NASA CONTRACTOR REPORT

NASA CR-2364

NASA CR-2364

SEEDED GAS THRUSTERS AND RELATED SYSTEM COMPONENTS

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • JANUARY 1974

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA CR-2364		
4. Title and Subtitle SEEDED GAS THRUSTERS AND RELATED SYSTEM COMPONENTS		5. Report Date January 1974 6. Performing Organization Code
7. Author(s) John W. Poole and Merle L. Thorpe		8. Performing Organization Report No. None 10. Work Unit No.
9. Performing Organization Name and Address Humphreys Corporation Dow Road Concord, New Hampshire 03301		11. Contract or Grant No. NAS 3-17192 13. Type of Report and Period Covered
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546		Contractor Report 14. Sponsoring Agency Code
15. Supplementary Notes Final Report. Project Manager, Chester D. Lanzo, Power Systems Division, NASA Lewis Research Center, Cleveland, Ohio		

16. Abstract

This report describes a program involved with the construction and test of a number of laser heated thrusters. These thrusters, with a cavity approximately 23 cm long and 3.5 cm in i.d., are to be tested by NASA at a later date with a laser beam focused through the throat to heat hydrogen propellant containing an opacifier. The heated propellant exhausts through a supersonic nozzle with a 0.6 cm throat at 3000° C. Thrust stands and control systems were furnished with the thrusters. The report describes r.f. plasma heated hot and cold flow simulation tests by the contractor.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Lasers; Thruster; Propulsion; Fluid mechanics; Plasma; Heat transfer	Unclassified - unlimited

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified	26	Domestic, \$3.00 Foreign, \$5.50

* For sale by the National Technical Information Service, Springfield, Virginia 22151

TABLE OF CONTENTS

SUMMARY

The apparatus supplied on this contract is designed to provide the necessary hardware and instrumentation to measure the effectiveness of laser heating as the energy source for propulsion devices. Five laser thrusters in three configurations were tested with cold gas flow and powder addition to determine the flow characteristics of each design. Each configuration was also run hot with r.f. power addition to a plasma located on the axis of the device. These experiments were designed to simulate laser heating and to evaluate the three initial configurations, and to indicate areas for possible improvement.

A total of 20 documented runs were made with the thruster designs in the TAFA laboratory. Two of the designs exhibited severe operational limitations as induction plasma heaters. Only the tangentially slotted tube provided the proper gas flow regime to produce a stable r.f. plasma.

Based on these tests, it is anticipated that two of the configurations should perform satisfactorily with laser energy addition. The radially slotted tube exhibited the most favorable cold flow powder trajectory and containment. The wafer configuration exhibited one severe problem but ideas are presented to improve its performance. The tangentially louvered tube may not perform satisfactorily because the vortex flow introduced by the swirling of the propellant tends to throw the seeding powder out of the core of the unit. This would make it difficult to achieve effective laser energy absorption.

INTRODUCTION

The goal of this program is to measure the effect of coupling laser energy into a seeded gas stream within a thruster. This contract was the hardware manufacture and simulated testing phase of the program. The apparatus included five sets of parts for each of three thruster configurations. Two water cooled nozzles were specified, either of which could be used with a given thruster and attached to either of two thrust stands. A control console was provided which included control circuitry, gas metering panel, and differential temperature and thrust measurement instrumentation. Two powder hoppers were supplied to introduce seed into the propellant gas stream for wall protection and laser energy absorption. These various components of the system will be described in the following sections of the report.

The thrusters, the water cooled nozzles and the thrust stands were all manufactured to NASA drawings. The thruster configuration includes a stainless steel base, a center section with an outer quartz tube pressure vessel and an inner distribution tube of quartz. A water cooled nozzle is attached to the outlet flange which in turn supports one end of the tubing and is connected to the base with four reinforced plastic tie bolts. In all, four of the base plates, two of the water cooled nozzle assemblies, and 15 sets of quartz parts were manufactured on the contract.

