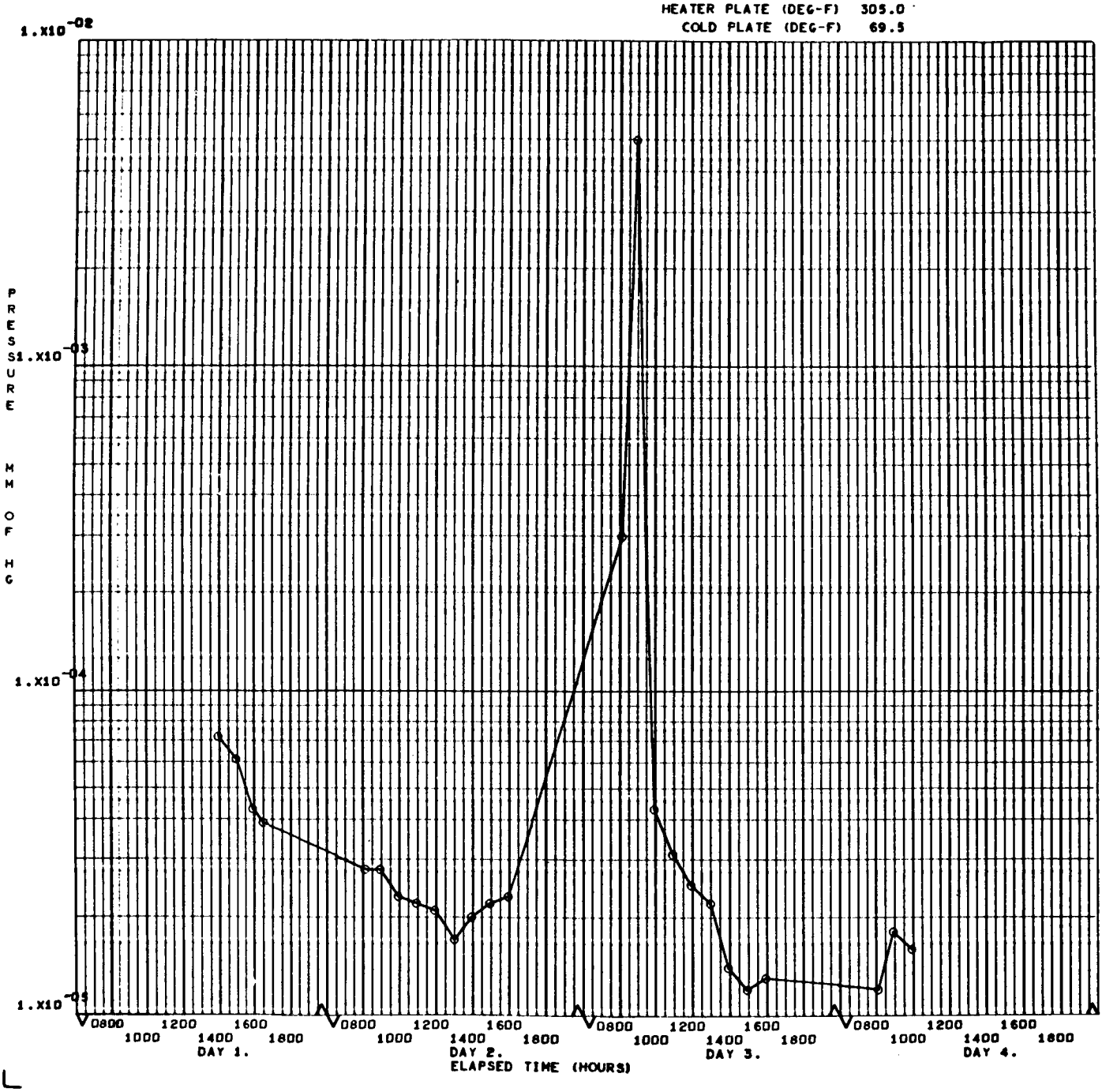


FIGURE 35.C

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 15.2
SAMPLE THICKNESS (IN.) 0.1875
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 305.0
COLD PLATE (DEG-F) 69.5

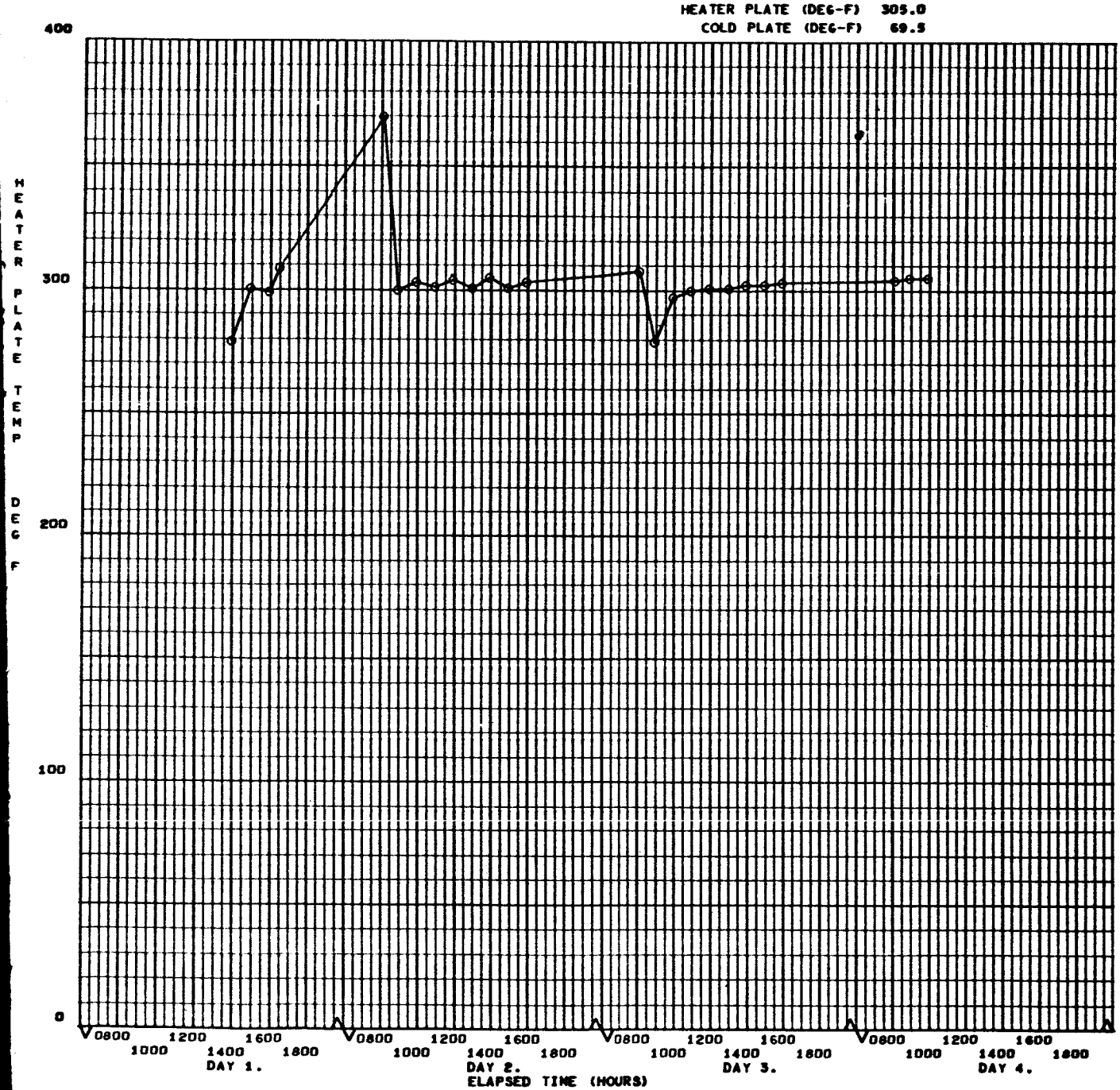


FIGURE 35.D

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 15.2
SAMPLE THICKNESS (IN.) 0.1875
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 305.0
COLD PLATE (DEG-F) 69.5

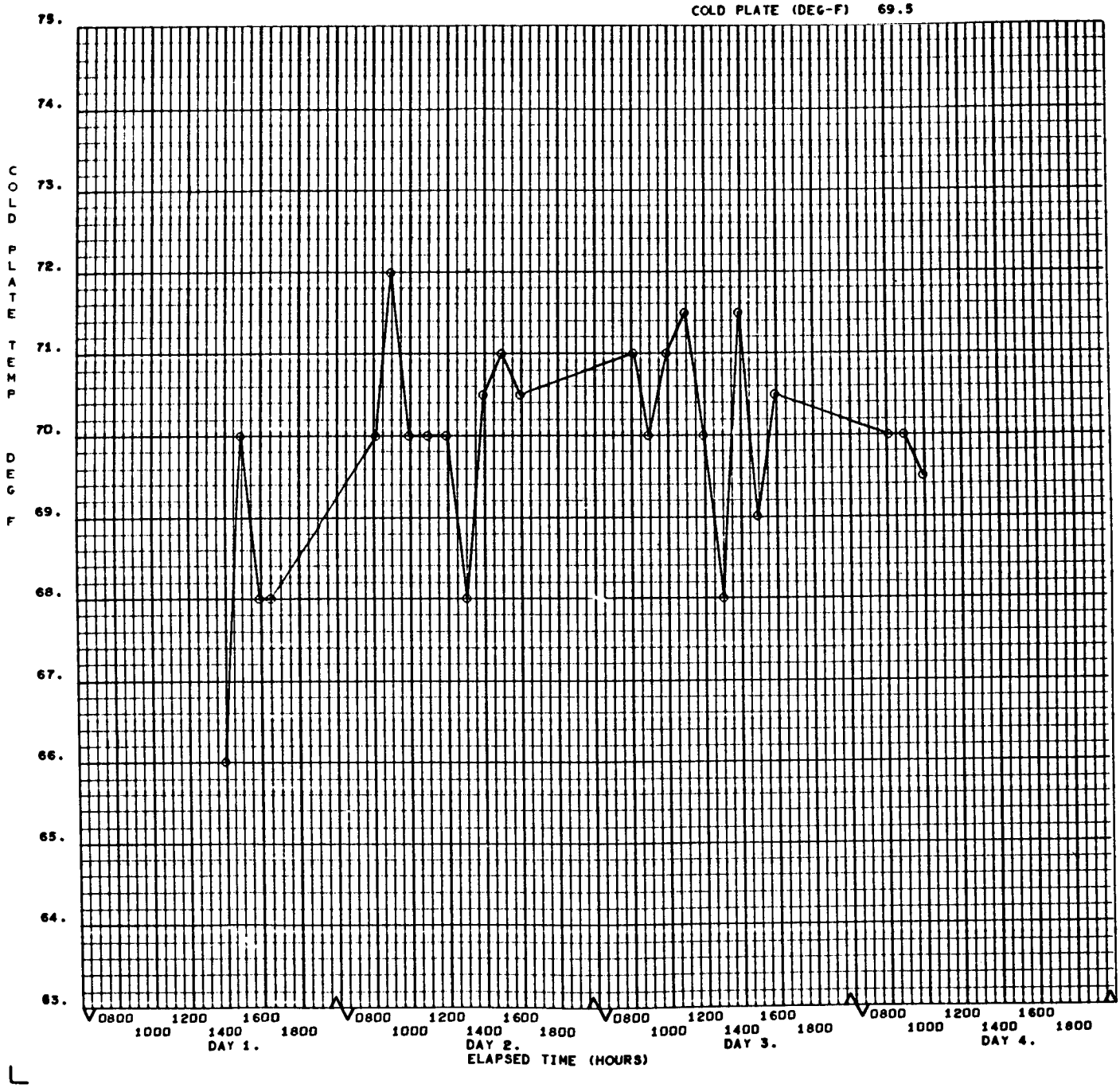


FIGURE 35.E

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 15.2
SAMPLE THICKNESS (IN.) 0.1875
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 305.0
COLD PLATE (DEG-F) 69.5

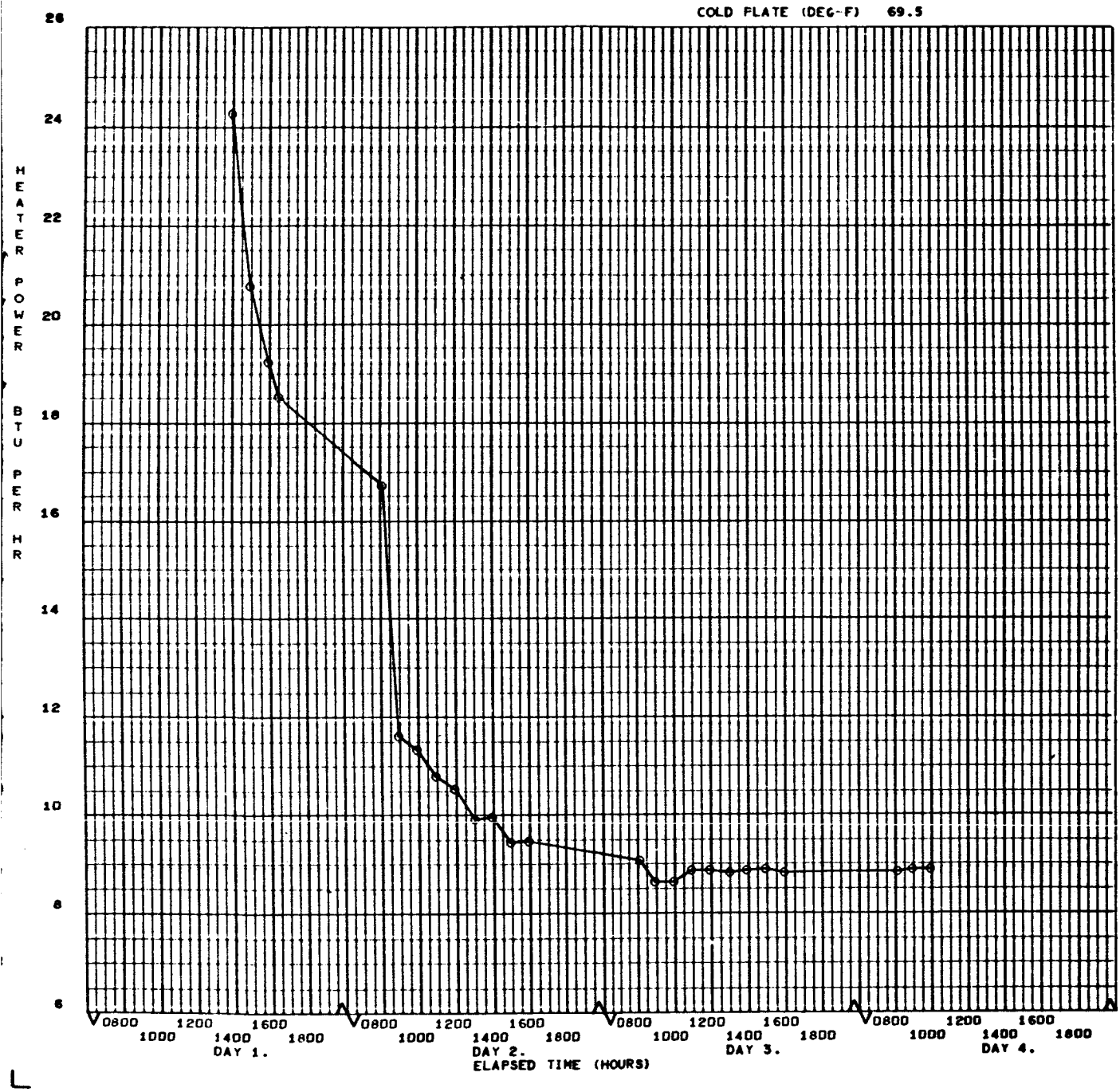


FIGURE 36.A

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 16.1
SAMPLE THICKNESS (IN.) 0.2500
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 79.5
COLD PLATE (DEG-F)- 310.0

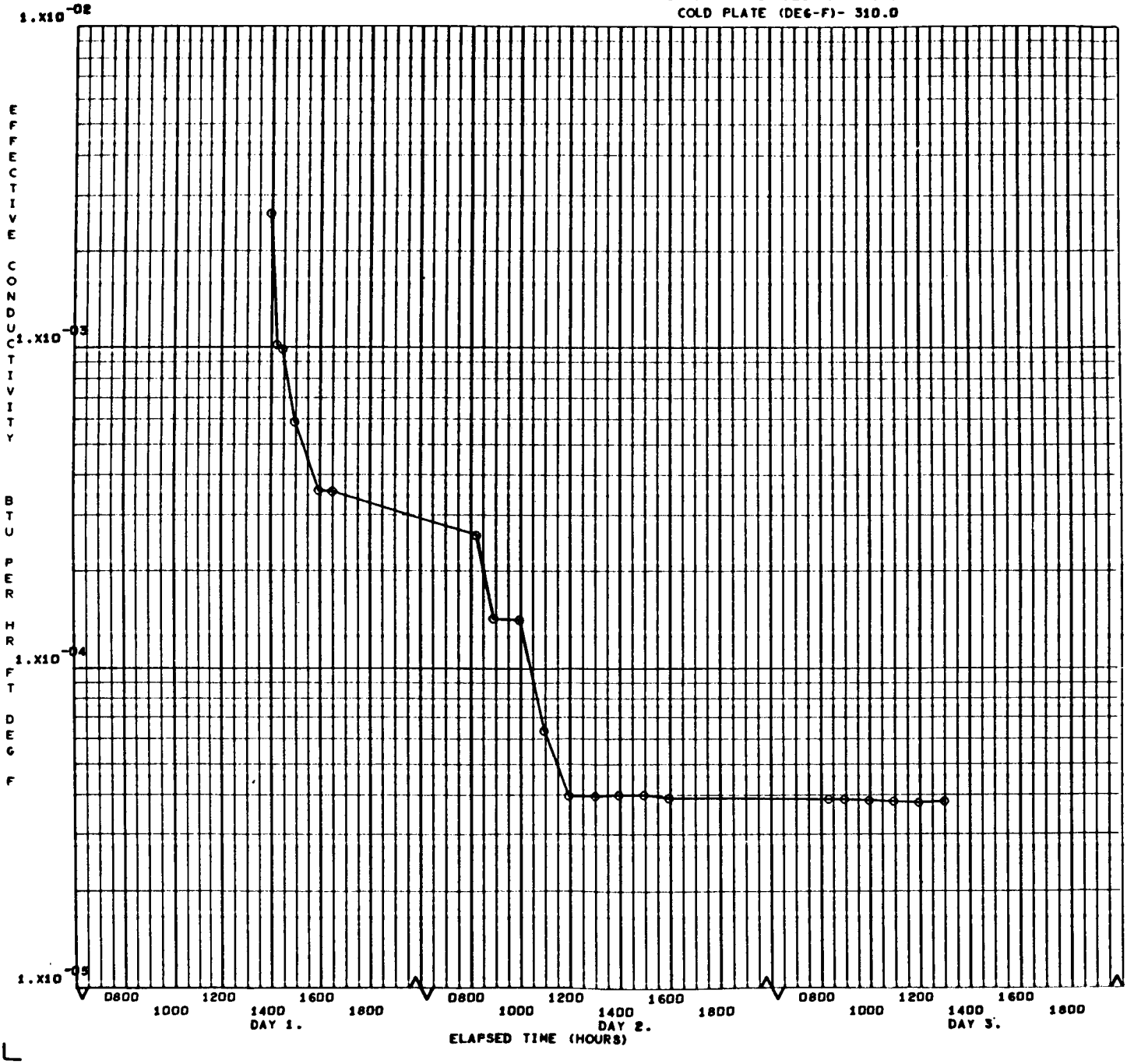


FIGURE 36.B

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 16.1
SAMPLE THICKNESS (IN.) 0.2500
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 79.5
COLD PLATE (DEG-F)- 310.0

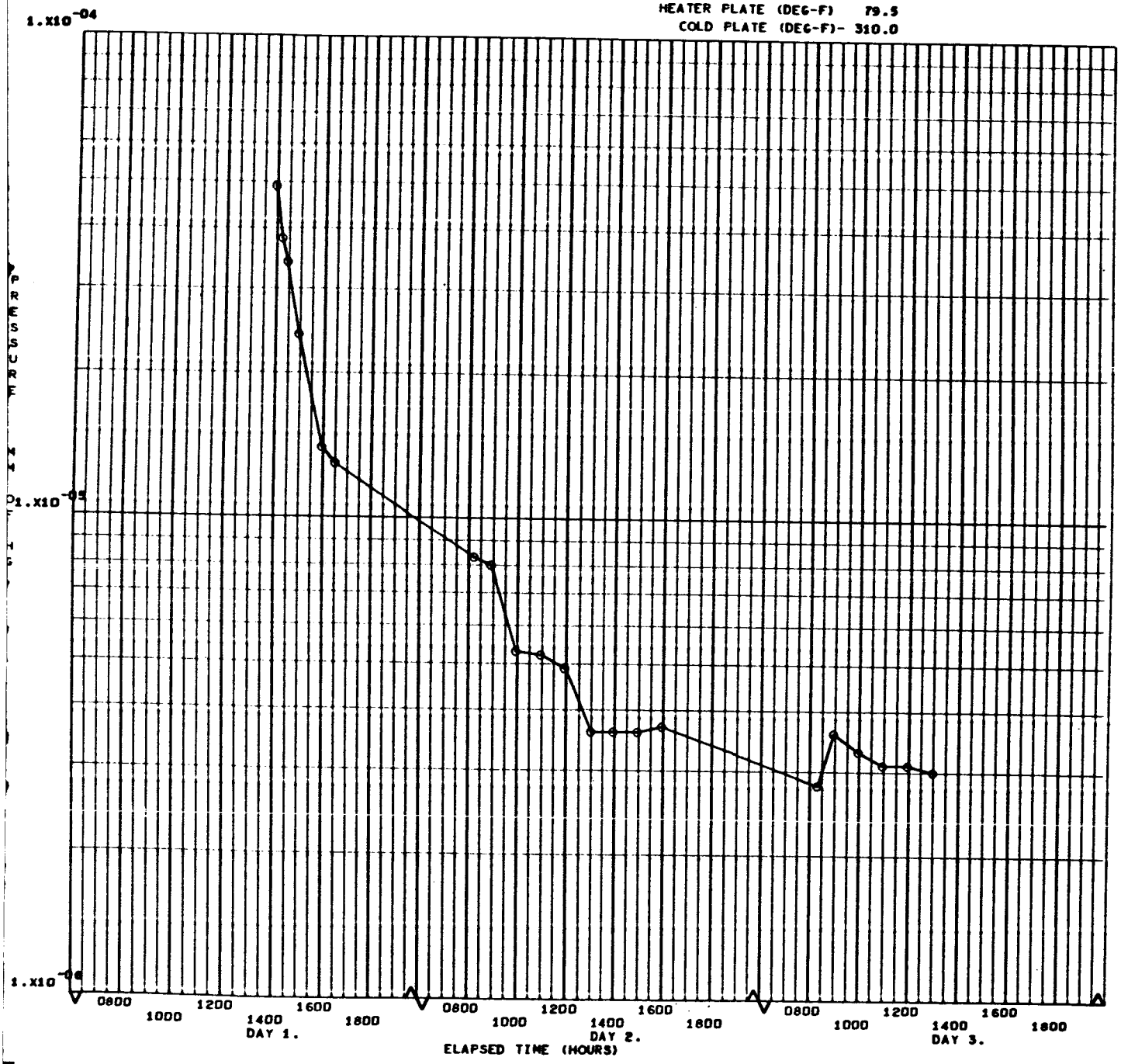


FIGURE 36.C

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 16.1
SAMPLE THICKNESS (IN.) 0.2500
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 79.5
COLD PLATE (DEG-F)- 310.0

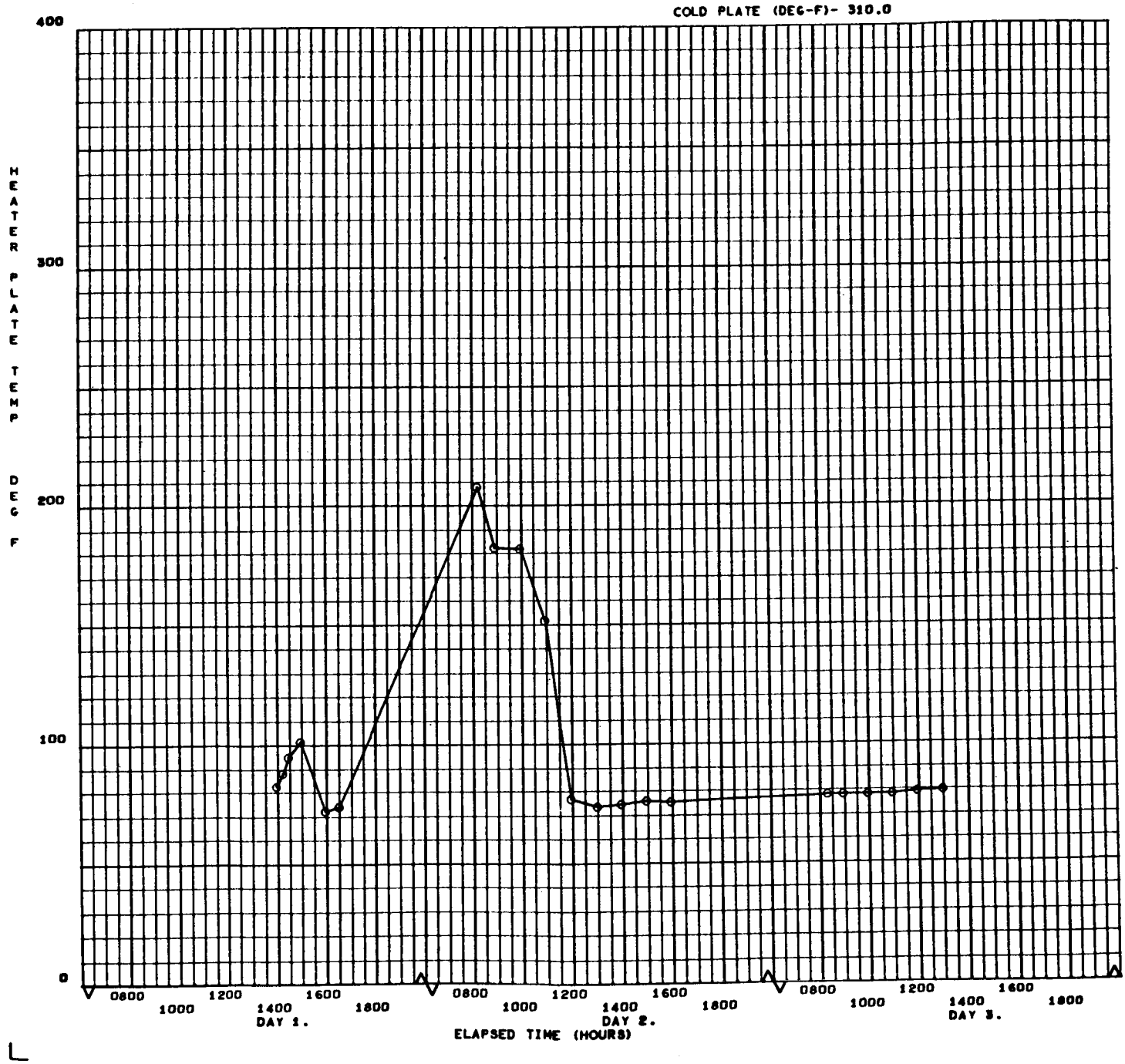


FIGURE 36.D

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 16.1
SAMPLE THICKNESS (IN.) 0.2500
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 79.5
COLD PLATE (DEG-F)- 310.0

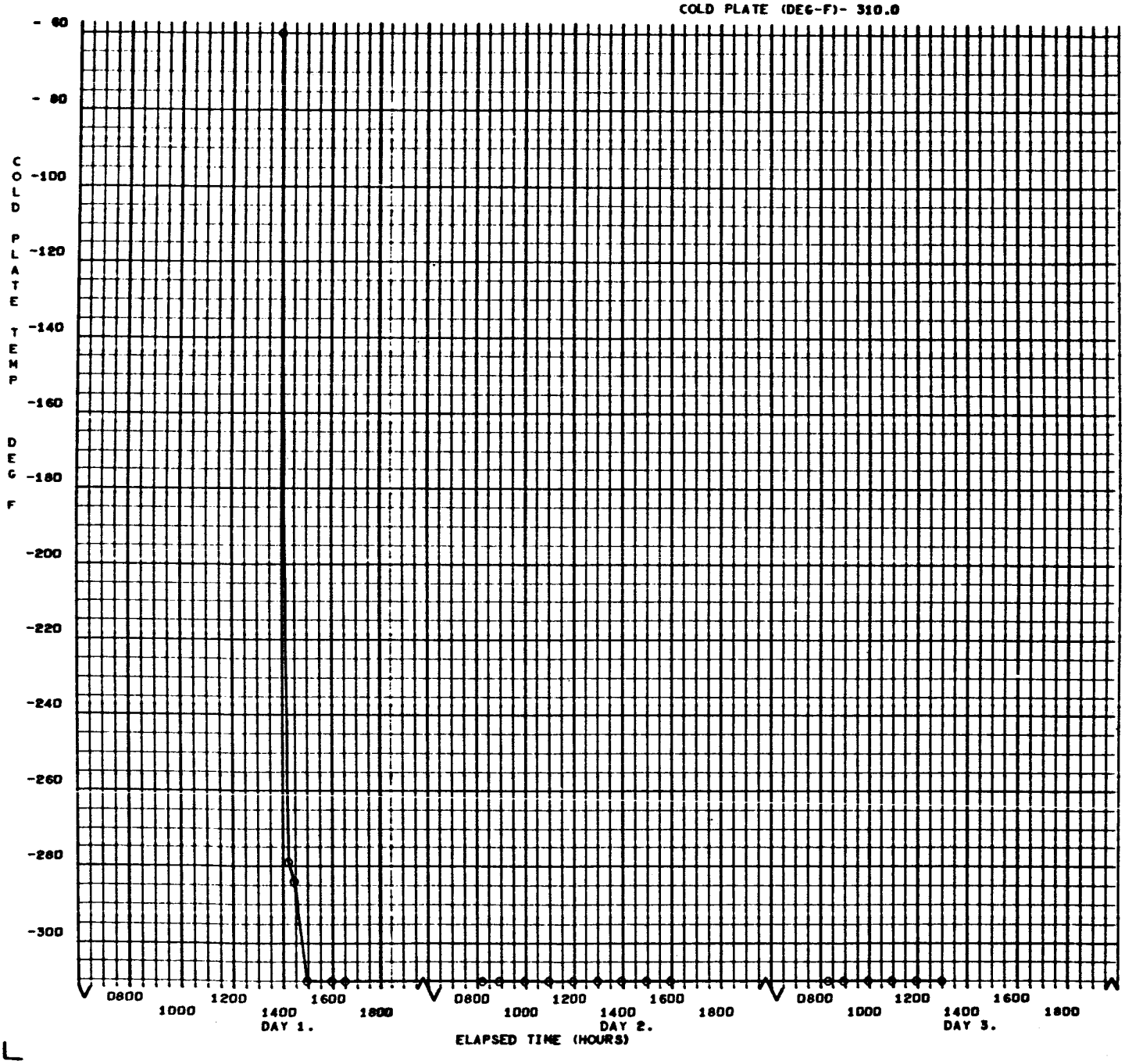


FIGURE 36.E

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 16.1
SAMPLE THICKNESS (IN.) 0.2500
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 79.5
COLD PLATE (DEG-F)- 310.0

