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SC-RR-64-2138

ANALYSIS AND TESTING OF RFD-2
CAPSULES IN SIMULATED RE-ENTRY
(Title Unclassified)

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January 1965

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ABSTRACT (CRD)

This report describes some Sandia tests performed in the Martin Company 200-kilowatt hyperthermal arc-powered tunnel. Capsules representing the types to be used in the RFD-2 flight test were tested with the conditions shown. Included in the analyses of capsule performance are comparisons between behavior predicted by computer analysis and actual behavior at measured parameters. Calculations on the oxidation of the tantalum liners are presented.

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TABLE OF CONTENTS

	<u>Page</u>
List of Symbols	5
Introduction	7
Specimen Description	8
Phase I	8
Phase II	11
Test Facility and Description	11
Test Description	15
Facility Calibration	15
Test Procedure	15
Instrumentation	15
Test Runs	16
Phase I	17
Phase II	18
Thermal Analysis	19
Computer Analysis	20
Analysis of Temperature	20
Analysis of Tantalum	27
Discussion and Conclusions	29

LIST OF ILLUSTRATIONS

<u>Figure</u>		
1.	Internal capsule test configuration	8
2.	Cutaway of internal capsules	8
3.	Cutaway of external capsules	10
4.	External capsule test configuration	10
5.	Model holder orientation	12
6.	RFD-2 external capsule re-entry environment	12
7.	Test facility with instrumentation	16
8.	Temperature response of internal capsules	21
9.	Temperature response of 50-mil and 100-mil Haynes capsules	21
10.	Temperature response of Model T-1	22
11.	Temperature response of Models A-1 and A-2	22
12.	Temperature response of Model T-6	23
13.	Temperature response of Models S-1E and S-2E	23
14.	Temperature response of Models I-3 and I-4	24
15.	Temperature response of Model A-3	24
16.	Temperature response of Model A-4	25
17.	Temperature response of Models T-7 and T-8	25
18.	Temperature response of Models S-3E and S-4E	26

LIST OF ILLUSTRATIONS (cont)

<u>Figure</u>		<u>Page</u>
19.	Temperature response of Models T-9 and T-10	26
20.	Ablation sequence of Model S-1	30
21.	Ablation sequence of Model B-2	31
22.	Ablation sequence of Model G-2	32
23.	Ablation sequence of Model A-3	33
24.	Ablation sequence of Model I-4	34
25.	Ablation sequence of Model I-1	35
26.	Ablation sequence of Model S-1E	36
27.	Ablation sequence of Model T-9	37

LIST OF TABLES

<u>Table</u>		
I	External Capsule Dimensions	9
IIa	Test Parameters - Phase I	13
IIb	Test Parameters - Phase II	14
III	Material Properties	20
IV	Comparison of Calculated and Actual Tantalum Oxidation	28
V	Tantalum Oxidation Results	29

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LIST OF SYMBOLS

At.wt. - atomic weight
H - enthalpy, BTU/lb
 $\dot{m}$ - gas flux at model surface, lb/ft²-sec
M - total gas flow at model surface, lb/ft²
Mol.wt. - molecular weight
O - oxygen
P - pressure, lb/ft²
 $\dot{q}$ - aerodynamic heat flux, BTU/ft²-sec
R - model radius, feet
t - thickness, inches
Ta - tantalum
 θ - time, seconds
 ρ - density, lb/ft³

SUBSCRIPTS

av - average value
ox - oxygen
s - stagnation value
Ta - tantalum
t₂ - stagnation value behind shock

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ANALYSIS AND TESTING OF RFD-2
CAPSULES IN SIMULATED RE-ENTRY

Introduction

The RFD-2 flight test will obtain much of its significant data through the use of cylindrical capsules loaded with tracer elements. A total of eight capsules, each containing a different tracer to make separate identification possible, will be used. Four of these capsules will be external to the re-entry vehicle, and will be ejected during the test; the remaining four capsules will be internally mounted within the re-entry payload.

The four external capsules, ejected at a predetermined altitude, will experience enough re-entry aerodynamic heating to cause considerable capsule ablation, and to expose tracer elements. Each of the four capsules has a different wall thickness of both Haynes-25 and tantalum; as a result, each should burn at a different altitude. Identifying the point during re-entry at which tracers are exposed will determine the ablation of the four configurations. Thallium, silver, indium, and strontium were selected as tracers for the four external capsules for several reasons. Primarily they were selected for their desirable spectral properties which would allow detection of these materials at the large distance involved between the point of tracer exposure and the detecting instrumentation. Also the physical properties of these materials are compatible with the encapsulating materials and they would withstand the expected re-entry temperature and pressure changes without causing exposure before the ablation of the capsule.

The capsules mounted internally will be used to indicate when the payload itself has ablated and disassembled enough to release the segmented housing of the capsules. Very quickly after release into the airstream, the 10-mil stainless-steel containers of these capsules will burn through and expose the tracers. These tracer elements--lithium, sodium, barium, and gallium--were again selected for their desirable spectral and physical properties consistent with the conditions of their use. Again it is important that no tracer exposure occur prematurely (in this case before generator disassembly).

This report describes the simulated re-entry test runs performed by Sandia Corporation early in 1964. A first series of tests were performed during the period from February 5 through February 12, 1964. Nineteen tracer-loaded capsule models and two calibration models were tested. Results of the Phase I portion dictated that further tests be performed; these tests, designated Phase II, were run from April 25 through May 1, 1964. They consisted of 20 runs: 18 tracer-loaded capsule models, with 2 of the models being used for 2 runs.

The tests examined capsule behavior in simulated re-entry conditions. High-speed film was used to record model behavior, and a continuously recording Infra-scope pyrometer monitored surface temperature. Data from these tests allowed a thermal analysis of the model to be compared with the results of computer analyses. In addition, data on tantalum ablation were examined, and empirical data on tantalum oxidation rates calculated.

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Specimen Description

Phase I

The models for these tests were designed to simulate as closely as possible the flight-test capsules. However, 2 inches was the maximum length that could be tested in the facility, and a 3/16-inch rod had to be placed through the specimen to attach it to the holding and rotating mechanism.

All internal models were constructed with a 10-mil-thick-stainless-steel outer container and 0.079-inch thickness of fiberfrax insulation. Within this cylindrical tube of insulation was the tracer and the 3/16-inch-diameter rod through the center of the model. The container ends were welded to the rod in most cases. Figure 1 shows an internal model; Figure 2 sketches the construction of the internal capsules. The test capsules contained tracers of sodium, barium, and strontium; lithium was not tested.

