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SNAP 19

TEST REPORT

FEASIBILITY TESTS, HIGH ENTHALPY
DISINTEGRATION OF MAGNESIUM

MND-3607-114

October 1966

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FOREWORD

This test report is submitted by the Martin Company, Baltimore, a division of the Martin Marietta Corporation in support of United States Atomic Energy Commission Contract AT(30-1)-3607, Item 4(1)(d), of the SNAP 19 Experimental Program.

ACKNOWLEDGMENT

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SUMMARY

The purpose of the preliminary test program was to experimentally evaluate the various techniques intended for application in a more extensive high enthalpy test program of magnesium alloys. To carry out the preliminary program it was necessary to make measurement or identification of the following:

- (1) Temperature history of the material by employing thermocouples at various desired locations.
- (2) Environmental conditions such as temperature or enthalpy, stagnation pressure, and heat flux input to the body by using thin skin heat meters and pitot tubes.
- (3) Time history of major events such as test specimen melting and combustion that may occur during the test with movies, spectrographs and thermocouples.
- (4) Rate of regression of the front wall with movies, regression gages and thermocouples.

Twenty-four magnesium alloy test specimens (eight HM31A alloy, SNAP 19 casing material and 16 ZH62A alloy, sensory ring structural material) and seven stainless steel heat meters were designed and fabricated at the Martin Company, Baltimore. The preliminary test program was conducted in two arc-jet wind tunnels located at the Ames Research Center, Moffet Field, California during June and July 1966.

Test results indicated that thermocouples can be used to define the regression rate of a metal surface as well as the temperature history of the material.

The use of simplified regression sensors to provide surface regression rates did not prove feasible because of spurious or no signal generation throughout the test runs.

The use of motion pictures to record surface regression rates appeared to be the most promising method of achieving good results. However, this method would be enhanced if it were coupled with stroboscopic photographic techniques to more clearly define the receding surface.

The failure of the movies to record the existence of combustion phenomena in no way indicates the nonexistence of such phenomena in the reentry of Nimbus B since the energy levels experienced during the tests were lower than expected.

Spectrographic records taken at fixed periods are not capable of sensing the onset of the emission of magnesium oxide (MgO) of wavelength 5078 Å or magnesium atoms of wavelength 5183 Å which accompany the start of melt. In addition, spectrography as used in the test program cannot discriminate between MgO formation resulting from slow oxidation or from combustion. If the spectrograph was coupled to a photomultiplier and recorder, a continuous record of the occurrence and intensity of an emission of given wavelength would be available.

Of secondary importance in the performance of the preliminary test program was an attempt to determine the fundamental mode or disintegration of the magnesium alloys. However, neither the vehicle geometry tested nor the data obtained were sufficient for use in establishing the failure mode. It is, therefore, strongly recommended that the main magnesium disintegration test series outlined in Ref. 1 be implemented to obtain the information necessary to establish the fundamental mode of magnesium destruction.

I. INTRODUCTION

During re-entry into the earth's atmosphere, a spacecraft is subjected to an extremely severe aerothermal environment which causes chemical reaction between the spacecraft material and the atmosphere. In Nimbus B/SNAP 19, the major construction material is magnesium alloy ZH62A which forms the separators and connectors of the 18 compartments of the sensory ring. The sensory ring contains numerous modules. The mode of failure of the sensory ring during re-entry may be one of melting away, ablation or combustion, depending on the heat flux due to re-entry, the reaction rate of magnesium, and the thermal properties and geometry of the structure. As the satellite re-enters with the sensory ring first, the front of the ring is heated rapidly and part of the heat is dissipated to the rest of the satellite. As the temperature of the sensory ring rapidly builds up, melting of the surface and formation of MgO commence almost simultaneously. Since MgO is highly soluble in Mg, a portion of the MgO formed will remain in the face of the sensory ring, thus forming a thermal barrier in the otherwise highly conductive magnesium. A part of the MgO formed will be carried away by the flow stream. Ablation or burning of the magnesium may follow somewhat later due to the presence of MgO in the molten magnesium. The exact process that will take place depends strongly on the oxygen concentration and structural geometry of the sensory ring. In order to determine the disintegration mode of the spacecraft during re-entry, it is necessary to know the temperature history of the various elements and the reaction characteristics of the materials involved. To achieve these objectives, two test programs were scheduled. First, a 1/10-scale thermal model of the Nimbus B/SNAP 19 was designed and fabricated by the Martin Company to be tested in a hypersonic hot gas tunnel to obtain the temperature information. Second, an experimental program to parametrically study high enthalpy disintegration of magnesium was proposed by the Sandia Corporation to investigate the reaction characteristics of ZH62A and HM31A (casing material of SNAP 19). The Sandia Corporation proposal is documented in Ref. 1. The plan proposes a total of 324 specimens to be tested under different stream enthalpies, pressures and chemical compositions.

