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MICROMETEOROID SATELLITE (EXPLORER XVI) STAINLESS-STEEL PENETRATION RATE EXPERIMENT

by Elmer H. Davison and Paul C. Winslow, Jr.

Lewis Research Center

Cleveland, Ohio



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SUMMARY

A successful experiment to assess the meteoroid hazard to thin stainless-steel skin material was flown as part of the Explorer XVI satellite. A total initial area of 3.625 square feet consisting of 0.001-, 0.003-, and 0.006-inch-thick AISI 304 stainless-steel segments was exposed in space for a period of 221 days. The 0.001-inch-thick surface experienced six penetrations, the 0.003-inch-thick surface experienced one penetration, and the 0.006-inch-thick surface experienced zero penetrations. This report describes the results of the experiment and the conclusions drawn from the results.

INTRODUCTION

Explorer XVI was a satellite experiment developed to assess the magnitude of the meteoroid hazard to present and future spacecraft in near-Earth orbits. One of the experiments aboard Explorer XVI exposed stainless-steel surfaces to determine if these surfaces were penetrated by micrometeoroids. The purpose of this report is to describe the stainless-steel experiment and the results obtained from it.

Explorer XVI was the third attempt to launch a satellite of the S-55 series. It should be noted that all three S-55 payloads were launched by development versions of the Scout vehicle. The first attempt was unsuccessful as a result of a vehicle malfunction. The second attempt, S-55A, was only a partial success, again as a result of a vehicle malfunction; however, S-55A was injected into an Earth orbit and operated successfully for a period of approximately $2\frac{1}{2}$ days before being destroyed by reentry into the atmosphere. The S-55A was designated Explorer XIII upon injection into orbit. Explorer XIII, as did XVI, carried four micrometeoroid penetration-type experiments and one micrometeoroid impact-detecting experiment. Although there were no penetrations recorded by any of the experiments aboard Explorer XIII during its brief lifetime, even this information permitted some important conclusions in regard to the number density of meteoroids in space. The conclusions based on the stainless-steel experiment were reported in reference 1. Reference 1 also gives a detailed description of the development of the stainless-steel ex-

periment, and, therefore, only the modifications to the experiment between Explorer XVI and XIII flights will be described herein. Some of the modifications described resulted from the reassessment made of the space (meteoroid) environment based on Explorer XIII experience.

Explorer XVI was launched on December 16, 1962. One of its two independent telemetry systems ceased transmitting useful data on May 29, 1963. The satellite continued to transmit useful data until July 25, 1963, when the second telemetry system failed. The total area of the stainless steel exposed was approximately equally divided between the two telemetry systems.

For all penetration experiments aboard the satellite, reference 2 presents preliminary data for the first 28 of 221 days of operation. For all but the stainless-steel experiment, references 3 and 4 give preliminary data for the next 133 days. The purpose of this report is to present all the data for the stainless-steel experiment, to analyze these data, and to compare the results with those from other sources. A particularly interesting comparison is made with the data from the beryllium-copper pressure capsules exposed on Explorer XVI. Temperature control of the experiment is also discussed.

DESCRIPTION OF EXPERIMENT

The purpose of the experiment was to detect meteoroid penetration of a surface of known material and thickness. The stainless-steel (AISI 304) material exposed was selected because of the general interest in austenitic stainless steel for space vehicles.

Background

On Explorer XIII, the respective areas and thicknesses of material exposed were as follows:

- (1) 3 Square feet of 0.003-inch-thick stainless steel
- (2) 0.75 Square foot of 0.006-inch-thick stainless steel

This area-thickness distribution was selected on the basis of an estimated variation of penetration rate with material thickness. Other considerations, as noted in reference 1, also determined the area-thickness distribution selected. One important consideration was the ability to detect actual rates that might be considerably different from the estimated rate. In this regard, departures from the estimated rate of two orders of magnitude or more could have been detected by the experiment; however, in the brief time ($2\frac{1}{2}$ days) that Explorer XIII remained in orbit, neither the 0.003-inch nor the 0.006-inch surface was penetrated. In reference 1, analysis of this result indicated that the original estimate of the rate of penetrations was high by at least two orders of magnitude.

Area-Thickness-Distribution Selection

As a consequence of the reassessment of the penetration rates based on Explorer XIII results, it was decided to expose thinner material on Explorer XVI for at least a part of the total area. The area-thickness-distribution selected for Explorer XVI was as follows:

Surface	1	2	3
Area, sq ft	1.50	2.00	0.25
Thickness, in.	0.001	0.003	0.006

The area-thickness distribution selected was based on the following considerations. If the new estimate of the flux were correct (ref. 1), surface 1 would have a high probability (0.78) of recording at least one penetration in as short a period as 2 weeks. Thus, barring the worst of luck, some concrete evidence of the damage capability of meteoroids was expected. Surface 2 was allocated sufficient area to give a high probability (0.62) of at least one penetration if the experiment lasted 6 months. If an experimental lifetime of 6 months were obtained, therefore, there would be a high probability of obtaining at least two points on the curve for penetration rate against material thickness and thus some indication of the slope of the curve would be obtained. The reasonableness of the other assumptions used to generate the estimated curves of reference 1 could also be assessed more accurately with two data points. A difference of at least an order of magnitude in rate of penetration was expected with the thicknesses of surfaces 1 and 2.

