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# Thermal Certification Tests of Orbiter Thermal Protection System Tiles Coated with KSC Coating Slurries

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# Thermal Certification Tests of Orbiter Thermal Protection System Tiles Coated with KSC Coating Slurries

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## 1.0 SUMMARY

Thermal tests of the Orbiter Thermal Protection System (TPS) tiles, which were coated with borosilicate glass slurries fabricated at Kennedy Space Center (KSC), were performed in both the Radiant Heat Test Facility (RHTF) and the Atmospheric Re-entry Materials & Structures Evaluation Facility (ARMSEF) at the Johnson Space Center (JSC). As a part of the certification process, the test program was needed to verify the coating integrity of these tiles after exposure to multiple entry simulation cycles in both radiant and convective heating environments.

For the radiant heat test, eight High Temperature Reusable Surface Insulation (HRSI, class 2 coating) tiles and six Low Temperature Reusable Surface Insulation (LRSI, class 1 coating) tiles were subjected to 25 cycles at peaked surface temperatures of 2300°F and 1200°F, respectively. For the LRSI tiles, an additional cycle at peaked surface temperature of 2100°F was performed. There was no coating crack on any of the HRSI specimens. However, there were eight small coating cracks (less than 2 inches long) on two of the six LRSI tiles on the 26th cycle. There was practically no change on the surface reflectivity, physical dimensions, or weight of any of the test specimens. There was no observable thermal-chemical degradation of the coating either.

For the convective heat test, eight HRSI tiles were tested for five cycles at a surface temperature of 2300°F. Each of the Lockheed Insulation (LI-900) and Fibrous Refractory Composite Insulation (FRCI-12) tiles received an additional cycle at peak surface temperature of 2600°F. Each of the Lockheed Insulation (LI-2200) tiles was also subjected to an additional heating cycle at peaked surface temperature of 2700°F. There was no thermal induced coating crack on any of the test specimens. However, due to the fragility of the coating itself, two one-inch cracks propagated from a small 'ding' that occurred during the test preparation. There was practically no change on the surface reflectivity and no observable thermal-chemical degradation with an exception of minor slumping of the coating under the painted TPS identification numbers.

The tests demonstrated that there were no significant differences in the performance of the specimens coated by glass slurries fabricated either at Lockheed Missiles & Space Company (LMSC) or at KSC. Thus, the results indicated that the KSC's TPS slurries and coating processes meet the Orbiter's thermal specification requirements.

## 2.0 INTRODUCTION

Often known as the Thermal Protection System, the thermal insulation covering almost the entire outer surface of the Space Shuttle Orbiter protects the Orbiter from the aerodynamic heating (during ascent and re-entry phases) and from the orbital heating (during on-orbit). The Orbiter's TPS consists of two distinct types: rigid and flexible. Commonly referred to as "ceramic tiles", the rigid type TPS currently has three different types: twelve pounds per cubic foot density Fibrous Refractory Composite Insulation (FRCI-12), nine pounds per cubic foot density Lockheed Insulation (LI-900), and twenty two pounds per cubic foot density Lockheed Insulation (LI-2200). These tiles are made up of mostly amorphous silica fibers.

Because the silica fibers are proned to abrasion and do not have the desired optical properties for radiative heat transfer, these tiles are coated with 0.015" thick of either a white class 1 or a black class 2 Reaction Cured Glass (RCG). Because the white tiles are used in low temperature areas (upper surface of the Orbiter, from 750°F to 1200°F), they are referred to as Low Temperature Reusable Surface Insulation (LRSI). The black tiles used in areas that experience temperatures up to 2300°F (underside of the Orbiter) are referred to as High Temperature Reusable Surface Insulation (HRSI).

The LRSI and the HRSI coatings (class 1 and class 2) have been certified up to 100 shuttle missions at 1200°F and 2300°F, respectively. This certification was performed for tiles manufactured with borosilicate glass coating slurries fabricated by Lockheed Missiles and Space Company (LMSC). In 1989, a tile production facility was installed at Kennedy Space Center (KSC) to quickly provide coated TPS tiles for the Orbiter fleet. At that time, this facility only had the capability to spray the coating on uncoated tiles using the coating slurries which were fabricated by LMSC. This year, KSC's tile production facility has developed the capability of fabricating the coating slurries. As a part of the certification process, a thermal test program including both radiant and convective tests was conducted at JSC to verify that tiles coated with KSC's coating slurries meet the Orbiter's thermal specification requirements.

## 3.0 OBJECTIVE

The objective of this test program was to verify both Class 1 and Class 2 coating integrity of FRCI-12, LI-2200, and LI-900 tiles which were coated with KSC fabricated slurries after exposure to multiple entry simulations in both convective and radiative heating environments.

## 4.0 RADIANT HEAT TEST

### 4.1 TEST SPECIMENS

The specimens for the radiant heat test were divided into two groups of surface coating classes. For Class 1 coating, there was a total of six specimens: three of FRCI-12 tiles and three of LI-900 tiles. These tiles have dimensions of 8 inches in width, 8 inches in length, and 1 inch in depth. For Class 2 coating, there was a total of eight specimens: two of FRCI-12, three of LI-2200, and three of LI-900. These tiles have dimensions of 6 inches in width, 6 inches in length, and 2 inches in depth. A summary of the test specimens is shown in Table 1. The tiles were installed into two arrays (free standing with no strain isolation pad or aluminum plate). The first array, shown in Figure 1, was for LRSI tiles. The second array, shown in Figure 2, was for HRSI tiles. The control tile (FRCI12-061-021452) for either array was an instrumented Class 2 FRCI-12 tile provided by JSC. It was located in the center of the tile array and was used to establish the desired temperature conditions.

Table 1: Radiant Heat Test Specimen Summary

| Specimen ID | Base Material | Coating Type | Fabricator |
|---|---|---|---|
| 794-165-1 | LI-900 | Class 1 | KSC |
| 794-165-2 | LI-900 | Class 1 | LMSC |
| 794-165-3R | LI-900 | Class 1 | KSC |
| 794-165-4 | FRCI-12 | Class 1 | LMSC |
| 794-165-5 | FRCI-12 | Class 1 | KSC |
| 794-165-6 | FRCI-12 | Class 1 | KSC |
| 1-9-051 | LI-900 | Class 2 | KSC |
| 2-9-143 | LI-900 | Class 2 | KSC |
| 3-9-047 | LI-900 | Class 2 | LMSC |
| 4-12-047 | FRCI-12 | Class 2 | LMSC |
| 6-12-051 | FRCI-12 | Class 2 | KSC |
| 7-22-047 | LI-2200 | Class 2 | LMSC |
| 8-22-143 | LI-2200 | Class 2 | KSC |
| 9-22-051 | LI-2200 | Class 2 | KSC |

## 4.2 TEST FACILITY

The radiant heat test portion of the test program was performed in chamber R-1 at the Johnson Space Center Radiant Heat Test Facility (RHTF). The radiant heater system consists of graphite heater elements enclosed in a fixture with a columbium susceptor plate. The heater elements were arranged to have a 30 inch by 39 inch surface area. The test specimens were placed about 2 inches away from this heated area. An overall view of the test setup is shown in Figure 3.

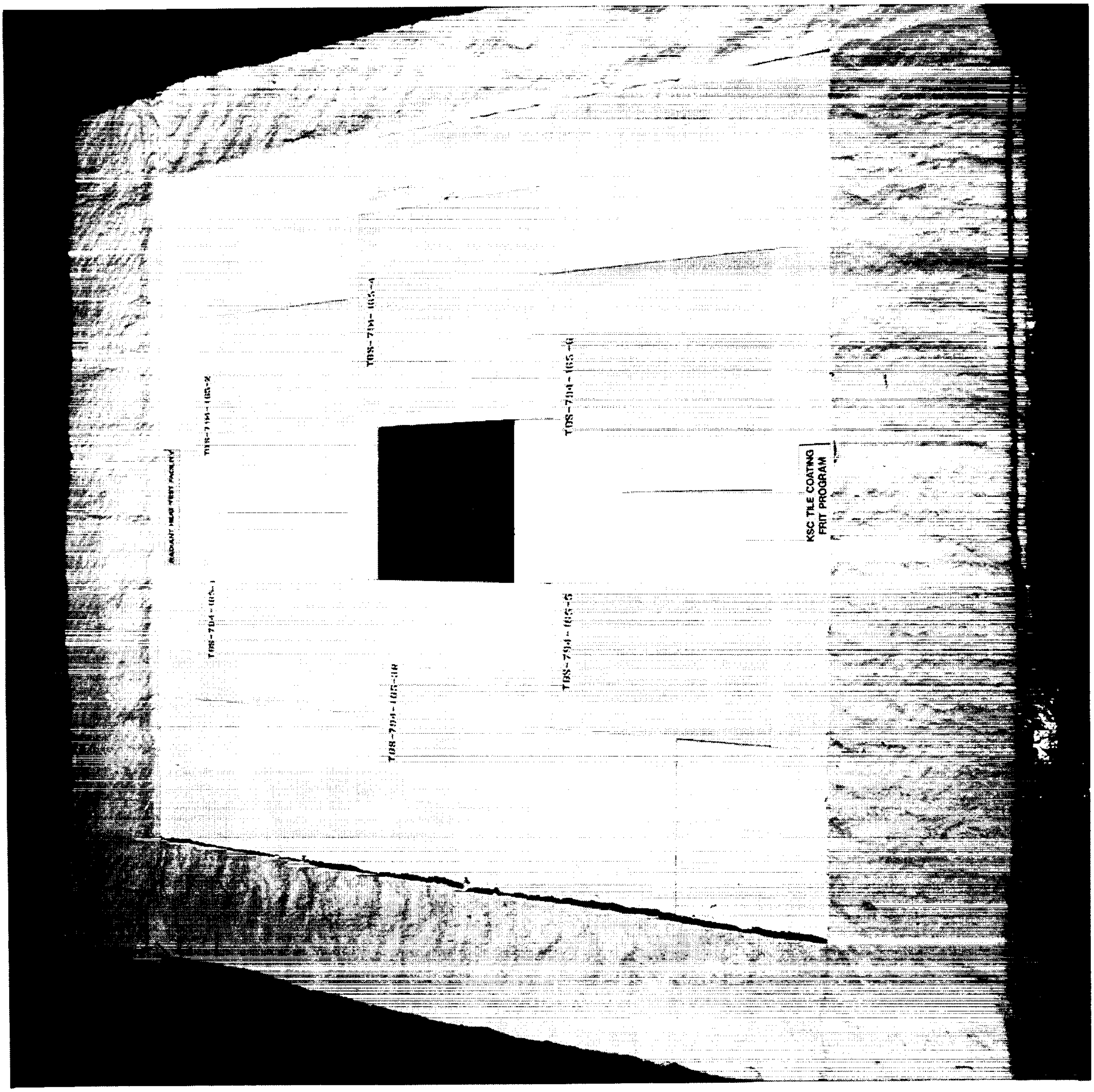





Figure 1: LRSI Tile Array

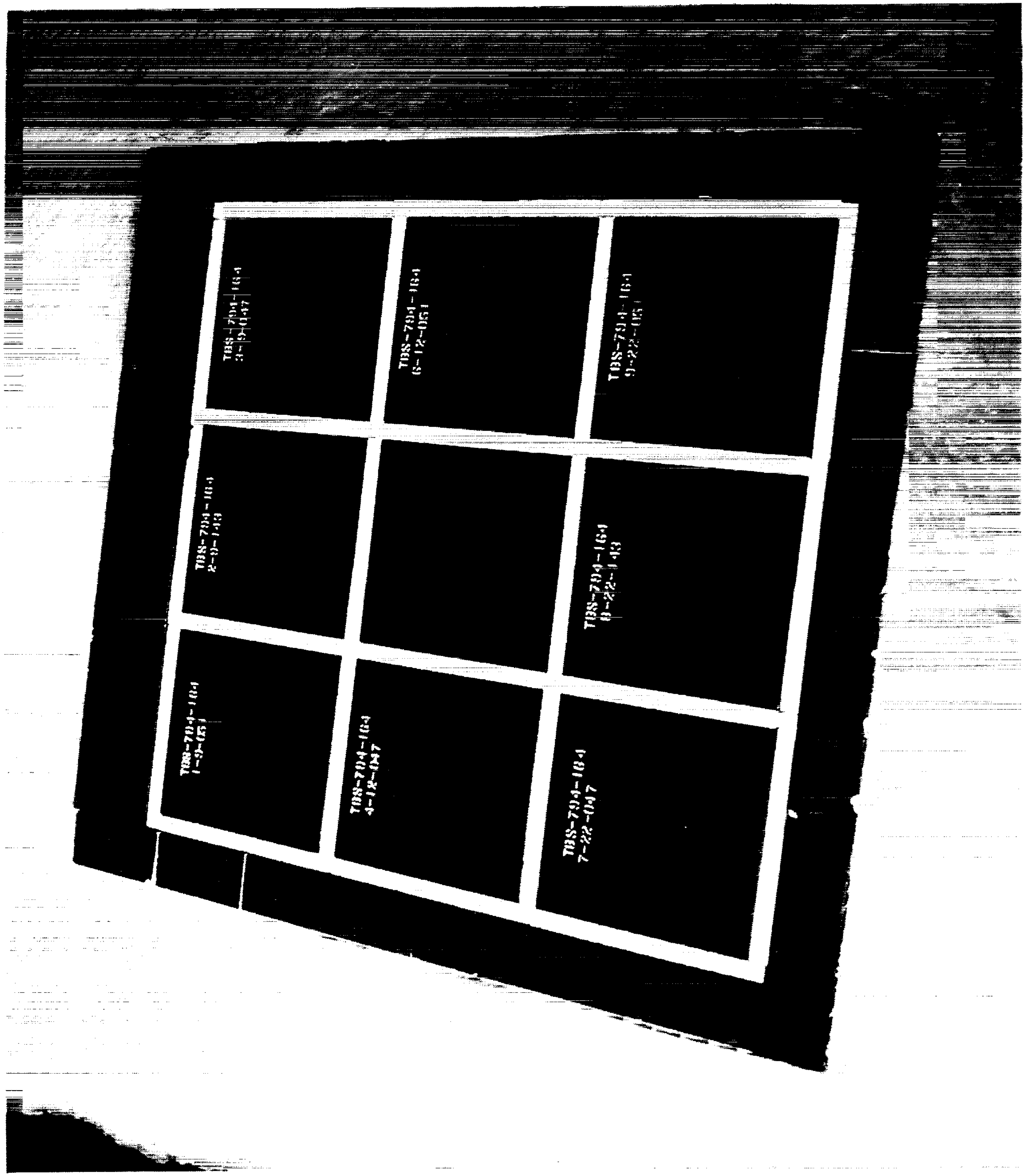




Figure 2: HRSI Tile Array

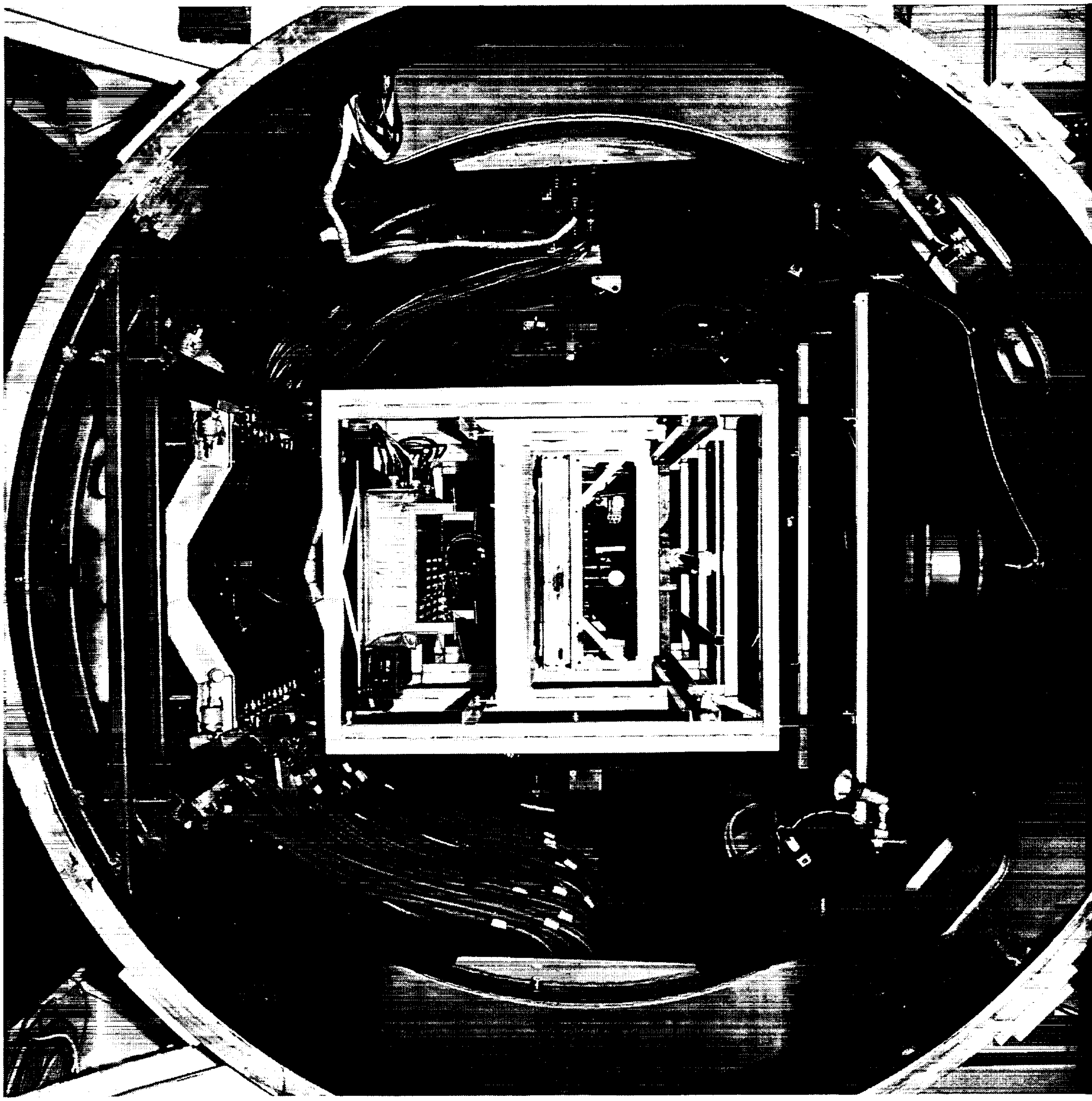


Figure 3: Radiant Heat Test Setup

## 4.3 TEST CONDITIONS

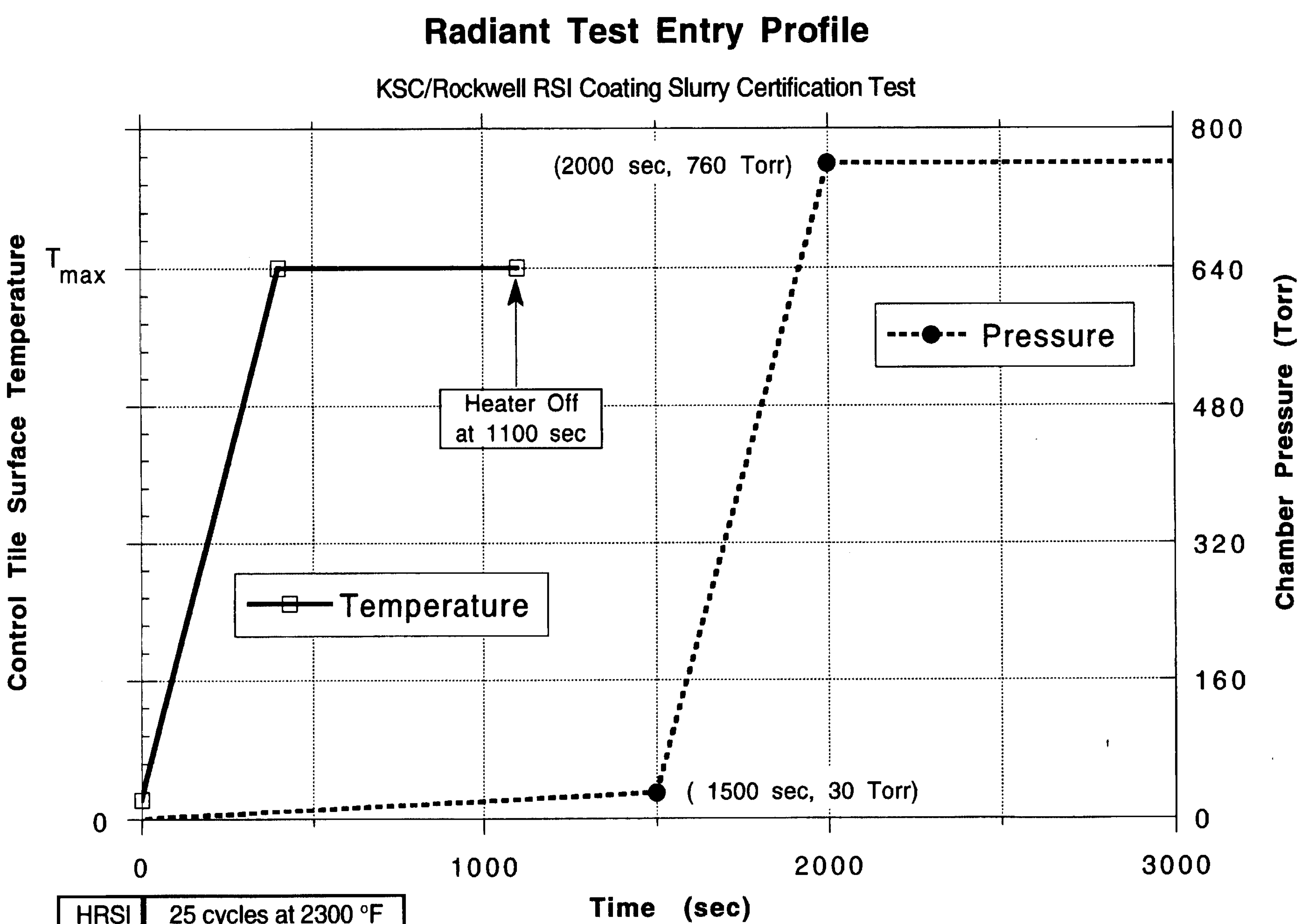
A total of 25 mission entry cycles was performed for the HRSI test specimens. In these heating cycles, the specimens were subjected to their multimission temperature limit of 2300°F. A total of 26 mission entry cycles was performed for the LRSI test specimens. For the first 25 cycles, the specimens were subjected to their multimission temperature limit of 1200°F. On the 26th cycle (the last cycle), the specimens were subjected to their single mission temperature limit of 2100°F. During testing, these temperatures can vary by ± 50°F. The desired entry temperature and pressure profiles are shown in Figure 4. The pressures can vary by ± 10% during testing.

## 4.4 TEST CALIBRATIONS

Initial calibration tests were conducted using a nine tile array of instrumented "dummy" HRSI tiles with the instrumented control tile in the center of the array. The purpose of these calibration runs was twofold: to determine proper control gains for the heater control system and to demonstrate adequate temperature uniformity over the surface of a nine tile array. Temperature uniformity exceeding test requirements was demonstrated at all test temperatures, with higher gradients experienced at the lower temperatures as expected. However, difficulty was experienced in achieving proper control to specified temperature profiles using temperature feedback control .

A qualitative analysis of this problem revealed the most likely cause to be the delay in heater response caused by the mass of the coated columbium susceptor (re-radiator) plate, coupled with the rapid thermal rise time specified in the test temperature profile, and the lack of any predictive element in the basic proportional / integrator / derivative (PID) control algorithm. Since there was no readily implementable solution to this problem, the decision was made to utilize open loop heater power control for this test program. Principal risks associated with open loop control are greater variability in temperature simulation from run to run and a gradual decrease in surface temperature as the test progresses due to increased reflector losses caused by contaminate deposition.

Calibration testing continued with the primary objective of determining the heater power profiles required to meet the specified test conditions. This objective was rapidly met using data derived from the previous calibration runs. It was also determined that the




| | |
|---|---|
| HRSI | 25 cycles at 2300 °F |
| LRSI | 25 cycles at 1200 °F |
| LRSI | 1 cycle at 2100 °F |

Figure 4: Radiant Test Entry Profile

principal variability between runs was not in the shape or ramp rate of the profile, but in the start time of the ramp. Thus, shifting the profile start time to the actual start time reduced high temperature errors to acceptable levels, although time at peak temperature might vary by 10 to 15 seconds as a result.

After acceptance of the calibration profiles, the control tile was installed in the HRSI test array and testing at 2300 °F commenced. As anticipated, peak temperatures declined slightly as contaminates accumulated on the heater reflectors. Power profiles were adjusted slightly throughout the test program to compensate for these losses and to maintain surface temperatures at acceptable levels. At the completion of 25 thermal cycles, the HRSI tile array was removed and work began on the LRSI test series.

The control tile was removed from the test array and installed in the calibration array. The heater was also disassembled at this time to clean the reflectors and to examine the condition of the heater elements. Calibration testing was then performed to determine the heater power profiles for the 1200 °F and 2100 °F LRSI tests. These tests progressed rapidly using the experience gained during the HRSI testing. The control tile was then removed from the calibration panel and installed in the LRSI tile array.

The LRSI test article was exposed to twenty-five 1200 °F thermal cycles without incident, although it was again necessary to monitor and adjust the power profile to compensate for reflector contamination. The single 2100 °F thermal cycle was also performed without incident.

## 4.5 TEST PROCEDURES

Prior to testing, all specimens were wiped with alcohol to detect coating cracks and were then photographed. After every fifth cycle, the tiles were wiped with alcohol again to detect any crack growth. At the end of the test program, the tiles were checked for cracks again and another set of photographs was taken.

Surface reflectivity was measured for each test specimen both before and after the test using the Gier-Dunkle long-wavelength reflectometer. The specimens' physical dimensions and weights were also measured before and after testing.

Rigorous test management and control were implemented by formal documentations (e.g., Discrepancy Reports, Anomaly Logs, Standard Operating Procedures, and Test Preparation Sheet). Quality assurance representatives witnessed all pre-test and post-test activities, monitored test systems configurations, insured that metrology requirements were met, and participated as test observers.

## 5.0 CONVECTIVE HEAT TEST

### 5.1 TEST SPECIMENS

For the convective heat test, the test specimens consisted of eight HRSI cylindrical 'pucks', 3.875 inches in diameter and 2.0 inches in thickness. Three were LI-900, three FRCI-12, and two LI-2200. A summary of the test specimens is shown in Table 2. Each test specimen was bonded to a 0.160-inch-thick Strain Isolation Pad (SIP), which was then bonded to a 0.032-inch-thick aluminium plate. The calibration specimen (LT-001-1079) was instrumented with four thermocouples: two Type R on the surface and two Type K, one at the tile/SIP bondline and the other on the aluminum plate's backface. The calibration specimen, provided by JSC, was manufactured by LMSC. The test specimens were instrumented with two type K thermocouples: one on the tile/SIP bondline and one on the aluminum plate's backface. Each test specimen was then mounted in a 5.0 inch O.D water-cooled holder (see Figure 5). A specimen and its holder were then mounted on an insertion arm inside the test chamber.

Table 2 : Convective Heat Test Specimen Summary

| Specimen ID | Base Material | Coating Type | Fabricator |
|---|---|---|---|
| 10-9-047 | LI-900 | Class 2 | LMSC- |
| 11-9-143 | LI-900 | Class 2 | KSC |
| 12-9-051 | LI-900 | Class 2 | KSC |
| 13-12-051 | FRCI-12 | Class 2 | KSC |
| 14-12-143 | FRCI-12 | Class 2 | KSC |
| 15-12-047 | FRCI-12 | Class 2 | LMSC |
| 16-22-051 | LI-2200 | Class 2 | KSC |
| 18-22-143 | LI-2200 | Class 2 | KSC |

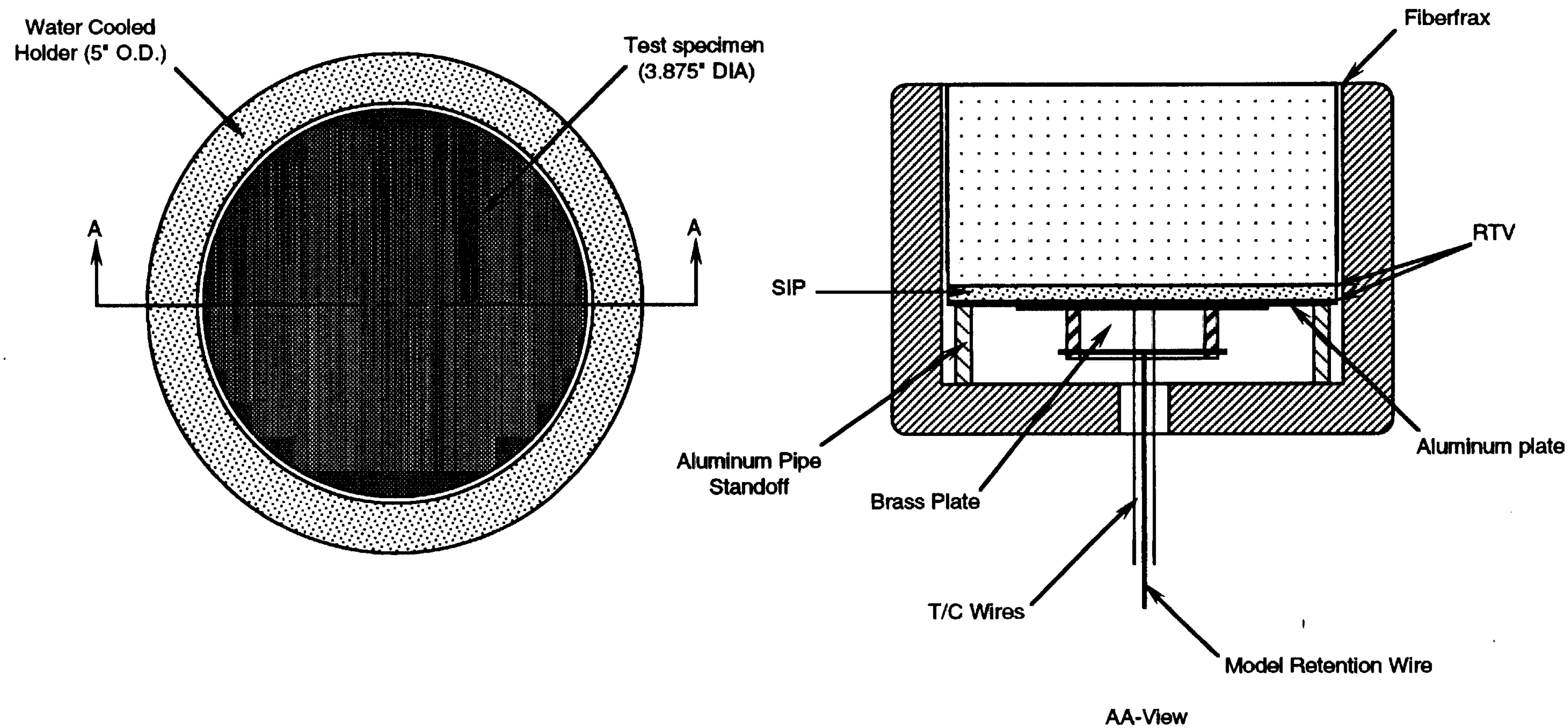



Figure 5: Convective Heat Test Specimen & Holder

## 5.2 TEST FACILITY

The convective heat test portion of the test program was performed in test position #1 (TP1) chamber of the ARMSEF. Test gases (23% $O_2$ and 77 % $N_2$ by mass), which simulated air, are heated by a segmented, constricted arc heater and injected into the chamber through a water-cooled 5 inches in diameter conical nozzle that has a 15° half angle. During testing, the chamber was evacuated by a four-stage steam ejector pumping system. The chamber static pressure was kept below 0.3 torr. Heater configuration 1-6 was used in this test program and is shown in Figure 6.

