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AN ATMOSPHERE ENTRY SIMULATOR

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INTRODUCTION

The purpose of this paper is to describe an apparatus for simulating the entry of long-range ballistic missiles into the earth's atmosphere. As is well known, such missiles traversing the atmosphere experience severe aerodynamic heating, and the attendant thermal stresses and ablation, melting or burning of the surface present serious problems. An apparatus devised for the study of these problems consists of a model of the atmosphere, scaled as to its density variation, through which a model of the missile is propelled. The model is observed throughout its flight and is recovered for later examination.

NOTATION

A reference area for drag evaluation

C_D drag coefficient

C_f' equivalent skin-friction coefficient

e 2.71828, the base of natural logarithms

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m	mass of missile or model
Q	total heat transferred
S	surface area
V	velocity
V_E	velocity at entrance to earth's atmosphere or simulator
y	altitude
β	constant in the altitude-density relation (fig. 1)
θ_E	angle of missile flight path to horizontal at entrance to earth's atmosphere
ρ	air density
ρ_o	reference air density (simulator reservoir or earth's surface)

PRINCIPLE OF SIMULATION

The simulator discussed here was proposed by A. J. Eggers of the Ames Research Center (ref. 1). It is based on certain simplifying assumptions; notably (1) that radiation has a secondary effect on missile heating, and (2) that gravity has a secondary effect on missile motion. These assumptions are suggested by an analysis (ref. 2) of the motion and aerodynamic heating of missiles entering the atmosphere. To facilitate analysis an exponential variation of atmospheric density with altitude has been assumed which closely approximates the earth's atmosphere between sea level and 200,000 feet altitude, which includes the region of interest.

The basis of simulation is shown in figure 1. The analysis of reference 2 gives the expression shown for the total heat absorbed per unit mass, by a missile which has descended through the atmosphere to altitude y. If we wish to duplicate this quantity in model tests in the simulator, the various factors in the equation must remain the same. Thus for similitude

(a) The same entrance velocity, V_E, for both model and missile is required.

(b) Geometric similarity between missile and model is required, with the resultant duplication of S/A, the ratio of surface to cross-sectional area.

(c) The same Reynolds number for both model and missile is required, which results in the duplication of the equivalent skin-friction coefficient, C_f', and in conjunction with the previous requirement of geometric similarity, duplicates the total drag coefficient, C_D.

(d) The same value of βy is required which means that the density ratio at corresponding points in the atmosphere and the simulator must be the same.

(e) The same value of $C_D \rho_o A/\beta m \sin \theta_E$ is required, which, as shown in reference 1, results in the same missile velocity at corresponding points in the atmosphere and in the simulator.

With these conditions established the total convective heat transfer per unit mass will be duplicated. The requirements for similitude also determine the test chamber length and air density distribution in the simulated portion of the atmosphere. The analysis of reference 1 also shows that the heat-transfer rates for the model are higher in proportion to the ratio of the missile to the model size and that if the model is geometrically similar, the thermal stresses will be duplicated, provided identical materials are used.

APPARATUS AND TEST PROCEDURE

Atmosphere Entry Simulator

A practical simulator based on the requirements set forth above is shown schematically in figure 2. A hypervelocity gun launches the model with the required entrance velocity into the test chamber. The test chamber consists of a supersonic nozzle so shaped that the density distribution follows the required exponential variation with altitude. Compressed air is discharged from the reservoir through the nozzle and is led by a large pipe to an evacuated sphere. It has been shown (ref. 2) that the major part of the aerodynamic heating of a ballistic missile entering the atmosphere occurs within an altitude range of about 100,000 feet. The corresponding density range can be obtained between the reservoir and the exit of a Mach number 5 supersonic nozzle. In contrast to the atmosphere the air in the nozzle is in motion and provides an effective increase in entrance velocity of about 2,300 feet per second. The use of the relative velocity in this manner is permissible to the accuracy of the simulation.

The simulator is operated in the following manner. A copper diaphragm is placed between the reservoir and the nozzle. The reservoir is pumped to the desired pressure, between 100 and 600 pounds per square inch, depending on the altitude range to be simulated. The diaphragm is ruptured by a remotely operated plunger and, after a delay of approximately 1/10 of a second to allow the flow to stabilize, the model is fired from the gun upstream through the nozzle.

