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RESEARCH MEMORANDUM

EXPLORATORY TESTS OF THE BEHAVIOR OF SEVERAL MATERIALS IN A SUPERSONIC AIR JET AT 4,000° F

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FOR AERONAUTICS
WASHINGTON
July 29, 1957

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

RESEARCH MEMORANDUM

EXPLORATORY TESTS OF THE BEHAVIOR OF SEVERAL MATERIALS IN A SUPERSONIC AIR JET AT 4,000° F

By Russell N. Hopko and Otto F. Trout, Jr.

SUMMARY

Several materials have been tested in the ceramic-heated jet (laboratory model) at a Mach number 1.96 with a stagnation temperature of approximately 4,000° F. Test models made of molybdenum were less affected by temperature than titanium, stainless steel, and an alloy of 90 percent tungsten, 6 percent nickel, and 4 percent copper. Titanium and steel burn with highly exothermic reactions when subjected to the 4,000° F air jet. A flame-sprayed zirconia-coated graphite model suffered no evident damage.

INTRODUCTION

The attainment of supersonic and hypersonic speeds by airplanes and missiles has indicated the need for materials to withstand extreme temperatures. There is at the present time, therefore, great interest in the behavior of materials subjected to high air temperatures for relatively short times. The Langley Laboratory of the National Advisory Committee for Aeronautics has undertaken an exploratory investigation to determine the behavior of various materials subjected to high-temperature high-velocity air.

In the continuation of this investigation, models made of molybdenum, titanium, tungsten alloy, stainless steel, graphite, and a zirconia coating on molybdenum and graphite have been tested in a small 4,000° F air jet supplied by a ceramic pebble-bed heat exchanger. The Mach number of the jet was 1.96 at a corresponding Reynolds number of 1.72×10^6. More complete details of the exchanger and its operation are found in reference 1. Motion pictures were taken during the tests with 16-millimeter cameras and a description of these observations is reported herein.

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MODELS

The configurations used in this investigation are shown in figure 1. Configuration 1 is a 36.8° total-angle cone having a maximum diameter of 1/2 inch. Configuration 2 is a solid $\frac{1}{2}$-inch-diameter cylinder with a hemispherical face. Configuration 3 is a solid 1/2-inch-diameter cylinder having a flat face with rounded corners. Configuration 4 is a 20° included half-angle cone with base diameter equal to 3/4 inch.

TESTS

The models were located in the second test rhombus of the ceramic-heated jet (laboratory model) at $M \approx 1.96$ with a stagnation temperature of 4,000° F having a velocity of approximately 5,100 feet per second. The nozzle exit was 0.78 inch in diameter.

A quick acting pneumatic cylinder effected the entry of the model into and the removal of the model out of the jet during the tests. Motion pictures of the tests were obtained with a 16-millimeter Fastax camera, recording 500 frames per second on black-and-white film and a 16-millimeter Bell and Howell camera recording 130 frames per second on color film.

Figure 2 presents estimated stagnation temperature conditions against time for a typical test. The stagnation temperature of the jet has been measured with thermocouples in a total temperature probe up to 3,000° F and compared with the temperatures of the pebble bed as measured with an optical pyrometer. Measurements up to 3,000° F show that stagnation temperature of air is close to the temperature of the pebble bed. Above 3,000° F measurements of bed temperature have been obtained with both recording and optical pyrometers. Temperature during the tests reported herein was maintained within ±50° F from one test to another.

RESULTS AND DISCUSSION

Figure 3 presents photographs of the configurations during various stages of the tests.

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Titanium

Figure 3(a) shows the behavior of burning of commercially pure titanium. Configuration 1 ignited at approximately 0.6 second after entry into the jet. Configuration 2, the hemispherical-faced model, ignited at 8.6 seconds and configuration 3, the flat-faced model, survived the test which lasted 23 seconds. The lower heat transfer to the blunt shapes increases the time to melt or time to ignite. This is in agreement with the results of reference 1. Titanium burns on its surface and loses mass rapidly. The reaction of titanium with air is a highly exothermic reaction producing the titanium dioxide and releasing 4,550 calories of heat per gram of titanium (ref. 2). Titanium melts at 3,074° F having a heat of fusion of 104.3 calories per gram. Titanium is also known to have affinity for nitrogen as well as oxygen; however, a chemical analysis of the remaining portion of the model showed no trace of nitride formation.