All of the thruster configurations were operated in the TAFA laboratory in both cold and hot flow experiments. Color movies were taken of all of the experiments and are analyzed carefully in a later section of this report. The hot flow experiments were limited by inner quartz wall heating to tests of approximately 45 second duration. Enough information was gathered during the testing to be able to evaluate the performance potential for each of the configurations. The experiments with r.f. power addition differ from the proposed laser-heated experiments in that the r.f. induced arc tends to expand to a diameter close to the inside wall diameter and produces a high level of both radiant and convective heating. For the laser heated experiment the energy addition will all be along the axis of the thruster so that there will be a much thicker seeded propellant sheath between the heated material and the inner wall to intercept most of the radiation. In addition maximum laser gas temperatures will be several thousand degrees below arc temperatures which will reduce both convective and radiant heating significantly. Thus, it may be concluded that the overheating of the inner wall during r.f. experiments does not mean that the walls will be overheated during the laser experiments, even though they will be carried out at significantly higher power levels.

GENERAL SYSTEM LAYOUT

A. Control Console

The control console for the system is arranged in two separate cabinets which have been fastened together as shown in Figure 1. The upper cabinet includes all flow control functions for gas metering and a pressure gage for the thruster pressure readout. A pressure regulator is mounted on the side of the console to permit variation of gas metering pressure during a run.

The lower section of the console includes all of the electrical circuitry for the various control functions, a thrust readout system, and a two-channel differential temperature system. Two speed regulators are included at the bottom for the powder delivery system to the thruster.

B. Powder Feeders

The powder feed system includes two Model 1000A variable delivery powder feeders which are connected in series with the core and wall gas flows from the gas metering console. Powder flow rate is controlled by the rheostat dials at the bottom left and right of the control panel. These units are energized when the powder start button is pushed. Power is available only when the gas metering system is in the helium operation or hydrogen operation position. Switch positions and functions are described in detail in the instruction book furnished with this equipment. The range of powder delivery rate may be extended by using a second set of drive gears shipped with the units.

C. Instrumentation

<u>Thrust Measurement System</u>.- Each of the two thrust stands is equipped with a ten pound load cell which is plugged into the remote instrumentation connection box. This system is set up

for indicating only with the readout on the meter in the control console directly in pounds thrust from 0 to 10 pounds. The hook and pulley arrangement on the back end of the test stand is used to calibrate the system with a known weight.

Differential Temperature System. - A two-channel differential temperature system is included in the right-hand center section of the control panel. This is a battery powered unit with two thermistor bridges operating from a common battery. The meter provided can be used to monitor either system during set up and checkout. The fourth stop of the operating switch is the run position. In this position the meter is not connected in the circuit and the output from both ΔT circuits are available as galvanometer outputs.

D. System Safety Features

The safety features built into this system are primarily designed to make the apparatus safe against possible hydrogen leaks. The isolation of the gas metering in a separate section of the control console without electrical switching is an important feature. The gas metering area of the console is continually vented with a fan mounted at the top. An additional feature includes the automatic purging of the gas lines for 15 seconds every time the unit is switched to hydrogen. A third feature purges the pressure hose from the thruster whenever the bypass valves are opened. However, even with all of these features it is important to check all gas line connection points frequently for leaks by pressurizing the hoses with helium and checking with a good bubble leak detector. This should be done whenever the system is activated after having been unused for a period of time, and regularly during periods of continuous operation.

E. Laser Thrusters and Thrust Stands

The three laser thruster configurations supplied on this contract were manufactured to drawings supplied by NASA. The only significant deviations from the drawings are features that have been added to the thruster bases.

1. Because of the radiant heat loading anticipated on the center powder feed disc (Dwg. CF 353996, Item 1) during laser experiments, the disc material was changed from stainless steel Rigimesh filter media to pressed and sintered tungsten.

2. Water cooling was added to the thruster base.

3. A removable insert was added at the rear of the base to allow cleanout of any powder that accumulated behind the feed disc. These changes are all shown in Figure 2, which shows the center section of the thruster base.

All of these changes represent improvements in the original design and were made with the concurrence of the Technical Monitor on the contract (Mr. C. Lanzo). These changes were made at no additional cost to the Government in the interest of improved thruster performance.

The two thrust stands were manufactured to NASA Dwg. CF 353991 and have not been modified in any way. The units were shipped with solid dowels in place of the free flex pivots that are used to support the thruster support cylinder. This is being done as a safety precaution because of the delicate nature of the pivots.

