NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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Development of a Chemical Heater for a Mars Rough-Landing Capsule

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Preface

The work described in this report was performed by the Engineering Mechanics Division of the Jet Propulsion Laboratory.

Acknowledgment

The author acknowledges the excellent work of Stephen P. Vango in investigating chemical reactions for the chemical heater, and also the painstaking work of Albert Topits, Jr., in fabricating and testing mechanical elements of the chemical heater.

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Abstract

This report describes preliminary work performed on one version of a chemical heater, sized to provide one night of survivability for a Mars rough lander. The effects of the impact environment and heat sterilization requirement on the design are discussed. The resulting chemical heater utilizes chlorine trifluoride and boron reactants, weighs 3 lb, and has a heat yield of 1940 Wh.

Development of a Chemical Heater for a Mars Rough-Landing Capsule

I. Introduction

Studies of unmanned missions to the surface of Mars within the next few years have concluded that the scientific value of such a mission can be greatly enhanced by having the capability of surviving the Martian night.

During the Martian night, surface and atmosphere temperatures drop to approximately $-100°F$, well below the lower survival temperature limit of current spacecraft equipment. It will, therefore, be necessary to either insulate the capsule or to provide an on-board heat source, or to do both, depending upon the size and the required lifetime of the lander.

An ideal heater for this application would be lightweight and would be capable of varying its heat output to maintain the capsule temperature at a preset level. Additionally, for use on a Mars capsule, the heater must be capable of withstanding heat sterilization and high impact.

Three types of heat sources have been considered for this application: radioisotope heaters, battery-powered heaters, and chemical reaction heaters. Table 1 gives the specific output and general characteristics of these heat sources.

Table 1. Lander heat sources

Heat source	Specific output	Comments
Radioisotope heater	5 W/lb	Rate of heat delivery cannot be varied.
Battery-powered heater	15 Wh/lb	Easily controllable. Capable of high heat delivery rate.
Chemical reaction heater	>600 Wh/lb	Easily controllable. Capable of high heat delivery rate. Development required.

II. Description of the Problem

A. Mars Lander

A JPL study, made in the spring of 1966, resulted in the conceptual design of a planetary entry/landing capsule that could be delivered to Mars by a *Mariner*-type spacecraft. Approximately 10 days prior to Mars encounter, the capsule would be separated from the flyby spacecraft and would be deflected onto an entry trajectory. The capsule would make atmospheric measurements during entry, relaying these to earth via the spacecraft. At approximately Mach 1, a parachute would be deployed, extracting a small rough lander from the entry body and further decelerating it to approximately 120 ft/s.

The parachute would be released at impact, and the lander would then commence a 22-h surface operation, transmitting data directly to earth.

The lander is shown in Fig. 1 in the post-landing configuration. It is 22 in. in diameter by 9 in. high. The outside is partially covered with balsa wood to cushion the landing impact. Weight of the complete lander is 63 lb.