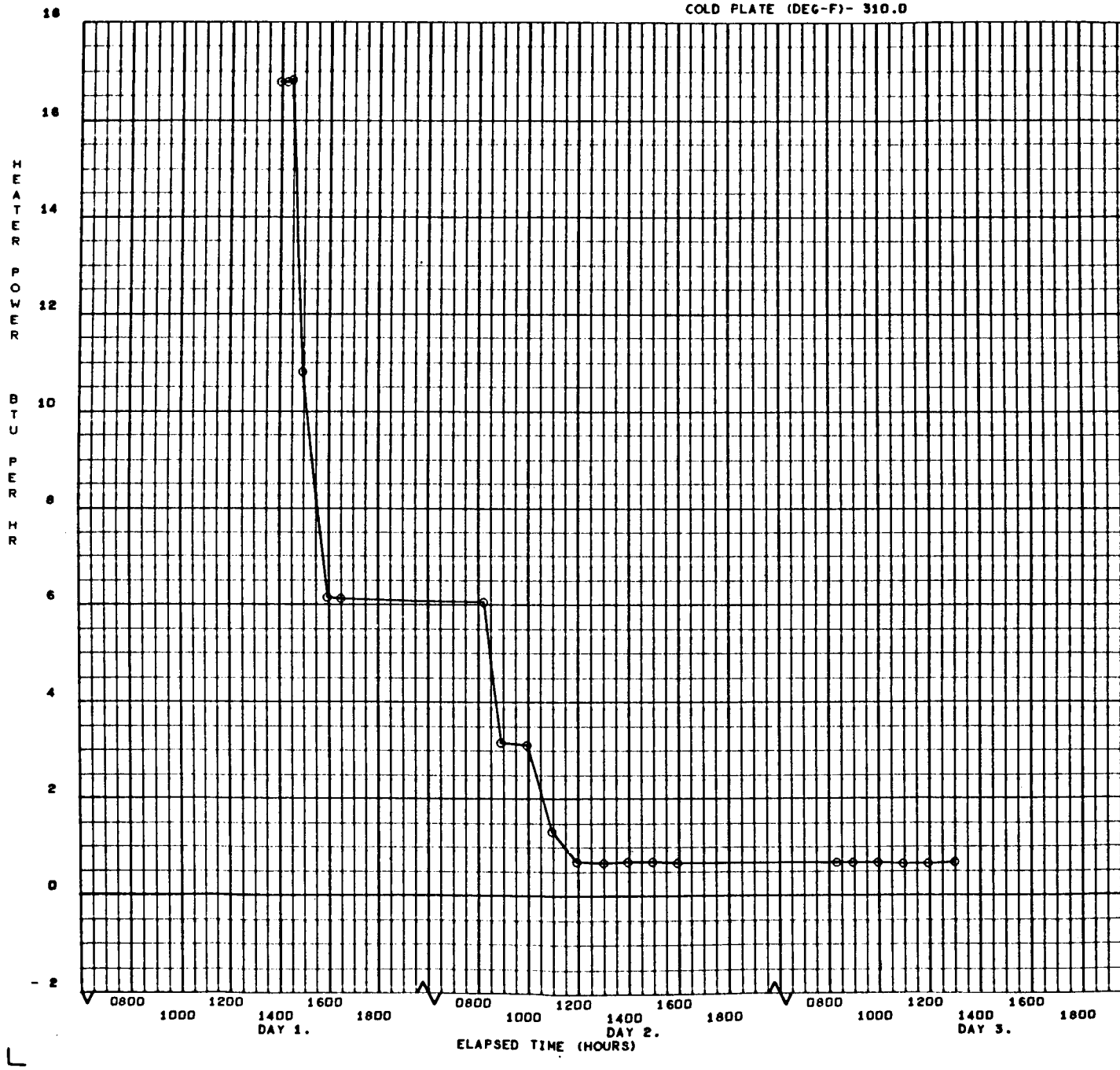


FIGURE 37.A

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 17.1
SAMPLE THICKNESS (IN.) 0.1875
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 67.5
COLD PLATE (DEG-F)- 310.0

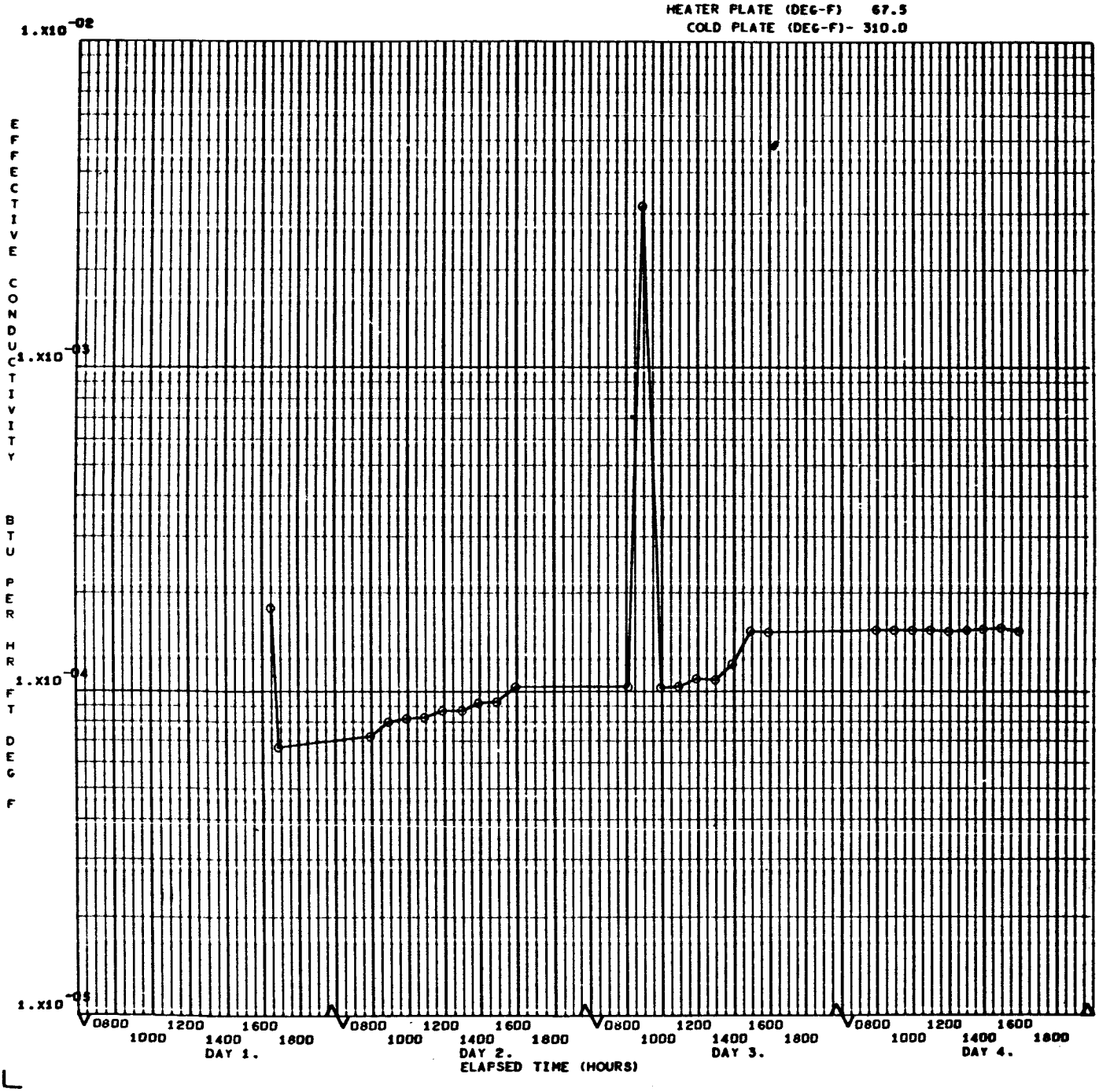


FIGURE 37.B

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 17.1
SAMPLE THICKNESS (IN.) 0.1875
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 67.5
COLD PLATE (DEG-F)- 310.0

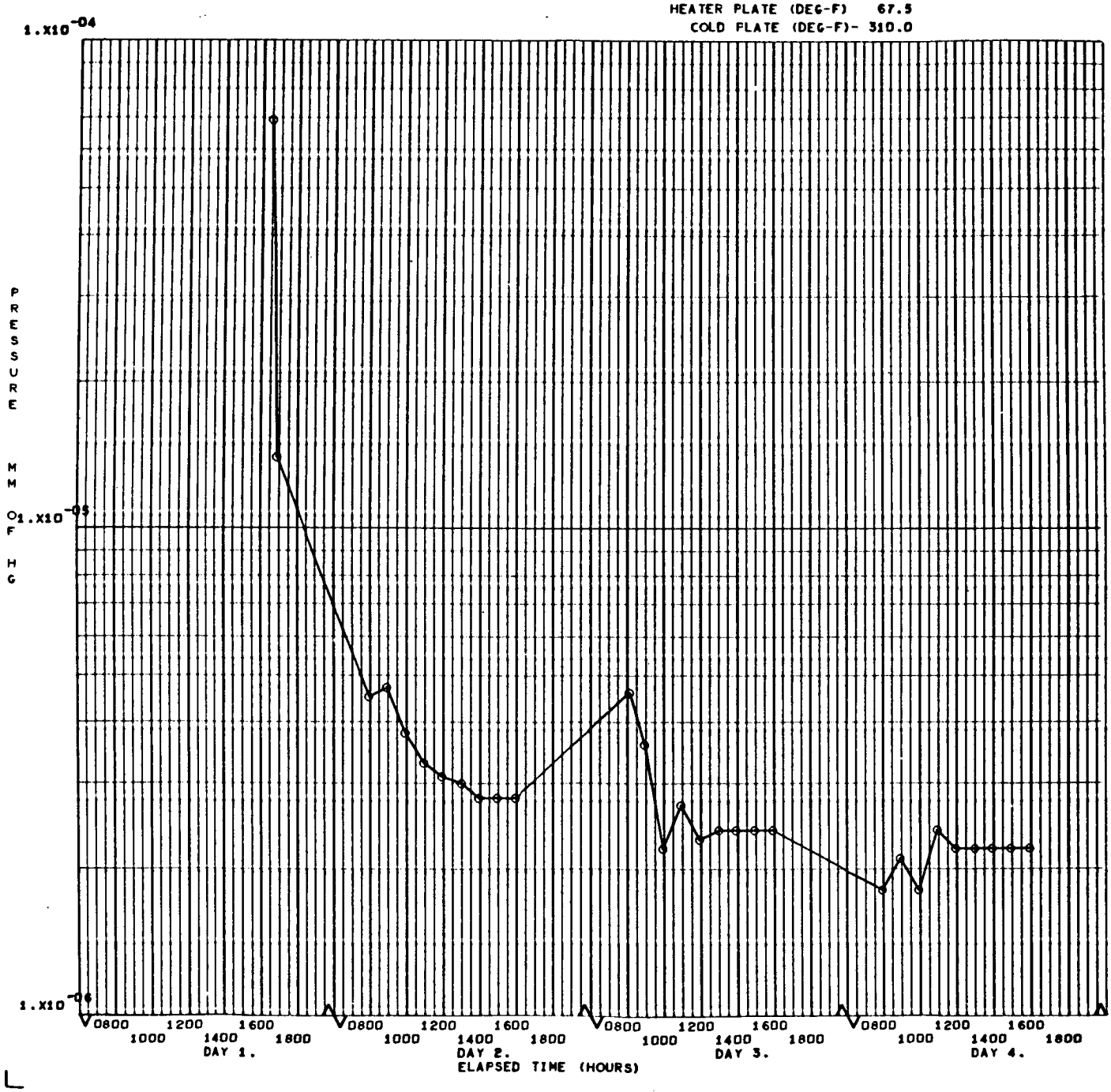


FIGURE 37.C

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 17.1
SAMPLE THICKNESS (IN.) 0.1875
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 67.5
COLD PLATE (DEG-F)- 310.0

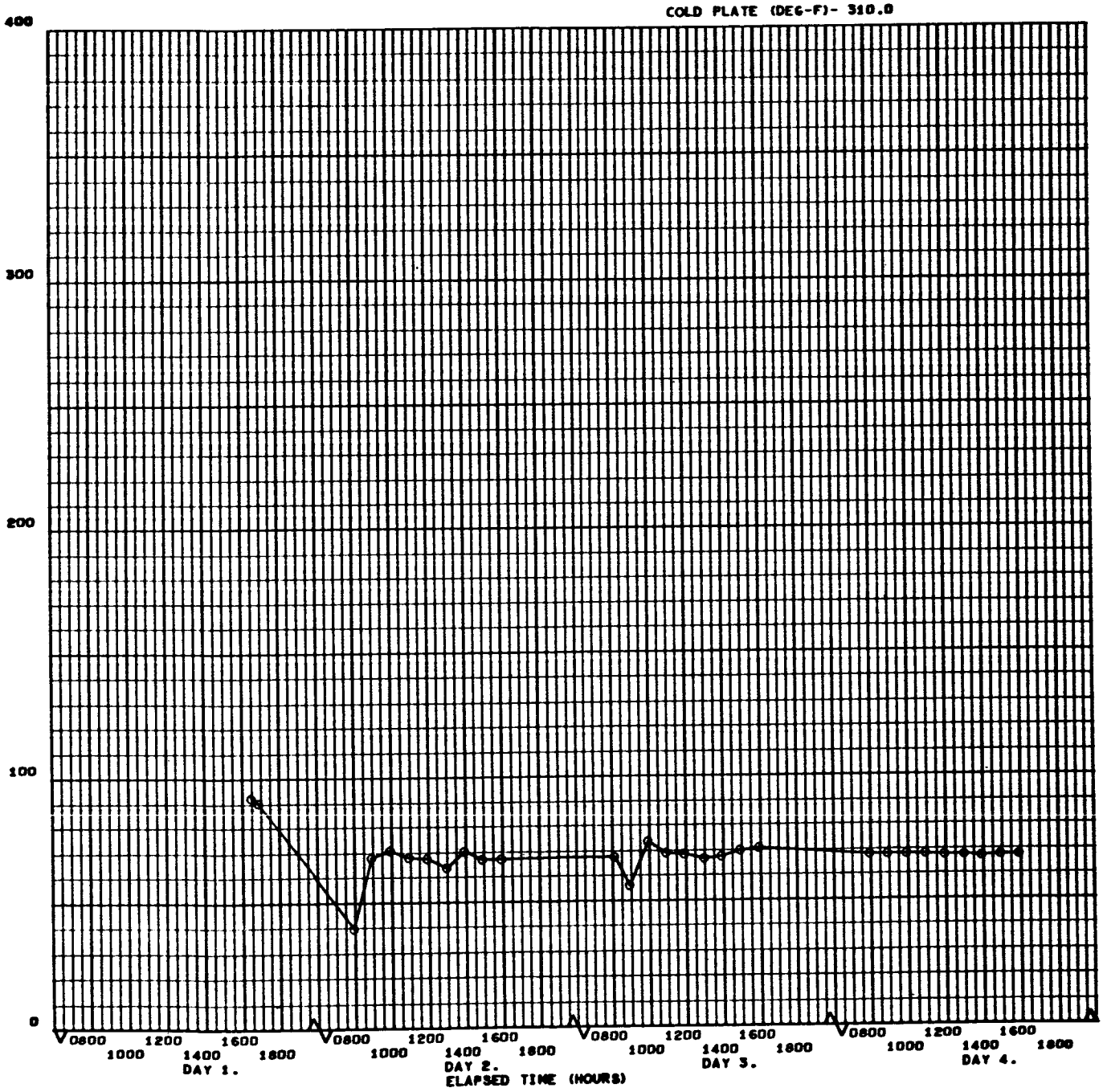


FIGURE 37.D

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 17.1
SAMPLE THICKNESS (IN.) 0.1875
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 67.5
COLD PLATE (DEG-F)- 310.0

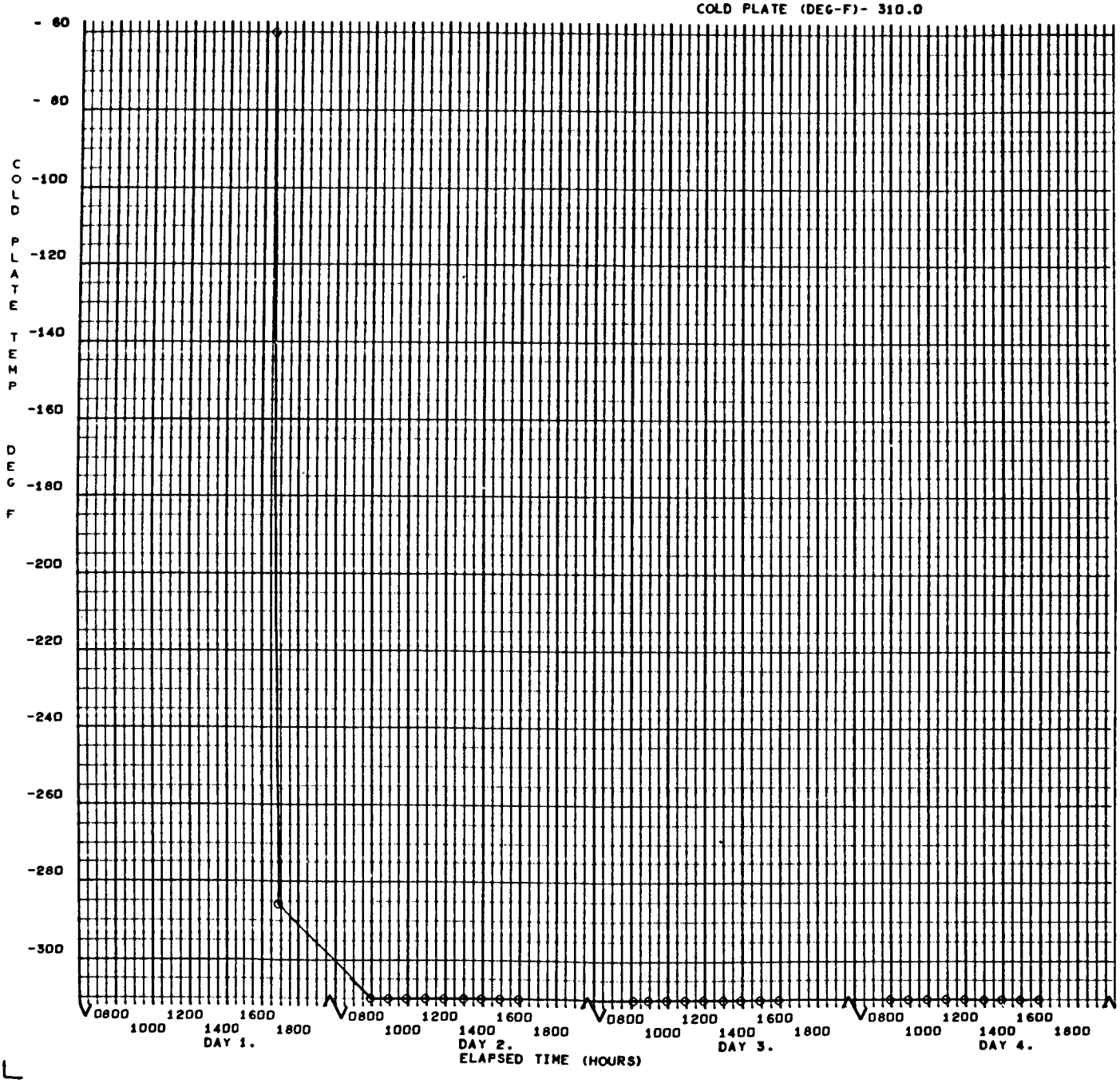


FIGURE 37.E

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 17.1
SAMPLE THICKNESS (IN.) 0.1875
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 67.5
COLD PLATE (DEG-F)- 310.0

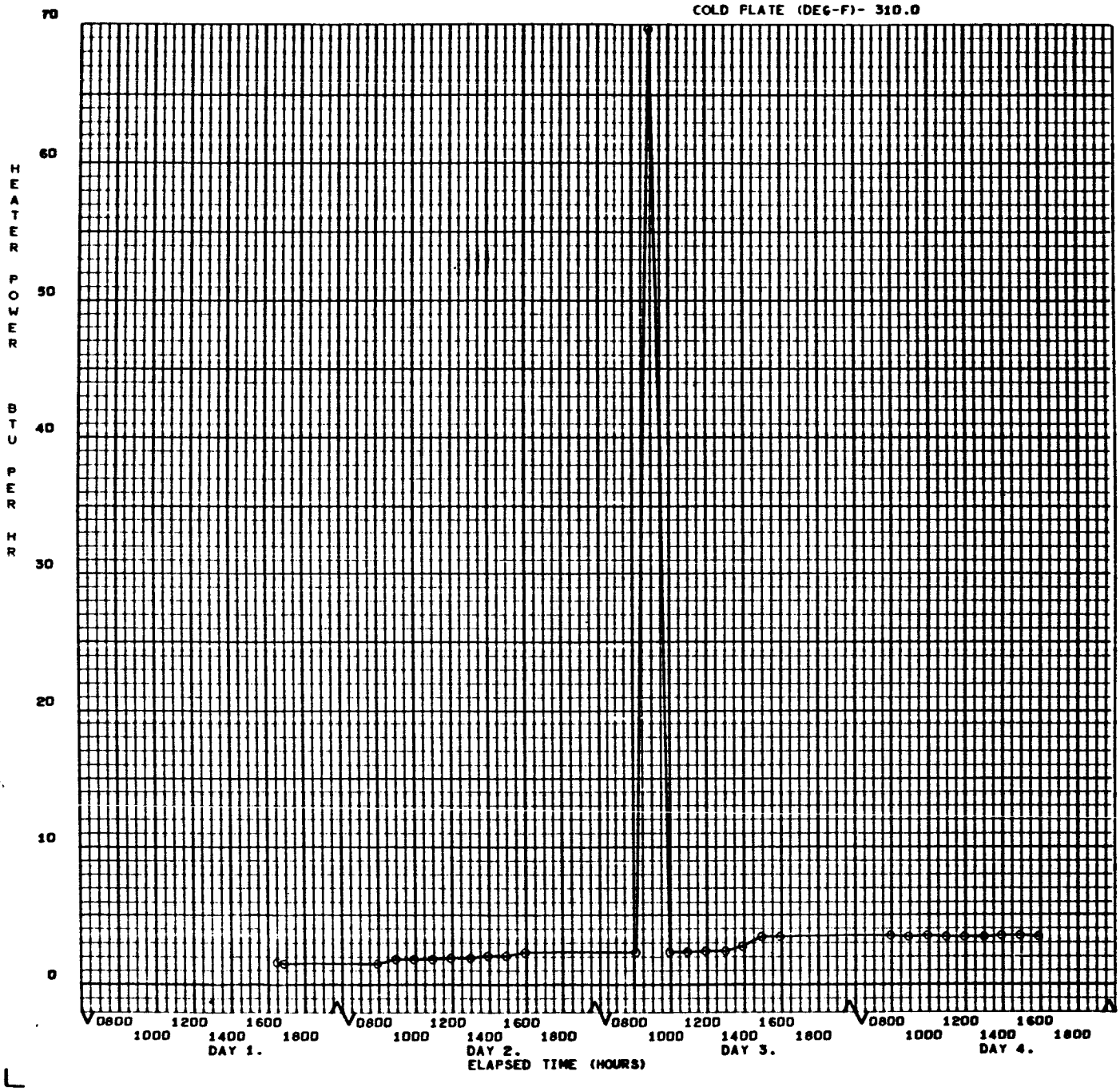


FIGURE 38.A

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 16.2
SAMPLE THICKNESS (IN.) 0.2500
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 296.0
COLD PLATE (DEG-F) 70.0

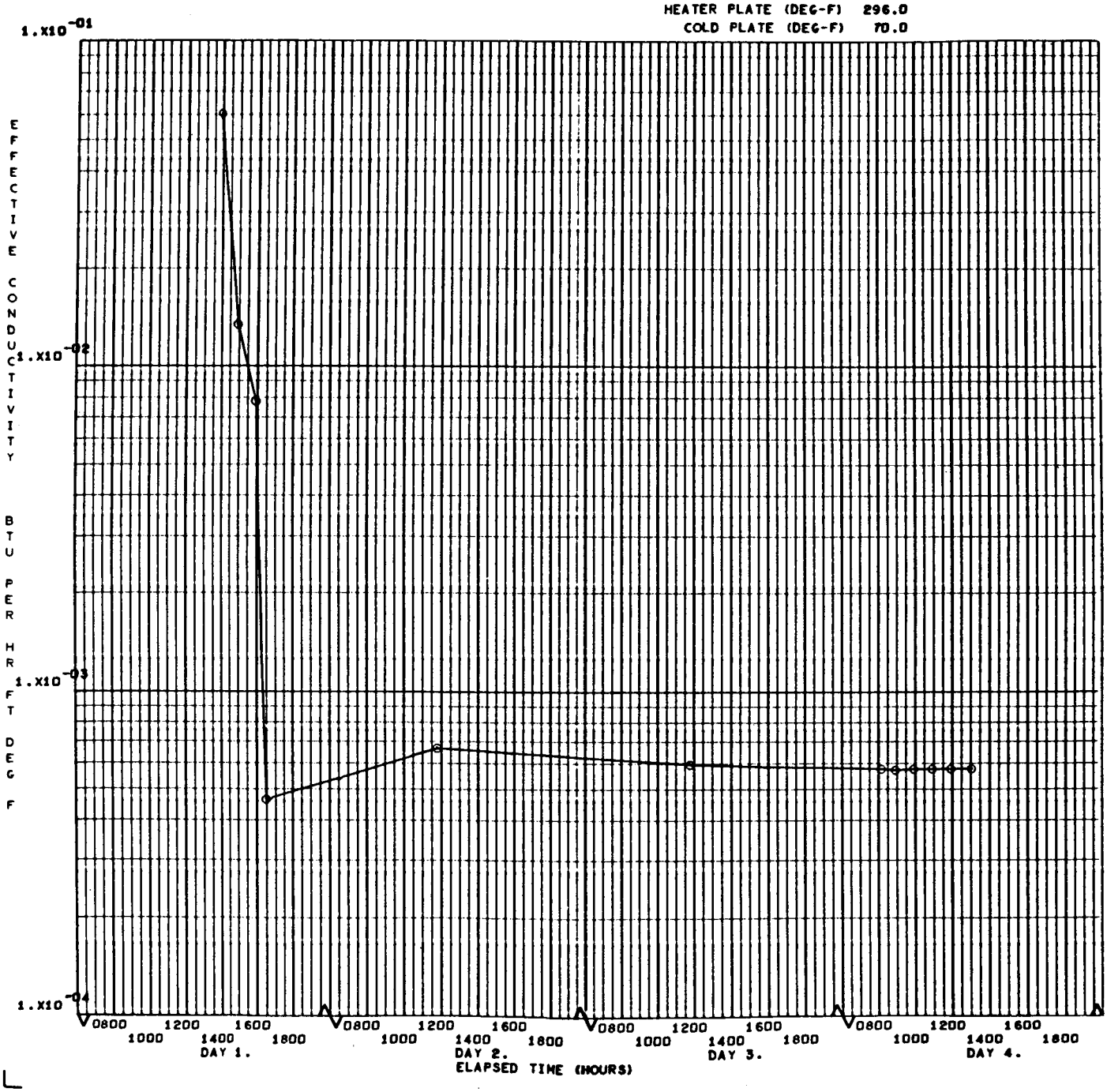


FIGURE 38.B

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 16.2
SAMPLE THICKNESS (IN.) 0.2500
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 296.0
COLD PLATE (DEG-F) 70.0

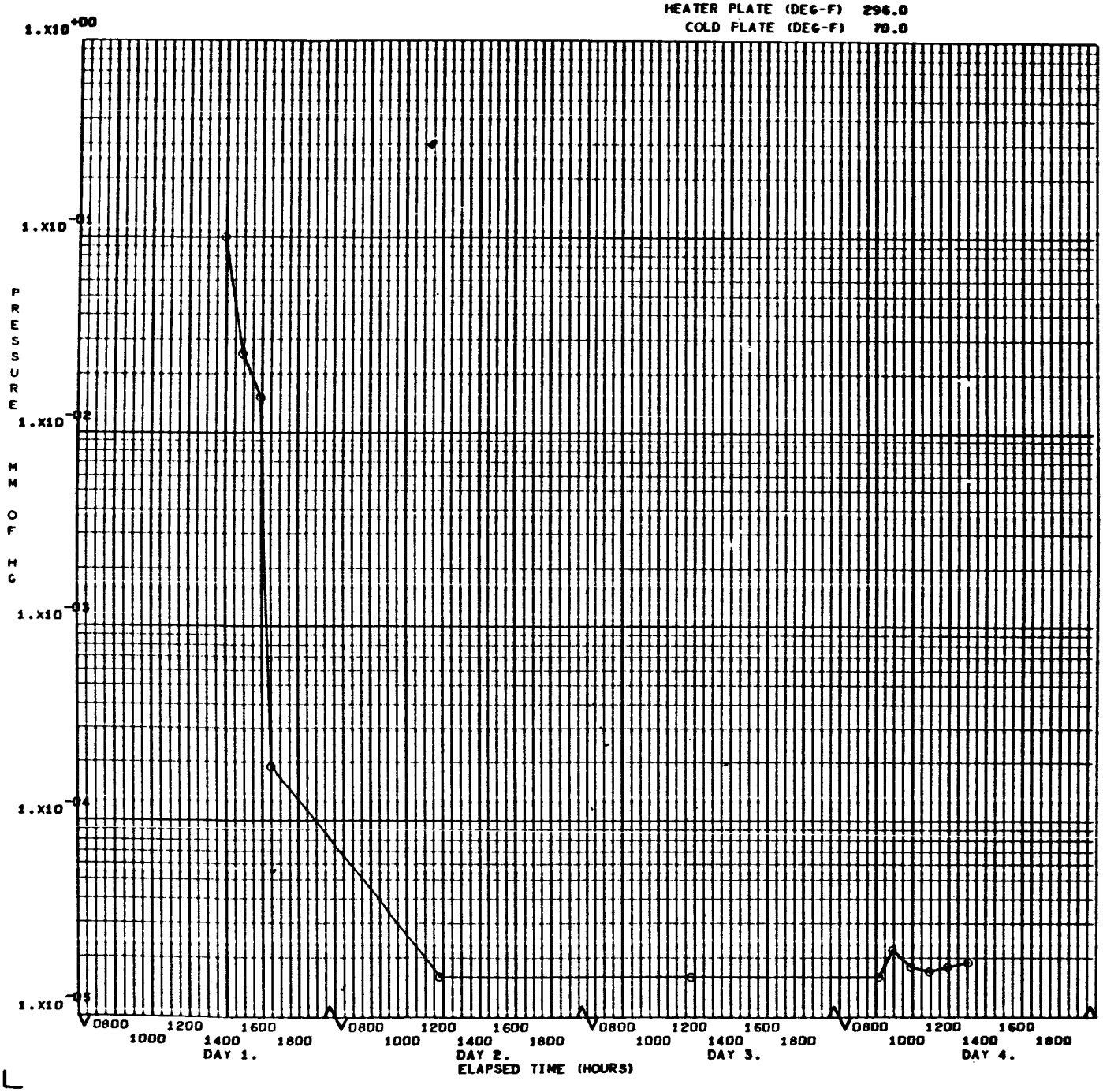


FIGURE 38.C

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 16.2
SAMPLE THICKNESS (IN.) 0.2500
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 296.0
COLD PLATE (DEG-F) 70.0