The committee sponsoring the SNAP 19 Extended Safety Program, i.e., Martin Company, Sandia Corporation, and Hittman Associates, Inc., advised that the feasibility of the various testing techniques proposed for use in the Sandia program be determined before the extensive study program was started. The objective of this preliminary program is, therefore, to experimentally evaluate the various techniques intended for application to the extensive high enthalpy test program of magnesium alloys.

The preliminary program was conducted at the NASA Ames Research Center, Moffet Field, California, during June and July 1966.

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II. TECHNICAL DISCUSSION

The primary objective of these preliminary tests is to investigate the feasibility of techniques proposed for use in the main magnesium disintegration test series outlined in Ref. 1. The objective of the main magnesium disintegration test program is to obtain information on material behavior under various conditions of body temperature, environmental heat flux input, partial pressure of oxygen and effect of mass action.

The reaction rate is a function of the temperature of the body and the environment, the vapor pressure of the material at that temperature and the pressure and composition of the environment.

The body temperature buildup is a function of the available heating rate, the formation and growth of an oxide layer on the surface, and possible heat blockage due to mass injection into the downstream boundary layer.

To carry out an experimental investigation of this nature, it was deemed necessary to be able to make measurement or identification of the following:

- (1) Temperature history of the material at various desired locations.
- (2) Environmental conditions such as temperature or enthalpy, stagnation pressure and heat flux input to the body.
- (3) Time history of major events such as melting and combustion that may take place during testing.
- (4) Rate of regression of the front wall.

It was decided by the Working Committee that a preliminary test program be performed as outlined in Ref. 2 to accomplish the following:

- (1) Determine the temperature history of points in the body by means of thermocouples embedded into the material at specific locations and continuously record the thermocouple outputs on tape, either by light or heat.
- (2) Determine the environmental conditions as follows:
 - (a) Measure the stagnation pressure behind the shock wave by means of a pitot tube.
 - (b) Measure the heat flux input to the body by means of thin skin heat meters of the same geometry as the test specimen.

- (c) Calculate the enthalpy of the plasma stream heated by an electrical arc. This state is very difficult to determine. The average enthalpy of the stream may be roughly calculated by means of a heat balance of the tunnel but the actual enthalpy to which the specimen is exposed depends on the uniformity of the enthalpy distribution and the size of the specimen. It was decided that the most feasible method under the circumstances is to calculate the enthalpy based on the measured values of stagnation pressure and heat flux.
- (3) Obtain color movies and spectrographs to mark such major events as melting, strong vaporization or combustion.
- (4) Measure the recession of the front face by locating the various thermocouples on the front face at different depths from the surface. It was expected that the thermocouple would increase its output drastically when exposed to the high temperature plasma stream. The movies could also act as a check on the position of the front face at various periods if the melting or ablation was uniform in a plane normal to the flow direction. Furthermore, a special make-and-break regression sensor would also be installed to provide the same information.

Most of the experimental techniques described are well established. However, magnesium has a high vapor pressure at higher temperatures and combines with air violently in an exothermic reaction. There was some doubt as to whether these techniques would render any useful information. For example, thermocouples may not be in good contact with the metal due to the high coefficient of expansion of the metal. The short time available may not enable the thermocouple to reach material temperature if contact is lost even though the thermocouple is in a small cell and is not loose. This same looseness, due to the difference in the coefficient of expansion, may also cause the proposed regression sensor to malfunction. Color movies may not be able to record any event after the start of a self-sustaining combustion of magnesium. Hence, it was necessary to evaluate these techniques in the operating environment.

III. TEST PROGRAM

The equipment, test specimens and the facility needed are detailed here. The test procedures are also discussed.

A. MODEL AND INSTRUMENTATION

The following is a list of the test models fabricated to perform this test program.

<u>Models (No.)</u>	<u>Materials</u>	<u>Purpose</u>
4	SS Type 321, uncoated	Heat meter
3	SS Type 321, coated*	Heat meter
5	Mg HM31A, uncoated	Boundary layer heat transfer effect
3	Mg HM31A, coated*	Boundary layer heat transfer effect
16	Mg ZH62A, uncoated	Combustion/ablation studies

*Coating: Zirconium oxide per Martin Process NPS-03-031, emissivity coating.

The test specimens were fabricated as shown in Figs. 1, 2 and 3.

The test specimens were instrumented with thermocouples, and, in addition, four ZH62A specimens were provided with regression sensors. The thermocouples installed in the front wall of the stainless steel specimens were intended to measure the heating rates into the specimen, whereas those installed in the magnesium specimens were to provide an indication of the material temperature history and ablation rate of the front face. The thermocouples installed on the walls were intended to measure the effect of vapor injection into the downstream boundary layer on the wall temperature. The ablation sensors installed in four ZH62A specimens were located adjacent to and in the same plane parallel to the face of the specimens as the thermocouples, to provide a check on the time that the receding surface uncovered the thermocouples.

