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REENTRY THERMAL PROTECTION FROM PIONEER F RTG INSULATION MATERIAL

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Summary

Ablation tests were performed on the insulation material used in the Pioneer F Radisotope Thermoelectric Generator (RTG) in the Ames Arc-Heated Planetary-Gas Wind Tunnel. Test results indicate that the material, trade name Min-K 1301, should experience little ablation for heat transfer rates below 40 BTU/ft^2-sec. If the current design were to be changed so that the various pieces of Min-K were fastened or interlocked together the total amount of heat delivered to the RTG heat source during an earth orbital decay reentry would be reduced by at least 22.7%.

Introduction

Results of analyses performed by McCulloch, Ref. 1, indicate that if a Pioneer RTG is abandoned in an earth orbit due to a malfunctioning booster, the heat source will overheat during reentry to such an extent that upon earth impact it likely will fracture and release its contents. The analyses are based on the realistic assumption that the heat source reenters free from the remainder of the generator. For example, with the current design and method of construction, the exterior case of the generator should disintegrate at a high altitude and the thermoelectrics with attached thermal insulation would quickly disperse. However, this insulation (brand name Min-K 1301) could be interlocked or attached together to serve as ablation material and help protect the heat source during the initial phase of reentry heating. In order to assess the feasibility and usefulness of such a design change, the Min-K 1301 material was tested in the ablative environment of an arc-heated air stream and the results used to estimate the thermal protection it can provide during reentry.

Models and Apparatus

The Pioneer RTG contains many pieces of a very frangible insulation material, called Min-K 1301, which surround the heat source. This material fills approximately half the volume of the RTG in thicknesses from 3/8" to 1-3/8" (see Fig. 1).

For the ablation tests, six specimens were cut into disks one-half inch thick and 2-3/8" in diameter and tested in air, in the Ames Arc-Heated Planetary-Gas Wind Tunnel. Model 1 was cemented to a stainless steel back-up plate with high temperature cement and Model 2 was clamped to a stainless steel back-up plate with four inconel clamps on its circumference. Both Models 1 & 2 suffered structural failure at the point of attachment and fell off the sting. Two other methods tried were successful. These were: 1) sewing the material to a 20-mil-thick stainless steel back-up plate by looping 5 mil tungsten wire through both the specimen and the back-up plate. (Fig. 2 and Fig. 3.) 2) clamping the material in a two-piece graphite holder (Fig. 4).

An optical pyrometer was used to monitor the front surface temperature and a thermocouple placed one-half model radius from center on the rear surface monitored the rear surface temperature (Fig. 4). In addition, motion pictures were taken of the specimens during each test.

Test Results

The stagnation heat-transfer-rate and stagnation-pressure calculated for an RTG surrounded by Min-K insulation undergoing a decaying entry from earth orbit is shown in figure 5. Included on the figure is the simulation of the environment to which Model 3 (Table 1) was exposed during the arc heater tests. The significant difference between this simulation and the calculated environment is that at the peak heat transfer rate, the stagnation pressure for the simulation was only 20% of what would be experienced by the body in flight.

Photographs of model 3 before and after the test are shown in figures 2, 3, and 6, and 7 respectively. The fine tungsten wires used to hold the material to the steel holder can be seen in all four photos. The Min-K material deteriorated considerably and lost 19% of its original mass during the orbital decay simulation. What remained at the end of the test had a strength comparable to that of cigar ash. In view of the higher pressures and attendant higher shear stress that would exist in an actual orbital decay reentry, the material can be considered to be 100% ablated. The front- and back-surface temperatures are shown in figure 8 along with the stagnation-point heat-transfer rates. The back surface temperature is an order of magnitude lower than the front surface temperature indicating that the insulation material is providing substantial thermal protection. It should also be noted that where there was no structural support on the rear surface, the material completely ablated away. The reason for no increase in back-surface temperature with an increase in heat-transfer rate from 70 to 110 Btu/ft^2 sec is not known. The total heat load to model 3 was approximately 63% of that for the orbital decay. Model 4 was tested under almost identical conditions except that it was clamped in a graphite holder. As with Model 3, Model 4 showed considerable deterioration and ablation. Although the test conditions were very similar for models 3 and 4, model 4 lost 73% of its mass as compared to a 19% loss for #3. This factor of 4 difference is very likely due to the method of attachment. The "ashes" were retained in place by the fine tungsten wires of model 3 while the cup feature of the graphite holder allowed them to be blown away.

Figure 9 illustrates the condition of model 4 after exposure to approximately 56% of the total heat load for the orbital decay. Note that Model 4 also completely ablated away in the center where there was no structural support from the rear. The front-surface and back-surface temperature measurements are shown in figure 10. Again, the back-surface temperature is an order of magnitude lower than the front-surface temperature.

Since all previous tests had essentially destroyed each test specimen, it was decided to scale down the exposure to the point where some virgin material would remain at the completion of the test. In this manner the value of the heat-transfer rate beyond which Min-K cannot survive can be bracketed. The total heat load for Model 5 was reduced therefore to 40% of the orbital decay entry; however, tests at this condition resulted in a 68% loss in mass (Table 1) essentially destroying the model. Motion pictures taken during the test indicated that deterioration of the model did not occur during the period when the heat transfer rate was 29 Btu/ft^{2}sec but deterioration did occur when the heat transfer rate was 62 Btu/ft^{2}sec (see Fig. 11). The tests on Model 6 were conducted at a heat transfer rate of 29 Btu/ft^{2}sec corresponding to the first step exposure of Model 5. Model 6 was exposed to 22% of the heat load of that for orbital decay. A post test photograph of this model is shown in figure 12 and the front surface temperature in figure 13. Model 6 experienced a slow delamination of the material not observed on any of the previous tests. Approximately half of the thickness of model 6 was unaffected by this delamination and only a 4% overall mass loss was observed (Table 1).

Analysis

If a design change is initiated in the Pioneer RTG that would permit retention of the Min-K 1301 insulation material during reentry, the amount of heat reaching the heat source during an earth orbital-decay trajectory would be reduced by at least 22.7%. The reason for this reduction is two fold: 1) The body, by retaining the Min-K insulation, is considerably larger and only slightly heavier than the heat source. This results in a more prompt reentry. 2) Ablation of the Min-K material during the initial phases of reentry helps insulate the heat source.

The variation of the ballistic coefficient with altitude during an earth orbital-decay entry is shown in figure 14 for Pioneer RTG with and without Min-K retention. The discontinuities in the curves at altitudes of 340,000 ft and 278,000 ft are due to the assumed instantaneous ablation of the magnesium case and Min-K insulation, respectively. The magnesium case was assumed to ablate instantaneously when the heat transfer rate reached the equilibrium radiation heat transfer rate for the melting point of magnesium. The Min-K insulation was assumed to ablate instantaneously when the heat transfer rate reached 40 Btu/ft^2-sec. This value was chosen because little ablation was observed at 29 Btu/ft^2-sec and very rapid ablation was observed at 62 Btu/ft^2-sec. All other changes in the ballistic coefficient are due to the gradual transition from free molecule flow to continuum flow. Perhaps more significant than the resulting change in ballistic coefficient is the actual ablation protection provided to the heat source by the Min-K insulation. The curves for heat-transfer rate vs time for the orbital-decay with and without Min-K retention are shown on figure 15. The shaded area represents the heat load not received by the heat source if the Min-K insulation were retained around the heat source and allowed to ablate away.