Figure 1.
Internal capsule
test configuration

Figure 2.
Cutaway of internal
capsules

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External-capsule tests included the following configurations. The indium capsule contained no tantalum, and a 0.100-inch thickness of Haynes 25. Because of the health-physics problem of ablated thallium, lead was substituted in models in which thallium will be used in actual flight; this thallium capsule contained no tantalum and a 0.050-inch thickness of Haynes 25. The silver tracer was encased in 0.006 inch of tantalum and 0.050 inch of Haynes 25, and the strontium tracer in 0.020 inch of tantalum and 0.100 inch of Haynes 25. In all the above cases, a 0.080-inch thickness of Fiberfrax insulation surrounded the tracer. In addition, many of the combinations of external-capsule wall configurations were tested without insulation and with a titanium tracer. (Testing models with no insulation thermally simulated fuel-containing capsules of the isotopic generator itself.) An attempt was made to seal the 3/16-inch holding rod to the encapsulating materials in all these models, but the electronic-beam welding was not always successful. However, no difference was apparent between the sealed and nonsealed units, and leakproof considerations were neglected in these tests. Figure 3 shows the construction of the external capsules; Table I shows the dimensions and material thicknesses.

To insulate the ends of the capsules and to provide for a two-dimensional flow pattern, Martin Company applied plasma sprayed alumina to either end of the specimens. The initial tests determined that an alumina bushing, cemented to the capsule and fired in a furnace, precluded local heating from end effects. Figure 4 shows the final configuration of Specimen A-2; the other external capsules were similar, except as noted in Table I and Figure 3.

TABLE I
External Capsule Dimensions

Model	Tracer	Haynes Thickness (inch)	Tantalum Thickness (inch)	Insulation Thickness (inch)	Tracer Radius	Model O.D. (inch)
T-4	Titanium	0.100	0.020	0	0.365	0.980
T-1	Titanium	0.100	0	0	0.365	0.980
T-2	Titanium	0.100	0.020	0	0.365	0.980
T-5	Titanium	0.050	0	0	0.358	0.840
T-6	Titanium	0.050	0.006	0	0.358	0.840
A-1	Silver	0.050	0.006	0.083	0.280	0.840
A-2	Silver	0.050	0.006	0.083	0.280	0.840
S-1E	Strontium	0.100	0.020	0.088	0.280	0.980
S-2E	Strontium	0.100	0.020	0.088	0.280	0.980
P-1	Lead	0.050	0	0.083	0.280	0.840
P-2	Lead	0.050	0	0.083	0.280	0.840
I-1	Indium	0.100	0	0.885	0.280	0.980
I-2	Indium	0.100	0	0.885	0.280	0.980
T-7	Titanium	0.050	0.006	0	0.36	0.840
T-8	Titanium	0.050	0.006	0	0.36	0.840
T-9	Titanium	0.100	0.020	0	0.365	0.980
T-10	Titanium	0.050	0.006	0	0.280	0.840
A-3	Silver	0.050	0.006	0.083	0.280	0.840
S-3E	Strontium	0.100	0.020	0.088	0.281	0.980
I-3	Indium	0.100	0	0.0885	0.280	0.980
I-4	Indium	0.100	0	0.885	0.280	0.980
A-4	Silver	0.050	0.006	0.083	0.280	0.840
S-4E	Strontium	0.100	0.020	0.088	0.280	0.980

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L = 2.00" PHASE I
L = 1.25" PHASE II

Figure 3. Cutaway of external capsules

Figure 4. External capsule test configuration

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Phase II

Certain modifications in the capsule design, both external and internal, were necessary as a result of the Phase I tests. The tests showed that the insulation withstood heating for a relatively long period of time after the containers ablated. Since the external capsule portion of the flight test is designed to measure the ablation characteristics of the Haynes and tantalum containers, any ablation time for the insulation would not be acceptable. To remove this possibility the insulation on all internal and external capsules was segmented and this modified design was tested.

In addition, the models used in the Phase II tests were shortened from 2 to 1.25 inches to reduce the effects of the heating gradient across the test stream. The cross sections of comparable models remained the same, and alumina bushings were again used. Strontium, initially used in both the internal and external configurations, was replaced by gallium in internal capsules because of the possible exposure of internal and external tracers at the same altitude during the re-entry test.

Test Facility and Description

The tests discussed in this report were performed in the Martin Company Plasma Arc Facility in Baltimore, Maryland. This 200-kw facility consists of a plasma generator, DC power supply, test chamber, a two-stage vacuum pumping system, and instrumentation for determining stream parameters and monitoring specimen behavior. The plasma generator, a gas vortex stabilized device, uses a thoriated tungsten cathode emitter (2-percent thorium) and a copper anode. Arc gas is injected tangentially to provide a vortex off the tip of the rear electrode, with a corresponding low-pressure area at the center of the vortex. The primary arc gas is nitrogen, with oxygen injected secondarily to simulate air composition. The arc-heated air discharges into a mixing chamber and is compressed to achieve sonic velocity at the nozzle throat. The plasma then expands supersonically in the contoured nozzle and achieves a nominal Mach 3 at the 3-inch-diameter exit.

The models rotated at approximately 90 revolutions per minute during the tests, thus providing uniform heating on the entire cylinder surface. The rotation mechanism consisted of a motor mounted in a water-cooled housing with a shaft protruding through the housing. The 3/16-inch-specimen holder rod was fitted to a hole in the end of the motor shaft and secured with a setscrew. The entire housing was moved to test position with a handle on the outside of the test chamber. A sketch of the model position and housing mechanism is shown in Figure 5.

Within the limits of the facility, the test conditions selected for the capsules were typical of the environments expected during the RFD-2 flight test. Figure 6 presents the environment expected for a nominal external capsule re-entry. Shown on this figure are the model stagnation pressure and the gas enthalpy parameters utilized in these tests. The pressure corresponds to an altitude of approximately 255,000 feet while the gas enthalpy is slightly greater than that expected for the RFD-2 flight. This higher enthalpy was necessary to obtain satisfactory heat flux levels and detracts in no way from the simulated condition. Table II indicates the order in which the models were tested in both Phase I and Phase II; the table also shows the pertinent test conditions and total test times.