Fig. 1. Thin Skin CRES Test Specimen for High-Enthalpy Disintegration Test

Fig. 2. Magnesium ZH62A Test Specimen for High-Enthalpy Disintegration Test

Fig. 4. Thermocouple Locations for Stainless Steel Type 321 Specimen

Fig. 5. Thermocouple Locations for Magnesium ZH62A Specimen

Thermocouples were of the chromel/alumel type, arranged on the models as shown in Figs. 4, 5 and 6.

The regression sensors, where used, consisted of a simple bilevel electrical circuit which included the model material as shown in Fig. 7. The function of the circuit was to provide time-related data by opening the energized circuit by ablation of the material at precisely the moment the surface regressed beyond the location of the strategically placed contact point. One common leg for all branches of the sensors in a model was used to complete the circuit.

Color still photos and/or movie film were used to record test events before, during and after test runs.

Spectrographs of the ablating models in the visible wavelength range of 3600 Å to 6000 Å, were taken.

Analog data acquisition and recording techniques were used to record the temperature-time test data indicated by the thermocouples.

The instrumentation coverage available for each test run is delineated in Table 1.

B. TEST FACILITY

The tests were performed in the 10- and 1-megawatt constricted-arc planetary gas facilities of the NASA Ames Research Center.

The employment of two facilities was necessary to provide the environmental conditions set forth in the test plan (Ref. 1).

A constricted-arc supersonic wind tunnel is capable of providing the continuous high enthalpy flow required to establish the chemical and physical changes in the test specimen which are dependent upon time.

The two tunnels operate on similar principles but differ, basically, in physical dimensions and performance capability. The basic differences in the two facilities are:

Fig. 6. Thermocouple Locations for Magnesium HM31A Specimen

Fig. 7. Instrumentation Installation--Typical Schematic

TABLE 1
Summary--Test Environment and Instrumentation

Facility		Tunnel Conditions												Instrumentation				
18 in.	2-1/4 in.	Run No.	Model	Material	Coated	Uncoated	Gas Composition (% vol)			Impact Pressure (mm Hg)	Average Enthalpy (MJ/kg)	Heat Flux (MW/m ²)	H _{c1} /H _{av} ⁽⁴⁾	Time-Temperature	Movies	Still Photos	Specimen Plates	Regression Sensor
							N ₂	O ₂	A									
x		253	25	Cres		x	73.7	20.0	6.3	1.0	19.6	0.285	3.15	x	x	-	-	-
x		254	2	ZH62A		x	73.7	20.0	6.3	1.0	18.5	0.285	3.15	x	x	x	x	-
x		255	25	Cres		x	74.6	20.0	5.4	1.54	22.6	0.303	2.80	x	x	x	-	-
x		256	25	Cres		x	76.5	20.4	3.1	1.54	23.2	0.344	2.80	x	-	x	-	-
x		257	1	ZH62A		x	76.5	20.4	3.1	1.54	22.8	0.344	2.80	x	-	x	x	-
x		258	18	HM31A		x	76.5	20.4	3.1	1.54	20.6	0.344	2.80	x	-	x	x	-
	x	14	8	ZH62A		x	48.0	48.0	4.0	30.4	20.8	3.79	1.86	x	x	x	x	x
	x	15	7	ZH62A		x	75.0	20.0	5.0	30.4	22.5	3.82	1.73	x	x	x	x	x
x		259	25	Cres		x	76.2	20.5	3.3	2.95	20.7	0.706	2.25	x	-	-	-	-
x		260	11	ZH62A		x	76.2	20.5	3.3	2.90	18.9	0.706	2.25	x	x	x	x	-
x		261	12	ZH62A		x	76.2	20.5	3.3	2.95	21.2	0.706	2.25	x	x	x	x	-
x		262	17	HM31A		x	77.6	20.8	2.6	2.95	21.2	0.706	2.25	x	x	x	x	-
x		263	25	Cres		x	62.0	35.5	2.5	3.6	19.7	0.786	2.30	x	-	-	-	-
x		264	9	ZH62A		x	62.0	35.5	2.5	3.6	19.7	0.786	2.30	x	x	x	x	-
x		265	10	ZH62A		x	62.0	35.5	2.5	3.6	20.1	0.786	2.30	x	x	x	-	-
	x	19	6	ZH62A		x	96.0	0.0	4.0	38.76	18.5	2.93	1.35	x	x	x	-	x
x		266	25	Cres		x	71.2	19.2	9.6	1.50	19.2	0.339	2.80	x	-	-	-	-
x		267	25	Cres		x	70.5	18.9	10.6	1.55	29.2	0.384	2.75	x	x	x	-	-
x		268	27	Cres	x		70.5	18.9	10.6	1.55	29.0	0.357	2.75	x	x	x	-	-
x		269	23	HM31A	x		70.5	18.9	10.6	1.50	28.9	0.357	2.75	x	x	x	-	-
x		270	19	HM31A		x	70.5	18.9	10.6	1.55	26.6	0.357	2.75	x	x	x	-	-
x		271	25	Cres		x	70.5	18.9	10.6	1.50	26.7	0.391	2.75	x	-	-	x	-
x		272	27	Cres	x		70.5	18.9	10.6	1.50	26.7	0.362	2.75	x	-	x	x	-
x		273	24	HM31A	x		70.5	18.9	10.6	1.50	24.4	0.362	2.75	x	x	x	x	-
	x	20	5	ZH62A		x	76.0	20.0	4.0	28.88	12.3	2.22	2.27	x	x	x	x	x
x		274	25	Cres (1)		x	65.5	27.2	7.3	3.0	13.9	0.631	2.30	x	-	-	-	-
x		275	25	Cres (2)		x	65.5	27.2	7.3	3.0	13.9	0.544	2.30	x	-	-	-	-
x		276	25	Cres (3)		x	65.5	27.2	7.3	3.0	13.7	0.593	2.30	x	-	-	-	-
x		277	14	ZH62A		x	65.5	27.2	7.3	3.0	13.9	0.593	2.30	x	x	x	-	-
x		278	16	ZH62A		x	65.5	27.2	7.3	3.0	13.3	0.593	2.30	x	x	x	x	-
x		279	25	Cres		x	58.2	34.8	7.0	3.0	13.4	0.636	2.30	x	x	x	x	-
x		280	15	ZH62A		x	58.2	34.8	7.0	3.0	13.5	0.636	2.30	x	x	x	x	-
x		281	21	HM31A		x	58.2	34.8	7.0	3.0	13.3	0.636	2.30	x	x	x	x	-
	x	21	13	ZH62A		x	48.5	48.5	3.0	68.40	17.9	3.62	1.35	x	x	x	x	-
	x	22	3	ZH62A		x	48.0	48.0	4.0	43.32	21.3	3.80	1.71	x	x	x	x	-
	x	23	20	HM31A		x	76.0	20.0	4.0	27.36	10.8	2.30	2.31	x	x	x	x	-
	x	24	22	HM31A	x		76.0	20.0	4.0	28.12	12.5	2.51	2.52	x	x	x	x	-
	x	25	4	ZH62A		x	--	86.0	14.0	68.40	16.5	4.46	1.62	x	x	x	x	-

