# A STUDY OF CERAMIC LINERS FOR UNCOOLED ROCKET MOTOR CHAMBERS

Thesis by

Major Leroy C. Land, (CAC) FA

United States Army

In Partial Fulfillment of the Requirement for the Degree of

Mechanical Engineer

California Institute of Technology

Pasadena, California

1948

## ACKNOWLEDGMENTS

The author is indebted to many persons who have assisted directly and indirectly with the experimental work and the large amount of associative work necessary to perform the actual tests and prepare this thesis. He wishes particularly to thank Dr. Louis G. Dunn, Director of the Jet Propulsion Laboratory and Dr. Martin Summerfield of the Laboratory for extending to the author the facilities of the Laboratory, and allowing the experimental work to be done with these facilities. Mr. R. B. Canright of the Laboratory provided the author with his indoctrination into this field and supervised the experimental work.

The present form of this thesis is largely the result of the careful review and very helpful suggestions of the author's adviser, Dr. Pol Duwez. Much helpful criticism of the draft manuscript was given by Dr. Donald S. Clark and Dr. Donald E. Hudson.

The actual preparation of the manuscript was the result of the very efficient and conscientious efforts of the author's wife and Mrs. Mary Ankeny of the Jet Propulsion Laboratory.

## ABSTRACT

The purpose of this study was to test certain ceramic liner materials in a liquid propelled, uncooled rocket motor chamber to determine the best type liner material and study the temperatures encountered on the chamber casing wall and the outer ceramic liner wall.

The liner materials zirconia, zircon, beryllia and silicon carbide were tested in a stationary test rocket motor using acid-aniline propellant.

From this study it was determined that rocket motors using a zirconia chamber liner and operated under test conditions could be fired for periods up to approximately 220 seconds.

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# I. INTRODUCTION

There are two main purposes for using ceramic liners for rocket motor chambers. The first purpose is to reduce the heat transfer through the chamber thus making possible the use of regenerative cooling with liquid propellants that could not otherwise be used with conventional type rocket motors. The second purpose is to simplify the design of short-duration rocket motor chambers.

Previous work at the Jet Propulsion Laboratory has been directed toward the reduction of heat transfer through the chamber walls. In previous tests it was found that the best type ceramic chamber liners reduced the heat transfer to the chamber coolant by as much as 79 per cent.

The present work is concerned with the testing of ceramic liners for the purpose of determining which types of ceramic liners showed the most promise for use in uncooled rocket motor chambers of simple design.

In general, the liners used in the ceramic liner tests conducted at the Jet Propulsion Laboratory have been pure oxides or combinations of pure oxides. However, in addition to the oxides, carbides and various types of carbon liners have been tested. All the liners tested had a melting point above 3700°F.

Listed in Table I are the liners that have been tested at the Jet Propulsion Laboratory in a cooled rocket motor chamber.

The liners used in this study were selected on the basis of the results of the tests carried out with cooled chambers, and are listed in Table II.

Studies have been made at the Jet Propulsion Laboratory concerning the physical properties of various ceramic materials, including those materials used in this series of tests. The physical properties of interest to this study are included in this report as Table III and Figure 1.

## II. DISCUSSION OF THEORETICAL ANALYSIS

A theoretical analysis is not being made at this time because the physical properties of the materials at the temperatures encountered in this study are not known. It will be noted by observing Figure 1 that the thermal conductivities for the materials tested were determined in a temperature range from approximately 500°F to 1350°F. Since a theoretical analysis is largely dependent on the thermal conductivity of the material being investigated, it is obvious that this physical property must be determined quite accurately at the temperature of the analysis. For a theoretical analysis to accompany this experimental study, the thermal conductivity must be determined for temperatures near the melting points of the ceramic materials used.

At a first glance it might appear that an extrapolation of the curves presented in Figure 1 would serve the purpose. This was attempted for a one dimensional heat flow analysis, but the correlation between theoretical and actual temperature versus time curves was very poor and was discarded as valueless.

It is quite certain that at high temperatures the thermal conductivity of a porous material, such as used in these liner studies, increases rapidly. At low temperatures the thermal conductivity is determined by conductive heat transmission and is low because of the poor conductivity of the gases in the pores of the material and the low conductivity of the solid portions of the liner. At high temperatures, however, the heat transmission is increased by the effect of radiation through the pores of the material. Since heat transmission by radiation varies as the fourth power of the temperature difference and heat transmission by conduction varies as the first power of the temperature difference, the rate of increase of the value of thermal conductivity should be greater at higher temperatures. It is therefore quite obvious that an extrapolation on Figure 1 for high temperature thermal conductivities would be very dangerous and misleading. In this connection it should be noted that the porosity of the materials used varied between 20.8 and 37.3% as shown in Table III.

Even if the physical properties of the materials were known accurately, the analysis would be complicated by many different factors. Heat is being extracted from the liners at both ends. Both the injector and the nozzle are cooled--the injector by the liquid propellant and the nozzle by the coolant. The gas temperature varies from point to point both longitudinally within the chamber and circumferentially about the chamber. This can be observed in the various figures showing the condition of the liners after the tests. Heat is being radiated from the outer casing wall in a sizable amount. Computations considering black body conditions show that approximately 15% of the heat flowing through the liners is radiated from the chamber casing wall when a chamber casing wall temperature of $1450^{\circ}F$ is reached. The physical properties of the liner materials usually vary with temperatures.

Since the problem presented here is clearly a complicated three-dimensional heat flow problem, it is quite necessary to look for assumptions that can be made to simplify the problem considerably and still give a fairly accurate appraisal of what really happens. As in most heat flow analysis problems, average values of physical properties can be taken and a one-dimensional heat flow problem can be assumed as a first approximation. Only transient heat flow need be considered in such an analysis since steady state conditions will never be reached at the chamber temperatures encountered with an acid-aniline, liquid propellant rocket motor.

## III. EXPERIMENTAL PROCEDURE

All tests were made in a standard test pit as used at the Jet Propulsion Laboratory. All testing was done on a stationary test stand. The test stand was located in a test pit which was separated from the control room by thick concrete walls. Multiple thickness safety glass windows were provided for viewing the rocket motor under test from the control room. Figure 3 shows a test motor on the stationary stand. This figure shows the necessary plumbing to provide fuel, oxidizer and coolant water to the test motor as well as the various test connections to provide performance data. In this particular case, a rocket motor with a watercooled unlined chamber is on the test stand. This motor was used as a standard motor in checking out the system to be used in this study. Figures 4 and 5 show a ceramic-lined uncooled motor in place on the test stand.

The rocket motor used in this study was a 750-pound thrust motor using aniline ($C_6H_5NH_2$) as a fuel and red fuming nitric acid ($HNO_3$+$NO_2$) as an oxidizer. The nitric acid contained approximately 6.5% by weight of $NO_2$.

The motor was of simple design consisting principally of an injector, a nozzle, a chamber casing and a ceramic liner. Figures 6 and 7 show the main components of the rocket motor as disassembled and as assembled. The injector (see Figure 8) was of the multi-orifice type with the orifices yielding six impinging streams. A stainless steel adapter ring as shown in Figures 9 and 10 was necessary to fit the injector to the chamber casing and still allow the liner to fit loosely within the chamber casing. The nozzle was a copper, chrome plated nozzle as shown in Figure 11. The chamber casing was made of 347 stainless steel and provided the container for the ceramic liner. It was originally designed as shown in Figure 12 but later modified to adhere to the design shown in Figure 13. This change was necessitated by faulty design in the case of Figure 12. The liners to be tested were made of stabilized zirconia, zircon, beryllia, and silicon carbide (see Table II). For the physical dimensions of these liners see Table IV. Figure 14 shows a photograph of the four different liners before being tested.

The silicon carbide and zircon liners as received from the manufacturer were of such dimensions as to be easily inserted into the chamber casing without altering the outside diameters. However, the outer diameters of the beryllia and zirconia liners had to be reduced so as to fit into the casing.

A prepared liner was then placed in the chamber casing and the nozzle, injector adapter ring and injector were bolted to the casing. The thermocouples used to measure the temperature of the outer wall of the ceramic liner were then placed in the thermocouple wells provided on the casing. A gas-tight seal was obtained around the thermocouple leads by use of a gasket of No. 76 Sauereisen cement and powdered asbestos. This gasket-seal also held the thermocouple junction in contact with the ceramic liner wall throughout the test. Figures 4 and 15 show the thermocouple wells with some thermocouples in place. Figure 16 shows the location of the thermocouple well on the inside of the chamber casing wall. Thermocouples were then affixed to the outer wall of the chamber casing. Figure 5 shows these thermocouples in place on the casing. These two sets of thermocouples gave the primary temperature data for this study. Data concerning these two sets of thermocouples are given in Figure 2 and Table V. Temperature measurements were also taken of the coolant water for the nozzle. This measurement was accomplished by using a differential iron-constantan thermocouple pile and gave data regarding the heat flow through the nozzle with the various liners. A record of this heat flow is given in Table I, Appendix I.

All temperature data were recorded on recording potentiometers as indicated in Table V, except one control thermocouple attached to the chamber casing and shown as being attached to a calibrated millivoltmeter. More is said of this control device in the following paragraphs.

During the operation of the rocket motor the following data were also recorded: Flow rates of fuel, oxidizer and coolant water to the nozzle; the total consumption of fuel and oxidizer during a test; regulating pressures on the fuel and oxidizer supply tanks; thrust developed by the motor; chamber pressure of the motor; and the various pressures in the system so as to indicate line losses and injector losses in the pressure system.

The length of test possible during this study was controlled by one of two conditions. The first criterion was that tests were cut off if the calibrated millivoltmeter at the control panel indicated a temperature of approximately 1450°F. This millivoltmeter was connected to the thermocouple nearest the nozzle end of the test motor and recorded the highest temperature along the length of the chamber casing. If the rocket motor ran relatively cool and the outer chamber wall temperature did not reach 1450°F, the length of test was determined by the capacity of the oxidizer supply tank. This tank held approximately enough oxidizer for tests of 180 seconds at the mixture ratios and oxidizer flow rates used.

All tests were made by starting the motor on reduced flow rates of fuel and oxidizer (approximately 1/6 of normal flow rates). The reduced flow operation lasted only one to three seconds. As soon as the motor had started on the reduced flow the full flow rates were established through the use of solenoid operated quick opening valves. In this manner the initial shock to the motor was lessened and usually any malfunctioning of equipment was noted during the starting phase of the operation and could be corrected before full flow operation was attempted.

## IV. DISCUSSION OF RESULTS

The results obtained in this study can be evaluated in many different ways. The evaluation of merits of the various liners tested will be compared by the following methods:

1. The length of run possible under the conditions of the test.
2. The rise in temperature on the outer wall of the chamber casing.
3. The rise in temperature on the outer wall of the liners.
4. The condition of the liner after a test.

Any evaluation of liner materials for rocket motors must be carefully correlated with the physical properties of the material. Probably the two most important physical properties of a ceramic liner are its melting point and its thermal conductivity. Unfortunately, practically nothing is known of the thermal conductivity of the liner materials used in this study above temperatures of approximately 1350°F. Although thermal conductivities are known for the materials tested between the temperatures of 80°F and 1350°F, these values are of little significance at the temperatures encountered in these experiments, as indicated in Section II.

It is well to discuss those items that are common to all the tests before giving individual results for the various liners.

All liners were cracked during the testing. There were at least three contributing factors for this. First, the thermal stresses were very high through the liner. Although the gas temperature was not measured, it is quite certain that the temperatures were between 4000° and 5000°F. The thermal stresses set up by virtue of the large temperature differences between the cold outer surface of the liner and the heated inner surface of the liner at the outset of the test, were exceedingly large. Second, some cracking was undoubtedly the result of the stresses set up by the impulse imparted to the liner when the initial chamber pressure of 300 pounds per square inch absolute was established within the chamber. Third, all liners fitted quite loosely in the chamber casing, thus allowing the chamber pressure to force the liner out against the chamber casing wall. In only one out of twelve tests did any trouble result from this liner looseness. This occurred in one test of silicon carbide and will be noted in the individual evaluation.

In studying the various curves presented in this report it must be borne in mind that very large temperature gradients existed throughout the chamber section of the motor. Since a water cooled nozzle was used in this group of tests and the injector was cooled by the large quantity of fuel and oxidizer that flowed through it, both ends of the chamber were kept at relatively low temperatures. Both the injector and the nozzle were kept at temperatures between 100°F and 250°F throughout the tests. During the tests the chamber casing wall temperatures at a distance of 2-1/16 inches from the nozzle end of the chamber reached temperatures as high as 1450°F while the outer wall of the ceramic liners reached temperatures as high as 2450°F at a distance of 1-3/4 inches from the nozzle end of the chamber. It is a known fact that the gas temperatures within the chamber are not uniform from the injector end to the nozzle end of the chamber. It is assumed that the maximum gas temperature (near 5000°F) occurs near the nozzle end of the chamber. Furthermore, it can readily be seen by looking at any of the photographs of a liner after a test that the temperatures around the circumference of the chamber were not uniform. This shows up by the uneven melting and eroding of the liners as well as the injector patterns on the liner. With the various gas temperatures from point to point within the motor chamber it is quite obvious that heat is flowing in three directions at each point. This heat flow is radially out through the liner and casing, longitudinally along the liner and the casing, and circumferentially around the liner and casing. As is illustrated in Figure 15, the temperature measurements on the liner wall and the outer casing wall were taken at arbitrary points longitudinally along the motor. It is quite obvious that the highest temperatures of the liner and the casing walls were not necessarily recorded during these tests. Unfortunately time, materials, and measuring equipment available did not permit more tests or more temperatures to be taken during each test. A comparison of the curves as a whole presented in Figures 27, 36, 42, and 44 which are plots of time versus temperature of the outer ceramic wall will show quite clearly that the maximum temperature longitudinally along the chamber will be measured at or very near $1\frac{1}{2}$ inches from the nozzle end of the chamber. At distances of $\frac{1}{2}$ inch from the nozzle end the cooling effect of the cooled nozzle against the ceramic liner is shown quite conclusively by the tendency for the curves to level off and approach steady state conditions. This is also true of temperatures measured at distances of 2-3/4 inches and greater from the nozzle end of the chamber. This theory accounts for the tendency of many of the curves to appear to be approaching steady state conditions when it is known that melting and eroding is occurring to the liner.

Many materials go through allotropic transformations with increasing temperatures. These lattice structure transformations are not desirable for ceramic liner materials primarily because the transformation is normally accompanied by an expansion or contraction of the material. For this series of tests the materials chosen do not change lattice structure with increasing temperatures.

The test pit provided for this study did not have a means of varying the mixture ratio of oxidizer to fuel and it was necessary to make all tests using restrictors in the fuel and oxidizer lines to provide the desired mixture ratio. Once the desirable mixture ratio was established the restrictors were not changed during the entire group of tests. It was necessary, however, from time to time to change injector orifices due to corrosion and burning of the orifices. Unfortunately, the mixture ratios obtained from test to test varied and since control of mixture ratio was next to impossible with the test set-up as it existed, this condition was accepted as an error introducing variable. Since the average mixture ratios during individual tests varied from 2.91 to 3.45 there resulted a considerable variation in motor performance throughout the group of tests.

At this point it is well to introduce the parameter used in comparing motor performance of rocket motors. This parameter is called the "characteristic velocity" and is given by the symbol $c^*$.

$$c^* = \frac{p_c\, f_t}{m} = \frac{p_c\, f_t\, g}{w}$$

where: $p_c$ = rocket motor chamber pressure

$f_t$ = throat area of nozzle

$m$ = rate of flow of mass through the nozzle

$w$ = weight rate of flow through the nozzle

$g$ = acceleration due to gravity

It is seen that the characteristic velocity is determined only by quantities related to the combustion chamber and the nozzle throat dimensions. Since it is independent of exit conditions, it can actually be considered as a parameter of the combustion process. Another expression can be shown where $c^* = f(T_c/M)$ where $T_c$ is the chamber temperature and M is the molecular weight of the propellant. It is, therefore, shown that large values of the parameter c* are dependent on high chamber temperatures and low molecular weight of the propellant. Thus a high value of the characteristic velocity will indicate a high chamber temperature developed by a small amount of propellant and consequently shows high motor performance. Appendix I gives further data on the parameter c* as well as individual performance data for each test. A study of these data presented in Appendix I will show that one test with a liner of zirconia gave the highest performance data (c* = 4880 ft/sec based on sight glass readings of fuel and oxidizer consumption), one test with a liner of beryllia gave a c* = 4800 ft/sec, one test of a zircon liner gave a c* = 4730 ft/sec and one test of a silicon carbide liner gave a c* = 4590 ft/sec. As is borne out in the individual discussion of results of the various liners that follows this section, the performance data as obtained strengthens the conclusions as to the best type of liner tested.

## V. RESULTS OF EXPERIMENT
## ZIRCONIA (LZO-73)

Zirconia is interesting as a liner material primarily because of its high melting point (4928°F) and its relatively low thermal conductivity.

Unfortunately, pure zirconia normally has a monoclinic structure at room temperature and exists in other allotropic forms at elevated temperatures. It has been found, however, that it can be made to have a cubic structure at all temperatures up to the melting point by the addition of other oxides to it. The particular zirconia used in this experiment was stabilized by the addition of calcia. Since stabilized zirconia was used it was to be expected that there would be no changes in lattice structure during these tests.

Four tests were made with the stabilized zirconia type liner. The first test (B-83-N) was stopped after 121.1 seconds because of a malfunctioning of a pressure gage. A visual inspection of the liner after this test showed that some melting and erosion had occurred in the two-thirds of the liner nearest the nozzle. However, the condition of the liner was such as to make it usable again. Figures 23, 25, and 26 show the condition of the liner and nozzle after this test. A second test (B-84-N) was then made using this same liner. The duration of this run was 147.2 seconds and was stopped because of the limited amount of oxidizer available. (Following this test the capacity of the oxidizer storage tank was increased.) An inspection of the liner after this test showed that the liner had melted and eroded quite badly and in one place the liner thickness had been reduced from 0.375 inches to 0.120 inches. This point of melting was 2.25 inches from the nozzle end of the chamber and can be seen in Figure 29. Other photographs showing the liner condition after a total test time of 268.3 seconds are shown in Figures 28 and 30. A second series of two tests was made using a stabilized zirconia liner. The total test time for this second series was 363.5 seconds. The liner after these runs (B-89-N and B-91-N) had the same appearance as Figures 28 and 30. The minimum thickness of the liner after these two tests was 0.26 inch.

Figures 19 and 27 show graphs of time versus temperature for the tests mentioned above. It will be noted from Figure 19 that temperatures of the outer chamber casing wall only reached a value near the predetermined cut-off temperature of 1450°F during the second test of a series on the same liner. An extrapolation of the test giving the greatest rate of heating for a new liner (B-83-N at a point 4 inches from the nozzle end of the chamber) shows that it could be expected that a zirconia liner operated under the same conditions as the test could be fired for approximately 220 seconds before the outer wall of the chamber casing reached a temperature of 1450°F. Data available on 304 stainless steel indicate that at temperatures of 1700°F the tensile strength is great enough to provide a factor of safety of 4 in a chamber casing of the same design as used in this test and operating with a chamber pressure of 300 pounds per square inch absolute. Since it has been found that the hottest point along the length of the chamber is somewhere near a point $1\frac{1}{2}$ inches from the nozzle end, it is well to assume that 1450°F at 4 inches from the nozzle end is a maximum allowable temperature until the actual temperature is known at the hottest point. If Figure 27 is now considered it will be seen that the temperatures measured here are also relatively low compared to the gas stream, and that there is nothing to indicate that a test as predicted from Figure 19 is not possible. It will be noted from all the curves as presented in Figures 19 and 27 that a steady state condition is not approached in these tests. It is entirely probable that instead of the curves tending to "level out" or show a decreasing rate of heating as would be the case when a steady state condition is being approached, the curves would tend to show an increasing rate of heating. This tendency would be due to the melting and eroding of the liner and is reflected in the curves representing the second test on the same liner.

Reference to Figures 28 and 29 will show that melting and eroding occurred quite near the injector end of the chamber. In this case, it is believed that the melting and eroding rates were high enough at places other than the vicinity of the hottest region of the motor to cause all the curves of Figure 28 to show more or less constant rates of heating throughout the experiment. This is the only series of tests wherein temperature measurements away from the hottest point of the chamber liner did not show decreasing rates of heating with increasing time. This can be explained by viewing Figures 28 and 29 and noting that melting and erosion occurred in about 2/3 of the total length of the chamber. Since all temperature measurements were taken in the region in which melting and erosion occurred, it is believed that the melting and erosion rates were high enough in this region to keep the curves of time versus temperature of Figure 27 more or less straight lines.

The performance data for the tests of zirconia were the highest obtained for any of the liners tested. This means that the chamber gas temperatures were higher for these tests than for any of the other materials tested and, therefore, this liner was given the most severe test of the lot.

## ZIRCON LZS-78

Zircon is an interesting liner material because of low thermal expansion characteristics, high melting point (4532°F), good thermal shock characteristics, and its relative cheapness of manufacture.