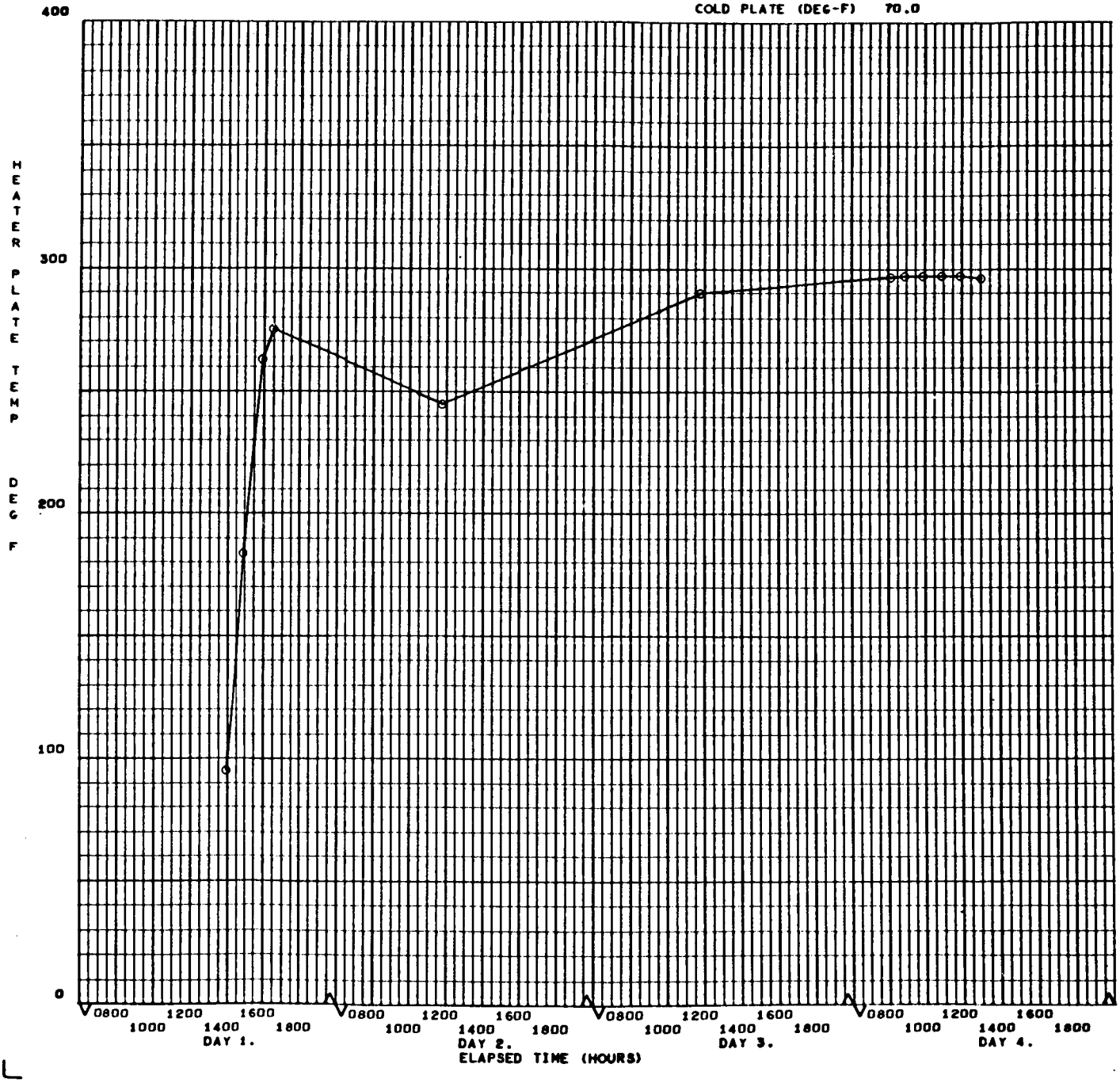


FIGURE 38.D

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 16.2
SAMPLE THICKNESS (IN.) 0.2500
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 296.0
COLD PLATE (DEG-F) 70.0

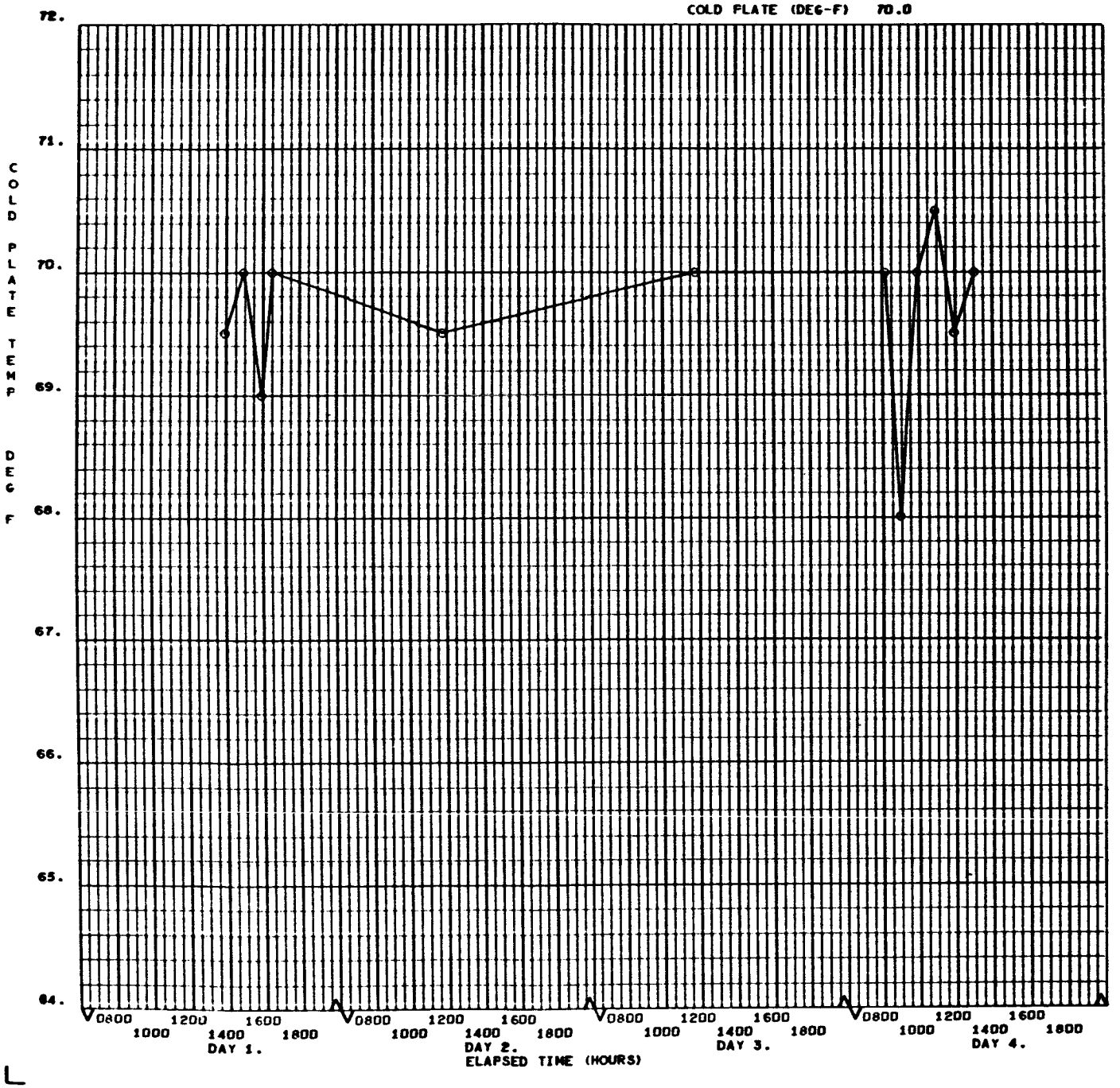


FIGURE 38.E

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 16.2
SAMPLE THICKNESS (IN.) 0.2500
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 296.0
COLD PLATE (DEG-F) 70.0

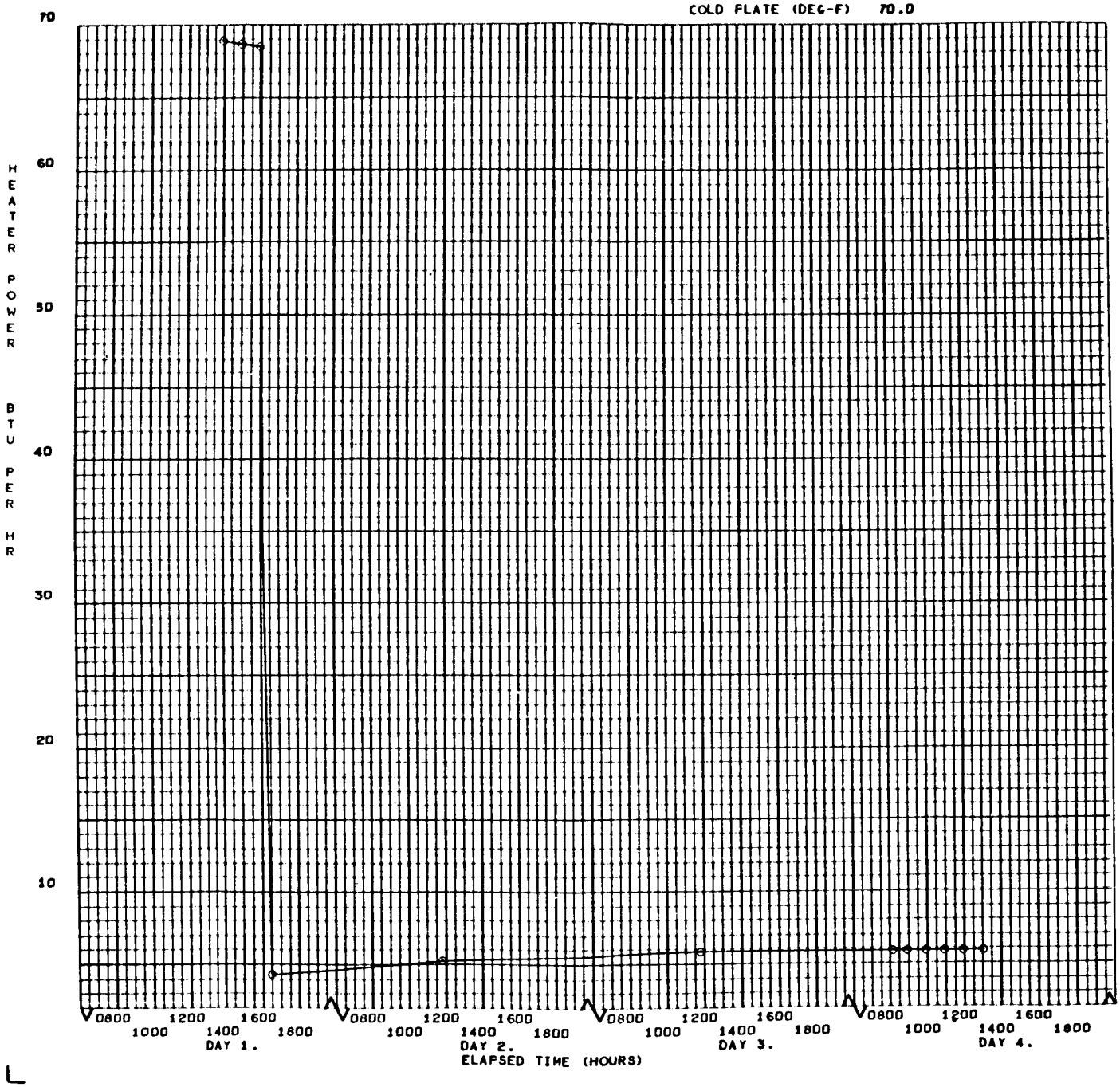


FIGURE 39.A

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 17.2
SAMPLE THICKNESS (IN.) 0.1875
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 295.0
COLD PLATE (DEG-F) 68.5

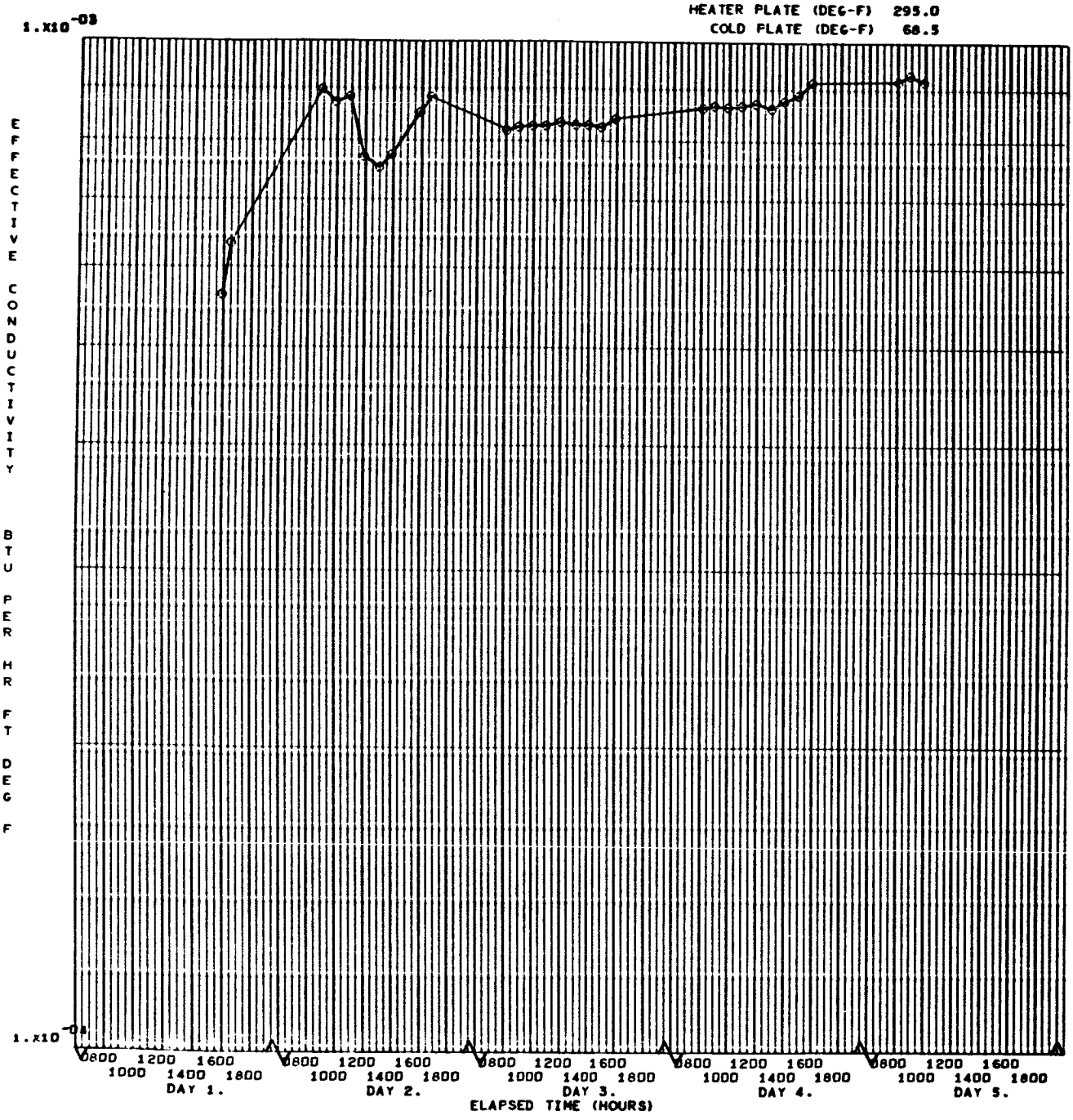


FIGURE 39.B

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 17.2
SAMPLE THICKNESS (IN.) 0.1875
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 295.0
COLD PLATE (DEG-F) 68.5

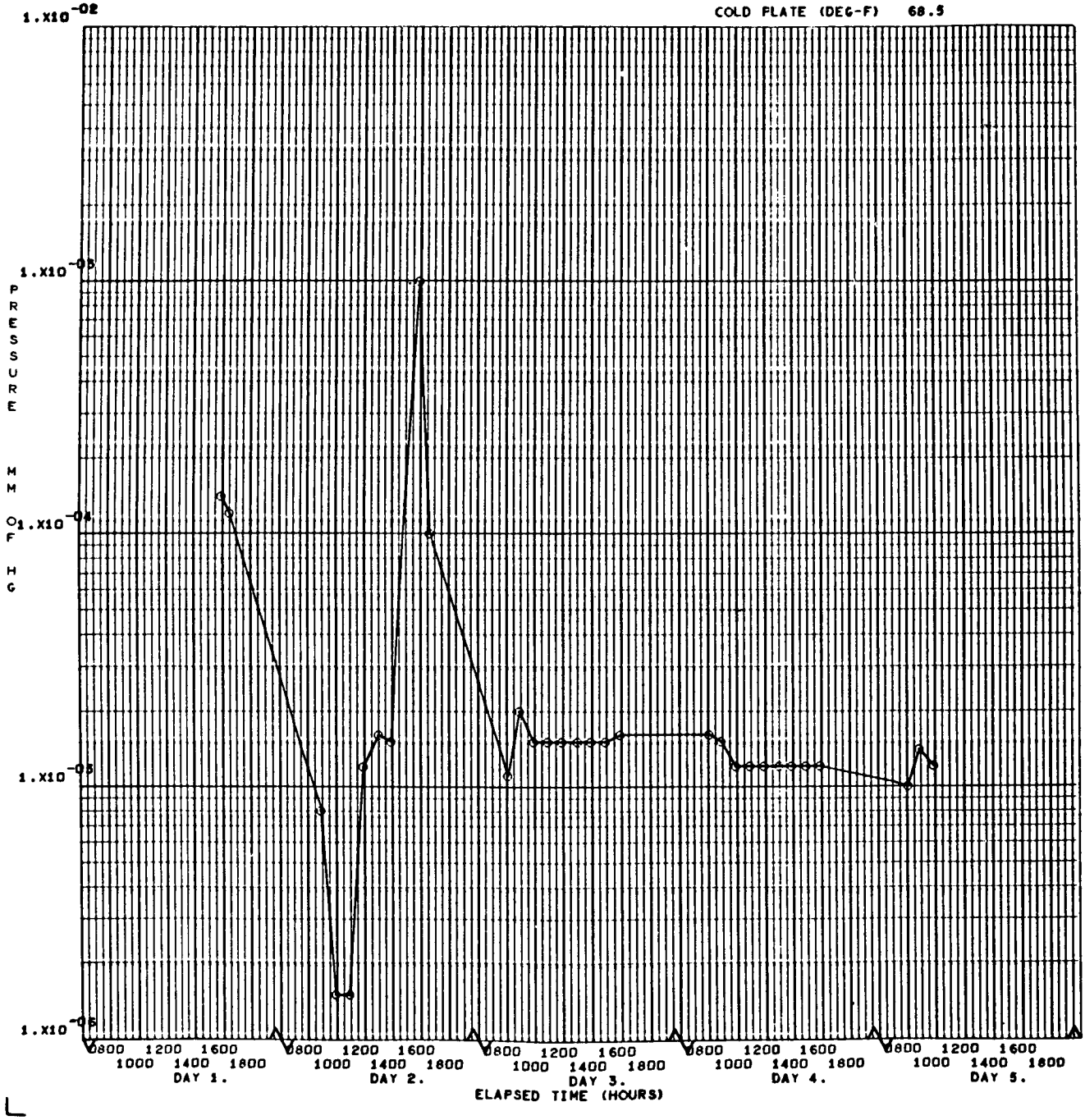


FIGURE 39.C

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 17.2
SAMPLE THICKNESS (IN.) 0.1875
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 295.0
COLD PLATE (DEG-F) 68.5

FIGURE 39.D

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 17.2
SAMPLE THICKNESS (IN.) 0.1875
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 295.0
COLD PLATE (DEG-F) 68.5

FIGURE 39.E

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 17.2
SAMPLE THICKNESS (IN.) 0.1875
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 295.0
COLD PLATE (DEG-F) 68.5

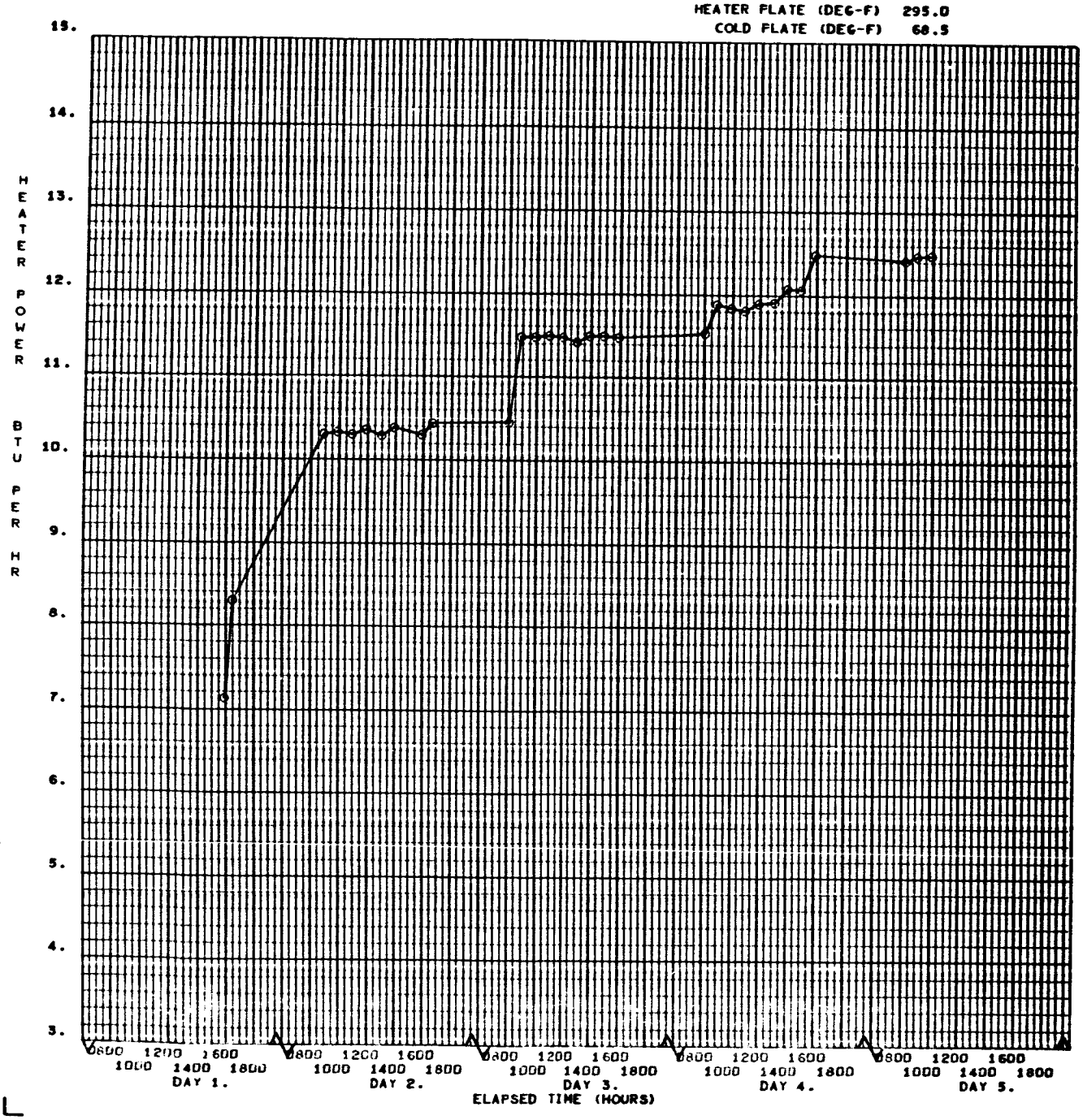


FIGURE 40.A

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 14.3
SAMPLE THICKNESS (IN.) 0.1875
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 67.5
COLD PLATE (DEG-F)- 310.0

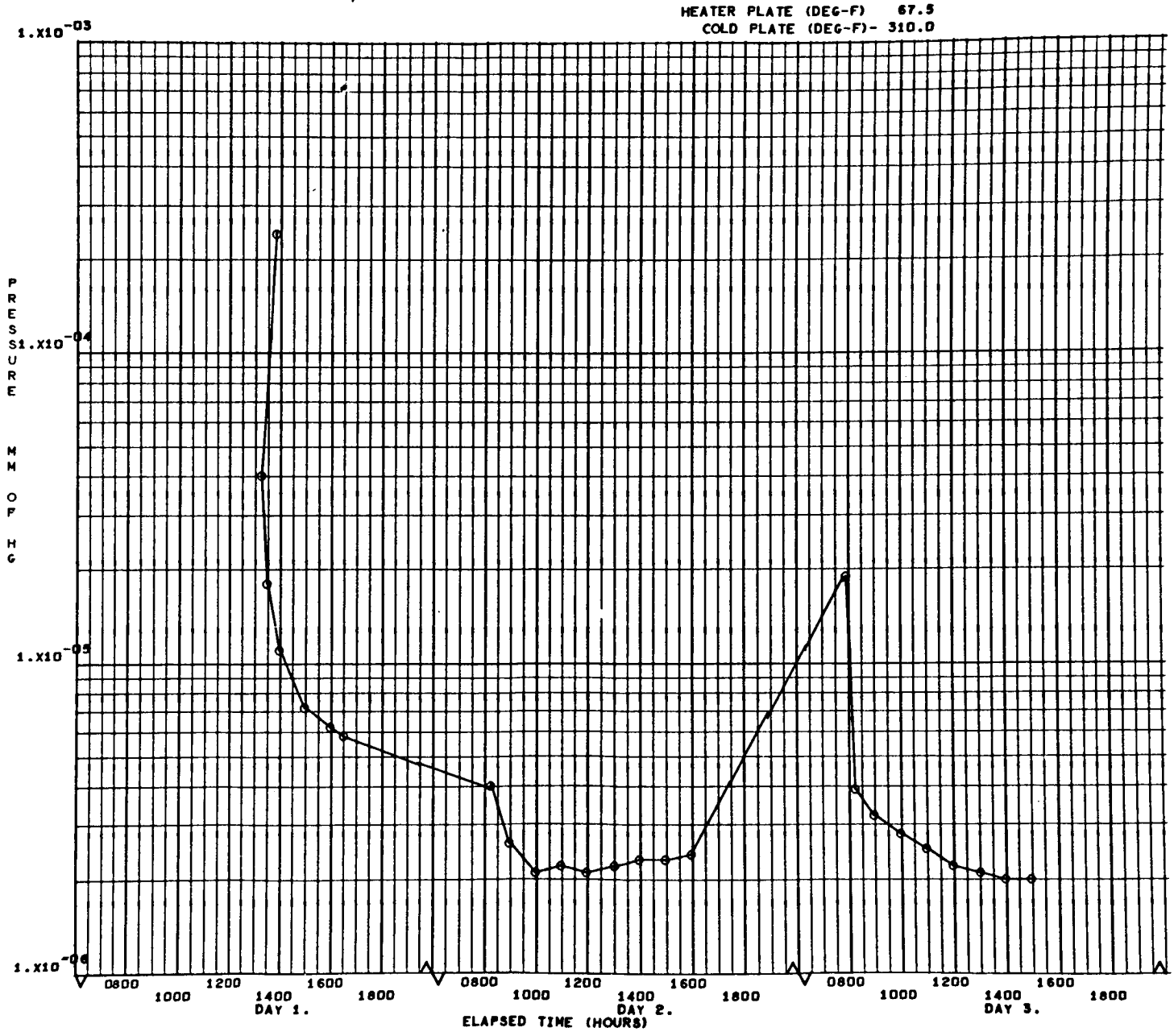


FIGURE 40.B

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 14.3
SAMPLE THICKNESS (IN.) 0.1875
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 67.5
COLD PLATE (DEG-F)- 310.0

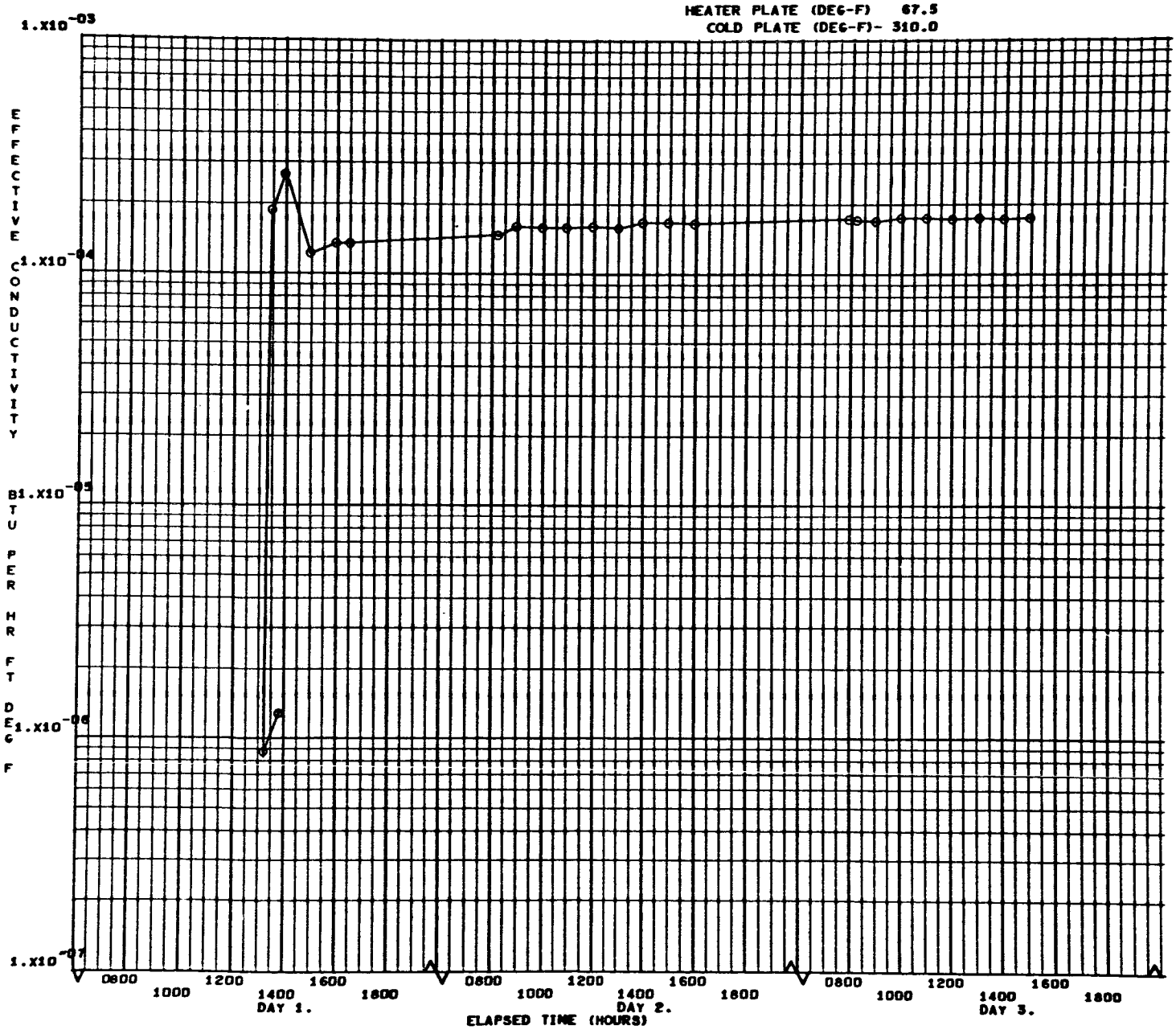


FIGURE 40.C

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 14.3
SAMPLE THICKNESS (IN.) 0.1875
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 67.5
COLD PLATE (DEG-F)- 310.0