NOTES: (1) No polishing
(2) Coated with vacuum pump oil
(3) Freshly polished
(4) 2-1/4-in. facility, centerline enthalpy (H_{c1}) derived from Ref. 4
18-in. facility, centerline enthalpy (H_{c1}) derived from Ref. 5.

Fig. 8. Constricted-Arc Wind Tunnel Component Arrangement

	<u>10-mw Tunnel</u>	<u>1-mw Tunnel</u>
Throat diameter (in.)	1	1/2
Test section diameter (in.)	18 exit, free jet	2-1/4 exit, free jet
Enthalpy, approximate (Mj/Kg)	19.1 to 138.8	8.6 to 138.8
Stagnation pressure (mm Hg)	1/4 to 5	3 to 200
Arc power, maximum (Mw)	5	0.8

Figure 8 schematically illustrates the component arrangement of a constricted-arc wind tunnel. The apparatus consists of three components: the upstream electrode, the constrictor nozzle and the downstream electrode.

The upstream electrode is the plasma torch. The water-cooled torch has a thoriated tungsten cathode and a copper anode. The tungsten is protected against oxidation by an argon atmosphere. Air or other gas enters the system without swirl through the flow ring just upstream of the constrictor nozzle.

The constrictor nozzle consists of a stack of copper discs, each with a hole drilled through it, electrically insulated from one another. Each of the discs is water-cooled. The electrical insulators are cooled by conduction through contact with the copper. The central hole through the stack of discs is contoured to form the supersonic nozzle. The water flow rate and temperature rise through each disc are monitored. Thus, the heat absorbed by each can be measured. Because the discs are electrically insulated from one another, they support the electrical field generated by the arc column.

The downstream electrode, the anode, is formed of loops of water-cooled copper tubing.

The test environments determined for each test run are tabulated in Table 1.

The initial run at each environment was performed with a stainless steel heat meter. Immediately following the calibration runs, the magnesium specimens were inserted into the gas stream.

The environments were adjusted in an attempt to provide atmospheres conducive to combustion of the magnesium models.

C. TEST PROCEDURE

The model to be tested was placed in the plasma arc-jet wind tunnel relative to the tunnel nozzle as shown schematically in Fig. 8. Thermocouple leads from the model were routed through the model sting to a common terminal strip located in the test chamber; copper leads connected the terminal strip junctions to the oscillograph recorder. A radiation shield was used to protect the strip from direct radiation from the arc. Terminal strip temperature, which became the thermocouple reference temperature, was referenced to an ice bath. This permitted all thermocouple traces to be adjusted to a 32° F baseline for ease of data reduction.

Thermocouple and recording system calibrations were accomplished after the model was installed on the sting by alternately immersing the model in an ice bath and boiling water. The model was protected from direct contact with the water by placing it in a pliable thin wall plastic bag. Water pressure fitted the plastic tightly to the model surface and expelled air from the bag, thus assuring optimum heat transfer between the water and the model. When thermal stability was achieved at each reference temperature, a temperature trace was recorded. The deflection between the recorded traces constituted the thermocouple system calibration.

