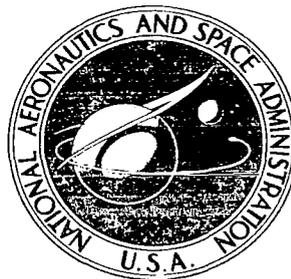


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THERMAL INVESTIGATION OF
AN ION ENGINE MICROTHRUSTOR

by *N. J. Stevens and D. C. Briehl*

Lewis Research Center

Cleveland, Ohio

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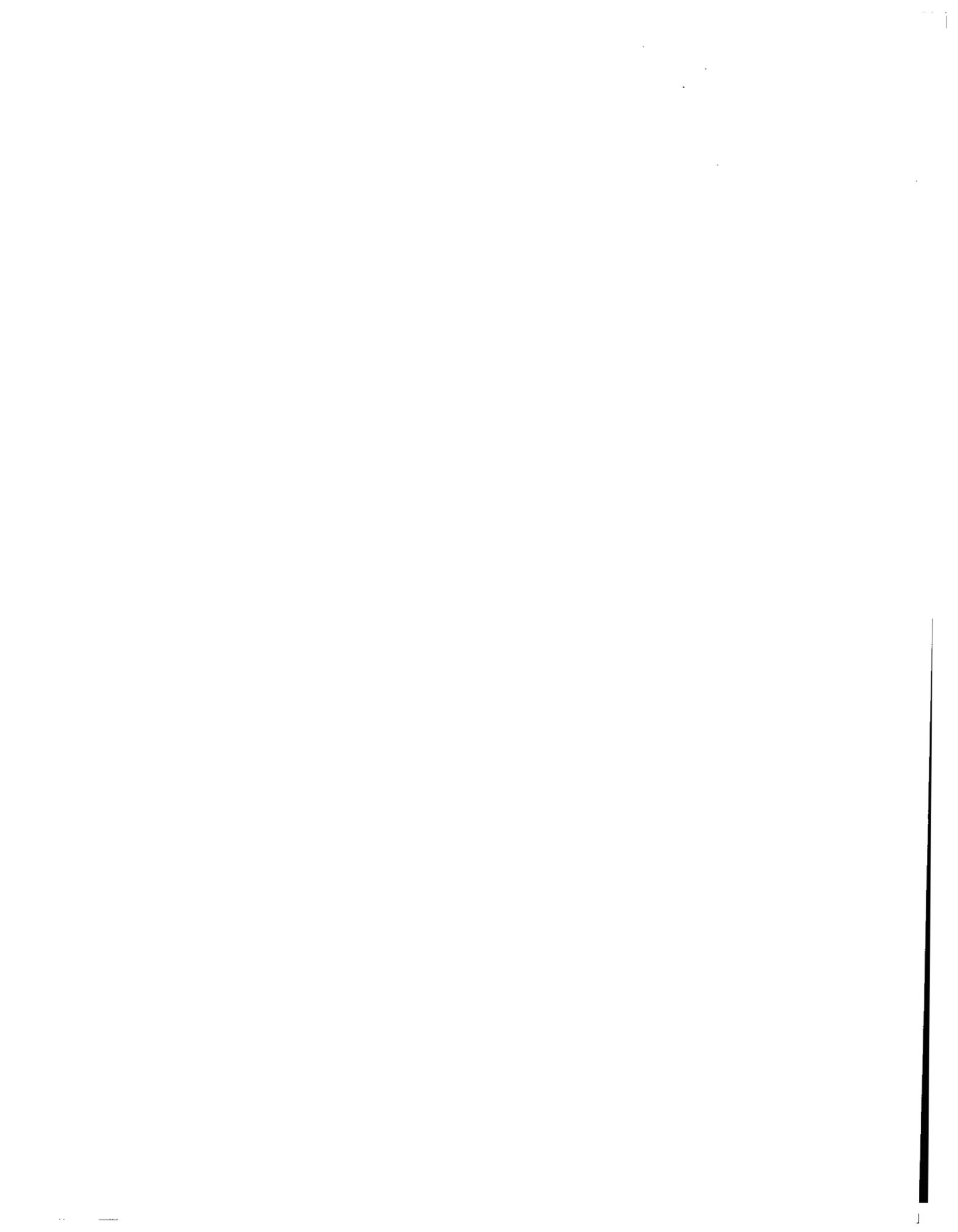
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SUMMARY

A cesium contact-ion microthruster that was designed at the Lewis Research Center was studied to determine the heat transfer conditions necessary to minimize the heater power. The microthruster was simulated on a resistance analog network which was balanced to an experimentally obtained set of temperatures and power inputs from a full-size thermal model test. No cesium was used in the thermal model.