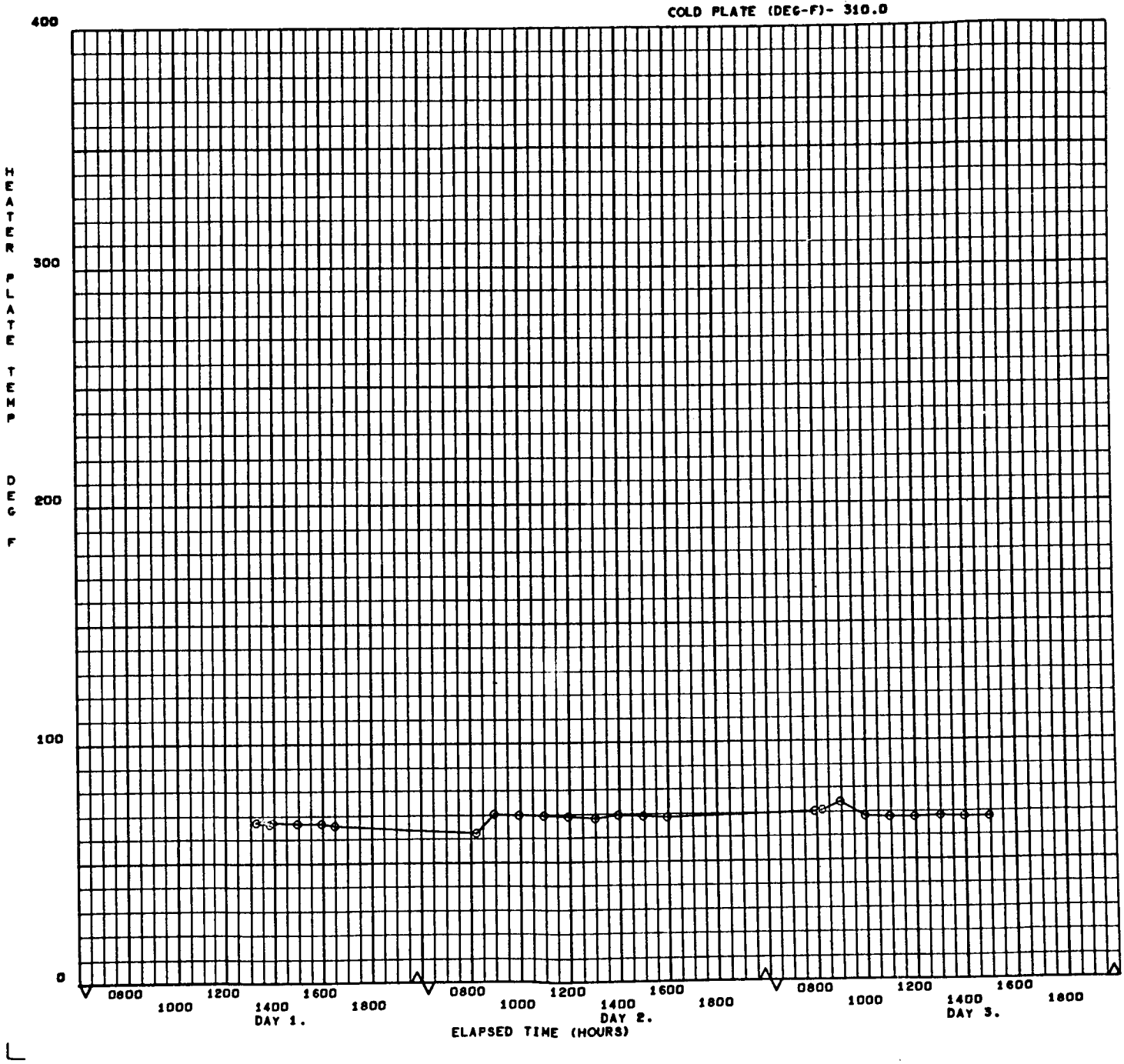


FIGURE 40.D

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 14.3
SAMPLE THICKNESS (IN.) 0.1875
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 67.5
COLD PLATE (DEG-F)- 310.0

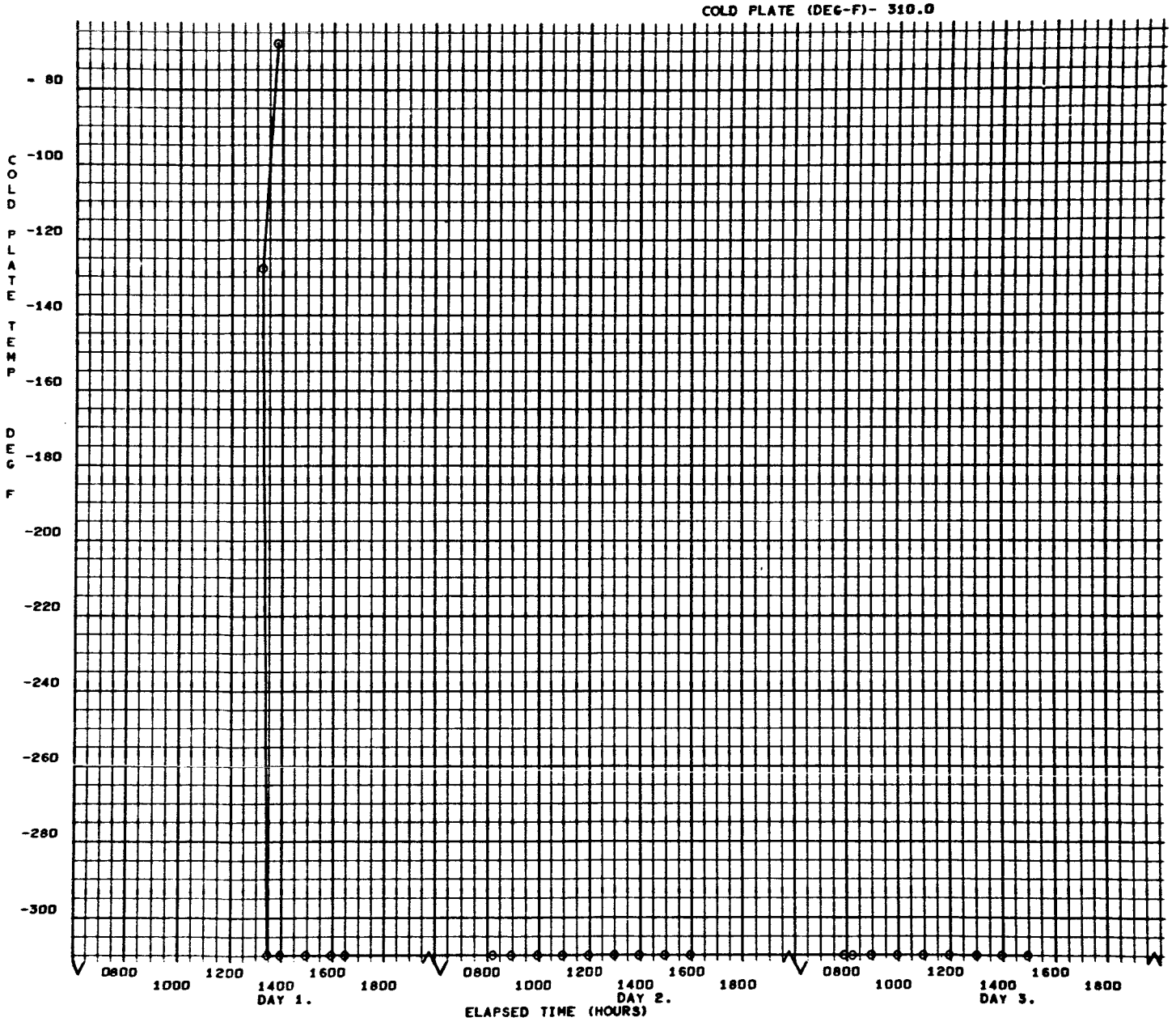


FIGURE 40.E

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 14.3
SAMPLE THICKNESS (IN.) 0.1875
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 67.5
COLD PLATE (DEG-F)- 310.0

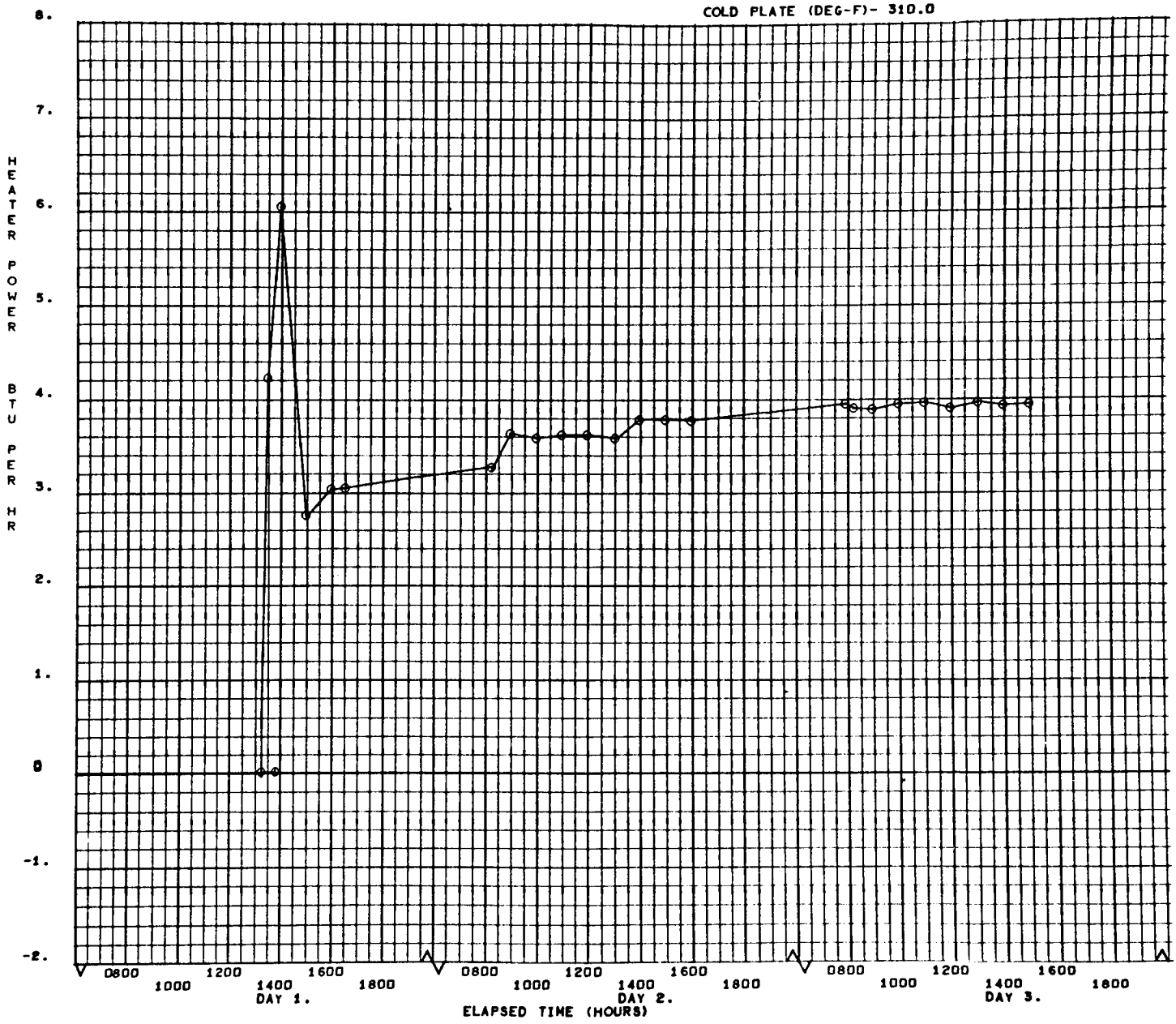


FIGURE 41.A

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 18.1
SAMPLE THICKNESS (IN.) 0.2500
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 78.0
COLD PLATE (DEG-F)- 310.0

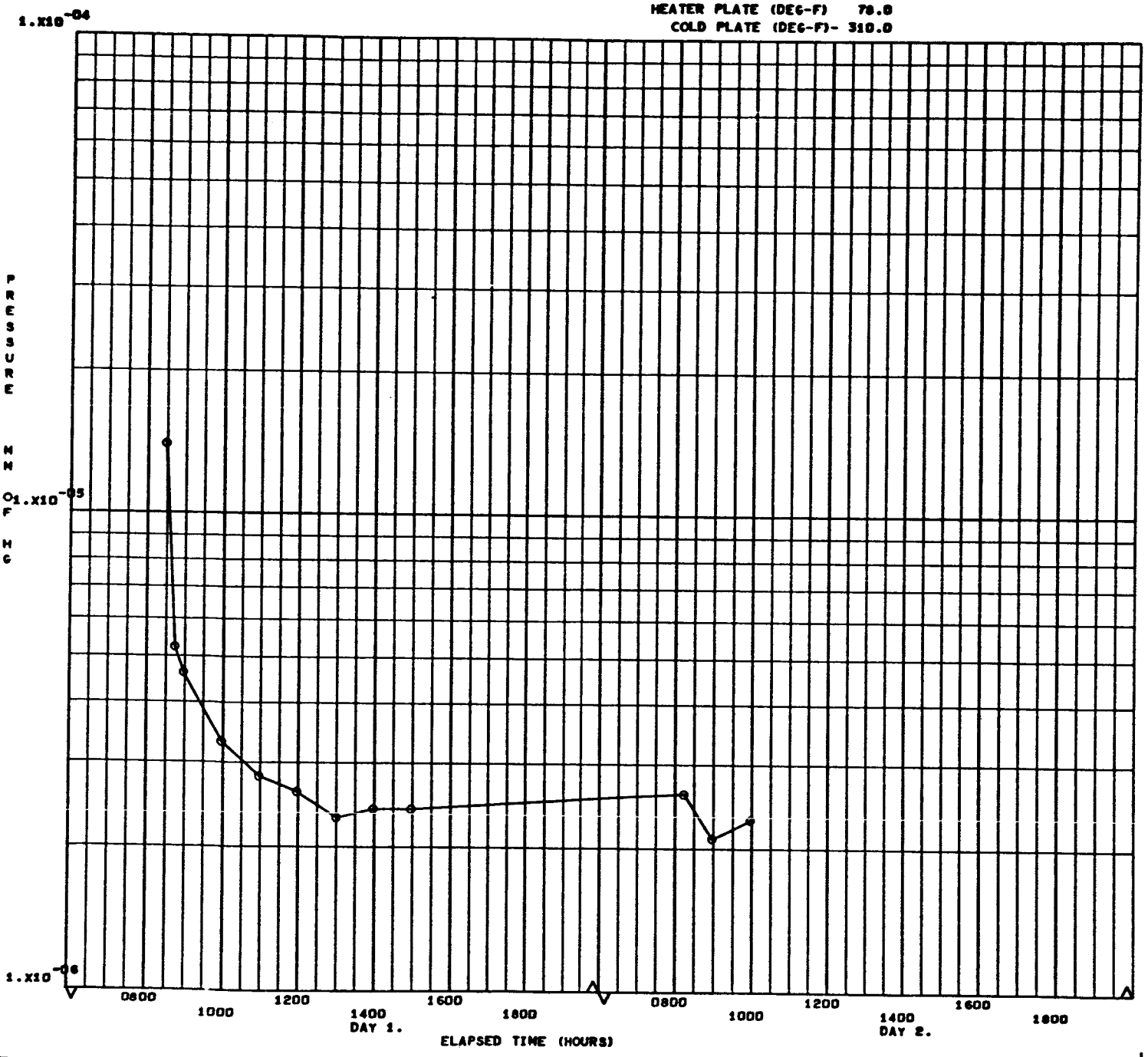


FIGURE 41.B

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 18.1
SAMPLE THICKNESS (IN.) 0.2500
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 78.0
COLD PLATE (DEG-F)- 310.0

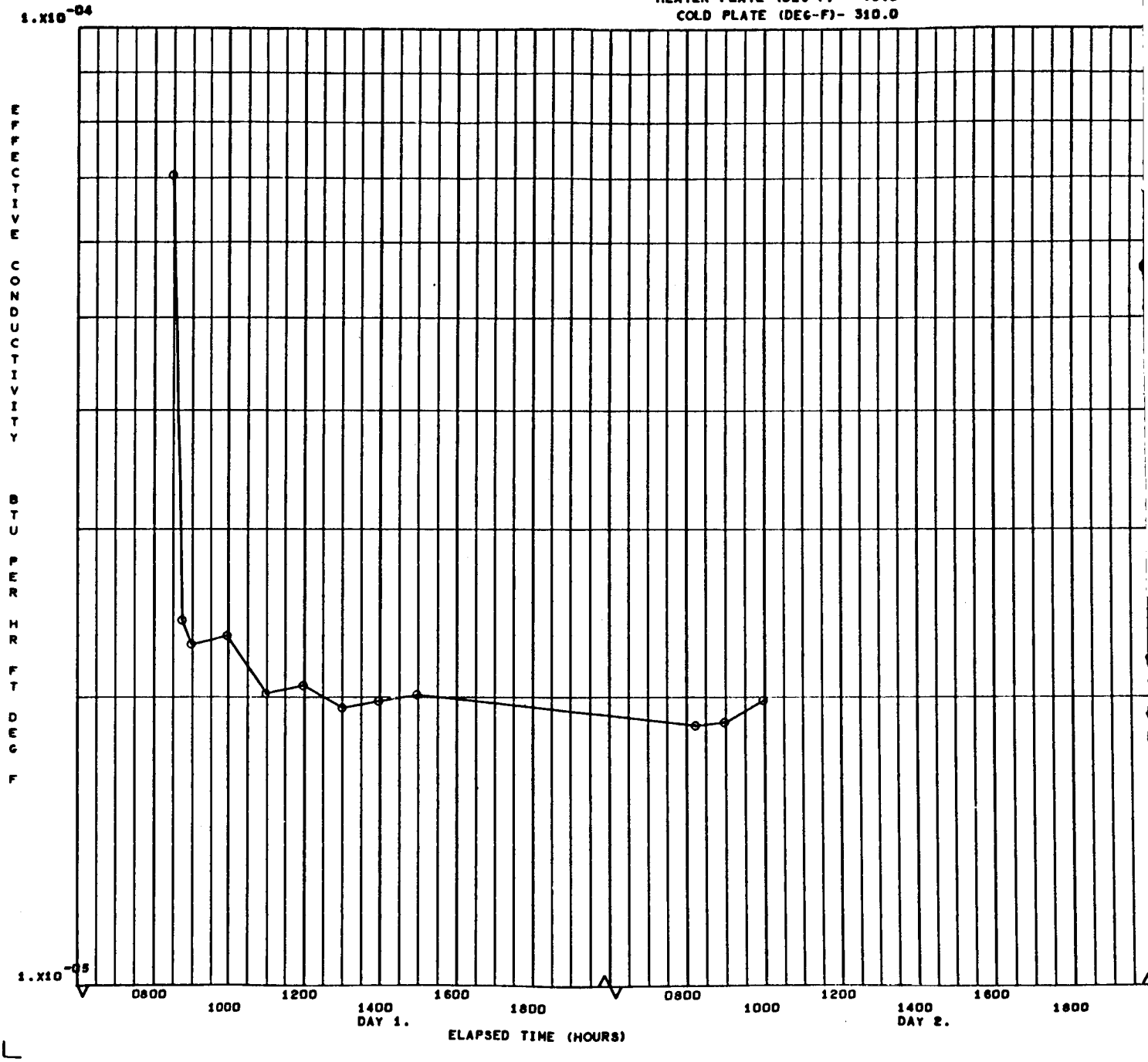


FIGURE 41.C

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 18.1
SAMPLE THICKNESS (IN.) 0.2500
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 78.0
COLD PLATE (DEG-F)- 310.0

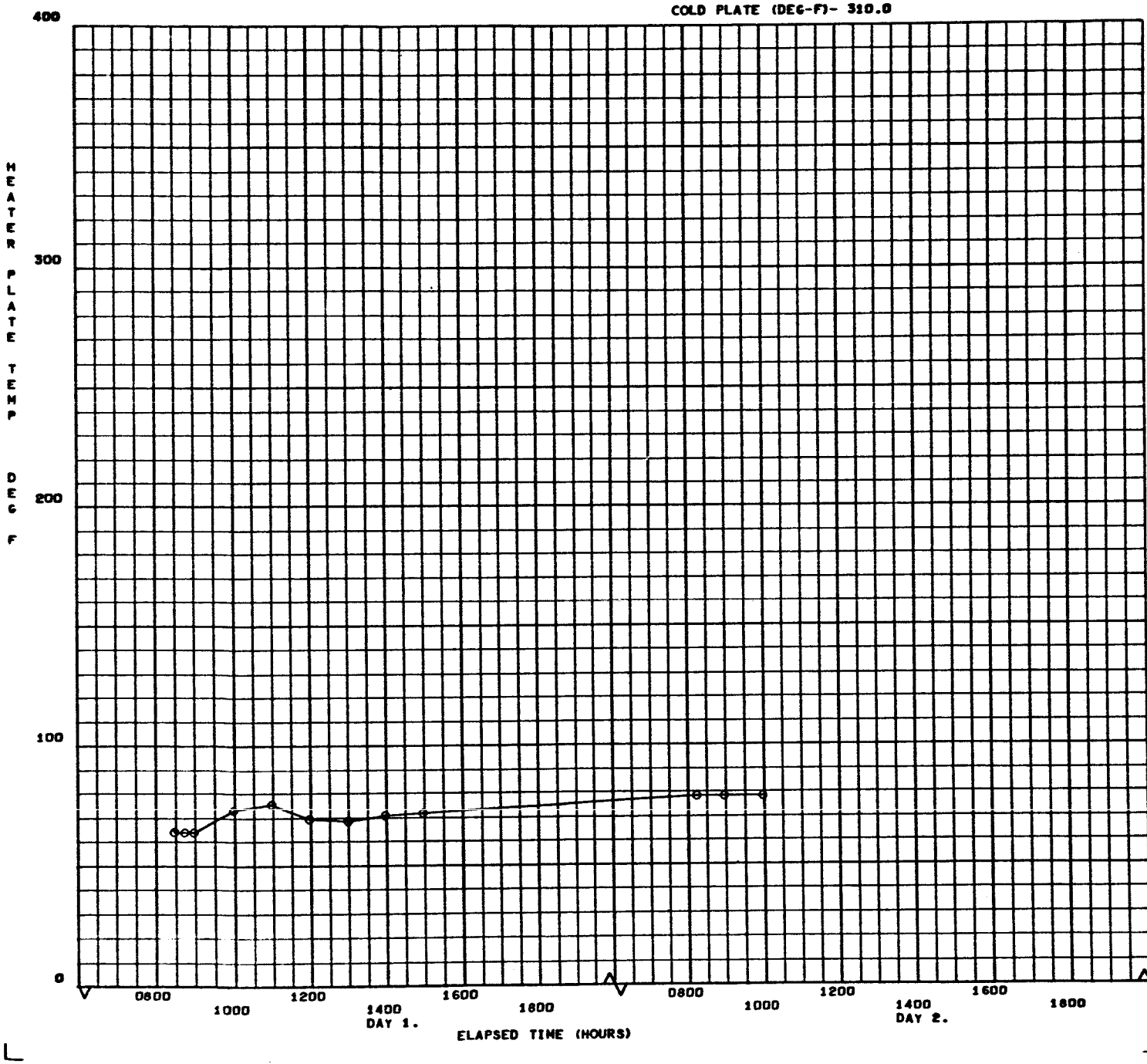


FIGURE 41.D

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 18.1
SAMPLE THICKNESS (IN.) 0.2500
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 78.0
COLD PLATE (DEG-F)- 310.0

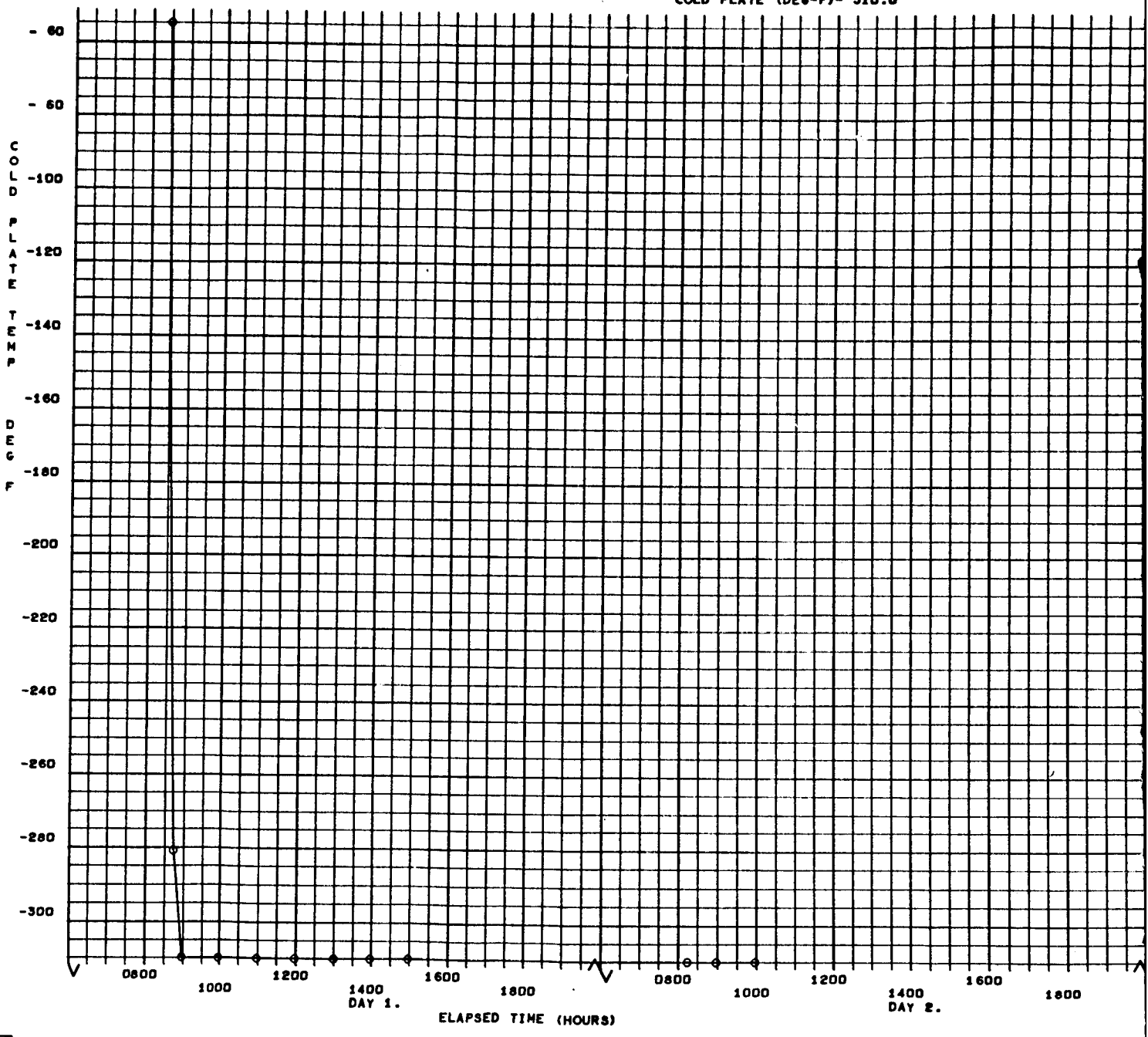


FIGURE 41.E

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 16.1
SAMPLE THICKNESS (IN.) 0.2500
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 78.0
COLD PLATE (DEG-F)- 310.0

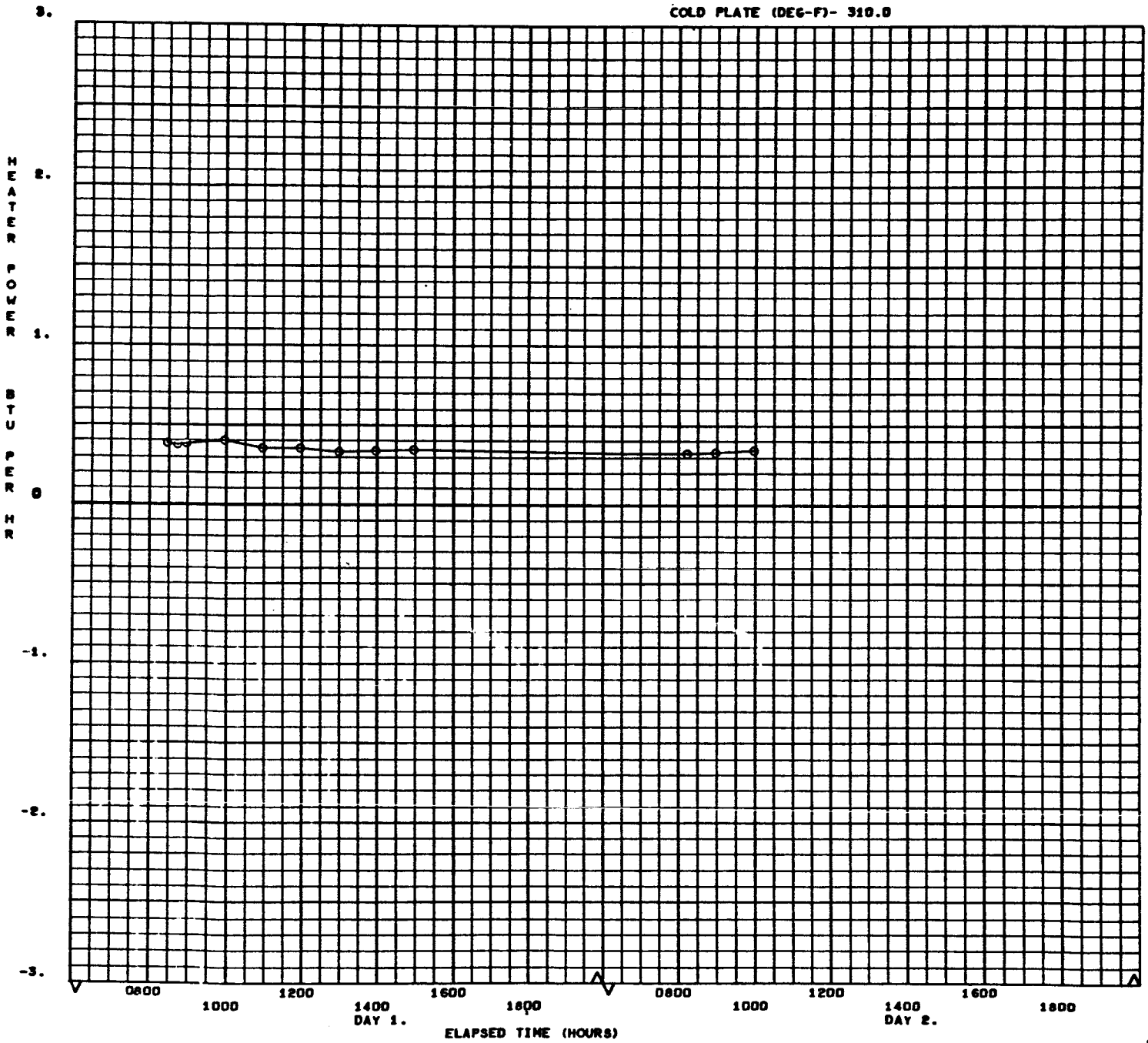


FIGURE 42.A

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 11.2
SAMPLE THICKNESS (IN.) 0.2500
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 76.0
COLD PLATE (DEG-F)- 310.0