Sting alignment was carefully checked after each model was installed to assure that the model was aligned with the center of the tunnel nozzle.

Tunnel operating conditions, e.g., power input, tunnel pressures and gas mixtures, etc., were observed and/or recorded on instrumentation included as part of the facility operating panel.

When model installation was completed and the tunnel access hatch closed and sealed, predetermined tunnel conditions for the run were established.

A water-cooled guard was installed in the plasma stream of the 18-inch facility to protect the test models during insertion into the tunnel. The guard was removed and the model exposed to the stream after the model temperature had stabilized behind the guard. Removal of the guard from in front of the model constituted the start of a test run. The run length was terminated by the reinsertion of the guard in front of the model when stainless steel heat meters were used, or upon destruction of the magnesium models. The use of a quadruple mounting arm in the 18-inch facility permitted substitution of one model for another behind the guard without disturbing the flow setting in the tunnel.

The 2.25-inch tunnel incorporated a two-armed mount without a water-cooled guard. Therefore, tunnel operating conditions had to be preset prior to insertion of the heat meters and magnesium models, and the tunnel reactivated after the models were installed.

Oscillographs and movie cameras were started prior to the inserting of a model into the flow stream. Recordings were continuous for the duration of the run.

The motion picture cameras were positioned so that the complete model could be viewed continuously for regression of the leading edge and the occurrence of significant events. In the 18-inch facility, the camera viewed the top of the model, while in the 2.25-inch facility, the camera viewed the side of the model. The initial frame of each film sequence had a number superimposed to identify each run.

One or more spectrographic photos were taken during each test run at the discretion of the operator.

Color photos were taken of the models after each test. These were identified by model and run number.

D. ACCURACY OF DATA

Thermocouple readings for all test runs except run No. 258 are considered to be accurate within $\pm 13^\circ\text{F}$. The accuracy of run No. 258 is $\pm 17^\circ\text{F}$. The difference in accuracy for this run is due to the use of improperly sized resistors in the instrumentation circuitry.

The tolerances stated were established by considering the thermocouple wire characteristics, readout accuracies and calibration repeatability.

The accuracies of the data received from the Ames Research Center are as follows:

	<u>Error (%)</u>
Heating rates based on stainless steel heat meters	<10
Calculated enthalpy	<5
Stagnation pressure transducers	<0.1
Gas composition	
Normal air	0
Oxygen enriched	5 to 10
Argon content	<2

Blank

IV. DATA PRESENTATION

A summary of data pertaining to the environmental conditions established in the tunnels for each test run is given in Table 1. The information contained describes the composition of the atmospheric gas, the impact pressure of the gas stream at the model location and a calculation of the average enthalpy (H_{av}) of the stream determined from a heat balance of the tunnel.

The ratio of centerline enthalpy (H_{cl}) to H_{av} is also given. H_{cl} for the 2.25- and 18-inch facilities was derived by Ames Research Center personnel from Refs. 4 and 5, respectively.

The instrumentation techniques used for each test run are also tabulated in Table 1.

All data reduction was accomplished at Ames Research Center. Tabulated information, movies and spectrographic results were forwarded to all members of the committee.

Thermocouple temperatures, as a function of time from start of the test run, have been plotted in Figs. 9 through 32.

The regression rates of the front face of several test specimens have been plotted in Figs. 35 through 46.

Fig. 9. Thermocouple Temperatures--Model No. 2, Magnesium ZH62A, Run No. 254, 18-Inch Arc-Jet Wind Tunnel

Fig. 10. Thermocouple Temperatures--Model No. 1, Magnesium ZH62A, Run No. 257, 18-Inch Arc-Jet Wind Tunnel

Fig. 11. Thermocouple Temperatures--Model No. 18, Magnesium HM31A, Run No. 258, 18-Inch Arc-Jet Wind Tunnel

Fig. 12. Thermocouple Temperatures--Model No. 11, Magnesium ZH62A, Run No. 260, 18-Inch Arc-Jet Wind Tunnel

Fig. 13. Thermocouple Temperatures--Model No. 12, Magnesium ZH62A, Run No. 261, 18-Inch Arc-Jet Wind Tunnel

Fig. 14. Thermocouple Temperatures--Model No. 17, Magnesium HM31A, Run No. 262, 18-Inch Arc-Jet Wind Tunnel

Fig. 15. Thermocouple Temperatures--Model No. 9, Magnesium ZH62A, Run No. 264, 18-Inch Arc-Jet Wind Tunnel

Fig. 16. Thermocouple Temperatures--Model No. 10, Magnesium ZH6aA, Run No. 265, 18-Inch Arc-Jet Wind Tunnel

Fig. 17. Thermocouple Temperatures--Model No. 23, Magnesium HM31A (coated), Run No. 269, 18-Inch Arc-Jet Wind Tunnel

Fig. 18. Thermocouple Temperatures--Model No. 19, Magnesium HM31A, Run No. 270, 18-Inch Arc-Jet Wind Tunnel