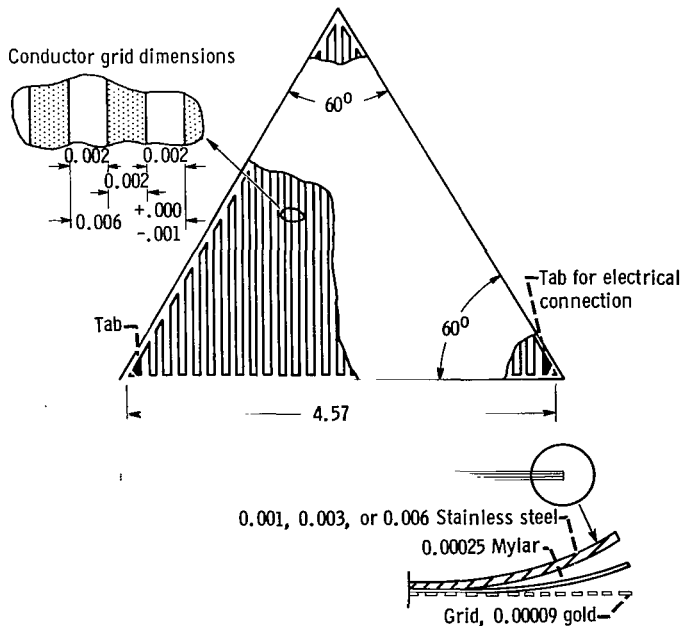


Figure 1. - Gold grid sensor (All dimensions are in inches.)

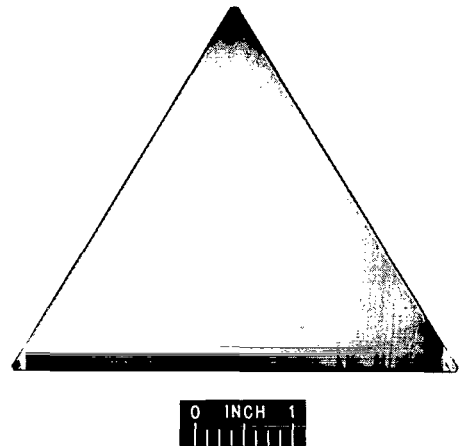


Figure 2. - Sensor with attached lead wires.

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Penetration of surface 3, the 0.006-inch-thick stainless steel, was considered unlikely unless a meteoroid shower of great magnitude was encountered.

Surface 3 also served the other purpose of acting as a control measurement for the experiment as a whole because the surface 3 sensors were not expected to be ruptured by a penetration (i.e., surface 3 sensors were subjected to exactly the same environment as surface 1 and 2 sensors, serving as a check, therefore, that sensor failures were not due to causes other than penetration).

Penetration Sensors

The penetration sensors are described in detail in reference 1; therefore, the following description is brief. The element used to detect penetration of the stainless steel was a very fine gold grid that had electrical continuity. The dimensions and details of this grid are shown in figure 1. The fine gold grid was bonded to a dielectric (Mylar) material, which, in turn, was bonded to the rear (or unexposed) surface of the stainless steel. The sensor mounted on stainless steel with lead wires attached is shown in figure 2. Penetration of the metal surface covering this grid ruptures the grid and destroys its electrical continuity. This change in continuity results in a resistance change in the telemetry circuit that modifies the frequency of one of the transmitted tone bursts.

Area Segmentation

The three surfaces exposed were segmented into smaller areas, and these areas were monitored for penetration by means of the aforementioned sensors. If a skin segment was penetrated by a meteoroid, the sensor associated with the skin segment penetrated would become inoperative. This type of experiment has a self-storing feature and requires power only during interrogation. This feature was considered desirable for this early experiment where it might not always be possible to interrogate the system as frequently as desired and where data could be lost because of poor reception once the satellite interrogation was initiated. Within the design restrictions imposed, it was possible to divide surface 1 into 16 segments, surface 2 into 24 segments, and surface 3 into 4 segments. The segment areas used were either 9 or 18 square inches. The 18-square-inch segments were formed by putting two sensors in series. Although a sensor area of 9 square inches was selected in accordance with early satellite plans, subsequent limitations imposed by telemetry resulted in the somewhat arbitrary grouping of 60 sensors into 44 segments. The restrictions imposed on the experiment in this and other respects are detailed in reference 1.

The manner in which the individual segments were grouped by telemetry channel is shown in table I. The segments were mounted on a cylindrical support structure (see fig. 3(a)); the physical arrangement of the sensors is shown in figure 3(b) in a developed view. In addition to the segments with their associated sensors, four thermistors for surface temperature measurements were located as indicated in figure 3(b). The four thermistors were a matched set for the temperature range of -12° to 112° C.

Sensor Assembly Mounting

One other major change in the Explorer XIII configuration was made for

TABLE I. - EXPERIMENT PARAMETERS

Channel	Exposure parameters				Telemetry circuit parameters				
	Number of segments	Area per segment, sq in.	Thickness, in.	Material	Total area, sq ft	Number of parallel legs per channel	Sensors in series per leg	Percent change of full-scale reading per penetration	Telemetry system
1	8	18	0.001	Stainless steel ↓	1.0	8	2	10.4	A
2	8	18	.003		1.0	8	2	10.4	A
3	4	9	.006		.25	4	1	20.8	A
4	8	9	.001		.5	8	1	10.4	B
5	8	9	.003		.5	8	1	10.4	B
6	8	9	.003		.5	8	1	10.4	B

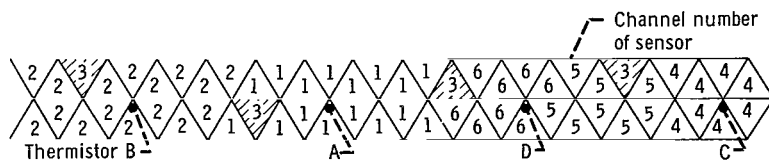
Explorer XVI. For Explorer XIII, the stainless-steel sensor assemblies (fig. 2) were mounted on silicone rubber. On Explorer XVI, the mounting was changed to 1/8-inch-thick urethane foam. This mounting provided the sensors with a floating support and thus made them less susceptible to damage due to distortion of the supporting aluminum structure under thermal and other loads.