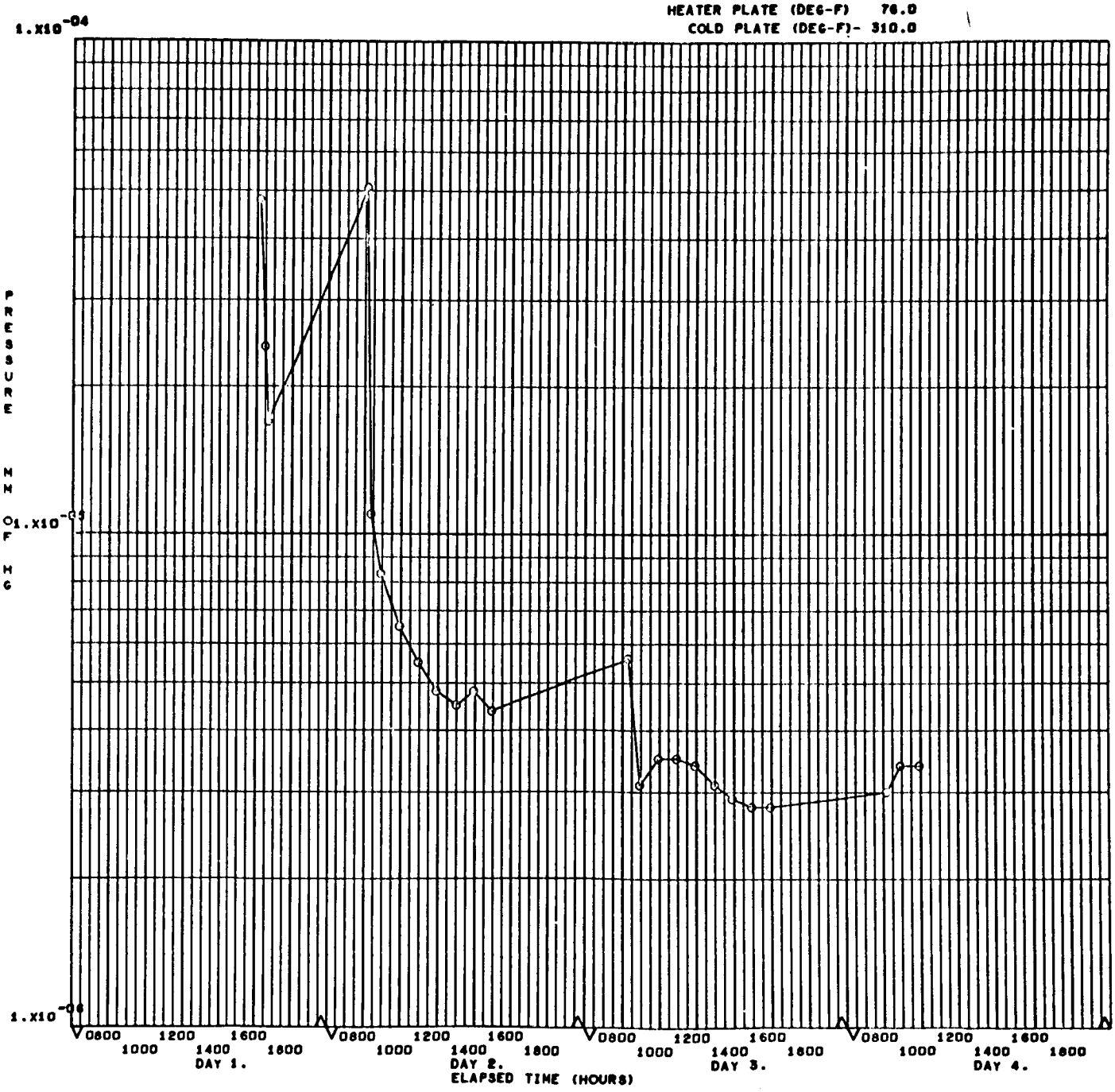


FIGURE 42.B

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 11.2
SAMPLE THICKNESS (IN.) 0.2500
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 76.0
COLD PLATE (DEG-F)- 310.0

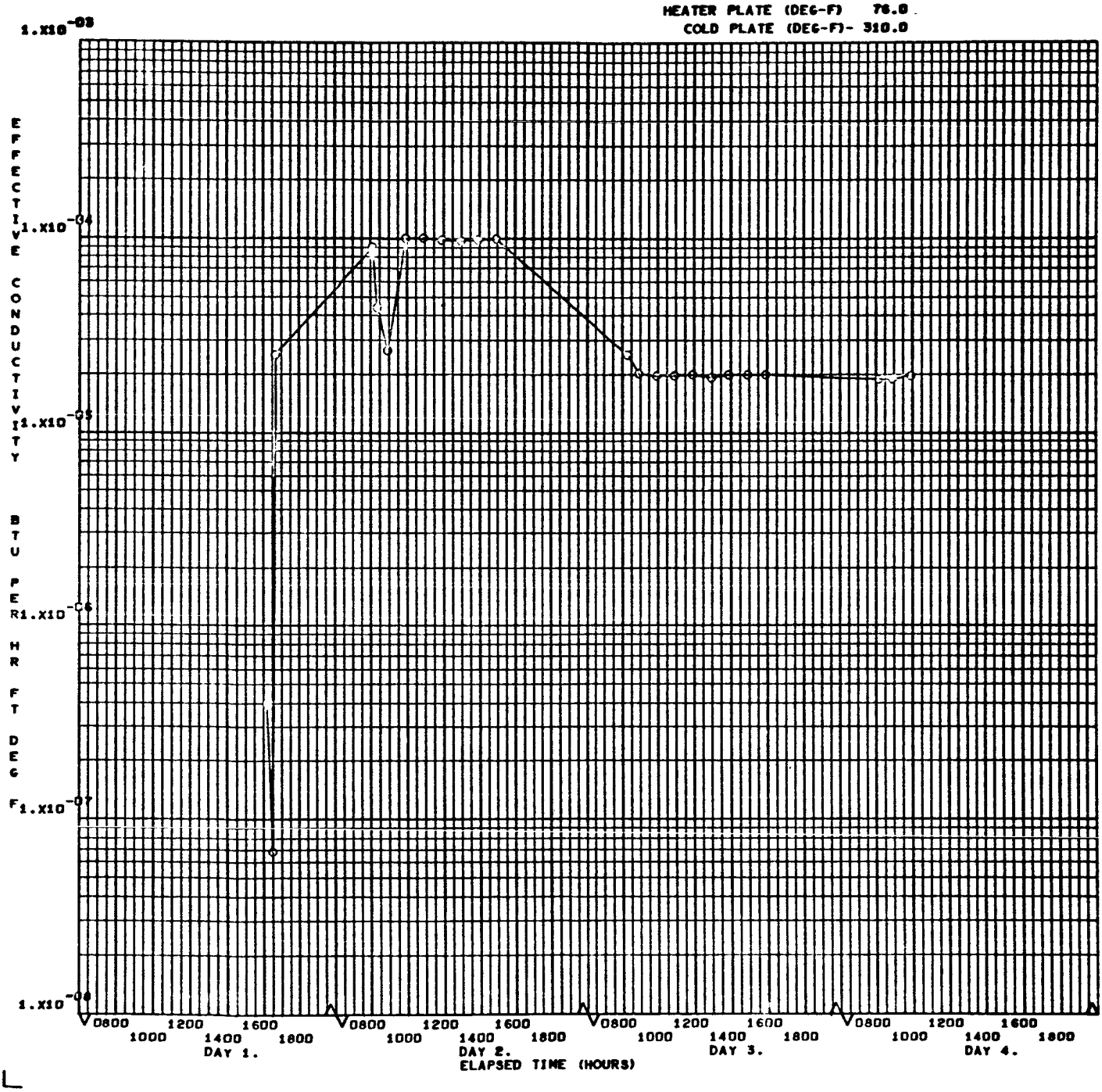


FIGURE 42.C

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 11.2
SAMPLE THICKNESS (IN.) 0.2500
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 76.0
COLD PLATE (DEG-F)- 310.0

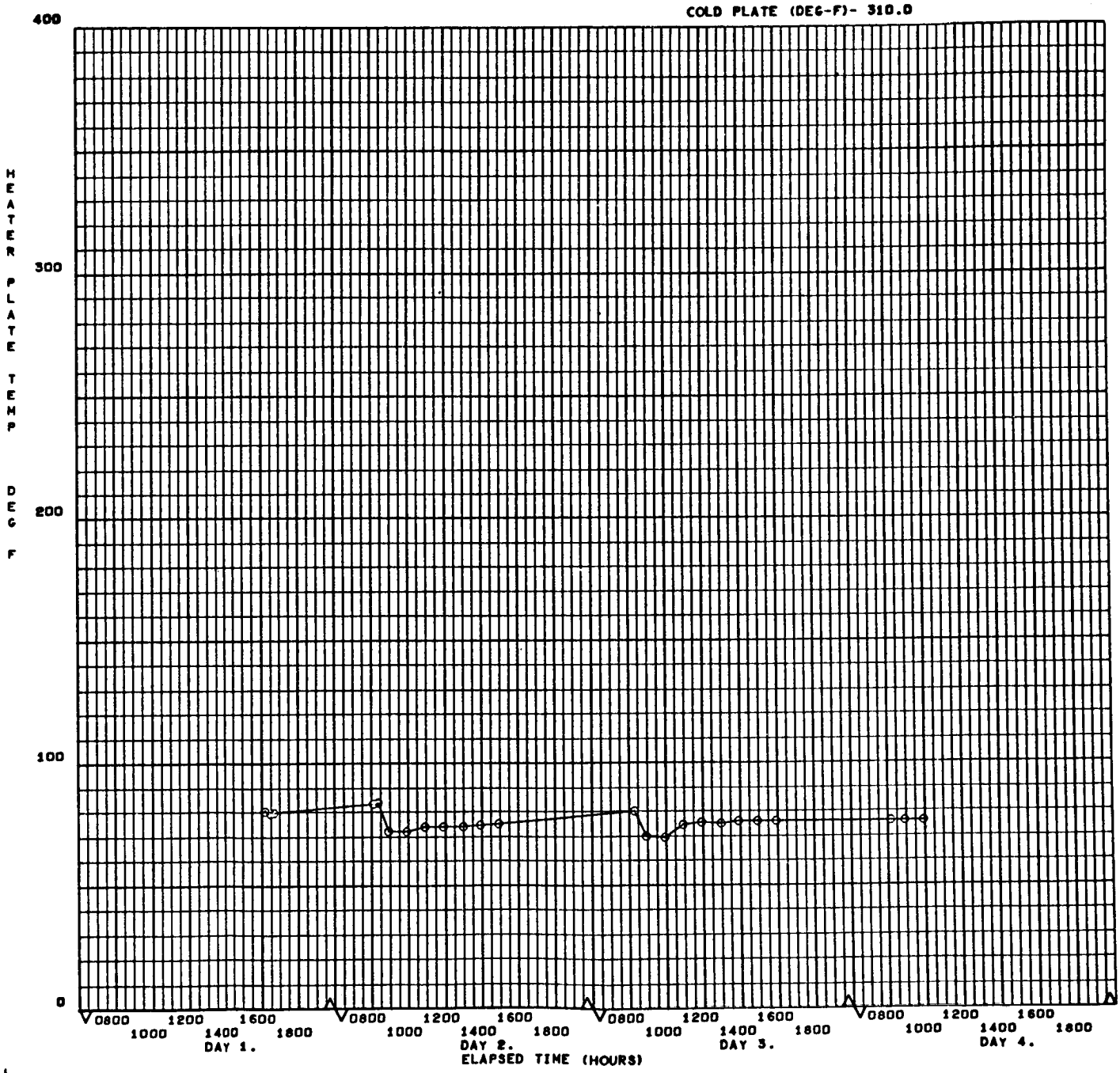


FIGURE 42.D

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 11.2
SAMPLE THICKNESS (IN.) 0.2500
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 76.0
COLD PLATE (DEG-F)- 310.0

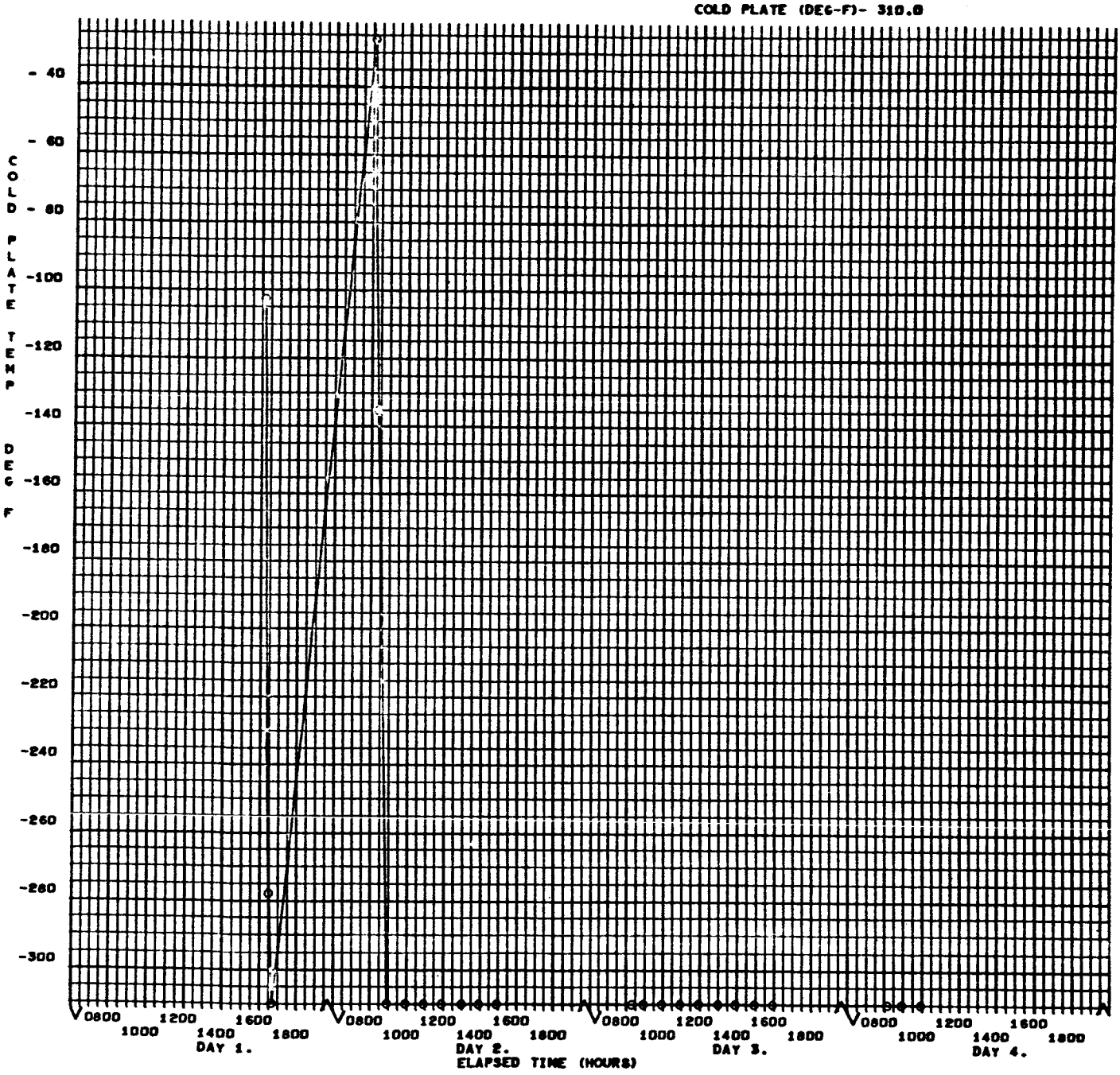


FIGURE 42.E

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 11.2
SAMPLE THICKNESS (IN.) 0.2500
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 76.0
COLD PLATE (DEG-F)- 310.0

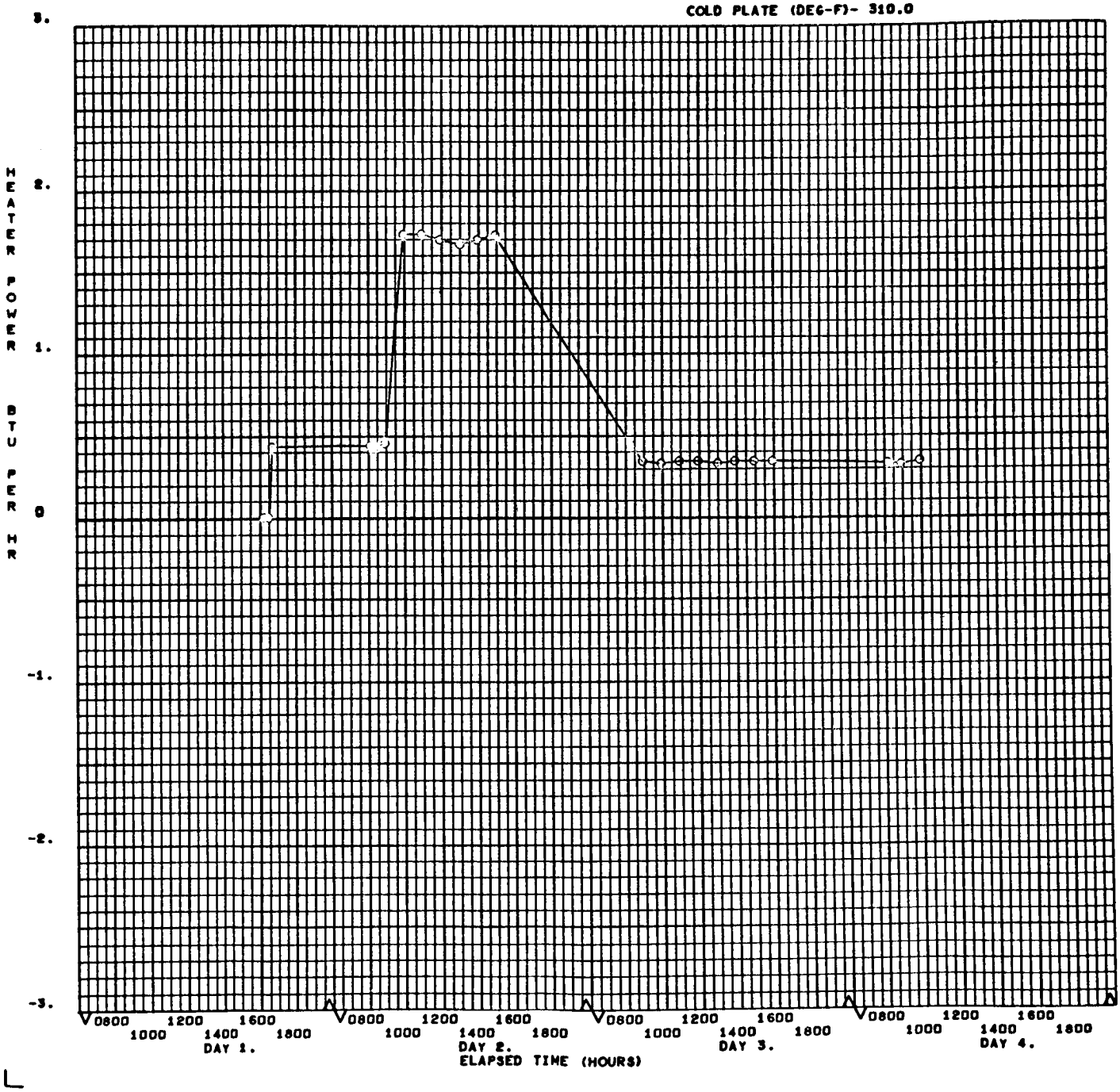


FIGURE 43.A

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 6.4
SAMPLE THICKNESS (IN.) 0.2500
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 70.0
COLD PLATE (DEG-F)- 310.0

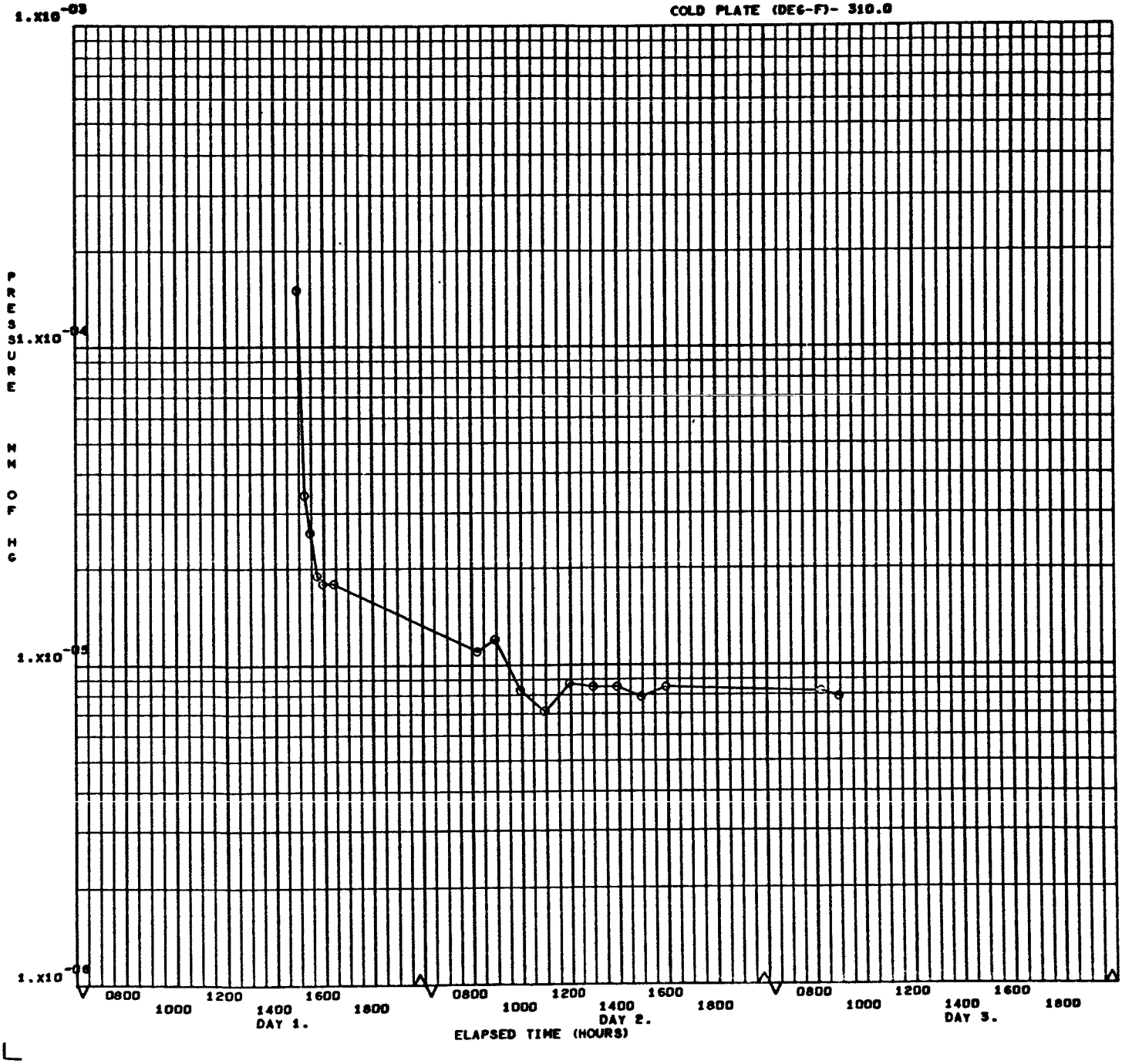


FIGURE 43.B

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 6.4
SAMPLE THICKNESS (IN.) 0.2500
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 70.0
COLD PLATE (DEG-F)- 310.0

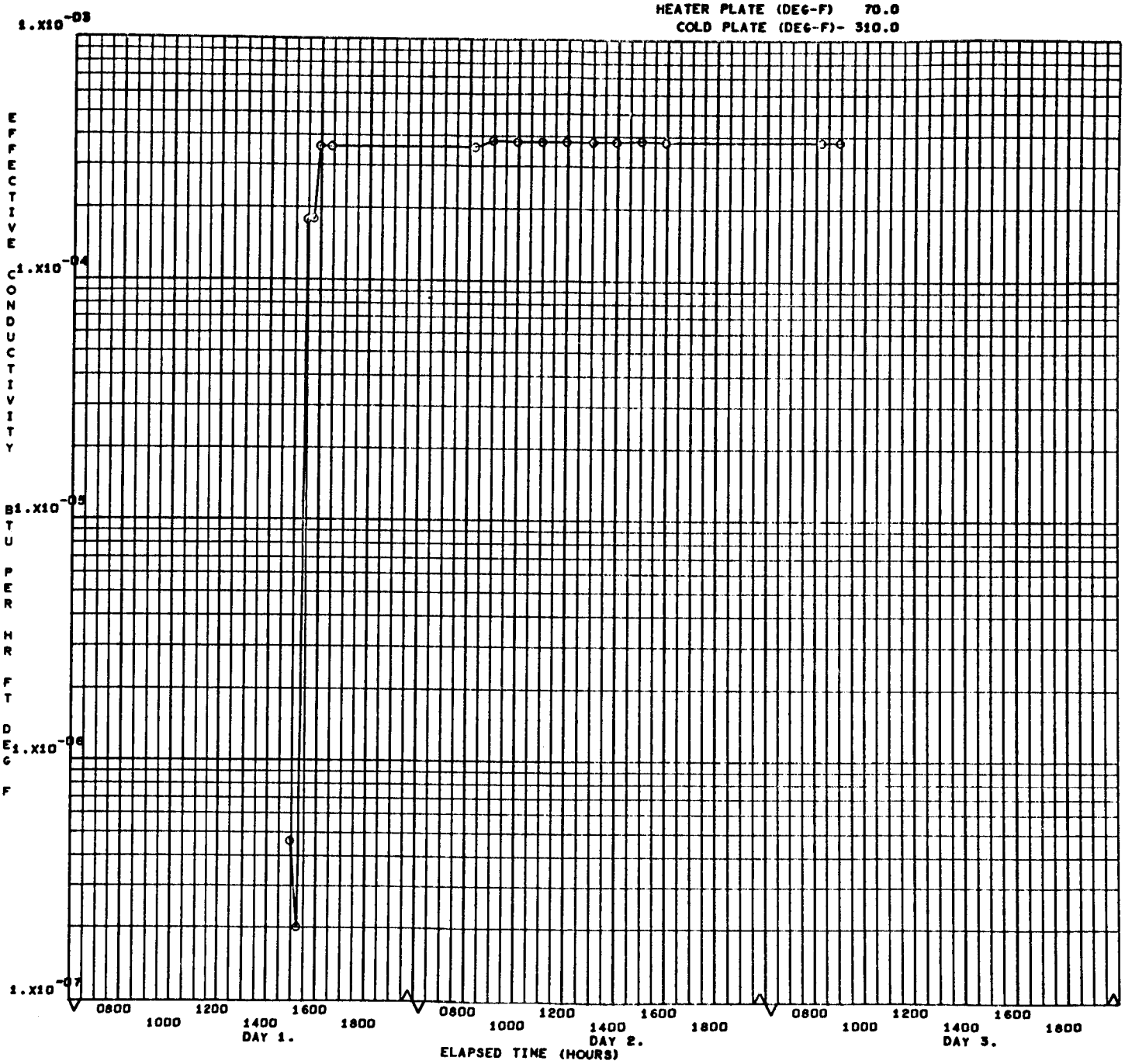


FIGURE 43.C

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 6.4
SAMPLE THICKNESS (IN.) 0.2500
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 70.0
COLD PLATE (DEG-F)- 310.0

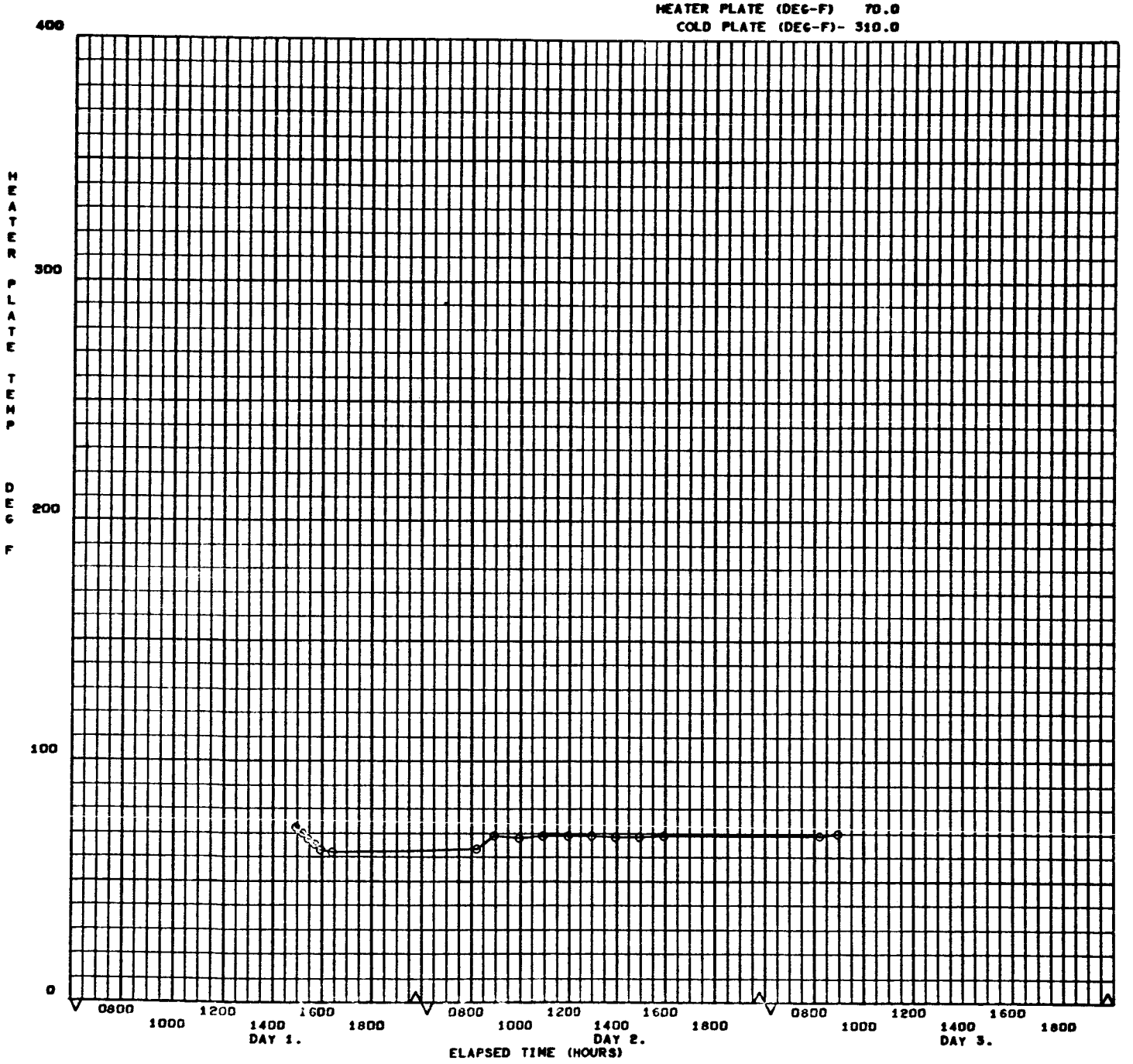


FIGURE 43.D

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 6.4
SAMPLE THICKNESS (IN.) 0.2500
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 70.0
COLD PLATE (DEG-F)- 310.0