Fig. 19. Thermocouple Temperatures--Model No. 24, Magnesium HM31A (coated), Run No. 273, 18-Inch Arc-Jet Wind Tunnel

Fig. 20. Thermocouple Temperatures--Model No. 14, Magnesium ZH62A, Run No. 277, 18-Inch Arc-Jet Wind Tunnel

Fig. 21. Thermocouple Temperatures--Model No. 16, Magnesium ZH62A, Run No. 278, 18-Inch Arc-Jet Wind Tunnel

Fig. 22. Thermocouple Temperatures--Model No. 15, Magnesium ZH62A, Run No. 280, 18-inch Arc-Jet Wind Tunnel

Fig. 23. Thermocouple Temperatures--Model No. 21, Magnesium HM31A, Run No. 281, 18-Inch Arc-Jet Wind Tunnel

Fig. 24. Thermocouple Temperatures--Run No. 14, Model ZH62A-8, 2.25-Inch Arc-Jet Wind Tunnel

Fig. 25. Thermocouple Temperatures--Run No. 15 Model ZH62A-7, 2.25-Inch Arc-Jet Wind Tunnel

Fig. 26. Thermocouple Temperatures--Run No. 19 Model ZH62A-6, 2.25-Inch Arc-Jet Wind Tunnel

Fig. 27. Thermocouple Temperatures--Run No. 20, Model ZH62A-5, 2.25-Inch Arc-Jet Wind Tunnel

Fig. 28. Thermocouple Temperatures--Run No. 21, Model ZH62A-13, 2.25-Inch Arc-Jet Wind Tunnel

Fig. 29. Thermocouple Temperatures--Run No. 22, Model ZH62A-3, 2.25-Inch Arc-Jet Wind Tunnel

Fig. 30. Thermocouple Temperatures--Run No. 23, Model HM31A-20, 2.25-Inch Arc-Jet Wind Tunnel

Fig. 31. Thermocouple Temperatures--Run No. 24, Model HM31A-22, 2.25-Inch Arc-Jet Wind Tunnel

Fig. 32. Thermocouple Temperatures--Run No. 25, Model ZH62A-4, 2.25-Inch Arc-Jet Wind Tunnel

Fig. 33. Magnesium ZH62A Specimen, Run No. 254, Post-Test

Fig. 34. Coated Magnesium HM31A Specimen, Run No. 273, Post-Test

Fig. 35. Regression Rate--Run No. 14, Model ZH62A-8

Fig. 36. Regression Rate--Run No. 15, Model ZH62A-7, Air

Fig. 37. Regression Rate--Run No. 19, Model ZH62A-6

Fig. 38. Regression Rate--Run No. 20, Model ZH62A-5

Fig. 39. Regression Rate--Run No. 21, Model ZH62A-13

Fig. 40. Regression Rate--Run No. 22, Model ZH62A-3

Fig. 41. Regression Rate--Run No. 23, Model HM31A-20

Fig. 42. Regression Rate--Run No. 24, Model HM31A-22

Fig. 43. Regression Rate--Run No. 25, Model ZH62A-4

Fig. 44. Regression Rate--Model No. 11, Magnesium ZH62A, Run No. 260, 18-Inch Tunnel

Fig. 45. Regression Rate--Model No. 12, Magnesium ZH62A, Run No. 261, 18-Inch Tunnel

Fig. 46. Regression Rate--Model No. 21, Magnesium ZH62A, Run No. 281, 18-Inch Tunnel

V. DISCUSSION

Data recorded during the test runs were intended to establish the feasibility of the instrumentation employed to adequately define a temperature history of the model, the regression rates of the material, the heat blockage due to vaporization downstream, and the existence, if any, of combustion of the magnesium under such environment.

Figures 9 through 32 are plots of the thermocouple temperatures recorded during all the test runs. It was expected that at the moment the thermocouples were exposed by the regressing surface, a sharp increase in temperature would result. The validity of this premise is clearly indicated in the test data for all runs except 254 and 273.

Run 254 was performed at the lowest energy level of all tests (Table 1) and the model experienced extensive oxidation of all of its surfaces with very little regression of the front face. The formation of magnesium oxide (MgO) on the thermocouples which were exposed to the gas stream resulted in the formation of a protective coating which caused a decrease rather than an increase in the temperature rise rate after 190 seconds of the test run as shown in Fig. 9. A post-test photo of the model, Fig. 33, clearly shows the MgO coating on the surfaces and the thermocouples.

Run 273 was conducted with a model of magnesium HM31A coated with zirconium oxide. The protective barrier created by this emissivity coating prevented the uncovering of the thermocouples as shown in Fig. 34. The data for this run, plotted in Fig. 19, show steady thermocouple readings after 100 seconds of the test run.

Assuming that the point at which the thermocouple temperature-time slope sharply increases is indicative of the moment the metal surface has regressed to the plane of the thermocouple tip, an attempt to correlate and substantiate this event with the other methods of determination of the regression rate was made.