## 5.3 TEST CONDITIONS AND CALIBRATIONS

The desired test temperature and pressure conditions are presented in Table 3. The surface pressure of the test specimen was established using a pressure model which had the same physical dimensions as the test specimen installed in its holder (5.0" O.D.). A laser pyrometer (NASA 1119198) was used to measure the surface temperature response of the calibration specimen. The output of the laser pyrometer was then correlated with the T/Cs' readings of the calibration model. An emissivity of 0.86 was used to compensate for the losses due to the optics. During the test, the laser pyrometer was the sole instrument used to monitor the surface temperature of the test specimens.

With the arc heater configuration 1-6 and a target distance (distance from the nozzle exit plane to the test specimen) of 13 inches, the first test point (2300°F, 100 psf) was achieved with a total test gas flow rate of 0.25 lbm/s and an arc heater current of 260 amps. The second test point (2600°F, 100 psf) was achieved with 0.21 lbm/s and 405 amps. The third test point (2700°F, 100 psf) was achieved with 0.2 lbm/s and 520 amps. It was decided at the Test Readiness Review that the convective test would be run at constant test conditions if the surface temperature of the test specimen did not drop below the desired temperature conditions. This was to ensure that no specimen would be under tested.

During the test, the actual surface temperature at 2300°F test point ranged from 2320°F to 2380°F. Members of the test control board believed that the LI-900 specimens would slump at some temperature slightly above 2300°F. Therefore, it was decided at a test

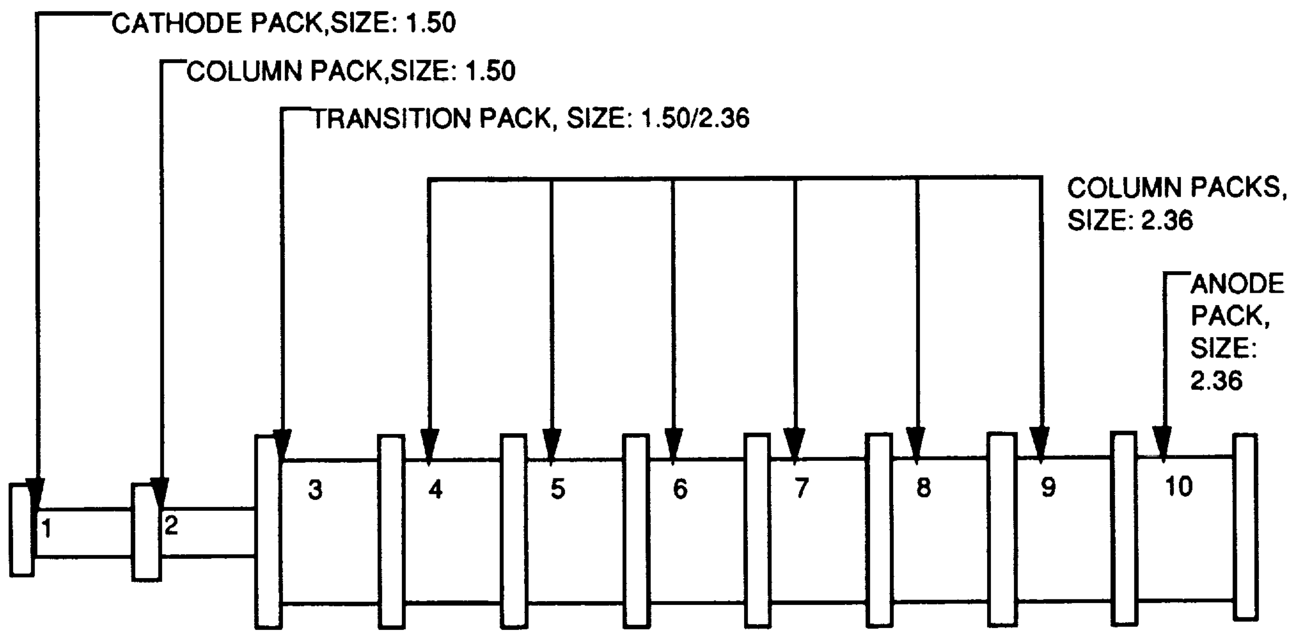
DUAL DIAMETER
CONFIGURATION RECORD #1-6

NOZZLE: 5" CONICAL NOZZLE MOUNTED OUTSIDE; ADAPTER PLATE MOUNTED INSIDE

COOLANT MANIFOLD: SINGLE PASS, COOLANT INLET SET @ 580 PSIG OR MAX OUTPUT

THROAT DIAMETER: 2.25"

CATHODE: TUNGSTEN
COLUMN LENGTH: 10 PACKS
TYPE PACKS: 1.25" -0-
1.50" 2
1.50/2.36" 1
2.36" 7




| COLUMN GAS INJECTION CONFIGURATION | | |
|---|---|---|
| GAS | PACK | SEGMENTS |
| N2 | 1 | 2, 4, 6 |
| N2 | 4 | 3, 13 |
| N2 | 5 | 3 |
| N2 | 10 | 17, 18, 19 |
| O2 | 6 | 3, 8, 13, 18 |
| O2 | 7 | 3, 8 |
| | | ZERO lines to Anode Plenum |

PRESSURE TRANSDUCER LOCATIONS: N2 MANIFOLD; PACK 1/SEG 10; PACK 5/SEG 8; PACK 10/SEG 16; ANODE PLENUM; O2 MANIFOLD.

5.0 OHM RIBBON WIRE RESISTOR BETWEEN ORIFICES IN ANODE PLENUM.

COMMENTS: EIGHT (8) 0.0635" DIAMETER ORIFICES IN ANODE PLENUM.

1.50" DIA. TO 2.36" DIA. TRANSITION AT SEGMENTS 4, 5 & 6 IN PACK 3.

VENT ORIFICES: GN2=0.3750" DIA. ; GO2=0.2187" DIA.

Figure 6: Arc Heater Configuration

control board meeting to vary the arc heater power to maintain constant surface temperature of 2300°F for specimen number 12-9-051.

Table 3 : Convective Heat Test Conditions

| Base Material | Test Mode | Pressure | Multi-mission Temperature | Single Mission Temperature |
|---|---|---|---|---|
| LI-900 | Stagnation | 100 psf | 2300°F | 2600°F |
| FRCI-12 | Stagnation | 100 psf | 2300°F | 2600°F |
| LI-2200 | Stagnation | 100 psf | 2300°F | 2700°F |

### 5.4 TEST PROCEDURES

The test specimens were subjected to the temperature and pressure conditions shown in Table 3. A total of six cycles, 900 seconds each, was performed on each of the convective test specimens. In the first five cycles, the test specimens were subjected to their multi-mission temperature limit of 2300°F. On the sixth cycle, they were subjected to their single mission temperature limits: 2600°F for LI-900 and FRCI-12 tiles and 2700°F for LI-2200 tiles. Before and after the test, each specimen was wiped with alcohol to detect coating cracks and photographed. Surface reflectivity was also measured using the Gier-Dunkle long-wavelength reflectometer.

## 6.0 RESULTS AND DISCUSSIONS

For the radiant heat test, typical surface conditions of a test specimen of both before and after the test are shown in Figures 7 through 10. The tiny white dots on the surface of the HRSI test specimen were speculated to be fiberfrax (insulation used around the tile arrays and the heater) particulates deposited onto the test specimens as the heater traveled in and out of a heating cycle. Typical surface temperature and pressure responses during the test are summarized in Appendices A-1 and A-2, respectively. Due to the contamination buildup on the heater reflectors and different initial conditions between test cycles, there were slight variations in the surface temperature responses. The dimensions, weights, surface reflectivities of each specimen before and after testing indicated insignificant changes and are summarized in Appendices A-3 through A-5. Appendix A-6 contains the crack maps of the only two LRSI tiles which developed minor cracks.

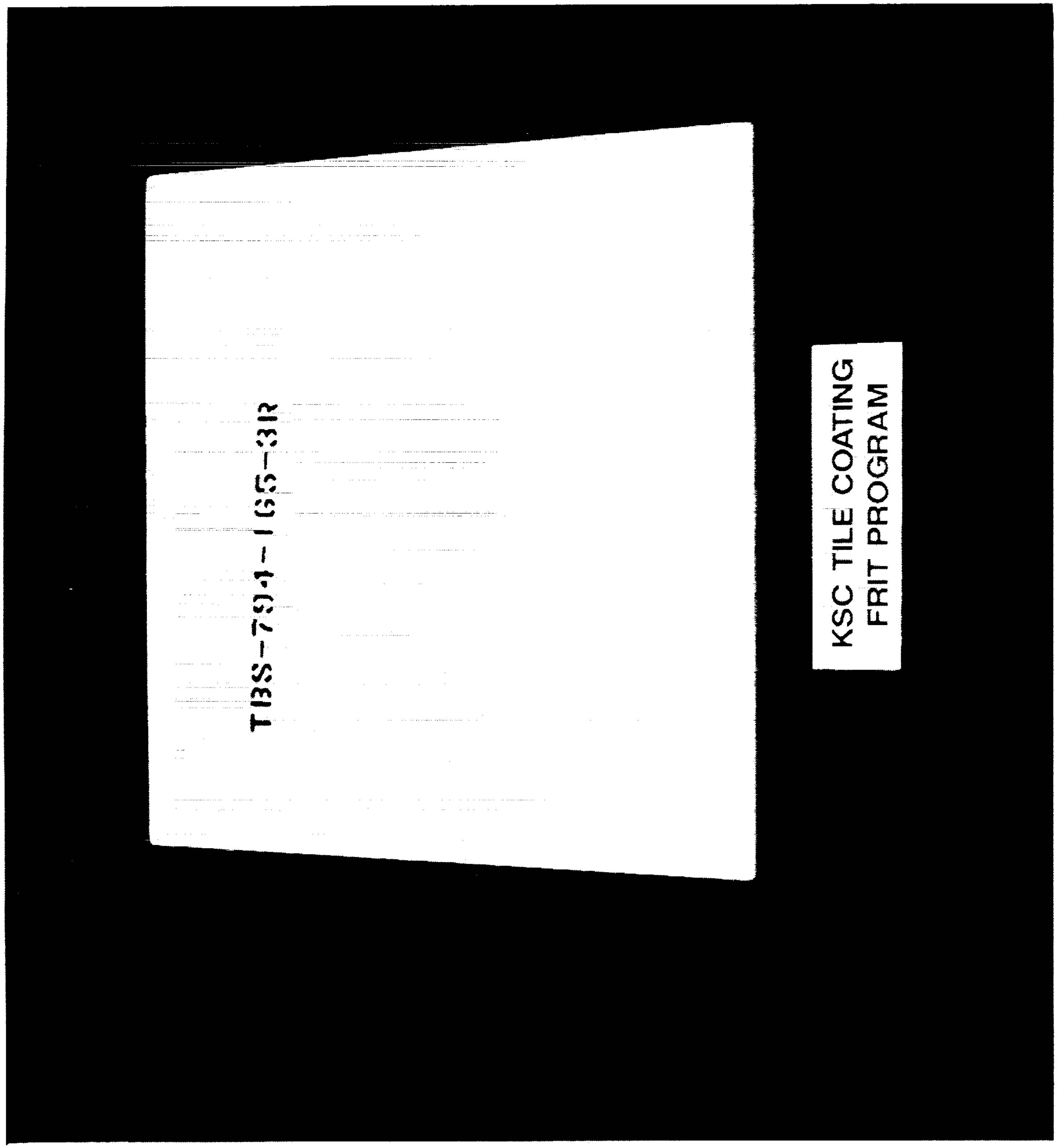



Figure 7: Pre-test Photo of a LRSI Specimen (Radiant)

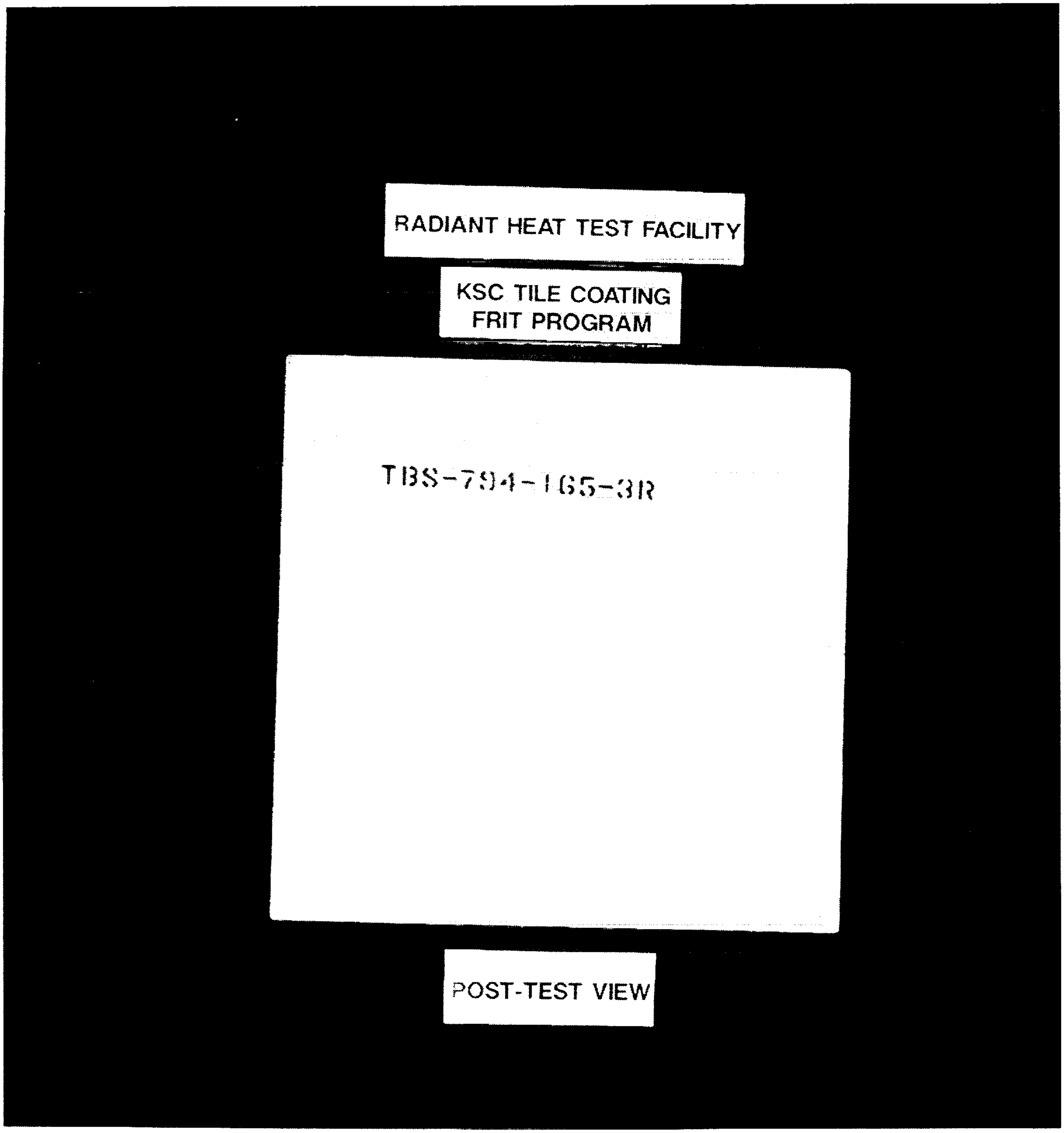



Figure 8: Post-test Photo of a LRSI Specimen (Radiant)

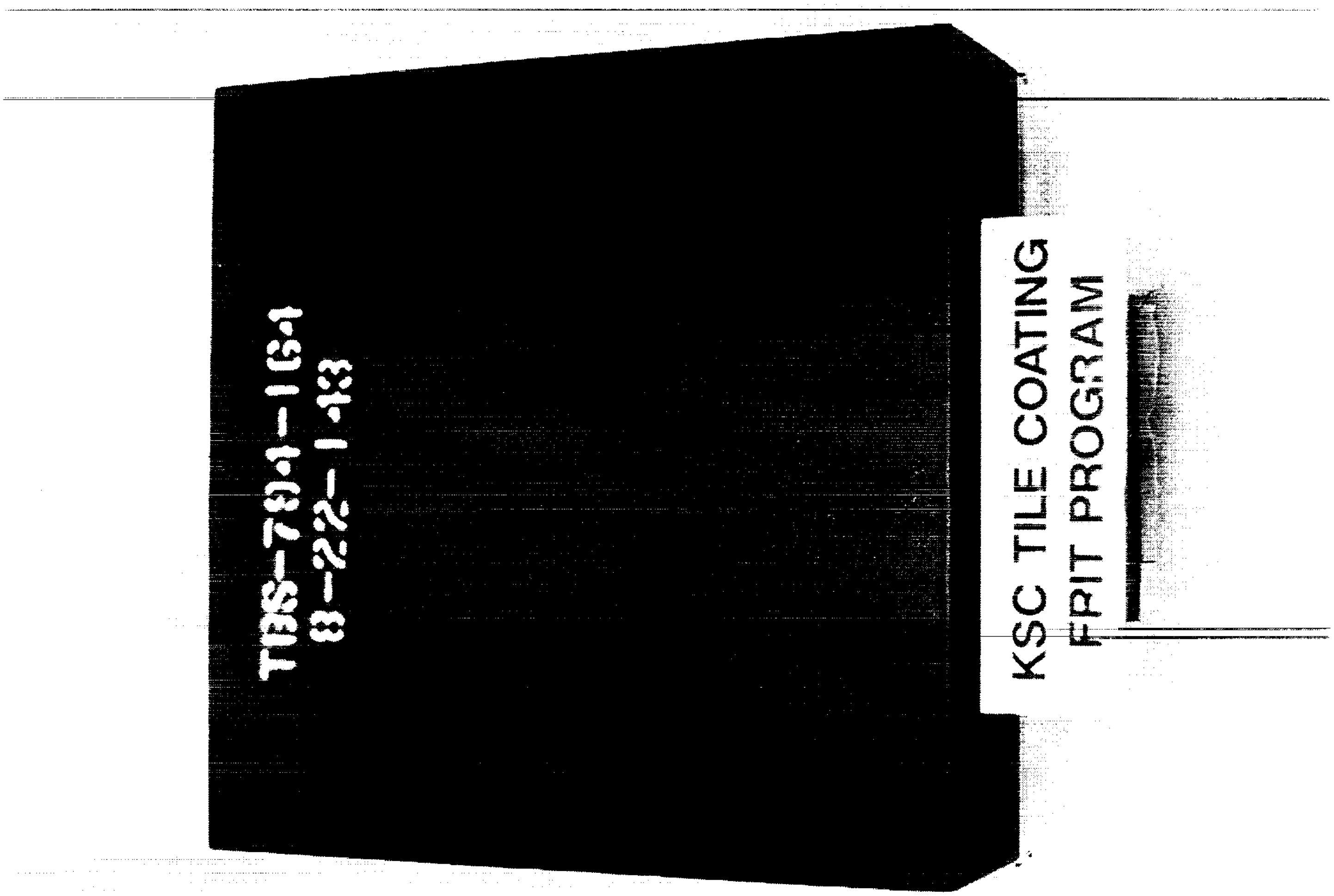





Figure 9: Pre-test Photo of a HRSI Specimen (Radiant)

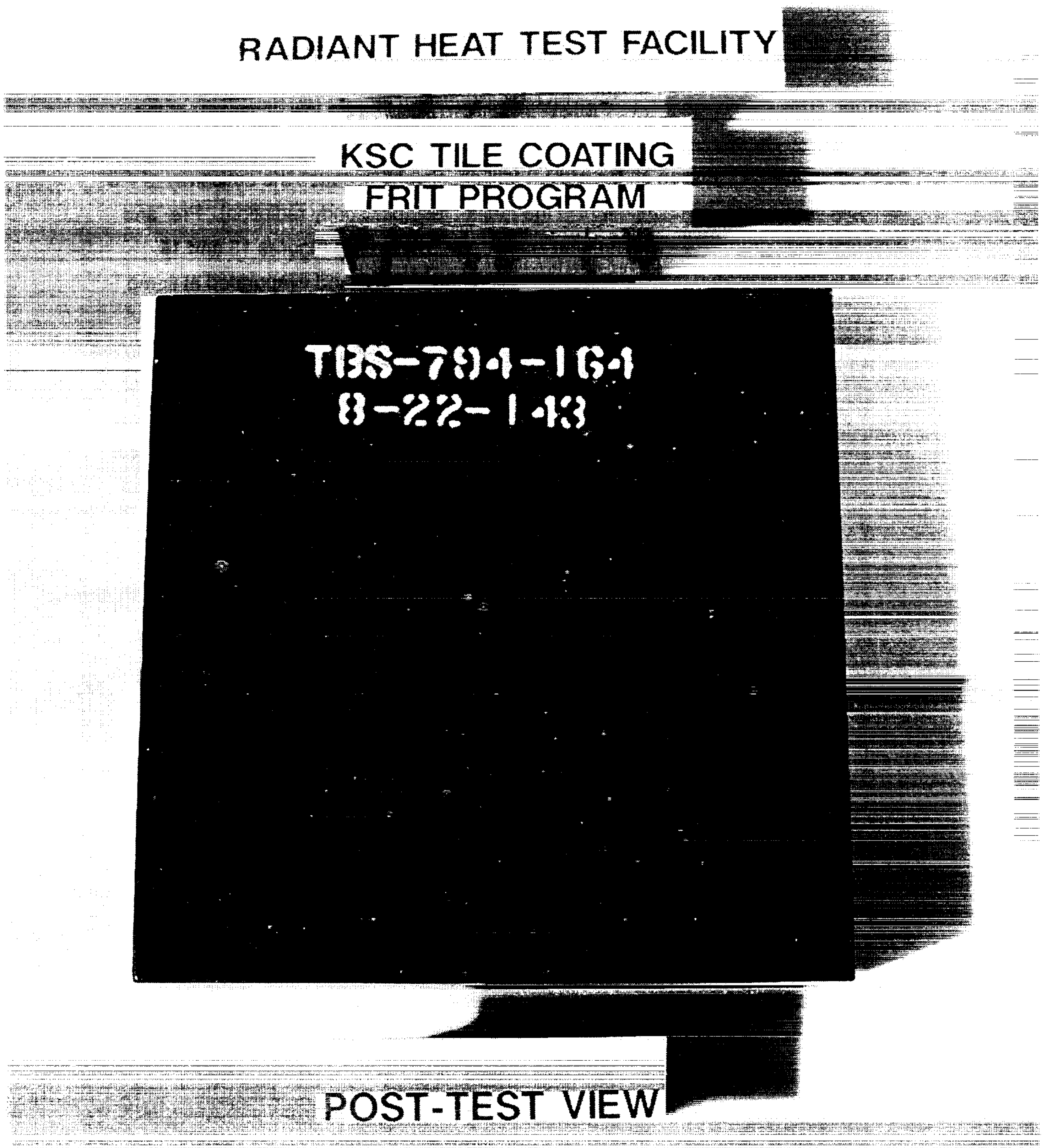



Figure 10: Post-test Photo of a HRSI Specimen (Radiant)

For the convective heat test, pre- and post-test photographs of a LI-900 test specimen are shown in Figures 11 and 12. Although not shown well in the photograph (Figure 12), the LI-900 test specimens have minor slumping underneath the painted identification number. This slumpage in the tiles was caused partially by the low emissivity of the paint, the low density of the tiles, and the stagnation pressure of the test. This phenomenon was not seen on the radiant test specimens because the emissivity of the test specimens became unimportant in the radiant test (blackbody radiation). Pre- and post-test photographs of a LI-2200 test specimen are shown in Figures 13 and 14. These figures indicated that the identification paint was burnt and evaporated at some temperature above 2700°F. Typical surface temperature plots are summarized in Appendix B-1. The surface reflectivities of the test specimens before and after testing are summarized in Appendix B-2. Appendix B-3 contains a crack map for the only tile that developed cracks. Because the convective test specimens were bonded to a SIP and an aluminum plate with RTV adhesive, the specimens' dimensions and weights can not be measured accurately and consequently were not performed.