The major thermal losses were identified as conduction through the tank mounts and radiation from the hot feed tube insulation, accelerator, and cesium tank. The thermal model with these losses minimized was predicted to operate at 13.1 watts, and actually it operated at 12.9 watts. Application of modifications to the actual thruster reduced the power requirements by the expected 13 percent.

INTRODUCTION

Considerable effort has been expended in developing small, lightweight thrusters that would be capable of maintaining the position of synchronous orbit satellites. These "station-keeping" thrusters are required to operate for extended periods of time in space, but they need only to have thrusts of the order of a few micropounds. Hence, they were given the name microthrusters.

A cesium contact-ionization microthruster was designed at the Lewis Research Center to meet the requirements of station keeping for a 1000-pound (450 kg) satellite in a synchronous orbit. The projected lifetime of the thruster was 1 year on a 50-percent duty cycle. The microthruster was to produce 10 micropounds (45×10^{-6} N) of thrust at a specific impulse of 5000 seconds and operate on less than 20 watts of electrical power.

The Lewis microthruster consisted of a cesium propellant storage tank, a zero-gravity feed system, a propellant feed tube, a porous tungsten ionizer, and an accelerator (see fig. 1). The cesium was vaporized at the interface region, and the vapor was thermally ionized on the surface of the porous tungsten. The interface temperature had to be high enough not only to vaporize the cesium but to maintain a sufficient vapor

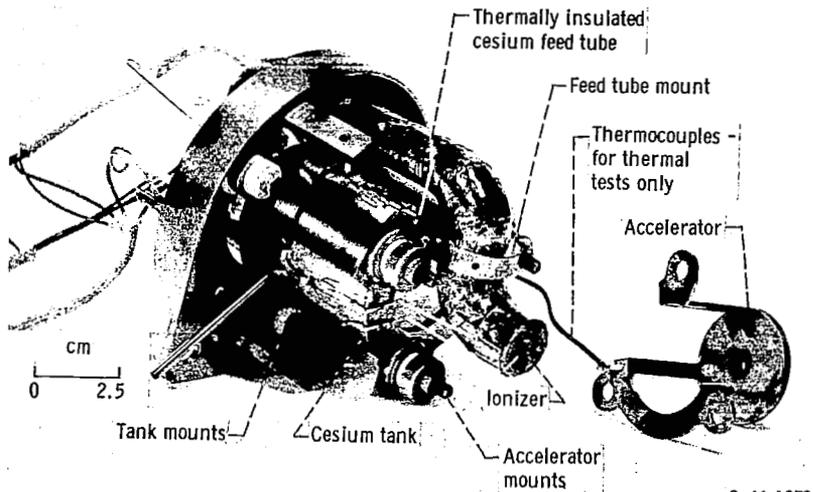


Figure 1. - Microthruster with shield removed.