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Figure 5. Model holder orientation

Figure 6. RFD-2 external capsule re-entry environment

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TABLE IIa
Test Parameters - Phase I

Run No.	Date	Spec. No.	H_T (BTU/lb)	$*q_{cw}$ (BTU/ft ² -sec)	$\dot{m}_{N_2}$ (lb/sec)	$\dot{m}_{O_2}$ (lb/sec)	$\dot{m}_{total}$ (lb/sec)	P_{stag} (atm)	P_{cell} (atm)	Test Time (sec)
4239	2/5/64	B-2	4,740	-	2.31×10^{-3}	0.69×10^{-3}	3.00×10^{-3}	0.00857	0.001317	-
4243	2/5/64	B-2	9,300	-	1.54×10^{-3}	0.46×10^{-3}	2.00×10^{-3}	0.01135	0.001276	-
4245	2/5/64	A-2	8,990	-	1.54×10^{-3}	0.46×10^{-3}	2.00×10^{-3}	0.01061	0.001185	-
4247	2/5/64	A-3	12,390	-	1.54×10^{-3}	0.46×10^{-3}	2.00×10^{-3}	0.01354	0.001395	-
4248	2/7/64	C-300	11,640	185.5	1.54×10^{-3}	0.46×10^{-3}	2.00×10^{-3}	0.01346	0.001409	75.0
4249	2/7/64	C-040	10,370	157.0	1.54×10^{-3}	0.46×10^{-3}	2.00×10^{-3}	0.01259	0.001489	12.0
4250	2/7/64	T-4	11,880	171.5	1.54×10^{-3}	0.46×10^{-3}	2.00×10^{-3}	0.01395	0.001514	80.0
4251	2/10/64	N-1	5,010	74.5	2.31×10^{-3}	0.69×10^{-3}	3.00×10^{-3}	0.00857	0.001210	53.3
4252	2/10/64	N-2	9,100	146.6	1.54×10^{-3}	0.46×10^{-3}	2.00×10^{-3}	0.01124	0.001184	9.1
4253	2/10/64	S-1	8,850	150.5	1.54×10^{-3}	0.46×10^{-3}	2.00×10^{-3}	0.01081	0.000947	87.4
4254	2/10/64	S-2	8,650	159.5	1.54×10^{-3}	0.46×10^{-3}	2.00×10^{-3}	0.01062	0.000947	82.0
4255	2/10/64	T-1	8,990	127.0	1.54×10^{-3}	0.46×10^{-3}	2.00×10^{-3}	0.01116	0.000947	91.2
4256	2/11/64	T-2	9,080	136.8	1.54×10^{-3}	0.46×10^{-3}	2.00×10^{-3}	0.01116	0.000960	146.4
4257	2/11/64	T-5	9,290	159.5	1.54×10^{-3}	0.46×10^{-3}	2.00×10^{-3}	0.01123	0.000974	58.6
4258	2/11/64	T-6	9,190	159.5	1.54×10^{-3}	0.46×10^{-3}	2.00×10^{-3}	0.01123	0.001025	108.2
4259	2/11/64	A-1	9,000	150.2	1.54×10^{-3}	0.46×10^{-3}	2.00×10^{-3}	0.01123	0.001079	177.8
4260	2/11/64	A-2	9,080	155.2	1.54×10^{-3}	0.46×10^{-3}	2.00×10^{-3}	0.01116	0.001025	186.4
4261	2/11/64	S-1E	8,870	146.5	1.54×10^{-3}	0.46×10^{-3}	2.00×10^{-3}	0.01104	0.001078	164.
4262	2/11/64	S-2E	8,790	153.0	1.54×10^{-3}	0.46×10^{-3}	2.00×10^{-3}	0.01068	0.001054	274.
4263	2/12/64	P-1	8,810	156.0	1.54×10^{-3}	0.46×10^{-3}	2.00×10^{-3}	0.01158	0.001131	39.3
4264	2/12/64	P-2	8,980	156.0	1.54×10^{-3}	0.46×10^{-3}	2.00×10^{-3}	0.01136	0.001145	52.8
4265	2/12/64	I-1	8,940	138.0	1.54×10^{-3}	0.46×10^{-3}	2.00×10^{-3}	0.01124	0.001105	92.3
4266	2/12/64	I-2	8,780	135.0	1.54×10^{-3}	0.46×10^{-3}	2.00×10^{-3}	0.01116	0.001064	96.7
4267	2/12/64	B-1	8,980	156.0	1.54×10^{-3}	0.46×10^{-3}	2.00×10^{-3}	0.01110	0.001080	54.2
4268	2/12/64	B-2	9,000	152.5	1.54×10^{-3}	0.46×10^{-3}	2.00×10^{-3}	0.01110	0.001080	44.8

* q_{cw} is cold-wall stagnation heat rate on cylinder in crossflow.