Conclusion

The results of arc-heated tests on Min-K 1301 insulation material, simulating the heating environment that would exist for an orbital decay entry of a Pioneer RTG, indicate that the material did not seriously deteriorate at a heat transfer rate of 29 Btu/ft^2-sec corresponding to the initial portion of the trajectory. However, at heat transfer rates above 62 Btu/ft^2-sec corresponding to later parts of the trajectory, the material deteriorated rapidly.

Trajectory calculations show that the heat source with Min-K insulation retention receives an integrated stagnation-point heat load of 35,160 Btu/ft^2 and the heat source without Min-K retention receives 45,470 Btu/ft^2. Thus, the retention of the Min-K insulation reduces the heat load on the heat source by at least 10,310 Btu/ft^2 or 22.7%.

A design change to take advantage of this heat load reduction could be affected by several means. The pieces could be fabricated with dove tail joints or they could be sewn together with tungsten wire. Neither of these changes should add any appreciable weight nor reduce performance of the RTG generator.

References

1. McCulloch, W. H.: Pioneer Heat Source Aerothermodynamic Analysis, Vol. IV -- Thermal Analysis, Sandia Laboratories, Report #SC-RR-71-0168 May 1971.

TABLE 1

EXPOSURE

MODEL #	TEST #	MATERIAL	METHOD OF ATTACHMENT	TIME SEC	$\dot{q}$ BTU/ft^{2}sec	P_{t_2} mm Hg	h BTU/lb	Q BTU/ft^2	INITIAL MASS, gm	FINAL MASS, gm	OBSERVATION
3	677	Min-K 1301	Sewn to S.S. Plate with 5 mil Tungsten wire	0-200 200-250 250-350	10 70 110	0.4 3.75 4.0	7,500 18,100 27,600	-- -- 16,500	11.75	9.527	1) 63% of orbit decay heat load 2) remains are extremely weak
4	678	Min-K 1301	Graphite holder	0-200 200-250 250-350	8.9 62 98	0.4 3.75 4.0	7,500 18,100 27,600	-- -- 14,680	9.375	2.550	1) 56% of orbital decay heat load
5	679	Min-K 1301	Graphite holder	0-200 200-300	29 62	.15 3.75	19,850 18,100	-- 12,000	10.143	3.280	1) 46% of orbital decay heat load
6	680	Min-K 1301	Graphite holder	0-200	29	0.57	19,850	5,800	10.011	9.589	1) 22% of orbital decay 2) delamination during test 3) approx. 1/2 virgin material remaining