In order to test the utility of such a simulator a small-scale unit was constructed with a nozzle 8-1/2 feet long, simulating a 100,000-foot segment of the atmosphere. Models were launched from a 0.22-inch-bore light-gas gun. Encouraging results were obtained with this unit and a larger simulator has been constructed as shown in figure 3. In this photograph the compressed air reservoir may be seen at the left. The nozzle is 40 feet long and simulates a 130,000-foot segment of altitude of the atmosphere. The large pipe in the background leads the air to an evacuated sphere outside the building. The gun which launches the models is located in a separate room on the far side of the pipe.

Figure 4 is a closer view of the nozzle. Optical glass windows at 12 stations along the nozzle permit light-beam-photocell units to detect the passage of the missile model. Signals from these photocells operate electronic counters to give a time-distance history of the flight of the model. From this history the velocity at each point in the simulator can be obtained. The photocell signals also operate through time delay circuits to take spark shadowgraphs of the model in both the vertical and horizontal planes.

Just as missiles are slowed to speeds of the order of 1,000 feet per second or less in traversing the atmosphere, so the model speed is reduced in traversing the simulator. Hence the model may be recovered in a catcher located inside the compressed-air reservoir. If the catcher is filled with soft material, such as sponge rubber, the model will be unaffected by the impact. Much can be learned by examining the surface of the model and by determining its weight loss.

Light-Gas Gun

If the simulator is to be useful in studying the atmospheric entry of long-range ballistic missiles, the models must be launched at muzzle velocities in the range of 16,000 to 20,000 feet per second, giving velocities relative to the air in the simulator in about the range of 18,000 to 22,000 feet per second. The launch gun used is shown schematically in figure 5. It is termed a two-stage light-gas gun because the driving medium, helium, is compressed and heated by a shock process in two stages.

The principal parts of the gun are: the first shock tube of 4-inch bore, the second shock tube of 2-1/4-inch bore, a light piston which operates in the second shock tube, and the launch barrel of 20-mm (0.787 in.) bore. A blast tank with internal baffles is placed at the muzzle of the launch barrel and connected to a vacuum system. Its function is to maintain as low a pressure as possible in the launch barrel up to the instant of firing, and to attenuate the blast of the gun entering the simulator nozzle.

The sequence of operation of the gun is as follows: A model is placed at the breech of the launch barrel and sealed with a light diaphragm. A piston of a plastic, such as Micarta, weighing about 125 grams is placed at the breech of the second shock tube and is held in place by a thin integral shear disk. A charge of smokeless powder is loaded in the breech of the first shock tube and both shock tubes are filled with helium to a pressure of the order of 300 pounds per square inch. When the powder is exploded by an electric primer, a strong shock wave travels down the first shock tube and is reflected from its partially closed end, compressing and heating the helium in this tube, which drives the piston down the second shock tube. The piston, being light, exceeds the speed of sound in the helium ahead of it. Hence a shock wave is driven down the second shock tube which is reflected several times between the end of the tube and the face of the advancing piston. This process compresses and heats the helium to a high pressure and temperature. This helium then drives the model through the launch tube. The maximum pressure of the helium reaches about 100,000 psi. The maximum temperature has not been measured but is estimated to be of the order of 8,000° R from the observed velocity of the projectile. These conditions are favorable for achieving high projectile velocities, and muzzle velocities of over 19,000 feet per second are obtained with models weighing 4-1/2 grams.

A view of the gun is shown in figure 6. The two shock tubes may be seen in the foreground. The launch barrel extends through the opening in the far wall of the room.