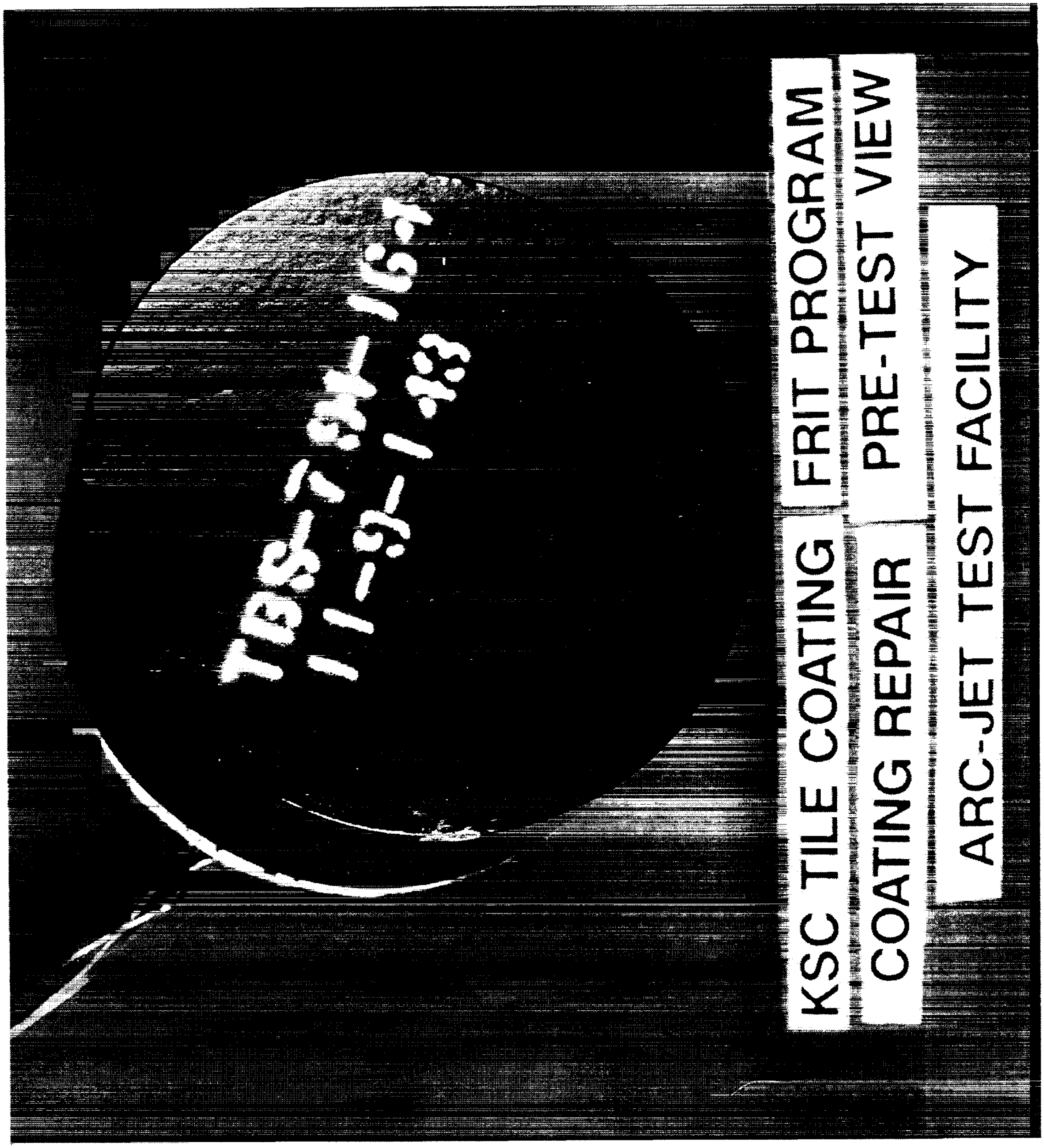





Figure 11: Pre-test Photo of a LI-900 Specimen (Convective)

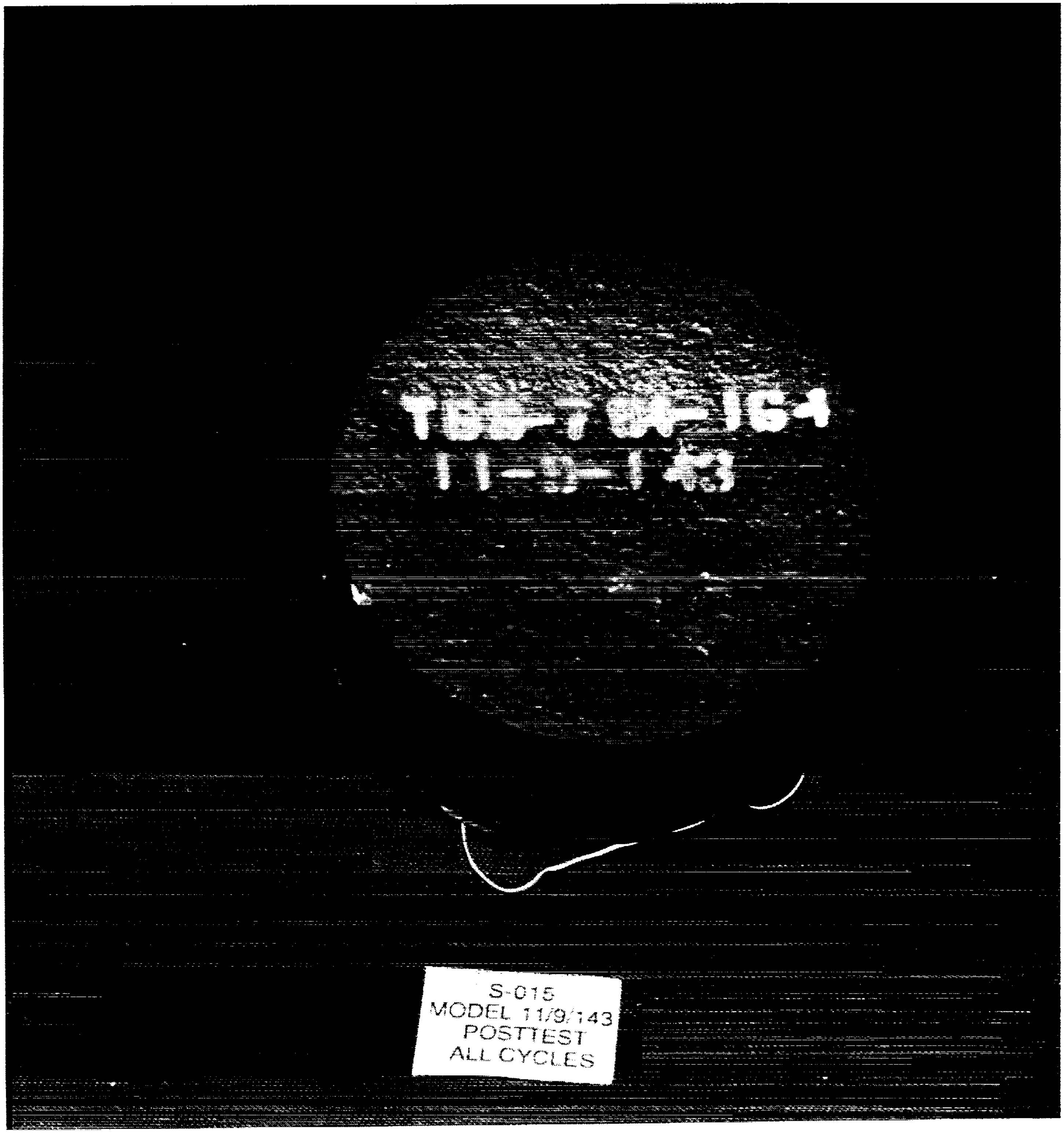



Figure 12: Post-test Photo of a LI-900 Specimen (Convective)

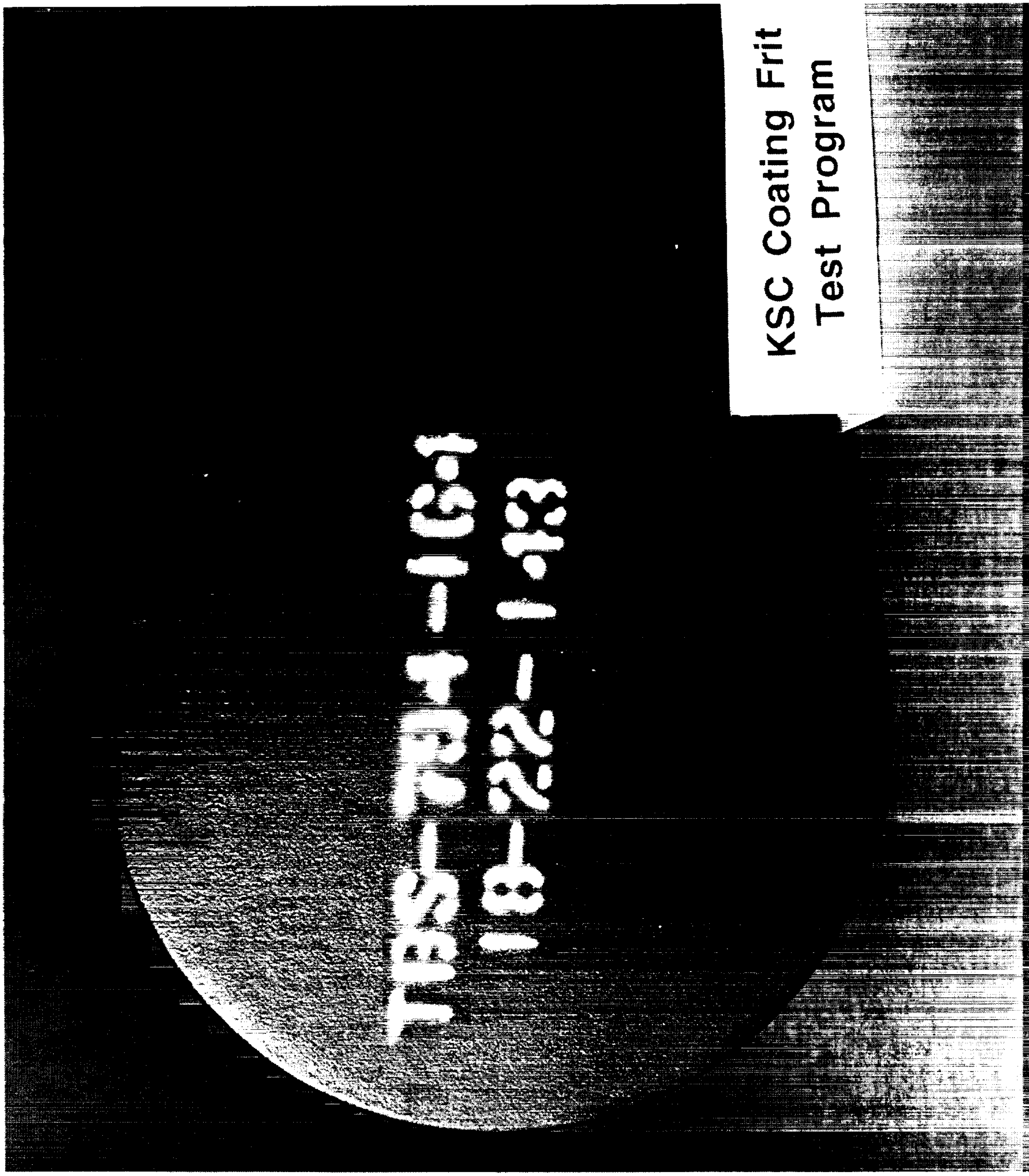





Figure 13: Pre-test Photo of a LI-2200 Specimen (Convective)

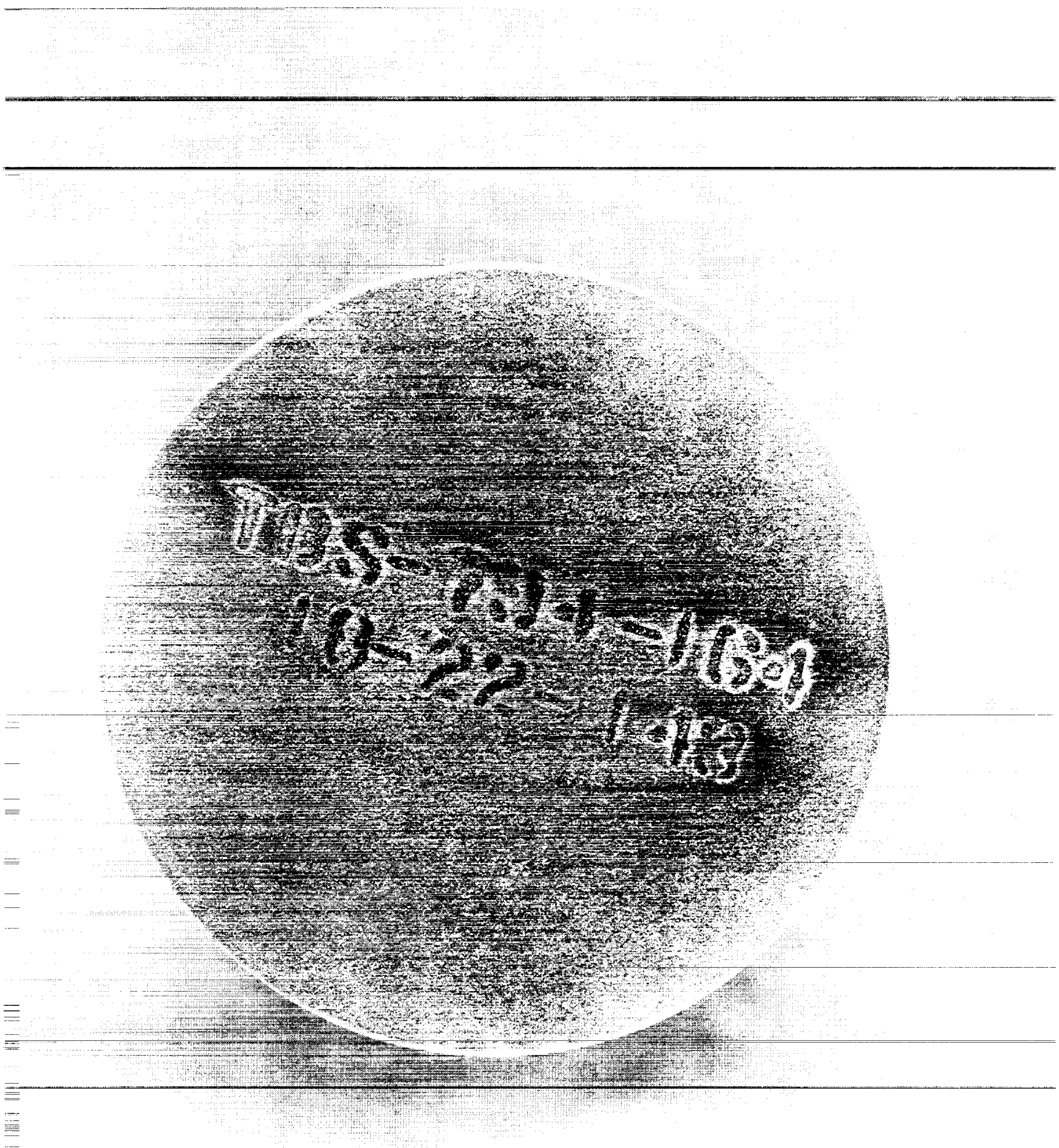


Figure 14: Post-test Photo of a LI-2200 Specimen (Convective)

## 7.0 CONCLUSION

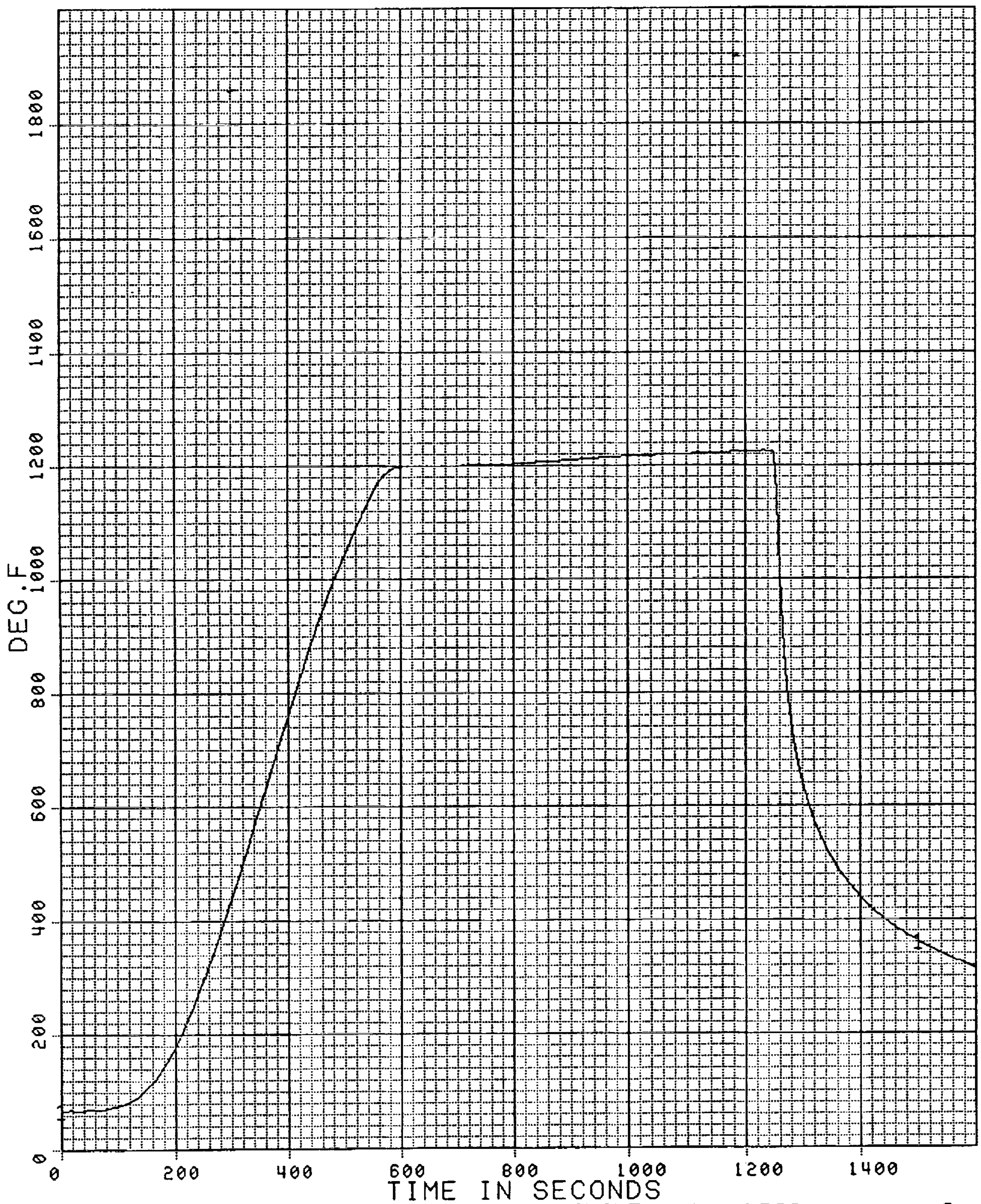
The thermal certification test of the KSC fabricated coating slurries was successfully completed in both RHTF and ARMSEF at JSC. Examination of the test specimens after the test program did not indicate any severe coating cracks or adverse thermal-chemical reactions. The results from both the radiant heat and the convective heat tests indicated that the TPS tiles coated with KSC fabricated slurries met the Orbiter's thermal specification requirements.

# Appendix A-1

Typical Surface Temperature Responses
(Radiant Heat Test)

KSC COATING FRIT 1200 DEG.F TEST CYCLE#1 92233R01 RDC # 3
DATE = 8/20/92 AVERAGE INTERVAL 5.0 SEC TIME = 19: 9: 3.6 TO 19:45:18.6
PROCESSING DATE 9/ 9/92

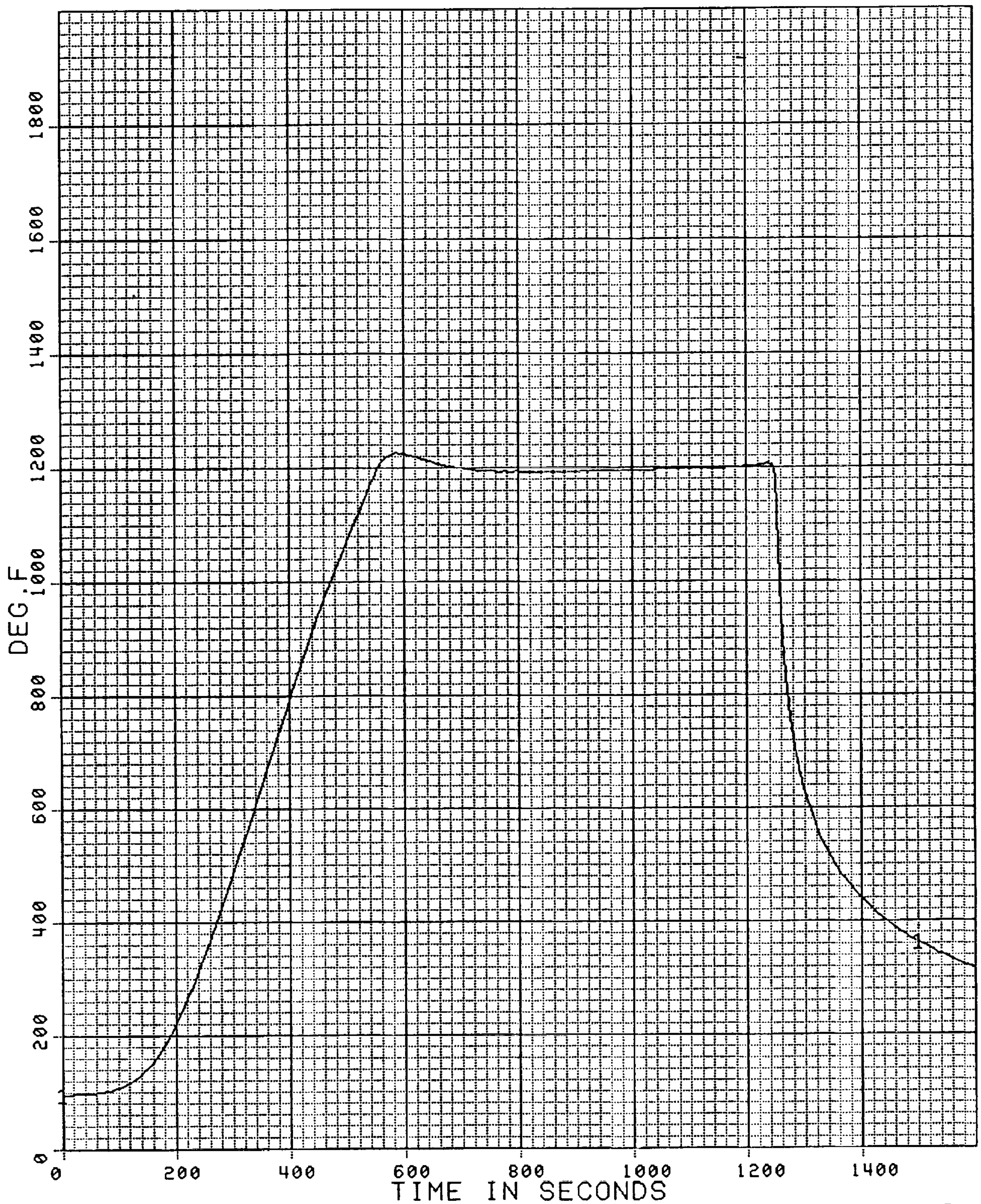
# FR12-TC1 CHANNEL NO. 22




CONTROL TILE SURFACE TEMPERATURE - TEST CYCLE # 1 - LRSI 2

KSC COATING FRIT 1200 DEG.F TEST CYCLE#10 92237R04 RDC # 3
DATE = 8/24/92 AVERAGE INTERVAL 5.0 SEC TIME = 22:31:38.2 TO 23: 7:23.2
PROCESSING DATE 9/ 9/92

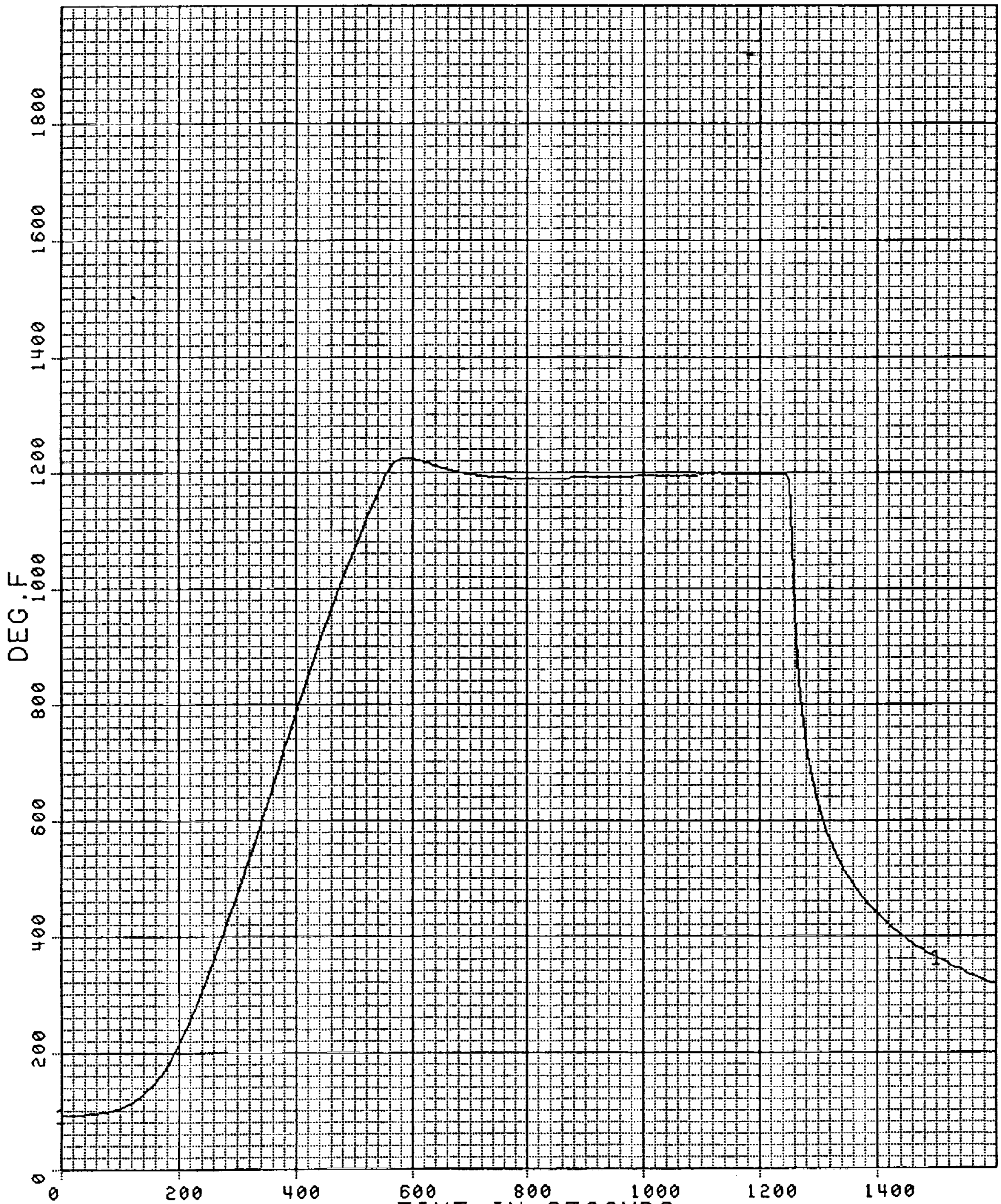
# FR12-TC1 CHANNEL NO. 22




CONTROL TILE SURFACE TEMPERATURE - TEST CYCLE # 10 - LRSI 2

KSC COATING FRIT 1200 DEG.F TEST CYCLE#25 92240R05 RDC # 3
DATE = 8/27/92 AVERAGE INTERVAL 5.0 SEC TIME = 22: 7:16.9 TO 22:43: 1.9
PROCESSING DATE 9/ 9/92

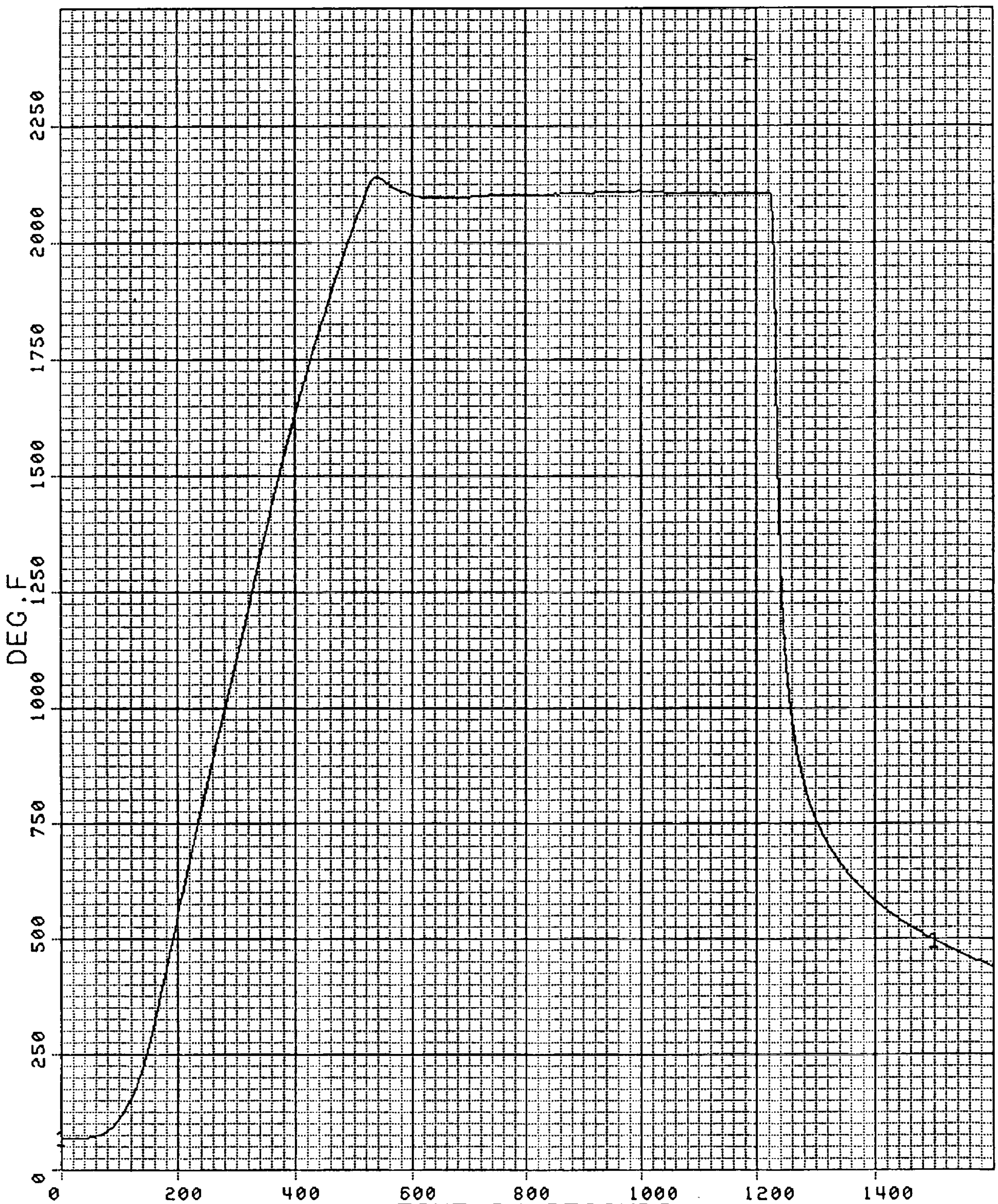
# FR12-TC1 CHANNEL NO. 22




CONTROL TILE SURFACE TEMPERATURE - TEST CYCLE # 25 - LRSI 2

KSC COATING FRIT 2100 DEG.F TEST CYCLE#26 92241R01 RDC # 5
DATE = 8/28/92 AVERAGE INTERVAL 5.0 SEC TIME = 16:41:44.7 TO 17:17: 4.7
PROCESSING DATE 9/ 9/92