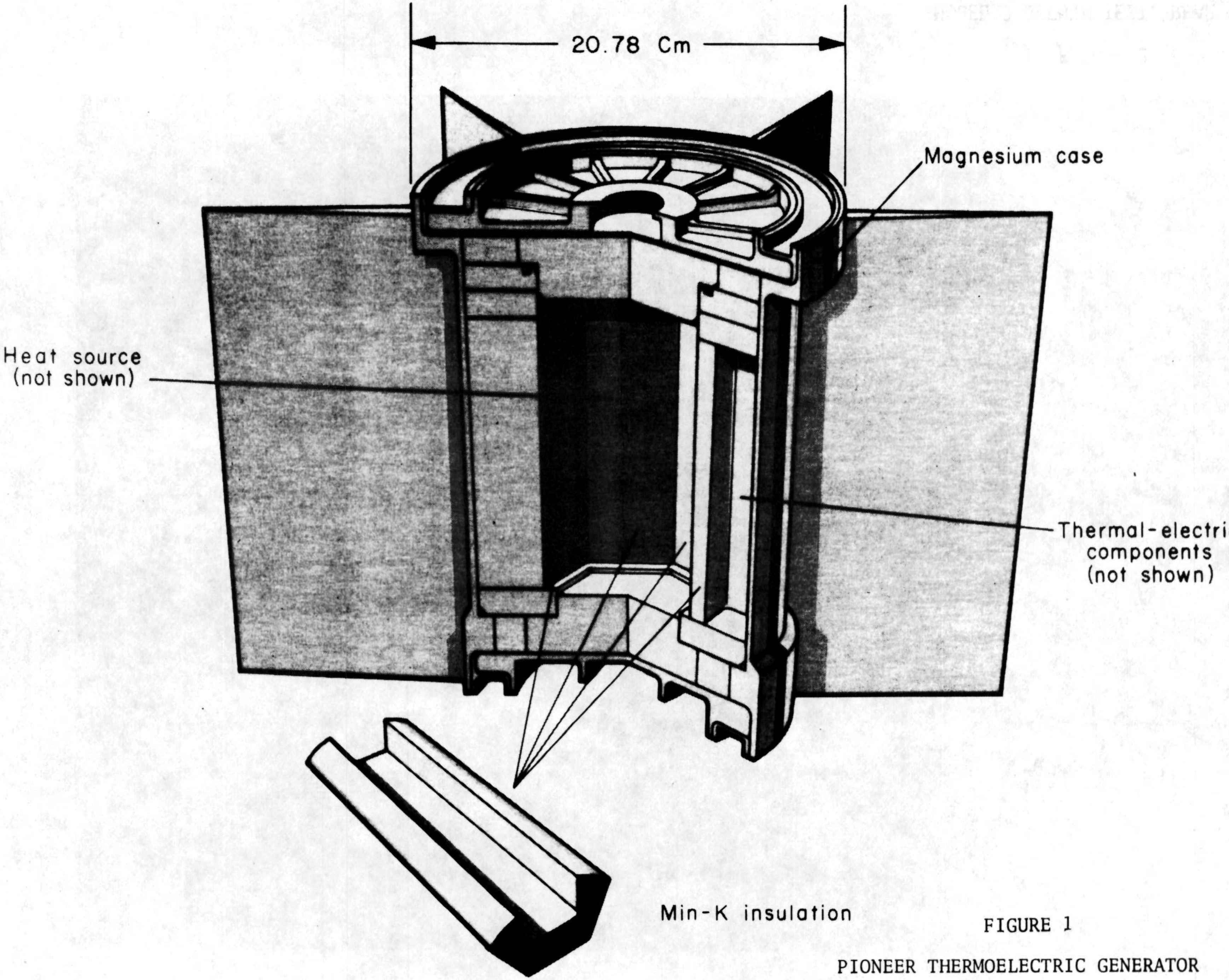

FIGURE 1

PIONEER THERMOELECTRIC GENERATOR

FIGURE 2

MODEL 3 BEFORE TEST, REAR VIEW

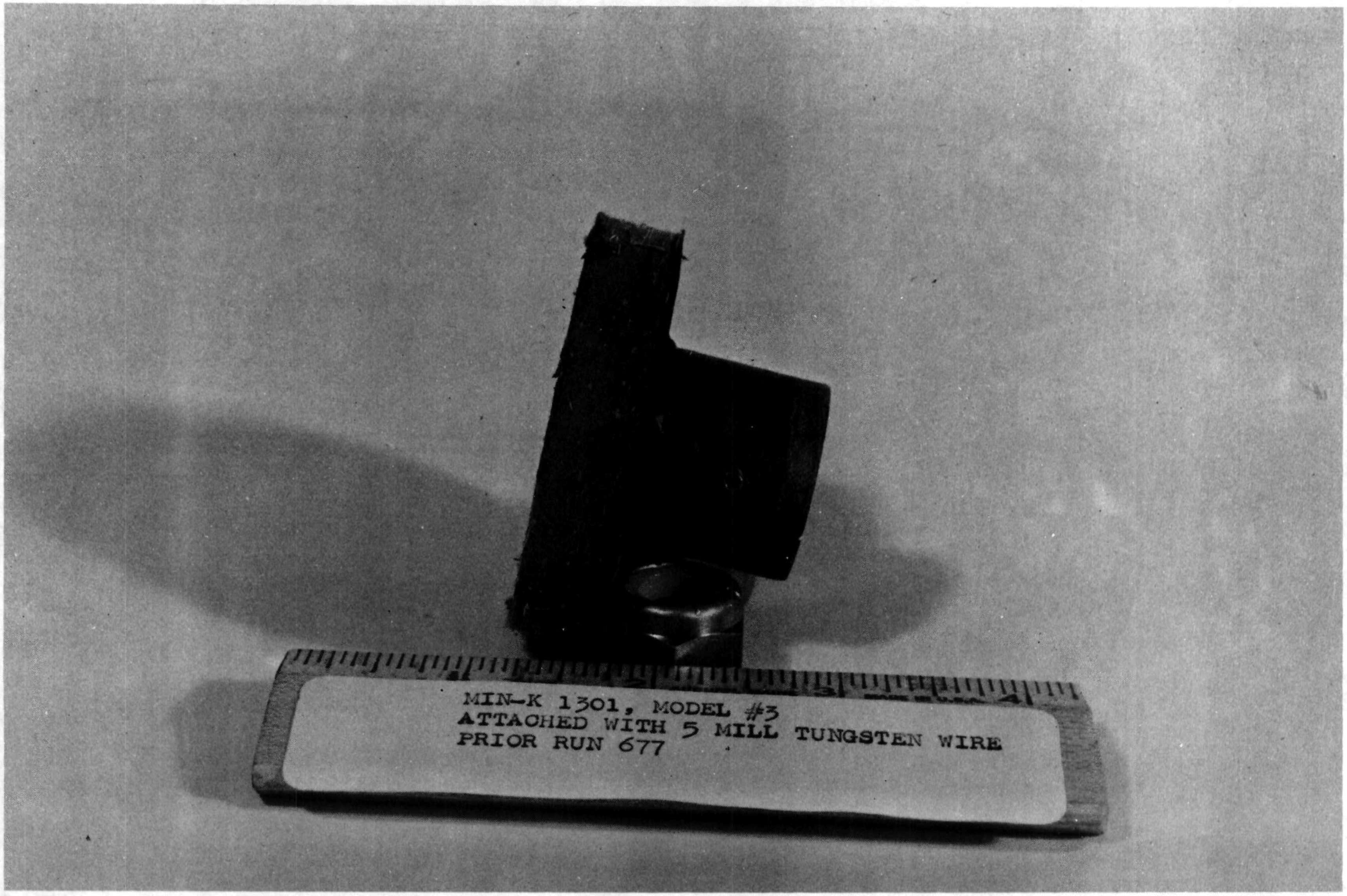

FIGURE 3