EXAMPLES OF RESULTS

As an example of the results obtained from the simulator, figure 7 shows shadowgraphs of a model taken at two stations. These shadowgraphs serve to show if the model is launched intact and if it flies straight and in proper orientation. The apparent distortion of the model is an optical effect due to the high density gradients in the surrounding air flow. Figure 8 shows a comparison of the calculated and experimental variation of velocity with altitude for the test illustrated in figure 7. The characteristics of the missile simulated are listed in figure 8. The curve labeled "theory" was calculated by the method of reference 2 for a missile with the characteristics listed, entering the earth's atmosphere. The experimental points shown are those observed for a model of this missile traversing the simulator. The general agreement between the curves indicates that the velocity at corresponding points in the trajectory is the same for both model and missile, which is one of the requirements for proper simulation. The curves further indicate that the range of altitude covered by the simulator includes the part of the trajectory where most of the velocity of the missile is lost. Since the kinetic energy varies as the square of the velocity and the heat absorbed is proportional to the loss in kinetic energy, it is apparent that nearly all the aerodynamic heating takes place in the portion of the trajectory covered by the simulator.

Figures 9 and 10 are photographs of a model before and after test in the simulator. This model is made of ethyl cellulose plastic. It was tested at an entrance velocity of 18,000 feet per second. The effects of ablation can be seen clearly and the total weight loss may be obtained by weighing the model before and after the test. In figure 11 the profile of a model after test is compared with a template which accurately fitted the model before the test. This photograph was made with a contour projector at a magnification of 10X on the original negative, permitting accurate measurement of the distribution of loss of material. The loss of material from the cylindrical portion of the model is believed to have occurred in the launch barrel of the gun. The total weight loss must be corrected for this effect to obtain the loss due to ablation. Loss of material from the sides of the model in the launch barrel may be avoided by the use of a "sabot" or launching shoe which surrounds the model during launching but falls behind as soon as the model emerges from the gun. This technique however reduces the maximum diameter of missile which can be simulated using a launch barrel of given bore.

The above illustrations show how the simulator may be used to study missile heat shields of the ablation type. Shields of the heat-sink type may also be investigated. Figure 12 shows photomicrographs of a copper heat-shield model before and after test. This model is 0.22 inch in diameter and was tested in the small-scale simulator first constructed. The model copper heat-shield is cemented to the face of a nylon cylinder which, being a poor conductor, should absorb relatively little heat. Although the model was launched at a velocity of only 14,300 feet per second corresponding to a range of about 1,500 miles, it will be noticed that the surface of the copper is considerably altered after traversing the simulator. The concentric machine marks and small scratches on the face are nearly obliterated, indicating that a portion of the outer surface has been melted or burned. Discoloration near the outer edge indicates that this area reached a higher temperature than the center which is in accord with theoretical prediction of convective heat transfer to the flat face of a cylinder. The craters which are noticed in the copper face after test are believed to be caused by impact with minute particles of zinc-chromate paint in the air stream.

A spectrograph of light emitted by the same copper faced model during its passage through the simulator is shown in figure 13. A large number of lines are visible indicating the presence of a number of elements, including several constituents of the aforementioned zinc-chromate paint. This spectrograph probably does not cover the most important range of wave lengths, but is included to indicate the possible use of spectroscopy in connection with the simulator.

CONCLUDING REMARKS

The results of initial experiments with the atmosphere entry simulator encourage us to believe that it will be a useful tool for investigating the re-entry of long-range ballistic missiles into the atmosphere. It may be used as a "go or no-go gage"; that is, if a model survives the traverse through the simulator it may be concluded that the full-scale missile will survive the re-entry trajectory simulated. The apparatus may also be used to compare the performance of different heat-shield materials and different missile shapes with a fair degree of quantitative accuracy, with the objective of minimizing heat-shield weight.

In conclusion it may be well to point out some of the limitations of the simulator. In view of the compressed time scale on which the simulator operates, processes which depend on relaxation times or reaction rates may not be properly simulated if these times are appreciable compared to the time of flow about the missile or model. Also the effect of radiation to and from the surface is not properly simulated because of the foreshortened time scale. These limitations should be kept in mind when interpreting the results obtained.

REFERENCES

1. Eggers, A. J., Jr.: A Method for Simulating the Atmospheric Entry of Long-Range Ballistic Missiles. NACA RM A55I15, 1955.