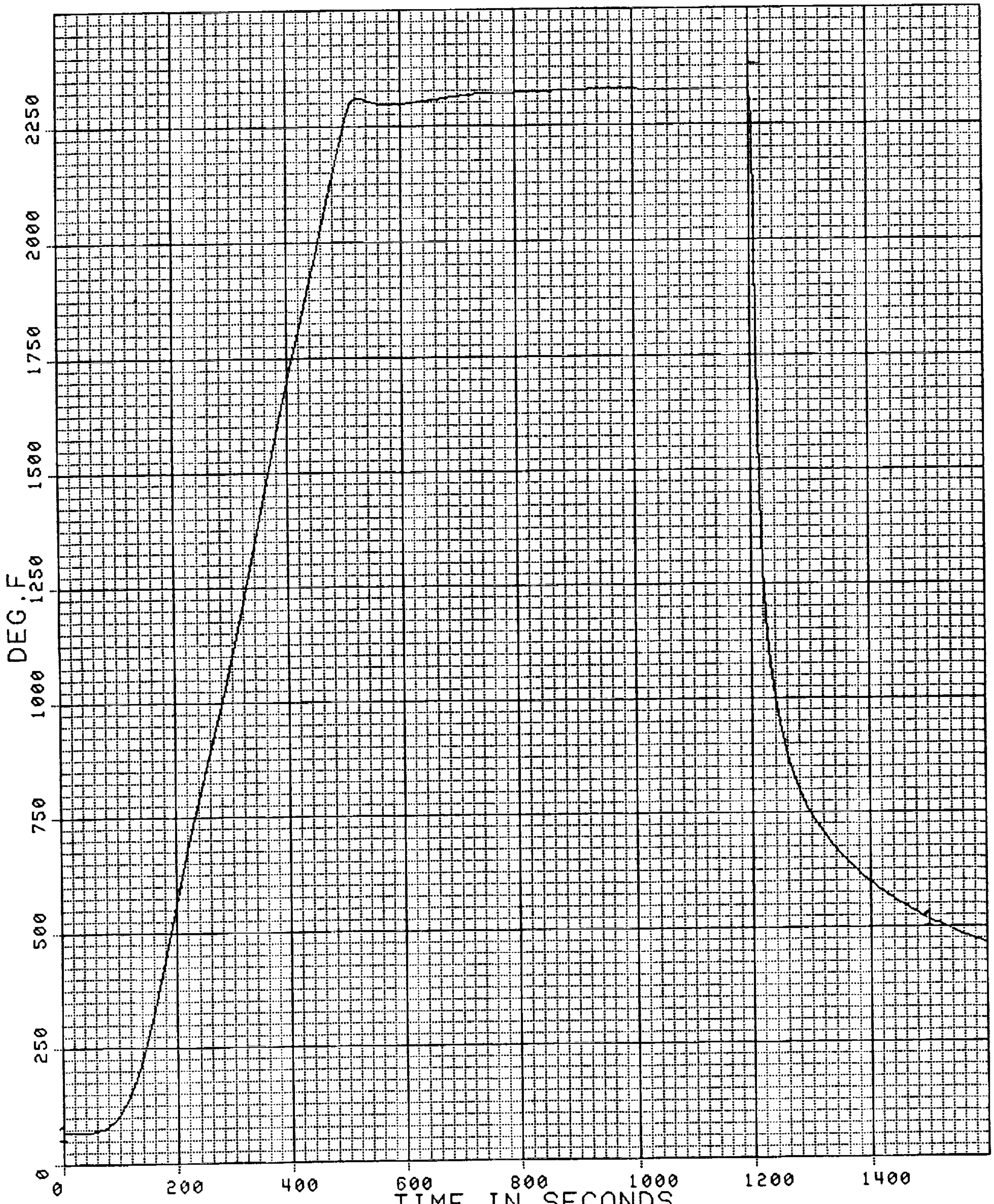
# FR12-TC1 CHANNEL NO. 22




CONTROL TILE SURFACE TEMPERATURE - TEST CYCLE # 26 - LRSI 1

SRHTF. KSC COATING FRIT 2300 DEG.F TEST CYC#1 92217R01 RODG
DATE = 8/ 4/92 AVERAGE INTERVAL 5.0 SEC TIME = 23: 7:31.9 TO 23:47:46.9
PROCESSING DATE 9/ 9/92

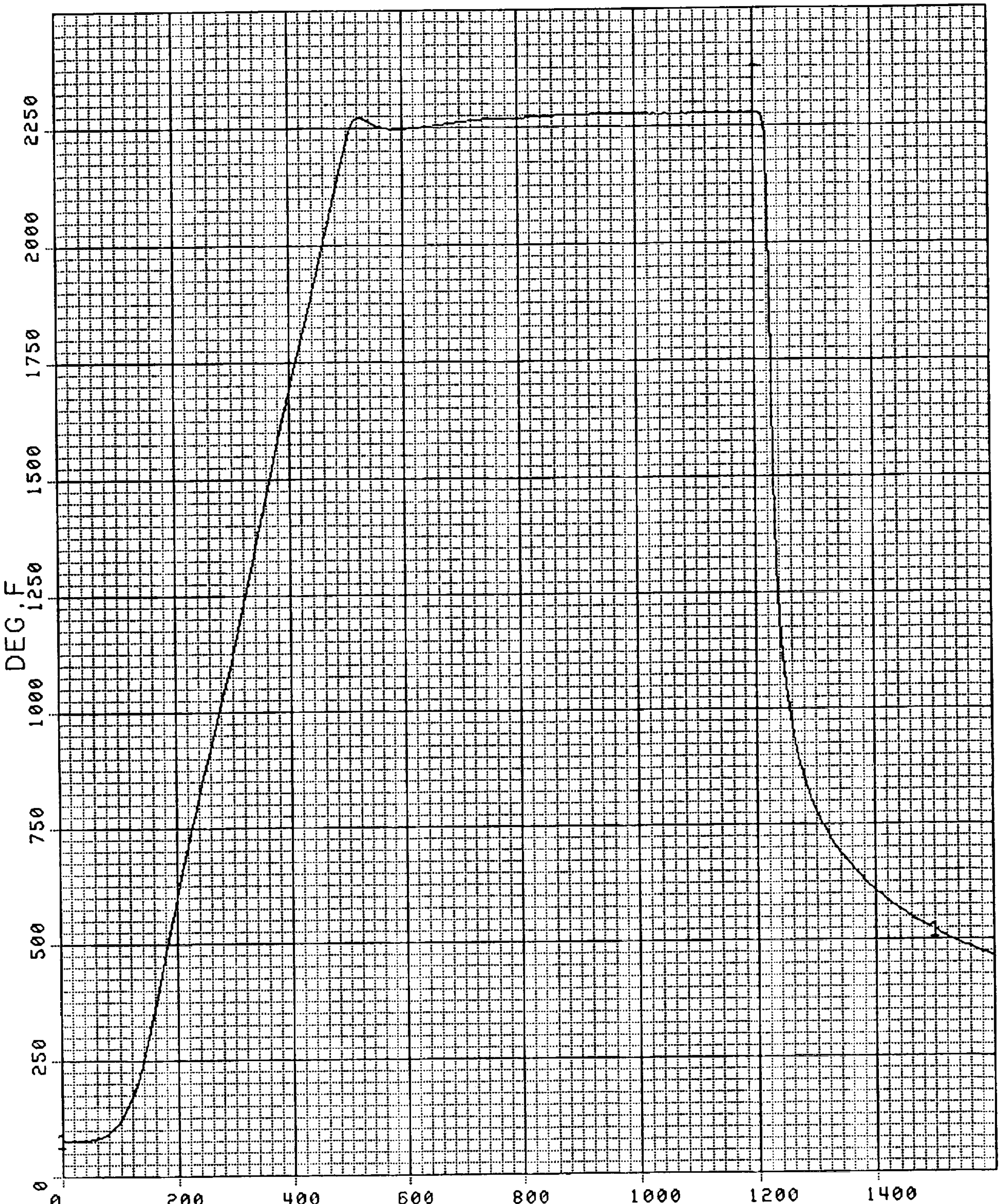
# FR12-TC1 CHANNEL NO. 22




CONTROL TILE SURFACE TEMPERATURE - TEST CYCLE #1 - HRSI 2

KSC COATING FRIT 2300 DEG.F TEST CYC.# 10 92223R01 ROD6
DATE = 8/10/92 AVERAGE INTERVAL 5.0 SEC TIME = 16:57:30.4 TO 17:32:40.4
PROCESSING DATE 9/ 9/92

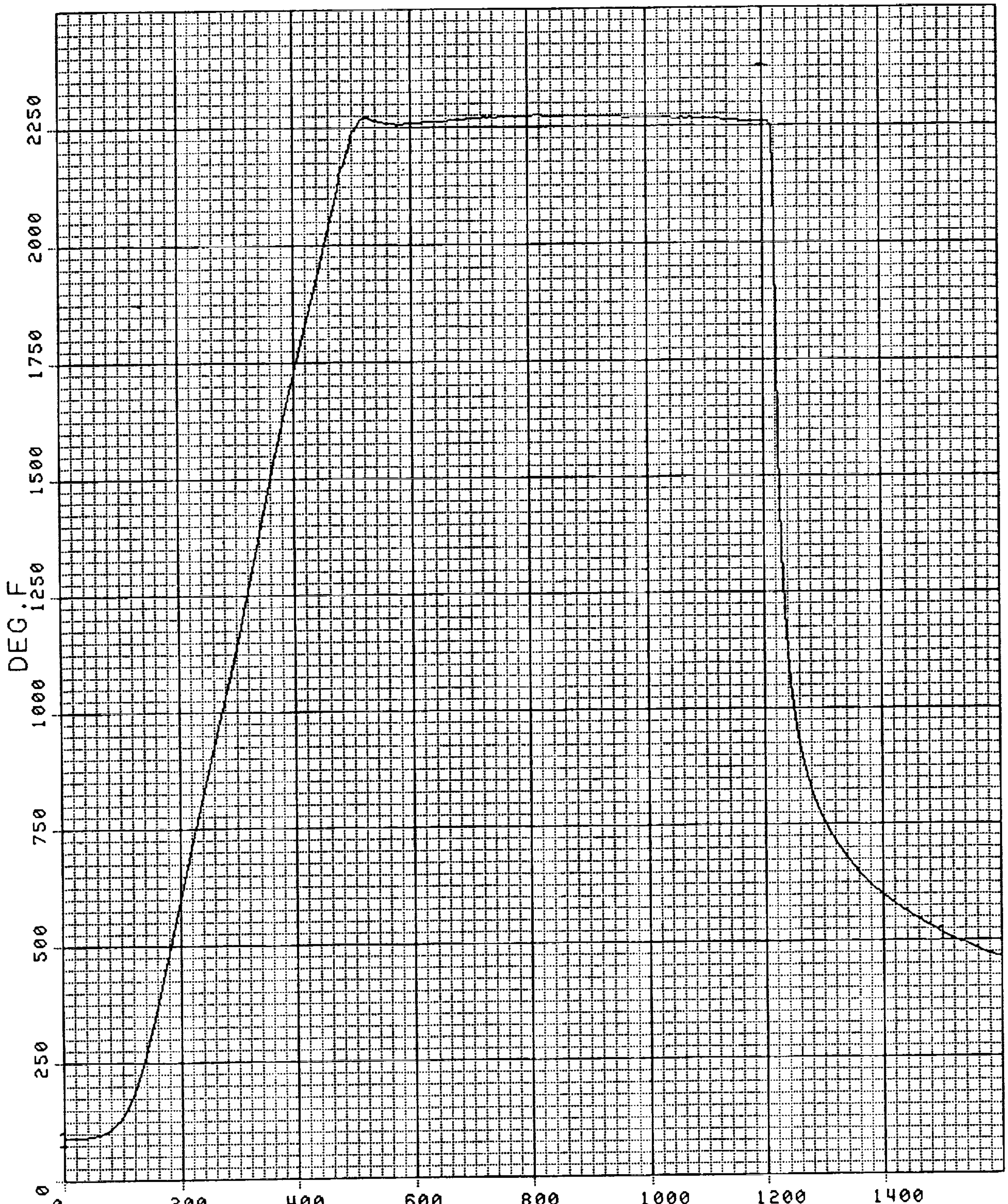
# FR12-TC1 CHANNEL NO. 22




CONTROL TILE SURFACE TEMPERATURE - TEST CYCLE #10 - HRSI 2

KSC COATING FRIT 2300 DEG.F TEST CYC.#25 92227R03 ROD6
DATE = 8/14/92 AVERAGE INTERVAL 5.0 SEC TIME = 20:54: 7.7 TO 21:29:17.7
PROCESSING DATE 9/ 9/92

# FR12-TC1 CHANNEL NO. 22



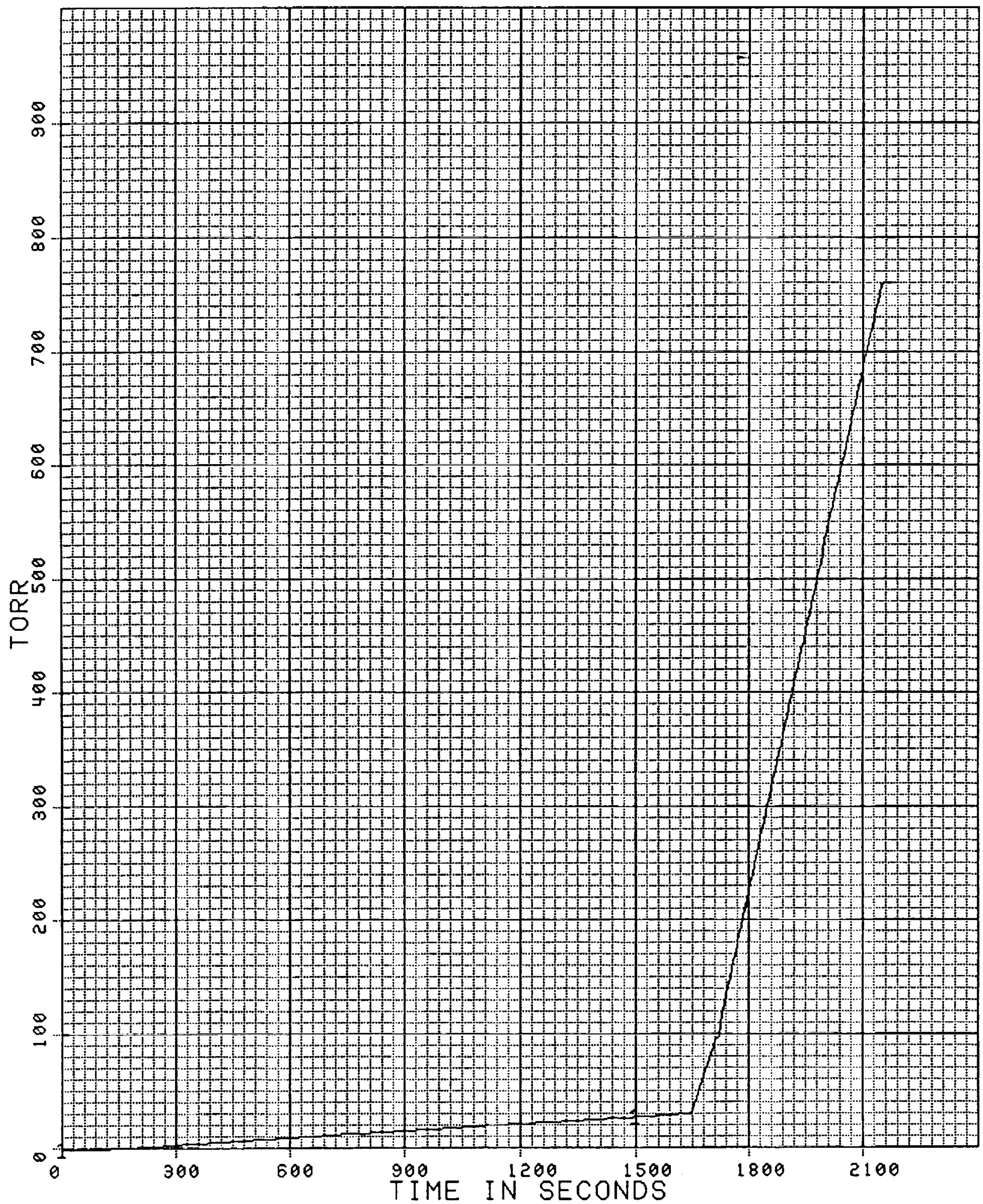

CONTROL TILE SURFACE TEMPERATURE - TEST CYCLE # 25 - HRSI 2

# Appendix A-2

Typical Surface Pressures
(Radiant Heat Test)

KSC COATING FRIT 1200 DEG.F TEST CYCLE#1 92233R01 RDC # 3
DATE = 8/20/92 AVERAGE INTERVAL 5.0 SEC TIME = 19: 9: 3.6 TO 19:45:18.6
PROCESSING DATE 9/ 9/92

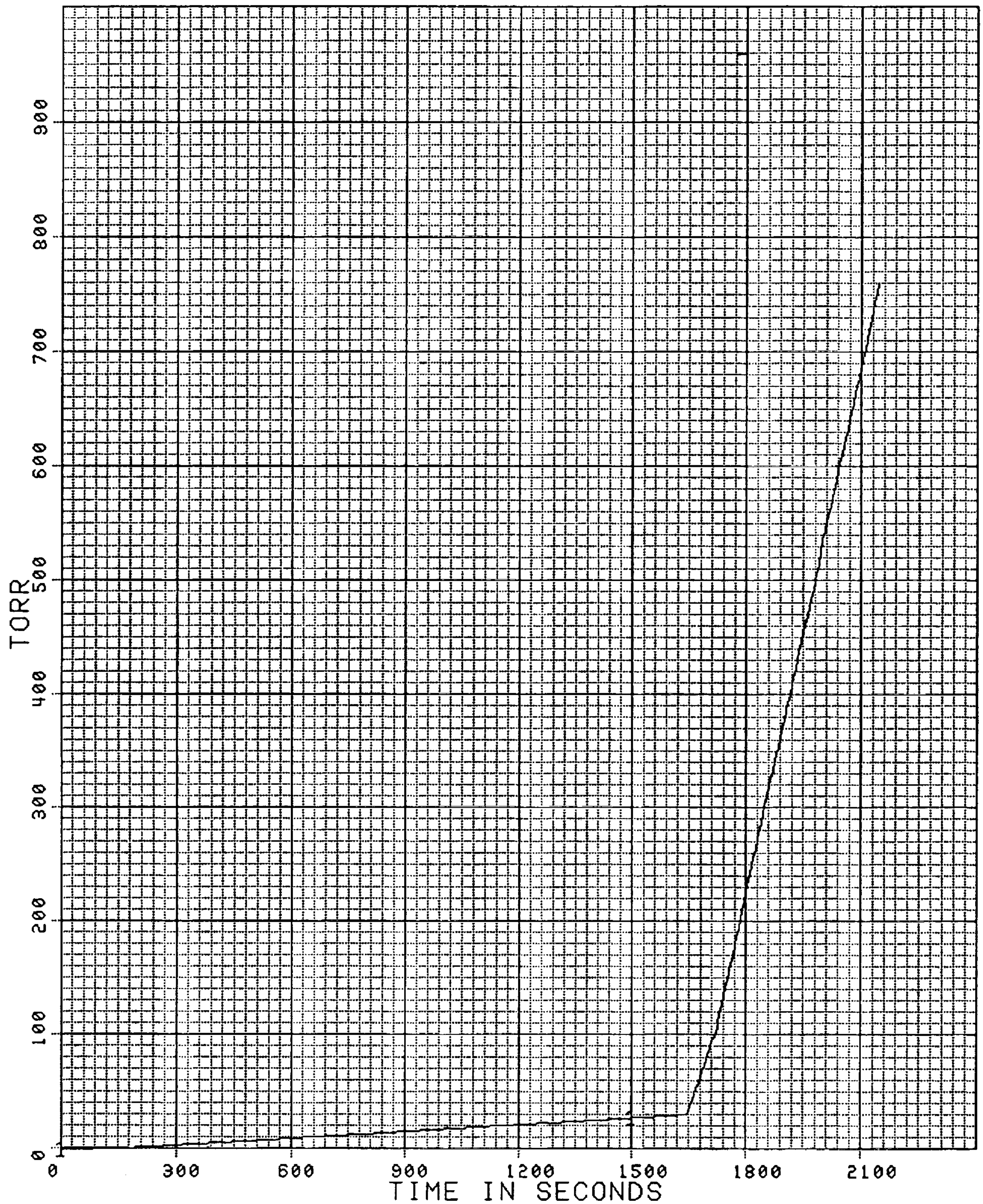
# VACUUM CHANNEL NO. 1




CHAMBER PRESSURE - TEST CYCLE # 1 - LRSI 1

KSC COATING FRIT 1200 DEG.F TEST CYCLE#10 92237R04 RDC # 3
DATE = 8/24/92 AVERAGE INTERVAL 5.0 SEC TIME = 22:31:38.2 TO 23: 7:23.2
PROCESSING DATE 9/ 9/92

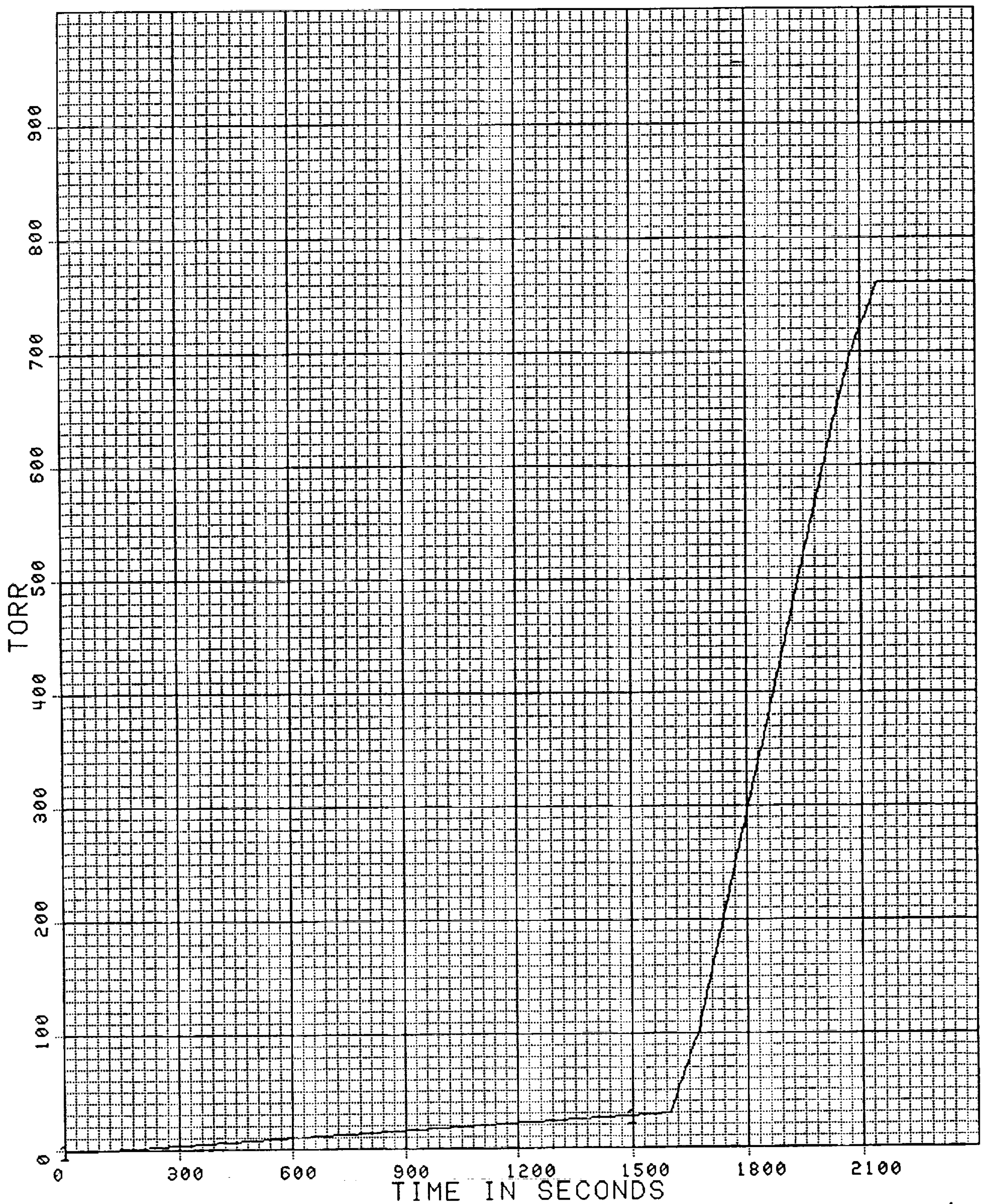
# VACUUM CHANNEL NO. 1




CHAMBER PRESSURE - TEST CYCLE # 10 - LRSI 1

SRHTF. KSC COATING FRIT 2300 DEG.F TEST CYC#1 92217R01 RCD6
DATE = 8/ 4/92 AVERAGE INTERVAL 5.0 SEC TIME = 23: 7:31.9 TO 23:47:46.9
PROCESSING DATE 9/ 9/92

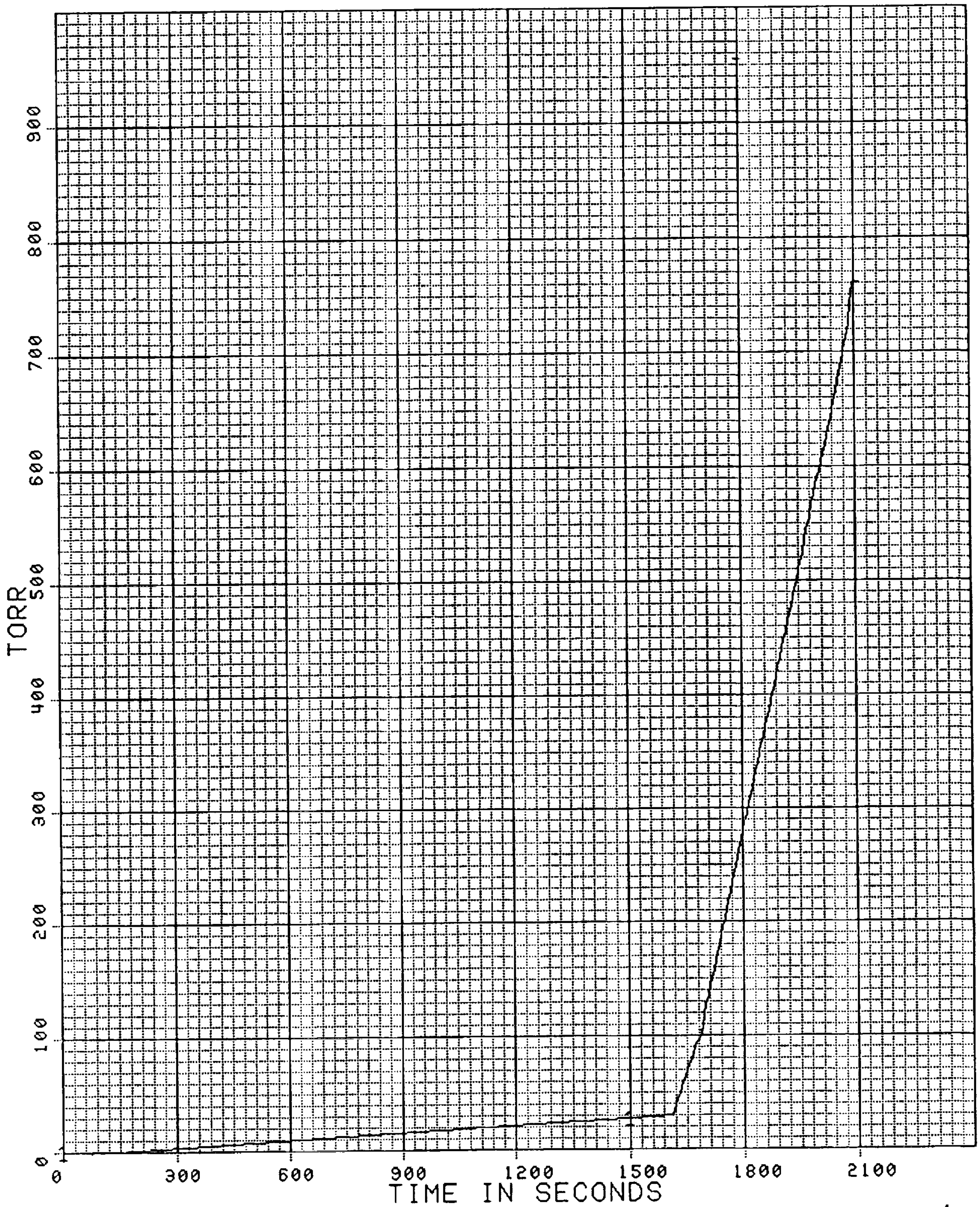
# VACUUM CHANNEL NO. 1




CHAMBER PRESSURE - TEST CYCLE #1 - HRSI 1

KSC COATING FRIT 2300 DEG.F TEST CYC.# 10 92223R01 ROD6
DATE = 8/10/92 AVERAGE INTERVAL 5.0 SEC TIME = 16:57:30.4 TO 17:32:40.4
PROCESSING DATE 9/ 9/92

# VACUUM CHANNEL NO. 1

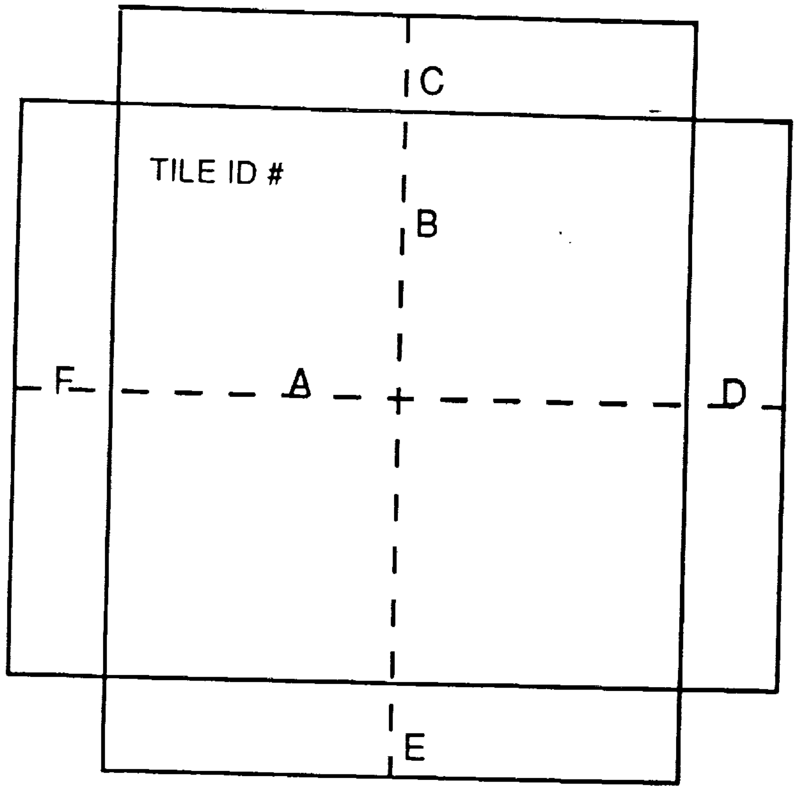



CHAMBER PRESSURE - TEST CYCLE #10 - HRSI 1

# Appendix A-3

Specimen Dimensions
(Radiant Heat Test)

# KSC TILE DATA SHEET




ID # 794-165-1 DATE: 7-23-92 INITIALS [illegible]