(a) Mounted sensors and satellite support structure.

EXPERIMENTAL RESULTS

Explorer XVI was launched on December 16, 1962 from Wallops Island, Virginia at 14:33 Greenwich mean time. The orbit parameters for the satellite were as follows:



(b) Developed view showing sensor distribution by telemetry channel.

Figure 3. - Sensor assembly details.

Inclination, deg 52.00
 Perigee, km 750.2
 Apogee, km 1180
 Anomalistic period, min 104.4

Orbital Telemetry History

Table II shows the orbital telemetry history for the experiment. It should be noted that the area of 0.003-inch-thick stainless steel exposed initially is 18 square inches less than that indicated in table I. It was known

TABLE II. - PENETRATION DATA

Thickness of stainless steel, in.	Time of first interrogation subsequent to event		Time of last interrogation prior to event		Cumulative number of penetrations	Total effective exposed surface area remaining, sq in.	Remarks
	Date	Greenwich mean time	Date	Greenwich mean time			
0.001	12-16-62	14:33			0	216	Launch
	12-19-62	10:10	12-18-62	19:42	1	198	
	1-6-63	9:34	1-4-63	22:04	2	189	
	1-25-63	5:40	1-24-63	5:36	3	171	
	5-13-63	12:39	5-12-63	22:03	5	153	
	5-29-63	7:30	5-28-63	14:46	6	144	
	5-29-63	15:10	5-29-63	7:30	6	36	Telemetry system A lost
	7-25-63				6	0	Telemetry system B lost
0.003	12-16-62	14:33			0	270	Launch (one sensor out)
	5-20-63	19:31	5-20-63	9:38	1	261	
	5-29-63	15:10	5-29-63	7:30	1	135	Telemetry system A lost
	7-25-63				1	0	Telemetry system B lost
0.006	12-16-62	14:33			0	36	Launch
	5-29-63	15:10	5-29-63	7:30	0	0	Telemetry system A lost

prior to launch that one leg (an 18-sq-in. segment leg, two sensors in series) had lost continuity. The loss of these two sensors in series was discovered too near launch to make repair practical, however, and, hence, the experiment was flown as indicated by the launch condition in table II.

For ease of visualization, the area-decrease history shown in table II for each thickness of stainless steel exposed is plotted in figure 4. As noted in figure 4, telemetry system A ceased transmitting useful information on May 29, 1963. This failure reduced the area from which data could be obtained for each

stainless-steel thickness as follows:

Thickness, in.	Area before loss of telemetry system A, sq in.	Area after loss of telemetry system A, sq in.
0.001	144	36
.003	261	135
.006	36	0

The experiment per se was terminated on July 25, 1963 at which time telemetry system B also ceased transmitting useful data.

Penetration Rates

Average rates of penetration were calculated for the 0.001- and 0.003-inch-thick surfaces exposed. The rate was calculated by dividing the number of penetrations for a particular thickness by the area-time product of exposure obtained from either figure 4 or table II (i.e., the area under the re-