TABLE IIb
Test Parameters - Phase II

Run No.	Date	Spec. No.	H_T (BTU/lb)	$^*q_{cw}$ (BTU/ft ² -sec)	$\dot{m}_{N_2}$ (lb/sec)	$\dot{m}_{O_2}$ (lb/sec)	$\dot{m}_{total}$ (lb/sec)	P_{stag} (atm)	P_{cell} (atm)	Test Time (sec)
4373	4/27/64	T-7	8,875	134	1.54×10^{-3}	0.46×10^{-3}	2.00×10^{-3}	0.01171	0.001078	93.
4374	4/27/64	T-8	8,795	137	1.54×10^{-3}	0.46×10^{-3}	2.00×10^{-3}	0.01144	0.001078	44.8
4375	4/27/64	T-9	9,120	121	1.54×10^{-3}	0.46×10^{-3}	2.00×10^{-3}	0.01144	0.001092	146.
4376	4/27/64	T-10	9,450	119	1.54×10^{-3}	0.46×10^{-3}	2.00×10^{-3}	0.01132	0.001078	145.
4377	4/27/64	A-3	8,915	144	1.54×10^{-3}	0.46×10^{-3}	2.00×10^{-3}	0.01105	0.001092	127.7
**4378	4/27/64	S-3E	8,939	127	1.54×10^{-3}	0.46×10^{-3}	2.00×10^{-3}	0.01118	0.001092	282.
4380	4/28/64	I-3	9,065	127	1.54×10^{-3}	0.46×10^{-3}	2.00×10^{-3}	0.01149	0.001092	68.5
†4382	4/28/64	I-4	9,438	127	1.54×10^{-3}	0.46×10^{-3}	2.00×10^{-3}	0.01144	0.001092	70.
4383	4/28/64	S5E-A	9,405	144	1.54×10^{-3}	0.46×10^{-3}	2.00×10^{-3}	0.01138	0.001092	108.
4384	4/28/64	N-3	9,460	144	1.54×10^{-3}	0.46×10^{-3}	2.00×10^{-3}	0.01144	0.001092	7.5
††4385	4/28/64	N-4	8,925	144	1.54×10^{-3}	0.46×10^{-3}	2.00×10^{-3}	0.01131	0.001092	10.
4386	4/28/64	G-1	8,825	144	1.54×10^{-3}	0.46×10^{-3}	2.00×10^{-3}	0.01144	0.001092	8.7
4387	4/28/64	G-2	9,490	144	1.54×10^{-3}	0.46×10^{-3}	2.00×10^{-3}	0.01144	0.001092	10.1
4388	4/28/64	S5E-B	9,440	144	1.54×10^{-3}	0.46×10^{-3}	2.00×10^{-3}	0.01144	0.001092	246.
4390	4/28/64	B-3	8,560	144	1.54×10^{-3}	0.46×10^{-3}	2.00×10^{-3}	0.01171	0.001092	13.5
4391	4/28/64	B-4	9,325	144	1.54×10^{-3}	0.46×10^{-3}	2.00×10^{-3}	0.01157	0.001092	20.
4392	4/28/64	E20-E-A	9,450	144	1.54×10^{-3}	0.46×10^{-3}	2.00×10^{-3}	0.01164	0.001092	182.
4393	4/28/64	E20-E-B	9,585	188	2.19×10^{-3}	0.632×10^{-3}	2.75×10^{-3}	0.01513	0.002039	55.
4395	4/28/64	A-4	10,924	188	2.19×10^{-3}	0.632×10^{-3}	2.75×10^{-3}	0.01513	0.001644	45.7
4397	4/28/64	S-4E	9,705	188	2.19×10^{-3}	0.632×10^{-3}	2.75×10^{-3}	0.01368	0.001513	220.5

* q_{cw} is cold-wall stagnation heat rate on cylinder in crossflow.

**Discovered water leak in plasma generator.

†Steady-state calorimeter not functioning properly for Runs 4377 through 4397.

††Test condition setup with enthalpy and model stagnation pressure only.

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Test Description

After the following general description of test calibration, test procedure, and test instrumentation, the details of each test run are provided in summary descriptions.

Facility Calibration

The specified test conditions were calibrated by operating personnel in pre-test calibrations. The normally measured facility parameters including pressures, temperatures, power input, gas flow, and cooling water flow were monitored and varied until the desired enthalpy and stagnation pressure conditions were established. The model stagnation pressure was measured directly with a water-cooled flat-faced pitot probe. An average stream enthalpy was calculated by the heat balance method, consisting of measuring both the input energy and the energy lost to the cooling medium and assuming the remaining energy remains in the gas as enthalpy.

The stagnation heat flux was measured in the calibration by two instruments. A steady-state, water-cooled, flat-faced, cylindrical calorimeter of known diameter was inserted into the stream and the heat flux to this instrument recorded. Since this calorimeter was also inserted into the stream during the tests before each model was exposed, it provided assurance that the calibrated condition was being reproduced during the tests. The stagnation heat flux on a cylinder in crossflow was measured with a transient calorimeter. This cylinder, of diameter equal to the test models, was equipped with three copper slugs of known mass whose temperature response was monitored with iron constantan thermocouples. The three readings along the stagnation line ensured that no unknown irregular stream cross-section distributions existed.

Comparisons were made of the measurements taken from the steady-state calorimeter and the pitot before each model was tested and those recorded in the pretest calibration. In addition the facility operating parameters for the tests were compared with the corresponding pretest calibration readings. This resulted in accurate calibration of the actual test stream conditions. The measured enthalpy and pressure were used for calculating the stagnation heat flux with the relationship

$$\dot{q}_s \sqrt{R_{\text{cyl}}} = 6.3 \times 10^{-4} H_s (P_{t2})^{\frac{1}{2}}. \quad (1)$$

The measured heat flux allowed a comparison between the actual values and the values calculated from the above relationship.

Test Procedure

The procedure for conducting the tests began with setting the input conditions as determined from the pretest calibration. The actual conditions for each test were then measured with the model in a retracted position out of the flow. When the desired conditions were verified, the model was immersed in the stream concurrent with starting all instrumentation. When failure of the model could be visually assured, the facility and all instrumentation were stopped, and the model remains removed. Another model was then inserted and the process repeated until all models were tested.

Instrumentation

The equipment used to record the specimen behavior during the Phase I tests was of three general types. A continuously recording infrascopy radiation pyrometer was used to monitor the front surface temperature of the models. This instrument performed satisfactorily during all tests, and provided a continuous record of the surface temperature for correlation to event film records. The test events were recorded with two 16-mm cameras. The documentary camera was operated at 24 frames per second during all tests. The event camera in the Phase I tests was a Milliken camera equipped with a 63-mm focal length lenses with f stops adjustable from f/2.7 to f/22. This camera was operated at 400 frames per second for shorter runs and was reduced to 200 frames per second to give a continuous record of the entire burnup sequence of the longer runs. The f stops were varied manually by

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Instrumentation for recording spectrographic information from the tracers was used in the Phase I series. This record consisted of a 9-1/2-inch film, pulled continuously through a modified K37 aerial camera which provided time resolution. A 102 x 128-millimeter, 600-line-per-millimeter grating was used in front of the lens to produce the spectrum. The camera was tilted to put the grating zero order at one edge of the film, and the resulting dispersed spectrum identified both the particular spectrum and the time of tracer exposure. No spectrographic instrumentation was required for the Phase II tests. Figure 7 shows the test facility with cameras and instrumentation in position.

Figure 7. Test facility with instrumentation

operators observing the model brightness. Both cameras used color film, and the high-speed camera in particular provided excellent records of the actual surface ablation. For the Phase II tests, the event camera was operated at 128 frames per second.

Test Runs

The following summaries of the tests, given in the order they were run, indicates the type of material exposed and the time of material ablation. Particularly noted are any occurrences during the run that would make the data invalid or would affect interpretation in any way.

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Phase I

Runs 1 and 2 -- Calibration check runs on stainless-steel containers.