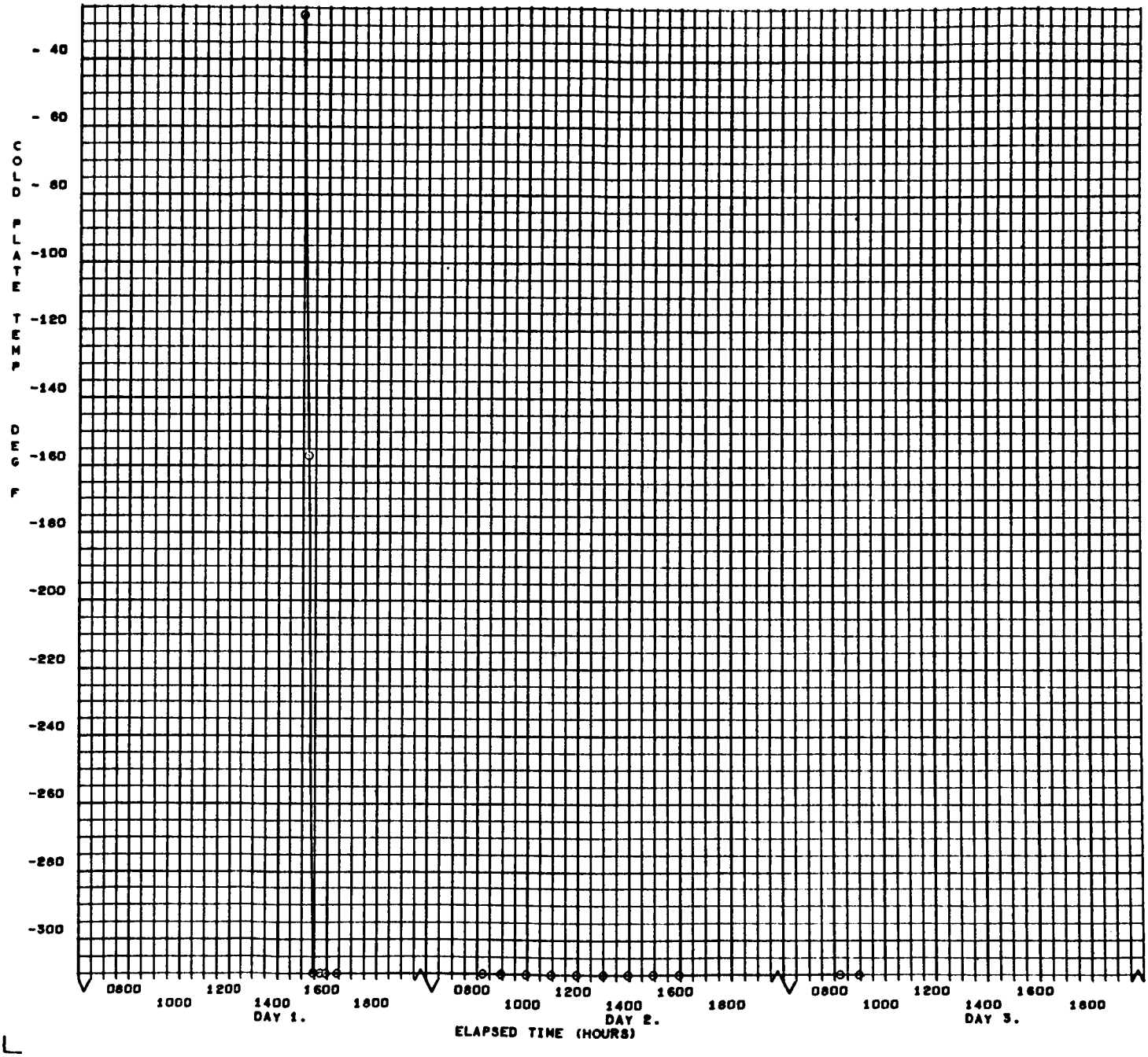


FIGURE 43.E

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 6.4
SAMPLE THICKNESS (IN.) 0.2500
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 70.0
COLD PLATE (DEG-F)- 310.0

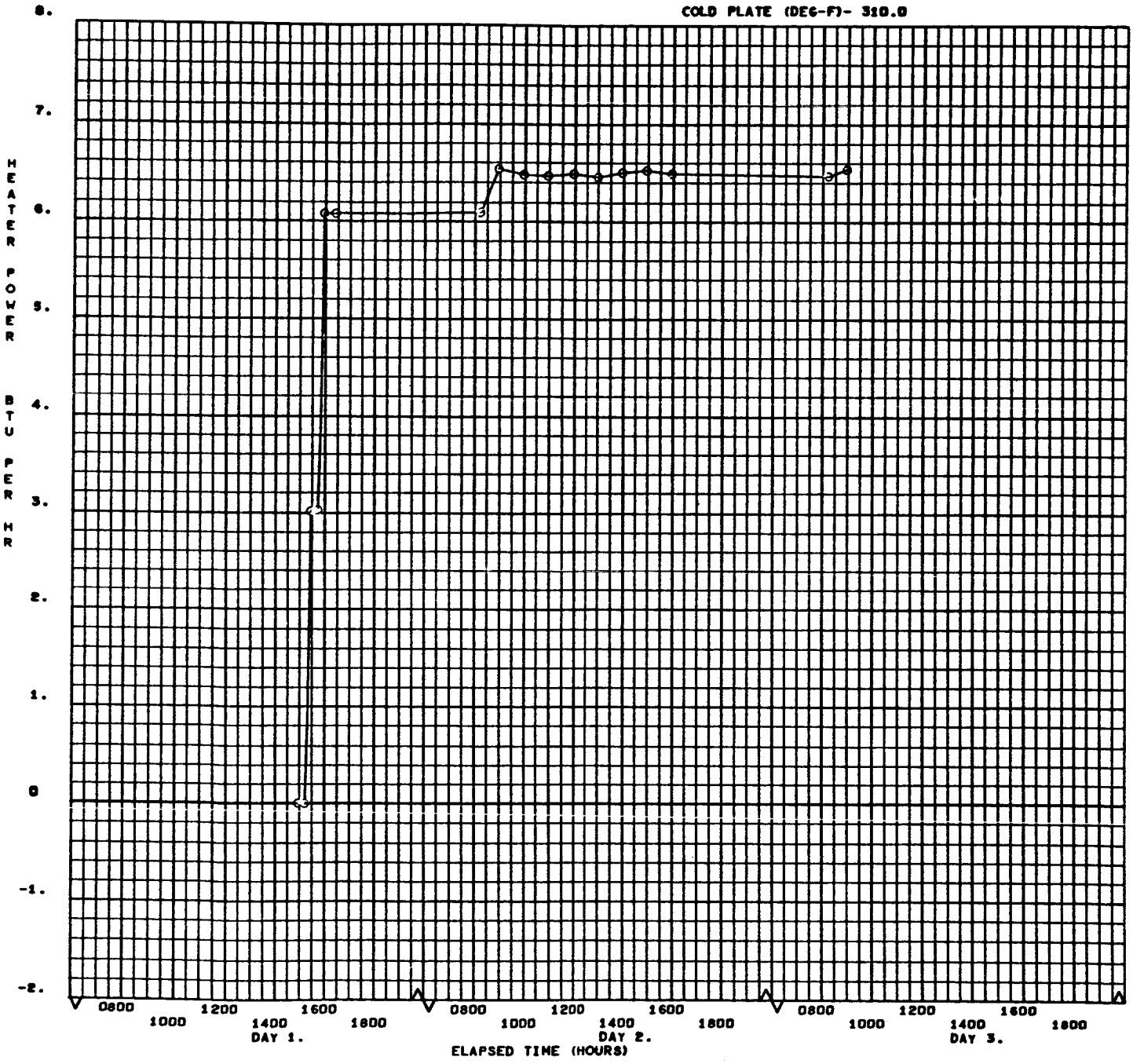


FIGURE 44.A

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 19.1
SAMPLE THICKNESS (IN.) 0.2500
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 76.0
COLD PLATE (DEG-F)- 310.0

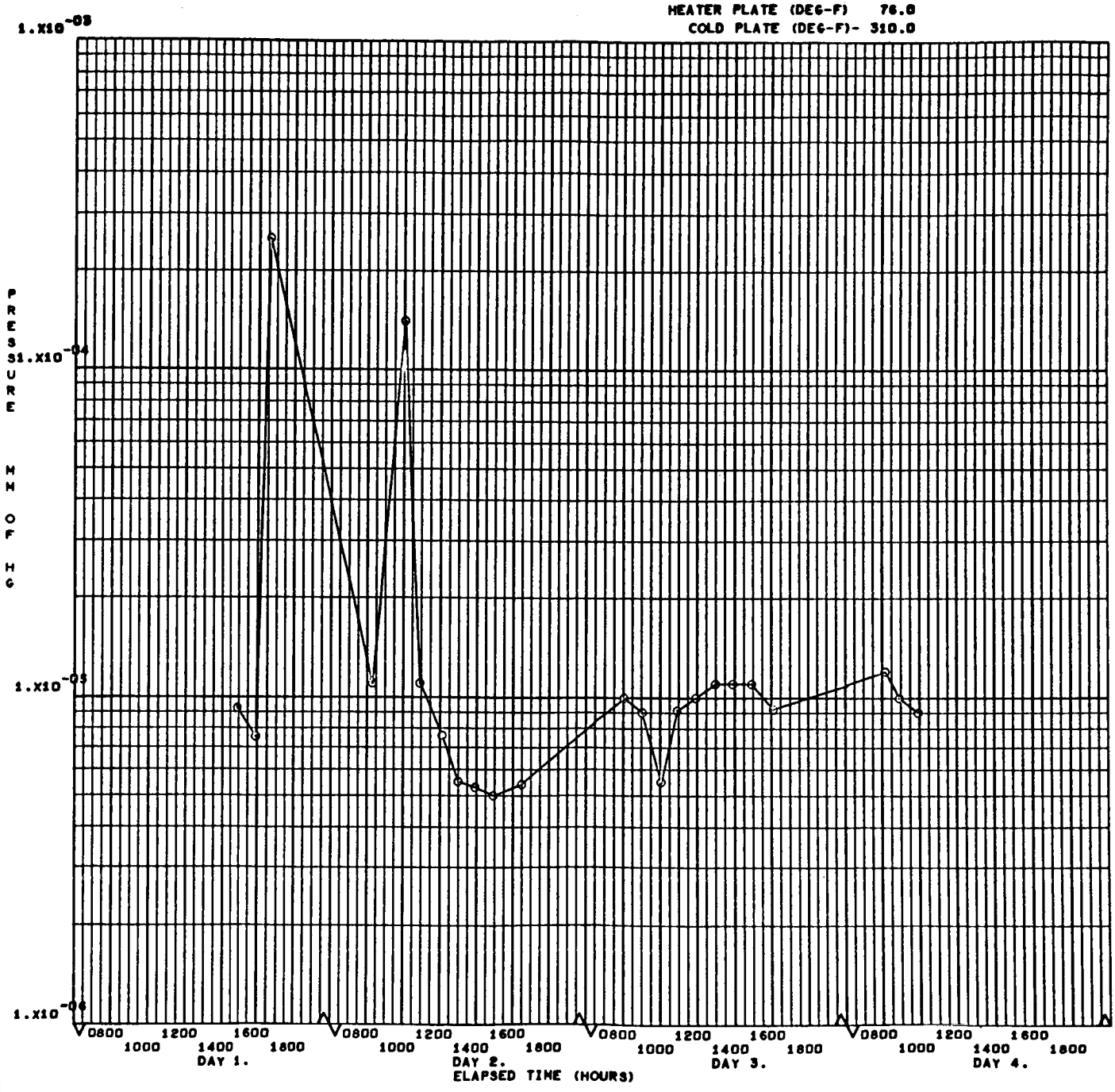


FIGURE 44.B

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 19.1
SAMPLE THICKNESS (IN.) 0.2500
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 76.0
COLD PLATE (DEG-F)- 310.0

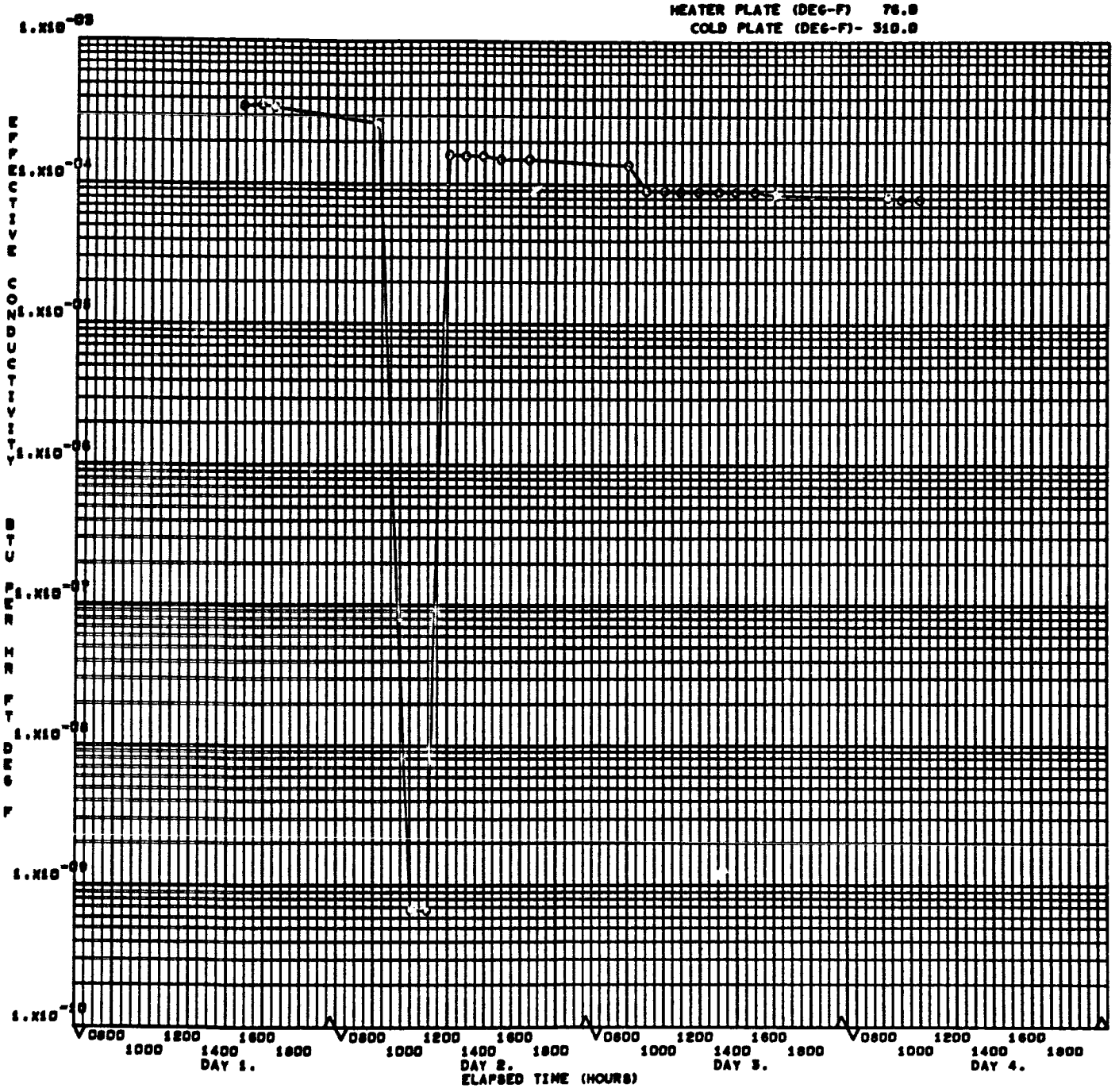


FIGURE 44.C

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 19.1
SAMPLE THICKNESS (IN.) 0.2500
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 76.0
COLD PLATE (DEG-F)- 310.0

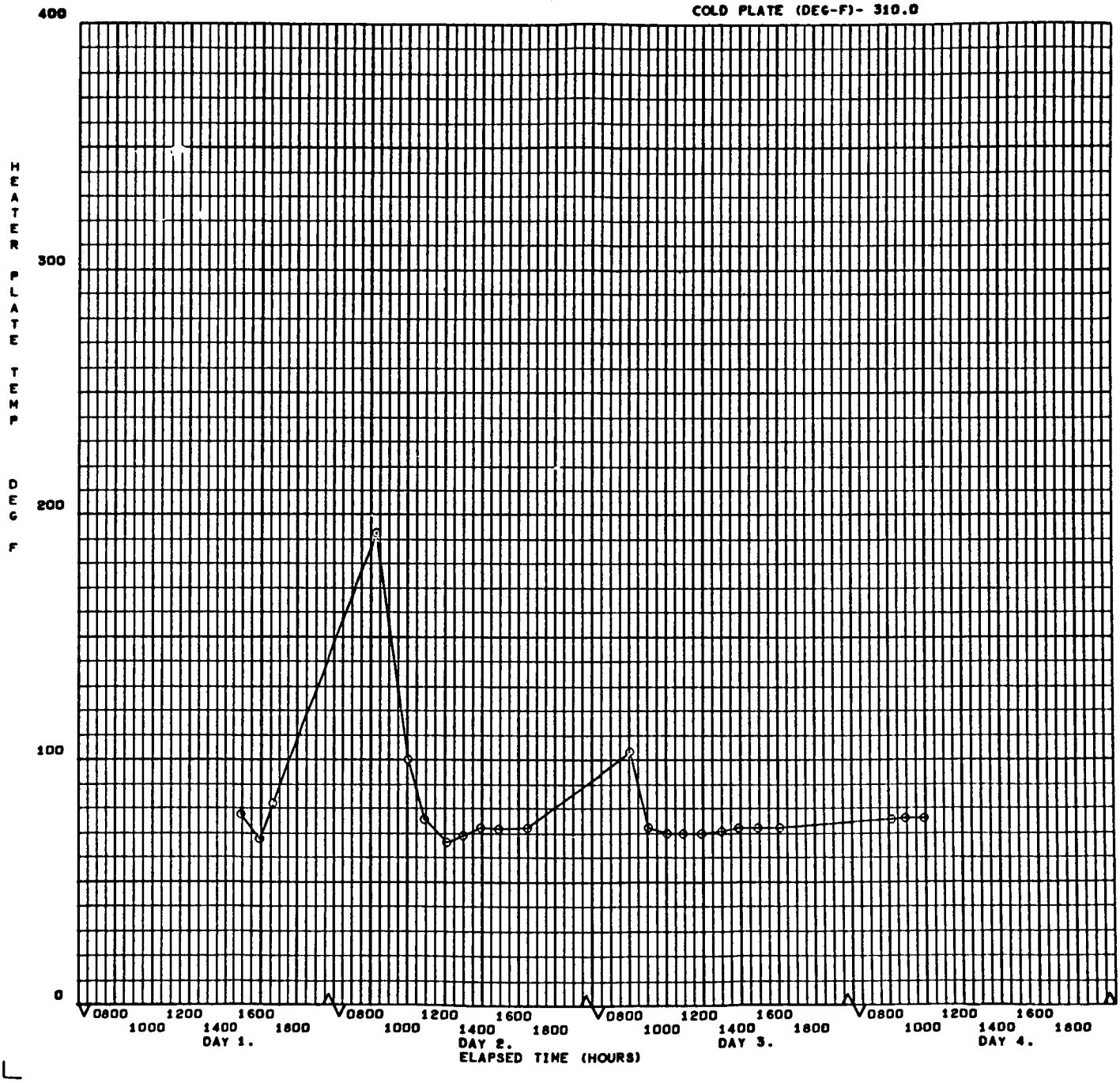


FIGURE 44.D

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 19.1
SAMPLE THICKNESS (IN.) 0.2500
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 76.0
COLD PLATE (DEG-F)- 310.0

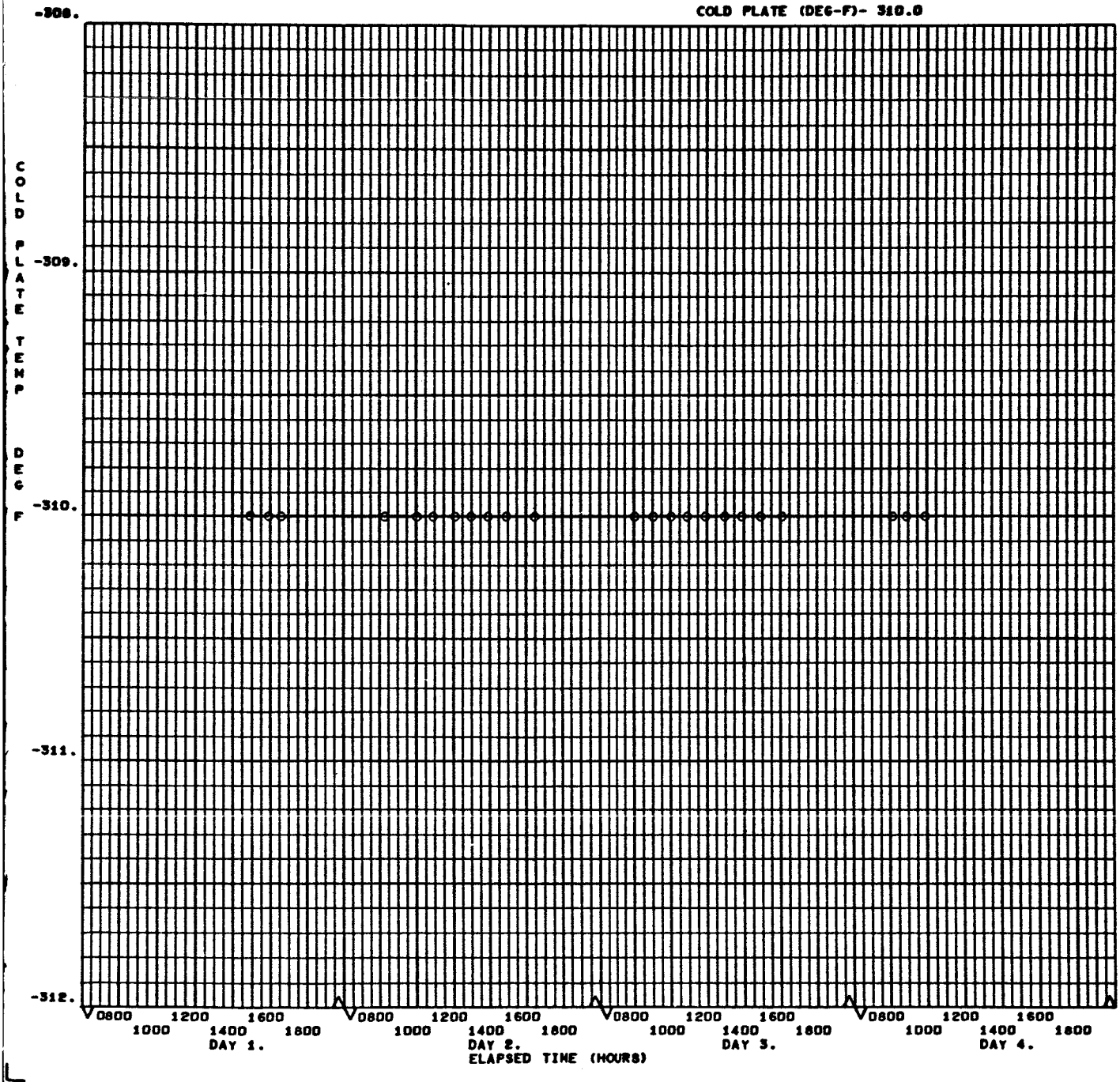


FIGURE 44.E

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 19.1
SAMPLE THICKNESS (IN.) 0.2500
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 76.0
COLD PLATE (DEG-F)- 310.0

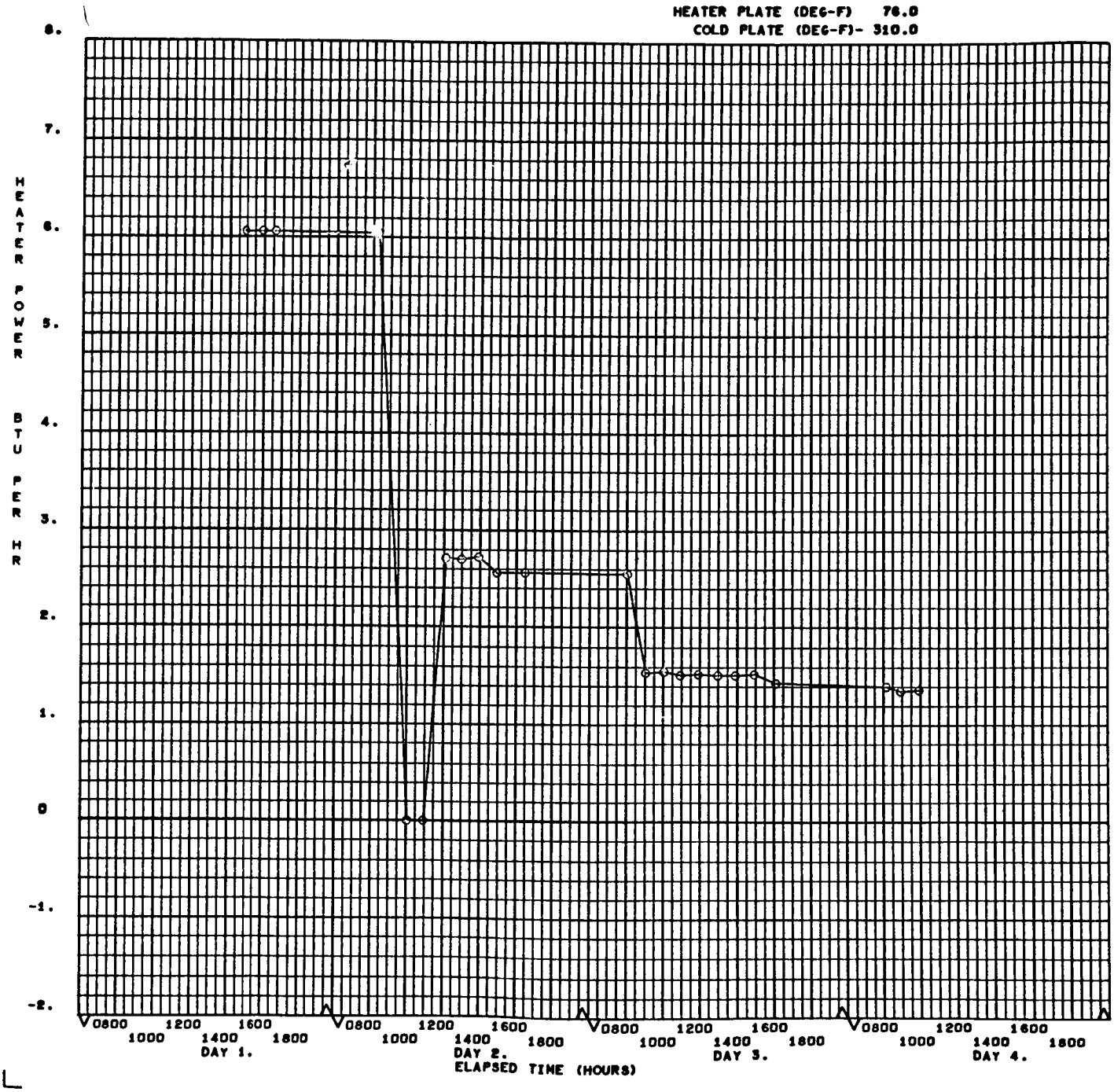


FIGURE 49.A

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 14.4
SAMPLE THICKNESS (IN.) 0.1875
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 71.0
COLD PLATE (DEG-F)- 310.0

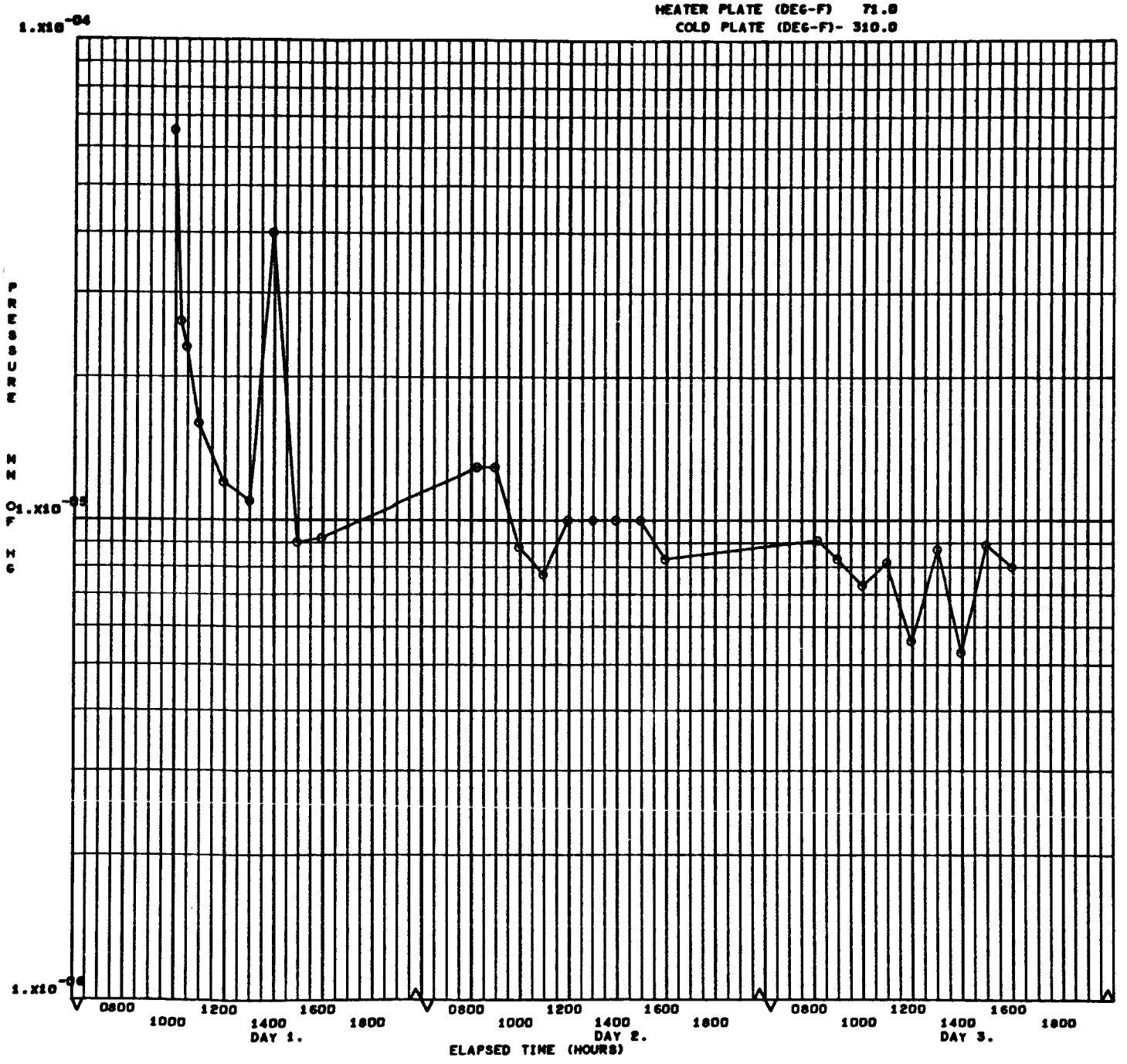


FIGURE 45.B

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 14.4
SAMPLE THICKNESS (IN.) 0.1875
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 71.0
COLD PLATE (DEG-F)- 310.0