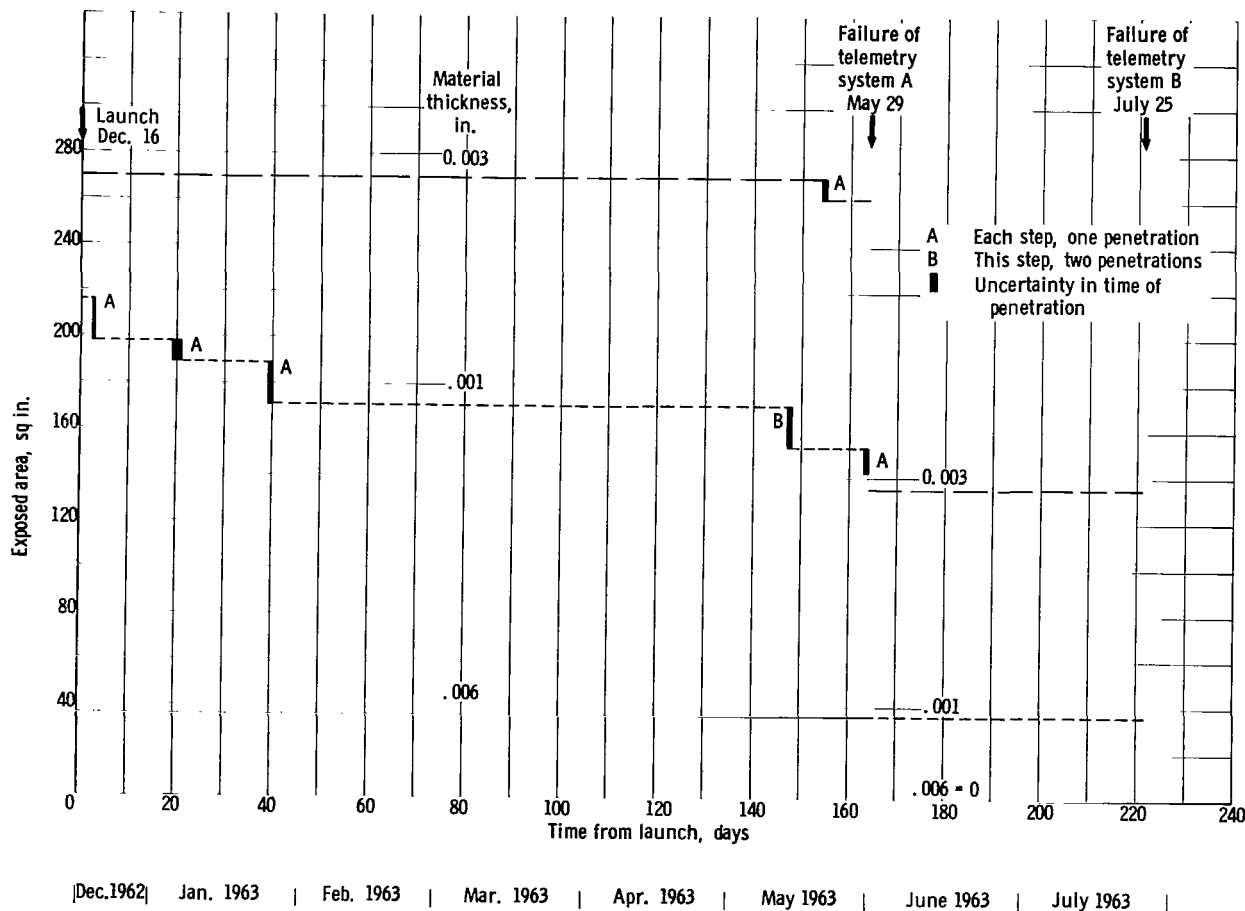


Figure 4. - Area-time history of experiment.

spective thickness curve in fig. 4 is the area-time product of exposure for that thickness). The area decrease due to a penetration was assumed to have occurred at the time of the interrogation that first revealed the penetration. It should be mentioned that the uncertainty of the time of penetration would have only a minor effect on the calculated rate.

The values obtained for the rate of penetration for the 0.001- and 0.003-inch-thick surfaces are plotted in figure 5. A two sigma deviation for the 0.001-inch rate (based on six penetrations or events) is also indicated in figure 5. It is rather questionable that any statistically significant variation can be attached to the 0.003-inch rate of penetration, which is based on only a single penetration. The rate does, however, represent a best estimate.

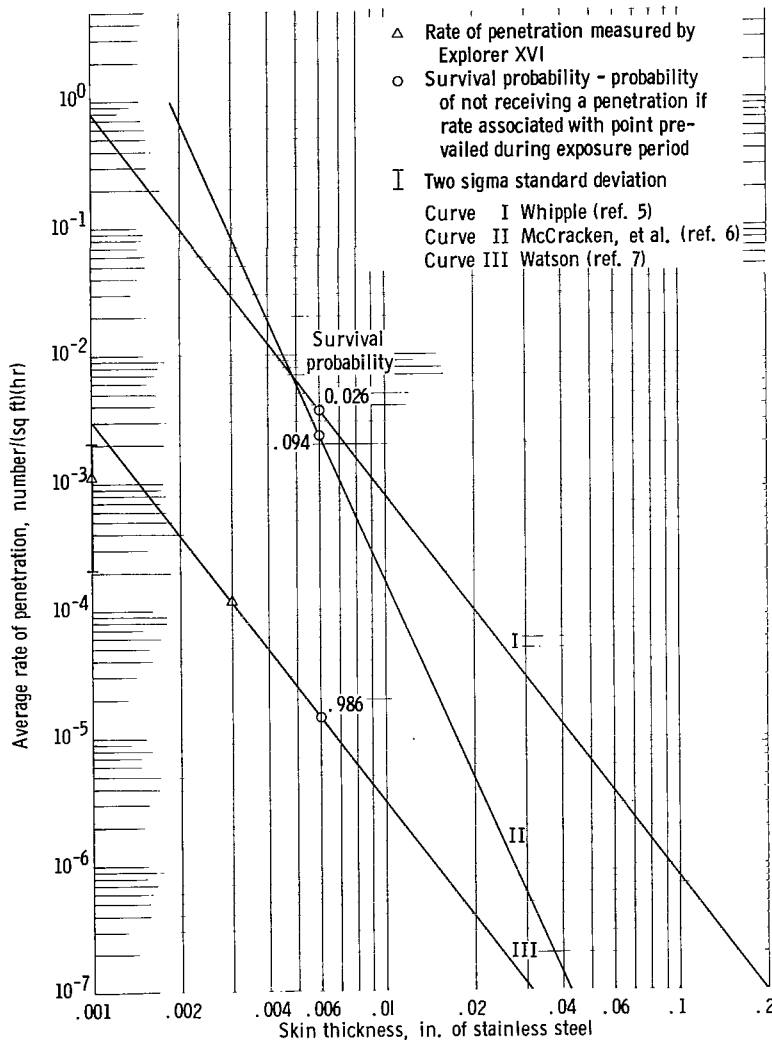


Figure 5. - Penetration rate data and estimates based on following assumptions: impact velocity, 15 kilometers per second; micrometeoroid density, 2.7 grams per cubic centimeter; Summer's penetration criteria for quasi-infinite targets (ref. 8) multiplied by 1.5.

Shown also in figure 5 are three estimates of the rate of penetrations against thickness. These estimates are the same as those shown in the Explorer XIII report (ref. 1). The following assumptions in conjunction with the mass-flux distributions indicated were used in estimating rates: (1) an impact velocity of 15 kilometers per second, (2) a micrometeoroid density of 2.7 grams per cubic centimeter, and (3) Summers' penetration criteria for quasi-infinite targets (ref. 8) multiplied by a correction factor of 1.5 for a thin sheet. Earth-shielding effects are not incorporated in the comparisons of the estimated against measured rates because the effect is minor and not clearly definable. The effect would increase the measured rates at most by a factor of approximately 1.3 relative to the estimated rates. With the rate uncertainties involved, the Earth-shielding effect is considered inconsequential.