Run 3 - Model T-4 -- This model, consisting of 100 mils of Haynes, 20 mils of tantalum (no insulation) and a titanium tracer, was exposed to an enthalpy of 11,880 BTU/lb. The Haynes ablated at 36 seconds with the tantalum requiring an additional 44 seconds.

Run 4 - Model N-1 -- The sodium tracer of this internal model erupted before the stainless-steel container was ablated. The low heat flux to which this model was exposed resulted in unrealistic run times and was not used in further tests.

Run 5 - Model N-2 -- The results were similar to Run 4 except that the higher heat flux resulted in more realistic times for complete ablation.

Run 6 - Model S-1 -- The stainless-steel container ablated very uniformly in 5 seconds to expose the insulation. The insulation then withstood the flow, with the flare erupting, for 82 additional seconds.

Run 7 - Model S-2 -- Results of this test were the same as Run 6.

Run 8 - Model T-1 -- This model with 50 mils of Haynes and a titanium tracer heated uniformly until the Haynes ablated in 87.5 seconds.

Run 9 - Model T-2 -- The model rotation during this test stopped at 120 seconds. The Haynes had ablated at 74 seconds, and the tantalum was oxidizing at a constant temperature when the rotation stopped. In 4 additional seconds the tantalum burned through.

Run 10 - Model T-5 -- Slight modifications made to the model rotation system prior to this test were not sufficient, and rotation stopped at 18 seconds. The Haynes and titanium then ablated in an irregular fashion.

Run 11 - Model T-6 -- This model, containing 50 mils of Haynes, 6 mils of tantalum, and a titanium tracer, rotated satisfactorily with Haynes ablation at 37 seconds and complete tantalum ablation in 50 additional seconds.

Run 12 - Model A-1 -- The Haynes on this model ablated in 35 seconds with the tantalum oxidation requiring an additional 33 seconds. After the tantalum was removed the Fiberfrax insulation continued to undergo ablation with the silver flare leaking out until about 160 seconds.

Run 13 - Model A-2 -- In this repeat of the previous run the Haynes ablated in 35 seconds. Approximately three-fourths of the tantalum was ablated at 69 seconds with the remaining portion being ablated at 79 seconds. Again the insulation required a substantial period of exposure before failure.

Run 14 - Model S-1E -- This model was exposed for 163 seconds with the 100 mils of Haynes requiring 70 seconds for ablation and the 20 mils of tantalum requiring an additional 85.5 seconds. During the period of tantalum oxidation the strontium flare began erupting from holes in the liner at 105 seconds.

Run 15 - Model S-2E -- This model was exposed for 274 seconds with Haynes ablation requiring 70 seconds. At 60 seconds the strontium flare began to erupt from the model and continued rather strongly for 50 seconds. The effect of this strontium on the oxygen and the surface of the tantalum is thought to have contributed to the extremely long time (compared to other tantalum tests) required for the tantalum to ablate.

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Run 16 - Model P-1 -- This model of 50 mils of Haynes with lead substituted for the thallium tracer underwent a sudden rupture at 16.8 seconds with molten flare erupting from this break at 24.8 seconds. The Haynes ablated in 25.9 seconds.

Run 17 - Model P-2 -- This test was a repeat of the previous run. There was no rupture, and the Haynes ablated at 24.8 seconds. Again the insulation withstood the heating for a substantial period of time after Haynes ablation.

Run 18 - Model I-1 -- This model contained an indium tracer within the insulator and 100-mils-thick Haynes container. Ablation of the Haynes occurred at 63.2 seconds with a smooth temperature increase up to ablation; the insulation required an additional 29 seconds for destruction.

Run 19 - Model I-2 -- This run was a repeat of the previous test, with Haynes ablation requiring 65.7 seconds after a smooth temperature increase.

Run 20 - Model B-1 -- This internal capsule required 7.5 seconds for ablation of the 10-mil stainless steel. Again destruction of the remaining insulation required a substantial period of time.

Run 21 - Model B-2 -- This test repeated the previous test, but only 5 seconds were required to ablate the stainless-steel container. The insulation required 40 additional seconds to ablate.

Phase II

Run 1 - Model T-7 -- This specimen contained titanium in a 6-mil liner of tantalum and a 50-mil capsule of Haynes. The Haynes ablated in 55.5 seconds with the tantalum requiring an additional 31.2 seconds.

Run 2 - Model T-8 -- The specimen tested in this run was identical to that tested in the previous run. Upon Haynes ablation at 44.5 seconds the test was stopped to observe any indication of molten Haynes wetting the tantalum surface.

Run 3 - Model T-9 -- The 100-mil Haynes capsule ablated from this model in 76.7 seconds with the tantalum requiring an additional 69.3 seconds for complete ablation. The tantalum oxidized evenly, showing a rather porous wall before final failure.

Run 4 - Model T-10 -- This capsule and test were identical to the previous one with Haynes ablation in 70 seconds and tantalum removal in an additional 68 seconds.

Run 5 - Model A-3 -- The model underwent uniform heating until the 50 mils of Haynes ablated at 26.4 seconds. For complete oxidation of the 6 mils of tantalum an additional 38 seconds were necessary. The tantalum surface became very porous, indicating an even oxidation over the entire surface.

Run 6 - Model S-3E -- The 100 mils of Haynes was ablated in 54.4 seconds, but the tantalum did not ablate in 282 seconds. A small water leak in the plasma generator affected the surface temperature and oxygen flux sufficiently to make the data invalid.

Run 7 - Model I-3 -- This model apparently did not heat evenly, since the 100 mils of Haynes ablated unevenly. Enough Haynes had ablated at 63 seconds to allow one segment of the insulation to be stripped away. However, the remaining Haynes was not sheared away until 65.6 seconds.

Run 8 - Model I-4 -- This model, identical to the previous specimen, heated more evenly; Haynes ablation occurred in 64 seconds.

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Run 9 - Model S5E-A -- This test and Test No. 14 used the same model. This specimen was a 20-mil liner of tantalum with a strontium tracer and no Haynes capsule. The two tests were for facility checkout purposes after the difficulties experienced in Test No. 6, and no quantitative data were obtained.

Run 10 - Model N-3 -- This internal capsule required 4.42 seconds to ablate the 10-mil stainless-steel wall. Only 0.62 additional seconds was required to remove the segmented insulation. This and the following tests showed the segmented insulation would function as designed.

Run 11 - Model N-4 -- This capsule was similar to the one in Test No. 10. It ablated in 4.37 seconds.