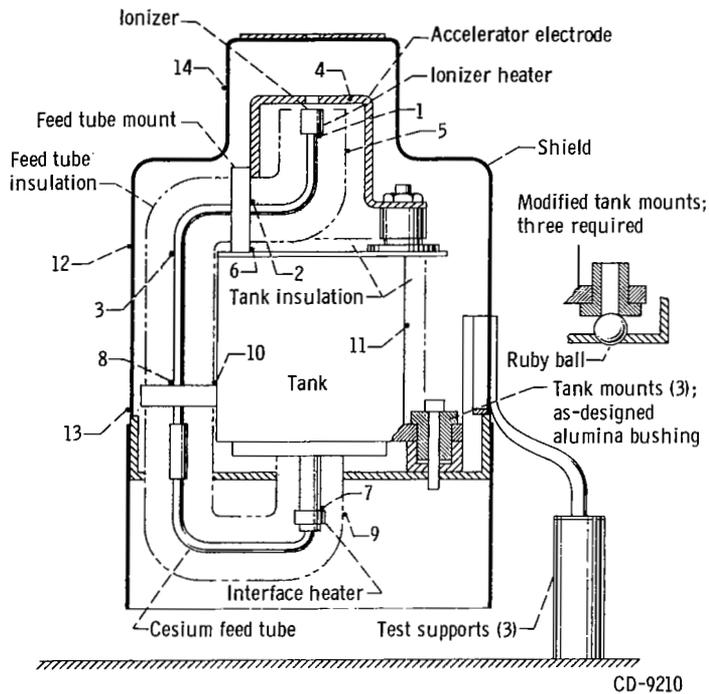


Figure 2. - Microthruster thermal model. Numbers correspond to thermocouple locations.

pressure to ensure the proper cesium flow through the ionizer. The ionizer surface temperature controlled the ionization rate. The positively charged cesium ions were accelerated away from the ionizer by an electrostatic field. The exhaust plume was neutralized by the insertion of electrons. More detailed discussions of contact ionization thrusters are given in references 1 and 2.

The requirement for operation of the microthruster on low power made knowledge of the thermal losses mandatory. Hence, an investigation of the Lewis microthruster

was undertaken to determine the heat losses and to investigate ways of reducing these losses. This report summarizes the results of this investigation.

The thermal efficiency was to be improved by minimizing the power required in the two heaters (see fig. 2). The interface heater was required for the vaporization of the liquid cesium as it is withdrawn from the supply tank. The ionizer heater was to heat the porous tungsten sufficiently to ionize the vaporized cesium. The other power requirements of the microthrustor, that is, losses in the accelerator circuit, the neutralizer power requirements, and power conditioning losses, were believed to be independent of thermal considerations and were neglected. From thrustor tests it was known that the ionizer surface had to be maintained at 1020° C and the liquid-vapor interface at 300° C for proper thrustor operation.

The long exterior cesium feed tube destroyed the symmetry of the system and complicated any analytical investigation by making the problem a three-dimensional study. It was decided to use an electrical analog simulation of the thrustor to perform the thermal analysis. A full-size thermal model test program was run to obtain the equilibrium temperature distributions. Adjusting the analog resistors to give the voltages corresponding to the experimentally obtained temperatures gave accurate values of the "lumped" thermal resistance. Once the thrustor analog network had been established, the effect of various thermal loss reductions on the heater power requirements could be evaluated.

THERMAL INVESTIGATION

Analysis

The concept of treating heat-flow problems in terms of electrical networks has been well developed (ref. 3) and is based on the equivalence of the electrical and thermal conductance equations. In equilibrium the thermal equation reduces to an Ohm's law form similar to the electrical equation:

$$Q = \frac{\Delta T}{R}$$

where Q is the heat flux (W) and is analogous to the electrical current, ΔT is the temperature difference (°C) and is the driving potential analogous to the voltage, and R is the thermal resistance (°C/W) analogous to the electrical resistance.

The thermal resistance is related to the thermal conductivity by

$$R = \frac{l}{kA}$$

where k is the thermal conductivity ($W/({}^{\circ}C)(cm)$), l is the length of the flow path under consideration (cm), and A is the cross-sectional area perpendicular to the heat flow (cm^2). This network analogy can be extended to include radiation by treating radiation heat fluxes in terms of equivalent conduction fluxes (ref. 4).

Electrical Analog

The concept presented in the previous section was utilized to divide the micro-thruster into nodes representing the temperature distribution and to formulate it into the electrical resistance network shown in figure 3. The temperatures T_1 to T_{10}