TESTING PROCEDURE

The experimental setup for both the cold flow and hot flow tests is shown in Figure 3. The thruster and thrust stand are mounted on a shelf that is attached to the side of the 189 kW r.f. oscillator. Additional gas meters are shown attached to the r.f. oscillator. In the right background are the water flowmeters and temperature gages used for heat balances. A precision strain gage load cell was used to measure the thrust produced. The thrust during each run was recorded on a Sargent Model SRG millivolt recorder not shown in the photograph.

A special thruster base was designed and fabricated at TAFA to provide the special gas flow control required for the proper stabilization of an r.f. plasma. This base had exactly the same provision for the introduction of the outer gas flow in the thruster as is provided in the standard thruster base. The significant difference was that in place of the front plug in the standard base a Model 56 torch gas injector was installed. This allowed the injection of gas down the core of the thruster with a controllable axial and tangential component. In order to provide the proper introduction of powder along the axis of the thruster a series of special inserts were designed for insertion into the 0.625 cm hole on the center of the gas injector. Several replaceable plugs were made to provide different injection patterns. Some produced parallel flow along the axis and one produced a helical flow pattern. This special base was used for almost all of the experimental runs listed in Table I. The powder was eventually fed through the center of an extended graphite rod on the centerline of the thruster.

In order to accomplish the desired heat balances, the water cooling to the system was set up on three different flow circuits. One circuit cooled the plate of the oscillator tube and measured the plate dissipation during the operation of the oscillator. The second circuit cooled the load coil and the thruster base. The third circuit was for the water cooled nozzle assembly. Careful tare measurements were made to calibrate the system before each heat addition run.

For the hot flow tests it was found necessary to introduce a conductor along the axis of the thruster. A 1.6 mm diameter tungsten rod, approximately 40 cm long, was used for this purpose. Figure 4 shows the result of a starting effort without this rod. A stable arc was established between the inside and outside walls of the thruster. This produced rapid heating of the inside wall and this operating mode could only be avoided by using a starting rod. For the hot flow tests, it was also found desirable to include a 6 cm long, 0.625 cm diameter graphite rod protruding from the laser base to aid starting. The powder flow passage was a 0.15 cm hole on the axis of that rod. This feature aided materially in the powder flow visualization, and may have been a factor in the smooth injection of powder in the hot flow test. If the graphite injector used in these experiments and shown in the figures as part of the arc starting apparatus provides a desirable injection scheme, it could be fitted to the standard laser thrusters that have been supplied on the contract. By removing the clean out plug in the back of the thruster base, a graphite insert could be fitted to provide exactly the same injection that was used for these tests.

TESTING PROGRAM

The goals in operating the thruster configuration at TAFA were threefold:

1. To observe the powder and gas flow patterns during cold and hot flow operation.

2. To measure the change in thrust as powder was introduced.

3. To obtain comparative evaluations of the thrusters for use in the laser heated experiments.

The experimental program was limited by several factors which were not related in any way to TAFA's ability to carry out the testing program. Since these factors have an important affect on the overall program they will be explained carefully in the following paragraphs.

All three thruster configurations were operated with cold flow and powder addition, and in the hot flow mode with r.f. power addition. Sixteen millimeter colored movies were made of the cold flow and hot flow experiments with each of the configurations. These movies and the inferences that can be made from them are probably the most important experimental result of the program. The conclusions that can be drawn concerning the gas flow patterns inside the thrusters lead to an estimation of the performance characteristics of the units for laser heating experiments as reported in the results and conclusions section.

As mentioned earlier, there were several factors that limited the operating power level and the run length for experiments with r.f. power addition. Primary among these factors was the heating of the inner wall of the thruster assembly. This, in turn, was influenced by the gas flow pattern which affects convection to the wall, the types of gas used, the r.f. power level and frequency and the operating pressure level which influences the radiation from the arc. Experience during the initial experiments indicated that an operating power level above 15 kW could not be sustained without melting the inner tube in a few seconds. With the load coil used for these tests and the significant gap between the load coil and the plasma inside the inner wall (resulting in a poor load to coil ratio), the operating point was normally at 6 kV and 2.5 amps.

During all successful runs the thruster was operated on argon through the Number 2 and Number 3 gas injection ports (radial and swirl flow). The outer wall gas flow was normally helium, although some tests were made with nitrogen. Performance data is included in Table I.