The reader should note that the estimate of curve 1 is based on an early flux prediction by Whipple (ref. 5). This curve is presented in figure 5

merely to be consistent with reference 1 and because it represents one of the higher early estimates. Neither curve I nor II represents a good estimate of the rate of penetration to be expected in light of the data shown in figure 5 from Explorer XVI (i.e., the measured penetration rates for the 0.001- and 0.003-in. stainless steel and survival probability calculated for the 0.006-inch stainless steel are only consistent with the rate estimates of curve III). This result was anticipated from the data presented in reference 1. Curve III does represent a reasonable rate estimate for the data obtained to date. As indicated in figure 5, the survival probability¹ for the 0.006-inch surface based on the rate obtained from curve III was 0.986. The fact that no penetrations were recorded in the 0.006-inch surface is consistent, therefore, with the estimate given by curve III, which is consistent also with the data obtained from Explorer XIII and Vanguard III (see ref. 1). Of greater importance, however, is the fact that curve III is consistent with the more statistically significant data of reference 4 as well. The data have more statistical significance because the exposed area of 0.001-inch-thick beryllium-copper was approximately seven times that for the stainless-steel experiment.

The combination of assumptions used to arrive at the estimates of curve III fits the measured data; however, other combinations of assumptions could probably be made to fit equally well. The agreement between curve III and Explorer XVI data should be viewed, therefore, with the preceding facts in mind. It should be further recognized that the slope of curve III has not been firmly substantiated by the experimental data nor has the validity of the curve been substantiated for thicknesses of material greater than those exposed on Explorer XVI. It should also be remembered that only very gross results were obtained from the stainless-steel experiment because of experimental limitations.

The data presented in reference 4 for the beryllium-copper can experiment warrants further comment because it compliments the data presented herein. Rates of penetration calculated from both sets of data are consistent even though two entirely different techniques of measurement were employed. A comparison of the penetration rates and/or the survival probabilities in the event of zero penetrations for the two experiments is shown in figure 6. The rates and survival probability shown in figure 6 for the beryllium-copper can thicknesses exposed were calculated on the same basis as those for the stainless-steel experiment, figure 5. No effort was made to equate a beryllium-copper thickness to an equivalent thickness of stainless steel for comparison purposes. The two materials can be considered as roughly equivalent in stopping power, and any difference in this regard is overshadowed by the uncertainty in measured rates and difference in measuring technique. It can be seen from figure 6 that these data from the two experiments agree reasonably well. The

¹The survival probability, based on Poisson statistics, for a surface exposed in space is calculated from the following equation: $P_0 = e^{-rat}$ where r is the average rate of penetration anticipated, a is the area of surface exposed, t is the time of exposure, and P_0 is the survival probability or probability that there will be no penetrations in area a in time t if rate r is the prevailing average rate.

agreement between data obtained by two entirely different techniques gives added confidence to the validity of the data from either experiment.

Comparison With Radar Meteor Data

It can be noted from figure 4 that the penetrations recorded for the stainless-steel experiment were grouped into two time intervals. The one interval (involving three penetrations) occurred during late December through late January. The other time interval (involving four penetrations, one of which was in the thicker 0.003-in. material) covered the last half of May, after which a sharp reduction of exposed area occurred due to the loss of data

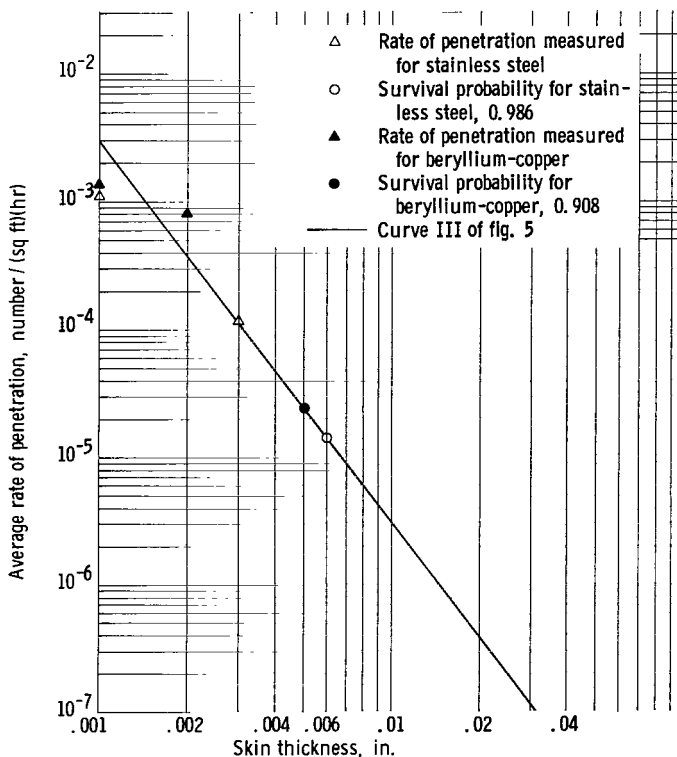


Figure 6. - Penetration rate data comparison. Beryllium-copper can data of reference 4 compared with stainless steel data of figure 5.

from telemetry system A. It is of interest to note that the latter period of penetration activity occurred during the most active annual period of radar meteor recordings as noted in reference 9. The other period of penetration activity occurred during a similarly active (but less pronounced) annual period of radar meteor recordings in the December-January time interval. The lack of any penetrations during the February-March-April period also corresponds to the most quiet period of the year for radar meteor recordings. It might also be noted from reference 9 that active known showers occur during or near both periods of penetration activity. Unfortunately, the data reported herein for the stainless-steel experiment are too few to do other than point out as an interesting observation the correlations noted.