DATE: 8-28-92 (POST-TEST)

COMMENTS: ____________________

| PRE-TEST | | POST-TEST | |
|---|---|---|---|
| A | 8.017 | A | 8.016 |
| B | 8.019 | B | 8.018 |
| C | 1.002 | C | 1.000 |
| D | 1.003 | D | 1.002 |
| E | 1.001 | E | 1.001 |
| F | 1.003 | F | 1.002 |

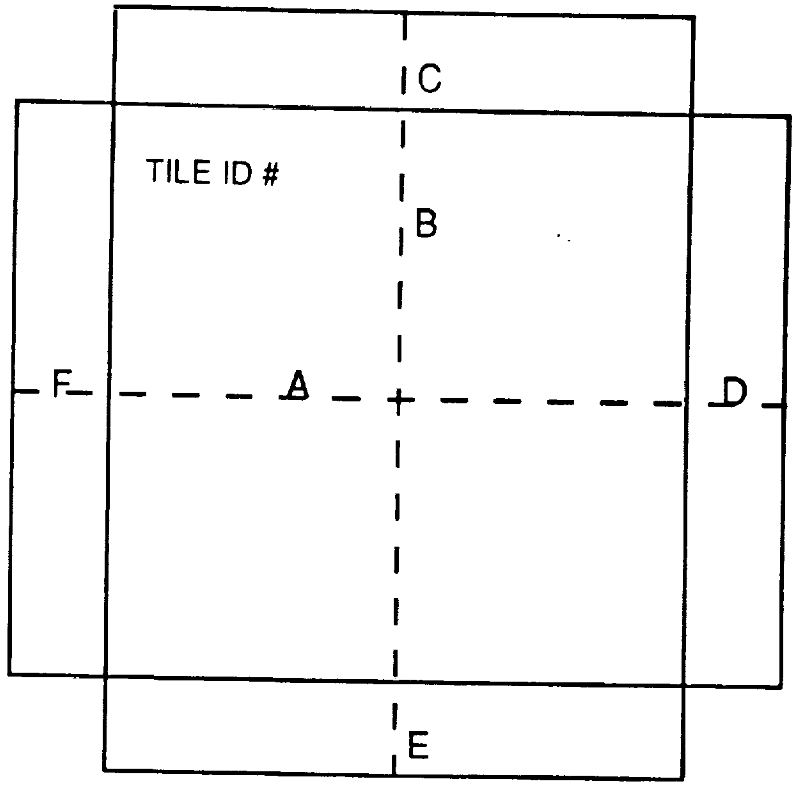
7-23-92

8-28-92

TABLE 2

TPS GT9220003
Page 3 of 3 (15 ea)

# KSC TILE DATA SHEET




ID # 794-165 2 DATE: 7 23 92 INITIALS Max

DATE: 8·28·92 (POST-TEST)

COMMENTS: ______________________

| PRE-TEST | | POST-TEST | |
|---|---|---|---|
| A | 8.020 | A | 8.020 |
| B | 8.021 | B | 8.021 |
| C | .998 | C | .998 |
| D | .999 | D | .998 |
| E | .999 | E | .999 |
| F | .998 | F | .997 |

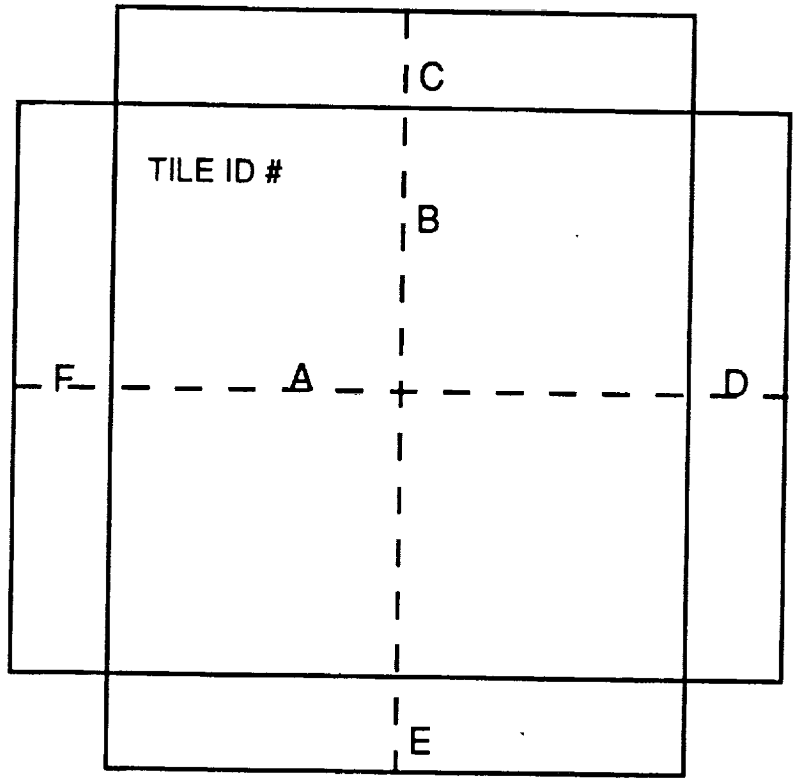
FORD 25 7-23-92

8·28·92

TABLE 2

TPS GT9220003
Page 3 of 3 (15 ea)

# KSC TILE DATA SHEET




ID # 794-165-3R DATE: 8-17-92 INITIALS Max

DATE: 8-28-92 (POST-TEST)

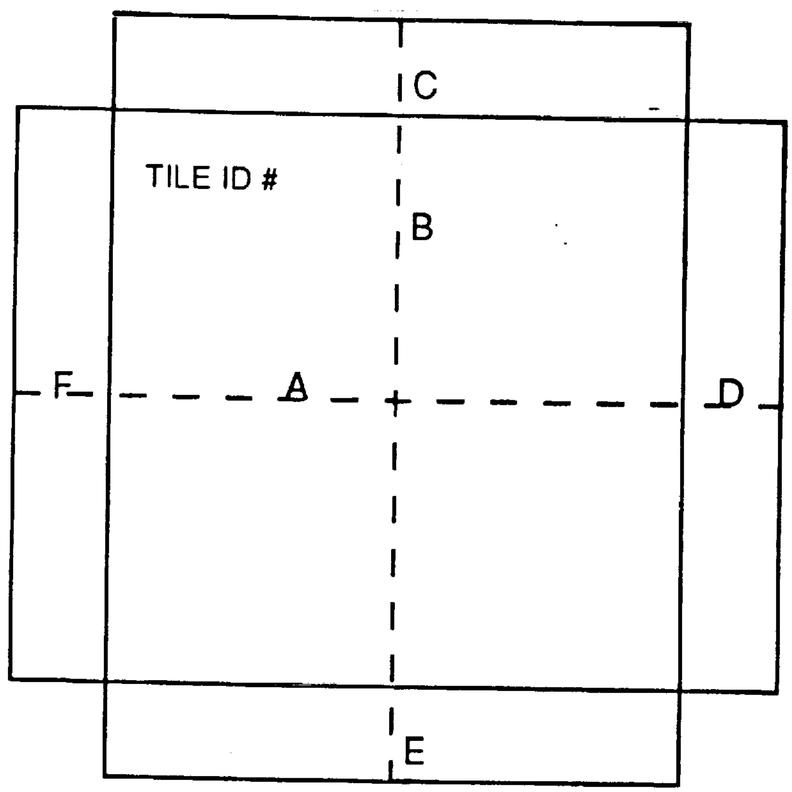
COMMENTS: ______________________

| | PRE-TEST | POST-TEST |
|---|---|---|
| A | 8.008 | 8.007 |
| B | 8.012 | 8.007 |
| C | 1.002 | 1.000 |
| D | 1.001 | .999 |
| E | 1.001 | 1.000 |
| F | 1.001 | 1.000 |

TABLE 2

TPS GT9220011
Page 3 of 4

# KSC TILE DATA SHEET




ID # 794-1654 DATE: 7-23-92 INITIALS Max

DATE: 8-28-92 (POST-TEST)

COMMENTS: ______________________________

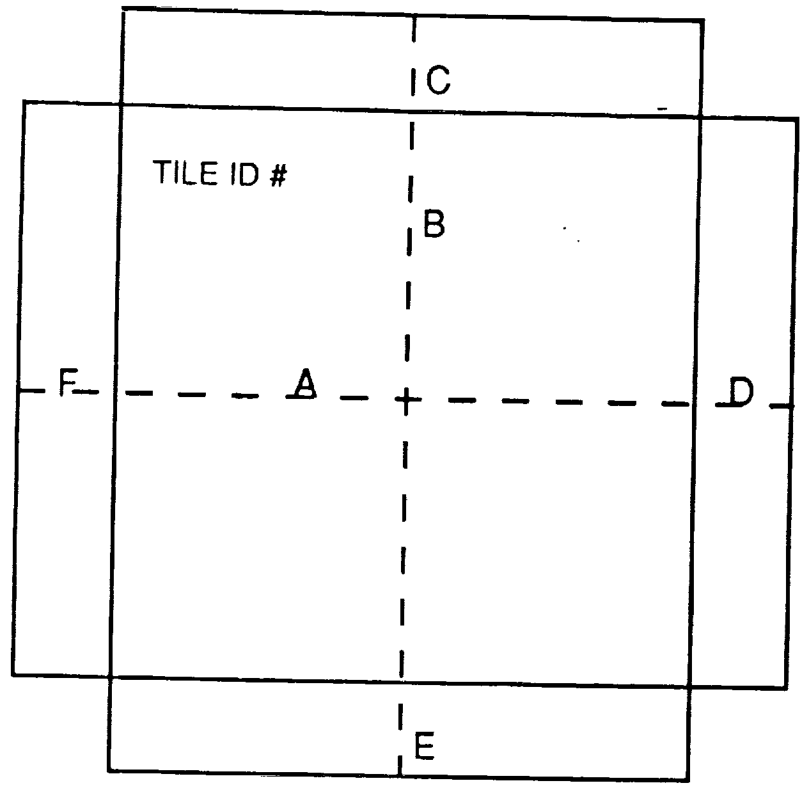
| PRE-TEST | | POST-TEST | |
|---|---|---|---|
| A | 8 022 | A | 8.023 |
| B | 8.022 | B | 8.021 |
| C | 1.004 | C | 1.003 |
| D | 1.002 | D | 1.002 |
| E | 1.002 | E | 1.002 |
| F | 1002 | F | 1.001 |

FORD 25
7-23-92

TABLE 2

TPS GT9220003
Page 3 of 3 (15 ea)

# KSC TILE DATA SHEET




ID # 794-165-5 DATE: 7-23-92 INITIALS Max

DATE: 8-28-92 (POST-TEST)

COMMENTS: ______________________________

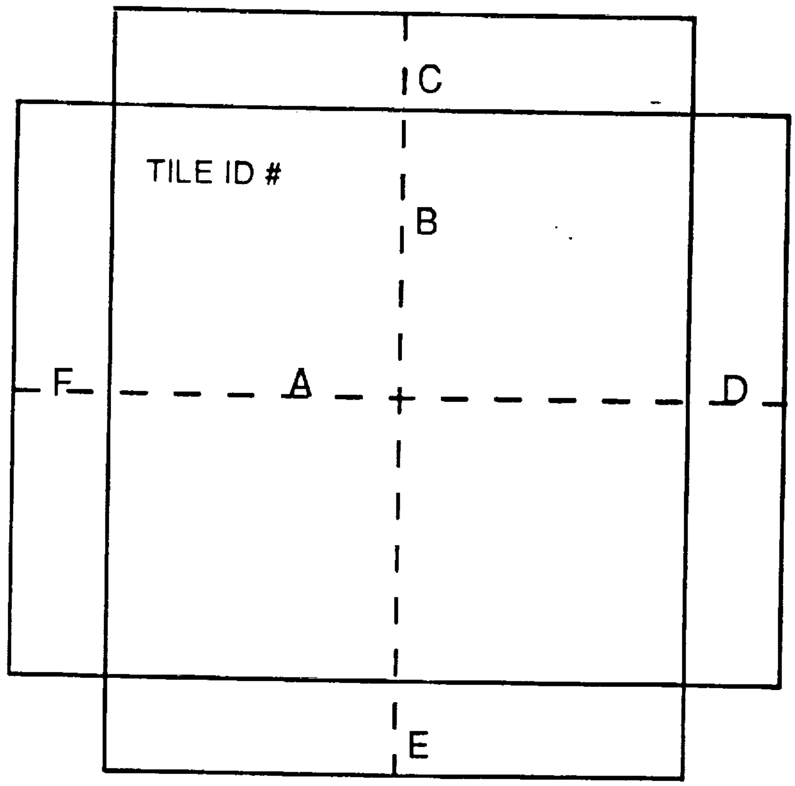
| PRE-TEST | | POST-TEST | |
|---|---|---|---|
| A | 8.023 | A | 8.021 |
| B | 8.022 | B | 8.021 |
| C | 1.004 | C | 1.002 |
| D | 1.005 | D | 1.005 |
| E | 1.004 | E | 1.003 |
| F | 1.004 | F | 1.002 |

FORD 25
7-23-92

TABLE 2

TPS GT9220003
Page 3 of 3 (15 ea)

# KSC TILE DATA SHEET




ID # 794-165-6 DATE: 7-23-92 INITIALS Max

DATE: 8-28-92 (POST-TEST)

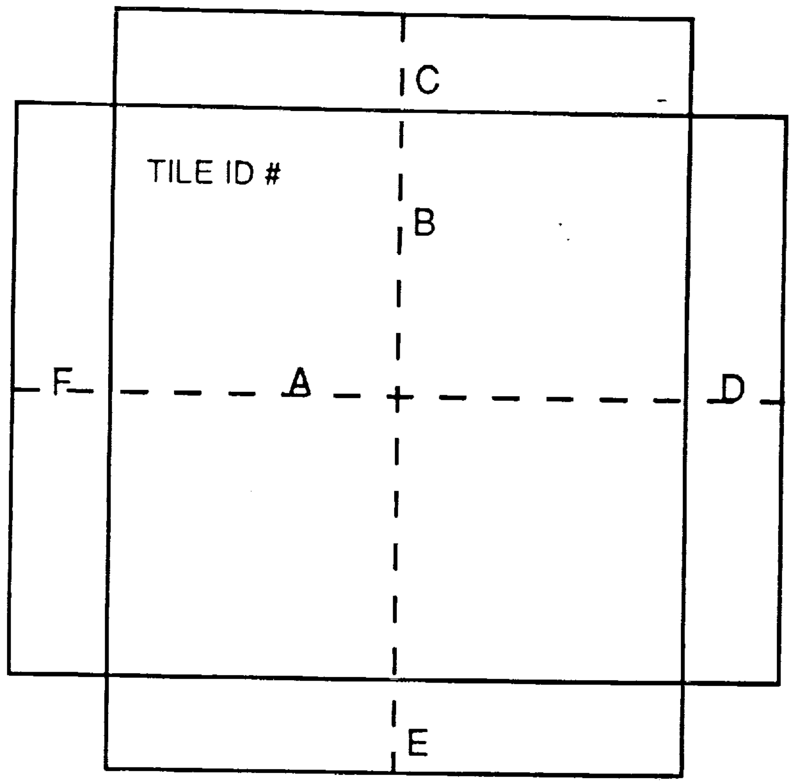
COMMENTS: ____________________

| PRE-TEST | | POST-TEST | |
|---|---|---|---|
| A | 8 016 | A | 8.015 |
| B | 8017 | B | 8.016 |
| C | 1002 | C | 1.000 |
| D | 1005 | D | 1.003 |
| E | 1002 | E | 1.002 |
| F | 1005 | F | 1.003 |

7-23-92

TABLE 2

# KSC TILE DATA SHEET




ID # 1-9-051 DATE: 7-23-92 INITIALS Max

DATE: 8.14.92 (POST-TEST)

COMMENTS: ______

| | PRE-TEST | POST-TEST |
|---|---|---|
| A | 6.011 | 6.011 |
| B | 6.012 | 6.013 |
| C | 2.003 | 1.999 |
| D | 2.003 | 2.000 |
| E | 2.002 | 2.000 |
| F | 2.003 | 2.001 |

FORD 25 7 23 92

FORD 23 8.14.92

TABLE 2

TPS GT9220003
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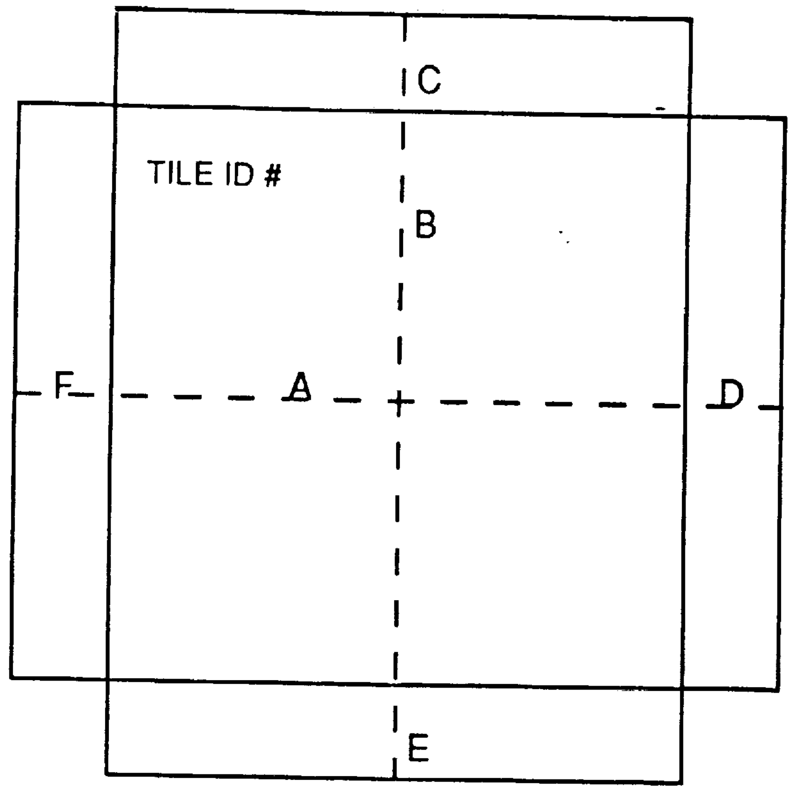
# KSC TILE DATA SHEET




ID # 2-9-143 DATE: 2-23-92 INITIALS Max

DATE: 8-14-92 (POST-TEST)

COMMENTS: ____________________

FORD 25 7-23-92

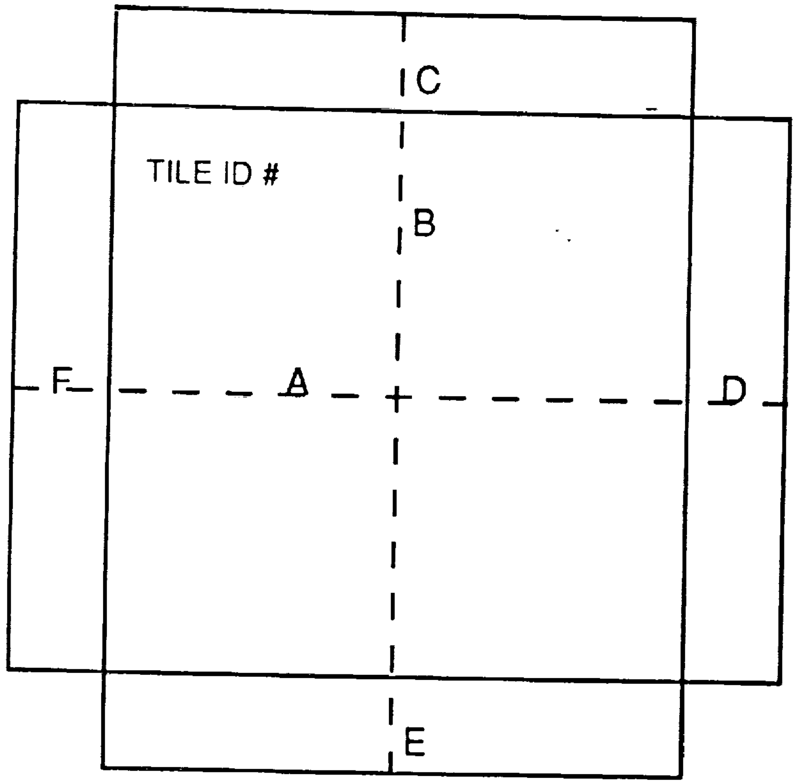
| PRE-TEST | |
|---|---|
| A | 6.012 |
| B | 6.010 |
| C | ~~2.008~~ 2.003 |
| D | 2.001 |
| E | 2.003 |
| F | 2.004 |

FORD 8-14-92

| POST-TEST | |
|---|---|
| A | 6.008 |
| B | 6.006 |
| C | 2.001 |
| D | 2.000 |
| E | 2.000 |
| F | 2.000 |

TABLE 2

# KSC TILE DATA SHEET




ID # 3-9-047 DATE: 7-23-92 INITIALS Max

DATE: 8-14-92 (POST-TEST)

COMMENTS: ________________________________

| | PRE-TEST | POST-TEST |
|---|---|---|
| A | 6.010 | 6.007 |
| B | 6.007 | 6.008 |
| C | 2.002 | 2.000 |
| D | 2.002 | 1.997 |
| E | 2.003 | 1.999 |
| F | 2.001 | 1.999 |

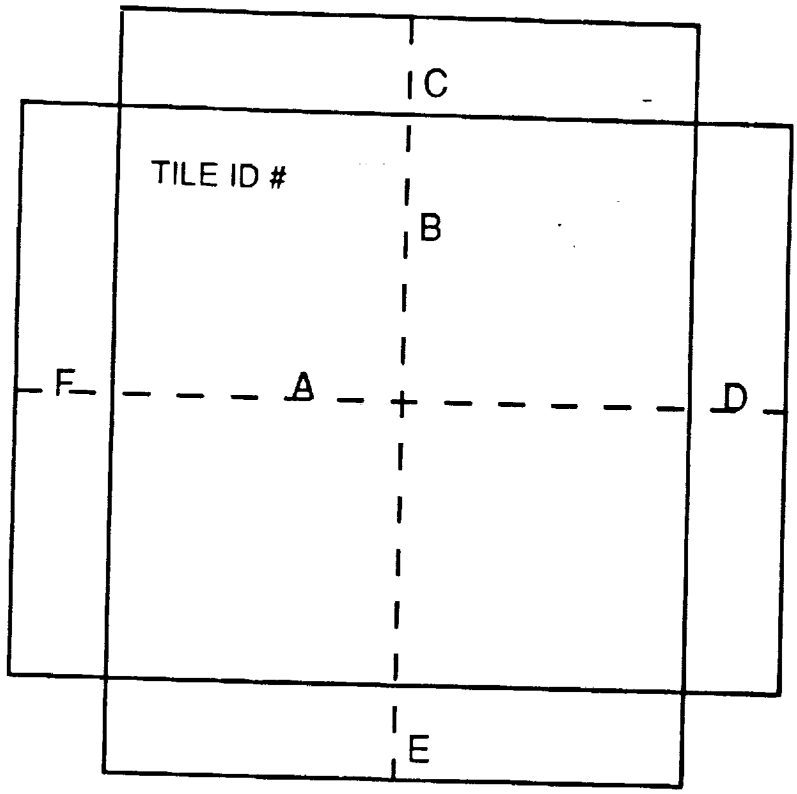
FORD 25 7-23-92

8-14-92

TABLE 2

TPS GT9220003
Page 3 of 3 (15 ea)

KSC TILE DATA SHEET




ID # 4-12-047 DATE: 7-23-92 INITIALS Max

DATE: 8-14-92 (POST-TEST)

COMMENTS: ____________________

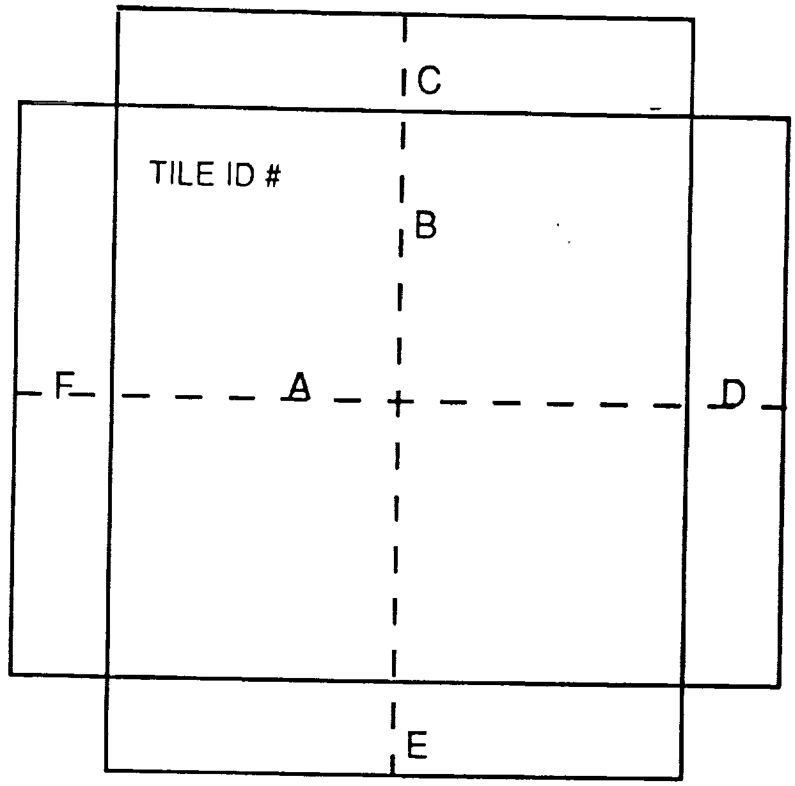
| PRE-TEST | | POST-TEST | |
|---|---|---|---|
| A | 6.012 | A | 6.010 |
| B | 6.011 | B | 6.008 |
| C | 2.003 | C | 1.999 |
| D | 2.003 | D | 1.999 |
| E | 2.002 | E | 2.000 |
| F | 2.003 | F | 2.000 |

FORD 25 7-23-92

8-14-92

TABLE 2

# KSC TILE DATA SHEET




ID # 6-12-051 DATE: 7 23 92 INITIALS Max

DATE: 8-14-92 (POST-TEST)

COMMENTS: ______________________

| PRE-TEST | | POST-TEST | |
|---|---|---|---|
| A | 6.011 | A | 6.010 |
| B | 6.012 | B | 6.011 |
| C | 2.004 | C | 2.000 |
| D | 2.004 | D | 1.999 |
| E | 2.001 | E | 1.996 |
| F | 2.004 | F | 2.000 |

FORD 25 7.23.92

8.14.92

TABLE 2

TPS GT9220003
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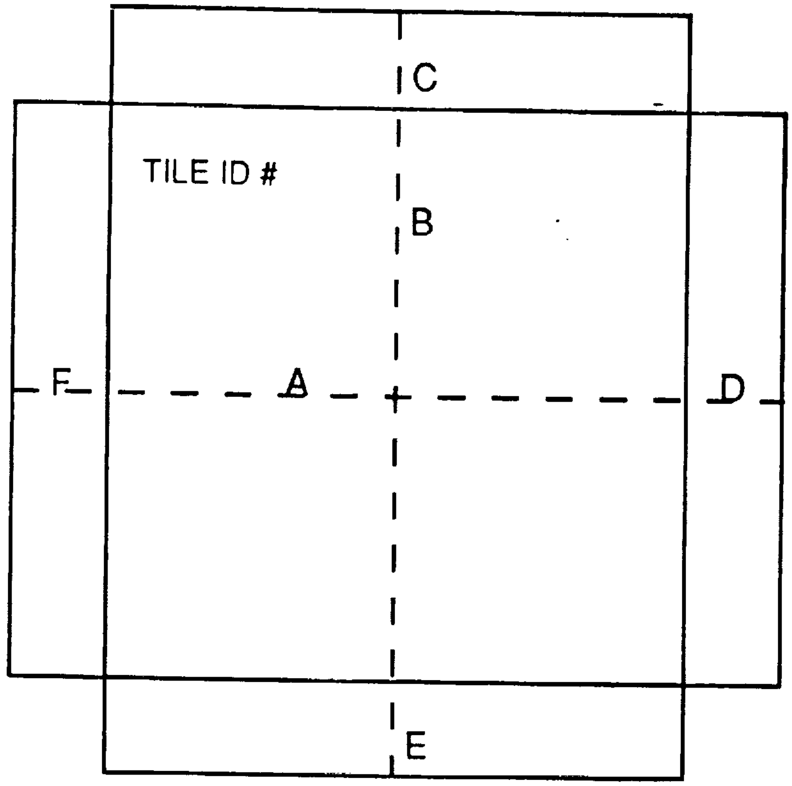
# KSC TILE DATA SHEET




ID # 7-22-047 DATE: 7-23-92 INITIALS Max

DATE: 8-14-92 (POST-TEST)

COMMENTS:

| PRE-TEST | | POST-TEST | |
|---|---|---|---|
| A | 6.020 | A | 6.020 |
| B | 6.021 | B | 6.020 |
| C | 1.999 | C | 1.998 |
| D | 2.002 | D | 2.001 |
| E | 2.002 | E | 2.002 |
| F | 2.000 | F | 2.001 |