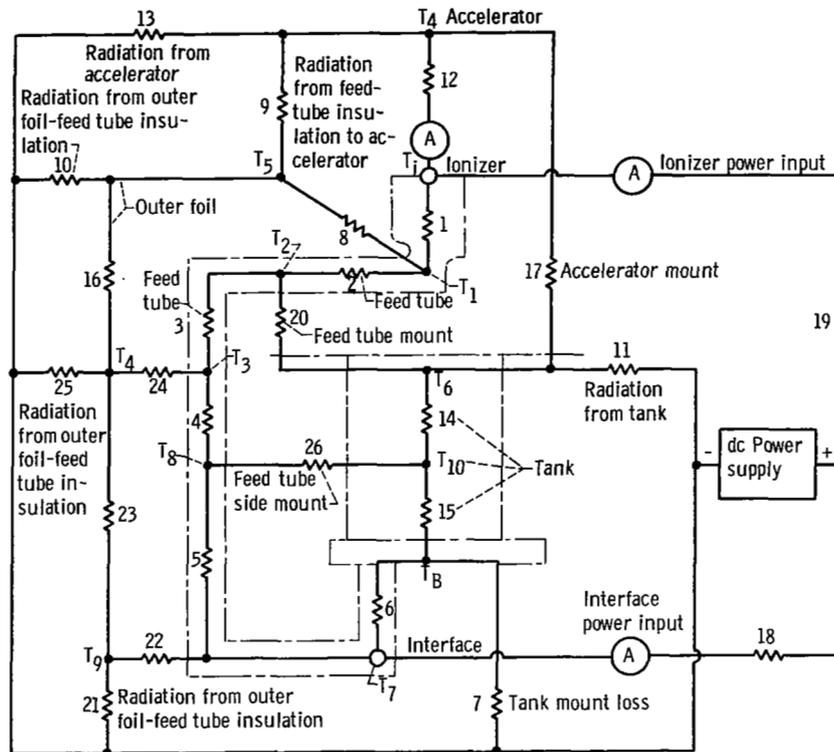


Figure 3. - Schematic diagram for analog board solutions.

were measured in the thermal model tests. The temperature T_i was previously determined to be $54^{\circ}C$ greater than T_1 in the temperature range of interest. The temperatures T_A and T_B were extrapolated from the surrounding temperature data. The thruster shield has been omitted from this network since it represents only an interface between the thruster and the ground. Hence, the temperatures T_{12} , T_{13} , and T_{14} do not appear in the network.

The radiation losses from the ionizer end of the feed tube were approximated as a superposition of two heat fluxes: the loss from the ionizer through the accelerator hole to space and the radiation interchange between the ionizer-insulation disk and the

accelerator. The direct radiation loss was assumed to be constant at 1 watt. For convenience, this direct radiation loss was left out of the network and the power to the network reduced by the equivalent of 1 watt. The radiation interchange between the ionizer and the accelerator was calculated for each case, and this heat flux was maintained in the network by varying resistor 12. Details of these calculations are shown in the appendix.

In this network approximation, only the following losses are considered:

Resistor 13 - radiation to ground from the accelerator electrode

Resistors 10, 25, and 21 - radiation to ground from cesium feed tube outer foil

Resistor 11 - radiation to ground from the tank

Resistor 7 - generalized loss consisting primarily of conduction losses through the tank mounts and radiation from the bottom areas of the tank

The resistance network was set up with 10-turn precision potentiometers: resistors 1 to 19 were 1 kilohm maximum, and resistors 20 to 26 were 10 kilohms maximum. The network was powered by a regulated direct-current power supply of 7.0 volts and 2 amperes maximum output. All voltages were read on a digital voltmeter and all currents read with milliammeters.

Thermal Model

As previously stated, it was decided to obtain the temperature distribution experimentally from a test on a full-size thermal model rather than to attempt to calculate values for all the various resistances. Four cases were studied with this thermal model, and these data were used to balance the resistance network. The procedure used in balancing the network was to estimate the values of conduction resistors and then to try to obtain the voltages corresponding to the experimentally determined temperatures by adjusting the loss resistors. If a balance could not be obtained, the conduction resistors were systematically varied until a balance was obtained. Once the network was balanced for the experimental data, heater power predictions could be made simply by reducing a given loss while maintaining T_1 at 1020°C and T_7 at 300°C , the temperatures required for proper thruster operation.