It was anticipated that the installation of a simple regression sensor, Fig. 8, in the same plane as the thermocouple tip might verify the accuracy of the regression rates as indicated by the thermocouples. However, the regression sensors installed on Models 5, 6, 7 and 8 performed very erratically and no information pertaining to the regression of the surfaces could be obtained with these devices. Faulty sensor operation manifested itself in the impression of extraneous voltages on the system or no signal voltage. It is conjectured that the difference in the expansion rates of the materials used and the unpredictable effect of the flow and/or accumulation of the molten material in the vicinity of the sensor contributed to the faulty performance of the sensors. The use of regression sensors of the type described must be considered a failure.

Comparison of the regression rates obtained from the thermocouple data with regression rates obtained from a frame count of the motion pictures was made. The results of these comparisons for a selected number of runs are shown in Figs. 35 through 45 inclusive. For these comparisons, it was assumed that for some of the models, the order of thermocouple uncovering, as shown in the thermocouple temperature plots, corresponded to the thermocouple position relative to the front face of the model and that the sequence of thermocouple numbering did not reflect the position of the thermocouples. It would be expected, if the two methods of obtaining the regression rates were precisely controlled, that the data points for both methods would fall along the same curve. Precise correlation of the respective zero time reference points for each mode of evaluation was difficult and the time differences shown in Figs. 35 through 46, in most part, are reflections of this difficulty. In addition, the location of the ablating surface, as viewed on the movie film, could not be precisely defined and this contributed to the differences noted. In general, the regression rates defined by the thermocouples correspond with those determined by the movies.

Spectrographs taken during many of the test runs verified the existence of MgO (5007 Å) after model exposure to the test environment and defined the existence of magnesium atoms with a wavelength of 5183 Å.

The existence of the MgO, however, could not be defined as combustion of the magnesium nor could combustion be identified in the movie film.

The appearance of the Mg atoms coincided closely with the start of melting as viewed in the colored movies. The start of melting generally was associated with the emergence of a green vapor in the wake of the model which corresponded to the wavelength band which includes the Mg atoms. A discrepancy in time between the appearance of the atoms on the spectrographic photos and the start of melt viewed on the movies can possibly be attributed to the exposure setting of the movie camera and the difference in the locations of the camera and the spectrograph. The former could conceal visual evidence of the onset of Mg atoms and the latter could make visible to one unit what the other cannot see. In addition, the time sampling technique used to obtain the spectrographs precludes precise definition of the appearance of the Mg atoms. The events, as defined by the two methods, are shown in Figs. 12 to 15, 19 and 21 to 23.

One of the major uncertainties to be resolved by the test series was the determination of the existence of combustion. Several methods were used in an attempt to define this phenomenon:

- (1) Photography (visual)
- (2) Spectrography
- (3) Material temperature history.

Photography is essentially a visual record of the happenings. It was expected that a sustained combustion process of magnesium could be identified by the brilliance of its light and rapid consumption of the material. Although this did not happen in any of the test runs, it in no way refutes the original idea. The simple conclusion which can be inferred is that sustained combustion did not occur at the lower than expected energy levels which existed in the tunnel (see Table 2). Therefore, the feasibility of using photography to identify the existence of combustion has neither been proved nor disproved. It can only be concluded that it is difficult to identify local combustion photographically.

The spectrographic procedure used in this test series provided a limited amount of information because the spectrographic plates were taken at irregular intervals for relatively short times. This procedure was not conducive to the precise identification of the onset of an event. The spectrographs taken covered the visible wavelength band from 3800 to 6000 Å. Two wavelengths were of particular interest in this range: the 5078 Å band which includes identification of MgO and the 5183 Å band which includes Mg atoms which were emitted with the onset of the magnesium melt. The relatively infrequent graphing of the spectrum therefore often disclosed the appearance of either of these products without clearly defining the exact moment at which emission began. The failure to clearly define the onset of emission resulted in an inability to correlate the event with either the photographic method or the material temperature history. In addition, since the intensity of the recorded wavelengths was not measured by the spectrograph, the appearance of MgO could not be defined as a slow oxidation or a combustion process.

TABLE 2
Comparison of 18-Inch Arc-Jet Tunnel Enthalpy

Run No.	Heat Flux (Mw/m ²) (measured)	Impact Pres (mm Hg) (measured)	Centerline Enthalpy H _{cl} (Mj/Kg) (calculated) ⁽¹⁾	Enthalpy Based on Measured Heat Flux, H _{calc} (Mj/Kg) (calculated) ⁽²⁾	$\frac{H_{calc}}{H_{cl}}$
253	0.285	1.00	61.74	17.35	0.281
255	0.303	1.54	63.28	14.84	0.234
256	0.344	1.54	64.40	16.88	0.262
259	0.706	2.95	46.58	25.04	0.537
263	0.786	3.60	45.31	25.23	0.558
266	0.339	1.50	53.76	16.85	0.312
267	0.384	1.55	80.30	18.78	0.234
268	0.357	1.55	79.75	17.47	0.219
271	0.391	1.50	73.43	19.44	0.265
272	0.362	1.50	73.43	18.00	0.245
274	0.631	3.00	31.97	22.19	0.694
275	0.544	3.00	31.97	19.12	0.598
276	0.593	3.00	31.51	20.85	0.663
279	0.636	3.00	30.82	22.36	0.542

(1) Calculated from arc-jet tunnel energy balance and constricted arc analysis discussed in NASA TM-X-54,065.