Three tests were made with this type of liner. The first test (B-85-N) was for a duration of 110.5 seconds and was halted by a motor burnout as shown in Figures 31 and 32. This failure showed the need for a redesign of the chamber casing and resulted in a chamber casing of the design shown in Figure 11. Figures 17 and 18 show the replacement of the metal lip of the original design with a ceramic ring of the same material as the chamber liner. Figure 31 shows the blistering effect that is usual in zircon liners. Figure 32 shows the usual cracking in a loosely fitted liner. In this relatively short test it was found that the liner had eroded to a minimum thickness of 0.26 inch at a distance of 1.75 inch from the nozzle end of the chamber. A second series of two tests was made on the same type liner. The first test (B-92-N) ran for 181.5 seconds with the modified chamber design. Figure 33 shows a photograph of the liner after this test. The projections into the chamber cavity are blisters that have flaked off the liner. The second test of this series (B-92-N) was for 173 seconds and was cut-off when the outer chamber casing reached a dangerous temperature. Figures 24, 34, and 35 show the condition of the liner and nozzle after the total run time of 354.5 seconds. The minimum thickness of the liner after this series was 0.10 inches.

Figures 20 and 36 show graphs of time versus temperature for the tests mentioned above. It will be noticed from Figure 20 that temperatures of the outer chamber casing wall reached a value near the predetermined cut-off temperature of 1450° only in the case of the second test on a liner. An extrapolation of the test giving the greatest rate of heating for a new liner (B-85-N at a point 3-13/16 inches from the nozzle end of the chamber) shows that it could be expected that a zircon liner under the same conditions as test conditions could be operated for approximately 195 seconds before the outer wall of the chamber casing reached a temperature of 1450°F. It will be noted that the rate of heating through zircon is higher than for zirconia. The curves of Figure 36 show a general tendency toward a reduced rate of heating with an increase in time. This can be explained by the statement made in the discussion section of this report wherein it was postulated that all temperature measurement at points away from the hottest points of the chamber casing would have a tendency toward approaching steady state conditions. It will be observed from the data appearing on Figure 36 that no temperature measurements were made at approximately 1½ inches from the nozzle end of the liner. If such a measurement had been made it is assumed that the curve of temperature versus time would approach a straight line curve.

The performance data for this series of tests were lower than for zirconia or beryllia and thus indicated that the chamber temperatures were lower. The lower chamber temperatures undoubtedly contributed to the decreasing rate of heating with time.

## SILICON CARBIDE (2509)

Silicon carbide is an interesting liner material because of low thermal expansion characteristics, good thermal shock characteristics, and its relatively high melting point or decomposition point. (Silicon carbide decomposes at a temperature above 4060°F in air.) Whether silicon carbide decomposes or melts is a function of the atmosphere around the material.

Three tests were made with silicon carbide. In the first test (B-88-N) a very loosely fitting liner was used. The test lasted for 63 seconds at which time a motor burnout caused the test to be terminated. This motor burnout was a direct result of the sloppy fit and the large cracks developed in the liner. Figures 37, 38, and 39 show this motor failure. It is the belief of this writer that the failure was caused by a piece of the liner falling from the inner face of the chamber casing wall and allowing the hot gases to come in direct contact with the metal wall. The piece of liner fell from the liner because the cracks were so large.

A series of two runs was then made with the silicon carbide liner cemented into place with a paste of magnesia. The average thickness of this layer of magnesia was 3/64 inches. Under these conditions cracking was very trivial and no trouble was encountered. The first test of this series (B-94-N) for 121.0 seconds and the second test (B-95-N) ran for 113.0 seconds. Figures 40 and 41 show condition of liner after test B-94-N. Both of these tests were ended when the outer casing wall reached a temperature of 1450°F. It is interesting to note that the minimum thickness of the liner after test B-88-N was 0.34 inches and the minimum thickness of the liner after runs B-94-N and B-95-N was 0.30 inches. This shows that after a total test time of 234.0 seconds approximately 0.07 inches of the silicon carbide liner had been eroded away as compared to 0.25 inches erosion and melting with zirconia for somewhat comparable testing times. By comparing the melting and erosion effect of zircon and zirconia it is seen that they are quite comparable and thus silicon carbide is a more rugged liner than either. This shows the silicon carbide liner to be a very rugged liner with a high overall thermal conductivity. Figures 21 and 42 show plots of time versus temperature for this type liner. By extrapolation on Figure 21 as done for zirconia and zircon it is found that tests of approximately 105 seconds could be run in the case of uncemented silicon carbide and tests of approximately 130 seconds could be run in the case of cemented silicon carbide before an outer chamber casing temperature of 1450°F was reached. Although only a very thin thickness of magnesia was used in cementing the silicon carbide into the chamber casing, it tended to reduce the heat transmission to the outer chamber casing wall by a considerable amount. In this connection it must be remembered that the thermal conductivity of silicon carbide is approximately thirty times that of magnesia.

As in the case of zircon, Figure 42 shows a reduced rate of heat transfer with time for silicon carbide. This is quite understandable in this case since the thickness of the liner was not being substantially reduced during the test. It will also be noted that all temperature measurements showing a decreasing heating rate were made at points away from the hottest points. The one temperature curve made for a point $1\frac{1}{2}$ inches from the nozzle end of the liner again showed more or less a constant heating rate up to a point just before the test was discontinued. It is also possible in this series of tests that the magnesia filler used and the low performance of the motor might have contributed to the tendency for the curve to approach steady state conditions.

BERYLLIA (LB-30)

This liner material is interesting for two primary reasons. It has a high melting point (4658°F) and a small weight per unit volume (0.069#/cubic inch as compared to zirconia - 0.144 #/cubic inch - and zircon - 0.125 #/cu. in.).

Two tests only were made with this liner. The first test (B-86-N) was for a duration of 87.4 seconds and the second test on the same liner (B-87-N) was for a duration of 68.1 seconds. Figure 43 shows the liner condition after test B-86-N and Figures 45 and 46 show the liner condition after the second test. A study of the photographs presented in Figures 45 and 46 shows the presence of chipping on the liner face. This is characteristic of a beryllia liner. The "chipped-out" area of Figure 46 has a minimum liner thickness of 0.24 inches. This represents a reduction of 1/3 from the original liner thickness. Although melting and eroding was not observed with this type of liner, the chipping of the liner resulted in a condition that is as serious as any other means of reducing the liner thickness. Both of the tests of this series were discontinued because the outer chamber casing wall reached a temperature of 1450°F.

Figures 22 and 44 show plots of time versus temperature for beryllia. An extrapolation of the curves of Figure 22 as previously done for zirconia, zircon and silicon carbide shows that firings of approximately 85 seconds can be expected before the outer chamber wall temperature reaches 1450°F.

The curves of Figure 44 for tests B-86-N and B-87-N at a point 6 inches from the nozzle end of the liner show a tendency to approach steady state conditions while the curve of the point 1-3/4 inches from the nozzle end shows no tendency in this direction. This is in direct agreement with the statements made previously for other liners.

## VI. CONCLUSIONS

Based on this group of tests it is concluded that:

1. Ceramic liners for the chambers of uncooled rocket motors of short duration--less than 220 seconds--are feasible with liquid propellants that develop chamber temperatures up to approximately 5000°F.
2. For overall performance stabilized zirconia was the best liner tested and the other liners in order of decreasing merit were zircon, silicon carbide, and beryllia. It is realized that under other conditions of operation and for lesser periods of operation, the order of merit might be completely changed.
3. Although cracking occurred for all liners, this was not serious and did not materially affect the motor performance. It is believed that cementing of liners into the casing is unwarranted unless extreme looseness of fit is observed. Extreme looseness is assumed if the average clearance between liner and casing exceeds 1/16 inch when the opposite side of the liner is in contact with the chamber casing.
4. Care must be taken in the design of a ceramic liner chamber to make sure that the entire length of chamber from injector to nozzle be ceramic lined.
5. When using a maximum outer chamber casing wall temperature of 1450°F as a criterion, a liquid propelled rocket motor with a ceramic lined chamber operating with a chamber gas temperature of approximately 4500°F can be operated for approximately 220 seconds with a zirconia liner, approximately 195 seconds with a zircon liner, approximately 130 seconds with a silicon carbide liner cemented into the chamber with magnesia, and approximately 85 seconds with a beryllia liner. All of these could be increased proportionately by allowing the outer chamber casing wall to go to higher temperatures than used in this group of tests.

6. A theoretical analysis at this time is not feasible since the physical properties of the liner materials have not been determined at the temperatures encountered in this study.

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5. Duwez, P., Meeks, P. J., Summerfield, M., "Proposal for Investigation of Special Materials for High Temperature Applications in Rocket Motors", Project Note No. 1-33, Jet Propulsion Laboratory--Pasadena, (1945).

6. Andrus, R. J., "Rocket Motor Materials", Unpublished Report--(Rough Draft at Jet Propulsion Laboratory--Pasadena).

7. Wilton, H. R., "The Investigation of Refractory Liners for Rocket Motors", Report No. XPR-1, Naval Ordnance Test Station--Inyokern, (1946).

8. Rasof, B., "On the Possibility of a Refractory Lined Uncooled Rocket Motor", Project Note 4-4, Jet Propulsion Laboratory--Pasadena, (1944).

9. Jet Propulsion Laboratory, "Jet Propulsion". Published by Jet Propulsion Laboratory--Pasadena for Air Technical Service Command (1946).

10. Reddick, H. W., and Miller, F. H., "Advanced Mathematics for Engineers", John Wiley and Sons, Inc., (1947).

11. McAdams, W. H., "Heat Transmission", McGraw-Hill Book Company, (1942).

TABLE I.

LIST OF LINERS TESTED BY CANRIGHT AND ROSEN IN WATER-COOLED, LIQUID-PROPELLED, 750-POUND ROCKET MOTOR
(See Reference 1)

| JPL Designation | Manufacturer | Manufacturer's Description |
|---|---|---|
| Alumina RA1191 | Norton Co., Worchester, Mass. | Pure alumina |
| RA 98 | Same | Clay bound alumina |
| Beryllia LB 30 | Norton Co., Worchester, Mass | |
| Zirconia LZO-73 | " | Stabilized zirconia Cone 35-3200°F |
| LZO-89 | " | Same |
| Zircon LZS-78 | " | Pure zircon body |
| TAM | Titanium Alloy | Same |
| Thoria TAM | Same | Probably fired around 3500°F |
| Silicon Carbide 2509 | Carborundum Co. | Metal bonded |
| Carbon Hard | National Carbon Co. | |
| #10 | Same | Porous material |
| #50 | Same | Same |
| Graphite #10 | Same | Porous material |
| #50 | Same | Same |

TABLE II.

LIST OF CERAMIC LINERS THAT WERE TESTED IN THIS STUDY

| JPL Designation | Manufacturer | Manufacturer Description |
|---|---|---|
| Beryllia LB-30 | Norton Company | |
| Zirconia LZO-73 | " " | Stabilized zirconia, Cone 35-3200°F |
| Zircon LZS-78 | " " | Pure Zircon body |
| Silicon Carbide 2509 | Carborundum Co. | Metal bonded |

TABLE III.

PHYSICAL PROPERTIES* OF CERAMIC LINER MATERIALS

USED IN THIS STUDY

| Liner Material | Melting Point °F | Specific Gravity -- | Apparent Specific Gravity -- | Weight Per Unit Volume #/in³ | Porosity % | Average Coefficient of Thermal Expansion: Coefficient $10^{-6}$ °F | Average Coefficient of Thermal Expansion: Temp. Range °F |
|---|---|---|---|---|---|---|---|
| Zirconia (LZO-73) | 4928 | 5.70 | 3.98 | 0.144 | 30.2 | 6.65 | 80-2000 |
| Beryllia (LB-30) | 4658 | 3.03 | 1.90 | 0.069 | 37.3 | 6.05 | 80-2000 |
| Zircon (LZS-78) | 4532 | 4.52 | 3.46 | 0.125 | 23.5 | 2.85 | 80-1800 |
| Silicon Carbide (2509) | Decomposes at 4060 | 3.17** | 2.51 | 0.091 | 20.8 | 3.15 | 80-1800 |

*Thermal conductivities are given as a set of curves in Figure 1

**Assumed value

TABLE IV.

PHYSICAL DIMENSIONS OF LINERS (BEFORE RUNS)
(ALL DIMENSIONS IN INCHES)

| Liner | Length Main Sect. | Length Segment | Inside Diameter | Thickness Minimum | Thickness Maximum | Thickness Average | # Clearance in Chamber | Longi-tudinal Fit | Test No. |
|---|---|---|---|---|---|---|---|---|---|
| Beryllia (LB-30) | 8" | 23/32" | 4-1/32" | 5/16" | 3/8" | 11/32" | None | Loose | B-86-N B-87-N |
| Si. C. (2509) | 7-15/16" | 5/8" | 3-15/16" | 11/32" | 3/8" | 11/32" | 3/32" | Loose | B-88-N |
| *Zircon (LZS-78-16) | 8" | *None | 3-31/32" | 3/8" | 3/8" | 3/8" | 1/32" | Loose | B-85-N |
| Zirconia (LZO-73-35) | 8-9/16" | None | 4" | 21/64" | 3/8" | 11/32" | Very Little | Loose | B-89-N B-91-N |
| *Zirconia (LZO-73-35) | 8" | *None | 4" | 21/64" | 3/8" | 11/32 | Very Little | Loose | B-83-N B-84-N |
| Zircon (LZS-78-16) | 8-5/8" | None | 3-31/32" | 3/8" | 3/8" | 3/8" | Very Little | Tight | B-92-N B-93-N |
| Si. C. (2509) | 7-15/16" | 5/8" | 3-15/16" | 11/32" | 3/8" | 11/32" | Cemented W/Magnesia | Tight | B-94-N B-95-N |

*These tests were made with a casing as shown in Figure 12. All other runs were made in a casing as shown in Figure 13.

#Clearance between the liner and casing was taken on one side only with opposite side against the casing.

## TABLE V.

Data concerning the placement of thermocouples for measurement of temperature of liner wall and casing wall (Note: this table to be used with Figure 2).

a) Chamber Casing #320 (Used for tests Nos. 83, 84, 86, 87, and 88)

| Thermo. No. | Type of Thermo. | Temp. Measured | Distance from nozzle end of liner | Measuring Device |
|---|---|---|---|---|
| 1 | Chromel-Alumel | Chamber | 5-3/4 inches | Brown* |
| 2 | " " | " | 4 " | " |
| 3 | " " | " | 2-3/4 " | Millivoltmeter |
| 4 | Pt-Pt+10% Rh | Liner | 8-1/8 " | not connected |
| 5 | " | " | 6 " | Speedomax** |
| 6 | " | " | 3-7/8 " | not connected |
| 7 | " | " | 1-3/4 " | Speedomax** |

b) Chamber Casing #322 (Used for tests Nos. 85, 89, 91, 92, 93, 94, and 95)

| Thermo No. | Type of Thermo. | Temp. Measured | Distance from nozzle end of liner | Measuring Device |
|---|---|---|---|---|
| 8 | Chromel-Alumel | Chamber | 5-9/16 inches | Brown* |
| 9 | " " | " | 3-13/16" | " |
| 10 | " " | " | 3-1/16" | Millivoltmeter |
| 11*** | Pt-Pt+10% Rh | Liner | 7-1/4" | Speedomax** |
| 12 | " | " | 5" | not connected |
| 13 | " | " | 2-3/4" | Speedomax** |
| 14**** | " | " | 1/2" | not connected |

*Brown 12-point recording potentiometer
**Leeds-Northrup 16-point recording potentiometer
***Starting with test B-89-N was connected to Brown potentiometer
****Starting with test B-89-N was connected to Speedomax potentiometer

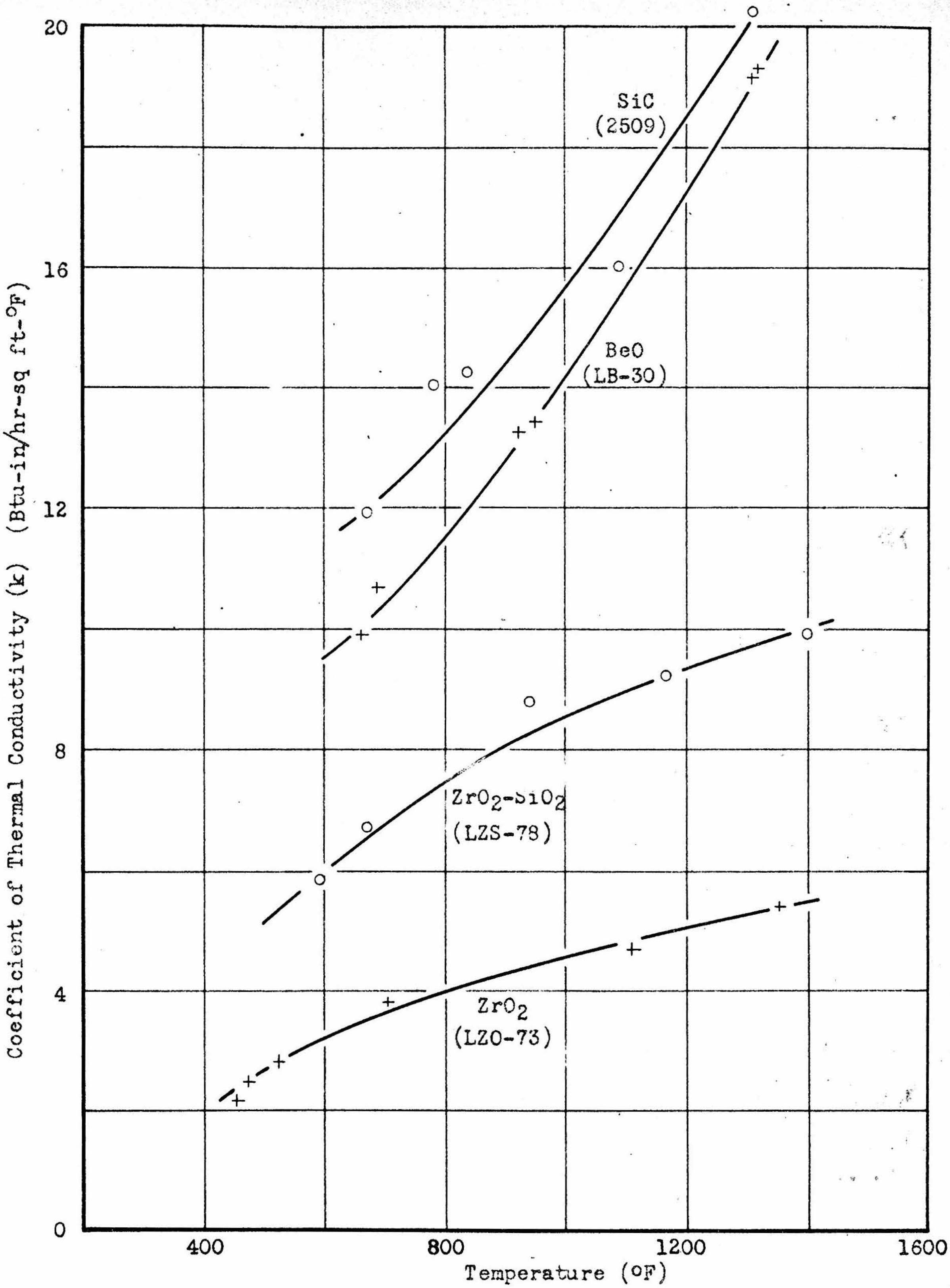
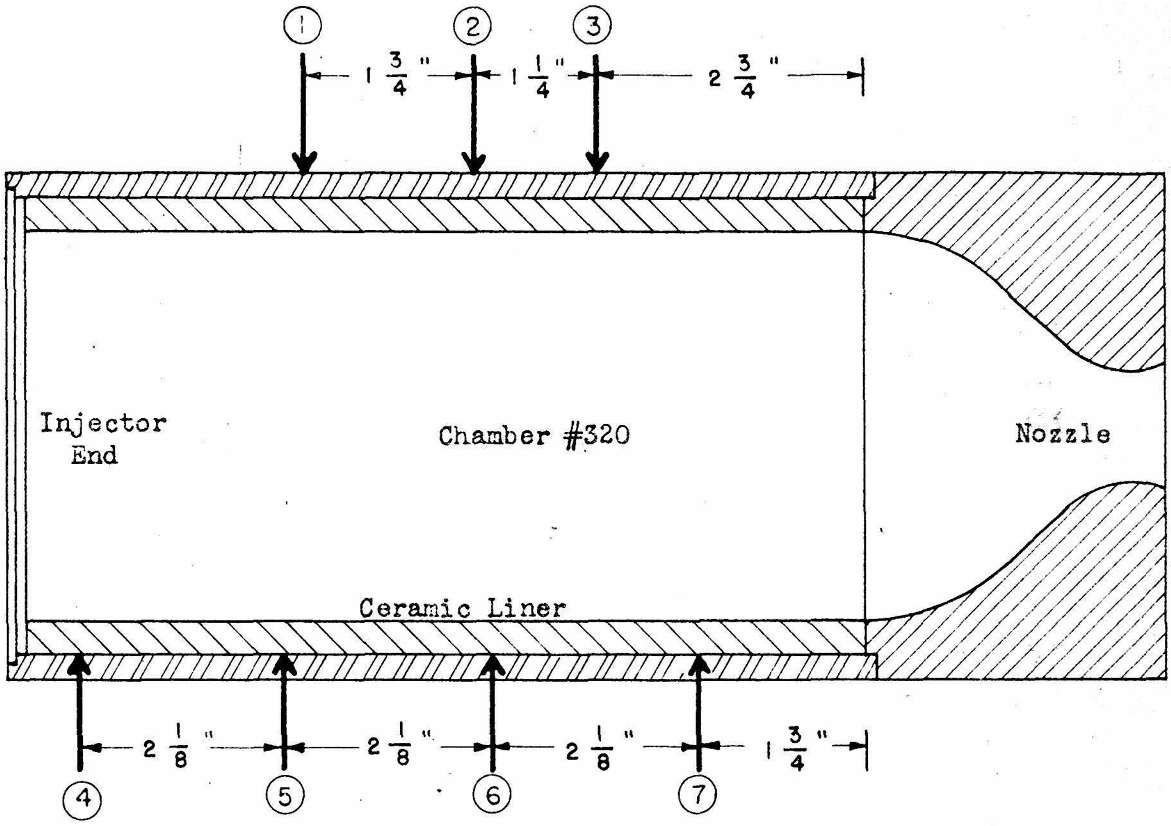
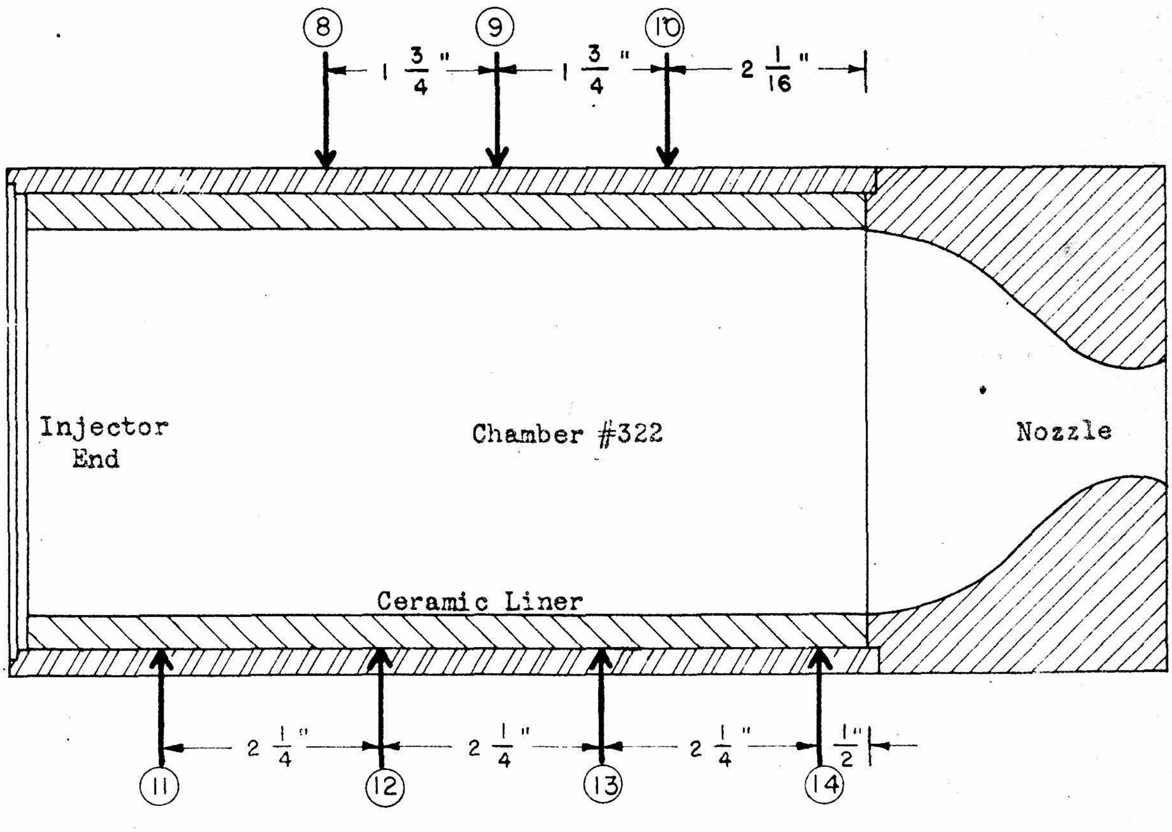