The thermal model used in this phase of the investigation is shown in figure 4. It was an early prototype system that had been used for thruster operation tests. This thruster was cleaned, and the feed tube was reinsulated with a low-conductivity blanket insulation, which was covered with a 2-mil (5×10^{-5} m) tantalum foil. Fourteen thermocouples, 6 chromel-alumel and 8 iron-constantan, were installed on the thruster as shown in figure 2. For these thermal model tests, cesium was not used. It was felt that the investigation of the heat losses could be conducted without the complications of cesium flow. The only expected contribution of the cesium was an increase in the interface

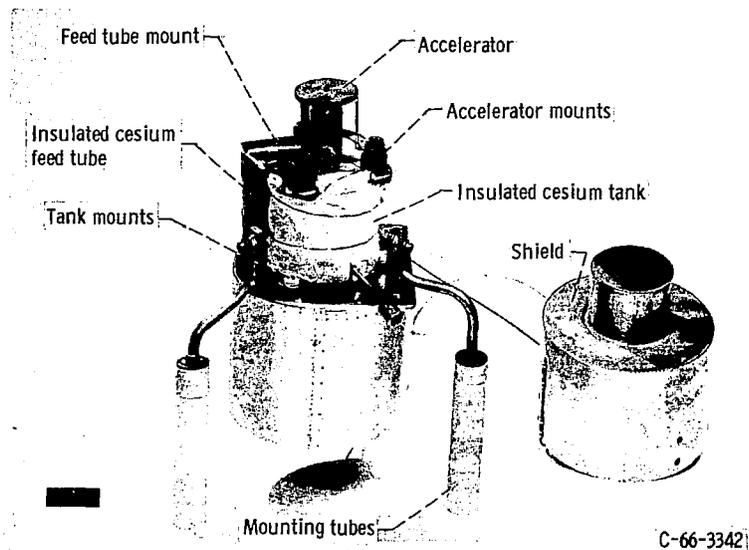


Figure 4. - Thermal model.

heater power, and this was checked in a later phase of the investigation.

The microthruster was mounted on three low-conductivity tubes, as shown in figure 4, to reduce conduction losses to the vacuum system. All tests were run in a large bell jar facility capable of maintaining pressures of less than 10^{-6} torr (1×10^{-4} N/m²) to ensure that heat rejection was primarily by radiation. The heaters were powered by two regulated direct-current power supplies rated at 40 volts and 5 amperes maximum. The thermocouple readings were made with a digital voltmeter capable of reading to 0.01 millivolt. An ice bath reference temperature was used.

Experimental Investigation

The four cases studied with the thermal model were

- A - Base
- B - Improved tank mount
- C - Radiation reduction
- D - Enclosed accelerator

The base case (A) was the thruster as designed but with an improved feed-tube mount. This mount was cause for concern since it must connect the hot feed tube with the tank so that the ionizer is properly aligned with the accelerator. The mount in the thermal model was compressed insulation. Case B (the improved tank mount) was similar to the first case except that the tank mounts were replaced by a system designed to reduce the thermal conductance losses. The tank was mounted on three ruby balls and held in place by its own weight (fig. 2). This arrangement was used to test the concept and was never intended to be used in a flight thruster. In case C (radiation reduction), in addition to the improvements made in case B (the improved tank mount), the exterior surfaces of

the accelerator and the interior surfaces of the shield were goldplated to reduce radiation losses. For case D (the enclosed accelerator), the thruster used in case C (radiation reduction) was modified by brazing a thin copper shield around the normally open sides of the accelerator. The outside face of this shield was also goldplated. The experimentally obtained heater powers were substantially different for each of these cases. The analog network also showed a change in the loss mechanism corresponding to the change in the thermal model, and therefore it is reasonable to assume that the network predictions were accurate.

The experimental parameters obtained in the thermal model tests are summarized in table I along with the analog network evaluation of the losses. As expected, the change