No cooling water heat balances were made during runs on the equipment since the runs were too short to permit the system to stabilize. From previous calibration runs, however, the power supply loss of 40 percent and coil loss of 10 percent was used. Thus, approximately 50 percent of the d.c. power or 7.5 kW was used for propellant heating. The fact that the quartz inner wall was glowing red at the end of each long hot flow run provided the necessary data to calculate that 2 kW of the energy was imparted to the wall via convective and radiative heating. Efforts to bring up the outer gas flow to constrict the arc and reduce the convective heating to the inner wall resulted in arc extinguishment. Thus, the complete experimental program had to be run with an upper limit of 15 kW operation and with runs less than 30 seconds long. At that operating power level the arc was extinguished immediately every time powder was brought into the thruster. Consequently, no thrust change measurements were made.

A. Operation of Standard Thruster Base

An effort was made to generate an r.f. plasma using the NASA designed laser thruster base and the tangentially slotted inner wall, which was the most stable inner wall configuration. A complete 16 mm film was taken of the efforts to start with this configuration (Film #1). During this test argon gas at various flow rates was introduced along the axis of the thruster through the powder feed holes. It was possible to establish a plasma for an instant, but as soon as the helium wall flow was turned on the arc was extinguished. This was caused by the improper gas flow pattern for the induction plasma at this low power level with the injection means that were available. (See Figure 3 of NASA CR-1527 for flow pattern.) For this reason, and since the TAFA thruster base with gas mixer allowed convenient starting and operation of the various thruster designs, all of the experimental runs were made with that modified base. This does not mean that the standard base will not operate with laser heat addition, but only that it is not versatile enough to provide the proper gas flow for r.f. heated experiments.

B. Operation of Radial Slotted Inside Wall Thruster

This wall configuration is shown as Item 3 on NASA Dwg. CF 353997. The inner tube of the thruster has six radial slots 0.75 mm wide running the length of the tube. Sixteen millimeter movie (Film #2) shows this configuration in operation. The configuration proved to be easy to start, but unfortunately, the flow became unstable as soon as the outside propellant flow was turned on. Figure 5 shows this assembly ready for test and Figure 6 shows a back-lighted picture of the configuration after the cold flow powder tests.

The cold flow results may be interpreted as indicating that this configuration is the most promising of the three for laser heater studies. The powder pattern issuing from the injector did spread out somewhat and resulted in a gradual powder deposition on starting at the center of the inner wall. However, none of the powder went through to the outer wall and no recirculating gas patterns were noted. It is entirely possible that by modifying the flow through the powder injection port it would be possible to keep the entire powder flow entrained along the axis of the thruster. Also, it should be noted that a slight tendency for accumulation of powder on the inside of the outer wall may not be a problem for laser heated experiments and may, in fact, be desirable. If this is the case, then this particular configuration is even more attractive.

Thus this design is probably the most promising for laser heating applications.

C. Operation of Tangentially Slotted Inner Wall Configuration

The tangentially slotted inner wall configuration is shown as Item 4 on NASA Dwg. CF 353997. It includes four 0.75 mm wide slots along the length of the inner wall that are tangential to the inside surface of the tube. Wall propellant flow through these slots establishes a strong vortex pattern inside of the thruster. This vortex flow of the gas was beneficial for stable operation during the r.f. heating experiments. However, the centrifugal force exerted by the vortex tends to throw the sub-micron sized tungsten seed to the outside of the vortex. This tendency probably makes this configuration the least attractive of the three for laser heating applications.

During the cold flow powder injection tests with the tangentially slotted configuration, the powder collected on the inside wall immediately downstream of the injector. A powder accumulation also took place on the inside of the outer wall, a fact which requires some explanation. When considering the cross section of the thruster, as shown on NASA Dwg. CF 353995, the outer propellant flow is injected at high velocity along the outside of the inner wall. It is hypothesized that this high velocity flow across the surface tends to establish a low pressure zone at the base end of the wall in comparison to the pressure further down the thruster. The result of this pressure differential is to create a flow pattern within the thruster which tends to make powder recirculate toward the thruster base and then actually flow out through the tangential slots into the annular region between the two walls. Once it is out in this region it is carried along by the outer propellant flow and is deposited on the outside of the inner wall and on the inside of the outer wall. This feature, plus the tendency of the vortex to throw the powder out of the core of the thruster, lead to the third place rating for this configuration.