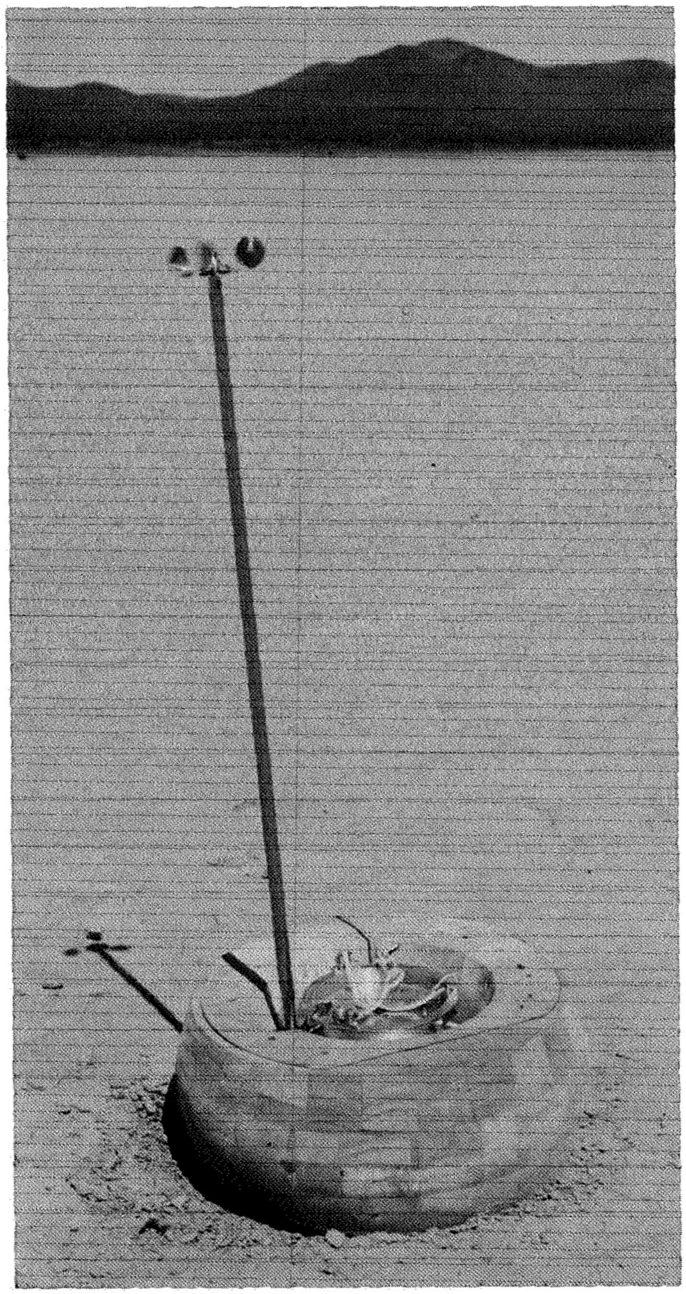

Fig. 1. Mars rough lander

B. Thermal Analysis

Temperature control of the lander during its useful lifetime on the Martian surface was investigated. The most significant problem found was that of keeping the lander warm during the 13-h Martian night, when the near-surface environment drops to approximately −100°F and when wind speeds in the thin 7-mbar atmosphere may reach several hundred miles per hour.

An analysis was made of three temperature control schemes employing as heat sources, battery-power, a radioisotope decay, and exothermic chemical reactions. The weights of these systems (including insulation, where its use resulted in a lower overall weight) were as follows:

Heat source	*Weight, lb*
Battery-powered heater	40
Radioisotope heater	10
Chemical reaction heater	3

As is seen, the battery-powered heater is very unattractive from a weight standpoint, and is eliminated from further consideration for that reason. The radioisotope heater, while not prohibitively heavy, does require solution of a number of problems, including the following:

(1) Rejection of surplus heat during interplanetary cruise, when the heater is well insulated by the lander, the entry capsule, and the sterilization canister.

(2) Developing an effective thermal insulation system that will satisfactorily transmit impact loads and remain effective thereafter.

(3) Obtaining government approval for launching a spacecraft containing a nuclear device.

The principal shortcoming of the chemical heater, at the time the comparative analysis was made, was that it was undeveloped and untried. Nevertheless, its potential weight advantage resulted in its conditional selection for the rough-lander application and provided the impetus for the development effort to be described.

C. Chemical Heater Requirements

From the results of the thermal analysis and from the lander systems studies, a set of requirements for the chemical heater was derived as shown in Table 2.

Table 2. Chemical heater requirements

Requirement	Value
Functional:	
(1) Total heat delivery	1940 Wh
(2) Maximum heat delivery rate	200 W
(3) Control temperature	50 ± 10°F
Physical:	
(1) Weight (maximum)	4.0 lb
(2) Size (maximum)	6 × 6 × 6 in.
Environmental:	
(1) Sterilization	300°F for 50 h
(2) Impact	2500 g in all directions
Operational:	
(1) Unit to be activated by a pyrotechnic event	
(2) Unit to be operable in any attitude	
(3) No electrical power required for operation	
(4) No venting of exhaust products	

III. Development Program

A development program for the chemical heater was divided into chemical and mechanical subdivisions, which were pursued concurrently. Milestones in the development program are shown in Table 3.

Table 3. Chemical heater development milestones

Date	Event
Aug. 1966	Mars capsule mission study
Oct. 1966	Temperature control study of night survivable capsule
Nov. 1966	Chemical heater configuration and preliminary design
Nov. 1966	Chemical reaction investigations
Jan. 1967	Preliminary selection of reactants
Feb. 1967	Heat yield of reactants verified
Feb. 1967	Sterilizability of reactants verified
Aug. 1967	Demonstration of chemical heater system

A. Chemical Development

The chemical effort centered around investigating chemical reactions that lend themselves to the chemical heater application. In particular, reactions were considered in which one of the reactants was in either liquid or vapor phase such that a simple metering valve could be used to control the heater output. Only reactant combinations that were thought to be hypergolic (spontaneously reacting) above 0°F were considered, since they would require no special provision for initiation or restart.

The reactants had to be compatible with sterilization temperatures of 300°F without decomposition and without exhibiting excessively high vapor pressures (which would dictate a heavy container). The reactants had to be capable of long-time storage at near-room temperature to endure the transit phase of a mission to Mars.

Finally, reactions were sought for which the products were solid phase. In solid phase, they could be stored compactly within the heater unit, obviating the need for contaminating the local Martian atmosphere.

Table 4 gives a partial list of the reactant combinations that were tested. Whereas several of the reactions were hypergolic, only two were restartable and capable of proceeding to completion. Both of these reactions produced vapor phase products; hence, their usage would require deletion of the no-venting requirement initially adopted.