TABLE I. - THERMAL MODEL TEST DATA AND ANALOG NETWORK PREDICTIONS

Quantity	Thermal model case				Analog network prediction					
	A	B	C	D	1	2	3	4	5	6
Temperature, °C:										
T _i	1021	1021	1016	1016	1016	1016	1016	1016	1016	1016
T ₁	967	968	962	962	962	962	962	962	962	962
T ₂	723	720	719	725	731	723	709	723	730	724
T ₃	482	477	482	485	497	487	470	489	498	489
T ₄	262	260	273	318	298	292	184	294	284	303
T ₅	410	388	438	450	544	444	420	444	531	490
T ₆	206	216	249	265	267	273	185	274	279	270
T ₇	298	296	300	300	300	300	300	300	300	300
T ₈	410	370	410	----	422	415	394	419	425	415
T ₉	159	182	193	193	198	193	193	193	198	195
T ₁₀	184	211	240	247	255	257	195	274	279	256
T _A	----	----	----	----	325	304	292	306	327	312
T _B	----	----	----	----	252	254	196	276	279	250
Heater power, W:										
Ionizer	12.6	12.1	11.2	11.3	10.7	11.1	7.7	11.1	8.0	11.3
Interface	3.2	2.5	2.2	1.6	1.9	1.8	3.4	1.2	1.0	1.8
Total	15.8	14.6	13.4	12.9	12.6	12.9	11.1	12.3	9.0	13.1
Radiation to accelerator, W	6.5	5.8	6.0	----	5.8	5.8	2.1	5.8	3.0	6.3
Thermal losses (from analog network), W:										
Direct to space	1.0	1.0	1.0	----	1.0	1.0	1.0	1.0	1.0	1.0
From accelerator (resistor 13)	1.5	2.2	4.1	----	4.5	4.3	2.7	4.4	4.3	4.5
From tank (resistor 11)	3.7	4.1	2.0	----	2.3	1.1	1.5	2.3	.8	2.2
From outer foil feed-tube insulation:										
Ionizer end (resistor 10)	2.6	2.8	1.8	----	0	1.8	1.7	1.8	0	.6
Middle (resistor 25)	.4	.6	1.0	----	1.1	1.0	1.0	1.0	.9	1.0
Interface end (resistor 21)	.9	.6	.9	----	1.0	.9	.9	.9	1.0	1.0
Through tank mounts (resistor 7)	5.6	3.5	2.8	----	2.8	3.0	2.3	.9	.9	2.9
Total	15.7	14.8	13.6	----	12.7	13.1	11.1	12.3	8.9	13.2

in the tank mounts (case B) produced a decrease in the loss through the tank mounts (resistor 7). This reduction produced changes in all the losses corresponding to the shifting temperature distribution. The gold plating of the various surfaces (case C), for example, the accelerator and the inside of the shield, resulted in a further reduction of the total heater power. The radiation from the accelerator increased, corresponding to an increase in the accelerator temperature. However, the radiation from the tank was reduced and the tank-mount loss was further reduced even though the change in the interface power was slight. The enclosing of the accelerator (case D) reduced the heater power requirements by reducing the heat loss from the ionizer end of the feed tube. The reasons for not analyzing this case on the analog network are discussed in the next section.

Analog Network Predictions

With the analog network balanced for the equivalent of case C, a series of prediction runs was made to determine the temperatures and the power requirements for various loss reductions. After each prediction the network was rebalanced to the case C thermal model data. Predictions were made for the following arbitrary reductions in the losses:

- 1 - No radiation loss from the hot area of the feed-tube insulation (corresponding to a totally enclosed accelerator)
- 2 - Radiation loss from tank reduced to about 1 watt
- 3 - Radiation from ionizer to accelerator reduced to about 2 watts
- 4 - Tank mount losses reduced to about 1 watt
- 5 - Changes 1 to 4 made simultaneously
- 6 - Radiation loss from ionizer reduced by partly enclosing accelerator

The only thermal losses that were not varied were the relatively small radiation losses from the lower part of the feed tube insulation (resistors 21 and 25). The results for these arbitrary reductions of thermal losses are summarized in table I. As can be seen from the predicted power requirements, only in case 5 was there a substantial power reduction. The analog network results show that the heat-flow pattern in the thruster is complex: heat from the ionizer is radiated to the accelerator and conducted into the tank thus reducing the interface power. However, in case 3, the network showed that the heat flow in the tank was negative and required the interface heater power to be increased to heat the tank.