Run 12 - Model G-1 -- This gallium-loaded internal capsule was tested as a replacement for the strontium-loaded internal tracer and responded satisfactorily. The 10-mil stainless-steel container ablated in 3.55 seconds, and the insulation required an additional 2.6 seconds.

Run 13 - Model G-2 -- This capsule was a repeat of Run No. 12 and ablated in 3.52 seconds. Insulation removal required an additional 1.2 seconds.

Run 14 - Model S5E-B -- See Run No. 9.

Run 15 - Model B-3 -- The 10-mil stainless-steel container on this capsule ablated in 4.08 seconds with the segmented insulation requiring an additional 1.2 seconds to remove.

Run 16 - Model B-4 -- The model was similar to Run No. 15 with ablation in 4.07 seconds.

Run 17 - Model E20-E-A -- This Martin Company model consisted of a 20-mil thickness of tantalum with no outside capsule and no internal tracer. The test was for the purpose of a facility checkout. The tantalum did not melt in 182 seconds and was withdrawn from the stream.

Run 18 - Model E20-E-B -- This test used the same model as the previous run in an increased gas enthalpy and pressure stream. The model ablated in 55 seconds. This test established conditions for the final two tests.

Run 19 - Model A-4 -- The 50 mils of Haynes ablated in only 15.4 seconds at the increased heat flux. The 6 mils of tantalum required an additional 17 seconds to oxidize and ablate.

Run 20 - Model S-4E -- The 100 mils of Haynes ablated in 44 seconds and exposed the tantalum. During the time that the 20 mils of tantalum was exposed the strontium tracer was erupting and could have interfered with the surface oxygen, since the tantalum required an additional 160 seconds for ablation.

Thermal Analysis

Analyses of the ablation tests were performed to show correlation between analytically predicted thermal responses and the actual responses as determined from the tests. The Haynes portion of the external capsules and the stainless-steel containers for the internal capsules can be analyzed using available material properties with applicable heat-transfer relationships. Calculations of the rate of tantalum oxidation and removal are made and compared with predicted values resulting from postulated thermochemical relationships.

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Computer Analysis

The Sandia computer program used for the thermal analysis is a high-speed numerical computation called HERMAN. The program utilizes a CDC 3600 computer, and will handle one-, two-, or three-dimensional networks. Problems with heterogeneous cross sections made up of materials whose physical properties are a function of temperature can be solved readily with this program. The problems can include not only varying or constant heat input, but also surface radiation to any surroundings. Each test model was programmed with the dimensions and materials mentioned earlier, and with material properties assumed as given in Table III.

TABLE III

Material Properties

Material	Specific Heat (BTU/lb-°F)	Density (lb/in. ³)	Thermal Conductivity (BTU/in.-sec-°F)	Latent Heat of Fusion (BTU/lb)	Emissivity
Silver	0.056	0.379	0.00494		
Indium	0.058	0.264	0.000318		
Tantalum	0.05	0.627	0.000995		0.4
Haynes 25	0.095-0° 0.22-3200°	0.33	0.000116-20° 0.000591-3200°	115	0.8
Insulation	0.26	0.0087	0.00000193		
Stainless steel	0.12	0.28	0.000218	120	0.3-1200° 0.7-1800° 0.7-2600°
Titanium	0.175	0.166	0.0003-40° 0.00025-600° 0.000227-1300°		0.24
Strontium	0.176	0.094	0.00168		

All temperatures are degrees Fahrenheit.

The computer has a switching network to compute the ablation of heterogeneous cross sections which ablate in layers. After calculating the point at which the inside Haynes surface reached its melting temperature and the Haynes had absorbed an amount of heat equal to its heat of fusion, the computer automatically drops the Haynes nodes and begins a computation of the aerodynamic heating now applied to the tantalum surface. The temperatures of internal nodes were calculated and represent the response of the materials within the capsules.

Analysis of Temperature

As stated previously, the model surface temperature was continuously recorded with a radiation pyrometer. This instrument senses the radiation in the 1.7- to 2.4-micron wave-length region and records the surface temperature with emissivity selector set to unity. As a result of this emissivity selection, the temperature must be corrected to account for surface emissivity other than unity. This correction is described in detail in Sandia Corporation Report SC-TM-64-1259.

Figures 8 through 19 show for each model type the corrected surface temperatures. In most cases two similar models were exposed to repeated test conditions, and temperature data from both models were plotted on one graph. One curve drawn through these points represents model response. However, where similar models did not experience the same test conditions, each model is represented by a separate curve. These figures also show surface temperature calculations that result from the computer analysis. A discussion of these compared data will be presented in a later section of this report.

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Figure 8. Temperature response of internal capsules

Figure 9. Temperature response of 50 mil and 100 mil Haynes capsules

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Figure 10. Temperature response of Model T-1

Figure 11. Temperature response of Models A-1 and A-2

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Figure 12. Temperature response of Model T-6

Figure 13. Temperature response of Models S-1E and S-2E

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Figure 14. Temperature response of Models I-3 and I-4

Figure 15. Temperature response of Model A-3

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Figure 16. Temperature response of Model A-4

Figure 17. Temperature response of Models T-7 and T-8

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Figure 18. Temperature response of Models S-3E and S-4E

Figure 19. Temperature response of Models T-9 and T-10

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Analysis of Tantalum

Analysis of tantalum is somewhat different from that of Haynes and stainless steel. Aerodynamic heating is not sufficiently high to melt tantalum metal. However, earlier Sandia tests (SC-RR-64-575) established that the removal of tantalum resulted from supplying sufficient oxygen to form tantalum oxide or oxides; the material thus formed will melt at approximately 1800°C. The rate of oxide formation and removal is a function of the oxygen flow to the surface, and possibly of other unknown parameters.

A detailed calculation of the gas flux which diffuses through a boundary layer and strikes a model surface may be found in Sandia Report SC-RR-64-575. It is sufficient for our purposes to state the final equation for calculating the oxygen flux at the surface as

$$\dot{m}_{\text{ox}} = 0.215 \dot{q}_{\text{av}}/H_s. \quad (2)$$

Calculation of the rate of tantalum removal is based on the following assumptions: (1) all oxygen which strikes the surface will react with tantalum to form an oxide; (2) the oxide or oxides formed melt at approximately 1800°C and are sheared away so that no surface buildup on the tantalum occurs to prevent further reactions; (3) a known oxide is formed. For our purposes, we will perform one analysis assuming Ta_2O_5 is formed, and one assuming formation of both TaO_2 and TaO .