The reactant combination that most nearly met all of the requirements and that appeared to lend itself to the simplest overall heater mechanization was crystalline boron and chlorine trifluoride. The reaction is the following:

$$4B\ (s) + 3\ ClF_3\ (l) = BCl_3\ (v) + 3BF_3\ (v)$$

with a heat release of 1220 Wh/lb of reactants.

After considering the species of products to be vented into the Martian atmosphere and after establishing the compatibility of science sensors that might be typically carried aboard such a lander with these species, the no-venting requirement was withdrawn.

Tests were next conducted to establish whether chlorine trifluoride could meet the sterilization environment of 300°F for 50 h. This testing was done by placing a specimen in a closed stainless-steel vessel and subjecting the specimen to the sterilization environment. The observed pressure did not increase with time, indicating that there was no decomposition of the chlorine trifluoride.

Heat-yield measurements for the reaction were made by calorimetric methods. The results showed excellent agreement with values derived from the handbook heats of formation.

B. Mechanical Development

Mechanical work had, as its chief aim, the development of control and valving elements for the chemical heater. The challenge was to design a temperature sensing and

Table 4. Chemical reactants tested

Reactants				Comment
Chemical	State[a]	Chemical	State[a]	
Lithium	ck	Chlorine	v	No reaction.
Lithium	ck	Chlorine pentafluoride	v	No reaction.
Lithium	ck	Chlorine trifluoride	v	No reaction.
Lithium	pr	Chlorine trifluoride	v	No reaction.
Lithium	pr	Chlorine pentafluoride	v	Spontaneous reaction, but would not restart.
Magnesium	cp	Chlorine pentafluoride	v	No reaction.
Magnesium	cp	Chlorine trifluoride	v	No reaction.
Magnesium	pr	Chlorine trifluoride	v	No reaction.
Magnesium	pr	Chlorine pentafluoride	v	No reaction.
Titanium	sp	Chlorine pentafluoride	v	Reacted, but not to completion.
Titanium	wr	Chlorine pentafluoride	v	No reaction.
Titanium	sp	Chlorine trifluoride	v	No reaction.
Titanium	pr	Chlorine pentafluoride	v	Reacted, but not to completion.
Titanium	wr	Chlorine	v	Reacted.
Calcium	ck	Chlorine pentafluoride	v	No reaction.
Calcium	ck	Chlorine pentafluoride	v	No reaction.
Calcium	ck	Chlorine pentafluoride	v	No reaction.
Zinc	ck	Chlorine pentafluoride	v	No reaction.
Iron	pr	Chlorine pentafluoride	v	No reaction.
Silicon	gr	Chlorine pentafluoride	v	Reacted, but not to completion.
Sodium	ck	Chlorine pentafluoride	v	Reacted, but not to completion.
Lead	gr	Chlorine pentafluoride	v	No reaction.
Boron	cr & pr	Chlorine trifluoride	v	Reacted to completion. Could be restarted easily.
Boron	cr & pr	Chlorine pentafluoride	v	Reacted to completion. Could be restarted easily.
Decaborane	pr	Chlorine trifluoride	v	Reacted to completion. Could be restarted easily.

[a]Key: ck = chunks; pr = powder; cp = chips; sp = sponge; gr = granules; wr = wire; cr = crystals; v = vapor phase

fluid control device that would be compatible with the highly corrosive liquid reactants and that could survive 300°F sterilization and 2500 g impact. In addition, it was desired that the device be small and require no electrical power for its operation.

The prototype valve developed using a temperature sensing and actuating element is shown in Fig. 2. The temperature sensing and actuating element is a ½-in. diameter by ¼-in. disc made of RTV-655 silicon rubber. This material is selected for its high coefficient of thermal expansion (1.8×10^{-4} in./in./°F) and good high-temperature stability.

Operation of the device is as follows. As temperature increases, the sensing and actuating element expands, displacing the teflon-faced diaphragm toward the central flow port and, thereby, constricting the flow passage. When the set-point temperature is reached, the diaphragm contacts the valve port, stopping the flow. Additional expansion of the actuating element resulting from exposure to temperatures above the set-point (e.g., heat