MODEL 3 BEFORE TEST, SIDE VIEW

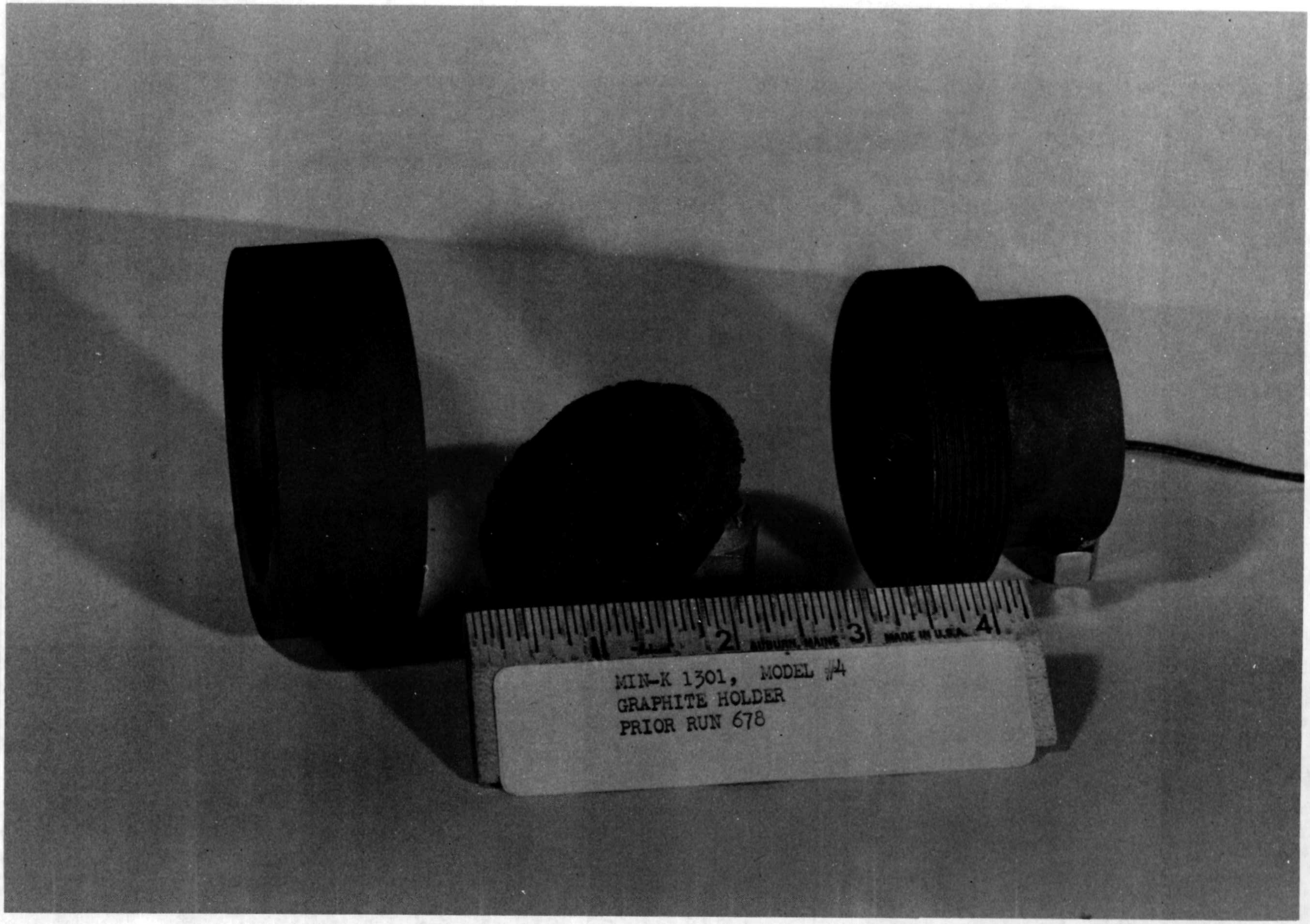

FIGURE 4

MODEL 4 BEFORE TEST, EXPLODED VIEW

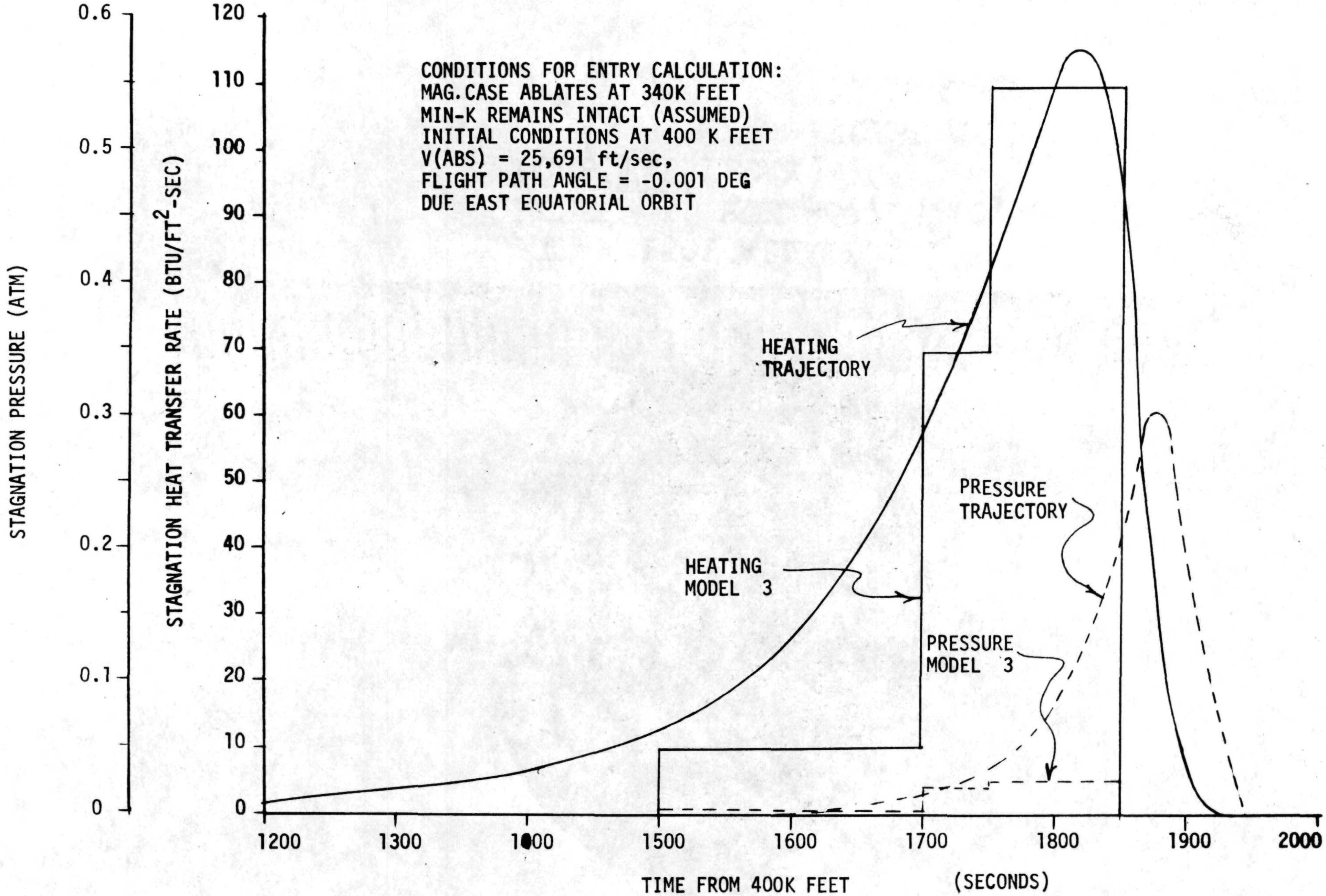

FIGURE 5