FORD 25

8-14-92

TABLE 2

TPS GT9220003
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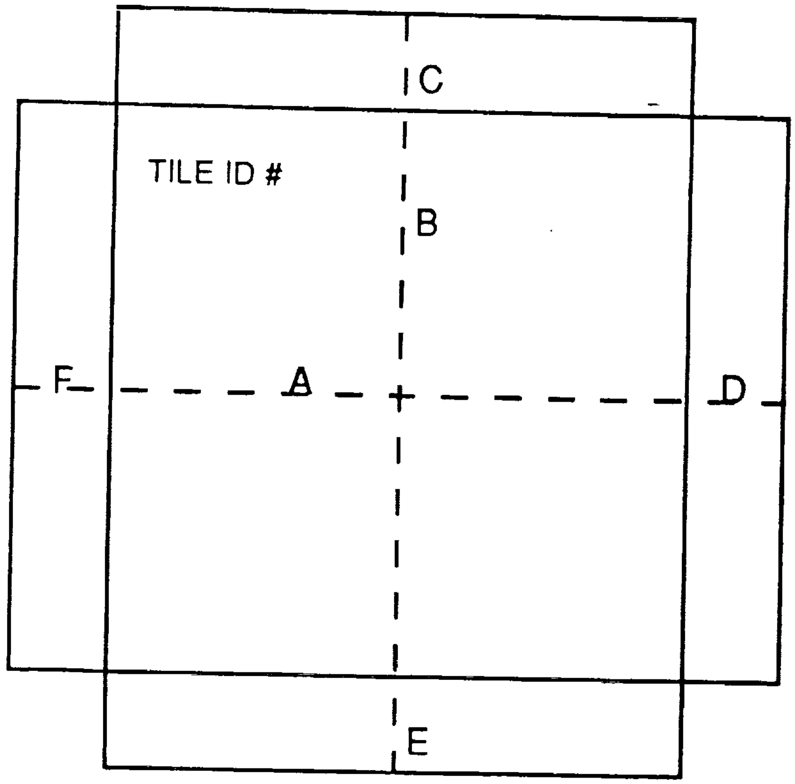
## KSC TILE DATA SHEET




ID # 8-22-143 DATE: 7-23-92 INITIALS Max

DATE: 8-14-92 (POST-TEST)

COMMENTS: ______________________

| PRE-TEST | | POST-TEST | |
|---|---|---|---|
| A | 6.022 | A | 6.022 |
| B | 6.025 | B | 6.022 |
| C | 2.002 | C | 2.000 |
| D | 2.002 | D | 2.000 |
| E | 2.003 | E | 2.002 |
| F | 2.003 | F | 2.001 |

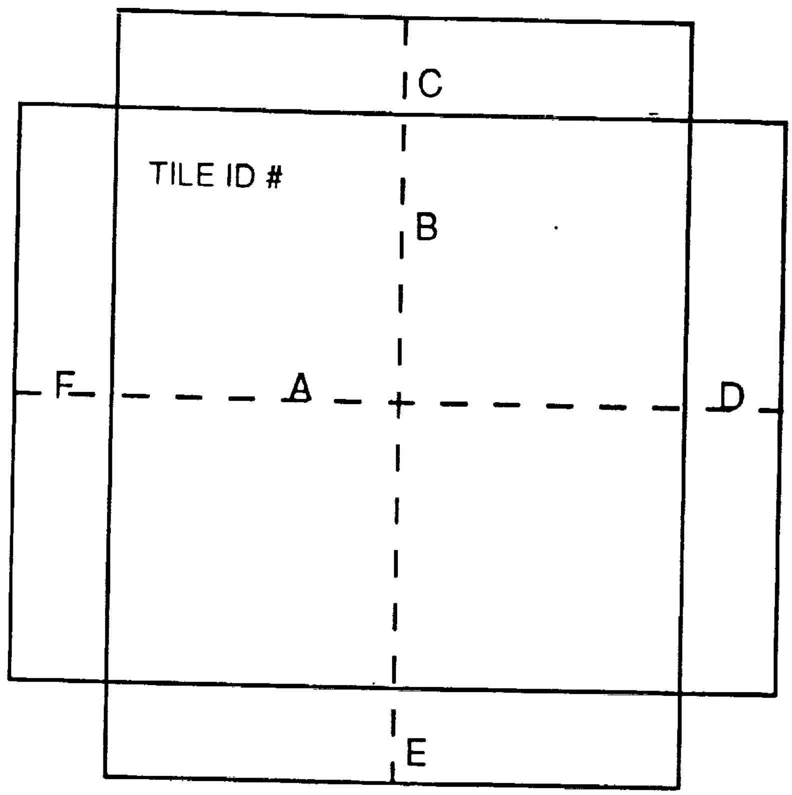
FORD 25 7-23-92

8-14-92

TABLE 2

TPS GT9220003
Page 3 of 3 (15 ea)

# KSC TILE DATA SHEET




ID # 9-22051 DATE: 7 23 92 INITIALS Max

DATE: 8 14 92 (POST-TEST)

COMMENTS: ______________________

| PRE-TEST | | POST-TEST | |
|---|---|---|---|
| A | 6.023 | A | ~~6.027~~ 6.021 |
| B | 6.022 | B | 6.023 |
| C | 2.001 | C | 1.999 |
| D | 2.001 | D | 2.000 |
| E | 2.001 | E | 2.001 |
| F | 2.001 | F | 1.999 |

FORD 25 7-23-92

FOR 23 8 14 92

TABLE 2



TPS GT9220003
Page 3 of 3 (15 ea)

# Appendix A-4

Specimen Weights
(Radiant Heat Test)

## KSC TILE WEIGHTS

| TILE ID | PRE-TEST WEIGHT | POST-TEST WEIGHT |
|---|---|---|
| 794-165-4 | 237.95 | 237.69 |
| 794-165-5 | 253.21 | 252.99 |
| 794-165-6 | 241.08 | 240.90 |
| 794-165-1 | 181.42 | 181.29 |
| 794-165-2 | 179.18 | 179.04 |
| 794-165-3R | 174.69 | 174.48 |
| 4-12-047 | 281.46 | 281.21 |
| 6-12-051 | 260.61 | 260.36 |
| 1-9-051 | 203.37 | 203.17 |
| 2-9-143 | 204.27 | 204.14 |
| 3-9-047 | 195.63 | 195.56 |
| 7-22-047 | 472.54 | 472.11 |
| 8-22-143 | 462.96 | 462.57 |
| 9-22-051 | 472.67 | 472.37 |

COMMENTS: The unit is in GRAM

TPS GT9220003
Page 2 of 3


11-5-92

# Appendix A-5

Specimen Reflectivities
(Radiant Heat Test)

## KSC TILE REFLECTIVITY MEASUREMENTS

| TILE ID | PRE-TEST | POST-TEST |
|---|---|---|
| 794-165-4 | 0.149 | 0.149 |
| 794-165-5 | 0.148 | 0.145 |
| 794-165-6 | 0.144 | 0.140 |
| 794-165-1 | 0.145 | 0.147 |
| 794-165-2 | 0.151 | 0.148 |
| 794-165-3R | 0.143 | 0.139 |
| 4-12-047 | 0.153 | 0.161 |
| 6-12-051 | 0.145 | 0.156 |
| 1-9-051 | 0.146 | 0.160 |
| 2-9-143 | 0.146 | 0.161 |
| 3-9-047 | 0.153 | 0.157 |
| 7-22-047 | 0.151 | 0.158 |
| 8-22-143 | 0.149 | 0.155 |
| 9-22-051 | 0.147 | 0.158 |

FORD
25
11-5-92

COMMENTS: ______

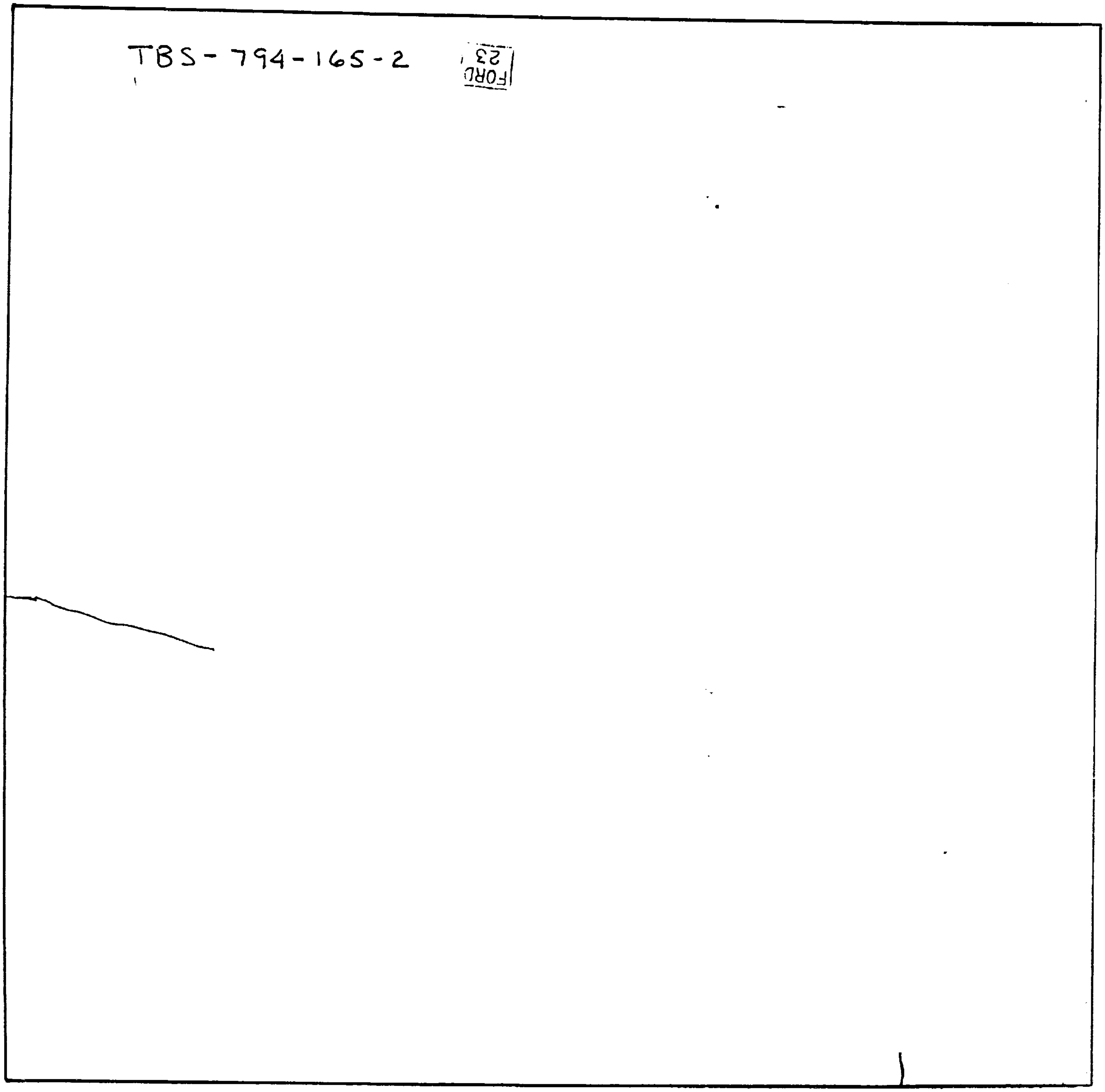
TPS GT9220004
Page 2 of 2

# Appendix A-6

Specimen Crack Maps
(Radiant Heat Test)

# KSC COATED TILE

## CRACK MAP




ID# 794-165-2

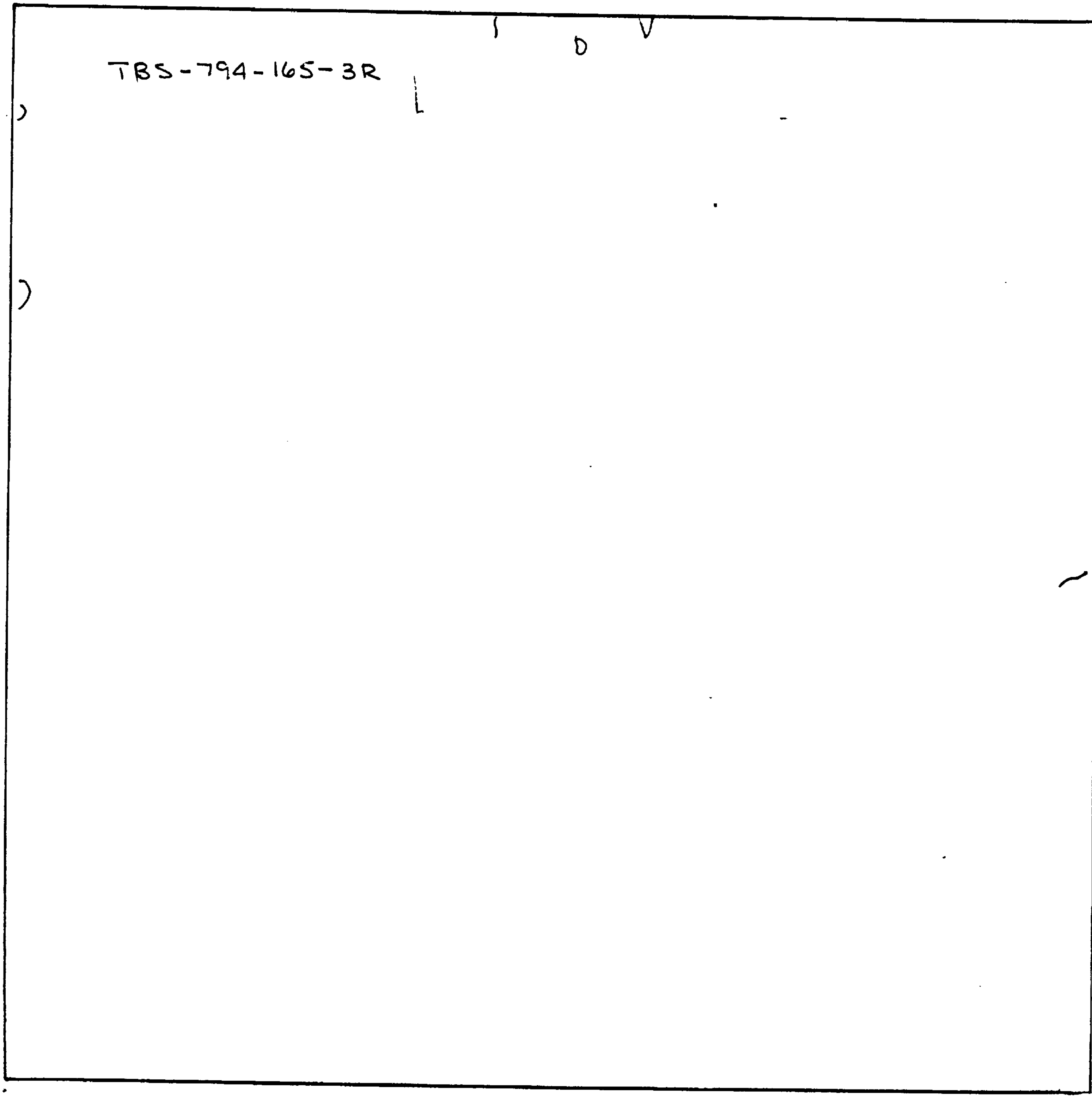
DATE: 8-28-92

CYCLES 26

TPS REF: GT922000S

# KSC COATED TILE

CRACK MAP




ID# 794-165-3R

DATE: 8-28-92

CYCLES 26

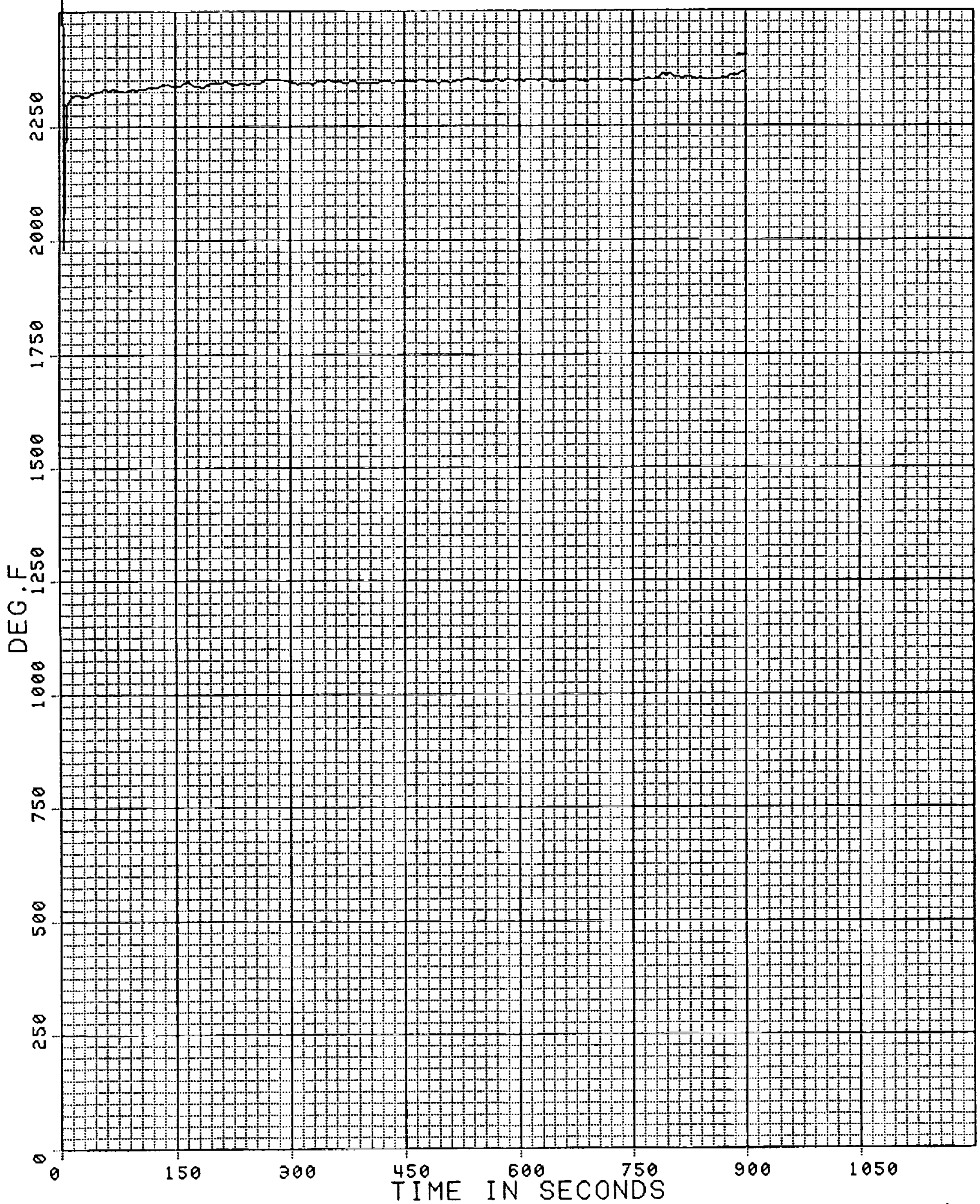
TPS REF: GT9220005

# Appendix B-1

Typical Surface Temperature Responses
(Convective Heat Test)

1-548-DD PROCESSING DATE 09/28/92
DATE = 9/15/92 AVERAGE INTERVAL 5.0 SEC TIME = 18:15:12.6 TO 18:30:17.9
ARMSEF KSC COATING FRIT L/A 10-9-047 R/A 11-9-143

# L PYRO C CHANNEL NO. 26

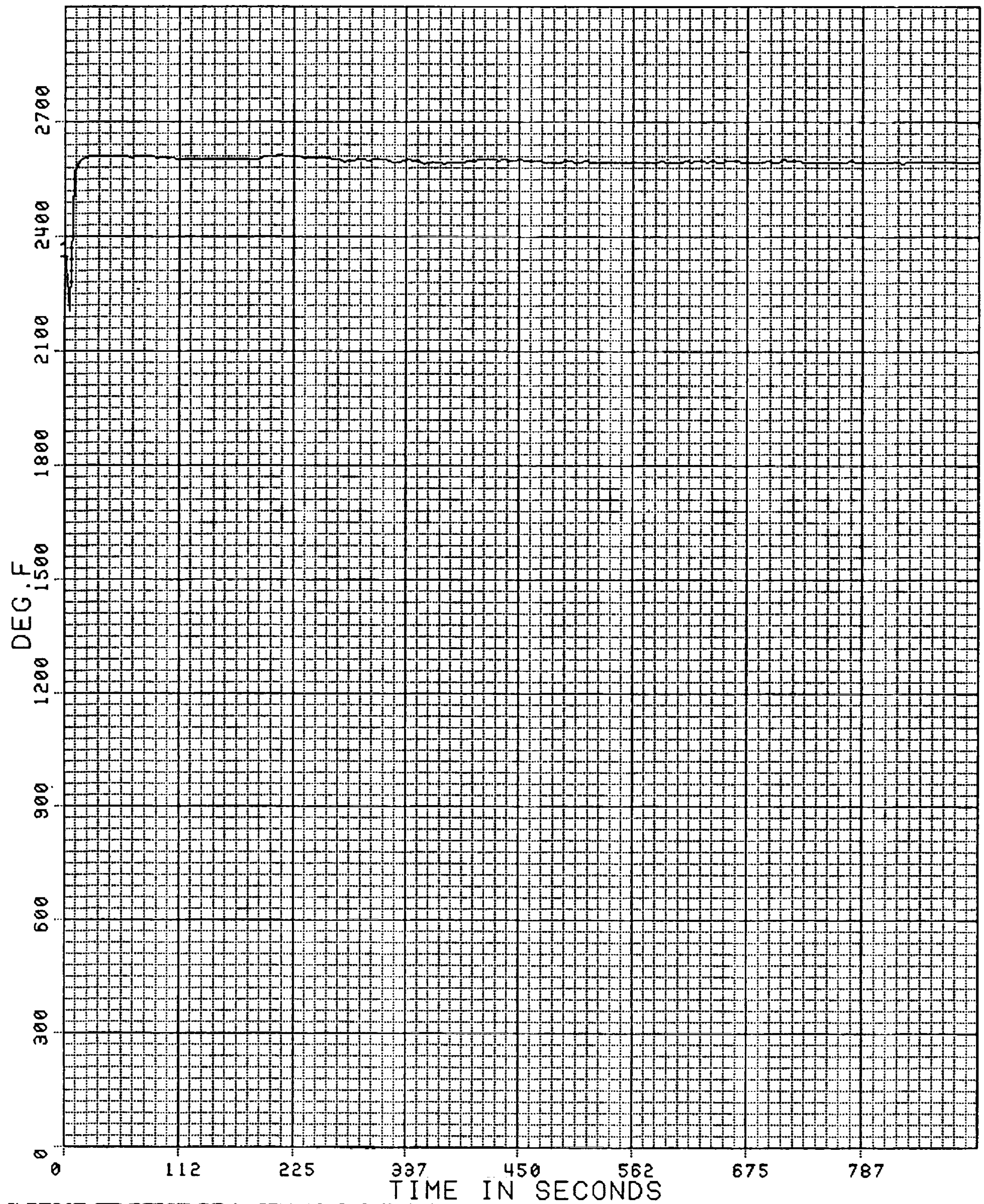



SURFACE TEMPERATURE L ARM 10-9-047 CYCLE # 1 1

1-552-DD
DATE = 9/24/92 AVERAGE INTERVAL 5.0 SEC TIME = 22:34:50.9 TO 22:54:51.1
ARMSEF KSC FRIT L/A 10-9-047 & R/A 11-9-143

PROCESSING DATE 11/05/92

# L PYRO C CHANNEL NO. 26

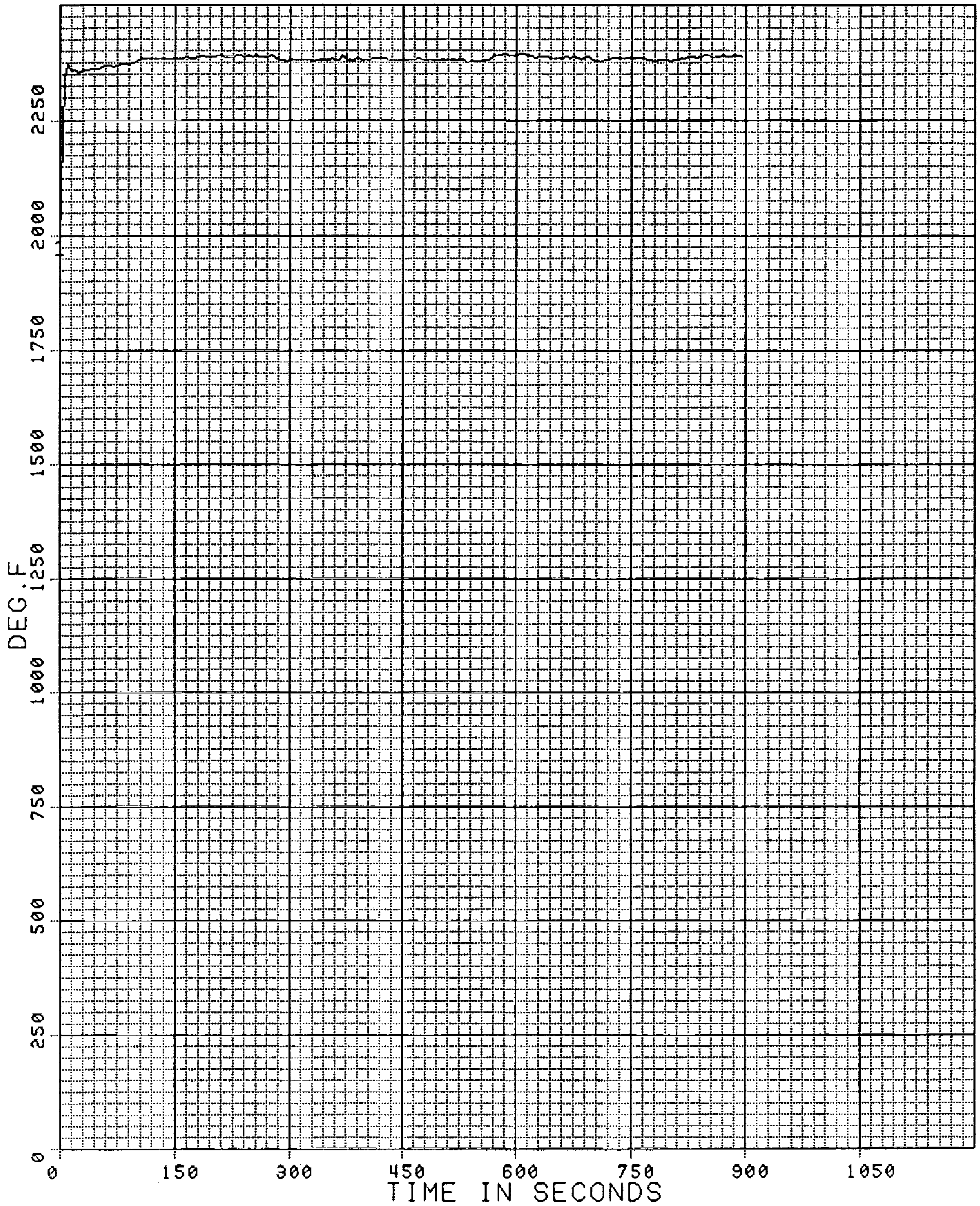



SURFACE TEMPERATURE L ARM 10-9-047 CYCLE # 6

1

1-548-DD PROCESSING DATE 09/16/92
DATE = 9/15/92 AVERAGE INTERVAL 5.0 SEC TIME = 18:31:47.7 TO 18:46:47.7
ARMSEF KSC COATING FRIT 2300 DEG.F L/A 10-9-047 R/A 11-9-143

# L PYRO C CHANNEL NO. 26

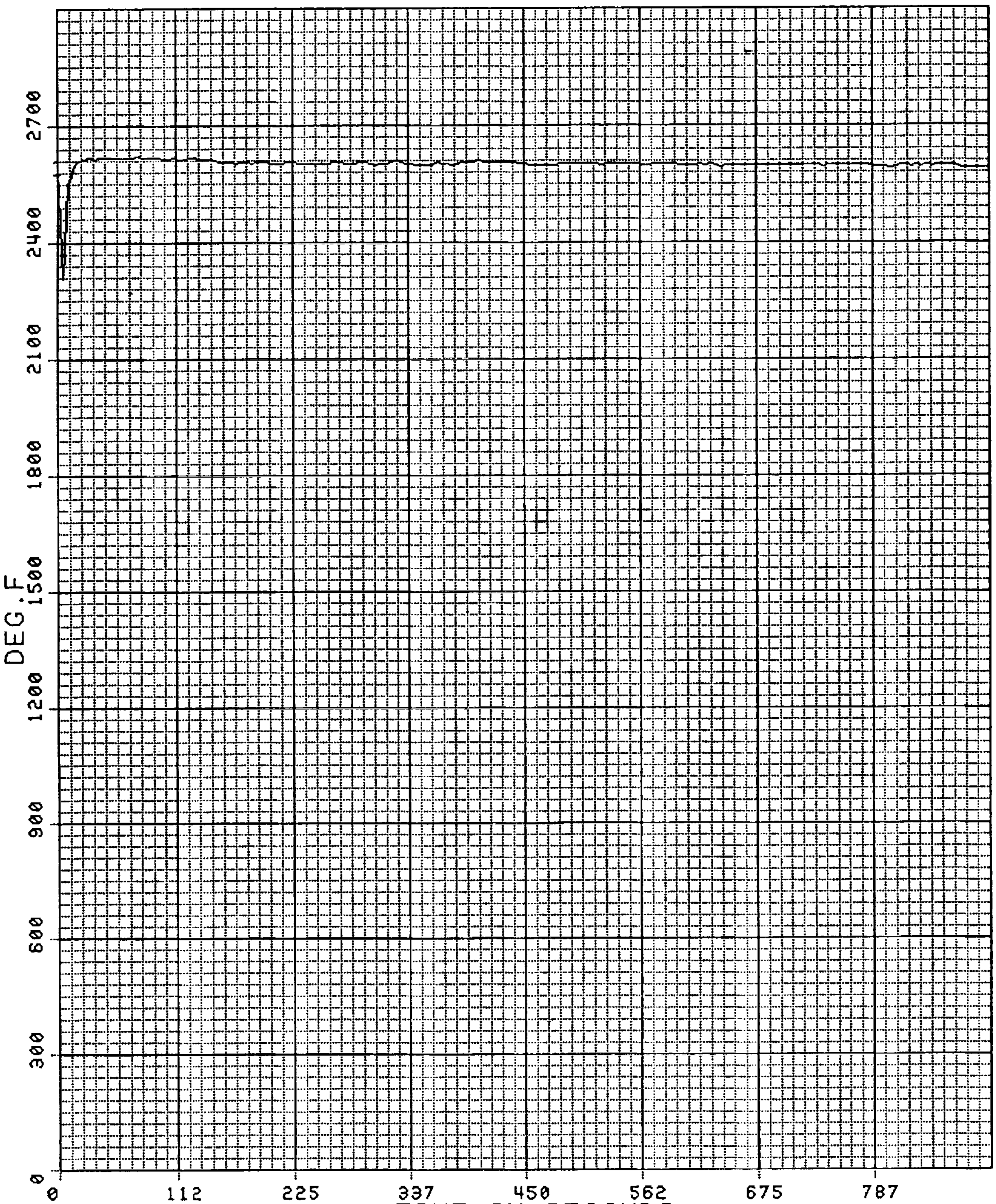



SURFACE TEMPERATURE R ARM 11-9-143 CYCLE # 1 5

1-552-DD
DATE = 9/24/92 AVERAGE INTERVAL 5.0 SEC TIME = 22:51: 6.1 TO 23:11: 6.3
ARMSEF KSC FRIT L/A 10-9-047 & R/A 11-9-143