Movie #3 shows three hot flow runs with the tangentially slotted wall. The furst run was made at the previously established gas flow rates (Table I). After the flow had stabilized the powder carrier gas and then the powder were introduced. The plasma was extinguished a fraction of a second after the powder started through the thruster. On the next run the outer gas flow was doubled in an attempt to improve the plasma stabilization, however, extinguishment occurred in the same manner when powder was introduced. For the third run the powder carrier gas was kept on throughout the run to avoid the possibility of its having an adverse affect on the plasma stability. The result was again the same when the powder was introduced. The most probable explanation for this extinguishment is that operation was close enough to the minimum sustaining power so that the presence of the tungsten powder cooled the plasma enough to extinguish the arc. In theory it should have been possible to increase the operating power level as the powder was introduced to prevent the extinguishment. The practical problems of accomplishing this manually without overheating the wall were demonstrated to be too great however.

An important observation from the movie of these plasma runs was that the tungsten powder seemed to be carried through the thruster without depositing out on the walls. This observation is based on limited experience however. Certainly this would not be the first time that the cold flow and hot flow characteristics of a plasma device have been found to be significantly different. Further testing will be required with laser heat addition to completely evaluate the hot flow characteristics of the powder trajectory.

D. Operation of Stacked Wafer Inner Wall Configuration

This configuration is shown in Figure 7 and represents a stack-up of the quartz rings shown as Item 5 of NASA Dwg. CF 353997. This configuration proved to be a tedious one to handle experimentally. It will probably be desirable to construct a mandrel upon which these rings could be assembled when working with this configuration in the field.

During cold flow operation a strong recirculation pattern was observed, caused by the low pressure zone at the base end of the inner wall. As is shown very clearly in movie #1 of the cold flow portion of the run, the powder flowing from the axial injector was carried back toward the entrance plate by a strong reverse flow of gas. This resulted in powder flowing out between the wafers at the base end of the thruster and very quickly covering the wafers and the inside surface of the outer wall assembly. Figure 8 shows that the entrance end of the outer wall was very heavily coated with powder whereas the center section of the tube opposite the injection point received the lightest coating. Downstream the gas slows down and the ability of the gas to support the particles decreases which resulted in a very heavy deposit of powder.

Three poassible ways to improve the cold flow pattern with the wafered inner wall are as follows.

1. A convergence of the annular gap between the inner and outer wall near the entrance to the thruster would produce a pronounced tendency for gas to flow through the wall in that region. This might be done with a converging shape to the outer wall or with a partial blockage of the gap between the two walls at a point a few centimeters downstream of the entrance.

2. Reducing the gap between the wafer elements of the inner wall to produce a significant pressure drop would overcome the minor pressure differential that exists because of the high velocity at the inlet end. Unfortunately, this solution would require the rework of a set of wafers.

3. A third possibility would be to make an adapter for the downstream end and bring the outer gas flow in at the nozzle end of the thruster. This might have the tendency to produce the same annular powder recirculation observed on the injector end. This would seem to be undesirable, hence items number one or two, or a combination would be preferable.

During the hot flow experiment with the wafer wall configuration, the plasma was established easily and the thruster ran nicely for about 15 seconds (Film #4). At that point the inner wall elements in the coil region overheated and began to sag and collapse into the plasma. Figure 9 shows the wall after this run, and shows the elements that were fused together. This collapse occurred after the wall flow had been turned up to the same flow rate used with the tangentially louvered wall (see Table I). Since the gas flow area available in this wall is some twenty times that of the tangentially slotted wall, there probably was not enough flow through the wall to offset the bouyant force on the plasma caused by its temperature. High flows under such conditions result in plasma extinguishment. As a result the plasma operated against and possibly between the wafers, resulting in rapid melting. If the thruster could be operated exhausting upward (simulating the lack of gravity in the proposed application), reduced wall heating would probably result. This was impossible with the thrust stand as constructed.

RESULTS AND CONCLUSIONS

1. The radially slotted wall showed the most potential for laser thruster applications. The powder stream diverged slowly from the injection point on the axis reaching the wall and producing some deposit at the center of the tube however.