STAGNATION HEATING & PRESSURE ENVIRONMENTS FOR PIONEER RTG ENTRY AND MODEL #3

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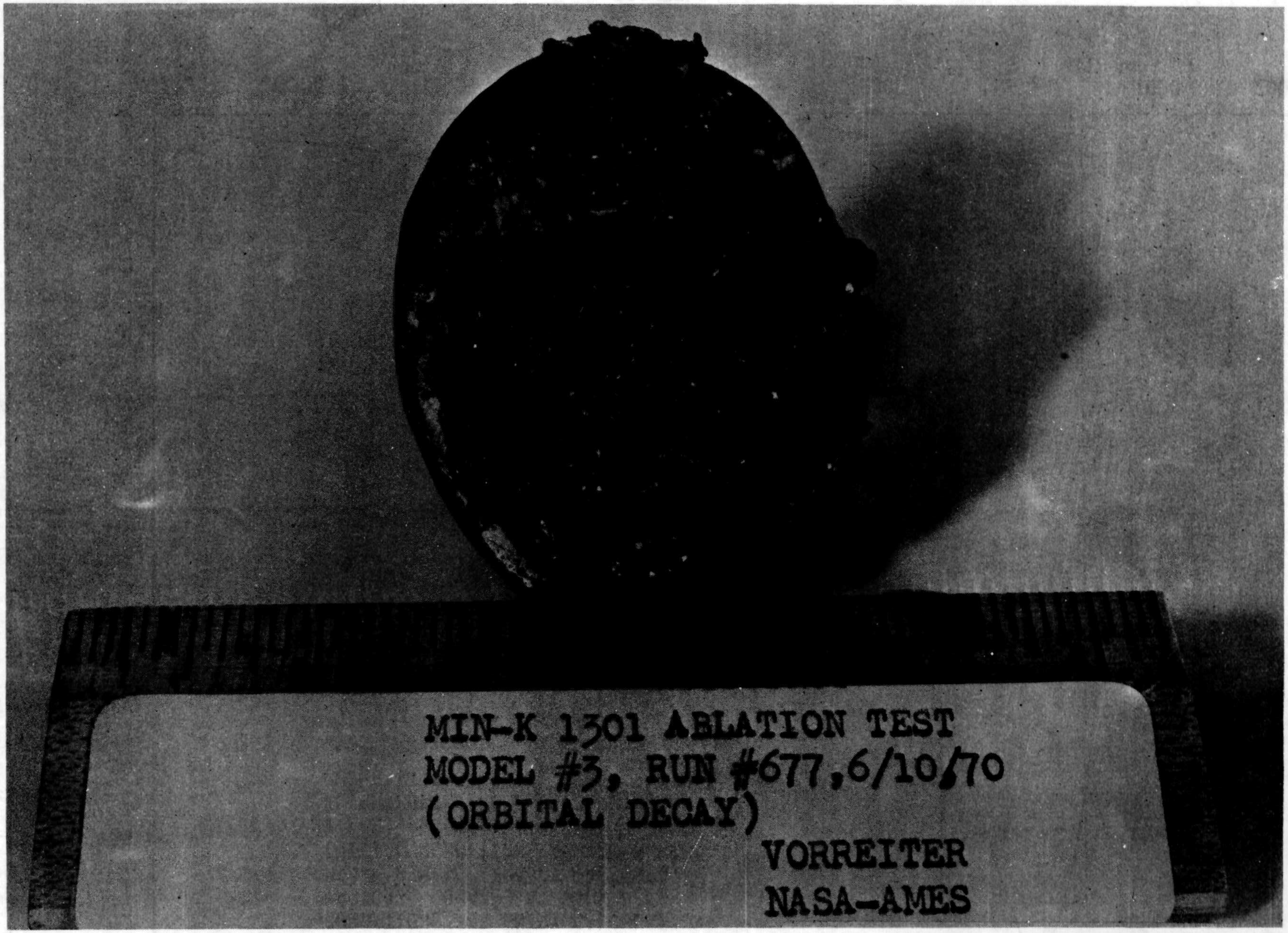