PROCESSING DATE 11/05/92

# L PYRO C CHANNEL NO. 26

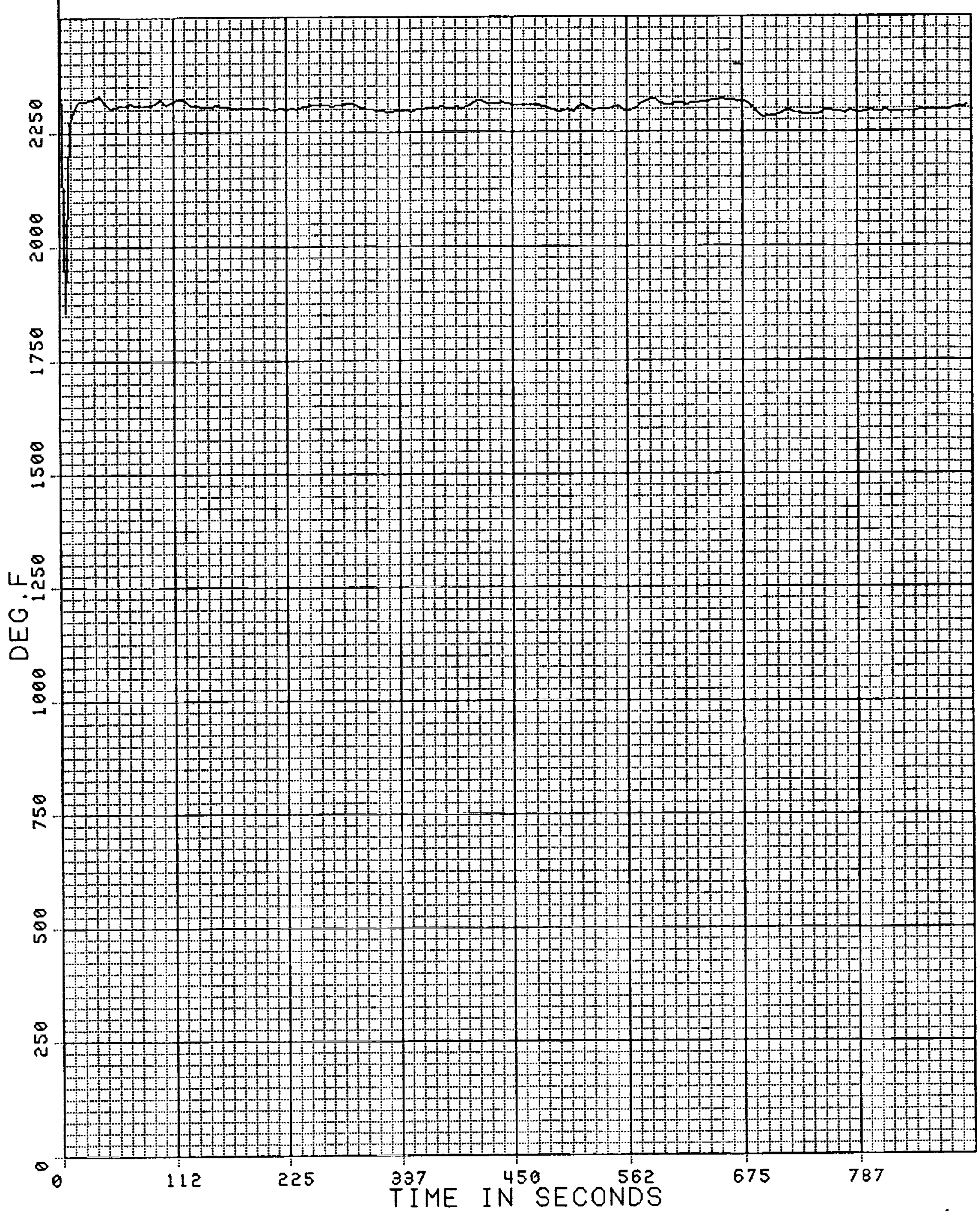



SURFACE TEMPERATURE R ARM 11-9-143 CYCLE # 6

2

1-555-DD
PROCESSING DATE 11/05/92
DATE = 9/25/92 AVERAGE INTERVAL 5.0 SEC TIME = 23:27:17.2 TO 23:42:17.3
ARMSEF KSC COATING FRIT L-ARM 12-9-051 RT- ARM 13-12-051

# L PYRO C CHANNEL NO. 26



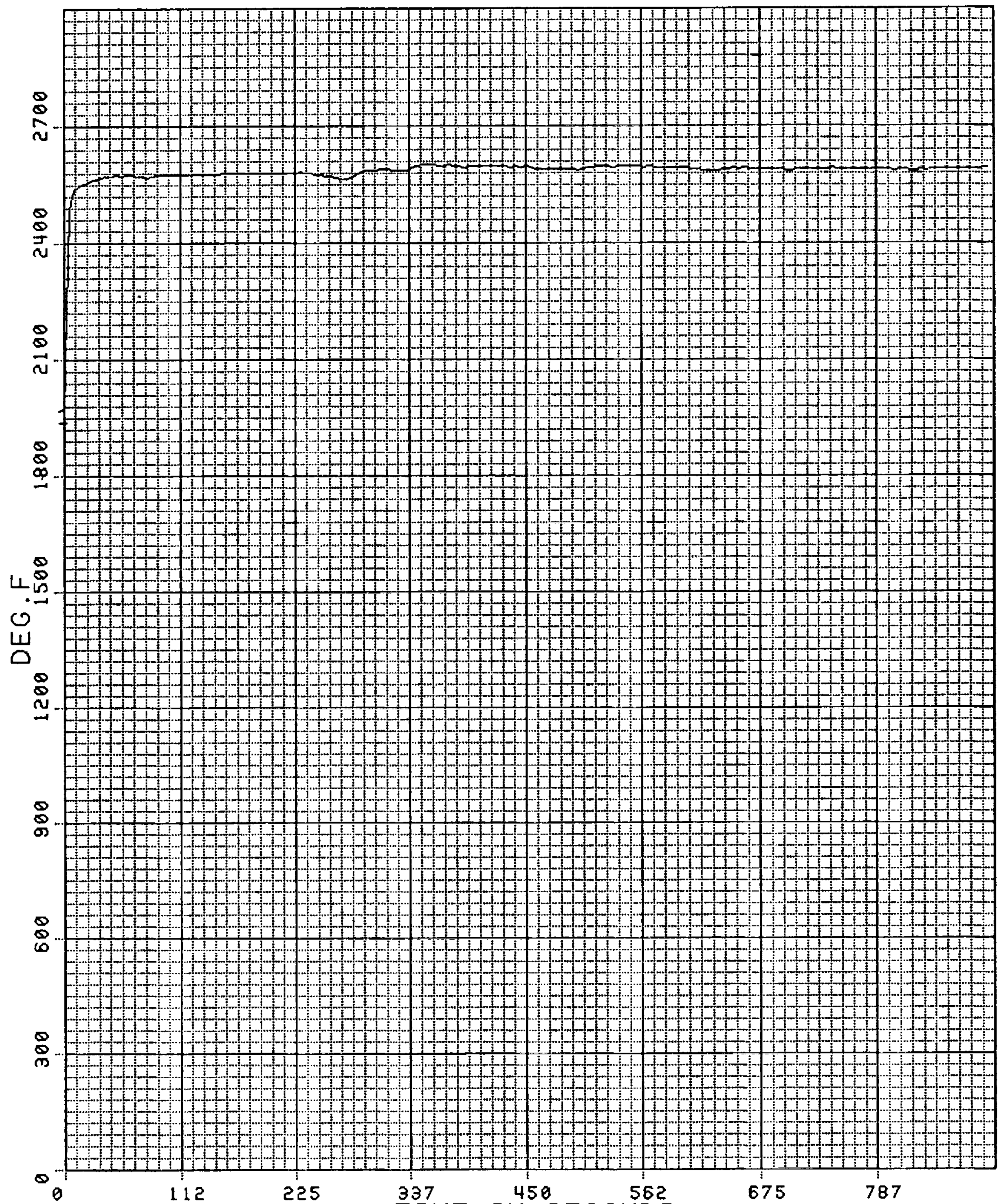

SURFACE TEMPERATURE L- ARM 12-9-051 CYCLE # 1

1

1-557-DD
DATE = 9/28/92 AVERAGE INTERVAL 5.0 SEC TIME = 21:44:44.7 TO 21:59:44.7
ARMSEF KSC COATING FRIT L- ARM 12-9-051 RT- ARM 13-12-051

PROCESSING DATE 11/05/92

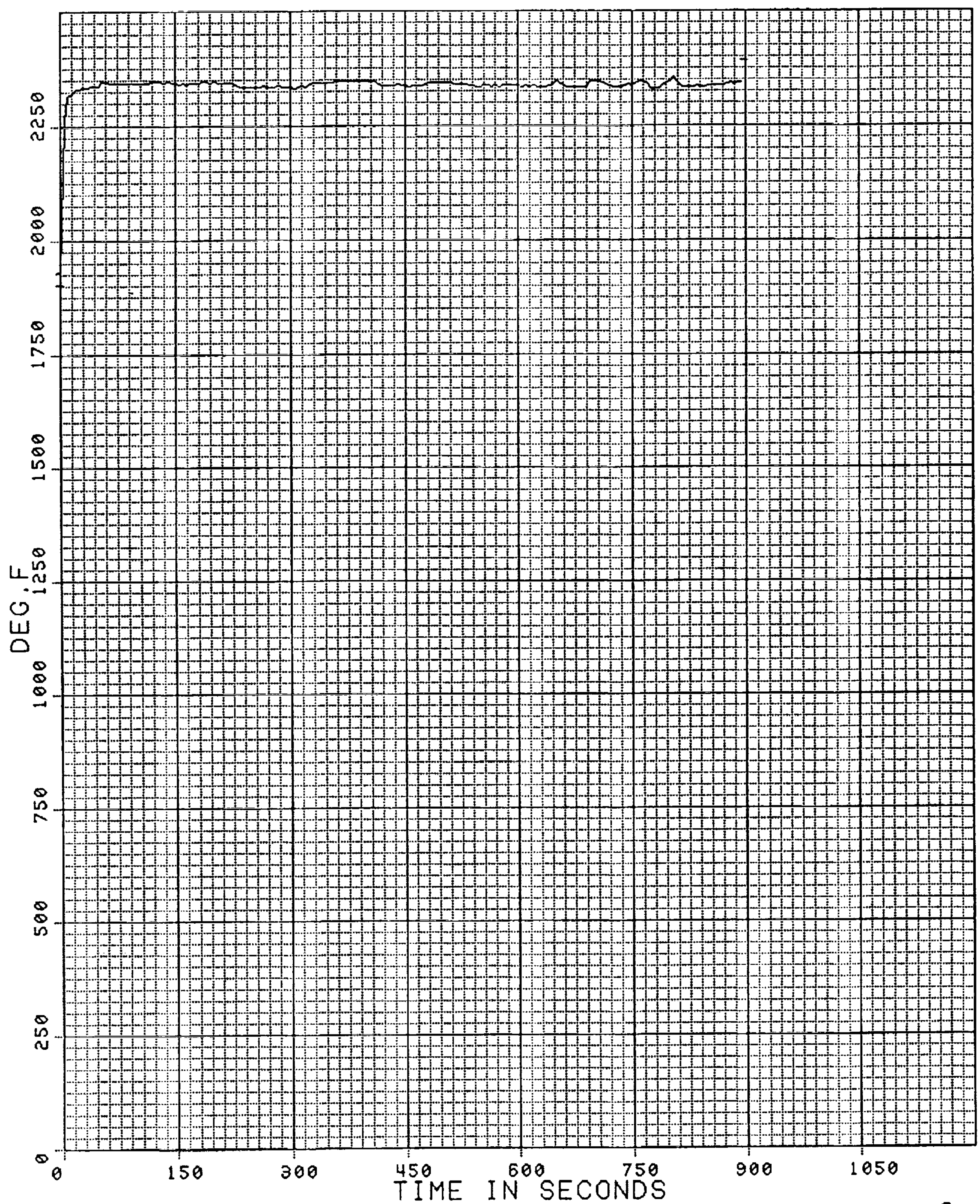
# L PYRO C CHANNEL NO. 26




SURFACE TEMPTERATURE L - ARM 12-9-051 CYCLE # 6 1

1-555-DD PROCESSING DATE 09/29/92
DATE = 9/25/92 AVERAGE INTERVAL 5.0 SEC TIME = 23:43:57.4 TO 23:58:57.4
ARMSEF KSC COATING FRIT L-ARM 12-9-051 RT- ARM 13-12-051

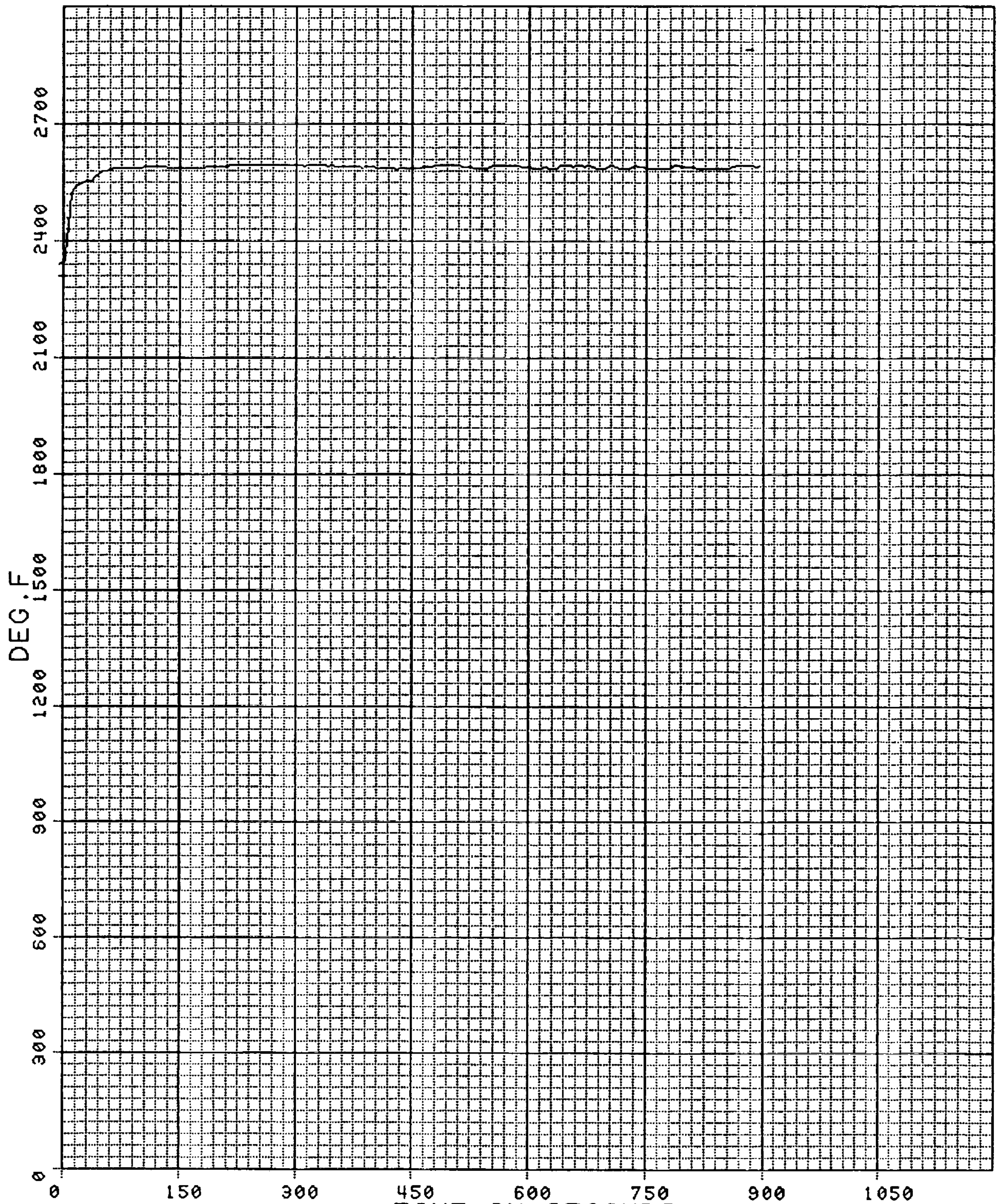
# L PYRO C CHANNEL NO. 26




SURFACE TEMPERATURE RT- ARM 13-12-051 CYCLE # 1 2

1-557-DD
PROCESSING DATE 09/29/92
DATE = 9/28/92 AVERAGE INTERVAL 5.0 SEC TIME = 22: 1:14.7 TO 22:16:14.7
ARMSEF KSC COATING FRIT L- ARM 12-9-051 RT - ARM 13-12-051

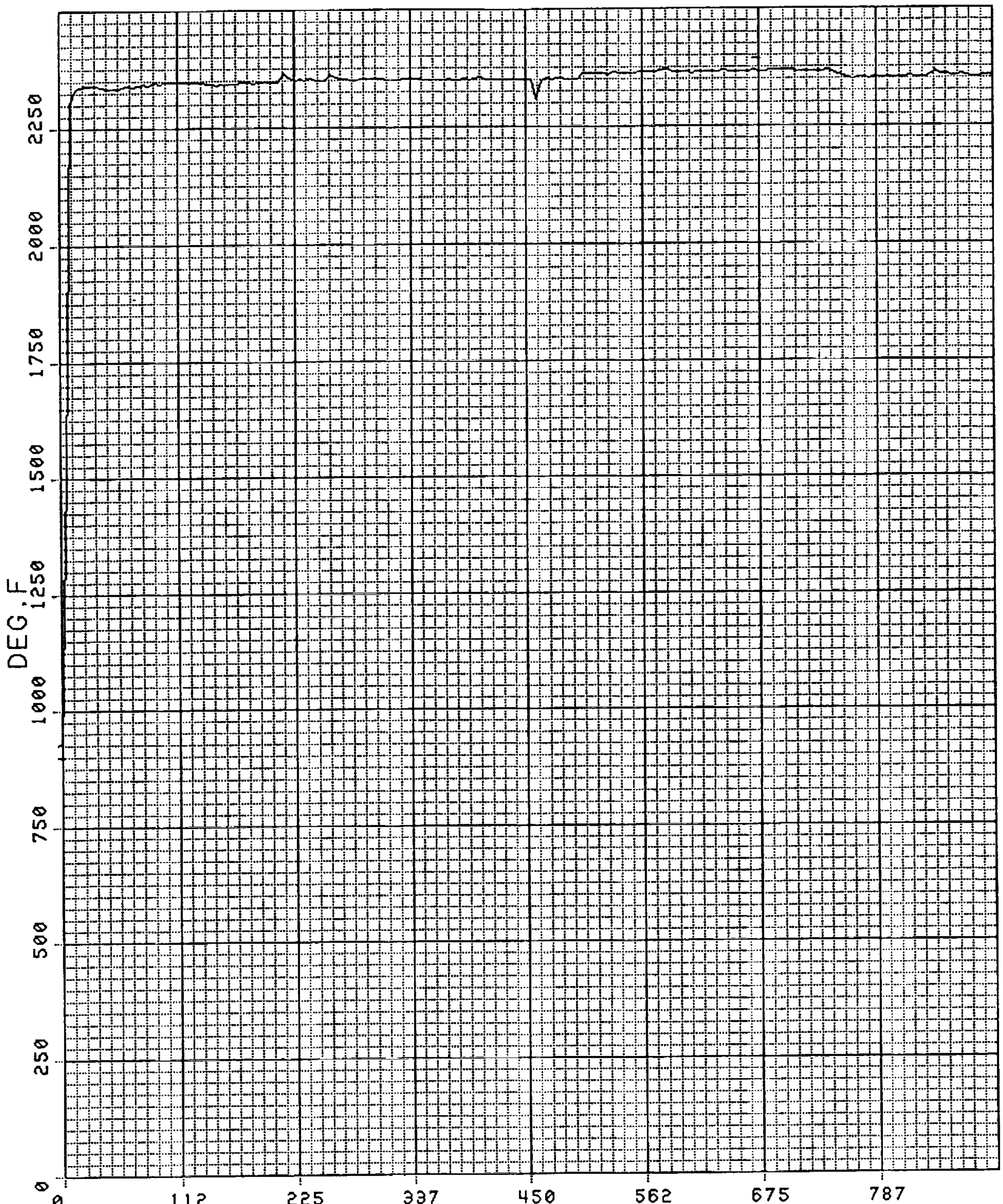
# L PYRO C CHANNEL NO. 26




SURFACE TEMPERATURE RT- ARM 13-12-051 CYCLE # 6 2

1-551-DD
PROCESSING DATE 11/05/92
DATE = 9/24/92 AVERAGE INTERVAL 5.0 SEC TIME = 18:48:37.6 TO 19: 8:37.6
ARMSEF KSC COATING FRIT 2300 DEG.F L/A 15-12-047 & R/A 14-12-143

# L PYRO C CHANNEL NO. 26

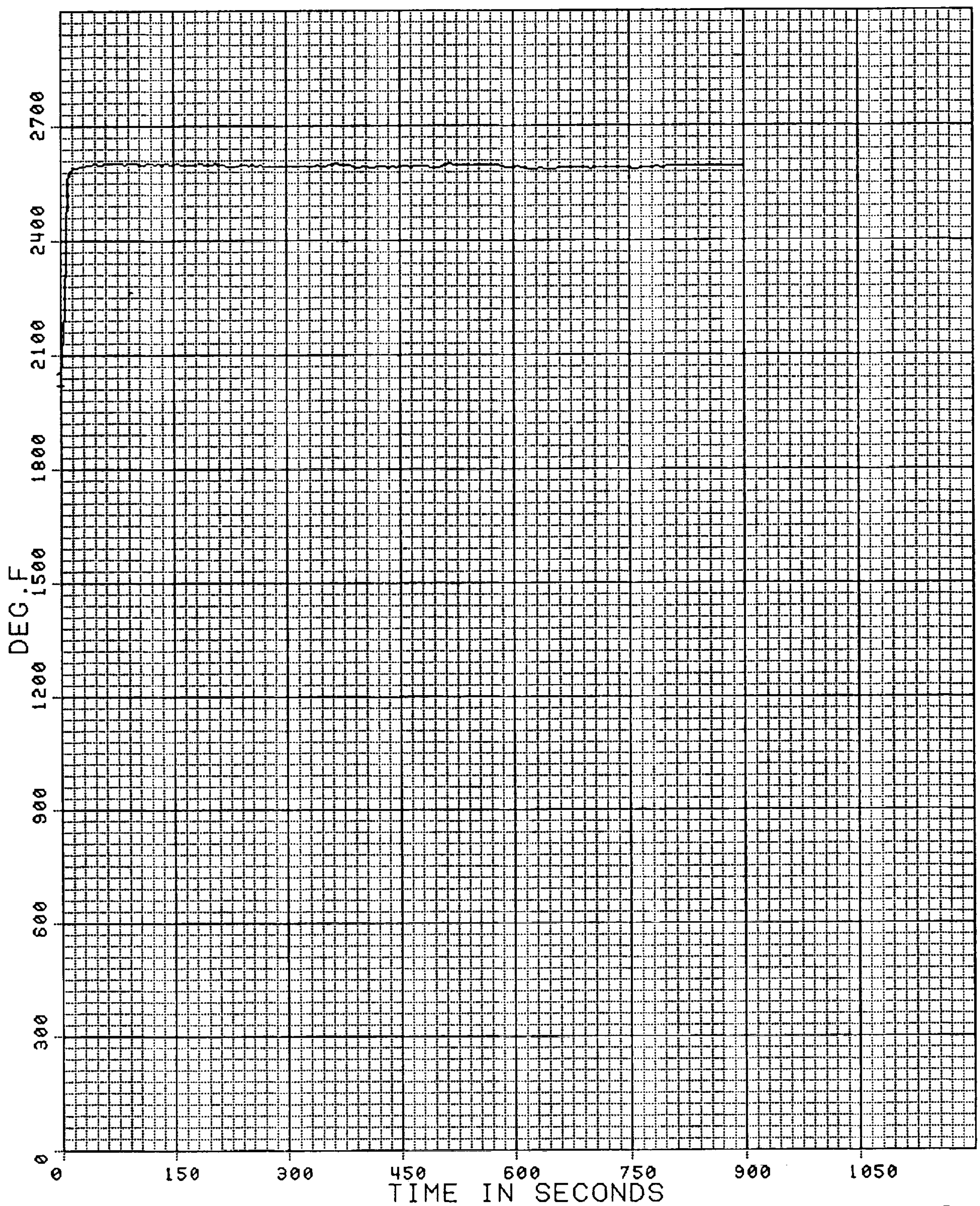



SURFACE TEMPERATURE R ARM 14-12-143 CYCLE # 1

1

1-554-DD PROCESSING DATE 09/29/92
DATE = 9/25/92 AVERAGE INTERVAL 5.0 SEC TIME = 21:33:18.0 TO 21:48:23.0
ARMSEF KSC COATING FRIT L- ARM 15-12-047 RT- ARM 14-12-143

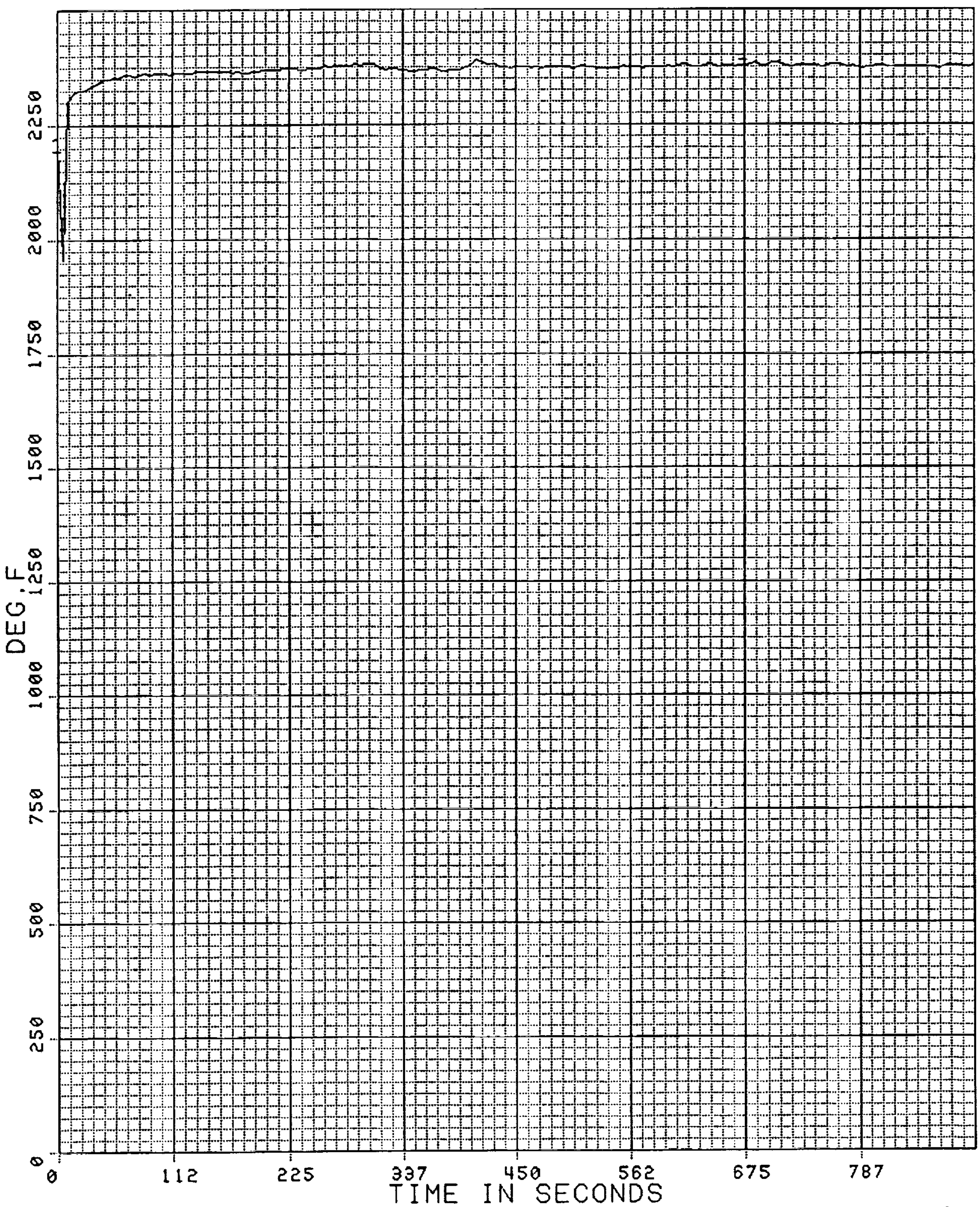
# L PYRO C CHANNEL NO. 26




SURFACE TEMPTERATURE RT- ARM 14-12-143 CYCLE # 6 2

1-550-DD PROCESSING DATE 11/05/92
DATE = 9/16/92 AVERAGE INTERVAL 5.0 SEC TIME = 19:16:53.6 TO 19:36:53.6
ARMSEF KSC COATING FRIT 2300 DEG.F L/A 15-12-047