2. Allen, H. Julian, and Eggers, A. J., Jr.: A Study of the Motion and Aerodynamic Heating of Ballistic Missiles Entering the Earth's Atmosphere at High Supersonic Speeds. NACA Rep. 1381, 1958. (Supersedes NACA TN 4047)

A-24639-1

ALTITUDE-DENSITY RELATION: $\dfrac{\rho}{\rho_0} = e^{-\beta y}$

HEAT ABSORBED PER UNIT MASS AT ALTITUDE, y

$$\frac{Q}{m} = \frac{V_E^2}{4}\,\frac{C_f' S}{C_D A}\left[1 - e^{-\frac{C_D \rho_0 A}{\beta m \sin\theta_e} e^{-\beta y}}\right]$$

FOR SIMILITUDE—

- SAME ENTRANCE VELOCITY, V_E
- GEOMETRIC SIMILARITY—SAME S/A
- SAME REYNOLDS NUMBER—SAME C_f', C_D
- SAME VALUE OF βy
- SAME VALUE OF $\dfrac{C_D \rho_0 A}{\beta m \text{ SIN } \theta_e}$

Figure 1.- Theoretical basis for simulation.

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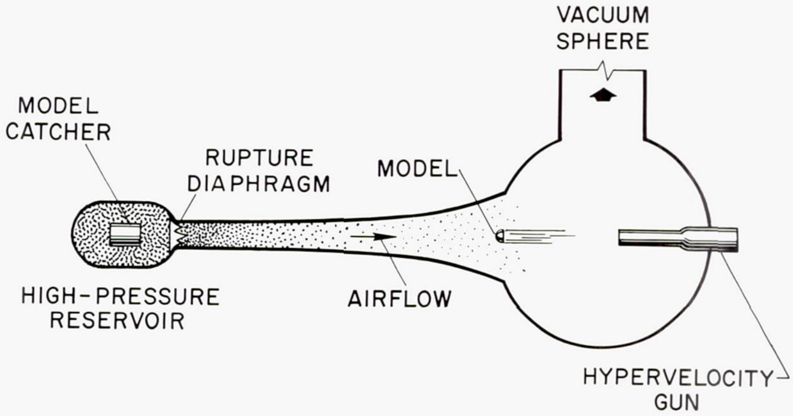
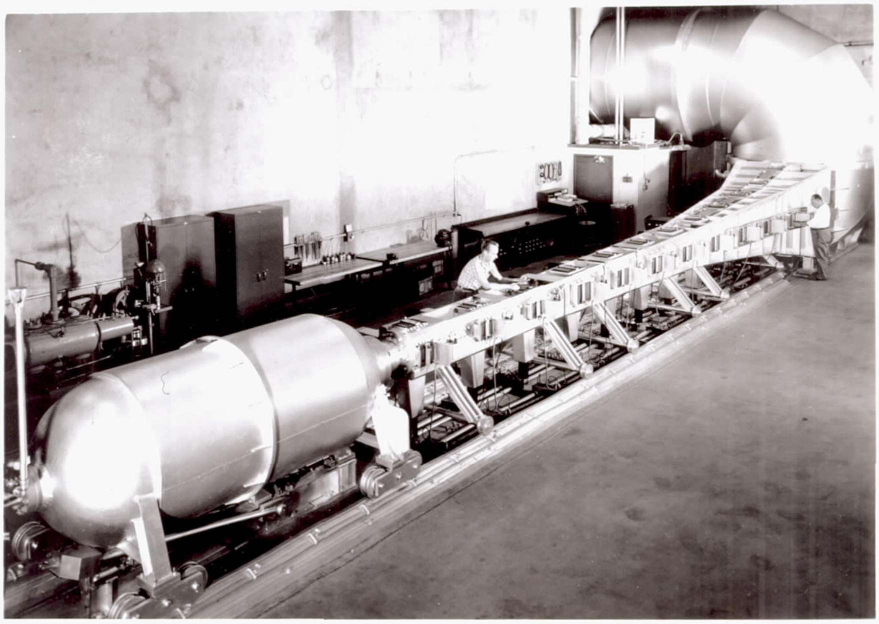


Figure 2.- Schematic diagram of atmosphere entry simulator.



A-24639-3

Figure 3.- Atmosphere entry simulator: Compressed air reservoir and nozzle.

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Figure 4.- View of nozzle.