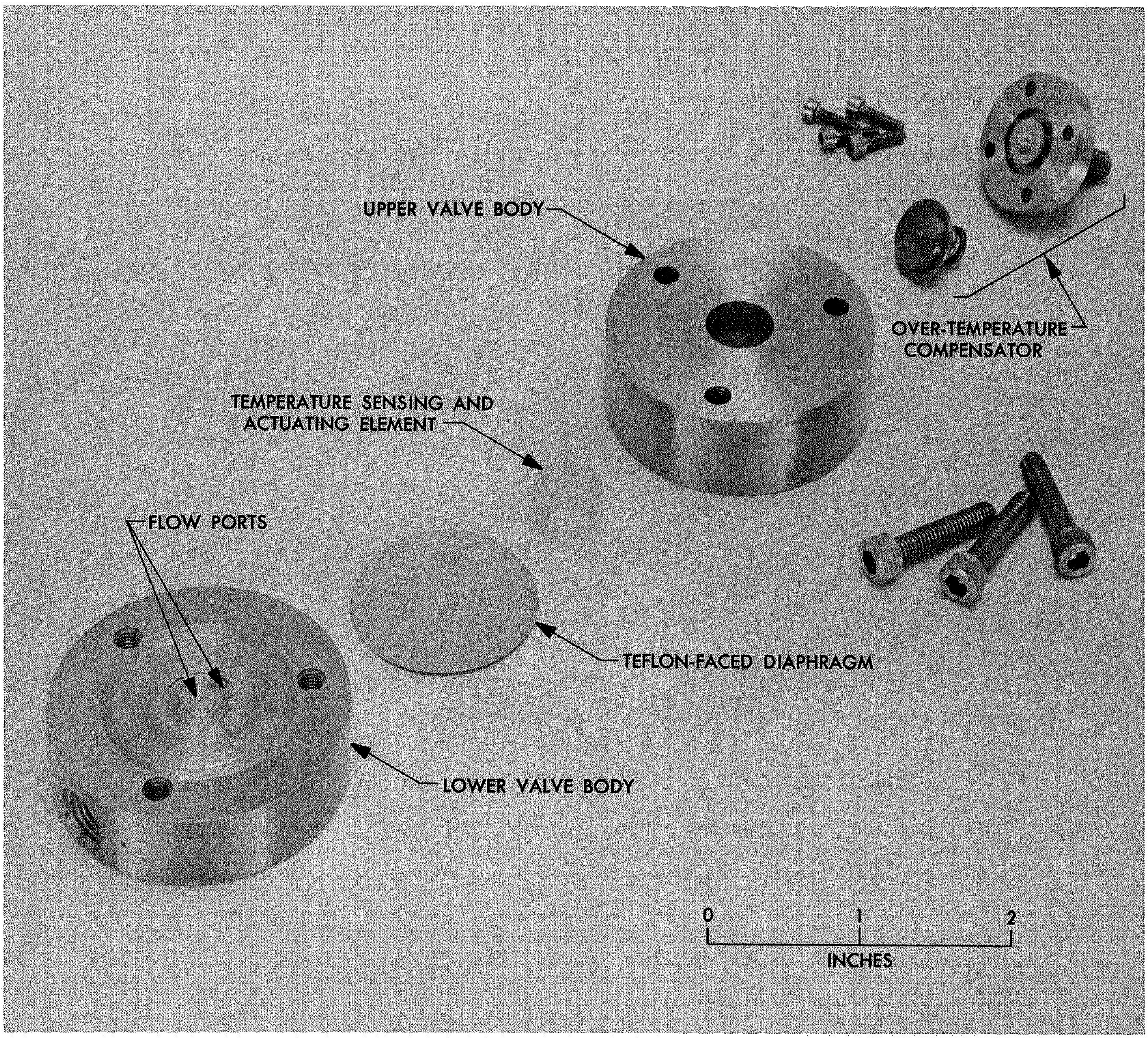

Fig. 2. Prototype temperature sensing and metering valve, disassembled

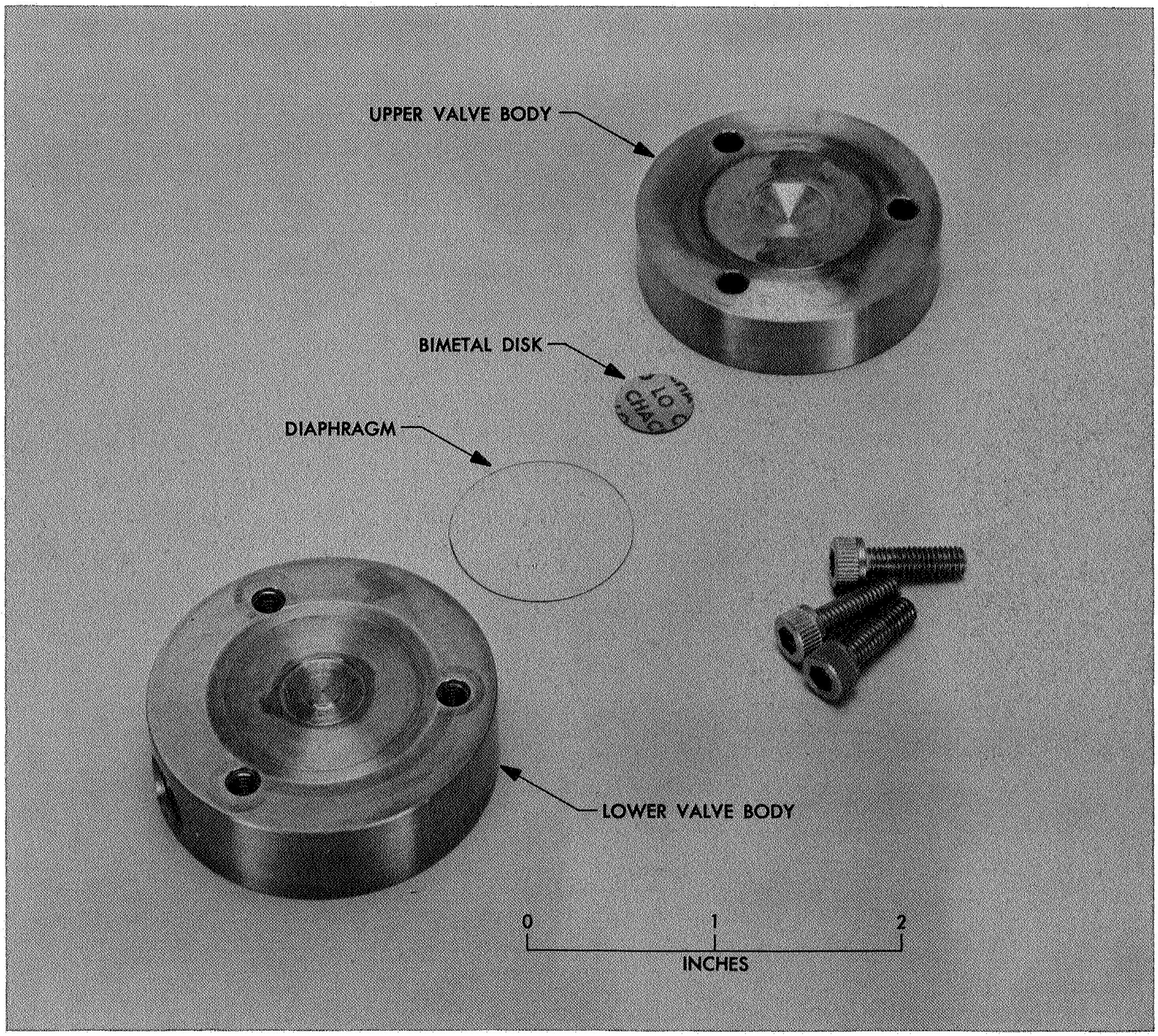

Fig. 3. Alternate temperature sensing and metering valve, disassembled

sterilization) is accommodated by the displacement of the spring-loaded piston on the upper side of the valve body.

High-impact survival capability results from the small size of the control unit, the low mass of its parts, and its rugged construction.

A promising variation of the temperature sensing and metering valve is shown in Fig. 3. It is similar in construction and operation to the unit described above, except that flow modulation results from the change in shape of a bimetal disc, instead of from the expansion and contraction of a silicon rubber disc.