The analog prediction run (case 6) was made as a final check on the validity of the network. With the network set up for the equivalent of case C, the effect of partly enclosing the accelerator was investigated. In this case it was assumed that the thermal resistance to ground (resistor 10) was about $5\frac{1}{2}$ times the resistance to the accelerator

(resistor 9). This division is approximately the reverse of that used in case C. The results of the case 6 run were then compared with the data of case D. As the results listed in table I show, the agreement is excellent. The total power input is within 0.2 watt and all temperatures are within 9 percent. This temperature difference between prediction and experiment could be reduced by changing the heat flux that was trapped by the accelerator (resistor 9). In view of the excellent agreement, it was concluded that the network did actually represent the microthruster and could be used to predict behavior.

The predictions do show the trend towards the obvious: the minimum power is obtained with no thermal losses. Unfortunately, the network does not tell one how to reduce the losses, it can only predict what will happen if the losses are reduced.

APPLICATION TO MICROTHRUSTORS

Since the thermal analysis was based on an experimental study using a thermal model and not the final flight unit, a check of the conclusions was made by experimentally obtaining the temperatures on an actual thruster. This flight unit had superinsulation (alternate layers of metal foil and quartz paper) on the cesium feed tube and the nickel-matrix, zero-gravity feed system. This is the unit shown in figure 1.

This thruster was instrumented with thermocouples and tested first in the as-received condition to determine the base power requirements and then modified in accordance with the results of the thermal study. These modifications consisted of changing the tank mounts to improve the thermal isolation and of insulating the tank. No cesium was used in either test. The results verified those obtained in the thermal model study. As received, the heater powers were 12.1 watts in the ionizer and about 3 watts in the interface heater to maintain the desired temperatures. With the modified thruster, the power requirements decreased by 1.6 watts in the ionizer heater and by about 0.3 watt in the interface heater. This approximately 13 percent decrease in the total power required agreed well with the results of the thermal model tests (case A compared with case B).

It could be argued that the lack of cesium in all these tests would cause a drastic underestimation of the interface heater power requirement since the highly conductive liquid cesium would act as another parallel thermal path from the interface to the tank. This argument, however, would not invalidate the results of the thermal study. The power requirements of the thermal model need not be the same as the actual thruster. But, the reduction of power based on the thermal model and analog network should be the same in the actual thruster.

To investigate this point, a thruster that incorporated the design changes was instrumented and tested both with and without cesium. In the test with cesium, the high voltage was applied to the accelerator and the thruster was run under the normal

operating conditions. A comparison of the temperature distributions did show a shift in temperatures in the interface area. The power requirements were as follows:

Without cesium:

Ionizer - 14.8 watts for an ionizer surface temperature of 993° C

Interface - 2.0 watts for a temperature of 328° C

With cesium:

Ionizer - 13.7 watts for an ionizer surface temperature of 1008° C

Interface - 3.0 watts for a temperature of 294° C

Based on this test, there is effectively no change in the total heater power when cesium was used. However, the division between interface and ionizer heaters did change. The reduction of the ionizer power with cesium probably was due to the added power received from leakage in the high voltage accelerator circuit. The increase in the interface power requirement is due to the reduction in the thermal resistance caused by the cesium. The total power required in these tests is higher than that required in the thermal model tests. Since the earlier flight models agreed with the thermal model results, it can be reasonably assumed that the increase in power levels was caused by flight thruster modifications. However, the changes recommended by this thermal study are still valid.

CONCLUSIONS

This investigation of an ion engine microthruster has shown that it is possible to combine thermal model studies with an electrical analog network to represent accurately a contact-ion microthruster and to recommend changes that would reduce the power requirements of actual thrusters.

The major thermal losses were identified as the conduction through the cesium storage tank mounts, radiation from the tank, and radiation from the accelerator. Based on the results of this investigation, thermal design criteria could be formulated. The following thermal guidelines should be utilized for the minimum heater power input:

- (1) The feed-tube mount should have a minimum effective thermal conductivity.
- (2) The principal point of thermal isolation should be at the cesium tank mounts.
- (3) The accelerator should act as a radiation shield for the ionizer and, in turn, should have minimal radiation to the microthruster shield.
- (4) The feed-tube insulation should be the best possible thermal insulator.
- (5) Radiation losses from the tank should be minimized.