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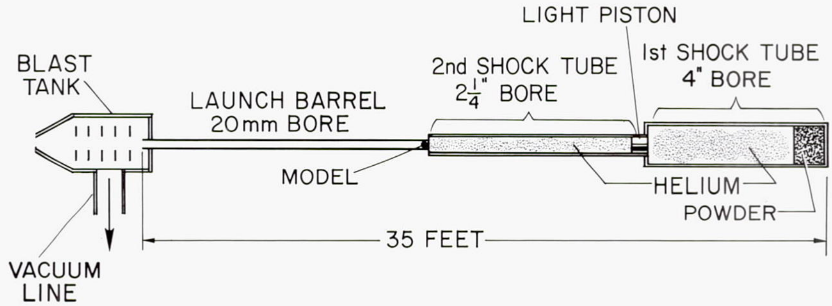

Figure 5.- Schematic diagram of two-stage light-gas gun.

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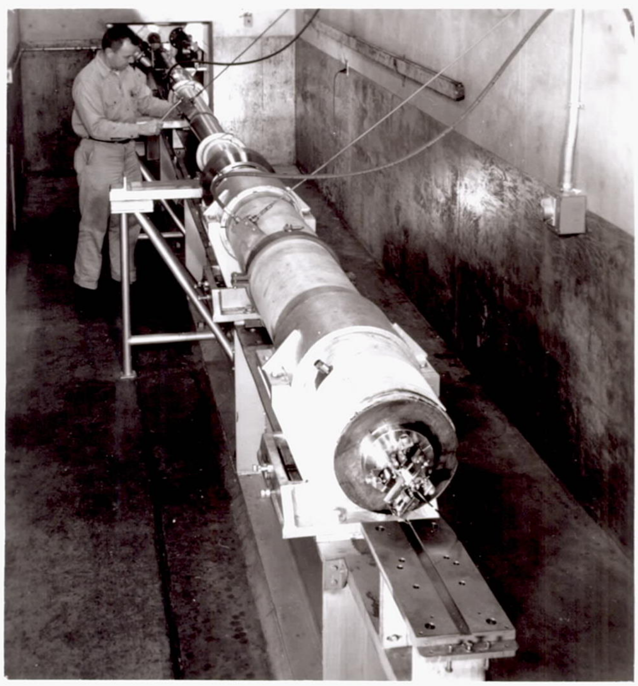

Figure 6.- View of two-stage light-gas gun.

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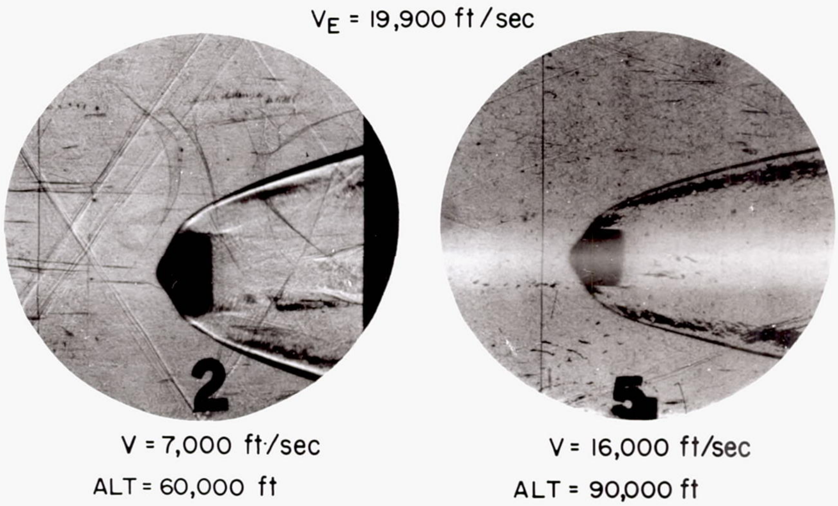

Figure 7.- Shadowgraphs of model in flight.