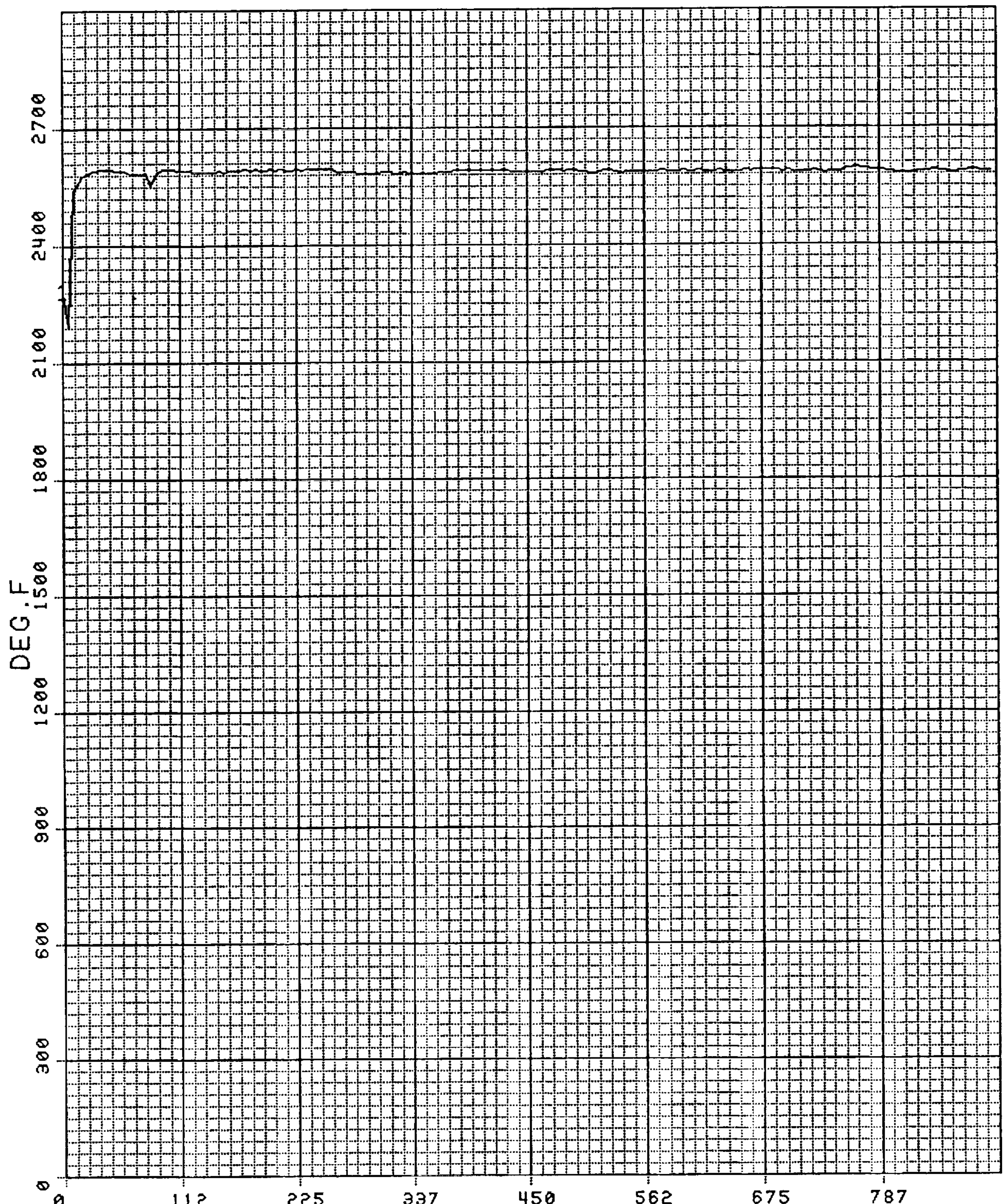
# L PYRO C CHANNEL NO. 26




SURFACE TEMPERATURE L ARM 15-12-047 CYCLE # 1 1

1-554-DD
DATE = 9/25/92 AVERAGE INTERVAL 5.0 SEC TIME = 21:12:47.9 TO 21:27:47.9
PROCESSING DATE 11/05/92
ARMSEF KSC FRIT L/A 15-12-047 R/A 14-12-143

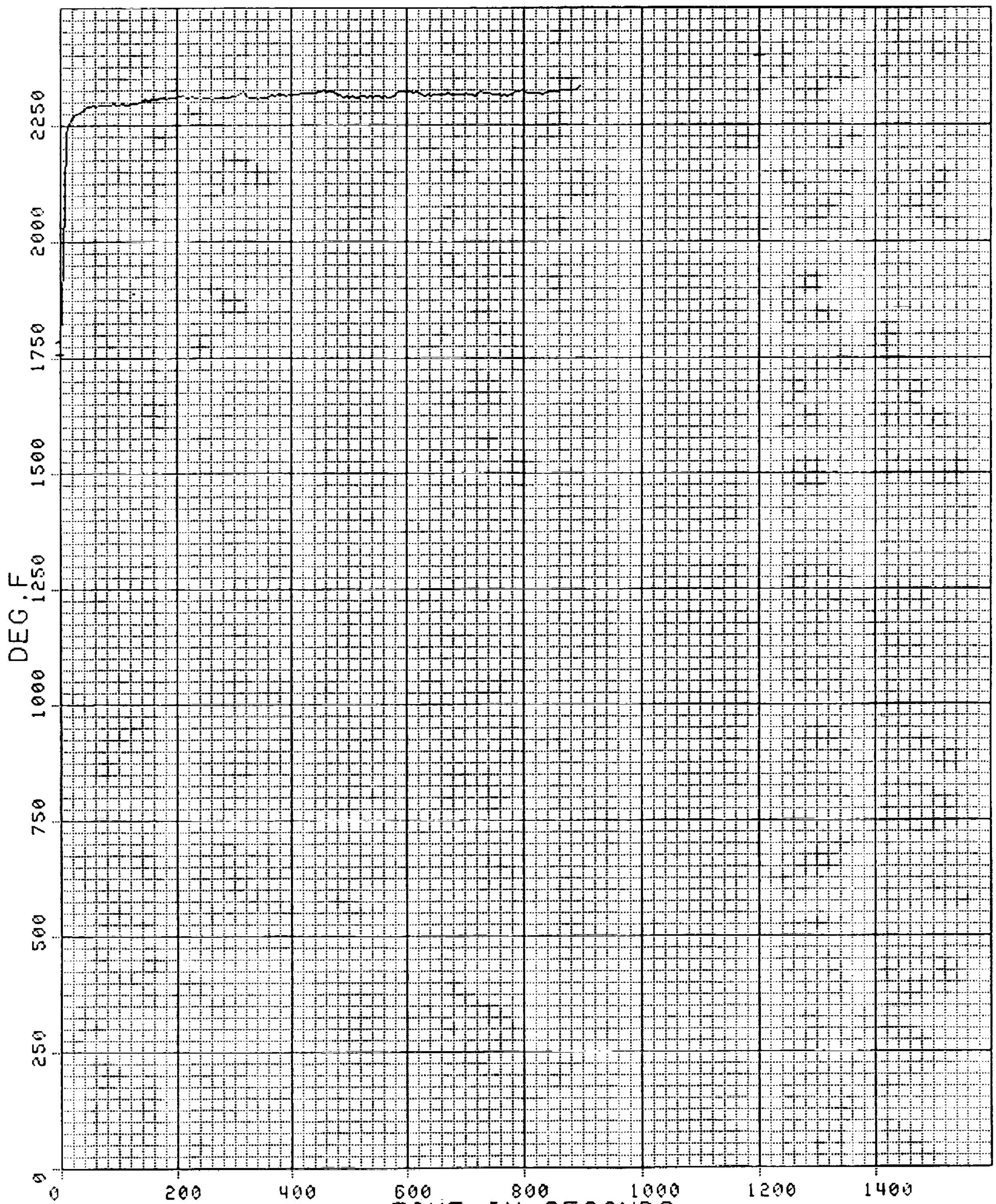
# L PYRO C CHANNEL NO. 26




SURFACE TEMPTERATURE L- ARM 15-12-047 CYCLE # 6 1

1-558-DD
PROCESSING DATE 11/03/92
DATE = 9/29/92 AVERAGE INTERVAL 5.0 SEC TIME = 16:54:42.6 TO 17: 9:42.7
ARMSEF KSC COATING FRIT 2300 DEG F L/A 16-22-051 & R/A 18-22-143

# L PYRO C CHANNEL NO. 26

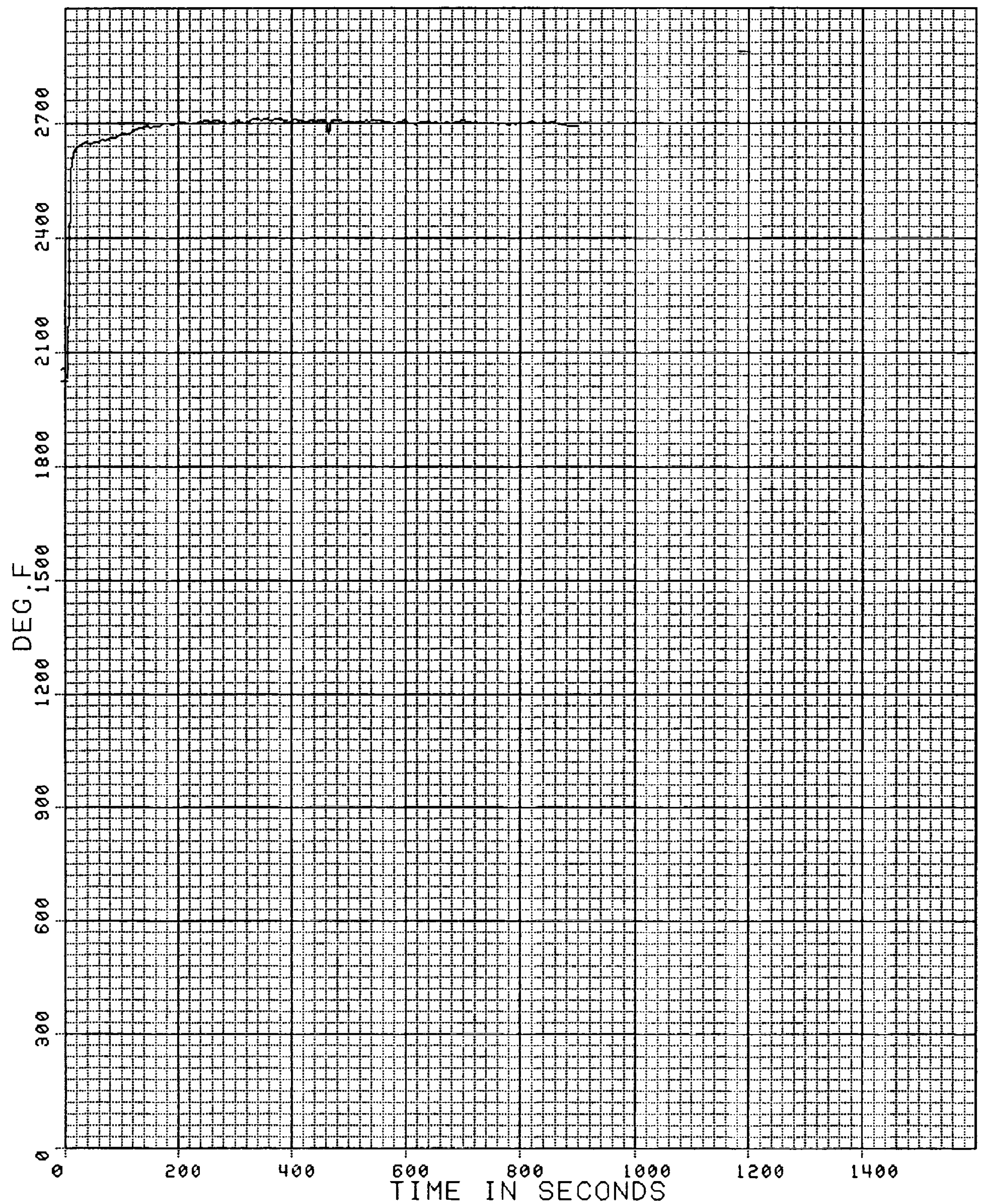



SURFACE TEMPERATURE L ARM 16-22-051 CYCLE # 1

2

1-559-DD
PROCESSING DATE 11/03/92
DATE = 9/29/92 AVERAGE INTERVAL 5.0 SEC TIME = 21:38: 8.1 TO 21:53:13.1
KSC COATING FRIT 2300 DEG F L/A 16-22-051 & R/A 18-22-143

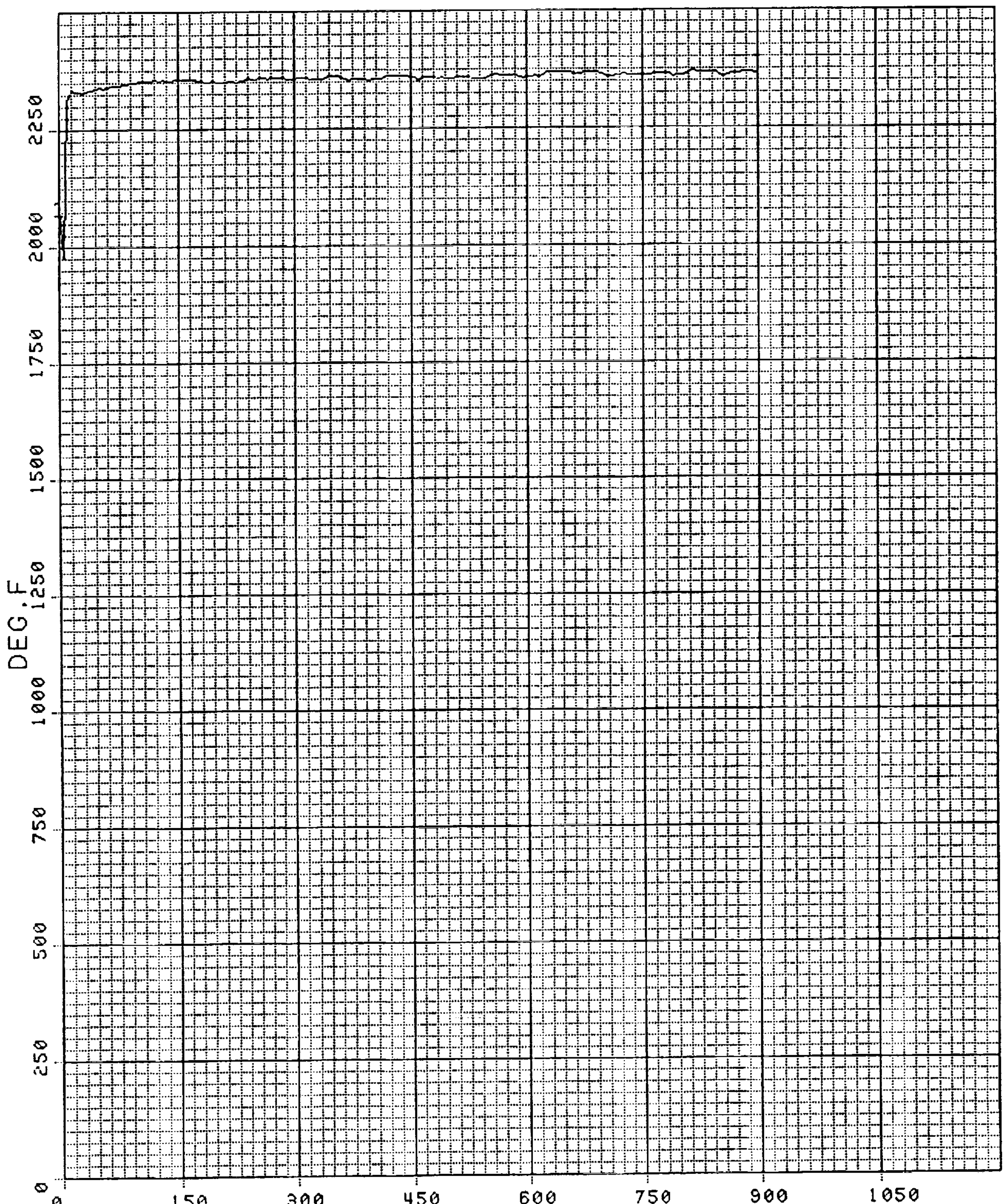
# L PYRO C CHANNEL NO. 26




SURFACE TEMPERATURE L ARM 16-22 051 CYCLE # 6 2

1-558-DD
PROCESSING DATE 11/04/92
DATE = 9/29/92 AVERAGE INTERVAL 5.0 SEC TIME = 17:11: 2.1 TO 17:26: 7.1
KSC COATING FRIT 2300 DEG F. L/A 16-22-051 & R/A 18-22-143

# L PYRO C CHANNEL NO. 26



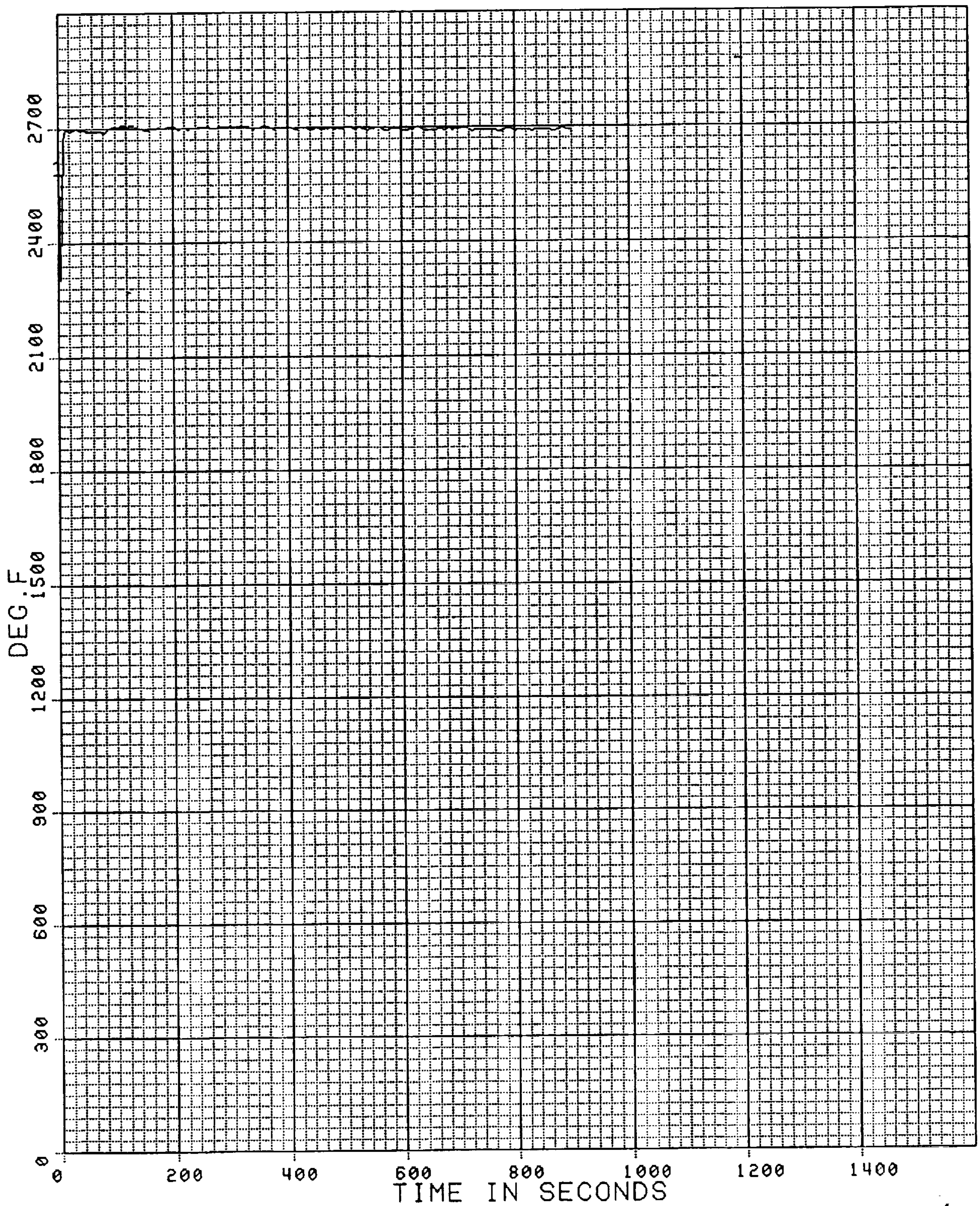

SURFACE TEMPERATURE R ARM 18-22-143 CYCLE # 1

1

1-559-DD
DATE = 9/29/92 AVERAGE INTERVAL 5.0 SEC TIME = 21:54:43.1 TO 22: 9:48.2
KSC COATING FRIT 2300 DEG F L/A 16-22-051 & R/A 18-22-143

PROCESSING DATE 11/03/92

# L PYRO C CHANNEL NO. 26




SURFACE TEMPERATURE R ARM 18-22-143 CYCLE # 6

1

# Appendix B-2

Specimen Reflectivities
(Convective Heat Test)

## KSC TILE REFLECTIVITY MEASUREMENTS

| EESL MODEL NUMBER | TILE I.D. | PRE-TEST REFLECTIVITY | POST-TEST REFLECTIVITY |
|---|---|---|---|
| 583 | 10-9-047 | 0.153 | 0.157 |
| 581 | 11-9-143 | 0.152 | 0.156 |
| 584 | 12-9-051 | 0.146 | 0.159 |
| 582 | 13-12-051 | 0.148 | 0.158 |
| 585 | 14-12-143 | 0.147 | 0.158 |
| 586 | 15-12-047 | 0.156 | 0.158 |
| 587 | 16-22-051 | 0.150 | 0.157 |
| 589 | 18-22-143 | 0.146 | 0.155 |

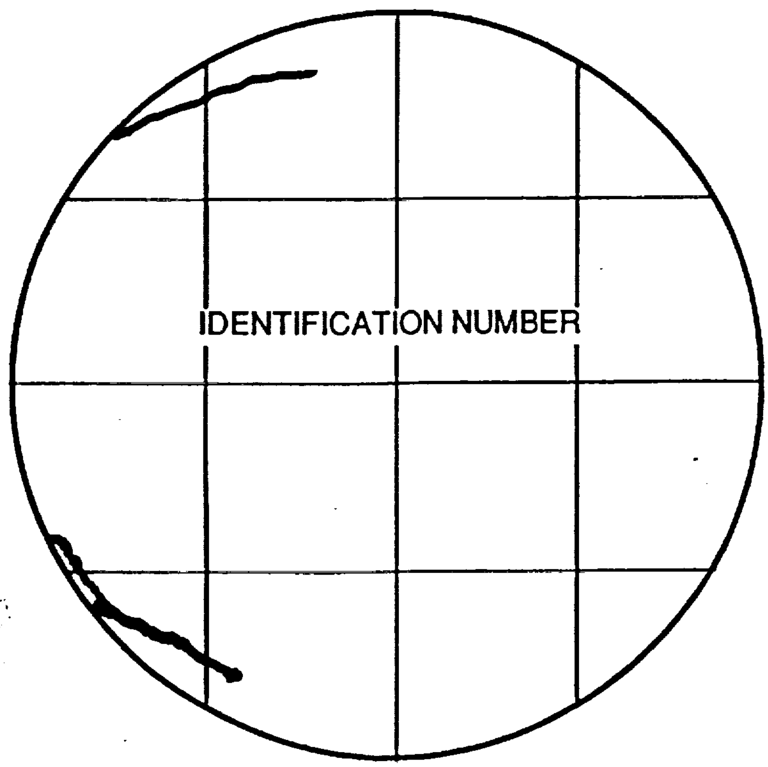
9-11-92 10-6-92

# Appendix B-3

Specimen Crack Maps
(Convective Heat Test)

# KSC COATING FRIT TEST PROGRAM

MODEL CRACK MAPPING WORK SHEET




MODEL ID 11-9-143

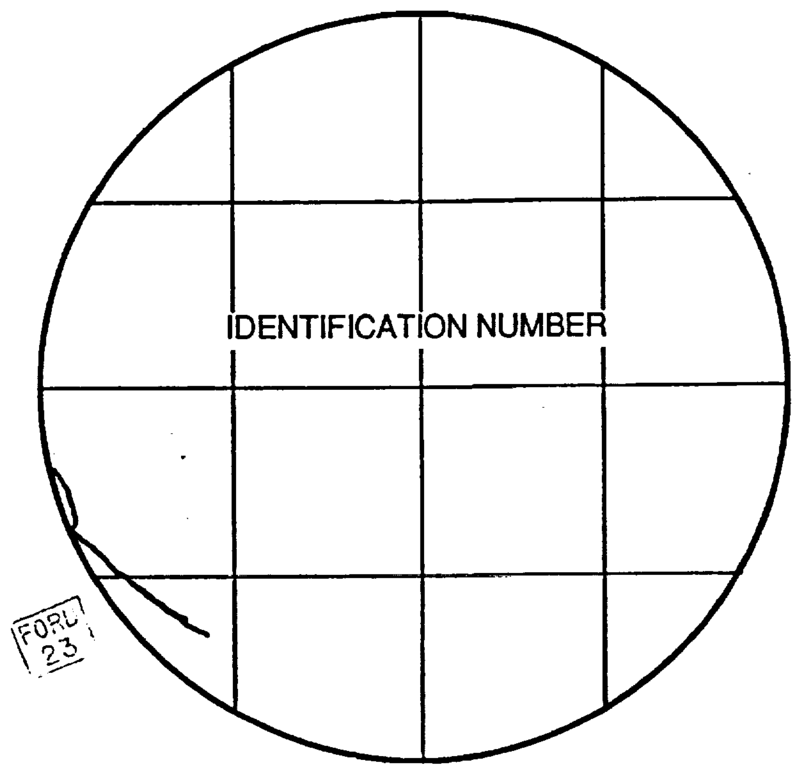
DATE 9 14 92

CYCLE NO. PRE TEST

TPS REF. A99220016

# KSC COATING FRIT TEST PROGRAM

MODEL CRACK MAPPING WORK SHEET




MODEL ID 11 - 9 -143

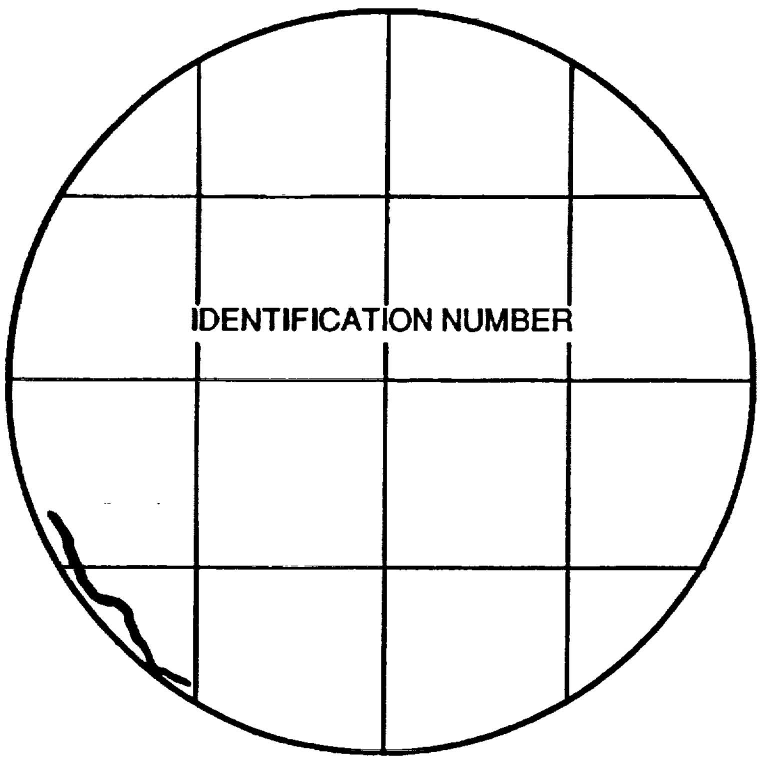
DATE 9 15 92

CYCLE NO. POST CYCLE #5

TPS REF. A99220016

# KSC COATING FRIT TEST PROGRAM

MODEL CRACK MAPPING WORK SHEET




MODEL ID 11-9-143

DATE 9/24/92

CYCLE NO. 6

TPS REF. A99220016

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Houston, Texas 77058

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13. ABSTRACT *(Maximum 200 words)*
Thermal tests of Orbiter thermal protection system (TPS) tiles, which were coated with borosilicate glass slurries fabricated at Kennedy Space Center (KSC), were performed in the Radiant Heat Test Facility and the Atmospheric Reentry Materials & Structures Evaluation Facility at Johnson Space Center to verify tile coating integrity after exposure to multiple entry simulation cycles in both radiant and convective heating environments. Eight high temperature reusable surface insulation (HRSI) tiles and six low temperature reusable surface insulation (LRSI) tiles were subjected to 25 cycles of radiant heat at peaked surface temperatures of 2300°F and 1200°F, respectively. For the LRSI tiles, an additional cycle at peaked surface temperature of 2100°F was performed. There was no coating crack on any of the HRSI specimens. However, there were eight small coating cracks (less than 2 inches long) on two of the six LRSI tiles on the 26th cycle. There was practically no change on the surface reflectivity, physical dimensions, or weight of any of the test specimens. There was no observable thermal-chemical degradation of the coating either. For the convective heat test, eight HRSI tiles were tested for five cycles at a surface temperature of 2300°F. There was no thermal-induced coating crack on any of the test specimens, almost no change on the surface reflectivity, and no observable thermal-chemical degradation with an exception of minor slumping of the coating under painted TPS identification numbers. The tests demonstrated that KSC's TPS slurries and coating processes meet the Orbiter's thermal specification requirements.

14. SUBJECT TERMS
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