Stainless Steel

The material tested was 347 stainless steel. Photographs made during these tests are shown in figure 3(b). Configuration 1 ignited in 0.4 second; configuration 2 ignited in 9.1 seconds. Upon ignition stainless steel burned with a highly exothermic reaction on the surface and produced unsymmetrical shapes.

Tungsten Alloy

The tungsten alloy tested was a sintered powder-metal alloy of 90 percent tungsten, 6 percent nickel, and 4 percent copper.

The behavior of the tungsten alloy (fig. 3(c)) is characterized by a slow disintegration of the forward surface of the model. Small particles were observed to break off unsymmetrically from the surface. Subsequent tests of pure tungsten have indicated that pure tungsten has much better resistance to the jet than the alloy reported herein and shows no tendency to break apart.

Molybdenum

The material tested was commercially pure molybdenum. Figure 3(d) shows photographs of molybdenum taken during the tests. Configuration 1 began melting at 4.9 seconds and configuration 2 began melting at 17 seconds. Configuration 3 did not melt but did suffer a loss of weight due to oxidation. A white smoke believed to be molybdenum trioxide was observed to leave the surface of the models. This molybdenum trioxide

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sublimes from the surface above approximately 1,300° F causing a slow loss of material. Surface temperatures of 3,400° F were read by an optical pyrometer before surface oxidation caused rapid ablation.

Molybdenum oxidizing in air produces molybdenum trioxide liberating 1,812 calories per gram of molybdenum trioxide above 1,292° F, which is below the melting point of the oxide which is 1,463° F (ref. 2). The melting point of molybdenum is approximately 4,750° F; therefore, considerable heat of oxidation has been added to the aerodynamic heat input in order to melt the molybdenum model.

Graphite

Graphite models of only the flat-faced cylinder (fig. 3(e)) were tested. Some damage occurred at the face; however, the steel support behind the model melted rapidly. Previous tests with a sharp-nose cone (ref. 1) showed no rapid deterioration of the nose.

Zirconia Coated

Coated molybdenum.- A flat-faced molybdenum model was coated with a layer of zirconia approximately 0.006 inch thick. The zirconia was applied by flame spraying. The oxide coating cracked off at 14 seconds during the test.

Coated graphite.- A graphite model, configuration 4, was coated with zirconia 0.004 inch thick, figure 3(f). This coating lasted for the duration of the test, 19 seconds, at which time the steel support melted. Visual observation of the model after the test showed that the graphite experienced no damage and appeared to be completely protected by the coating.

Behavior of Materials Tested

Material	Melting point, °F	Type of ablation	Remarks
Titanium	3,074	Burning on surface	Unsymmetrical mass loss
Steel	2,590	Melting and burning	Unsymmetrical mass loss
Tungsten alloy		Small particles breaking off	Unsymmetrical mass loss
Zirconia	4,870	None observed	(Ref. 3)
Molybdenum	4,750	Melting of molybdenum and sublimates of oxide	Symmetrical loss
Graphite	6,000 (Sublimes)	Slow burning on surface [redacted]	Symmetrical mass loss with no major damage

CONCLUDING REMARKS

Models made of titanium, 347 stainless steel, tungsten alloy, molybdenum, graphite, and zirconia coating on molybdenum and graphite were tested in the ceramic-heated jet (laboratory model) at a Mach number of 1.96 with a stagnation temperature of approximately 4,000° F.