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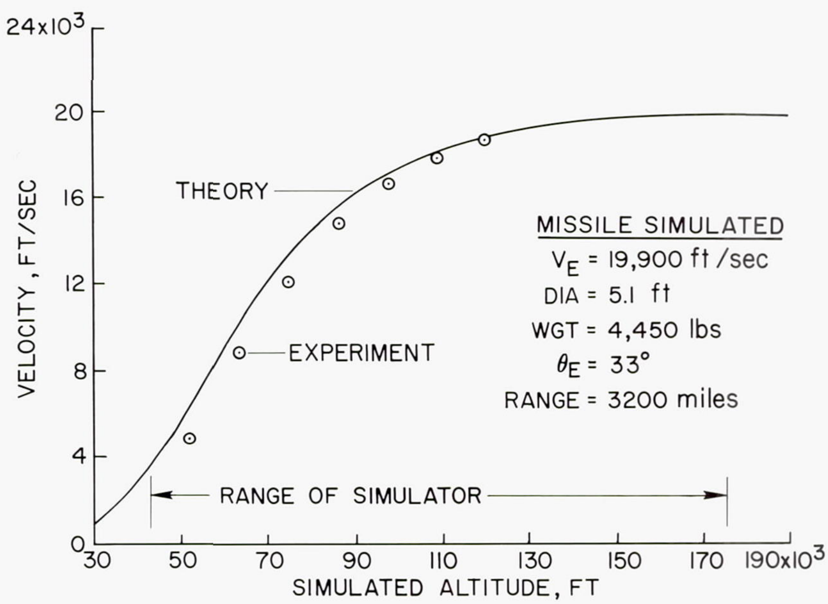

Figure 8.- Comparison of theoretical and experimental trajectories.

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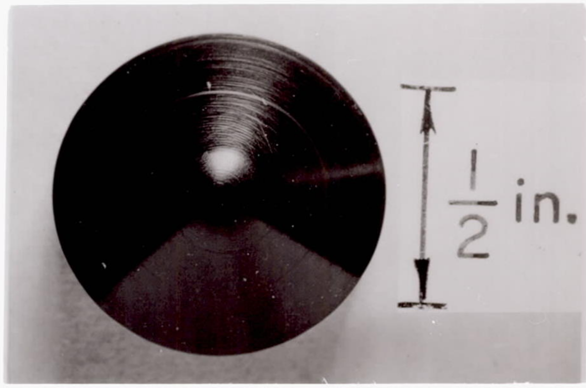

Figure 9.- Ethyl cellulose model before test.

A-24639-10

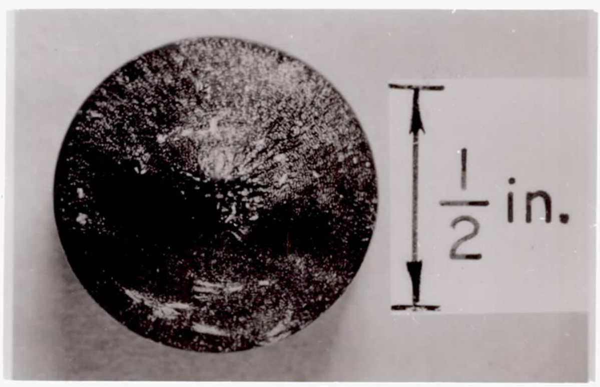

Figure 10.- Ethyl cellulose model after test.