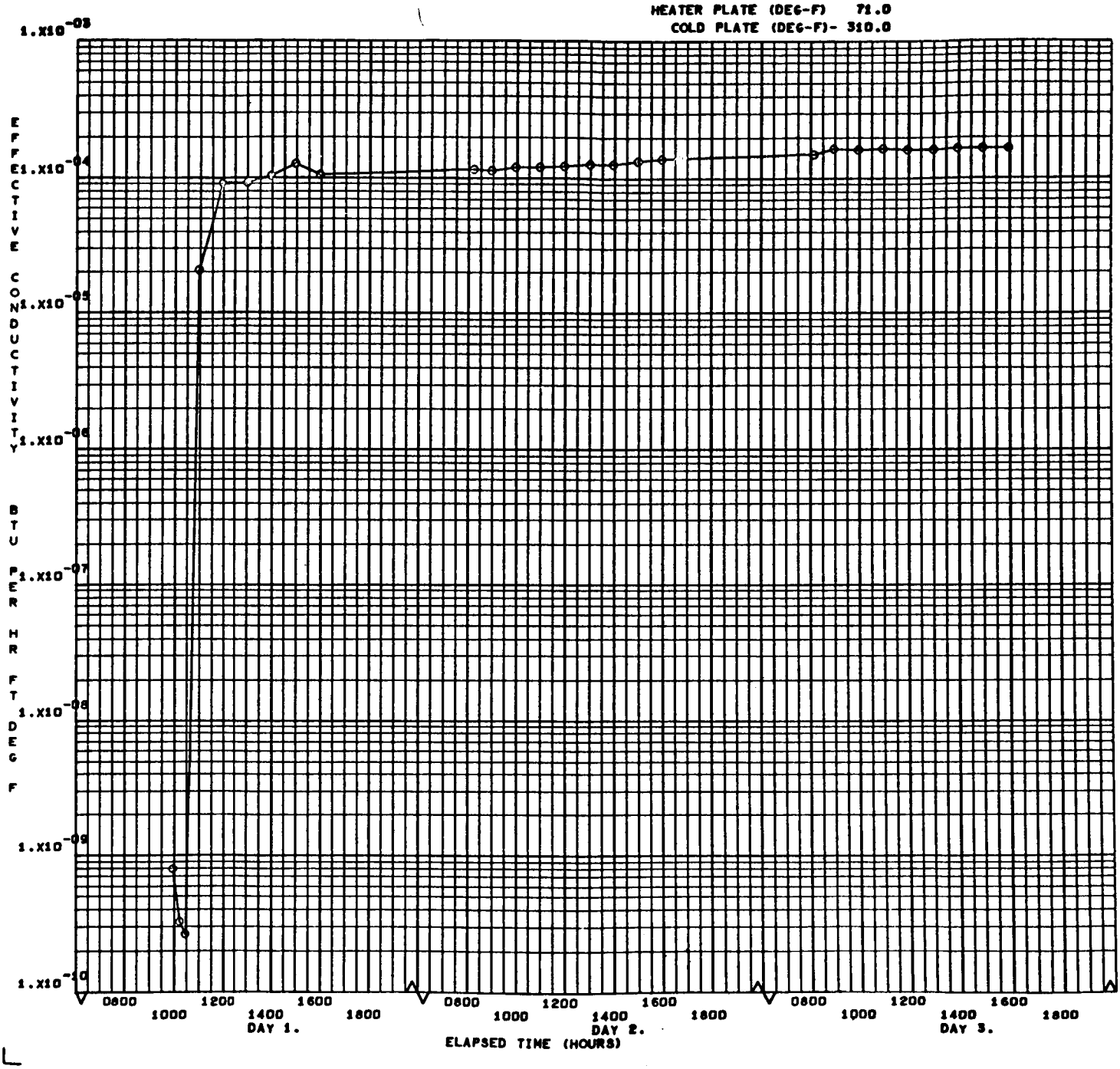


FIGURE 45.C

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 14.4
SAMPLE THICKNESS (IN.) 0.1875
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 71.0
COLD PLATE (DEG-F)- 310.0

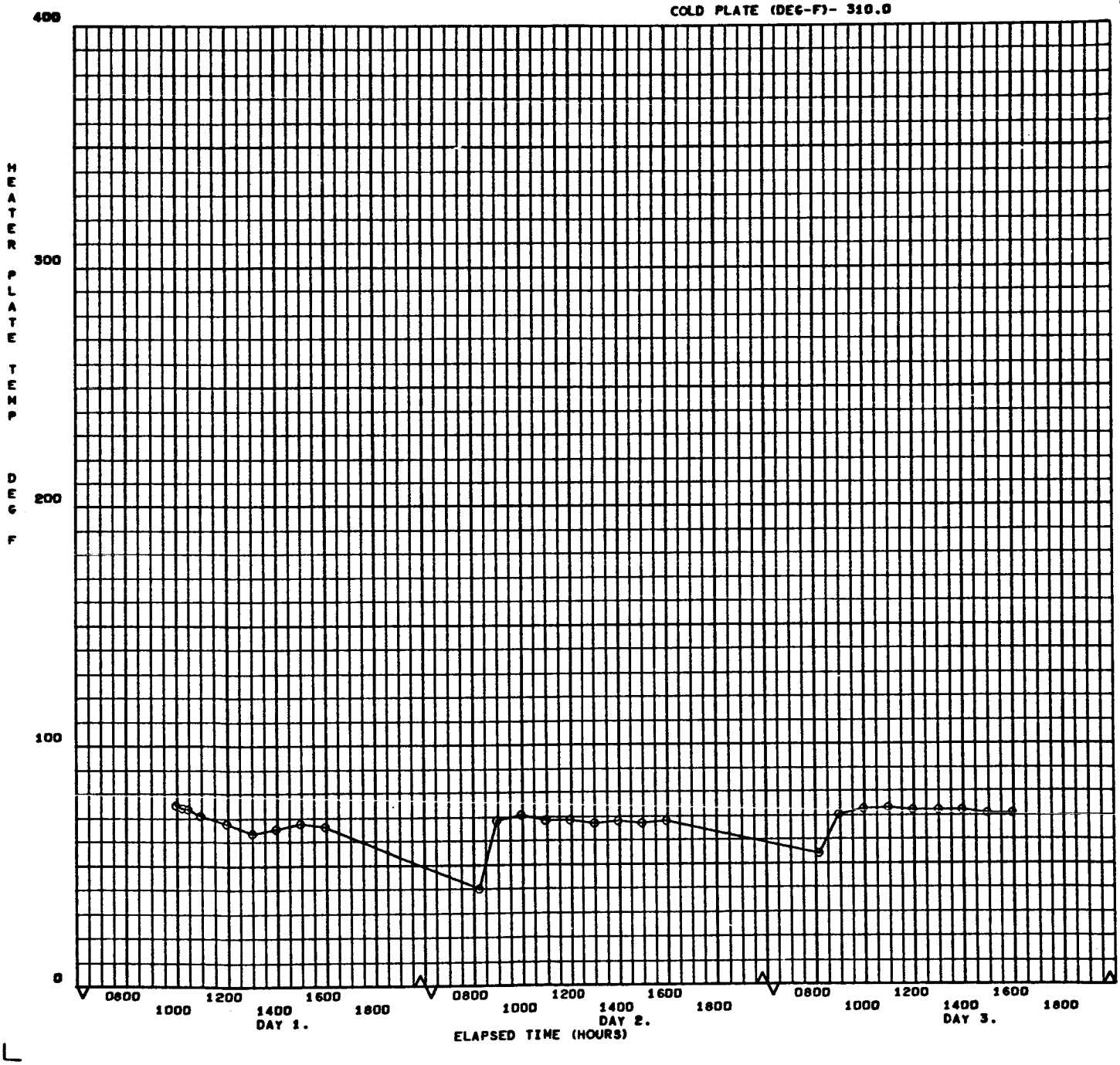


FIGURE 45.D

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 14.4
SAMPLE THICKNESS (IN.) 0.1875
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 71.0
COLD PLATE (DEG-F)- 310.0

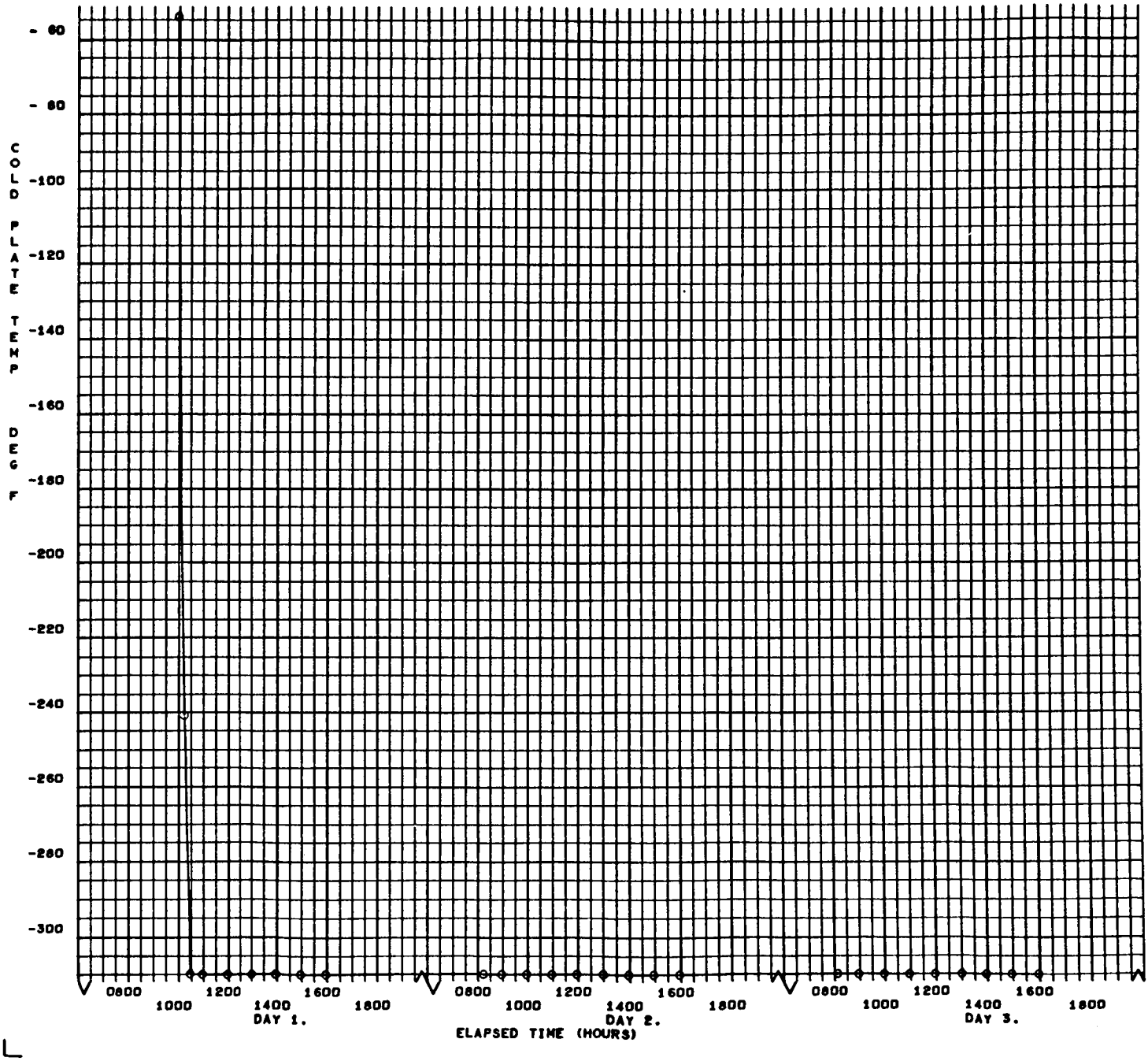


FIGURE 45.E

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 14.4
SAMPLE THICKNESS (IN.) 0.1075
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 71.0
COLD PLATE (DEG-F)- 310.0

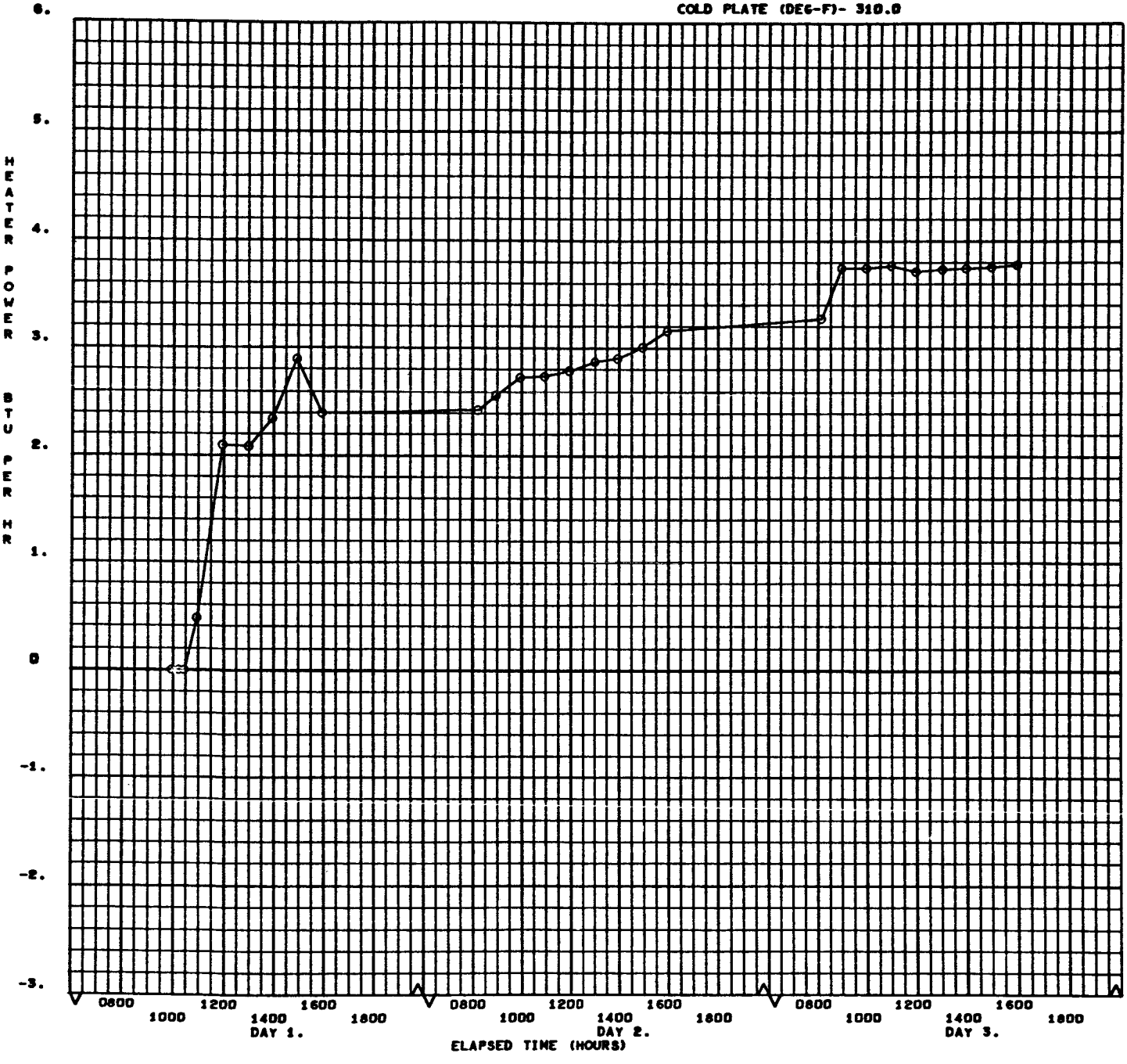


FIGURE 46.A

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 21.1
SAMPLE THICKNESS (IN.) 0.1570
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 300.0
COLD PLATE (DEG-F) 72.0

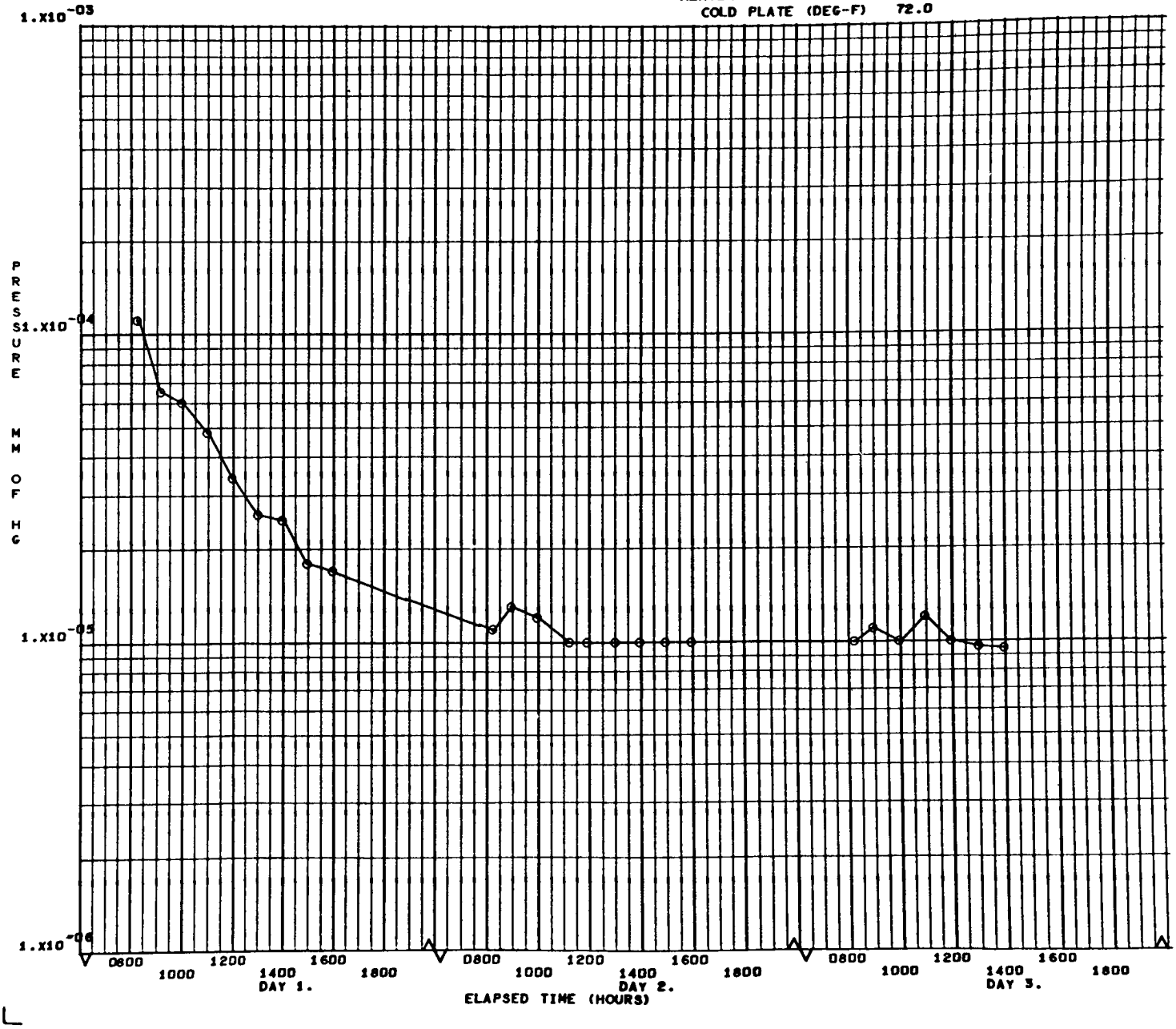


FIGURE 46.B

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 21.1
SAMPLE THICKNESS (IN.) 0.1570
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 300.0
COLD PLATE (DEG-F) 72.0

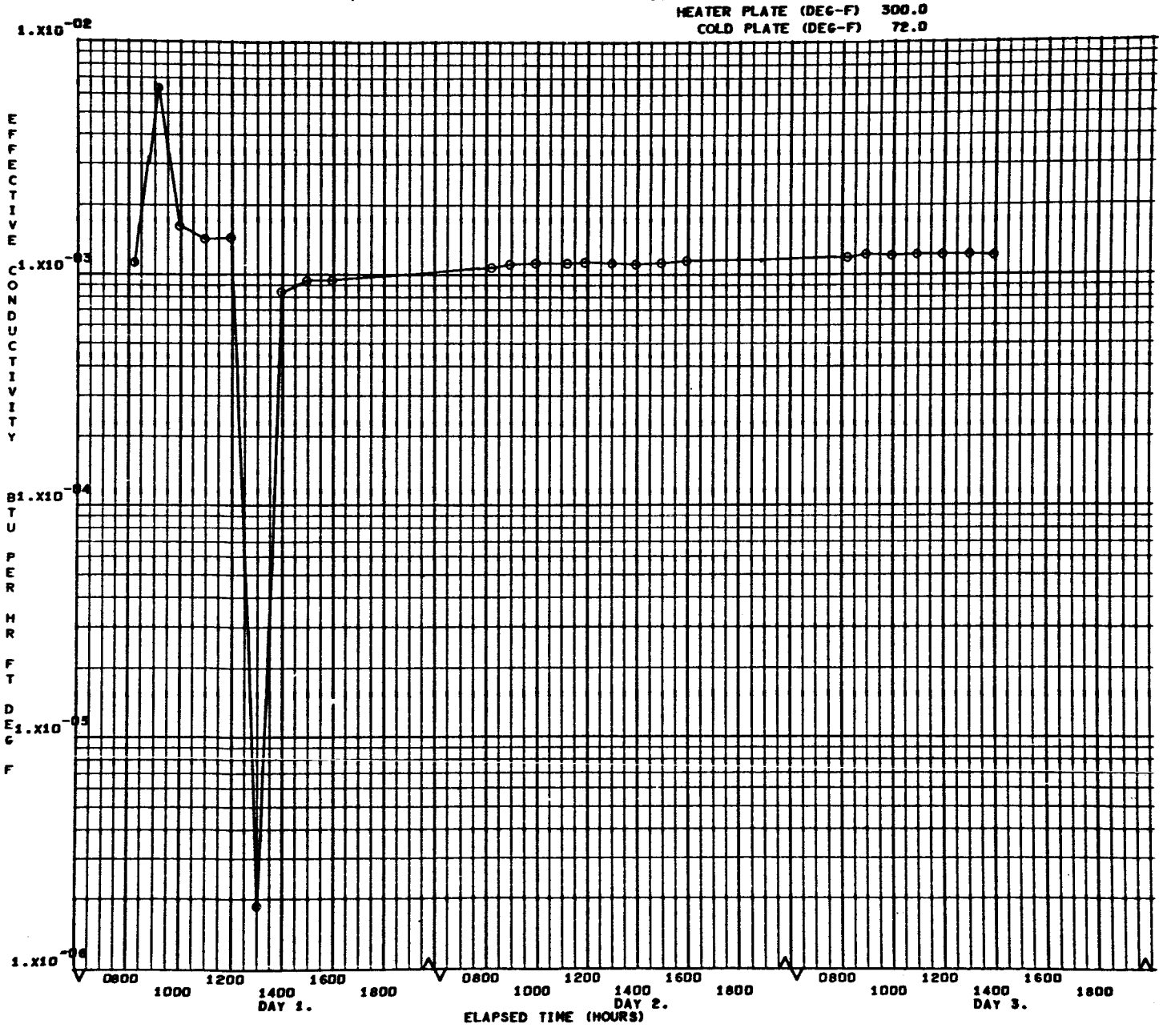


FIGURE 46.C

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 21.1
SAMPLE THICKNESS (IN.) 0.1570
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 300.0
COLD PLATE (DEG-F) 72.0

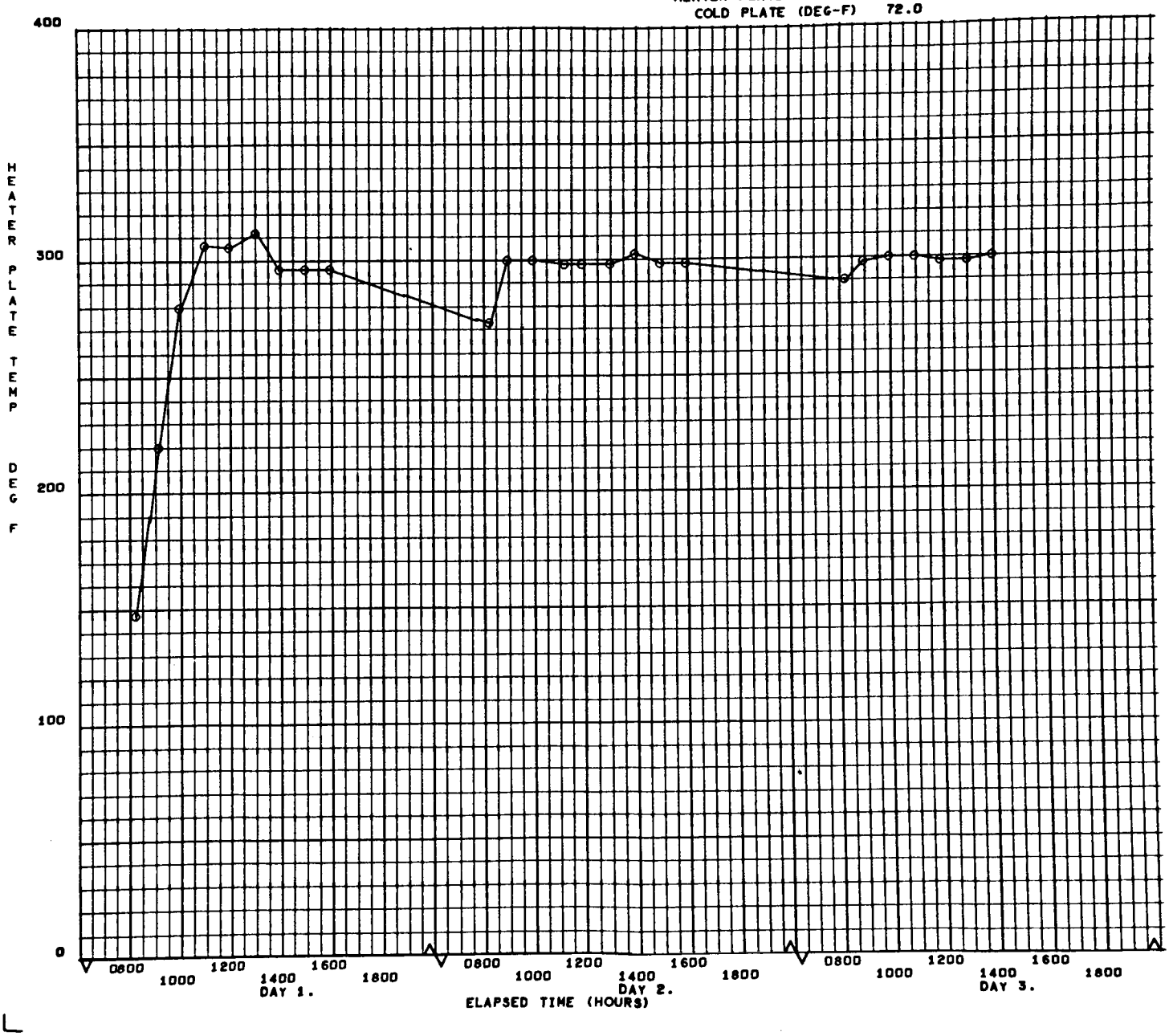


FIGURE 46.D

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 21.1
SAMPLE THICKNESS (IN.) 0.1570
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 300.0
COLD PLATE (DEG-F) 72.0

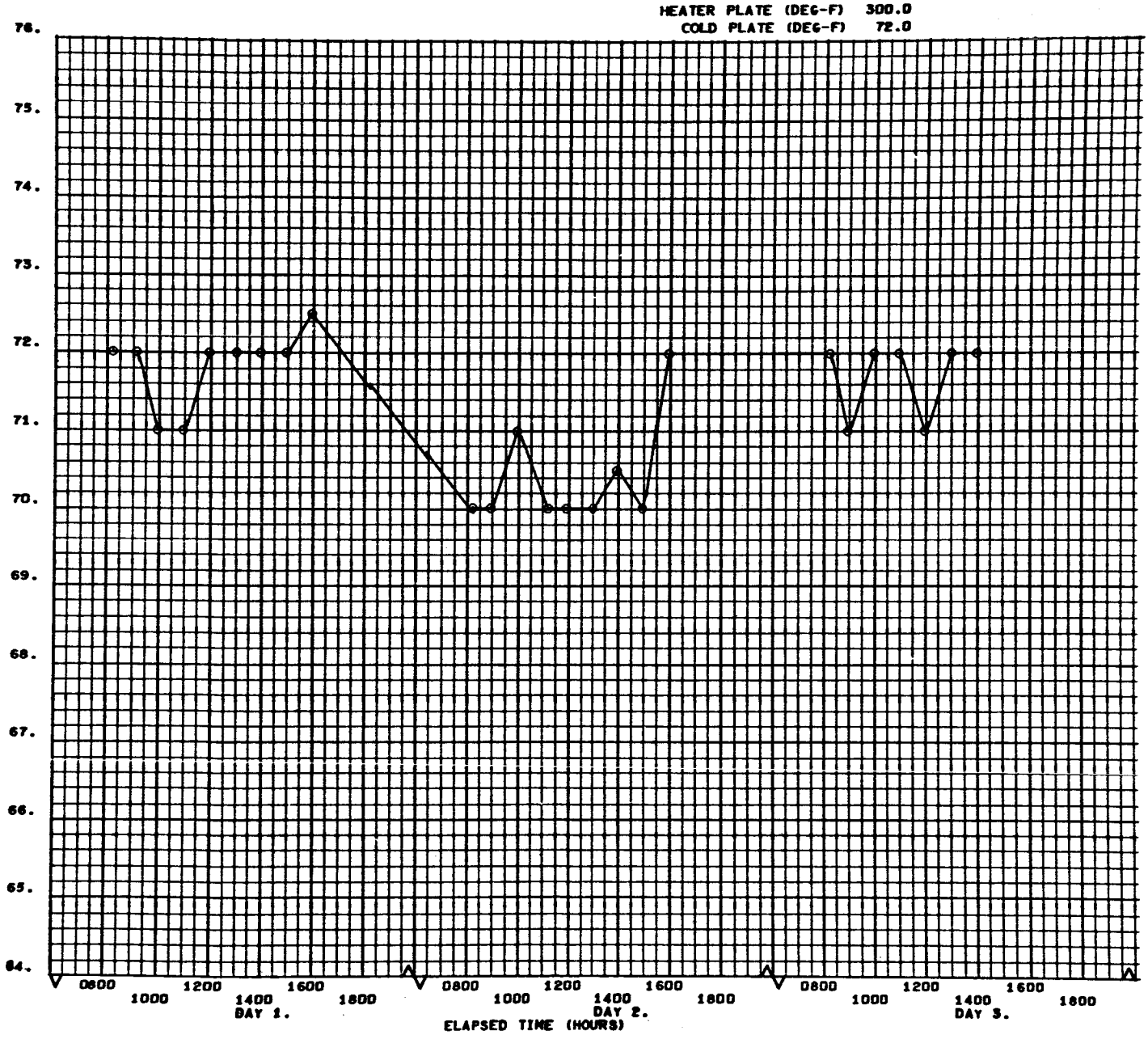


FIGURE 46.E

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 21.1
SAMPLE THICKNESS (IN.) 0.1570
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 300.0
COLD PLATE (DEG-F) 72.0