FIGURE 1--Thermal Conductivity vs Temperature Curves for Ceramic Liner Materials Used in This Study--From Reference 2.

FIGURE 2--Thermocouple Arrangement for Ceramic Liner Study.
(Use with Table V)



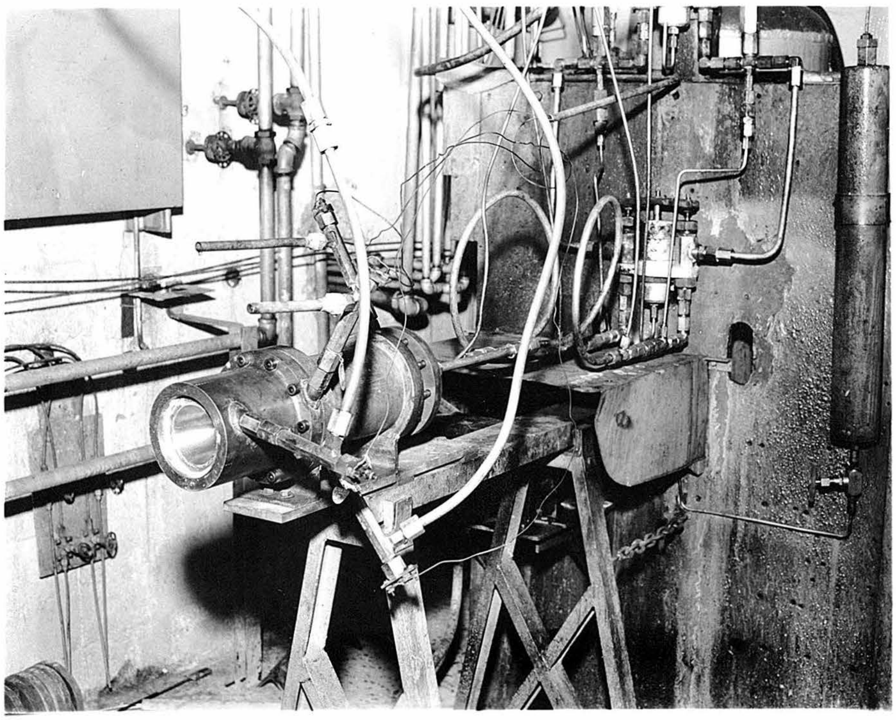


Figure 3--Photograph showing a 750-pound thrust liquid propellant rocket motor on stationary test stand. Note plumbing to provide oxidizer, fuel and cooling water. Solenoid operated quick opening valves can be seen mounted on shield in front of motor.

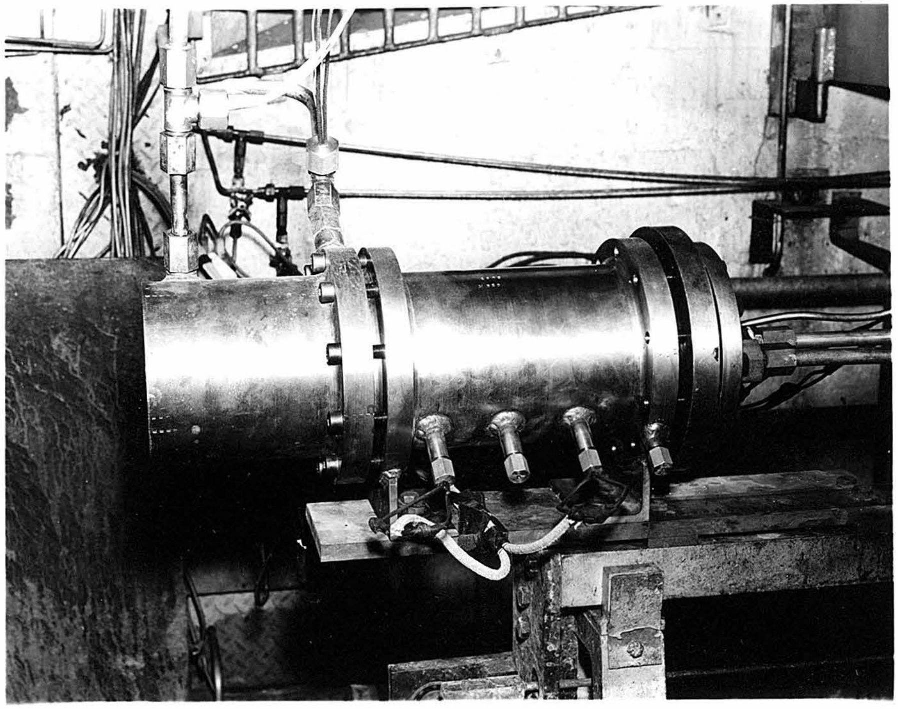


Figure 4--Photograph showing a ceramic lined, 750-pound rocket motor on the test stand. This is the right side of the motor. Note the location of thermocouple wells along the length of the chamber casing.

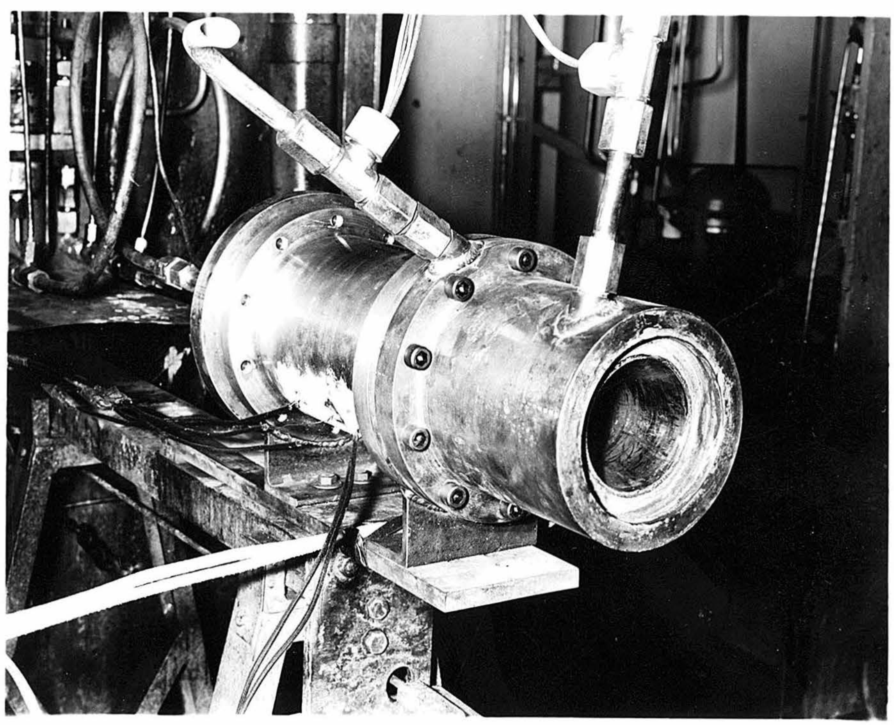


Figure 5--Photograph showing the same ceramic lined rocket motor as in figure 4 but from the rear-left side. Note the location of thermocouples brazed to side of chamber casing. This thermocouple arrangement was later changed to that shown in figure 15.

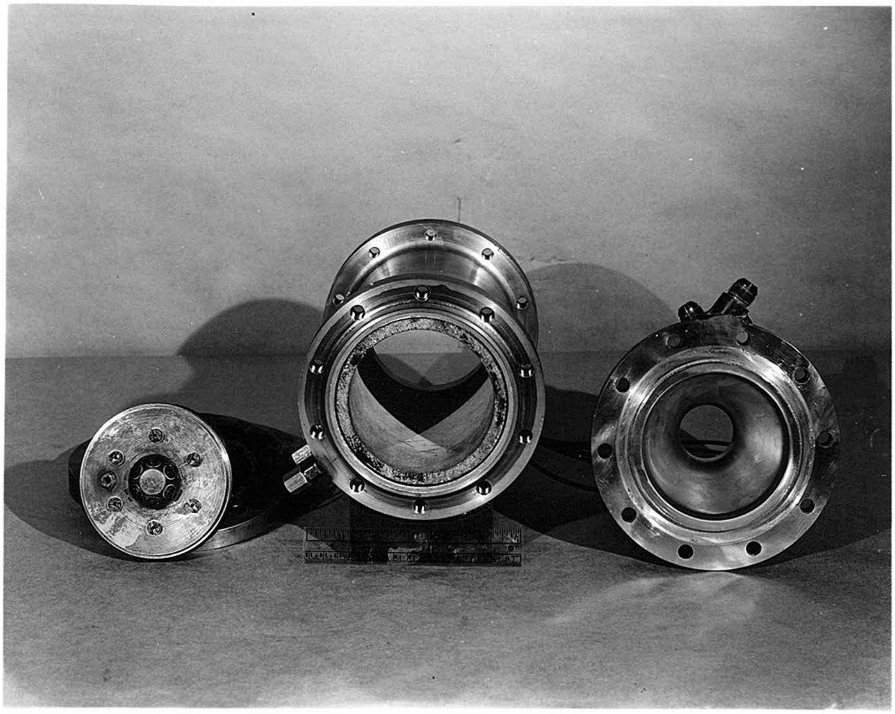


Figure 6--Photograph showing the three main parts of a rocket motor. On the left is the injector. In the center is the chamber casing with a ceramic liner in place. On the right is the nozzle.

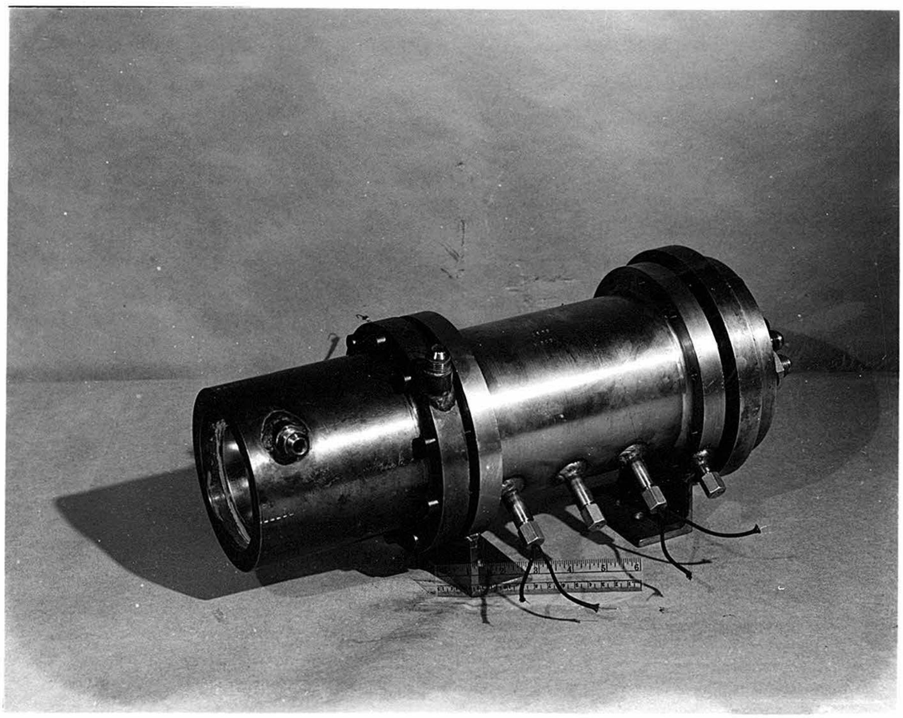


Figure 7--Photograph showing the main parts of the rocket motor assembled.

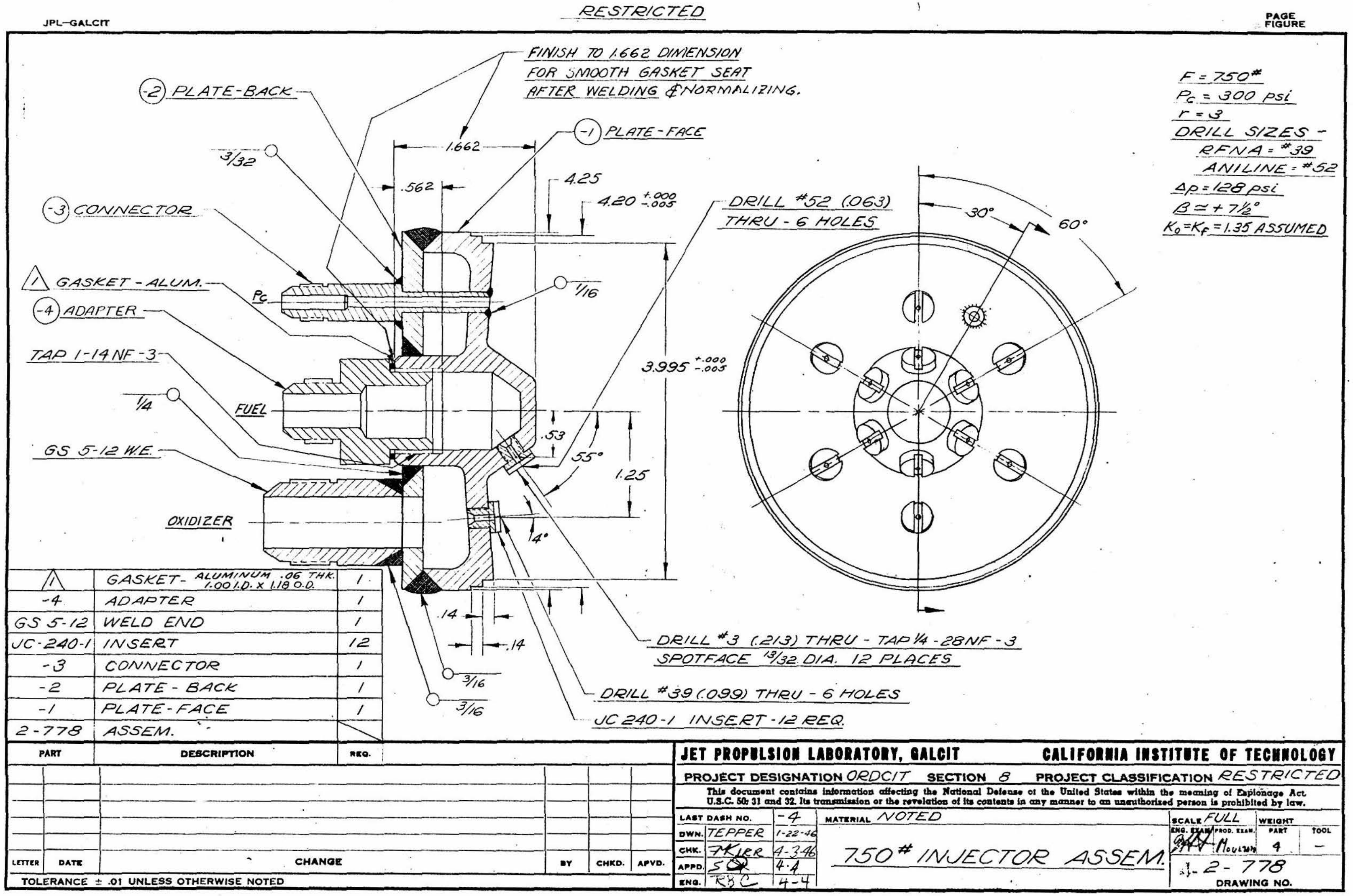



Figure 8--Drawing showing an injector assembly for a 750-pound, liquid propelled, rocket motor.

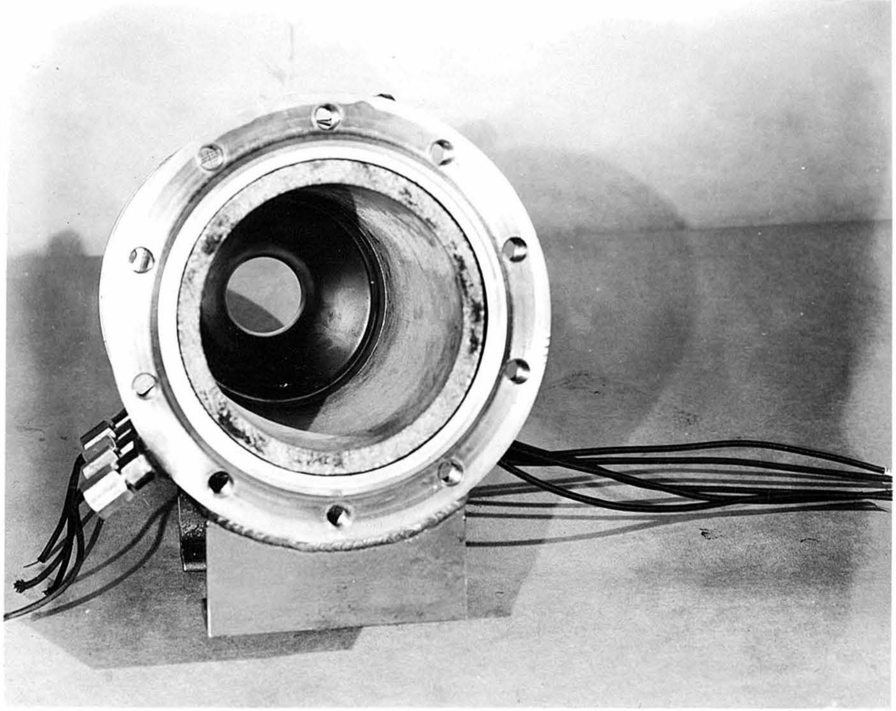


Figure 9--Photograph showing the chamber with nozzle attached before the adapter ring for the injector is placed in position.