FIGURE 6

MODEL 3 AFTER TEST, FRONT VIEW

FIGURE 7

MODEL 3 AFTER TEST, SIDE VIEW

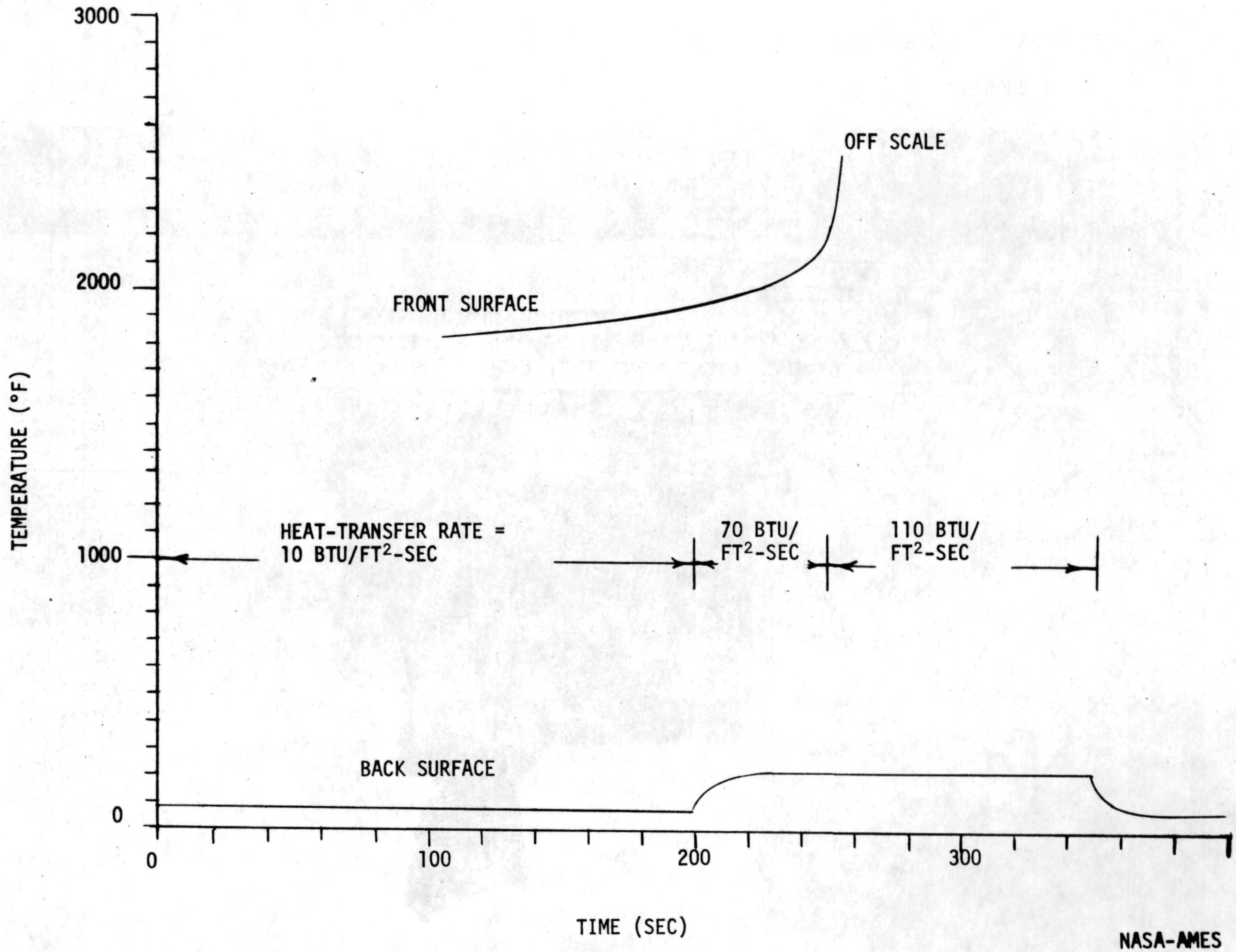

FIGURE 8

FRONT-AND BACK-SURFACE TEMPERATURES DURING THE TESTS FOR MODEL 3

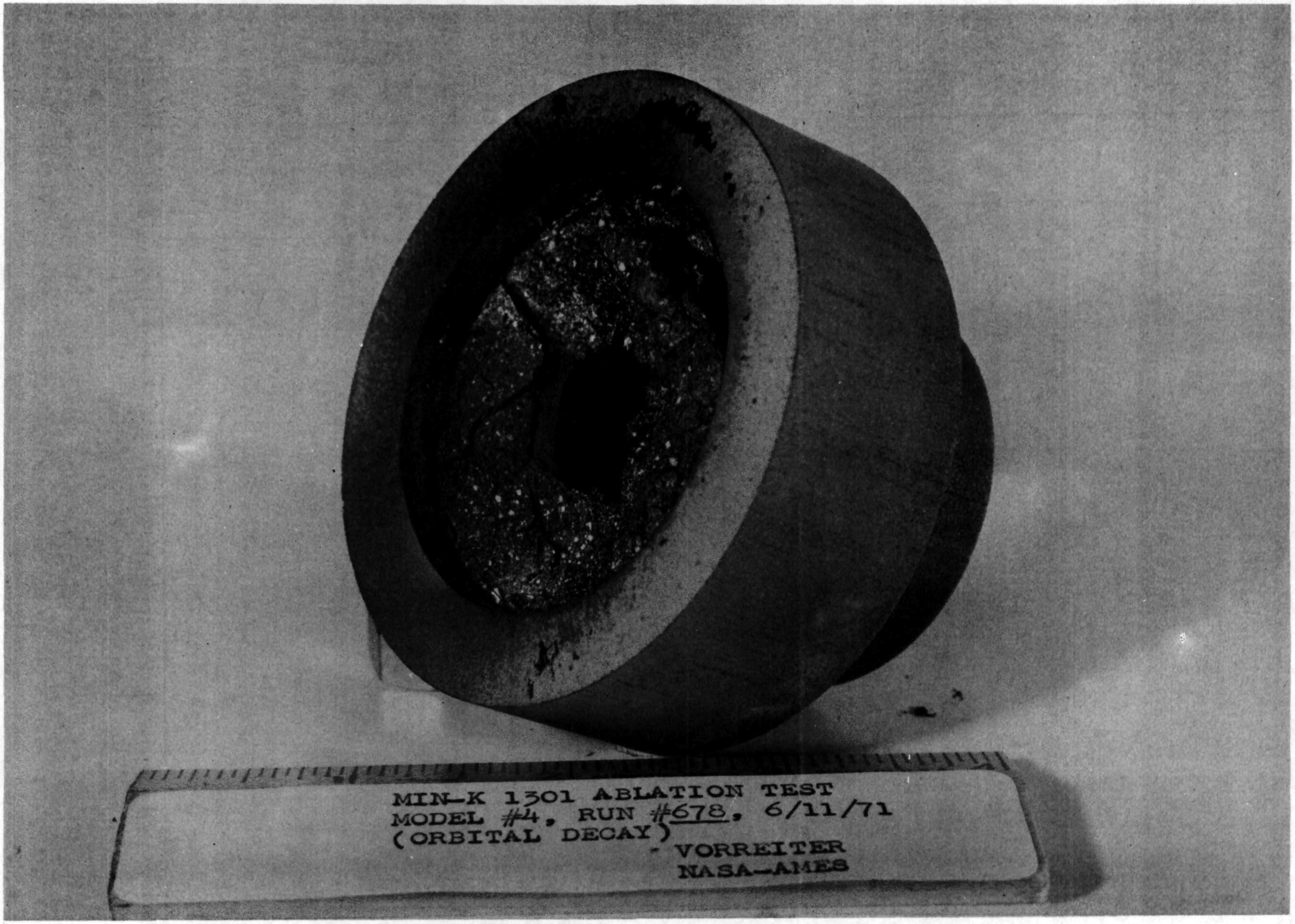

FIGURE 9