Tests were conducted on several variations of these two valves to establish their performance characteristics. Figure 4 presents the characteristics of the silicon rubber element valve, showing the variation in volumetric flow as a function of temperature for several pressures.

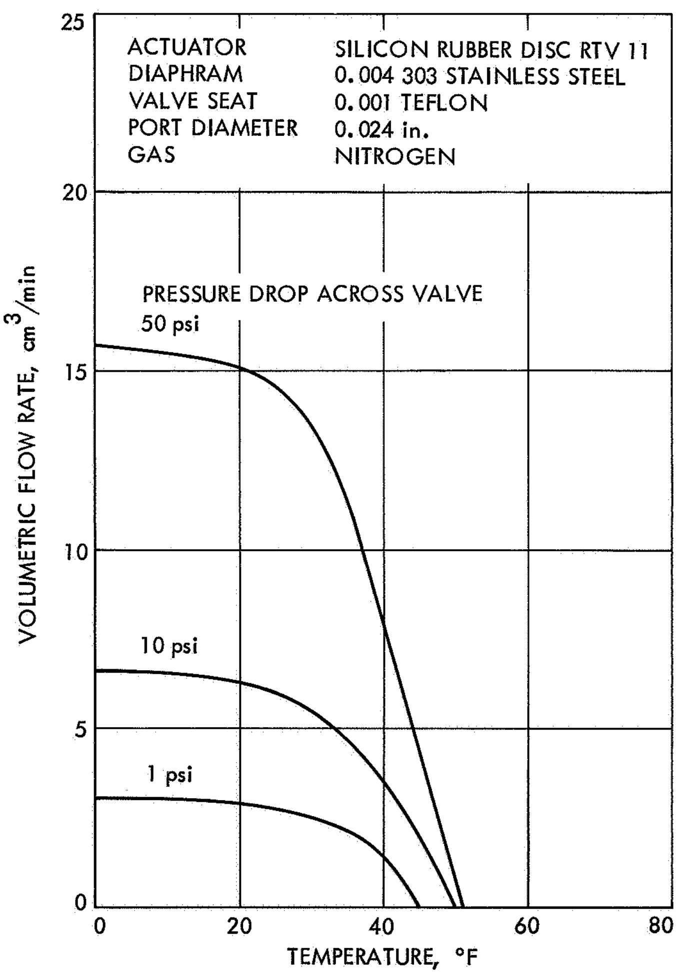

Fig. 4. Performance characteristics of temperature sensing and metering valve

IV. Chemical Heater Design

Following the work on chemical reactant selection and the preliminary development of a control valve, the chemical heater was configured as shown schematically in Fig. 5. The major elements of the system are the chlorine trifluoride tank, the pyro-activation valve, the sensing–metering valve, and the boron bed.