The data of reference 4 for 0.001-inch-thick beryllium-copper did not show a pattern similar to that discussed in the preceding paragraphs; however, the 0.002-inch-thick beryllium-copper did have an inactive period during February and March corresponding to the period of low radar meteor activity. Unfortunately the relative sensitivity (capacity for being triggered by penetrating particles) of the two detecting devices was never established, and it is quite likely that the 0.001-inch cans and 0.001-inch stainless-steel sensors are not equally sensitive. Therefore, the data from the two experiments should not be compared thickness for thickness except in the very gross sense as in figure 6. In any event, the observations noted for the stainless-steel experiment were considered interesting even though they must at this point be considered inconclusive. They do serve, however, to indicate the need for larger more sophisticated satellite experiments capable of resolving the meteoroid hazard characteristics of the space environment more effectively.

Thermal Control Results

The temperature recorded by the four thermistors located as shown in figure 3(b) are plotted in figure 7. No attempt to control temperature, other than to limit the maximum, was made. The surface coatings used for thermal control were required to maintain the sensor assemblies at temperatures less than 120° C. Temperatures of the order of 65° C or less were preferred (ref. 1). The temperature history of the experiment proved satisfactory, although a substantial number of the temperature readings were lower than the calibrated range (-12° to 112° C) of the thermistors. Modest circumferential variations in temperature were noted. The maximum difference between any two thermistor readings was of the order of 15° C with the difference, in general, being considerably less. There appeared to be a general warming trend with time for the experiment, but because of the nature of the experiment and the data, the trend cannot be conclusively established. The thin coating of white paint (approx. 0.0005-in.-thick sprayed coating) was expected to discolor with time as a result of exposure to solar ultraviolet radiation. A higher ratio of absorptivity to emissivity is associated with the discoloration (see ref. 1), and consequently a higher equilibrium temperature would be expected. The expected trend could easily be masked, however, because the experiment represented only a small fraction of the total mass of the satellite. The temperature data are interesting primarily because they indicate that very thin layers of paint are effective in controlling temperature over extended periods of time (i.e., at least 7 months). The results demonstrate that inexpensive coatings, which are easily applied, can be used for thermal control of space vehicles. As a frame of reference it might be pointed out that uncoated stainless steel could easily exceed a temperature of 120° C in a space environment.

As noted in reference 4, a malfunction of telemetry system A occurred on April 19, 1963 that invalidated the time-coded data. As a result, data from thermistors A and B are not shown subsequent to the malfunction because they were part of the invalid time-coded data. Data from thermistors C and D, however, did show that satisfactory control of the package was maintained for the life of the experiment. It should be noted also that the temperature data