MODEL 4 AFTER TEST, FRONT VIEW

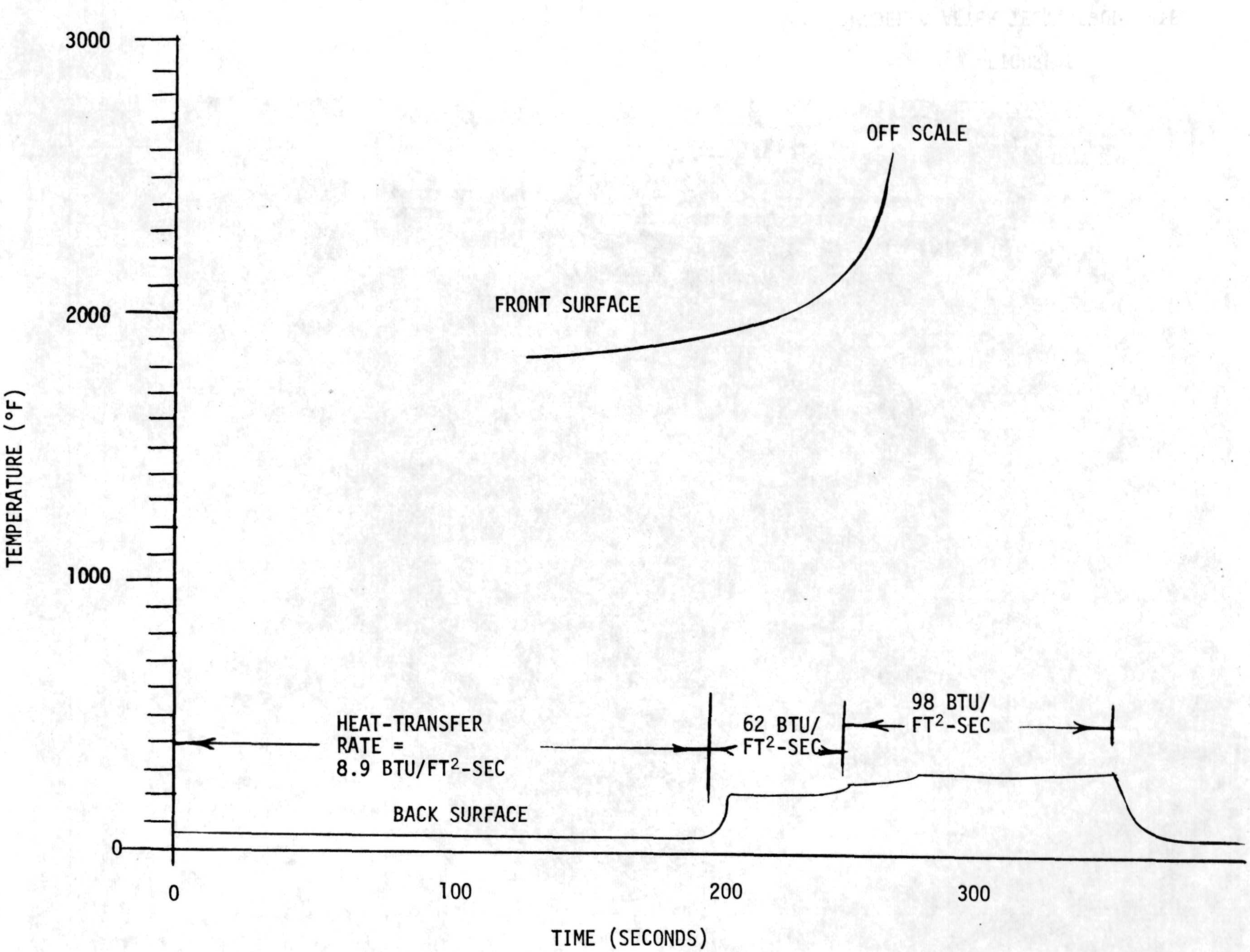

FIGURE 10

FRONT-AND BACK-SURFACE TEMPERATURES DURING THE TESTS FOR MODEL 4

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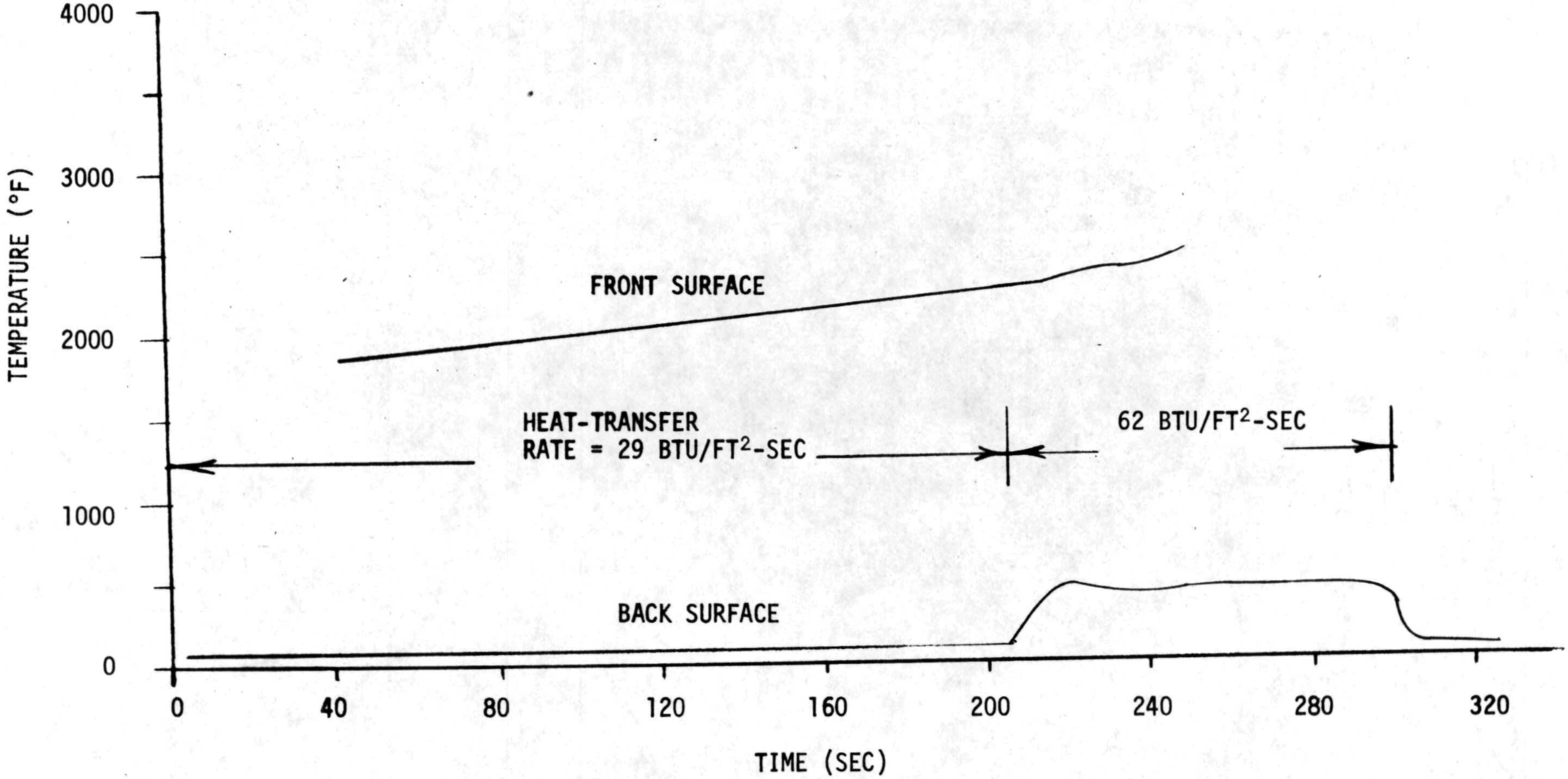