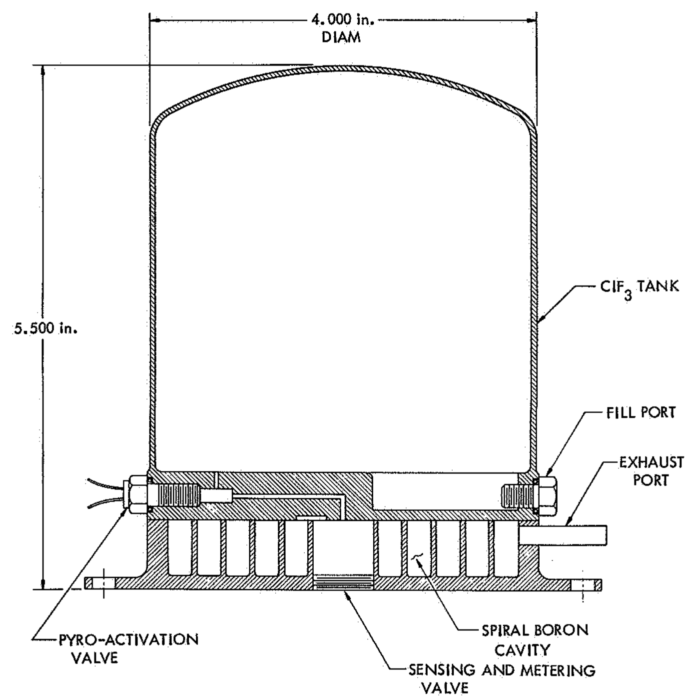

Fig. 5. Chemical heater (1940 Wh)

To initiate operation, the pyro-activation valve is opened, allowing the chlorine trifluoride to pass to the temperature sensing and metering valve. For temperatures below the set-point, the flow will pass through the valve to the boron bed where it reacts spontaneously with the boron, liberating heat. The reaction products are vapor phase and pass through the system to the exhaust port for disposal. Heat generated by the reaction is transferred to the heater base, and then by conduction to the capsule structure.

The chlorine trifluoride tank is made of Inconel 718 and is fabricated in two parts that are then welded together, heat treated, finish machined, and finally cleaned and passivated. The base or boron bed is machined from 6061

T6 aluminum alloy, which is selected for its high thermal conductivity and low weight.

The total dry weight of the prototype unit is estimated to be 1.5 lb. Reactant weight will be 1.56 lb, of which 1.32 lb is chlorine trifluoride. The unit is 5.5 in. in diameter by 5 in. long.

Calculated performance of the chemical heater is shown in Fig. 6 in terms of the heat output versus temperature. It is seen that the heat output stops at a set-point temperature of 50°F, and that the unit is capable of 200 W peak output at 28°F.