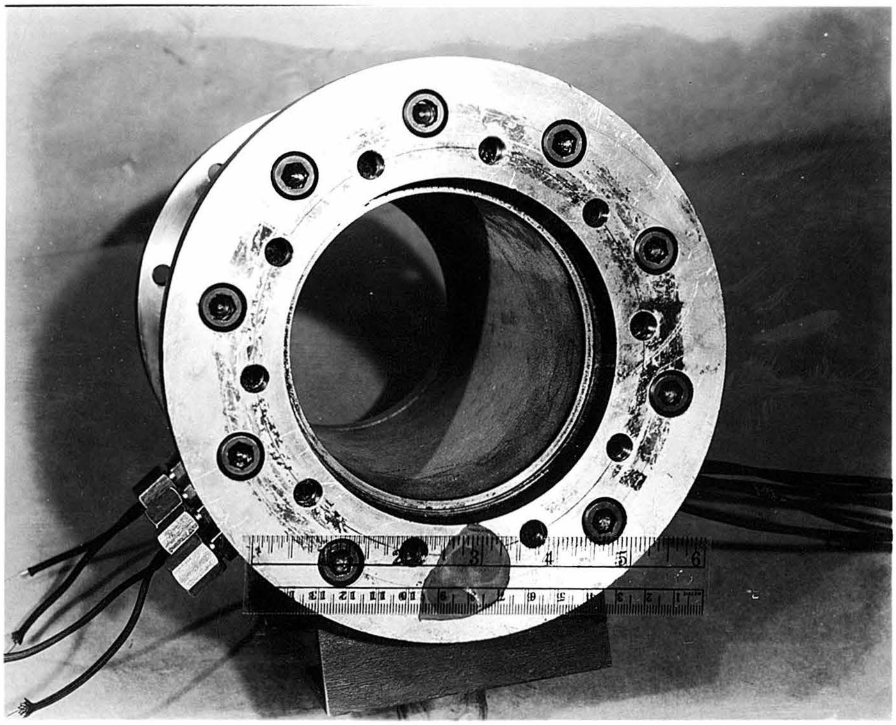


Figure 10--Photograph showing the chamber with the adapter ring for the injector bolted in place.

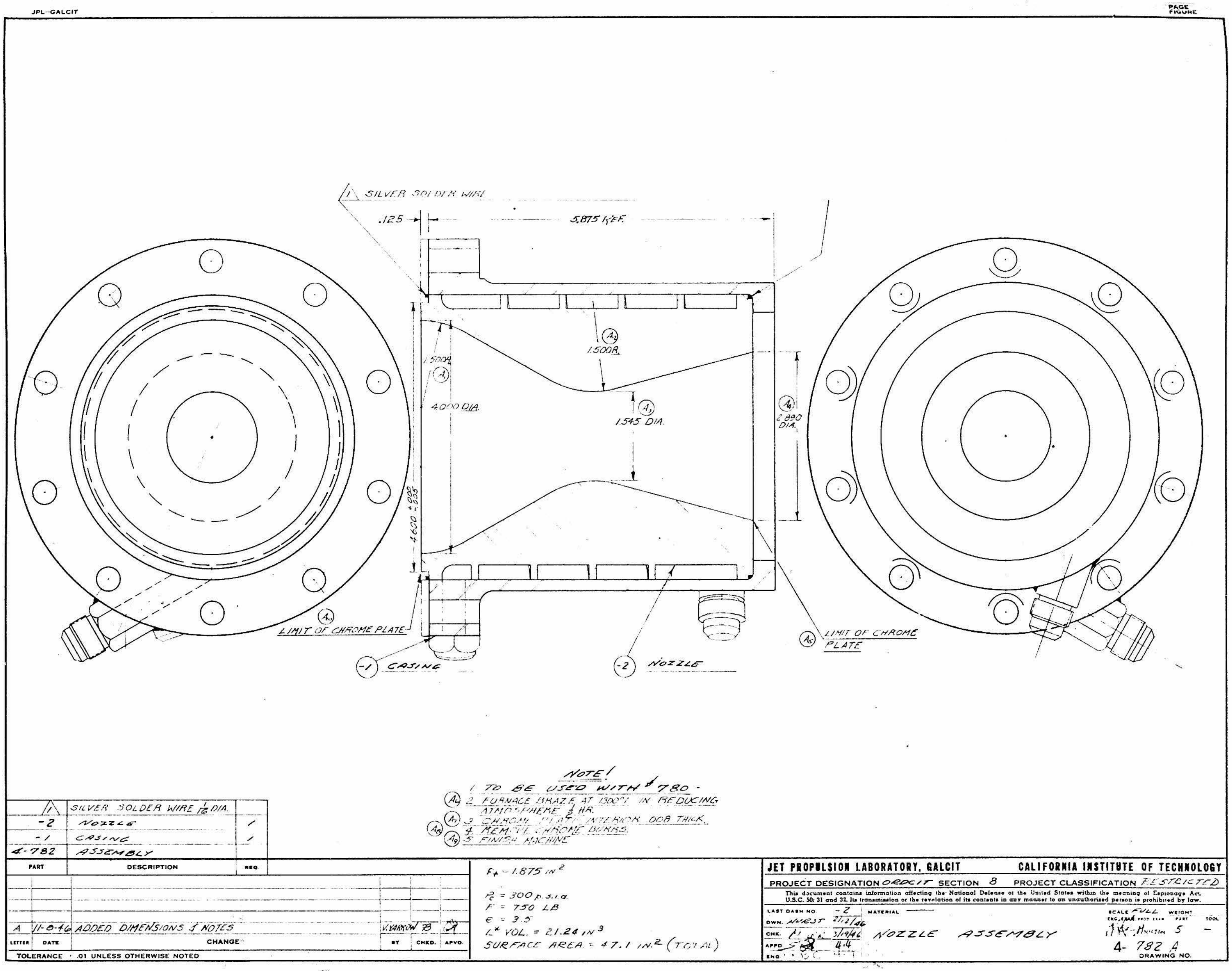



Figure 11--Drawing showing a nozzle assembly for a 750-pound, liquid propelled, rocket motor.

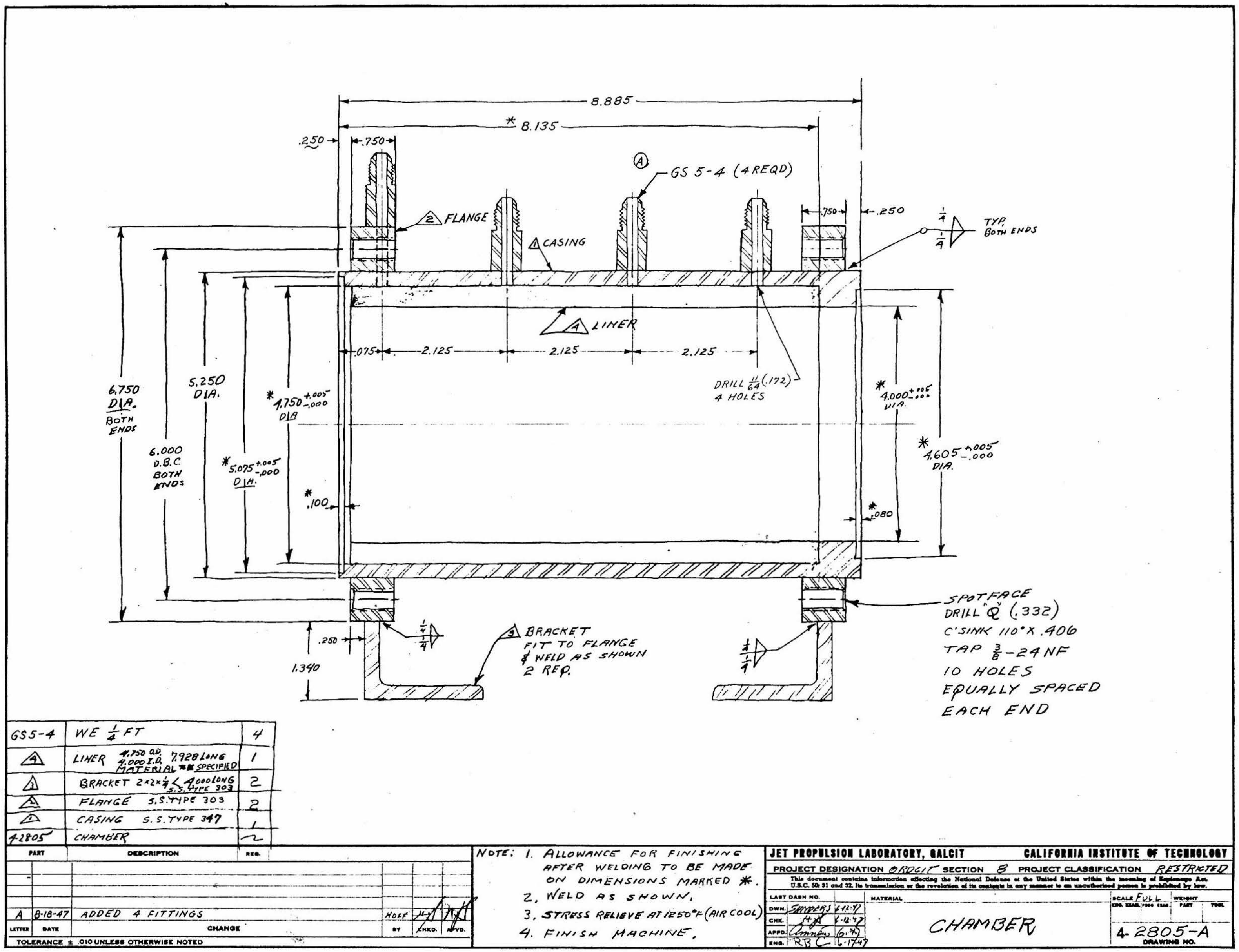



Figure 12--Drawing showing the original uncooled chamber casing used in these tests. Due to poor design, this chamber was replaced by a redesigned chamber as shown in figure 13.

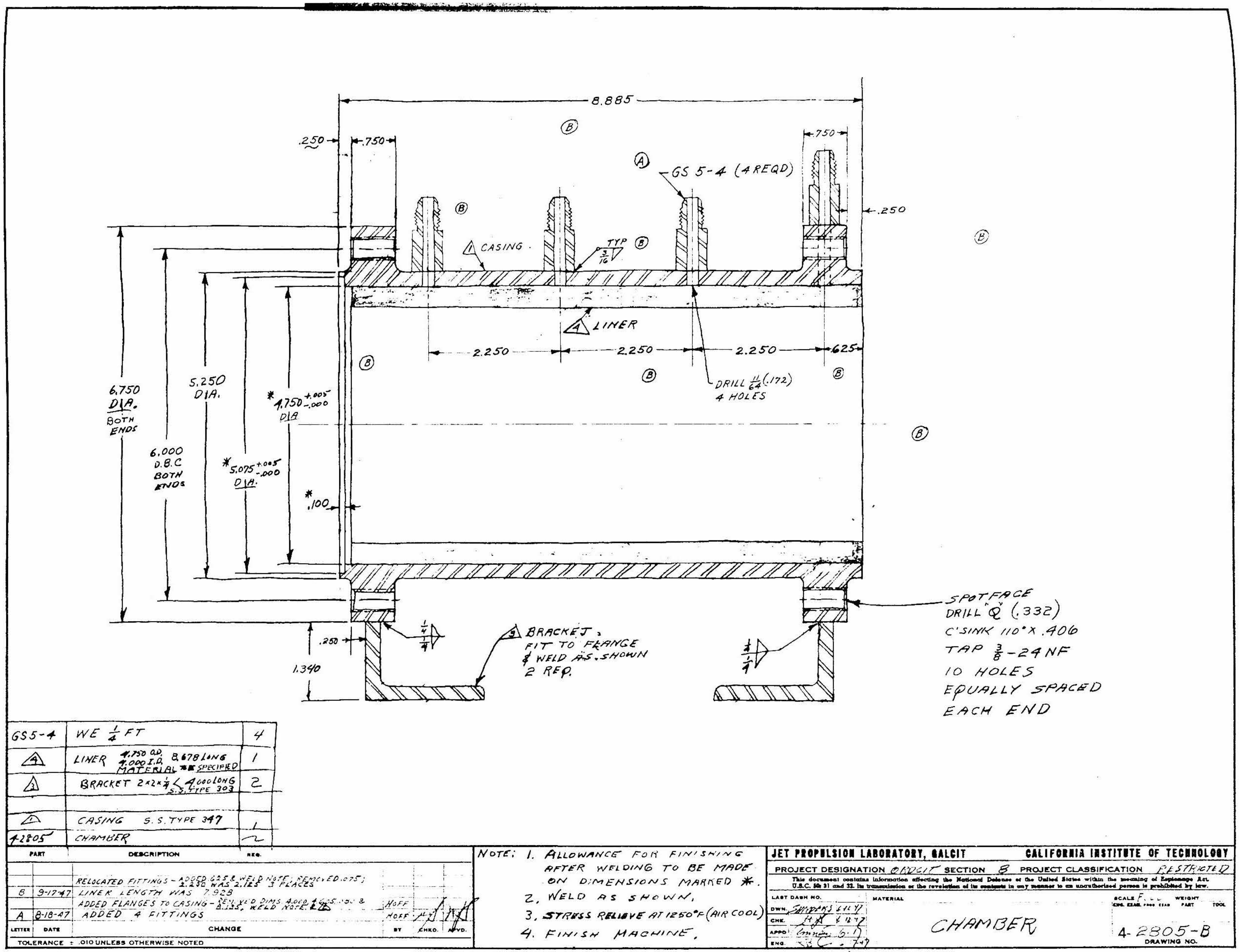



Figure 13--Drawing showing the redesigned uncooled chamber casing that was used for all but three of the tests made.

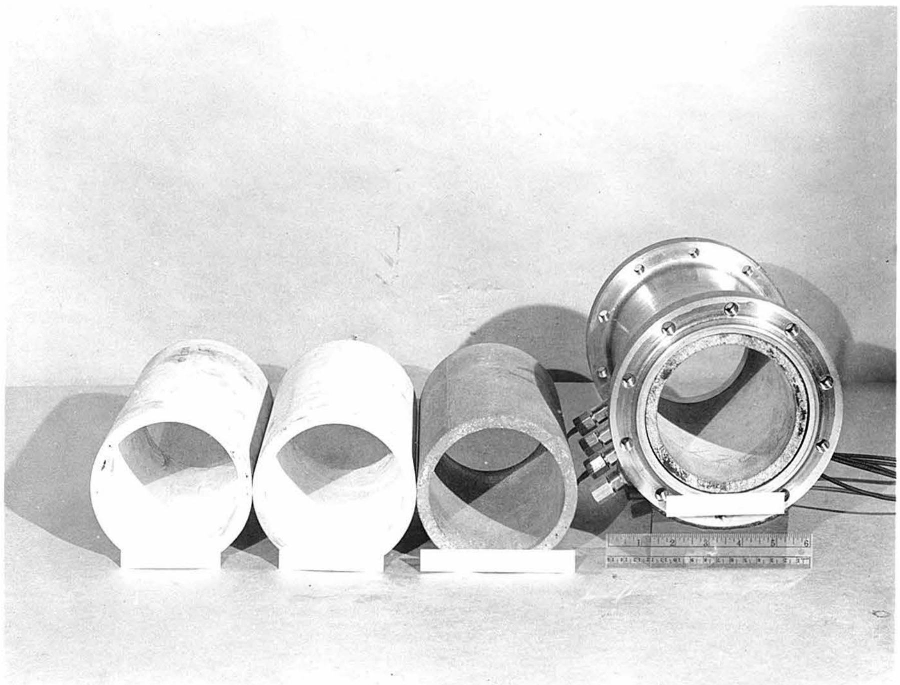


Figure 14--Photograph showing the four different kinds of ceramic liners that were used in these tests.

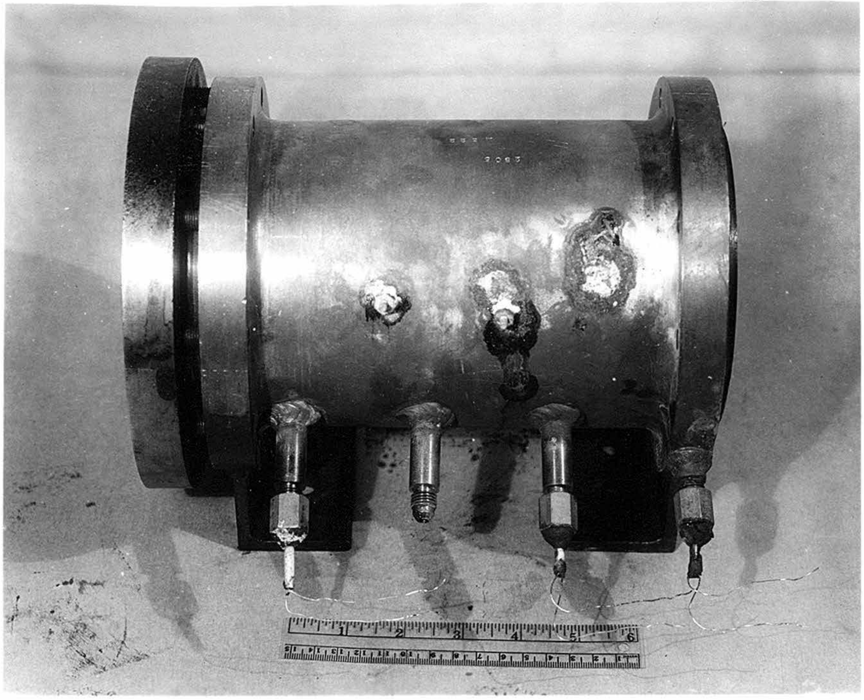


Figure 15--Photograph showing the location of thermocouples on both the outer chamber casing wall and the outer wall of the ceramic liner. The thermocouple wells shown at the bottom of the photograph go through to the ceramic liner wall. (See figure 16.) Positions of thermocouples on casing wall are indicated by brazed area and brazed bolts in place.

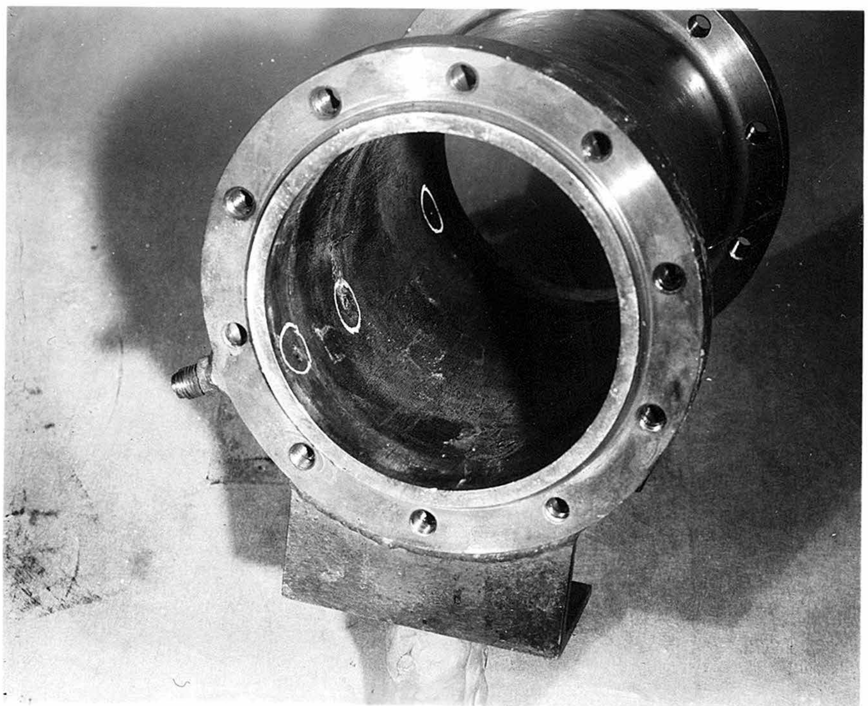


Figure 16--Photograph showing the location of the thermocouple well holes on the inside of the chamber casing.

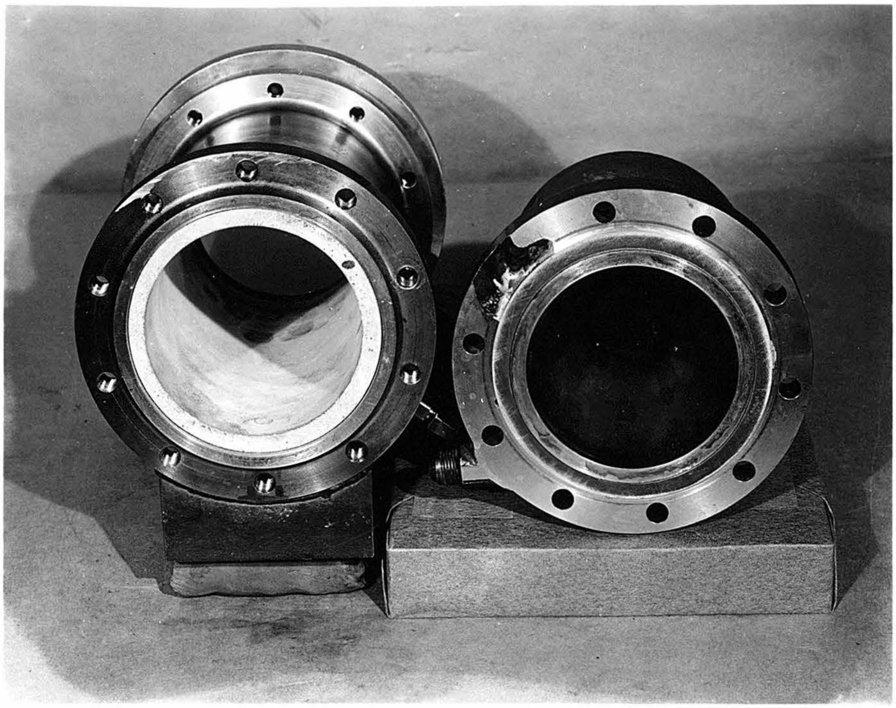


Figure 17--Photograph showing a copper gasket in place on the nozzle. This copper gasket was necessitated by a redesign of the chamber casing and provided a gas-tight seal between the nozzle and casing.