Molybdenum is less affected than steel or titanium because sharp points tend to round off rather than start burning as with steel and titanium. Although molybdenum has a moderate oxidation rate, above about 1,200° F the oxidation rate does not increase appreciably with air temperature until the metal reaches a temperature of about 3,400° F. At this point rapid oxidation caused surface melting with a more rapid loss of material.

Tests of zirconia-coated graphite show promise as a material for some high-temperature applications.

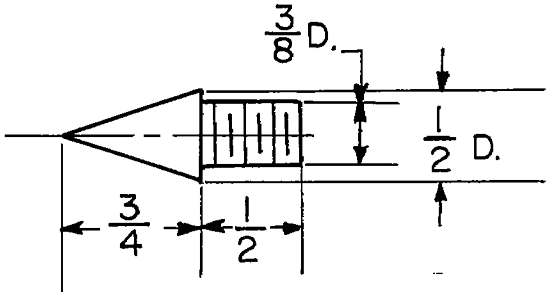
Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., May 2, 1957.

REFERENCES

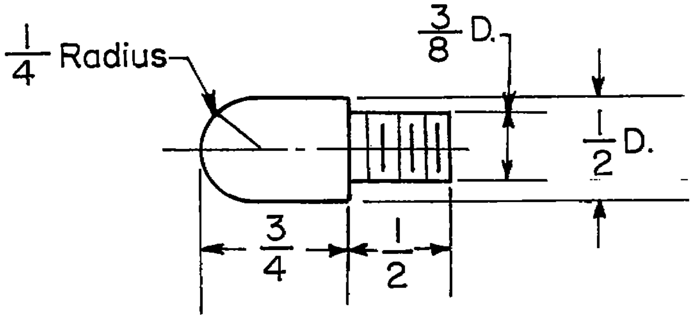
1. Purser, Paul E., and Hopko, Russell N.: Exploratory Materials and Missile-Nose-Shape Tests in a 4,000° F Supersonic Air Jet. NACA RM L56J09, 1956.

2. Hampel, Clifford A., ed.: Rare Metals Handbook. Reinhold Pub. Corp. (New York), 1954, pp. 271-289, 455-481.

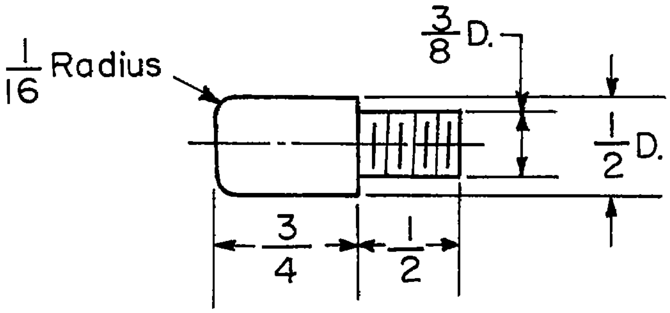
3. Norton, F. H.: Refractories. Third ed., McGraw-Hill Book Co., Inc., 1949, p. 357.



Configuration 1

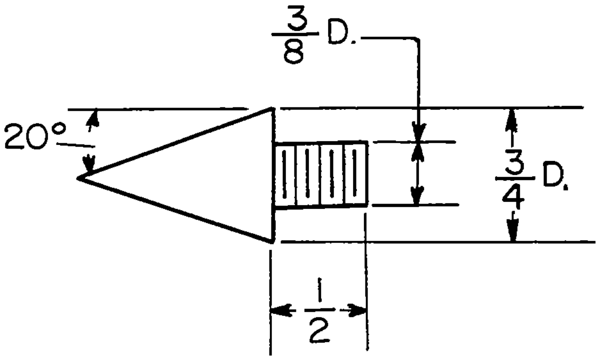


Configuration 2



Configuration 3

Figure 1.- Sketch of models. All dimensions are in inches.



Configuration 4.

Figure 1.- Concluded.