Employing these assumptions in analyzing the formation of tantalum pentoxide (Ta_2O_5), one finds that the amount of tantalum oxidized and removed in the time interval $\Delta\theta$ may be calculated as

$$t = \frac{48}{5} \frac{(\text{At.wt.})_{\text{Ta}}}{\rho_{\text{Ta}}} \frac{\dot{m}_{\text{ox}}}{(\text{Mol.wt.})_{\text{ox}}} \Delta\theta, \quad (3)$$

and assuming

$$\begin{aligned} \rho_{\text{Ta}} &= 1038 \text{ lb/ft}^3 \\ (\text{At.wt.})_{\text{Ta}} &= 180.95 \\ (\text{Mol.wt.})_{\text{ox}} &= 32 \end{aligned}$$

$$t = 0.0523 \dot{m}_{\text{ox}} \Delta\theta. \quad (4)$$

Since no positive identification of the oxide formed at the re-entry condition exists, and since the test data do not agree satisfactorily with calculations from Eq. (4), it seemed advisable to perform an additional analysis assuming a different oxide formation. Some previous work has indicated that oxides other than tantalum pentoxide may be formed at extremes of temperature and pressure. In particular TaO has been reported stable at high temperatures and low pressures by Schmidt.¹

Assuming in addition the formation of TaO_2 , one may write

Writing in the equation form necessary to calculate the thickness of tantalum removed in the time interval $\Delta\theta$, one gets

$$t = \frac{36}{2} \frac{(\text{At.wt.})_{\text{Ta}}}{\rho_{\text{Ta}}} \frac{\dot{m}_{\text{ox}}}{(\text{Mol.wt.})_{\text{ox}}} \Delta\theta. \quad (6)$$

¹Schmidt, F. F., "Tantalum and Tantalum Alloys." DMIC Report 133, July 1960, Defense Metals Information Center, Batelle Memorial Institute.

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Again substituting known values into this equation, one obtains,

$$t = 0.0981 \dot{m}_{\text{ox}} \Delta \theta. \quad (7)$$

Equations (4) and (7) can be used to calculate the thickness of tantalum that one would expect to be removed, first assuming Ta_2O_5 is formed and secondly that TaO_2 and TaO are formed. The surface oxygen flux is calculated from Eq. (2), and the time intervals of tantalum exposure to the flow were taken from the high-speed event film. These times are marked on the appropriate curves on Figures 8 through 19. Table IV tabulates the calculated thickness of tantalum removed (for both oxide assumptions), the actual thickness of tantalum ablated, and the ratio of actual value to the calculated value.

TABLE IV
Comparison of Calculated and Actual Tantalum Oxidation

Model	Actual Tantalum Thickness Removed (inch)	Predicted Tantalum Thickness Removed (inch) Eq. (4)	Ta(actual)/ Ta(predicted) Eq. (4)	Predicted Tantalum Thickness Removed (inch) Eq. (7)	Ta(actual)/ Ta(predicted) Eq. (7)
A-1	0.006	0.00228	2.63	0.00427	1.405
A-2	0.006	0.00248	2.42	0.00462	1.3
T-6	0.006	0.00336	1.785	0.0063	0.952
T-7	0.006	0.002	3.	0.00371	1.62
A-3	0.006	0.00252	2.38	0.0047	1.275
A-4	0.006	0.0012	5.	0.00222	2.7
S-1E	0.020	0.00585	3.42	0.0109	1.835
S-4E	0.020	0.0126	1.59	0.0236	0.85
T-4	0.020	0.00265	7.55	0.00495	4.04
T-9	0.020	0.00386	5.18	0.00723	2.77
T-10	0.020	0.00394	5.08	0.00737	2.71

Since these theories do not adequately describe the actual oxidation of tantalum, the test results are reduced to present some empirical data on tantalum oxidation and ablation. Assuming that Eq. (2) accurately describes the oxygen flux at the material surface, a calculation to determine the total amount of surface oxygen required to oxidize and ablate a given thickness of tantalum may be calculated as

$$M_{\text{ox}} = \dot{m}_{\text{ox}} \Delta \theta. \quad (8)$$

Table V shows this value calculated for each tantalum model tested successfully.

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TABLE V

Tantalum Oxidation Results

Model	Thickness Tantalum Removed (inch)	Total Oxygen Required (lb/ft ²) Eq. (8)
A-1	0.006	0.0435
A-2	0.006	0.0472
T-6	0.006	0.0633
T-7	0.006	0.0378
A-3	0.006	0.0479
A-4	0.006	0.0226
S-1E	0.020	0.1112
S-4E	0.020	0.24
T-4	0.020	0.0503
T-9	0.020	0.0735
T-10	0.020	0.075

Discussion and Conclusions

Data and film records obtained from testing the RFD-2 capsules in simulated re-entry have produced not only predictions of behavior, but also a greater confidence in capsule response in actual flight. No predictions for the RFD-2 re-entry are included as part of this report; however, data reduced from these tests were used for re-entry predictions, as detailed in Sandia Corporation Report SC-RR-64-1798.

As a result of the Phase I series of tests, modifications were made in the test capsule design, the most significant being the segmentation of the capsule insulation. Phase II tests indicated that splitting the tube of insulation along its cylindrical axis into 120-degree segments assured immediate flare exposure after container ablation.

Among the group of capsules tested in Phase I were both internal and external capsules with strontium tracers. Tests showed that the two capsules containing strontium could ablate at altitudes sufficiently close to preclude distinguishing between the two. Phase II testing of gallium in place of strontium for the internal capsule showed this design to be satisfactory.

Useful thermal data from these tests depended upon event film from high-speed cameras, correlated with records from an infrascopes radiation pyrometer for computer analysis. The high-speed cameras revealed the capsule ablation process in detail, and showed the times required for any event to occur. Film from both Sandia and Martin photography produced excellent images for data reduction, as shown in Figures 20 through 27. The photographs identify each model and note the times of significant events of capsule ablation.

As mentioned previously, the corrected measured surface temperature is plotted as the actual surface temperature in Figures 8 through 19. Specimen immersion and withdrawal from the flow automatically placed a signal on the strip chart. These marks allowed correlation of the event film with surface-temperature data from the Infrascopes radiation pyrometer.