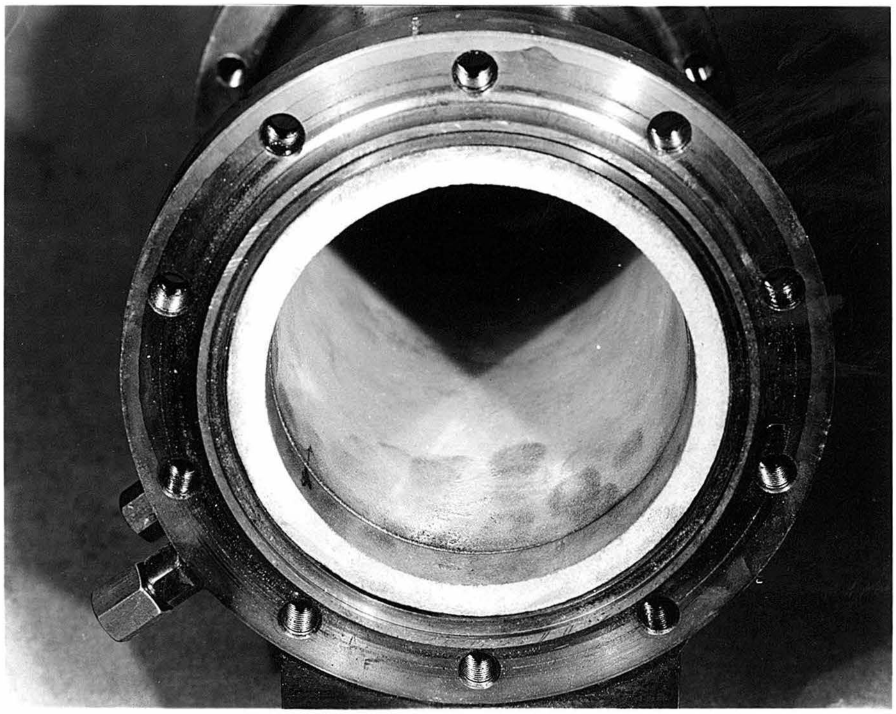


Figure 18--Photograph showing the ceramic segment that replaced the steel lip of the chamber casing upon redesign of the casing as shown in figures 12 and 13.

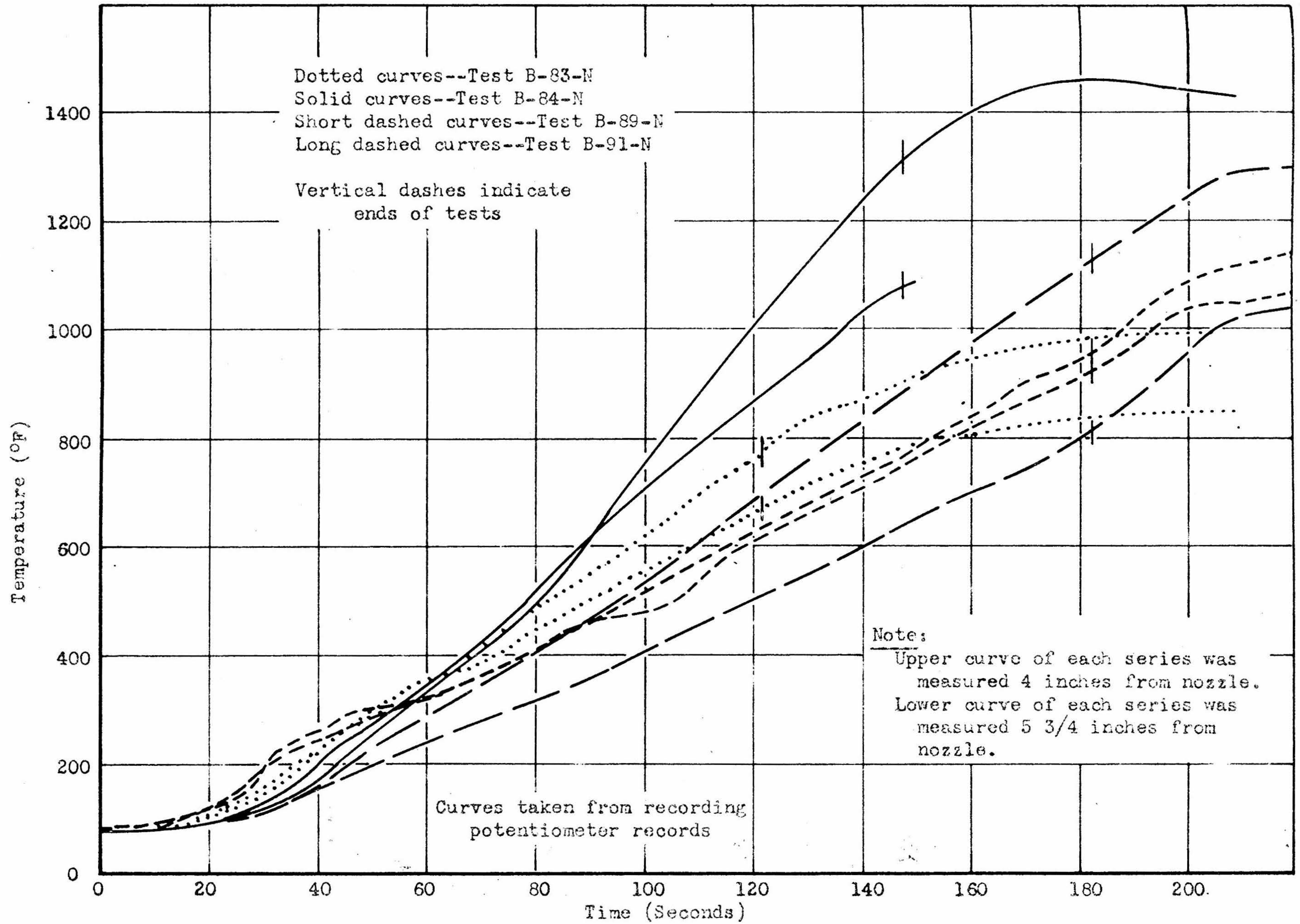



FIGURE 19--Plot of Time vs Temperature of Chamber Wall of 750-pound Uncooled Rocket Motor. (Zirconia Liner)

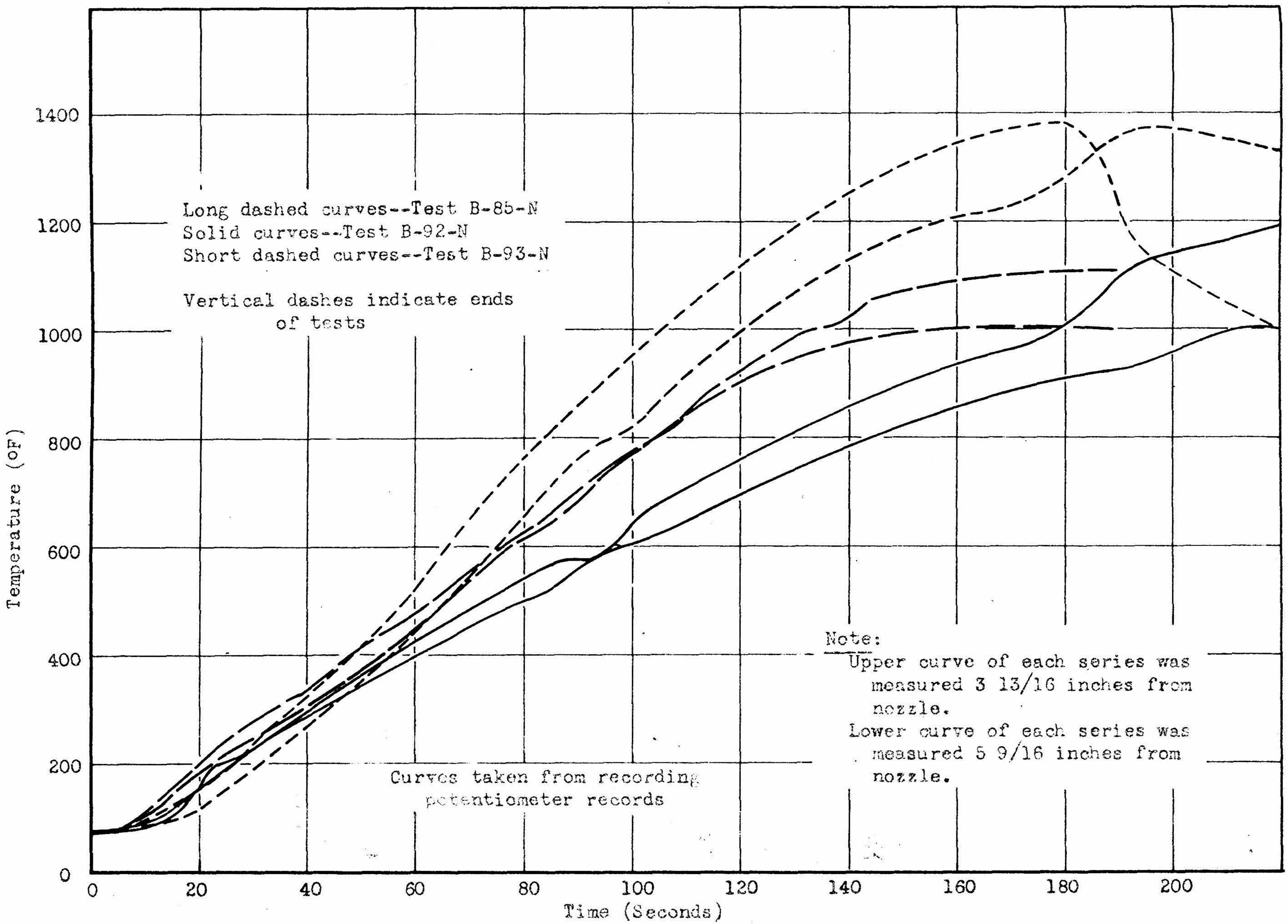



FIGURE 20--Plot of Temperature of Chamber Wall of 750-pound Uncooled Rocket Motor vs Time. (Zircon Liner)

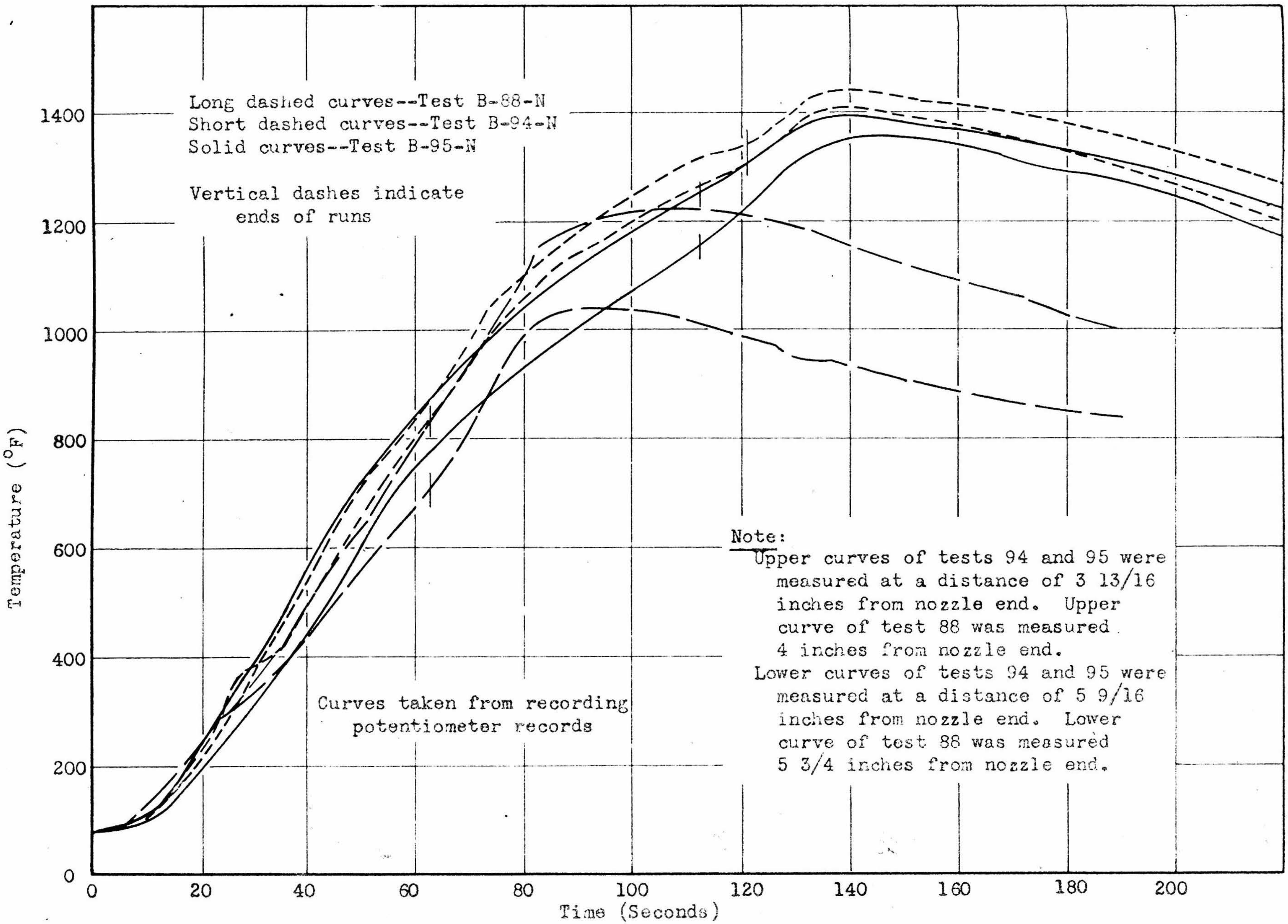



FIGURE 21--Plot of Time vs Temperature of Chamber Wall of 750-pound Uncooled Rocket Motor. (Silicon Carbide Liner)

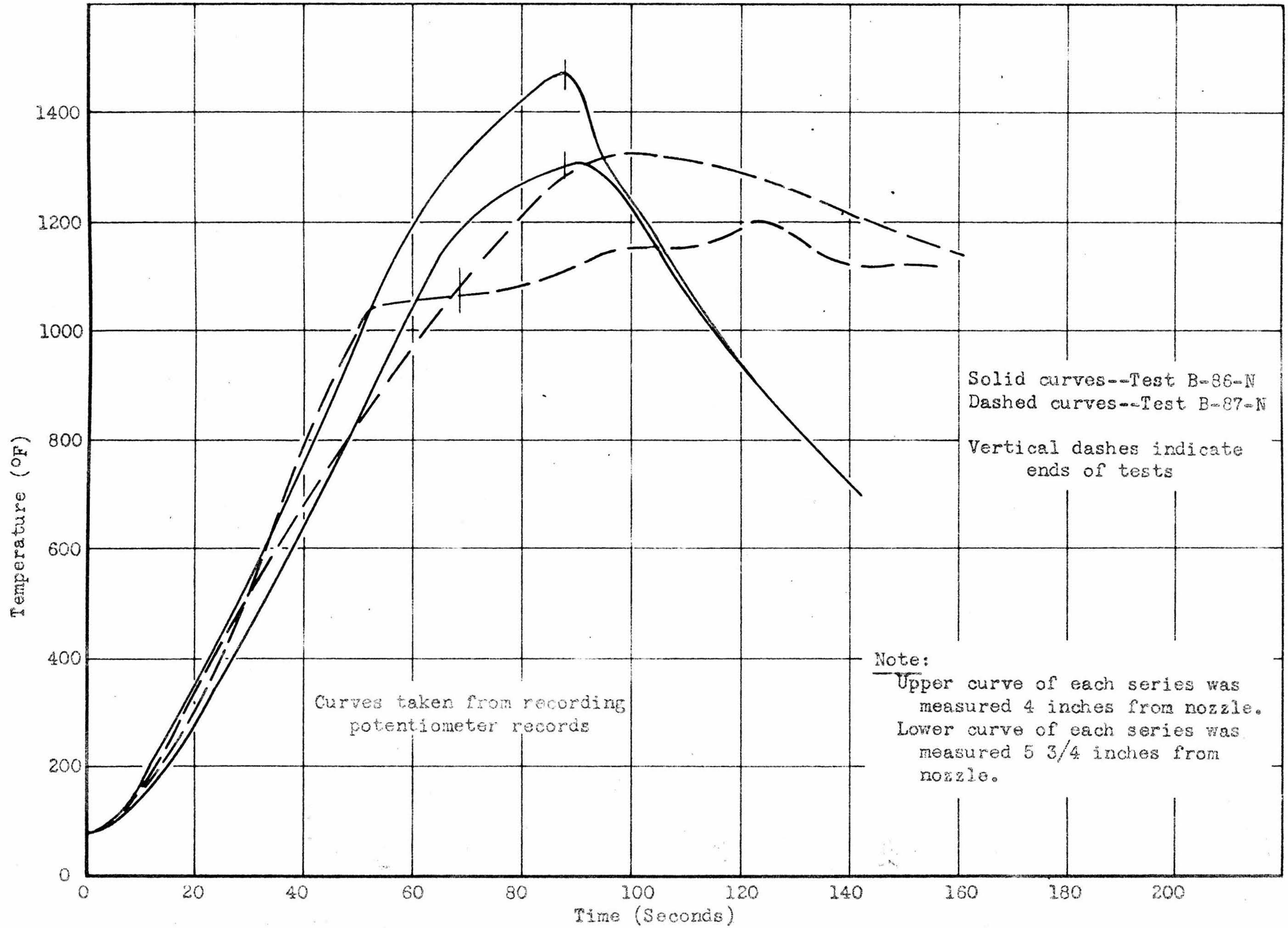



FIGURE 22--Plot of Time vs Temperature of Chamber Wall of 750-pound Uncooled Rocket Motor. (Beryllia Liner)

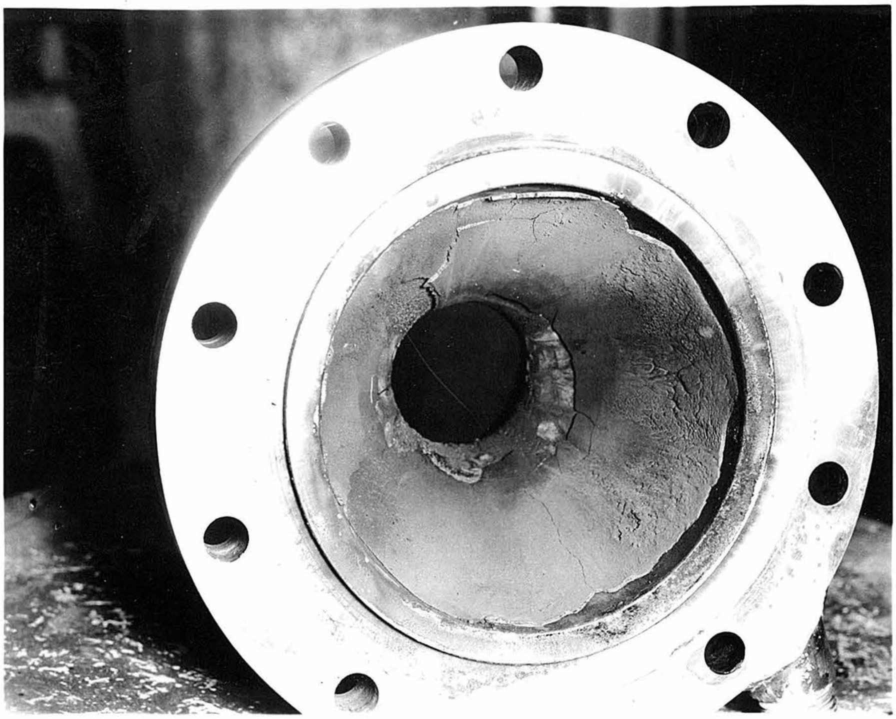


Figure 23--Photograph showing the flow of melted zirconia into the inlet end of the nozzle section following test B-82-N. Length of test was 121.1 seconds at a computed chamber temperature of 4830°F.