In a comparison thermal test of the thruster with and without the thermal modifications, the changes produced a 13 percent reduction in the total heater power requirements.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, August 9, 1967,
120-26-08-01-22.

APPENDIX - CALCULATION OF RADIATION HEAT FLUXES

The radiation heat flux from the ionizer end of the feed tube was approximated as the superposition of two heat fluxes: the direct radiation from the ionizer to space through the hole in the accelerator and the radiation interchange between the accelerator and the disk made up of the ionizer and the outer foil on the insulation (see fig. 5). The method of calculating these quantities is outlined herein.

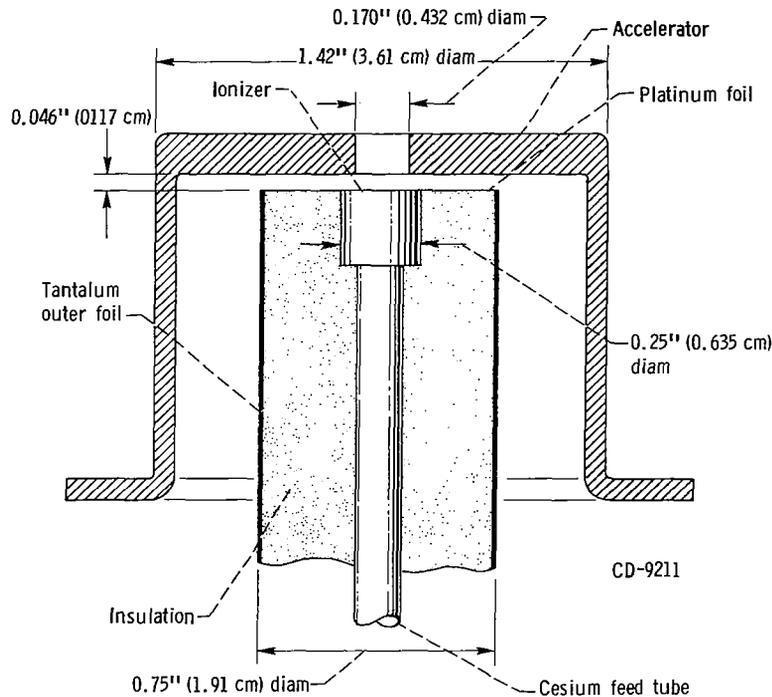


Figure 5. - Details of accelerator-ionizer system.

Direct Radiation to Space

The heat flux radiated from the ionizer through the hole in the accelerator to space was calculated from the relation

$$Q_{\text{rad}} = A\sigma F_{i-o} \epsilon (T_i^4 - T_o^4)$$

where

- A area of ionizer (0.049 in.² or 0.317 cm²)
- σ Stefan-Boltzmann constant (5.67×10^{-12} W/(cm²)(°K⁴))
- F_{i-o} view factor, or configuration factor
- ϵ emittance of porous tungsten ionizer (0.52)

T_i temperature of ionizer (1290° K)
 T_o temperature of space (assumed to be 0° K)

The view factor was calculated from the configuration consisting of parallel, directly opposed, plane circular disks (ref. 5), where one disk is the hole in the accelerator. The direct radiation is then calculated to be 1 watt.

Radiation Interchange with Accelerator

For the calculation of radiation interchange with the accelerator, the system is considered to consist of two parallel disks. One disk consists of the ionizer surface and the platinum foil outer shield of the insulation. The other disk is the accelerator. Because of the relative sizes, the hole in the accelerator was neglected. The radiation heat interchange is calculated from reference 3 as

$$Q_{\text{rad}} = A_1 F_{1-4} \sigma (T_1'^4 - T_4^4)$$

where

A_1 area of ionizer-foil disk (0.44 in.² or 2.85 cm²)

F_{1-4} overall interchange factor

σ Stefan-Boltzmann constant

T_1' average ionizer-foil disk temperature, °K

T_4 accelerator temperature, °K

The temperature T_1' was approximated as an average between the temperature of the ionizer surface T_i and the temperature of the outer foil of the insulation T_5 :

$$T_1' = \frac{T_i + T_5}{2}$$

The overall interchange factor was calculated from the standard relations for this type of configuration. The resulting calculations are tabulated in table I.

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