A-24639-11

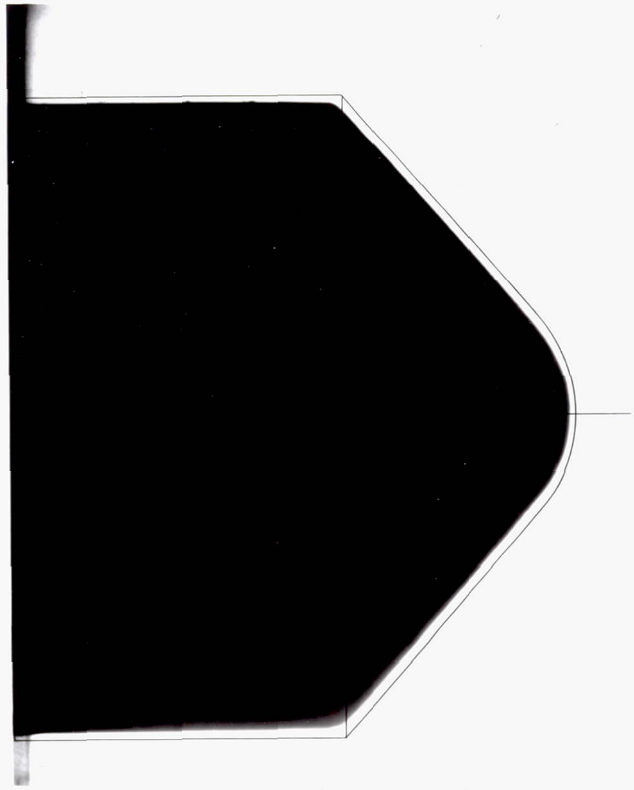

Figure 11.- Profile of model showing loss of material during test.

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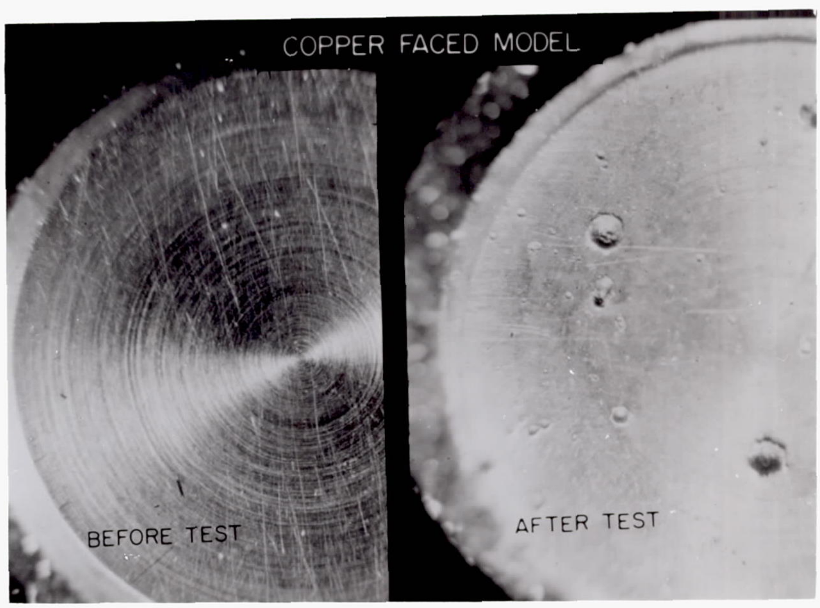

Figure 12.- Copper face of model before and after test.

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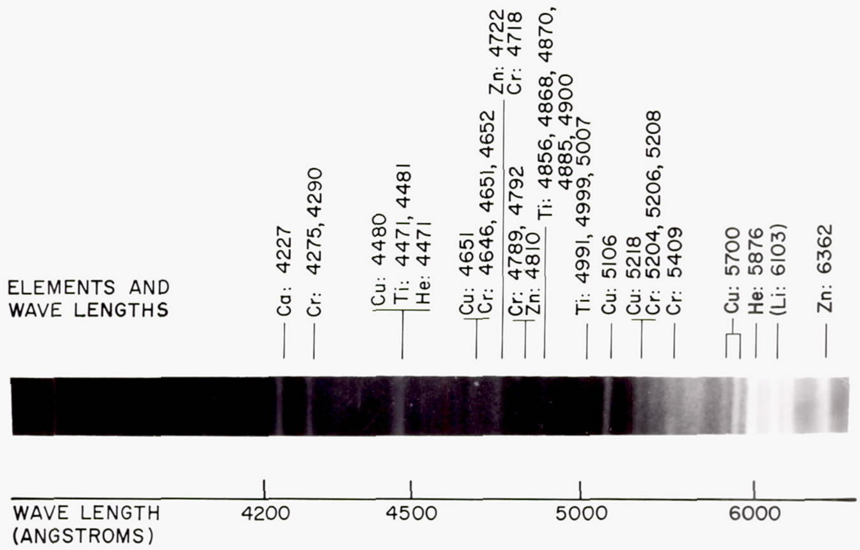

Figure 13.- Spectrum of illumination developed by copper-faced model at a simulated altitude of 103,000 feet and velocity of 11,400 feet per second.