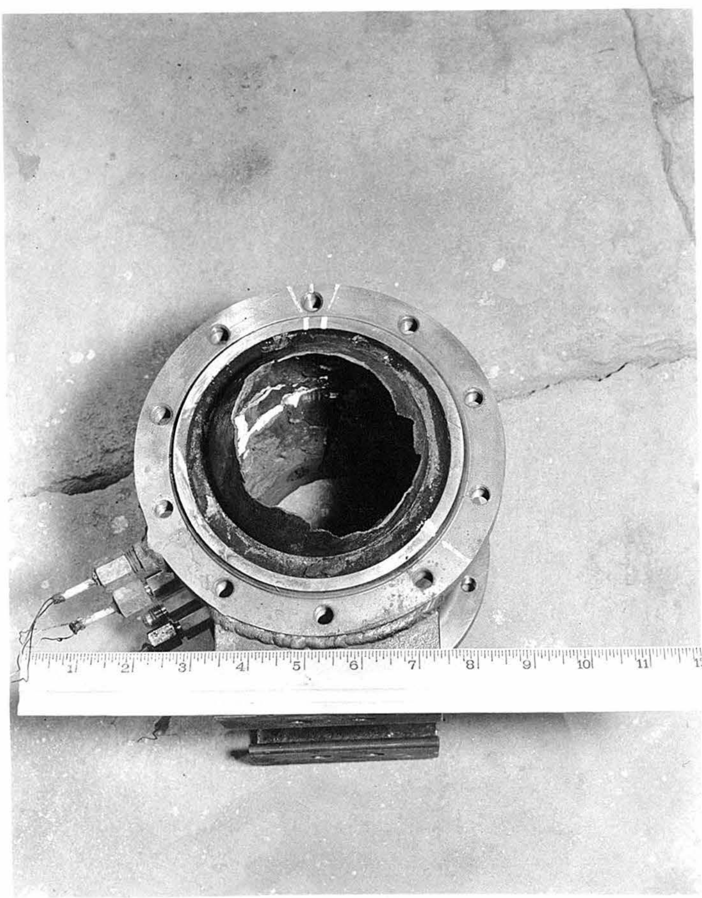


Figure 24--Photograph from nozzle end showing the condition of zircon liner after tests B-92-N & B-93-N. Note the sheet of melted zircon that has broken loose from the nozzle when nozzle was removed from casing. White area is where blisters have flaked off surface. Total test time with this liner was 354.5 seconds. (Test B-92-N for 181.5 seconds & test B-93-N for 173.0 seconds.)

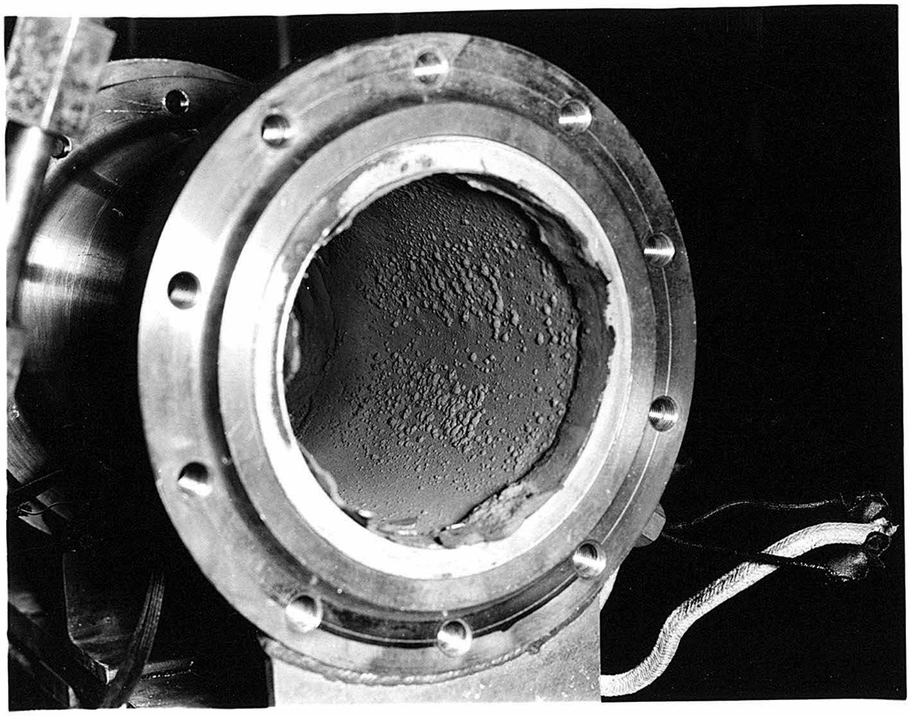


Figure 25--Photograph from nozzle end showing condition of zirconia liner after test B-82-N. Note melted zirconia over lip of chamber casing. Length of test was 121.1 seconds at computed chamber temperature of 4830°F.

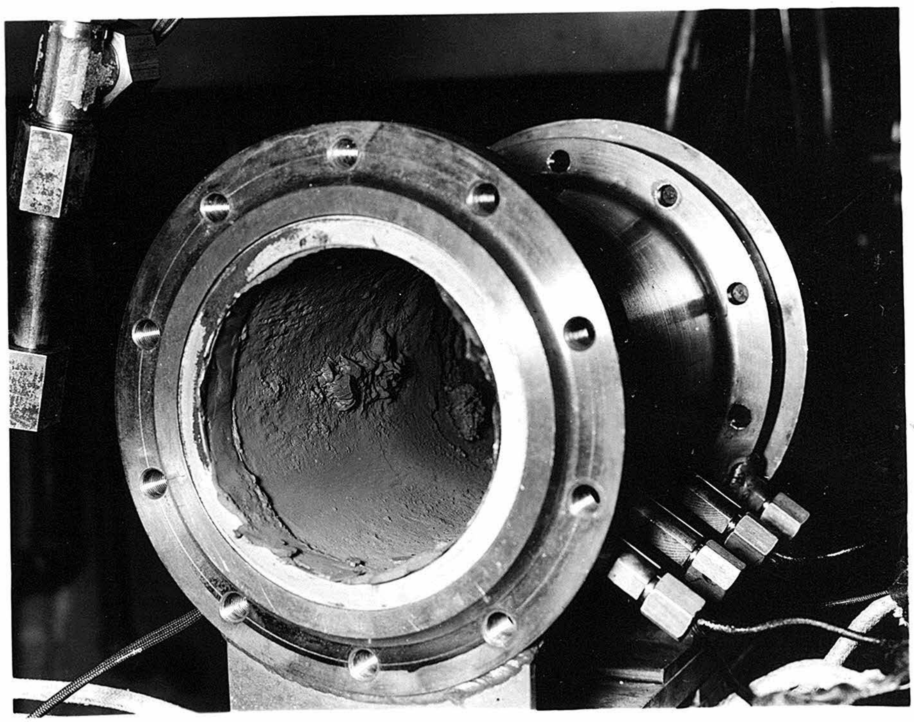


Figure 26--Photograph from the nozzle end showing the condition of a zirconia liner after test B-82-N. See figure 25 for test data.

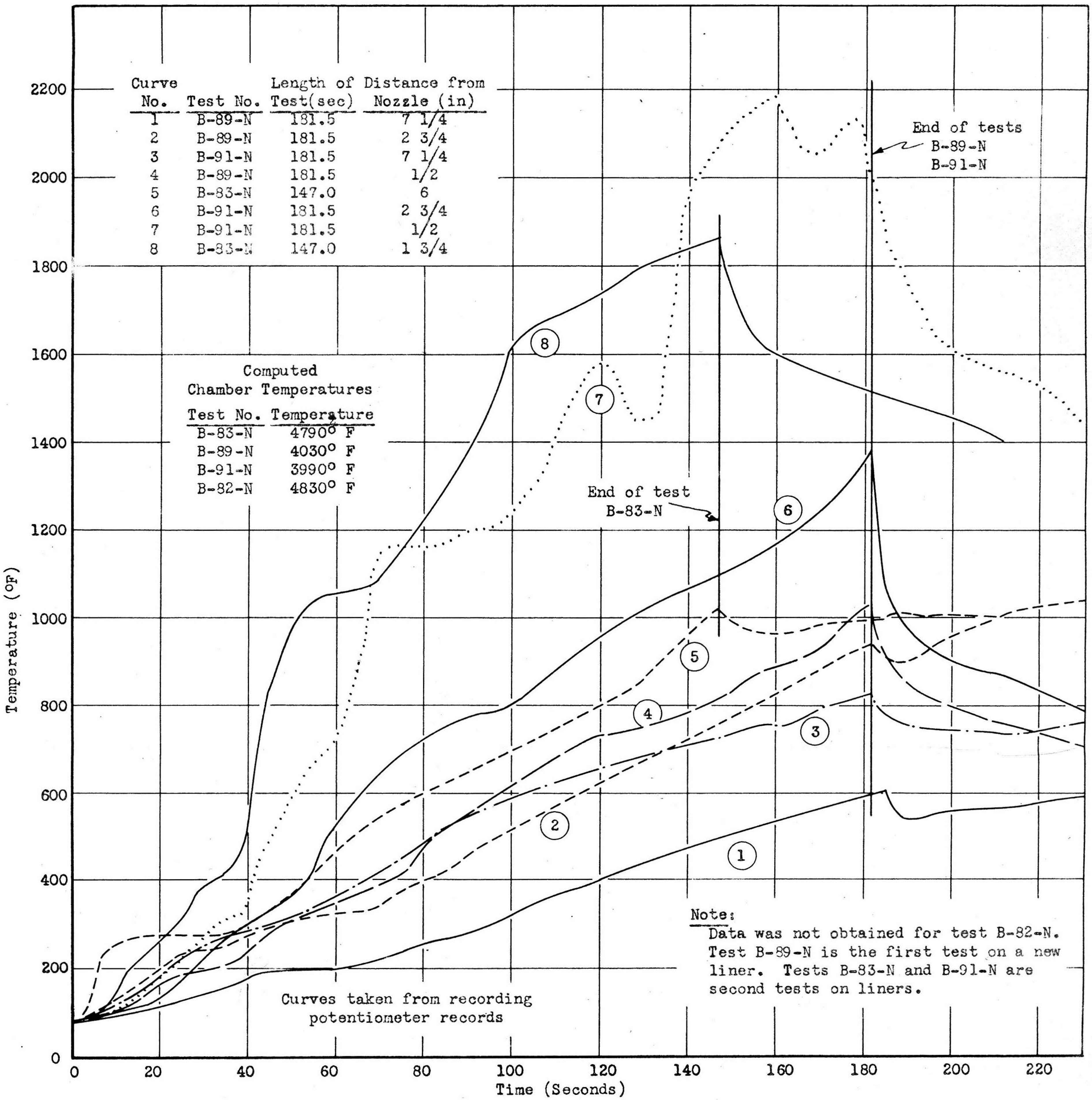



FIGURE 27--Time vs Temperature of the Outer Wall of a 3/8 " Zirconia Liner in a 750-# Rocket Motor.

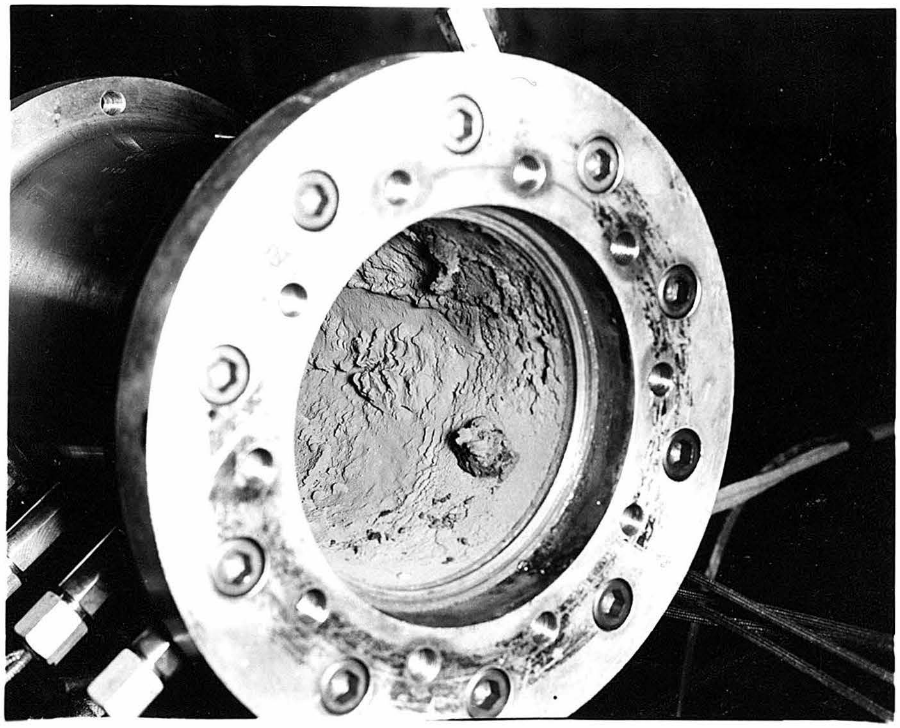


Figure 28--Photograph from the injector end showing zirconia liner after tests B-82-N and B-83-N. Note eroded condition of liner. Total test time with this liner was 268.3 seconds. (Test B-82-N for 121.1 seconds and test B-83-N for 147.2 seconds.)

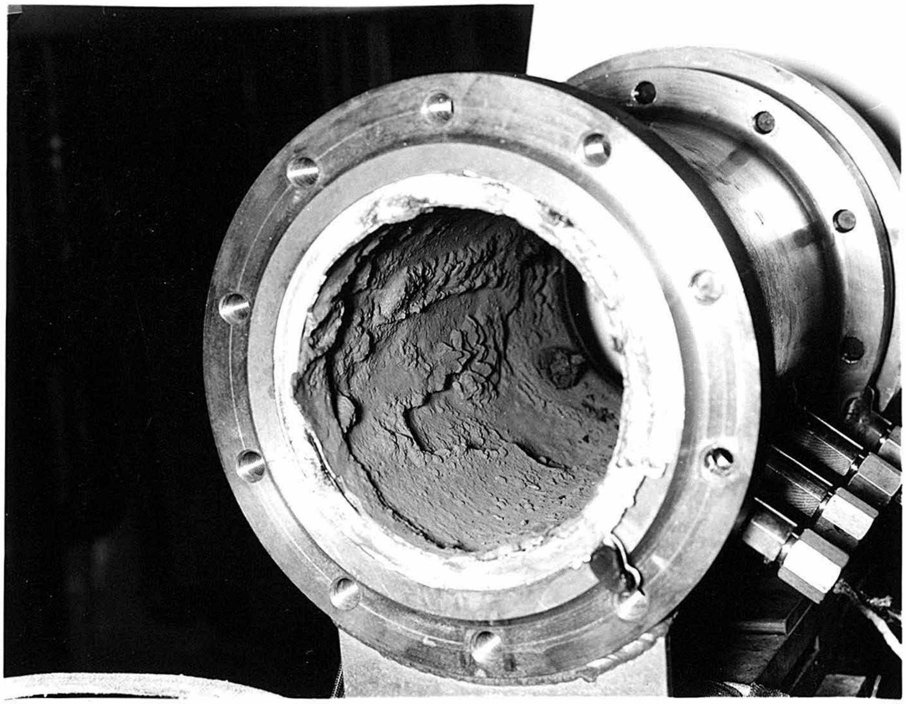


Figure 29--Photograph from nozzle end showing zirconia liner after tests B-82-N & B-83-N. Note deeply eroded areas of liner and flow of melted zirconia over lip of chamber casing. (See figure 28 for test data.)

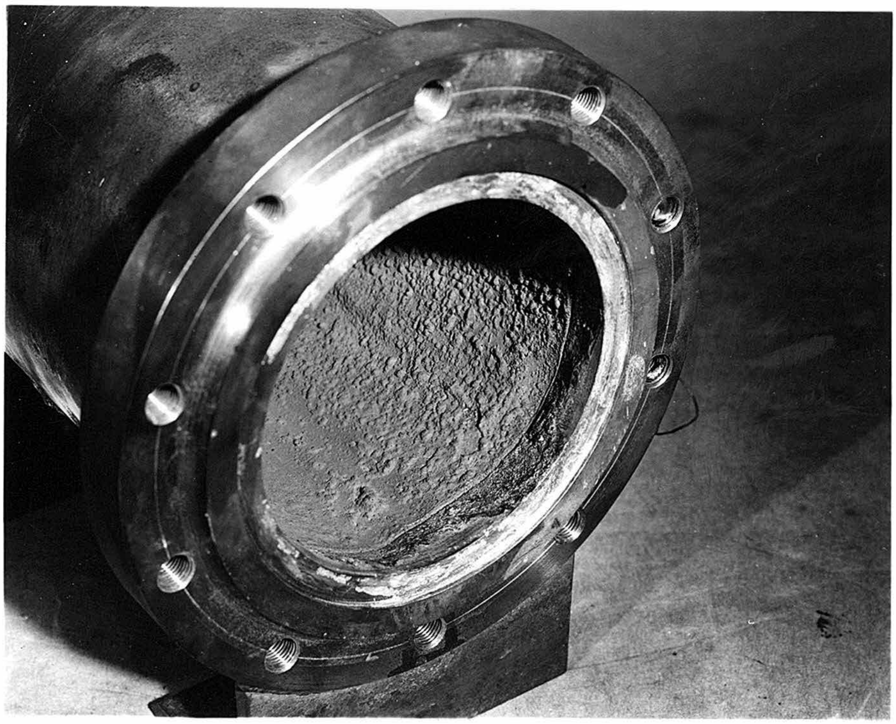


Figure 30--Photograph from nozzle end showing zirconia liner after tests B-82-N & B-83-N. Note that melted zirconia has been scraped off the lip of the casing. Note also that casing lip has been melted during these tests. (This lip was removed in later redesign of chamber casing.)

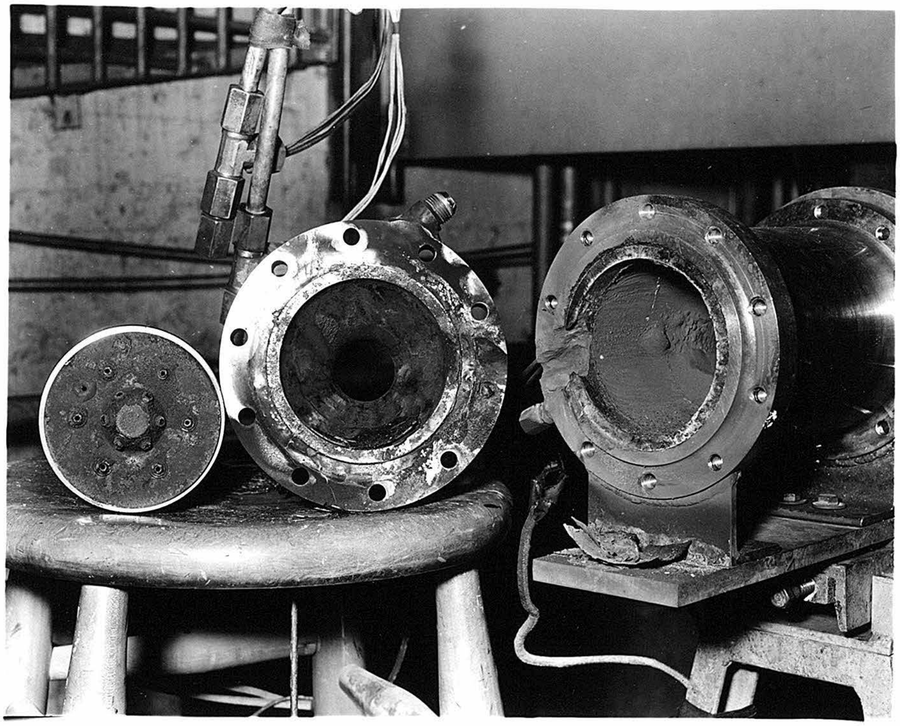


Figure 31--Photograph from nozzle end showing the condition of zircon liner and burned-out motor following test B-85-N. Note blistering of liner. Length of test was 110.5 seconds at computed chamber temperature of 4500°F.

Figure 32--Photograph from nozzle end showing the condition of zircon liner and motor burn-out following test B-85-N. Note cracks in liner. Flow lines of melted and eroded zircon can be seen along the length of the liner. Note place of burn-out.

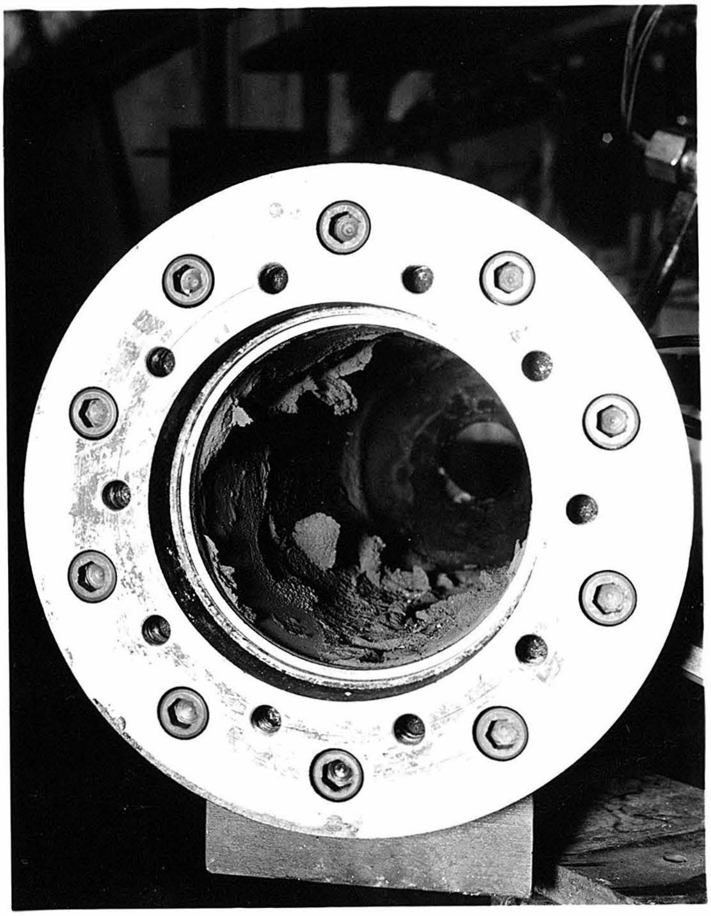


Figure 33--Photograph from injector end showing the condition of the zircon liner following test B-92-N. Note flakes hanging from liner wall. These flakes are from broken blisters that form on the surface of the zircon liner. Figure 31 shows the formation of a blister on the wall. Length of test was 181.5 seconds at a computed chamber temperature of 4315°F.