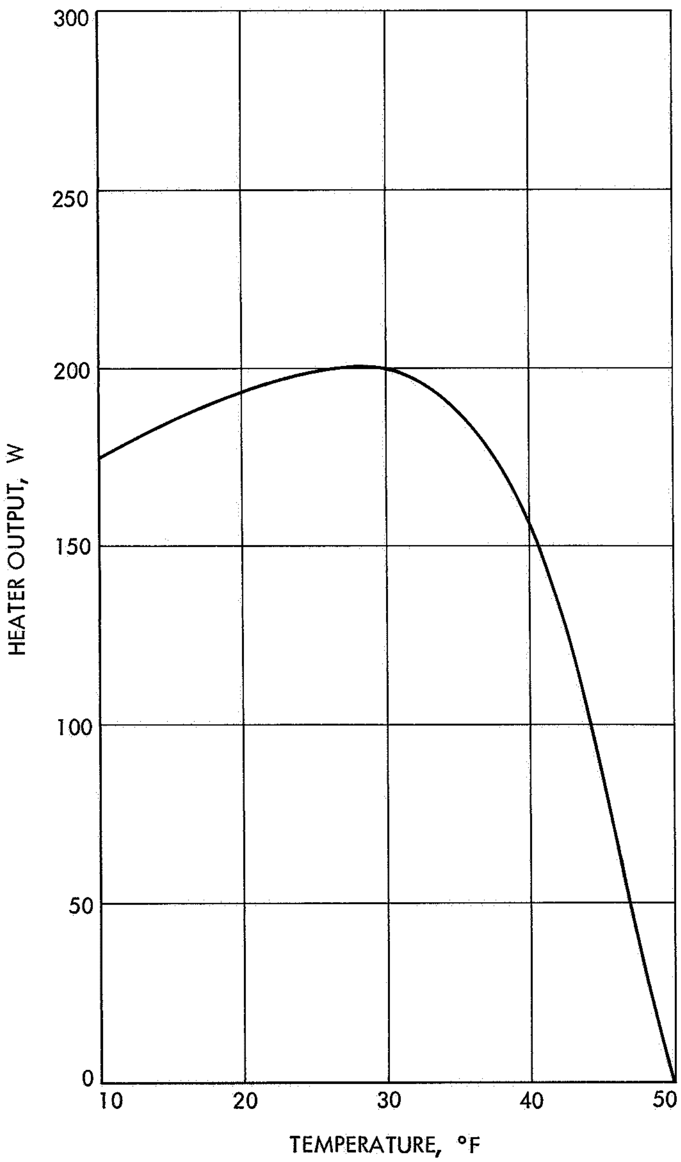

Fig. 6. Chemical heater performance

V. Demonstration Test

A test was conducted to demonstrate the functionality of the integrated heater system. The apparatus consisted of an Inconel heater base, shown in Fig. 7, fitted with a bimetal-disc-type temperature sensing and metering valve and charged with crystalline boron. Chlorine trifluoride was supplied from a tank, located remote from the boron bed for safety reasons. The heater base was bolted to an aluminum heat sink, which was liquid nitrogen cooled. Thermocouples were used to measure the temperature of the heater base.

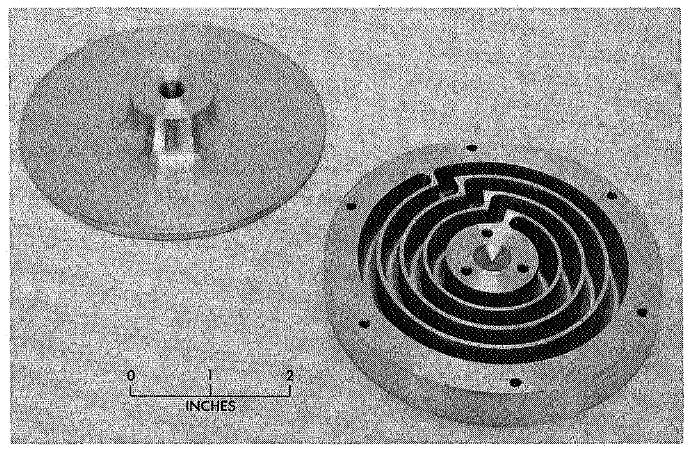

Fig. 7. Chemical heater test base

The heater was put into operation by opening a valve at the chlorine trifluoride tank. At an initial base temperature of 73°F, the heater remained inactive. Cooling was applied and, at a base temperature of 48°F, gaseous products were observed at the exhaust port, indicating that the control valve had opened and chemical reaction had commenced. When cooling was removed, the heater base temperature rose several degrees and the emanation of products from the exhaust port stopped.

VI. Remaining Development Work

The development of the chemical heater has been brought to the point of demonstrating a breadboard model. Considerable development work remains to bring this particular chemical heater concept to a technology ready-state. The outstanding work is:

(1) Configure chemical heater to be compatible with lander shape and mounting provisions. Figure 8 shows a mock-up of a chemical heater configured for a Mars rough lander. The installation of this

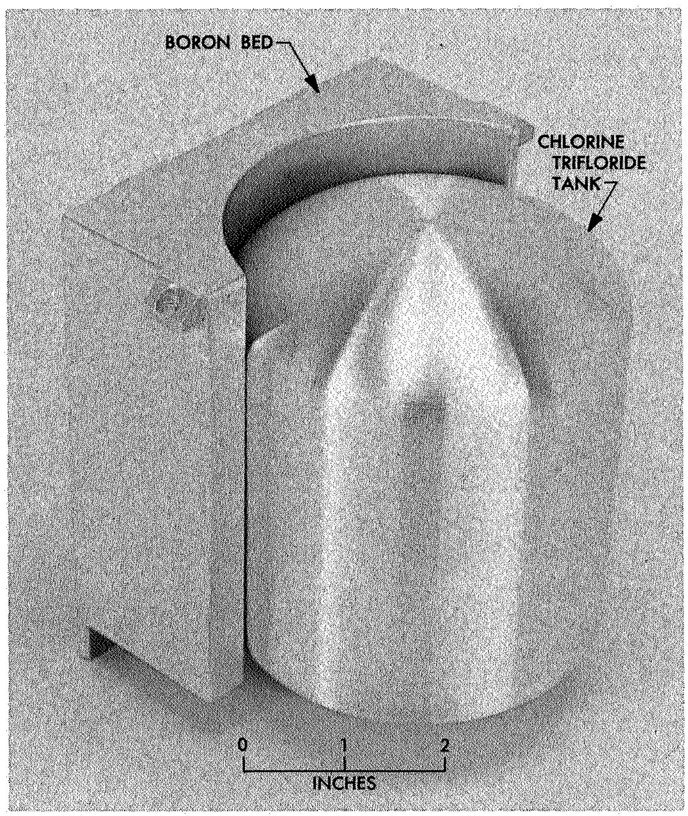

Fig. 8. Chemical heater mock-up

mock-up in a prototype lander chassis is shown in Fig. 9.