FIGURE 11

FRONT-NAD BACK-SURFACE TEMPERATURES DURING THE TESTS FOR MODEL 5

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FIGURE 12

MODEL 6 AFTER TEST, FRONT VIEW

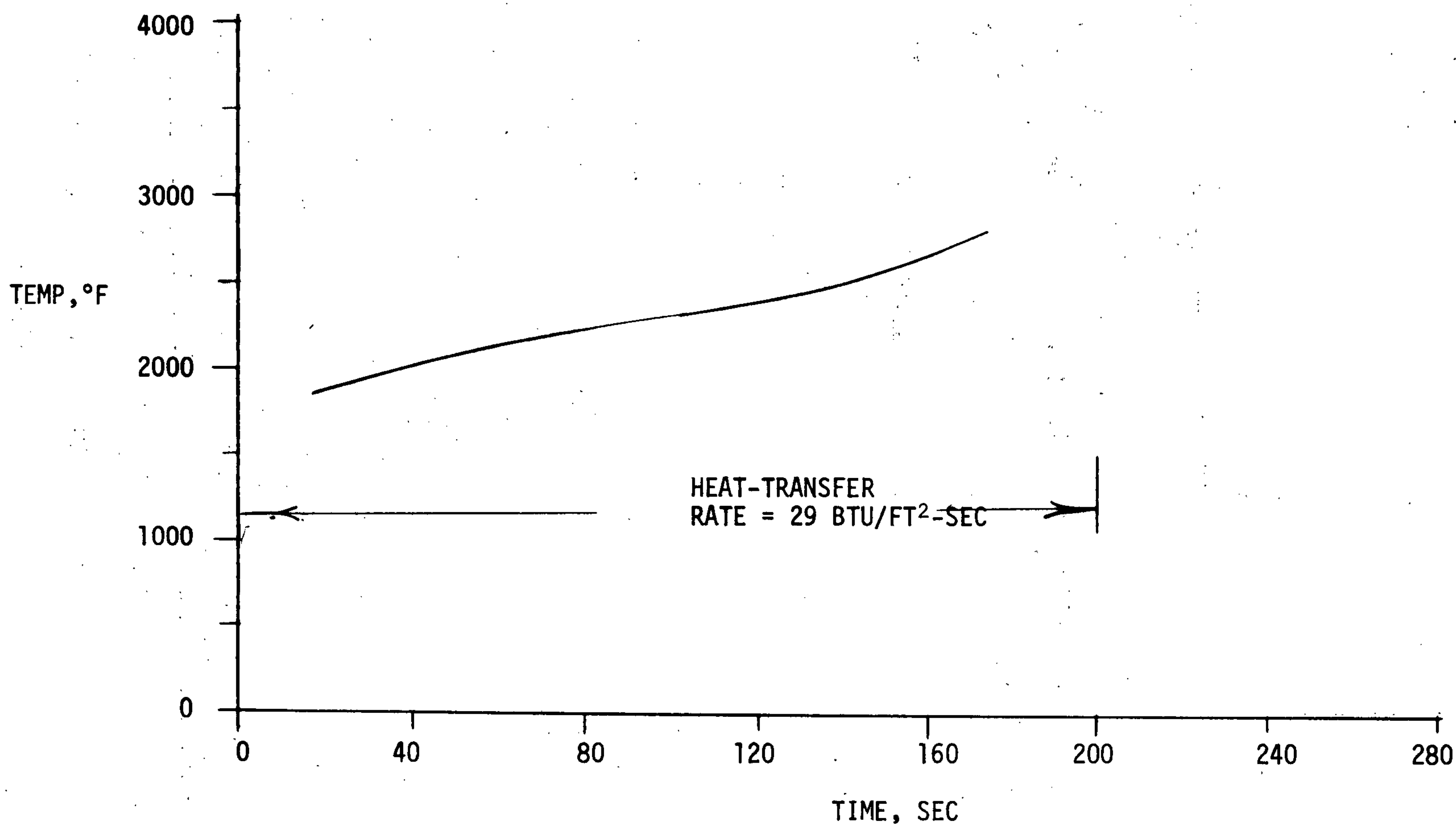

FIGURE 13

FRONT-SURFACE TEMPERATURE DURING THE TESTS FOR MODEL 6

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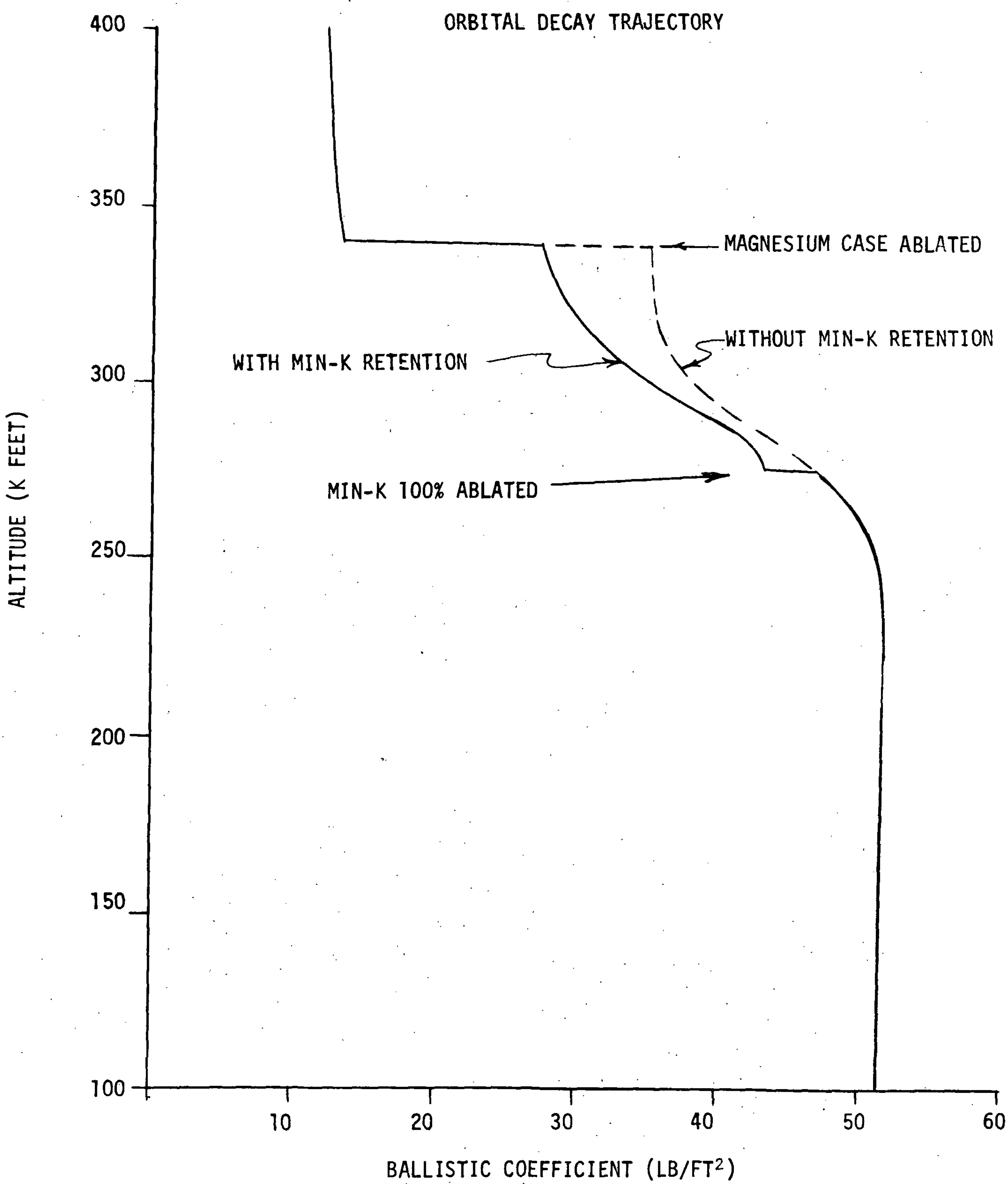

FIGURE 14
BALLISTIC COEFFICIENT WITH AND WITHOUT MIN-K RETENTION

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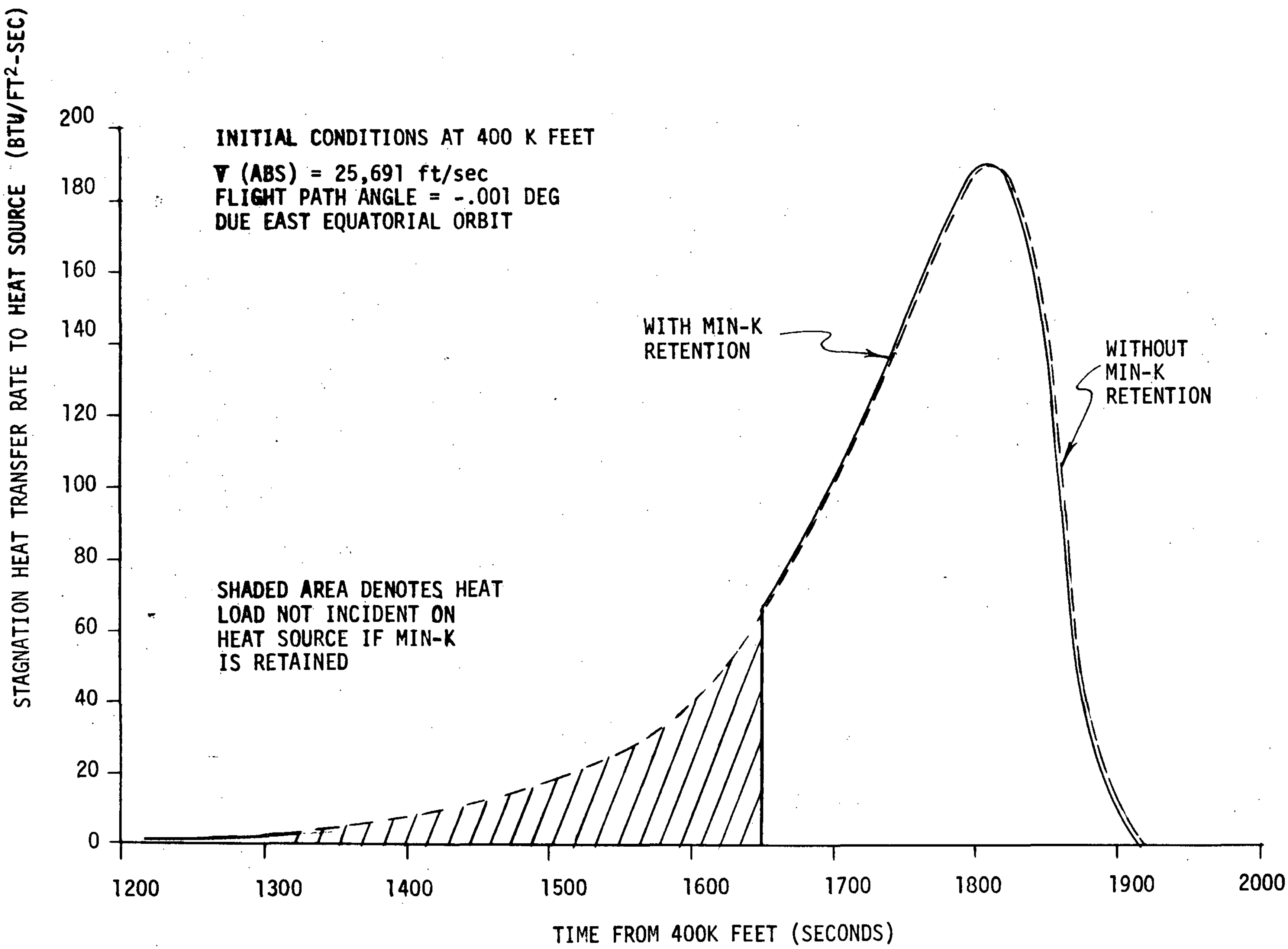

FIGURE 15

HEAT TRANSFER RATE HISTORY, ORBITAL DECAY TRAJECTORY

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