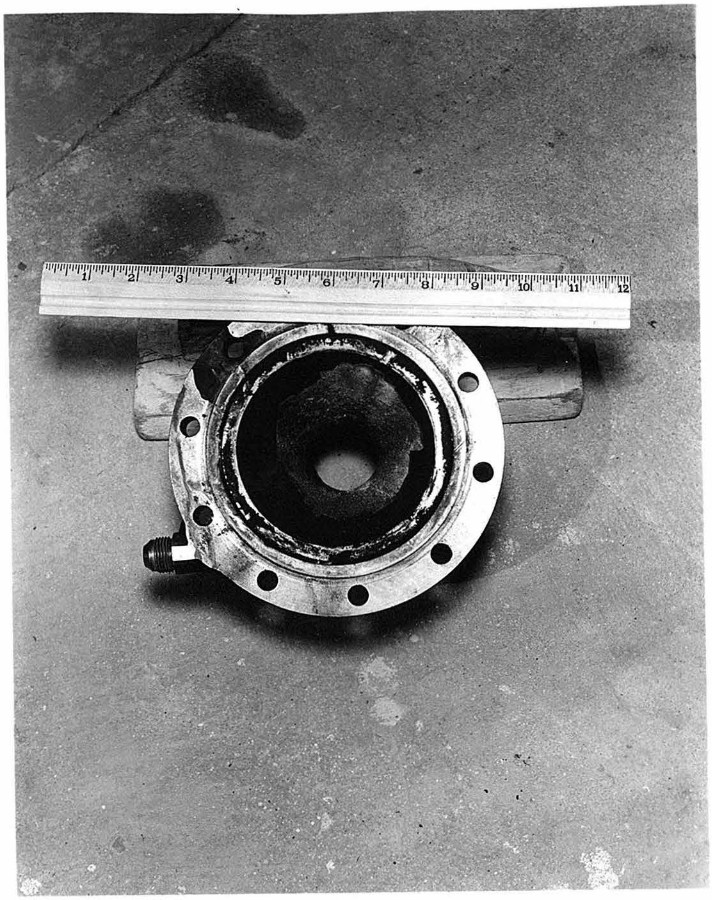



Figure 34--Photograph showing the flow of melted zircon into the inlet end of nozzle section following tests B-92-N & B-93-N. The portion of melted zircon missing from the nozzle can be seen in figure 24 as the sheet extending from the chamber casing. Also see figure 35. (See figure 24 for test data.)

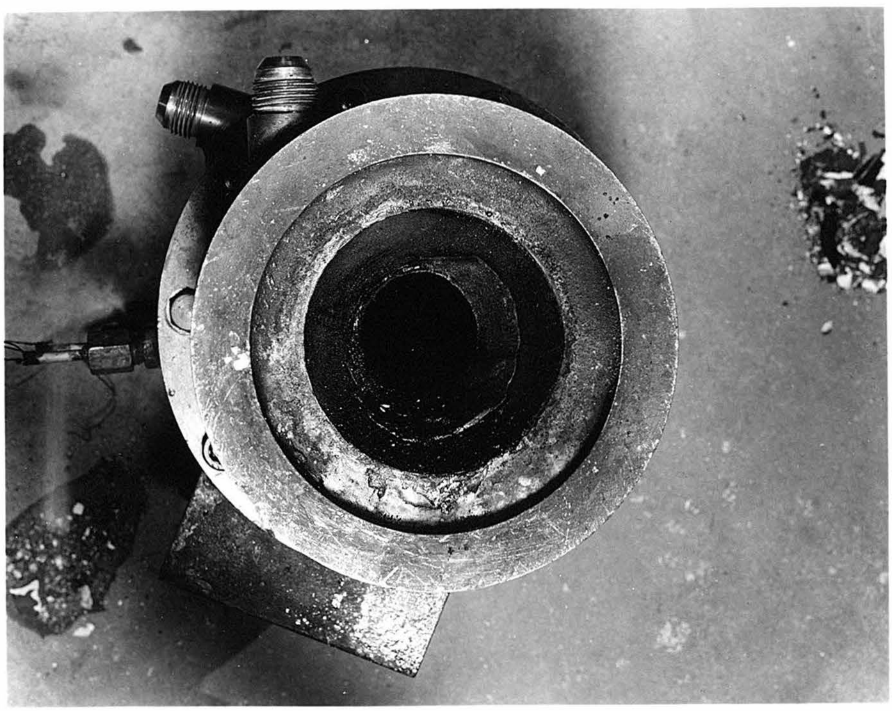


Figure 35--Photograph showing the exit end of nozzle after tests B-92-N & B-93-N with zircon liner. Note the melted zircon that has run through the nozzle throat. (Also see figures 24 and 34.)

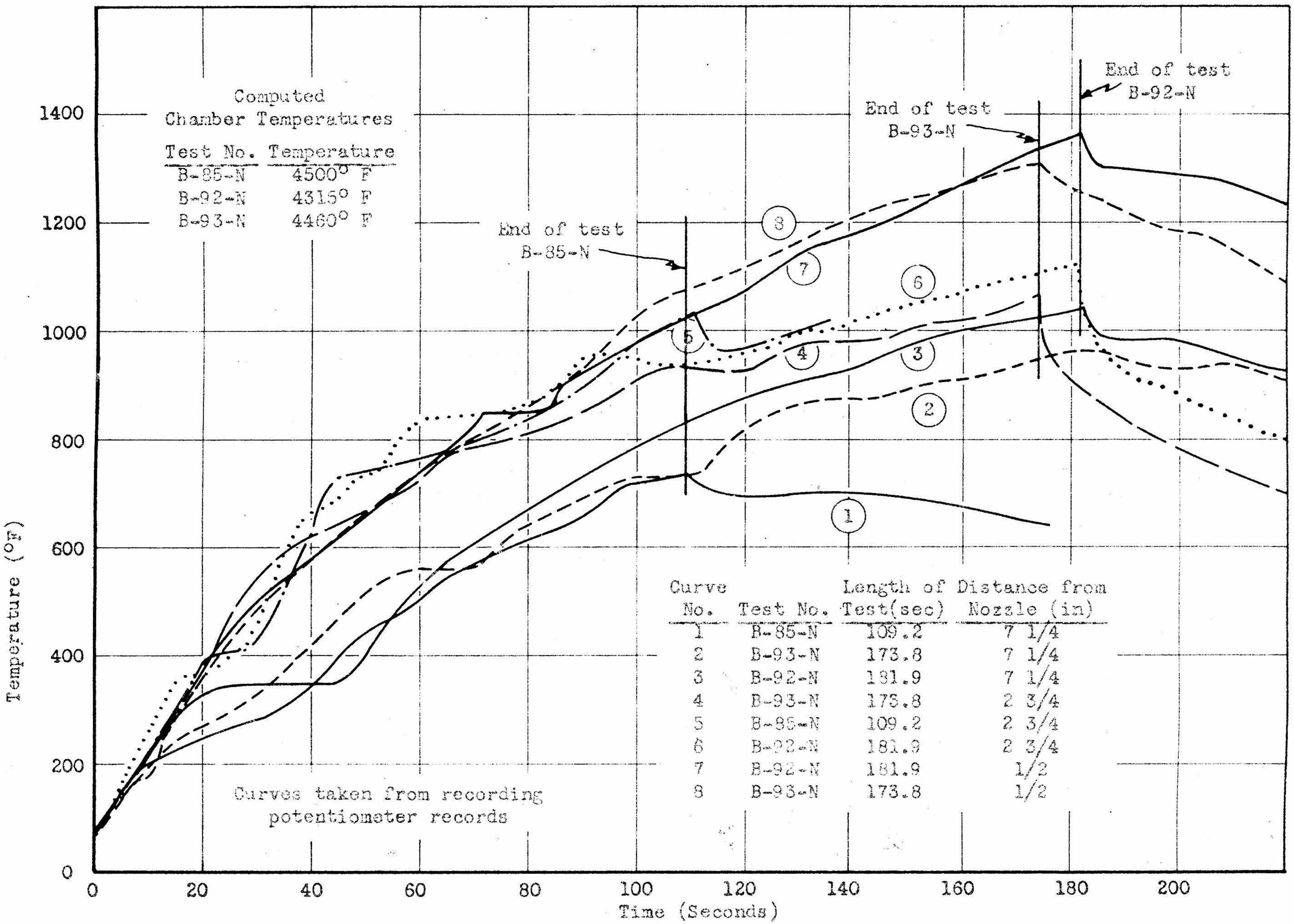



FIGURE 36--Time vs Temperature of the Outer Wall of a 3/8 " Zircon Liner in a 750-# Rocket Motor.

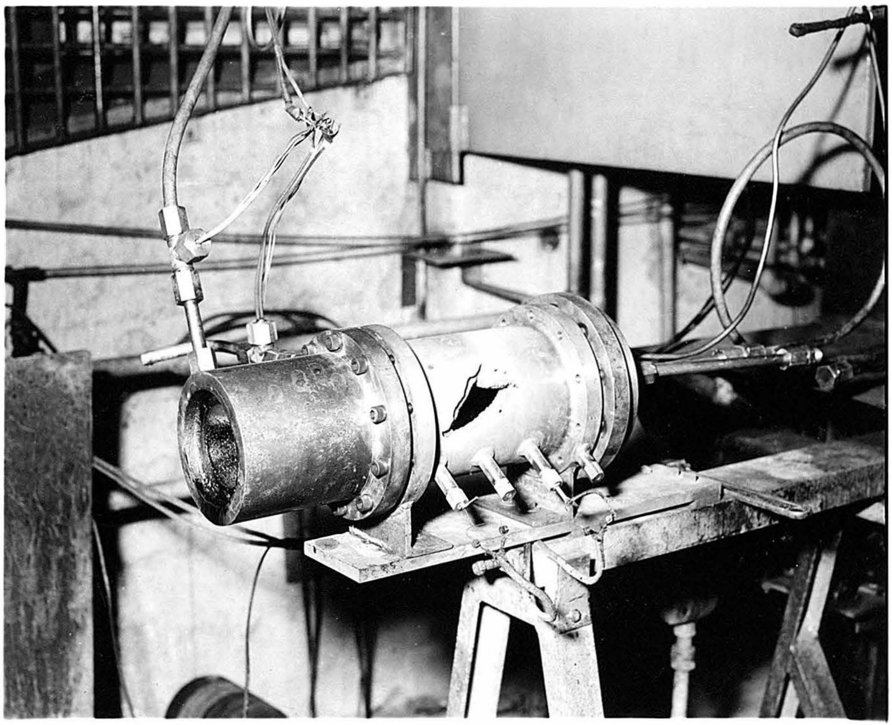


Figure 37--Photograph showing burned-out motor after test B-88-N with a silicon carbide liner. Length of test was 63.0 seconds at a computed chamber temperature of 3965°F. (Also see figures 38 and 39.)

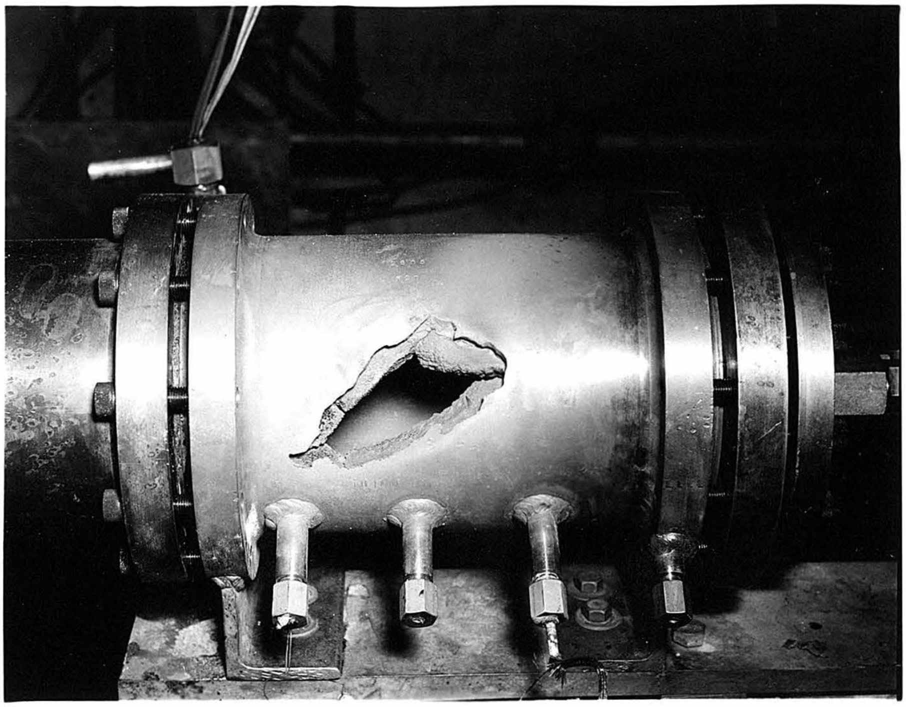


Figure 38--Photograph showing a close-up of burned-out motor after test B-88-N. Motor lined with a silicon carbide liner. (Also see figures 37 and 39.)

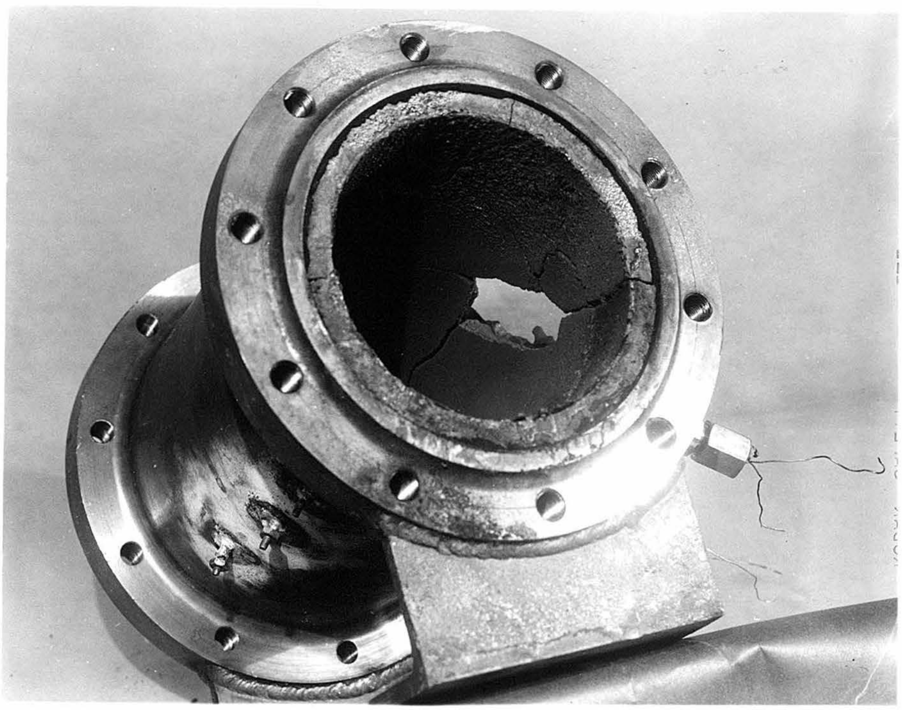


Figure 39--Photograph from nozzle end showing condition of silicon carbide liner after test B-88-N. Note the large cracks which led to the failure of this liner. Other views of the burn-out are shown in figures 37 and 38.)

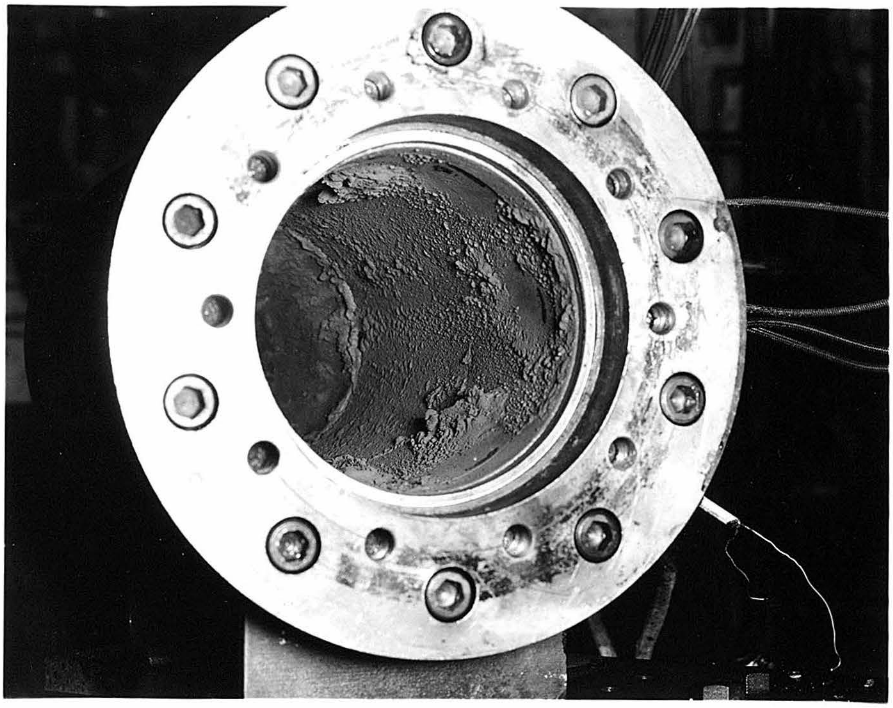


Figure 40--Photograph from injector end showing deposits on the silicon carbide liner after test B-94-N. These deposits were analyzed as primarily silicon oxide. Note also the injector pattern. Length of test was 121.0 seconds at a calculated chamber temperature of 4315°F.

Figure 41--Photograph showing deposits on silicon carbide liner after test B-94-N. Also see figure 40.

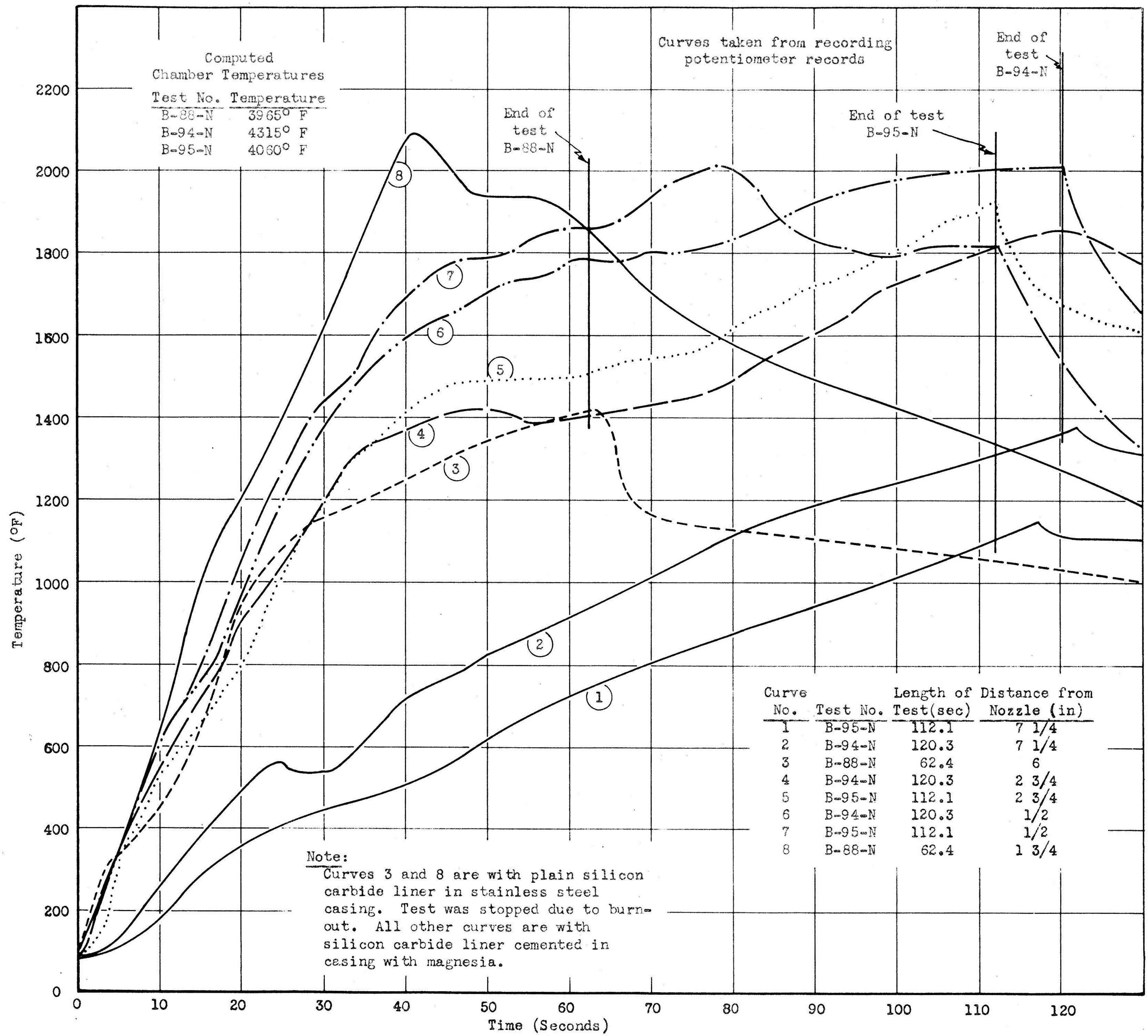



FIGURE 42--Time vs Temperature for Outer Liner Wall with a Silicon Carbide Liner.