(2) Develop an impactible tank and its mounting provisions for the liquid chlorine trifluoride reactant.

(3) Develop an hermetically sealing pyro-activation valve to isolate the reactants prior to heater first start.

(4) Verify that the characteristics of the temperature sensing and metering valve are unchanged following subjection to the heat sterilization environment.

(5) Verify the choice of materials for construction of the chemical heater with the reactants and reaction products for the conditions of service.

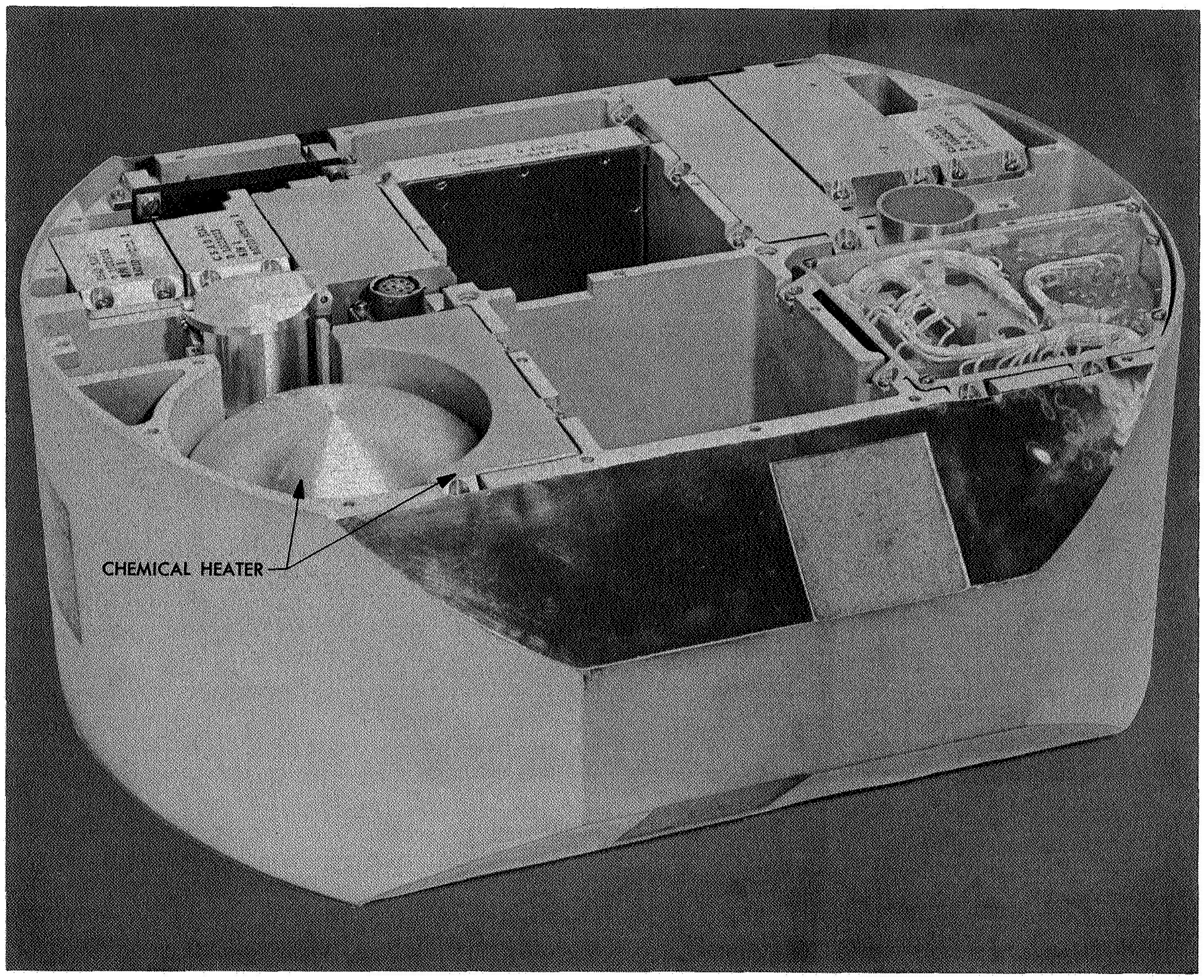

Fig. 9. Lander chassis with mock-up chemical heater installed