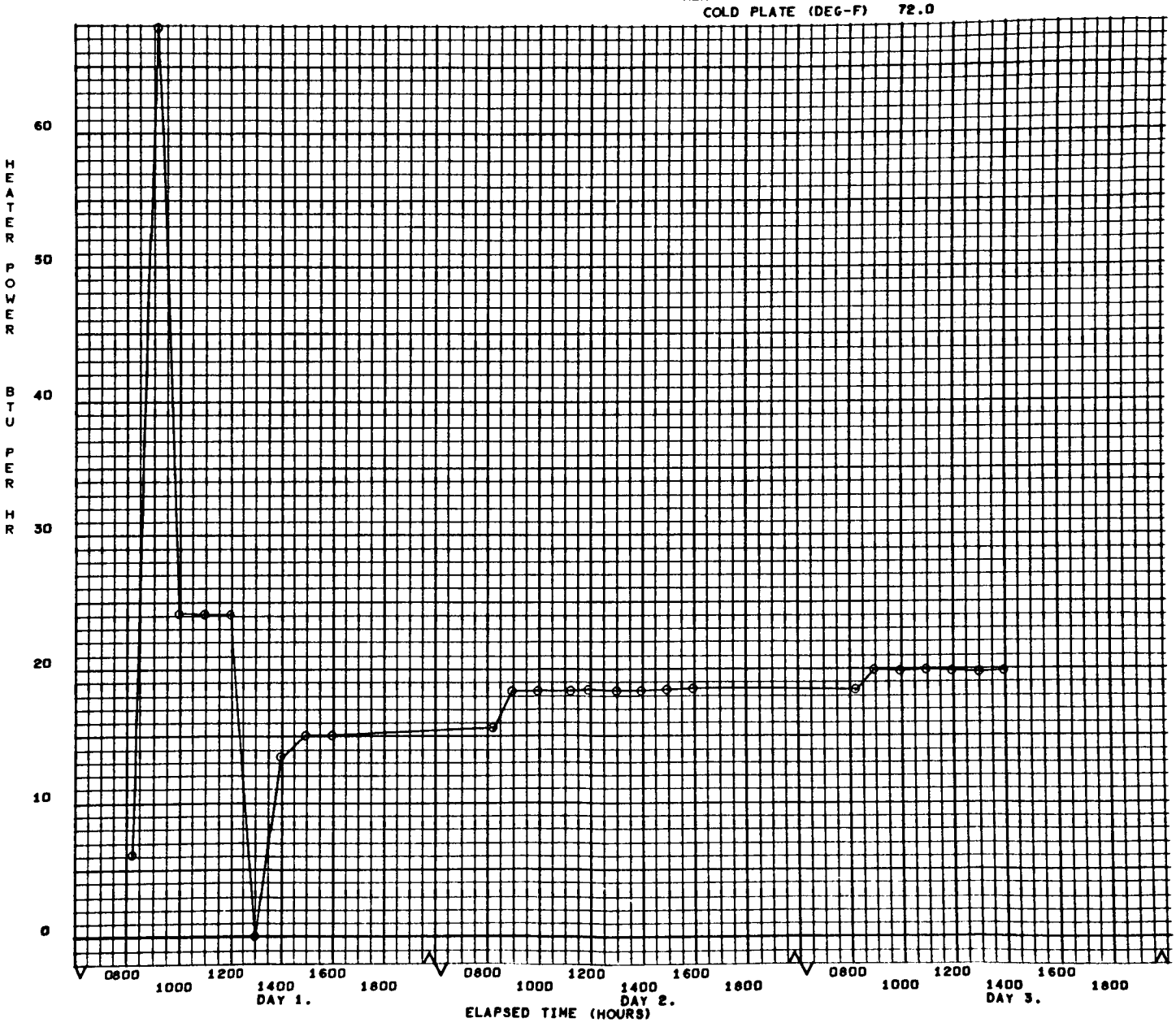


FIGURE 47.A

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 22.1
SAMPLE THICKNESS (IN.) 0.2188
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 300.0
COLD PLATE (DEG-F) 71.0

FIGURE 47.B

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 22.1
SAMPLE THICKNESS (IN.) 0.2188
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 300.0
COLD PLATE (DEG-F) 71.0

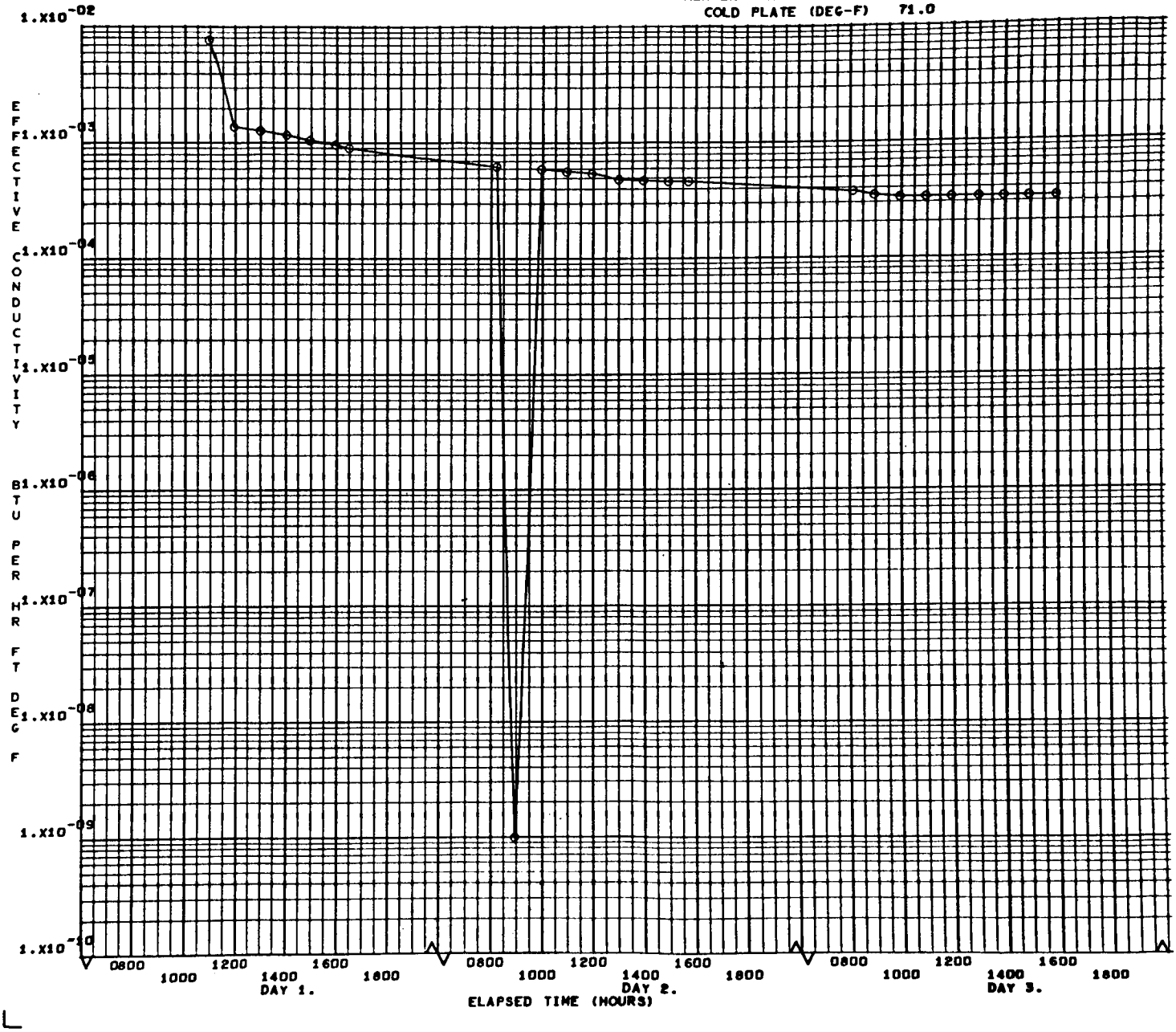


FIGURE 47.C

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 22.1
SAMPLE THICKNESS (IN.) 0.2168
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 300.0
COLD PLATE (DEG-F) 71.0

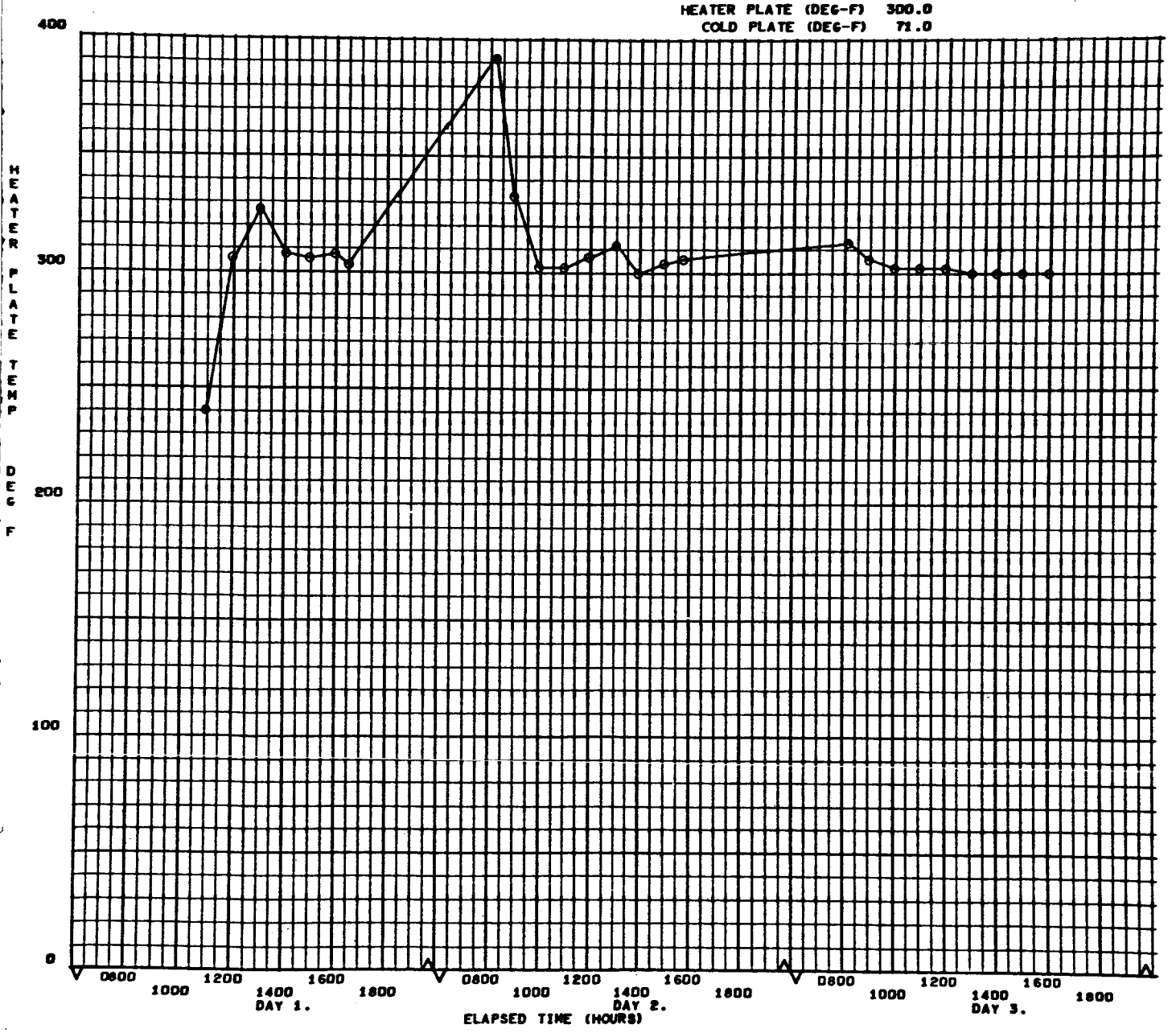


FIGURE 47.D

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 22.1
SAMPLE THICKNESS (IN.) 0.2188
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 300.0
COLD PLATE (DEG-F) 71.0

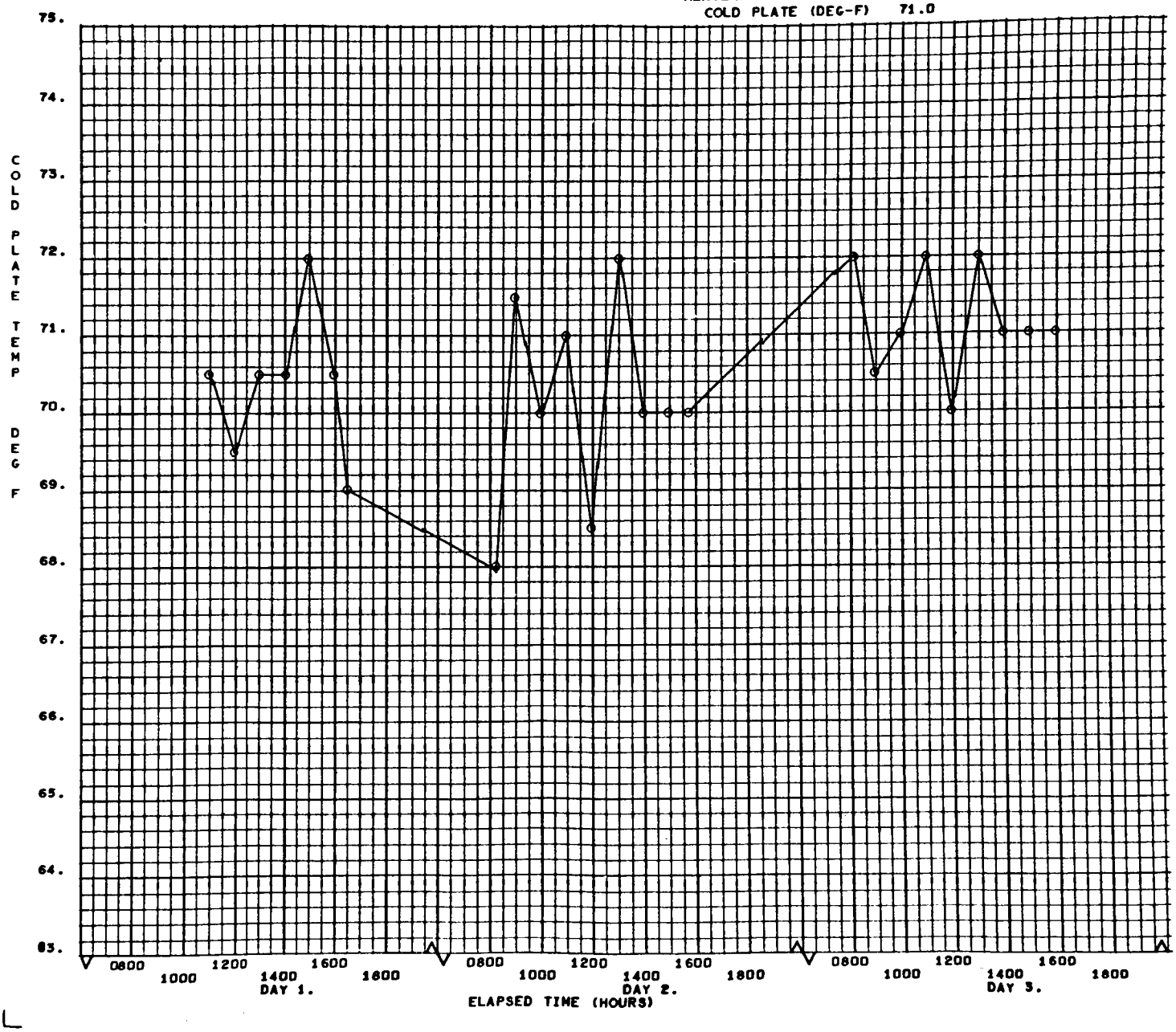
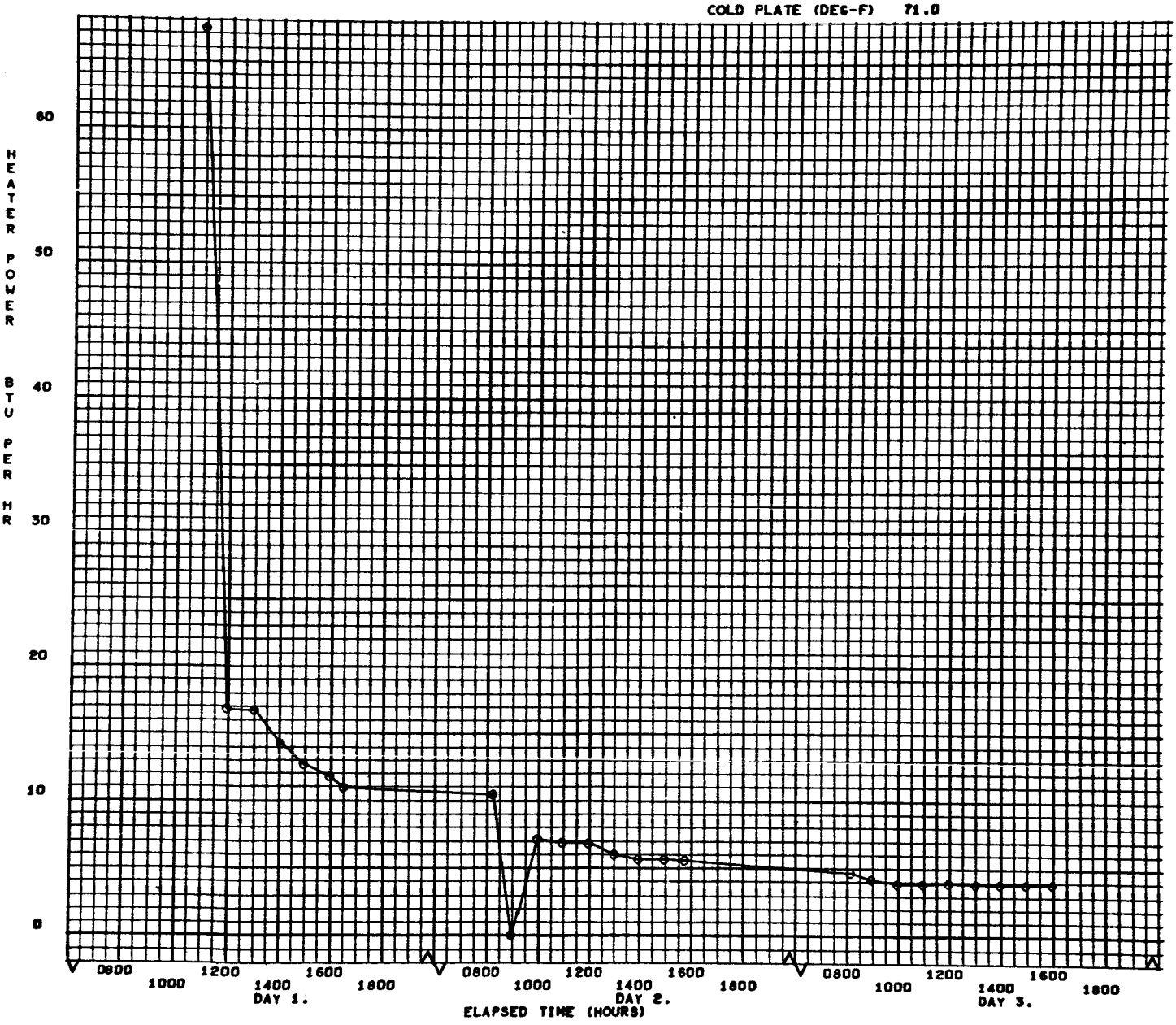


FIGURE 47.E

MULTI-LAYER INSULATION
TRANSIENT TEST DATA

TEST NO. 22.1
SAMPLE THICKNESS (IN.) 0.2188
BOUNDARY TEMPERATURES (FINAL)
HEATER PLATE (DEG-F) 300.0
COLD PLATE (DEG-F) 71.0



APPENDIX B

ERROR ANALYSIS

APPENDIX B

ERROR ANALYSIS

One of the sources of errors in the measurement of the apparent thermal conductivity of multilayer insulation in a guarded hot plate apparatus occurs in edge effects. An idealized mathematical representation of a guarded hot plate apparatus has been synthesized to establish order of magnitude effects. The physical arrangement of the guarded hot plate apparatus is shown in Figure B-1.

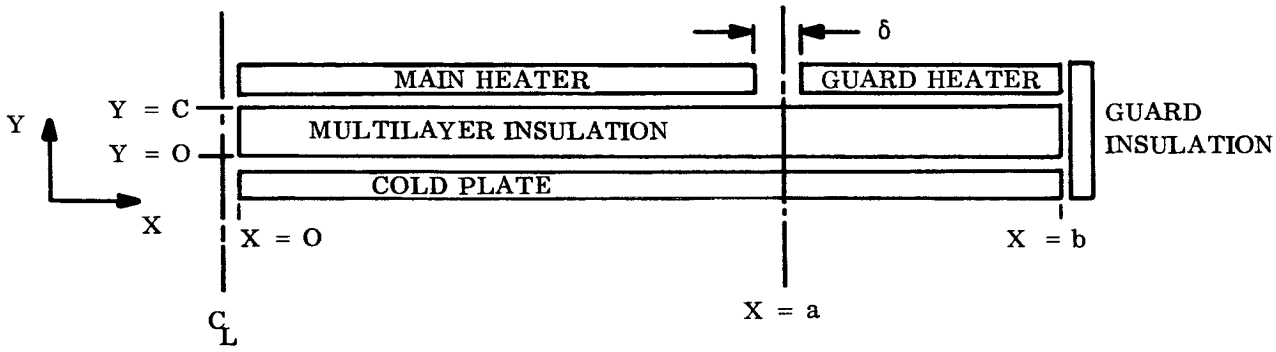


Figure B-1. Guarded Hot Plate Apparatus (Physical Arrangement)

The accuracy with which the difference in temperature between the main heater and the guard heater can be regulated determines a significant portion of the total thermal conductivity measurement error. In order to establish an order of magnitude, Figure B-2 illustrates graphically the assumed temperature distribution along the top face of the multilayer insulation sample resulting from a mismatch of temperature between the main and guard heaters.

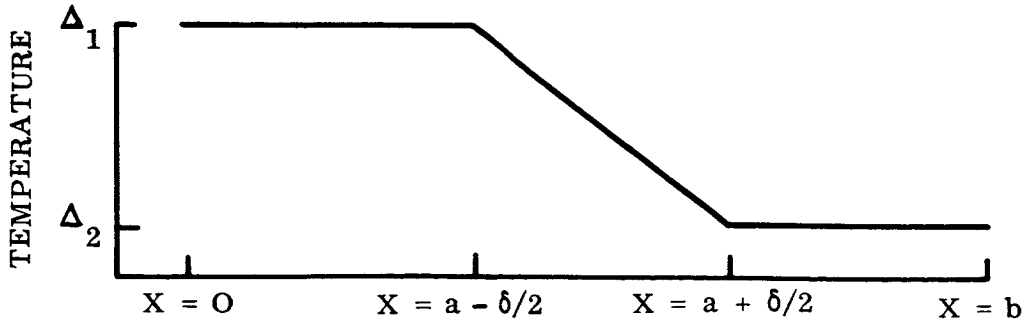


Figure B-2. Multilayer Insulation Temperature Distribution

The error in the measurement of heat flow through the insulation is

$$\text{Error } (\%) = \frac{100 \times \text{heat flow through face } (x = a,\ 0 \le y \le c)}{\text{heat flow through face } (y=0,\ 0 \le x \le a) + \text{heat flow through face } (x=a,\ 0 \le y \le c)}$$

If we consider the multilayer insulation as a homogenous body, we can write:

$$k_x \frac{\partial^2 T}{\partial x^2} + k_y \frac{\partial^2 T}{\partial y^2} = 0$$

where k_x, k_y = effective thermal conductivity in the x and y directions, respectively

The assumed boundary conditions are:

a. $\frac{\partial T}{\partial X}(o,\ y) = 0$

b. $\frac{\partial T}{\partial X}(b,\ y) = 0$

c. $$T(X, C) = \begin{cases} \Delta_1, & X \le a - \delta/2 \\ \left(\frac{\Delta_2 - \Delta_1}{\delta}\right) X - \frac{\Delta_2}{S}\left(a - \frac{\delta}{2}\right) + \frac{\Delta_1}{S}\left(a + \frac{\delta}{2}\right), & a - \delta/2 \le X \le a + \delta/2 \\ \Delta_2, & X \ge a + \delta/2 \end{cases}$$

d. $T(X, O) = 0$

where Δ_1, Δ_2 = temperature difference between the main heater and the cold plate and the guard heater and the cold plate, respectively

δ = separation distance between the main heater and guard heater.

If we assume a separable solution of the form

$$T = \psi(X)\, \phi(y)$$

then we obtain

$$\psi(X) = A \cos \beta x + B \sin \beta x$$

$$\text{where } \beta^2 = (k_y/k_x)\,\lambda^2 = \alpha^2 \lambda^2$$

$$\lambda = \text{eigenvalue}$$

$$\phi(y) = \begin{cases} C \cosh \lambda y + D \sinh \lambda y, & \lambda \neq 0 \\ E + F y, & \lambda = 0 \end{cases}$$

Using boundary conditions 1, 2, and 4, one can show that:

$$A = 0$$

$$B = 0$$

$$\beta = \frac{n\pi}{b}, \quad n = 0, 1, 2 \ldots$$

$$E = 0$$

The final resulting equation is:

$$T = F y + \sum_{n=1}^{\infty} B_n \sinh \frac{n\pi y}{\alpha b} \cos \frac{n\pi}{b} x$$

Boundary condition (3) can be expressed as a Fourier series:

$$T = a_o + \sum_{n=1}^{\infty} a_n \cos \frac{n\pi x}{b}$$

The coefficients can be determined as follows:

$$a_o = \frac{1}{b}\left[\int_o^{a-\delta/2} \Delta_1 \, dx + \int_{a-\delta/2}^{a+\delta/2} \left\{ \frac{\Delta_2 - \Delta_1}{\delta} x - \frac{\Delta_2}{\delta}\left(a - \frac{\delta}{2}\right) + \frac{\Delta_1}{\delta}\left(a + \frac{\delta}{2}\right) \right\} dx + \int_{a+\delta/2}^{b} \Delta_2 \, dx \right]$$

$$= \Delta_2 \left(1 - \frac{a}{b}\right) + \Delta_1 \left(\frac{a}{b}\right)$$

and,

$$a_n = \frac{2}{b}\left[\int_0^{a-\delta/2} \Delta_1 \cos\frac{n\pi x}{b}\, dx + \int_{a-\delta/2}^{a+\delta/2} \left\{ \frac{\Delta_2 - \Delta_1}{\delta} x - \frac{\Delta_2}{\delta}(a - \delta/2) + \frac{\Delta_1}{\delta}(+\delta/2) \right\} \cos\frac{n\pi x}{b}\, dx + \int_{a+\delta/2}^{b} \Delta_2 \cos\frac{n\pi x}{b}\, dx \right] \quad n \neq 0$$

$$= \frac{4\left(\Delta_1 - \Delta_2\right) b}{\delta n^2 \pi^2} \sin\frac{n\pi a}{b} \sin\frac{n\pi\delta}{2b}$$

The temperature distribution can be written as:

$$T = \left[\Delta_1\left(\frac{a}{b}\right) + \Delta_2\left(1 - \frac{a}{b}\right)\right]\frac{y}{c} + \sum_{n=1}^{\infty} \frac{4\left(\Delta_1 - \Delta_2\right) b}{\delta n^2 \pi^2} \frac{\sin\frac{n\pi a}{b} \sin\frac{n\pi\delta}{2b} \sinh\frac{n\pi x}{b}}{\sinh\frac{n\pi c}{\alpha b}}$$

The error in the measurement of the heat flow through the main portion of the insulation is as follows:

$$\text{Error } (\%) = 100 \times \left[\frac{-\int_0^a k_y \left.\frac{\partial T}{\partial y}\right|_{y=0} dx}{\int_0^a k_y \left.\frac{\partial T}{\partial y}\right|_{y=0} dx - \int_0^c k_x \left.\frac{\partial T}{\partial x}\right|_{x=a} dy} \right]$$

$$= \frac{100}{1 + \left[\dfrac{\dfrac{\pi\alpha}{2}\left(\dfrac{a}{c}\right)\left[\Delta_1\left(\dfrac{a}{b}\right) + \Delta_2\left(1-\dfrac{a}{b}\right)\right] + \displaystyle\sum_{n=1}^{\infty} \dfrac{2(\Delta_1-\Delta_2)b}{n^2\pi\delta} \dfrac{\sin^2\dfrac{n\pi a}{b}\sin\dfrac{n\pi\delta}{2b}}{\sinh\dfrac{n\pi c}{\alpha b}}}{\displaystyle\sum_{n=1}^{\infty} \dfrac{\dfrac{2b}{\delta n^2\pi}(\Delta_1-\Delta_2)\sin^2\dfrac{n\pi a}{b}\sin\dfrac{n\pi\delta}{2b}\left[\cosh\dfrac{n\pi c}{\alpha b} - 1\right]}{\sinh\dfrac{n\pi c}{\alpha b}}} \right]}$$

APPENDIX C

DATA CORRELATIONS

APPENDIX C

DATA CORRELATIONS

In order to correlate the experimental data on the multilayer insulation assemblies the following equation was assumed:

$$Q = K_1 (T_h - T_c) + K_2 (\sigma T_h^4 - \sigma T_c^4)$$

$$= K_1 X + K_2 Y$$

where Q = heat flow

T_c, T_h = cold plate and heater plate temperatures, respectively

σ = Boltzmann's constant

The constants were obtained by the method of least squares.

Define the residual R_i as follows:

$$R_i = K_1 X_i + K_2 Y_i - Q_i \tag{1}$$

In order to obtain a best fit to minimize $\sum_i R_i^2$, differential $\sum_i R_i^2$ with respect to the constants K_1 and K_2:

$$R_1 \frac{\partial R_1}{\partial K_1} + R_2 \frac{\partial R_2}{\partial K_1} + \ldots + R_n \frac{\partial R_n}{\partial K_1} = 0 \tag{2}$$

$$R_1 \frac{\partial R_1}{\partial K_2} + R_2 \frac{\partial R_2}{\partial K_2} + \ldots + R_n \frac{\partial R_n}{\partial K_2} = 0 \tag{3}$$

Inserting expressions for derivatives in Equations (2) and (3):

$$K_1 \sum_{i=1}^{n} X_i^2 + K_2 \sum_{i=1}^{n} X_i Y_i - \sum_{i=1}^{n} Q_i X_i = 0 \tag{4}$$

and

$$K_1 \sum_{i=1}^{n} X_i Y_i + K_2 \sum_{i=1}^{n} Y_i^2 - \sum_{i=1}^{n} Q_i Y_i = 0 \tag{5}$$

Solving Equations (4) and (5) simultaneously:

$$K_1 = \frac{(\sum_{i=1}^{n} Q_i X_i)(\sum_{i=1}^{n} Y_i^2) - (\sum_{i=1}^{n} X_i Y_i)(\sum_{i=1}^{n} Q_i Y_i)}{(\sum_{i=1}^{n} X_i^2)(\sum_{i=1}^{n} Y_i^2) - (\sum_{i=1}^{n} X_i Y_i)^2}$$

and

$$K_2 = \frac{(\sum_{i=1}^{n} X_i^2)(\sum_{i=1}^{n} Q_i Y_i) - (\sum_{i=1}^{n} X_i Y_i)(\sum_{i=1}^{n} Q_i X_i)}{(\sum_{i=1}^{n} X_i^2)(\sum_{i=1}^{n} Y_i^2) - (\sum_{i=1}^{n} X_i Y_i)^2}$$