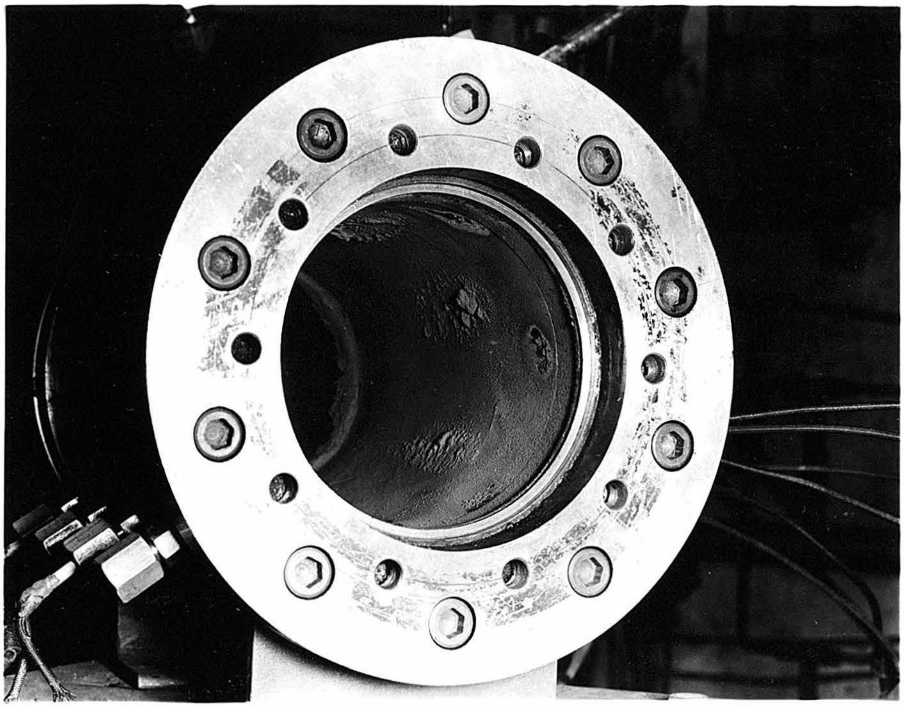


Figure 43--Photograph from the injector end showing condition of beryllia liner after test B-86-N. Note the injector pattern on the liner wall. Length of test was 87.4 seconds at a calculated chamber temperature of 4790°F.

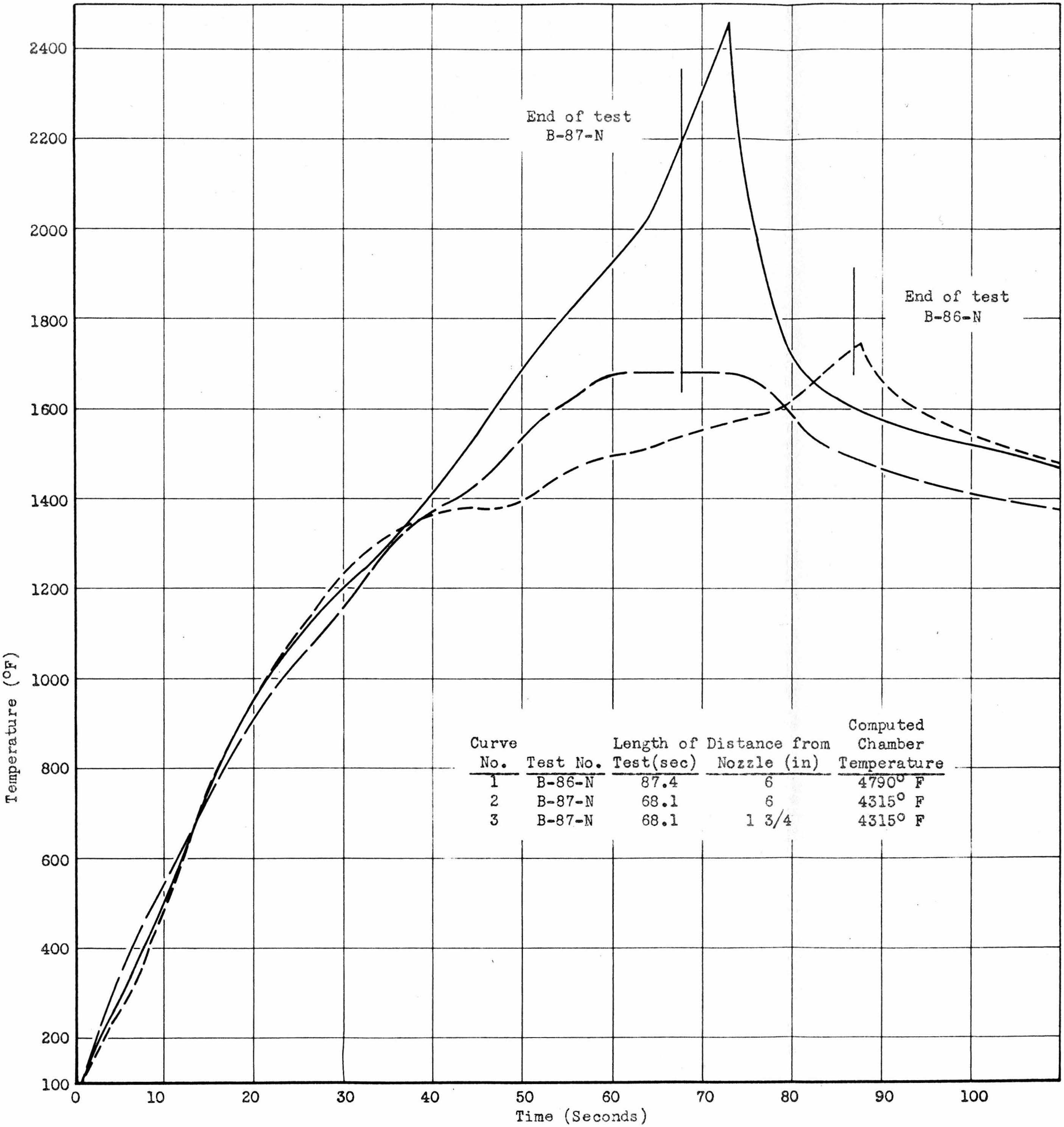



FIGURE 44--Time vs Temperature for Outer Liner Wall with a Beryllia Liner.

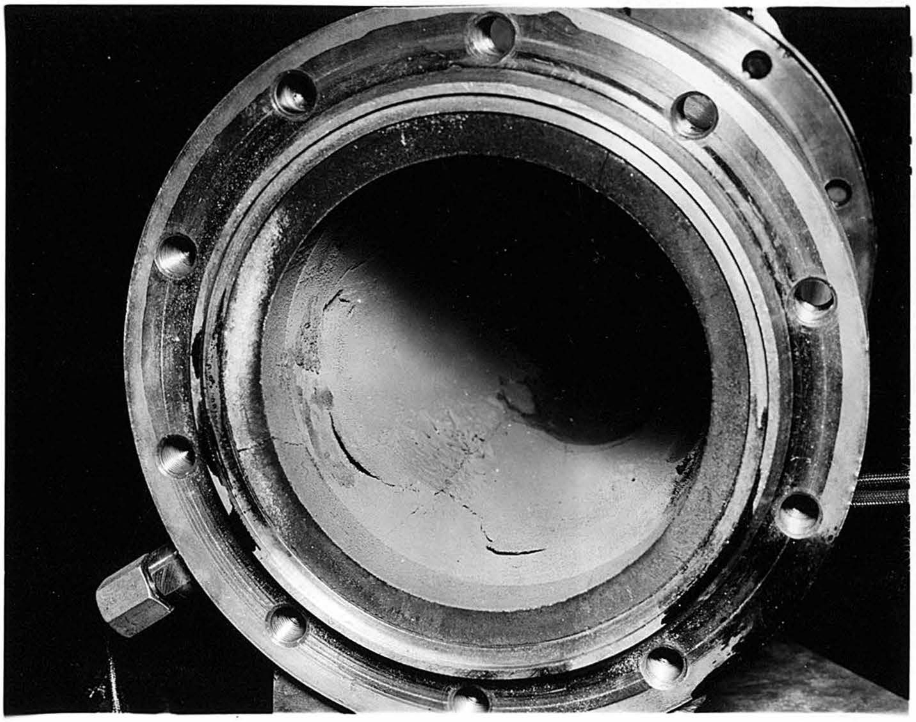


Figure 45--Photograph from injector end showing condition of beryllia liner after tests B-86-N & B-87-N. Note the chipping of the liner at the approximate impingment points of the injector. Total test time was 155.5 seconds. (B-86-N for 87.4 seconds & B-87-N for 68.1 seconds.)

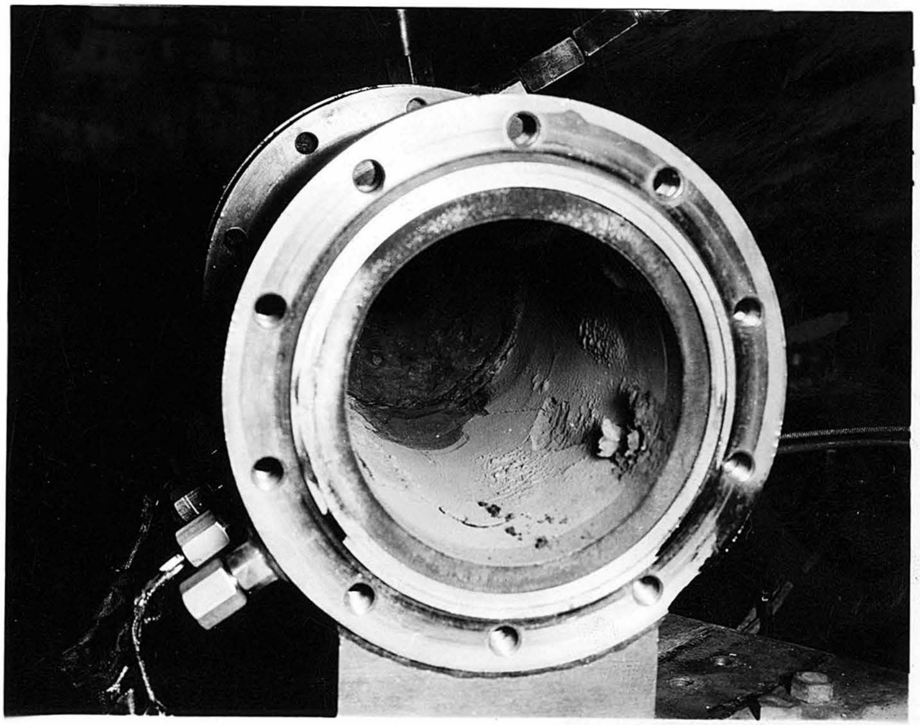


Figure 46--Photograph from injector end showing condition of beryllia liner after tests B-86-N & B-87-N. Note the chipped out area about half way down chamber casing length. Note also cracking and deposits on walls of liner. (For test data see figure 45.)

# A P P E N D I C E S

## COMPUTATIONS

### Computed Performance Parameter

All the performance parameters are computed from the theoretical formula presented in the book "Jet Propulsion" published by the Jet Propulsion Laboratory for the Air Technical Service Command.

a - Characteristic Velocity ($c^*$)

$$c^* = \frac{g\, p_c\, f_t}{w}$$

when $g$ = force of gravity
$p_c$ = chamber pressure
$f_t$ = nozzle throat area
$w$ = total fuel and oxidizer flow rate

b - Thrust coefficient ($C_F$)

$$C_F = \frac{F}{p_c\ f_t}$$

When $F$ = thrust

c - Effective Exhaust Velocity (c)

$$C = c^*\ C_F = \frac{g\, F}{w}$$

d - Specific impulse ($I_{sp}$)

$$I_{sp} = \frac{F}{W}$$

These formulas are fully explained in the reference mentioned above.

### Expected Chamber Temperature

The expected chamber temperature can be calculated in different ways but the following method was chosen based on the performance parameter, $c^*$. This particular value of $c^*$ used was based on the fuel and oxidizer consumption rates as measured by the sight glass readings on the acid and aniline supply tanks. It should be noted here that the values of computed chamber temperatures are quite low compared with the theoretical values based on the mixture ratio. It is assumed that the computed temperatures are lower than actually achieved because melting was observed in both Zirconia and Zircon yet they have melting temperatures of 4928°F and 4532°F, respectively.

The method of calculation was based on the following formula that is given in the book "Jet Propulsion."

$$c^* = \frac{1}{\Gamma'}\sqrt{\frac{\gamma \ Ru \ Tc}{M}}$$

Where: $\Gamma' = \gamma\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{2(\gamma-1)}}$

And: $\gamma$ = ratio of specific heats

Ru = universal gas constant

Tc = chamber temperature

M = weight of gas per mol

c* = characteristic velocity

Values for M and $\gamma$ were taken from theoretical curves plotted with the mixture ratio as one of the coordinate axes. The calculated chamber temperature for each run is listed on the plots of the ceramic wall temperature versus time, that is, Figure 27 for zirconia, Figure 36 for zircon, Figure 42 for silicon carbide and Figure 44 for beryllia.

A compilation of all measured and calculated data is given in Table I, this appendix.

# TABLE I.

## DATA FOR CERAMIC CHAMBER LINER TESTS

| Run No. | $P_c$ #/in.$^2$ABS M | F # M | $w_f$ #/sec M | $w_o$ #/sec M | w #/sec M | r - C | $f_t$ in.$^2$ M | c* 1/sec C | $C_F$ - C | C 1/sec C | $I_{sp}$ sec C | $q_n$ Btu/sec/in.$^2$ M | Liner Used - | Run Time Sec - | Gas Temperature Based on c* °F C | Run No. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| B-82-N | 302 | 742 | 0.850 | 2.680 | 3.53 | 3.15 | 1.850 | 4860 | 1.328 | 6470 | 200.3 | 1.833 | Check-out run | 64.0 | 4810 | B-82-N |
| B-83-N | 313 | 740 | 0.925 | 2.880 | 3.81 | 3.11 | 1.845 | 4880 | 1.281 | 6250 | 194.1 | 2.030 | Zirconia | 121.1 | 4830 | B-83-N |
| B-84-N | 309 | 733 | 0.897 | 2.860 | 3.760 | 3.19 | 1.834 | 4850 | 1.293 | 6280 | 195.0 | 2.235 | Zirconia | 147.2 | 4790 | B-84-N |
| B-85-N | 303 | 738 | 0.913 | 2.840 | 3.750 | 3.11 | 1.820 | 4730 | 1.338 | 6340 | 196.9 | 2.475 | Zircon | 109.2 | 4500 | B-85-N |
| B-86-N | 300 | 733 | 0.821 | 2.85 | 3.670 | 3.47 | 1.822 | 4800 | 1.341 | 6400 | 198.8 | 2.810 | Beryllia | 87.4 | 4790 | B-86-N |
| B-87-N | 300 | 733 | 0.954 | 2.780 | 3.730 | 2.91 | 1.827 | 4730 | 1.337 | 6330 | 196.6 | 2.320 | Beryllia | 68.1 | 4315 | B-87-N |
| B-88-N | 292 | 706 | 0.876 | 2.990 | 3.890 | 3.33 | 1.824 | 4410 | 1.326 | 5840 | 181.4 | 2.453 | SiC | 62.4 | 3965 | B-88-N |
| B-89-N | 296 | 712 | 0.952 | 2.850 | 3.800 | 2.99 | 1.819 | 4560 | 1.322 | 6030 | 187.3 | 2.471 | Zirconia | 181.7 | 4030 | B-89-N |
| B-90-N | 305 | 755 | 0.944 | 3.030 | 3.97 | 3.21 | 1.824 | 4510 | 1.357 | 6120 | 190.1 | 1.685 | Check-out run | 62.0 | 4080 | B-90-N |
| B-91-N | 302 | 766 | 0.938 | 2.980 | 3.92 | 3.18 | 1.800 | 4470 | 1.409 | 6290 | 195.3 | 2.270 | Zirconia | 181.8 | 3990 | B-91-N |
| B-92-N | 306 | 734 | 0.895 | 2.970 | 3.870 | 3.32 | 1.811 | 4610 | 1.324 | 6110 | 189.8 | 1.980 | Zircon | 181.9 | 4315 | B-92-N |
| B-93-N | 310 | 734 | 0.880 | 2.820 | 3.700 | 3.20 | 1.737 | 4690 | 1.363 | 6390 | 198.4 | 1.990 | Zircon | 173.8 | 4460 | B-93-N |
| B-94-N | 300 | 718 | 0.865 | 2.890 | 3.760 | 3.34 | 1.788 | 4590 | 1.339 | 6150 | 191.0 | 1.968 | SiC | 120.3 | 4310 | B-94-N |
| B-95-N | 305 | 712 | 0.849 | 2.930 | 3.780 | 3.45 | 1.716 | 4190 | 1.360 | 6065 | 188.4 | 1.596 | SiC | 112.1 | 4060 | B-95-N |

Note: The figures given in columns for $w_f$, $w_o$, and w are based on the average flow rate during a test. Total consumption during the test was taken from sight glasses on the oxidizer and fuel storage tanks. The value was divided by total time of test and gave average flow rates.

M Measured data

C Computed data

DIFFICULTIES ENCOUNTERED AND METHODS OF SOLUTION

Due to the short time that the author could occupy the test pit and the fact that much of the preliminary ground work had been laid for this study prior to his association with the Jet Propulsion Laboratory, many problems that occurred could not be completely solved in a satisfactory manner. However, a note is being made of problems encountered whether they were solved or not. It is hoped that the presentation of these problems may help some future experimenter.

1. Injector Orifices Much delay was encountered due to the slowness in fabricating of the injector and the last parts of the injector delivered were the orifices. These orifices were made by a commercial manufacturer of materials furnished by the Jet Propulsion Laboratory. The specifications called for stainless steel but some of the delivered articles were magnetic and showed signs of rust. A check proved that the material was not stainless steel. Since time was short, it was decided to use these orifices. During the tests a different mixture ratio of oxidizer to fuel was given for each test. This was due, at least in part and perhaps entirely, to these substitute orifices. Only four of thirty-six orifices delivered were satisfactory; that is, four were stainless steel.

2. Acid Barton Meter The use of a plastic separator in the lines connecting the Barton differential pressure meter to the acid line was considered as a large error inducing mechanism. The exact size of this error cannot be readily evaluated because the error varied from test to test. For this reason little dependence was placed on this meter and overall flow rates were determined from the sight glass readings on the acid tank. Check calibrations of the acid Barton flow meter showed quite conclusively

that the data taken for one run or at any particular time were in error a constant amount during that run or during a small interval of time. However, these calibrations also showed that the errors varied greatly from day to day and test to test.

3. Design of Chamber Casing. The chamber casing as originally designed had a 3/4 inch metal lip that was used as a seat for the nozzle as shown in Figure 12. The heat transfer through this metal lip was so great during the first test with a zircon liner that it caused the lip to fail by melting (see Figures 31 and 32). Figure 13 shows a redesign to eliminate this lip. With this simple redesign this sort of failure was eliminated entirely. Figure 18 shows how the metal lip was replaced by a piece of ceramic liner. Ceramic liner then extended from the nozzle to the injector. The redesign of this lip necessitated a change in the method of providing a gas-tight seal between the nozzle and the chamber casing. This was accomplished by placing a copper gasket between the nozzle and the chamber casing and is shown in place on the nozzle in Figure 17. It is believed that all ceramic liners used in the chamber should extend from injector to nozzle.

4. Loose Liners. When the silicon carbide liner was placed in the chamber casing without cement, a motor failure occurred (see Figures 37, 38, and 39). This was probably caused by the liner fitting too loosely in the casing. In this case the clearance between the casing and the liner was excessive and such a failure was anticipated. It may be hypothesized that upon starting the motor the high chamber pressure cracked the liner and forced the liner against the casing walls. Such large cracks occurred that the pressure was equalized on either side of the liner. The vibration of the motor then caused a section of the liner to fall into the chamber interior. The metal of the casing was then exposed to the direct flame and the metal melted away, causing a failure.

5. <u>Temperature Recording Devices</u>. The potentiometer set-up as used in this study was not entirely satisfactory. For the temperature gradients encountered in this type of a study only a single thermocouple should be connected into a potentiometer. In the case of a Brown 12-point recording potentiometer when a very steep temperature gradient is encountered much of the time during a run is spent in "hunting." This is because the Brown will not record unless it is in balance. However, when in balance, it will record every second. On the other hand the Leeds-Northrop 16-point recording potentiometer will normally print only every four seconds. With more than one thermocouple per instrument there are not enough recordings made to give a good curve of temperature versus time. For this type of test other types of potentiometers than those mentioned are needed. It is believed that better results might be obtained by the use of a calibrated millivoltmeter or microammeter connected to each individual thermocouple. The necessary number of such instruments could then be placed in a bank on a panel and photographed as a means of recording.

6. <u>Poor Grades of Acid Used in Tests</u>. Unfortunately, during this series of tests, three different lots of oxidizer (red fuming nitric acid) were used. In addition to other factors giving variations in performance from test to test, the different lots of acid varied considerably in purity and, therefore, added another variable to the test conditions.

This poor acid and the poor orifices in the injector were two of the primary reasons for poor performance data during this series of tests.