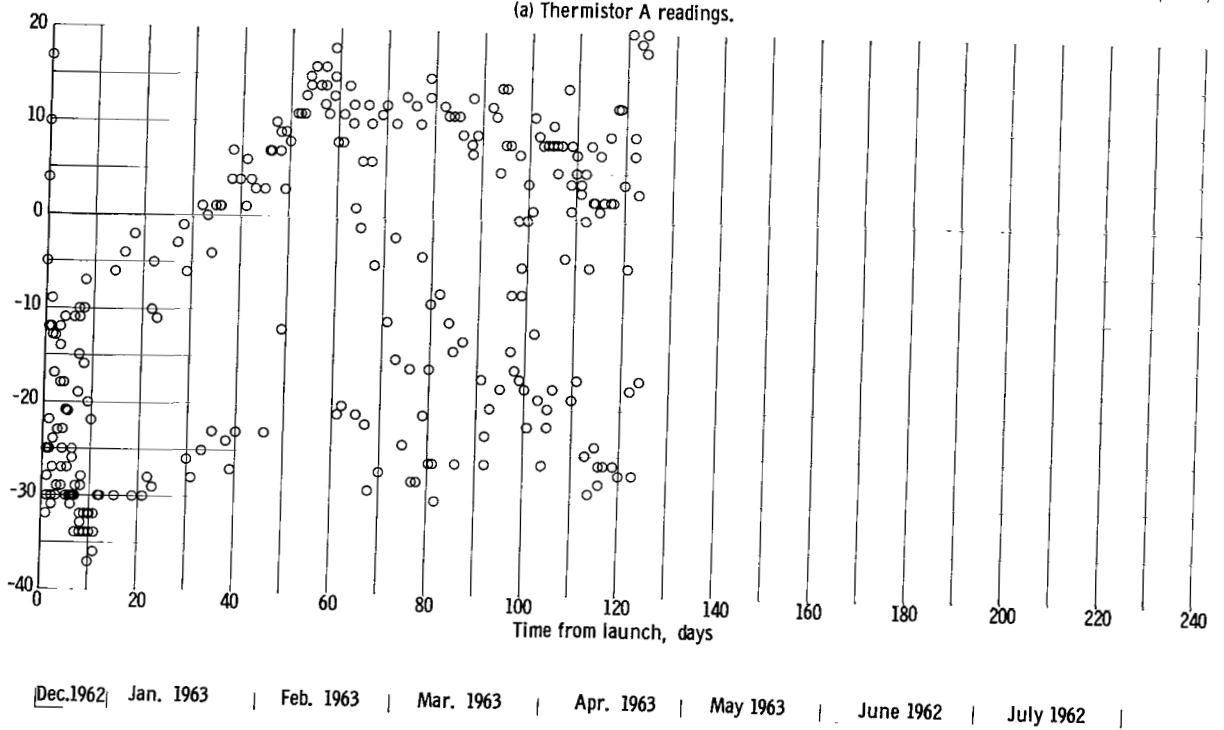
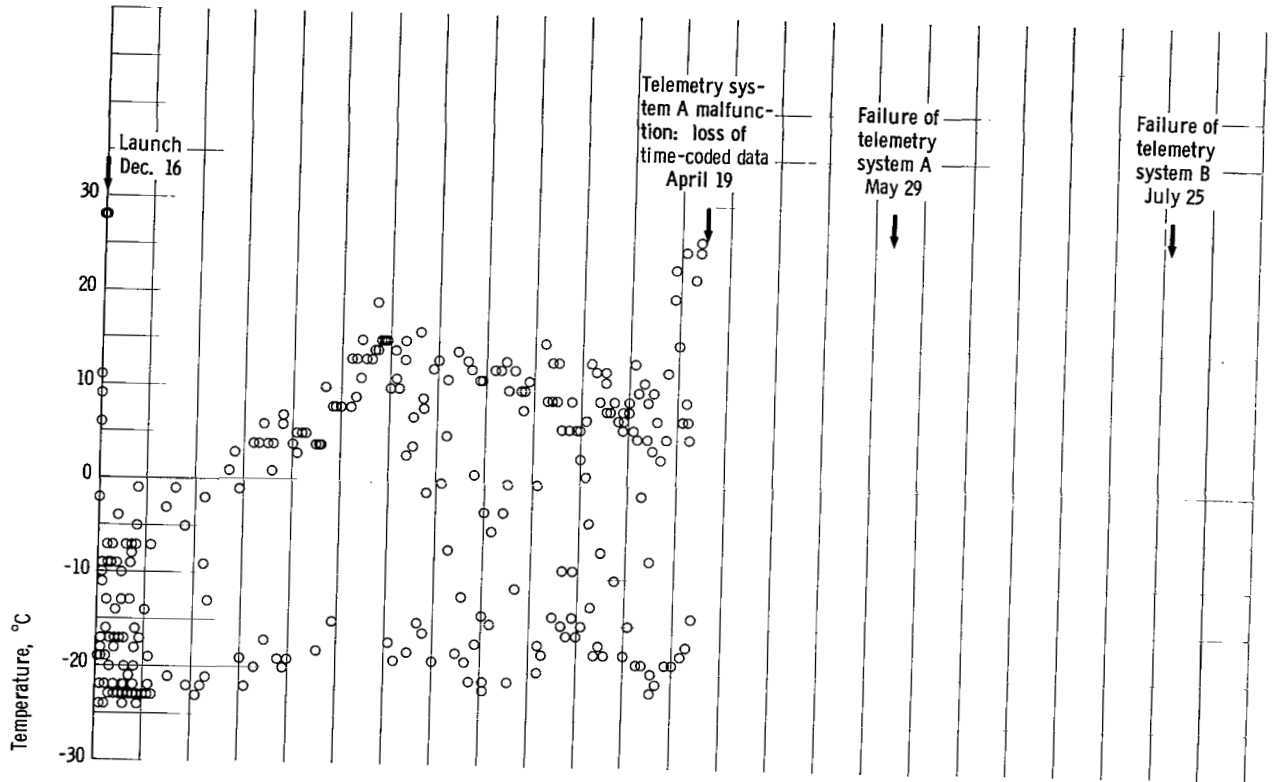
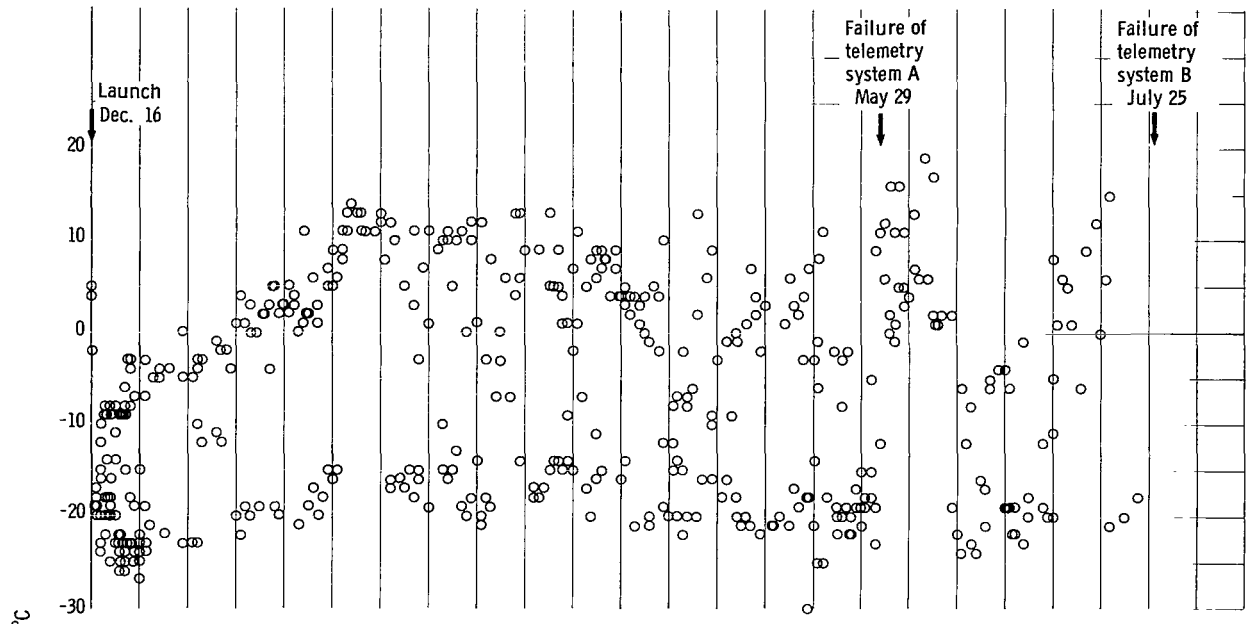
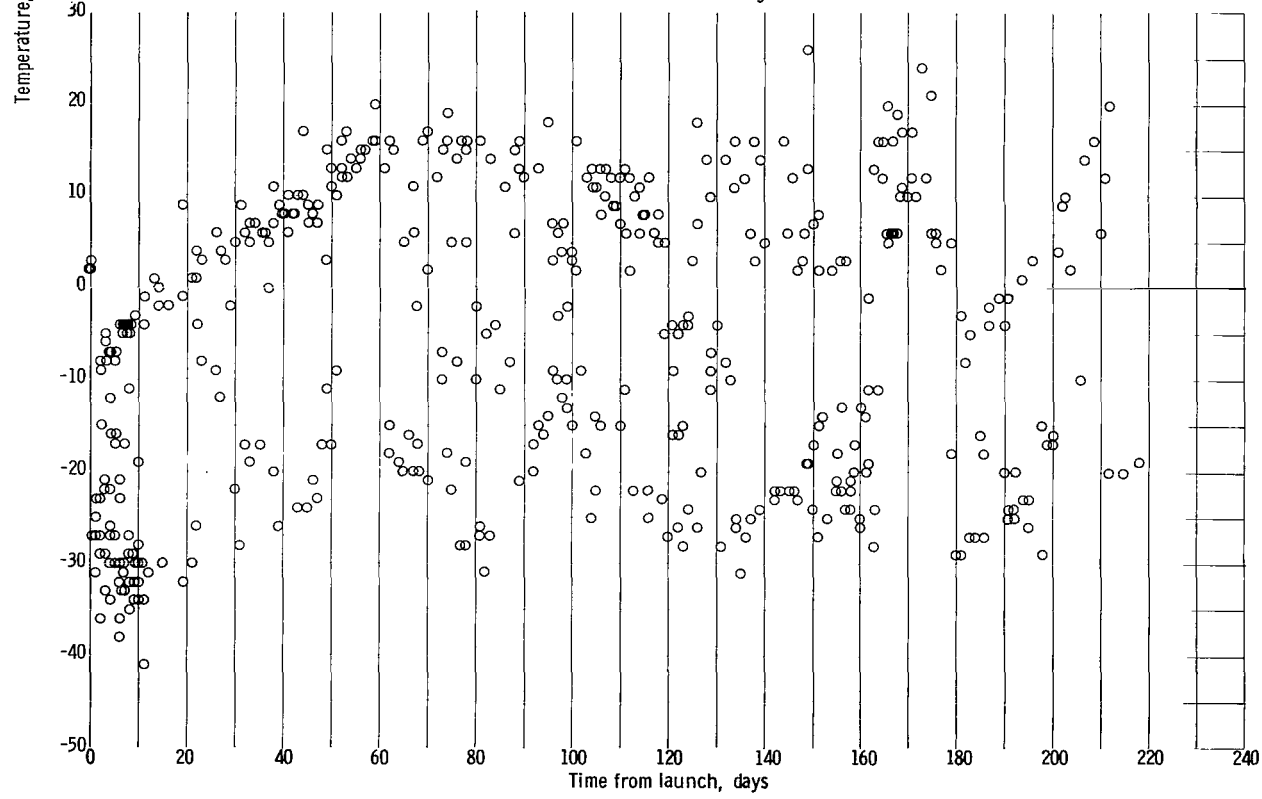