2. With the wafer wall configuration there was a strong reverse flow of gas at the inlet end which carried the powder back toward the base of the thruster. The flow did follow along the centerline for several centimeters after the injection point, however, and may be favorable for laser heating if the flow of powder outside the inner wall could be tolerated or eliminated.

3. Cold flow operation of the tangentially slotted inner wall configuration resulted in powder being thrown to the outside by the strong gas vortex. This may make this design of questionable value for laser heating where it is essential that the powder be available along the thruster axis to intercept the laser beam.

4. It was impossible to establish a stable plasma in a thruster using the standard base. Consequently, all of the experiments were done with the TAFA induction plasma gas injector.

5. Real time movies were taken of all three thruster designs in both cold flow and hot flow operation. For all of the movie sequences the powder injection was through a single hole along the axis of the torch.

6. Based on an analysis of the movies, it may be concluded that the radially slotted inner wall should perform the best under laser heating with the wafer section wall second, and the tangentially slotted wall third.

7. The operational stability of the thruster designs for r.f. power addition was in the opposite order to that indicated above.

8. Due to the problem of excessive heat transfer to the inner wall of the thruster the operating power level had to be restricted to between 15 and 18 kW. Even at this level the inner wall glowed red at the end of all runs. This resulted in a maximum of 7.5 kW coupled into the plasma during hot flow tests.

9. There was an accumulation of vaporized quartz from the wall downstream in the coil region after most hot flow runs.

10. At the allowable operating power levels of 15 to 18 kW the plasma was extinguished every time powder was brought in along the axis of the thruster. As a result, there are no thrust comparisons between operation with and without seeding.

11. The area expansion ratio on the nozzles was poorly matched to the gas flow and power levels which could be run. Consequently, thrust values measured during the hot flow runs were in the range of 30 to 75 grams.

TABLE I

OPERATING RUN DATA SELECTED FROM THRUSTER TEST PROGRAM

Thruster Configuration[a]	Test #4 Model T-1/4P	15 R-3/8	17 W-3/8	10 T-1/8	8 T-1/8	9 T-1/8	11 T-1/8	12 R-3/8	13 R-3/8	16 W-3/8	18 T-3/8	20 T-3/8
Gas Flow Core g/sec	0.28 Ar	0.28 Ar	0.28 Ar	1.38 Ar	0.83 Ar	0.83 Ar	1.1 Ar	1.38 Ar	0.83 Ar	0.83 Ar	1.1 Ar	.97 Ar
Gas Flow Wall g/sec	5.73 N_2	4.58 N_2	4.62 N_2	0.58 N_2	0.58 N_2	1.04 N_2	.17 He	1.0 He	1.40 He	3.18 N_2	.52 He	.87 He
Plate Power Input kW	0	0	0	9.7	12.7	15.0	14.7	15.0	16.0	17.4	15.0	15.0
Heat to Arc kW	0	0	0	4.8	6.4	7.5	7.3	7.5	8.0	8.7	7.5	7.5
Thrust grams	ND	ND	ND	ND	55	60	35	<5	<5	15	40	65
Chamber Pressure Atmospheres	ND	ND	ND	1.5	1.7	1.7	2.26	1.03	1.07	ND	1.03	1.05
Powder Feed Flow g/sec	0.22	1.2	1.2	0	0	0	0			0	0.3	0.3
Reference to report photos & movies furnished contract monitor		Movie #2 85-100' Fig. 6	Movie #4 70-100' Fig. 8					Movie #2 5-30' Fig. 5	Movie #2 30-60'	Movie #4 5-55' Fig. 7, 9	Movie #3 5-40'	Movie #3 70-100'
Special Remarks		Favorable powder trajectory	Showed flow reversal	Minimum sustaining power determination	Extinguished as N_2 increased	Same as Test 8	Wall overheated	Extinguished as He flow increased	Same as #5	Melted inner wall	Powder extinguished arc	Powder extinguished arc

[a]Model letters
T = Tangentially slotted tube
R = Radially slotted tube
W = Wafer configuration

Dimension
1/8 = .318 cm dia. water cooled nozzle
1/4P = 0.64 cm dia. plastic nozzle
3/8 = 0.95 cm dia. water cooled nozzle