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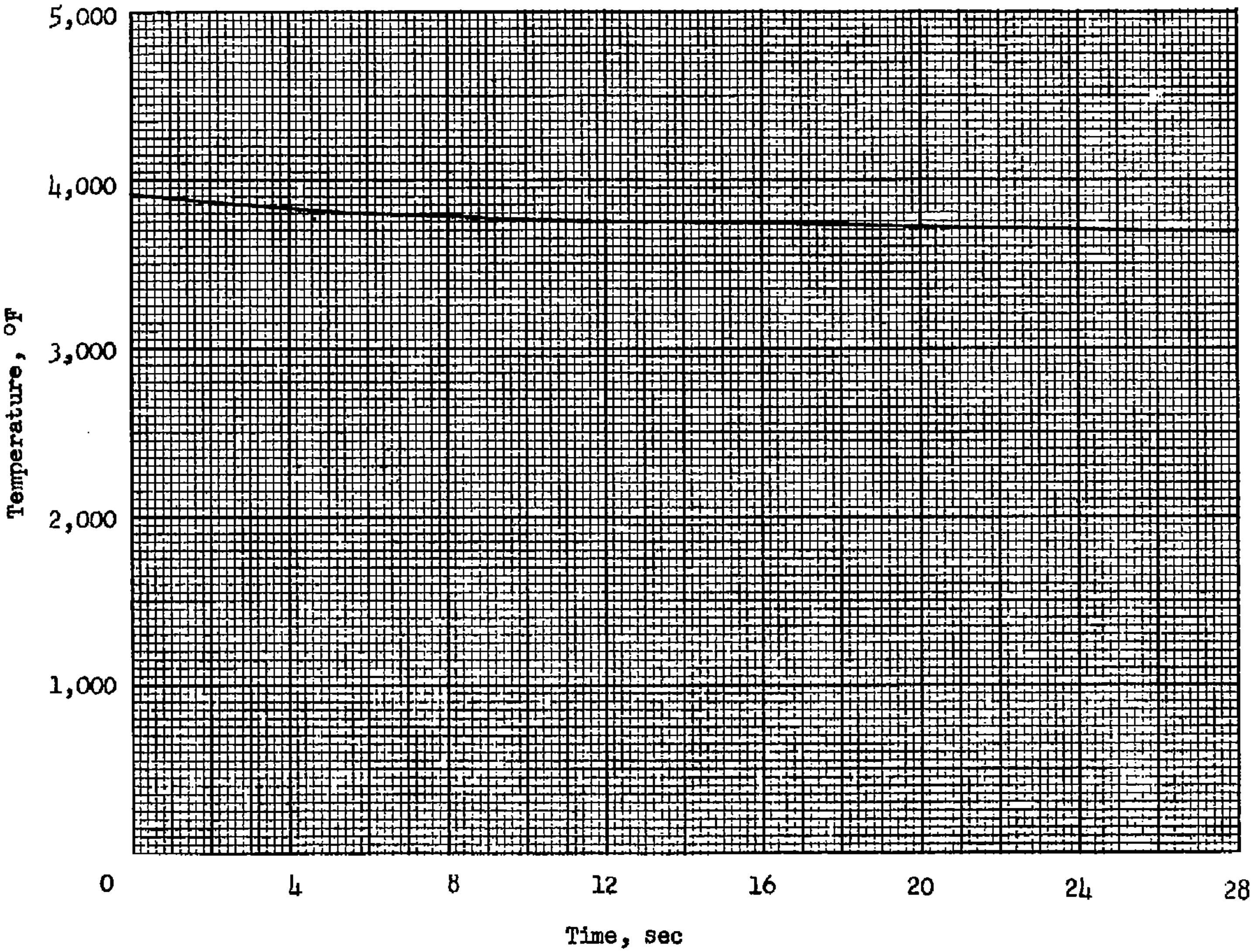