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$T = 0$

$T = 2.9$ seconds

$T = 3.375$ seconds
Container rupture

$T = 5$ seconds
Container ablated

Figure 20. Ablation sequence of Model S-1

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$T = 0$

$T = 3.8$ seconds

$T = 4.75$ seconds
Container ablation

$T = 5.25$ seconds
Container ablated

Figure 21. Ablation sequence of Model B-2

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T = 2.66 seconds
Container ablation

T = 3.75 seconds
Container ablation

T = 4.0 seconds
Container ablated

T = 5.0 seconds
Insulation removal

T = 5.38 seconds
All ablated

Figure 22. Ablation sequence of Model G-2

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$T = 0$

$T = 20$ seconds

$T = 24.5$ seconds
Haynes ablation

$T = 26.4$ seconds
Haynes ablated

$T = 64.1$ seconds
Tantalum ablation

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Figure 23. Ablation sequence of Model A-3

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$T = 0$

$T = 31.2$ seconds

$T = 60$ seconds
Haynes ablation

$T = 64$ seconds
All ablated

Figure 24. Ablation sequence of Model I-4

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T = 0

T = 41.7 seconds

T = 54.2 seconds
Haynes ablation

T = 63.2 seconds
Haynes ablated

Figure 25. Ablation sequence of Model I-1

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T = 0

T = 35 seconds

T = 65 seconds
Haynes ablation

T = 70 seconds
Haynes ablated

T = 96.5 seconds
Tantalum ablation

T = 155.5 seconds
Tantalum ablated

Figure 26. Ablation sequence of Model S-1E

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T = 0

T = 31.25 seconds

T = 54.2 seconds

T = 71 seconds
Haynes ablation

T = 76.7 seconds
Haynes ablated

T = 87.5 seconds
Tantalum ablation

T = 146 seconds
Tantalum ablated

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Figure 27. Ablation sequence of Model T-9

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The majority of data reduction from these tests provided satisfactory agreement with analytical calculations. As discussed in the thermal analysis section of this report, thermal models of the specimens, together with the test conditions, were submitted to a computer for analysis. Temperature at several points in the model was computed to infer conditions of the materials within the capsule. (The surface temperature calculations from these computer analyses are shown on Figures 8 through 19.) A comparison of actual measured temperature and the calculated temperature shows good agreement for the Phase I tests. Attempts to obtain closer agreement between the two would be unrealistic, because the relatively massive Haynes end caps affect thermal calculation, because the material properties vary to uncertain values at high temperature, and because the test heat flux and distribution can be measured to accuracy of only ± 10 percent of nominal.

For the Phase I tests the pyrometer-recorded surface temperatures at the time of melting correlated very well with the published melting temperatures. Published melting temperatures are indicated on the curves; the correspondences indicate pyrometer-recorded satisfactory data.

The temperature data resulting from the Phase II tests do not in general agree satisfactorily with the computer analyses (Figures 14 through 19). Several possible reasons have been considered. First the steady-state calorimeter was found to be malfunctioning during the tests so that the exact heat flux could not be measured correctly. Although satisfactory agreement was found between the measured heat flux and that calculated from Eq. (1) in the Phase I tests, the same process in Phase II tests yielded unsatisfactory correlation. The heat flux values used in computer analysis were those given in Table II, and may contribute to the differences shown on the temperature curves.

Secondly, for the Phase II test the corrected temperature from the pyrometer seems too high. From Figures 14, 15, 17, 18, and 19 one can see that the observed temperature at the time of Haynes ablation was well above the Haynes melting temperature. In most cases, the observed time of ablation was very close to computer prediction, even though the temperatures were significantly different. Using the same method for reducing the temperatures in Phase I tests had yielded good agreement between the tests and the predictions. A second indication of pyrometer error was its measure of tantalum temperature after Haynes removal; the pyrometer showed temperatures well above those which would result in radiation heat losses equal to the heat input. Another indication of error in Phase II pyrometer readings was the behavior of Model S-3E (Figure 19). The apparent tantalum surface temperature as recorded by the pyrometer and corrected for emissivity in the manner described previously was well above the temperature required in all other tests to allow surface melting. However in this run no tantalum melted in 282 seconds, indicating a temperature error.

In view of the suspected error in Phase II tests, and because of the Phase I test correlations, present computer techniques appear to describe satisfactorily the temperature response and ablation of Haynes in re-entry conditions.

The actual results of tantalum oxidation and ablation are not in complete agreement with calculated values. However, the same results were apparent from tests conducted previously by Sandia in a different facility and reported in SC-RR-64-575. From Table IV one can see that the measured removal of tantalum occurs faster than predicted by theoretical calculations. No satisfactory explanation for this difference exists. However, since the ablation of tantalum has been observed to occur at temperatures significantly below the melting temperatures of tantalum metal, the ablation is confidently believed to consist of oxidation of tantalum. Consequently data reduction for tantalum consists of calculating the amount of oxygen required during the test to cause the destruction of the entire liner at given thicknesses. Table V indicates that the 20 mils of tantalum ablated at a much faster rate than the 6-mil thickness. No explanation can be offered for this, since one would expect the amount of time and oxygen required to oxidize a material to be a direct function of the mass of the material. The temperature of the 20-mil liners was not significantly different from that of the thinner tantalum, but the faster rate on the thicker containers was observed in all tests. No large masses of tantalum were torn from the models; rather the tantalum could be observed undergoing surface melt, with the liner becoming porous before ablation.

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The results and conclusions of tests on RFD-2 capsules can be stated as follows:

1. The RFD-2 fuel capsules (as modified with the split insulation) function satisfactorily when exposed to typical RFD-2 simulated re-entry conditions.
2. The thermal response of the 10-mil stainless-steel internal capsules was predictable; their ablation in simulated re-entry can be calculated satisfactorily.
3. The test response of Haynes-25 capsules agreed with calculated values. This fact indicates that their re-entry responses will be predictable as well.
4. Even though the apparent rapid rates of tantalum oxidation cannot be explained, the rates are in agreement with the data from tests performed by Sandia at other plasma facilities.
5. Results from this and other tests show that tantalum can be removed at surface temperatures, gas enthalpies, model pressures, and surface oxygen fluxes that are typical of the RFD-2 and orbital decay re-entries.
6. The phenomena of tantalum oxidation in re-entry is apparently related to gas enthalpy, thickness of tantalum, and possibly other unknown effects. A detail understanding does not presently exist but with the current gross understanding, the mass removal of tantalum during re-entry can be estimated.

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