Figure 7. - Thermal history of experiment.



(c) Thermistor C readings.



(d) Thermistor D readings.

Dec. 1962 | Jan. 1963 | Feb. 1963 | Mar. 1963 | Apr. 1963 | May 1963 | June 1963 | July 1963

Figure 7. - Concluded. Thermal history of experiment.

below -12° C is based on an extrapolation of the calibration curves and, hence, is subject to some additional inaccuracy. The accuracy cited in reference 2 for similar thermistor data within a calibrated range is $\pm 5^{\circ}$ F.

CONCLUSIONS

The Explorer XVI experiment to obtain data on the rate of penetration of stainless steel by micrometeoroids was successful. The following conclusions were reached:

1. The experimental data was consistent with that obtained from the pressurized can experiment also carried on Explorer XVI.

2. The measured rates of penetration for stainless-steel thicknesses of 0.001 to 0.003 inch agree reasonably well with predicted penetration rates based on Watson's mass-flux distributions and the assumptions of (a) meteoroid density, 2.7 grams per cubic centimeter, (b) meteoroid impact velocity, 15 kilometers per second, and (c) Summers' penetration criteria. It should be noted, however, that other sets of assumptions could be selected to estimate rates that would also agree with the data. The slope of the rate curve (i.e., variation of rate of penetration with material thickness) is also not well defined by the data.

3. The thermal control measures taken to maintain the surface temperatures of the experiment within acceptable limits were adequate. The successful thermal control demonstrated that spray coatings of a suitable paint of about 0.0005 inch thickness can be relied on to control satellite temperature over a period of at least 7 months.

Lewis Research Center

National Aeronautics and Space Administration
Cleveland, Ohio, May 20, 1964

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