(2) Calculated from measured impact pressure and heat flux measured using stainless steel heat meters provided in test program (see Appendix A).

VI. CONCLUSIONS AND RECOMMENDATIONS

Partial success was achieved in proving the feasibility of the instrumentation used to accomplish the objectives of the preliminary test program.

The simple regression sensors, which were intended to provide backup support for the use of thermocouples as regression rate meters, were completely unsuccessful and no useful data were obtained. The use of thermocouples to record material temperature history and indications of the regression rate of the model front face was satisfactory.

The use of colored movie photography to record regression rates was of limited success due to the difficulty of defining the regressing surface profile throughout the event.

Movie photography and spectrography, as utilized in this test program, did not clearly define the existence of combustion of the magnesium or the onset of melt, primarily due to the lower than expected energy levels within the tunnels and the intermittent spectrographic recording technique used during these tests.

It can be concluded, however, that the techniques used showed promise of achieving the desired objectives if modified and applied with more precise control.

It is recommended that thermocouples be used in a secondary capacity as regression rate sensors to confirm information obtained from photographic techniques. To increase the usefulness of the temperature data for regression knowledge, precise control of the location of the thermocouple beads must be specified and recorded during specimen fabrication.

The use of movie photography is probably the most satisfactory method of those employed to record surface regression rates. The results could be enhanced if black and white stroboscopic photography techniques were employed to more clearly define the regressing surface. The camera setup should provide a vertical profile of the test specimen.

Correlation of movie and thermocouple methods of recording the regression of the surface can only be achieved if precise definition of the zero time reference point is simultaneously indicated on both sets of data. A significant event indicator (e.g., flash for photography and an events mark for the thermocouple trace) must be synchronized so that superposition of one set of data on the other becomes more meaningful, and noticeable time differentials are minimized.

Colored movie photography to support the results of the spectrograph should be retained. Film exposure must be accurately set to provide visual evidence of the wavelengths defined by the spectrographic analysis. Camera location should provide a viewing angle similar to that scanned by the spectrograph.

Spectrographic results can be more meaningful and correlation with movie and thermocouple events more accurate if it can be accomplished on a continuous basis with the zero time reference marker accurately coordinated with the other methods. An arrangement in which a monochromatic spectrographic output signal can be put through a photomultiplier and recorder would continuously monitor a spectral frequency and amplitude. Such an arrangement would make identification of combustion more positive.

Of secondary importance in the performance of the preliminary test program was the accumulation of test data pertaining to the reaction of magnesium alloys ZH62A and HM31A in the re-entry environments. Data evaluation toward these goals was out of scope for the present report and the data ascertained were not sufficient for use in establishing the fundamental mode of disintegration of the magnesium alloys. Nor was the specimen geometry representative of the vehicle and this precluded analysis of the failure mode. However, it was observed during the data evaluation performed for this report that the coating of zirconium oxide applied to the magnesium alloy greatly impeded the temperature rise rate of the base material and retarded the onset of melting. It is strongly recommended that the main magnesium disintegration test series outlined in Ref. 1 be implemented to obtain the information necessary to establish the fundamental mode of magnesium destruction.

REFERENCES

1. "Test Plan Report, High Enthalpy Disintegration Tests of Magnesium." Sandia Corporation. April 1966.
2. Shih, C. and Woolf, W. "Test Plan-Feasibility Tests--High Enthalpy Disintegration of Magnesium." June 1966.
3. Stine, H. A. "The Hyperthermal Supersonic Aerodynamic Tunnel." Proceedings of High Temperature Technology, Asilomer, Pacific Grove, California, September 8, 1963, published by Butterworth, 1964.
4. Hoshizaki, H. "Heat Transfer in Planetary Atmospheres at Super-Satellite Speeds." ARS Journal, October 1962.
5. Stine, H. A., NASA TMX-54,065.

APPENDIX A

ENTHALPY CALCULATIONS

The energies input to the magnesium alloy test specimens were calculated from the values of heat flux and impact pressure measured during the test runs. The calculated values of enthalpy were obtained by assuming continuum flow conditions in the tunnel and using the relationship

$$H_{\text{calc}} = \frac{\dot{q}}{K(0.1125)} \sqrt{\frac{K_2 r}{P}} \text{ Mj/Kg}$$

where

$\dot{q}$ = measured heat flux (Mw/m²)

r = body radius (in.)

P = measured stagnation pressure (atm)

K_1 = surface averaging factor for cylinder parallel to air flow = 1.2

K_2 = hemispherical equivalence factor = 3.5.