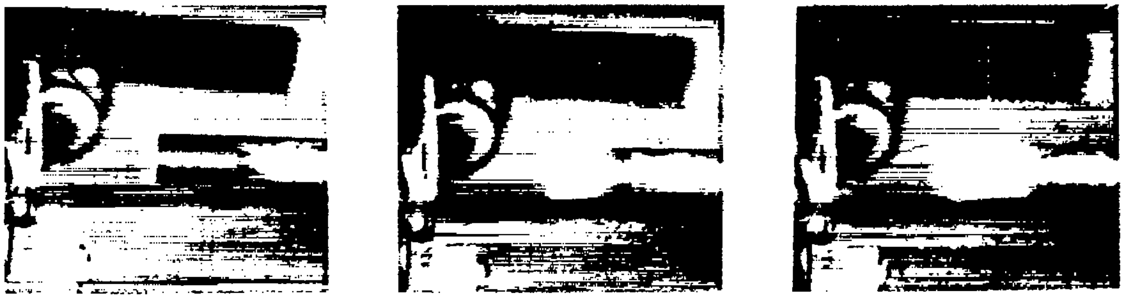
Figure 2.- Estimated variation of stagnation temperature against time for a typical run with heat exchanger heated to 4,000° F before run.

0.3 sec 1.0 sec 1.5 sec

Configuration 1

0.5 sec 8.6 sec 9.1 sec

Configuration 2

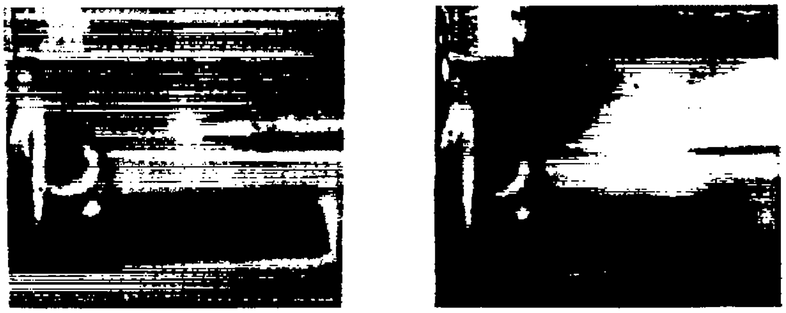


0.5 sec 12.0 sec 23.0 sec

Configuration 3

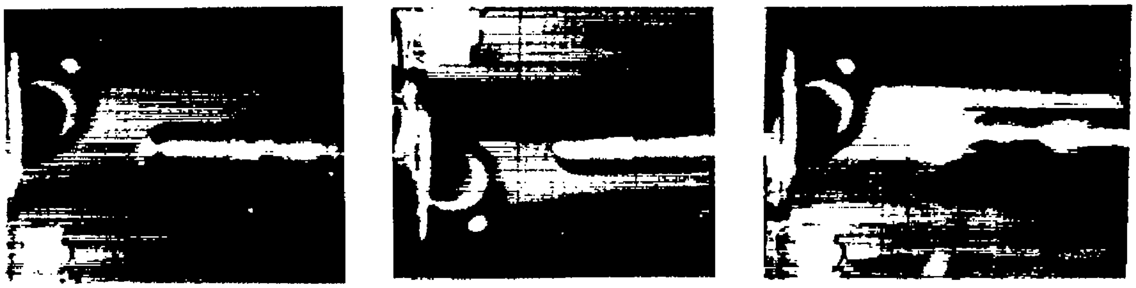
(a) Titanium. L-57-1590

Figure 3.- Discrete photographs taken during tests.



04 sec 2.0 sec

Configuration 1



0.1 sec 8.5 sec 10.5 sec

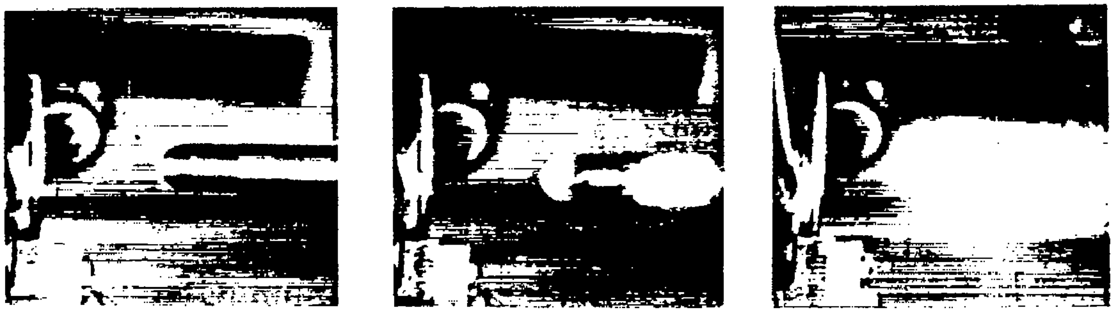
Configuration 2

(b) 347 stainless steel. L-57-1591

Figure 3.- Continued.

0.4 sec 3.0 sec 5.5 sec

Configuration 1



0.5 sec 9.0 sec 17.0 sec

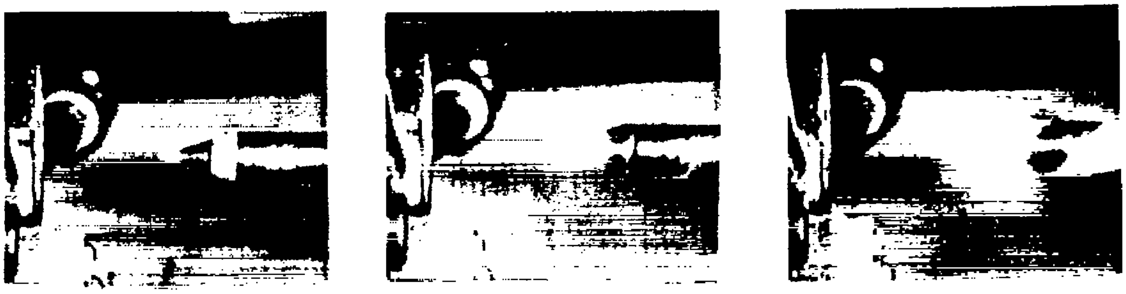
Configuration 2

0.5 sec 9.0 sec 13.0 sec

Configuration 3

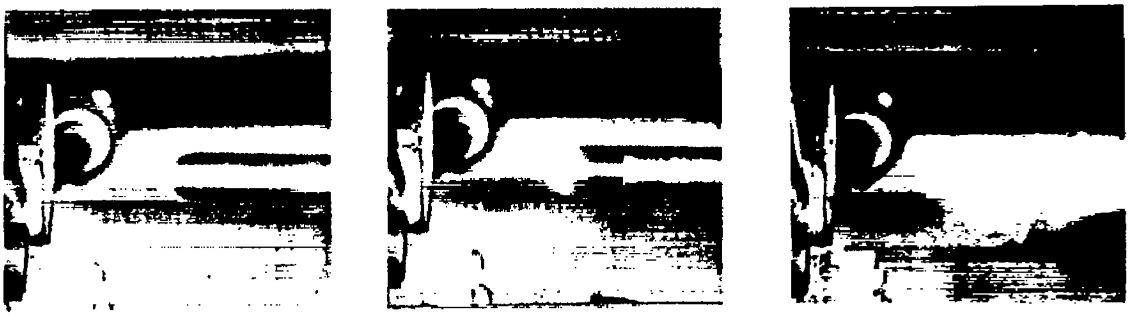
(c) Tungsten alloy. L-57-1592

Figure 3.- Continued.



2.1 sec 6.1 sec 11.0 sec

Configuration 1



0.5 sec 8.9 sec 18.3 sec

Configuration 2

0.5 sec 19.2 sec 27.6 sec

Configuration 3

(d) Molybdenum. L-57-1593

Figure 3.- Continued.

0.5 sec 10.0 sec 18.0 sec

Configuration 3

(e) Graphite.

0.5 sec 9.0 sec 19.0 sec

Configuration 4

(f) Zirconia-coated graphite. L-57-1594

Figure 3.- Concluded.

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