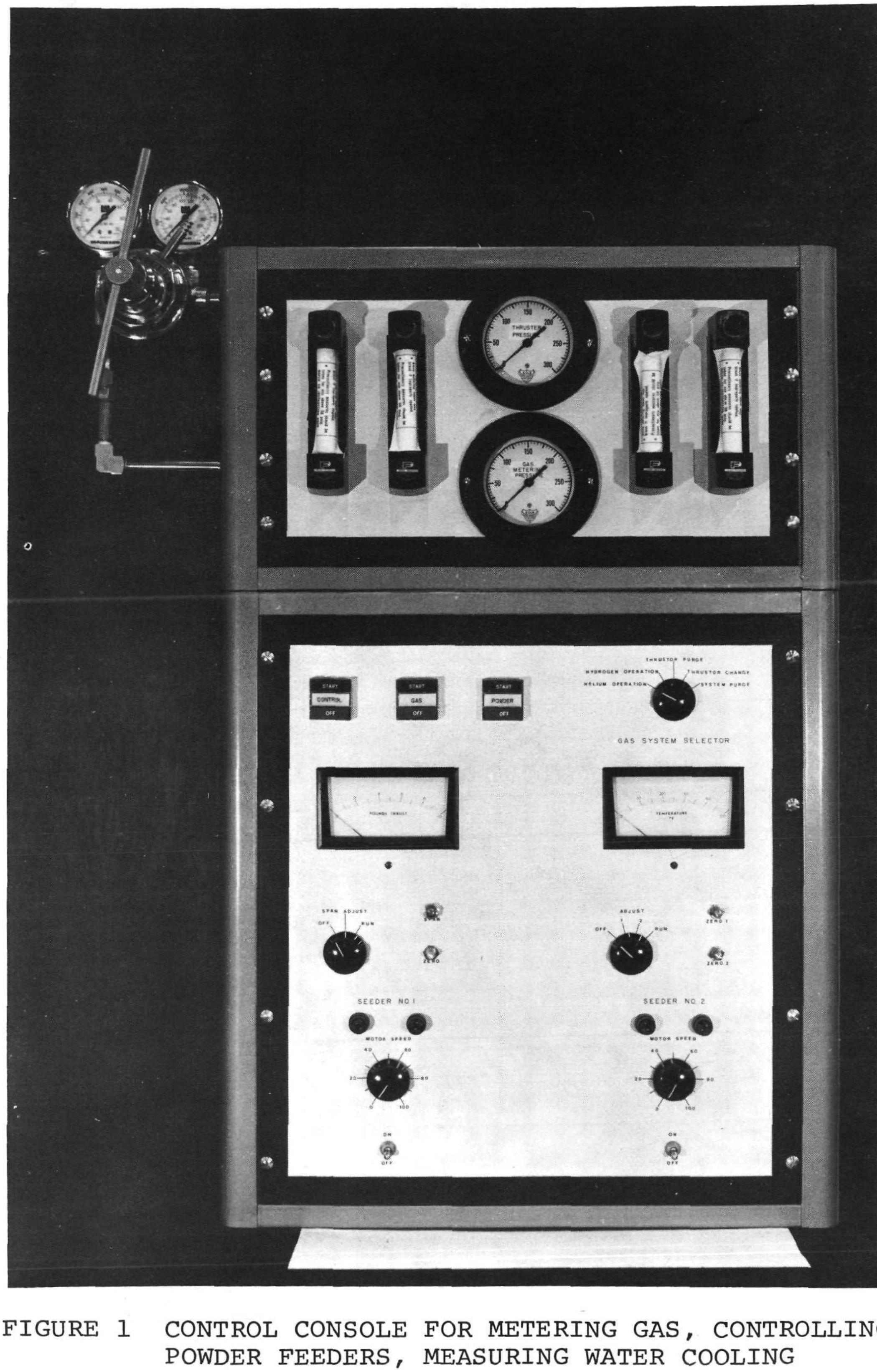

FIGURE 1 CONTROL CONSOLE FOR METERING GAS, CONTROLLING POWDER FEEDERS, MEASURING WATER COOLING TEMPERATURE RISES, AND THRUST

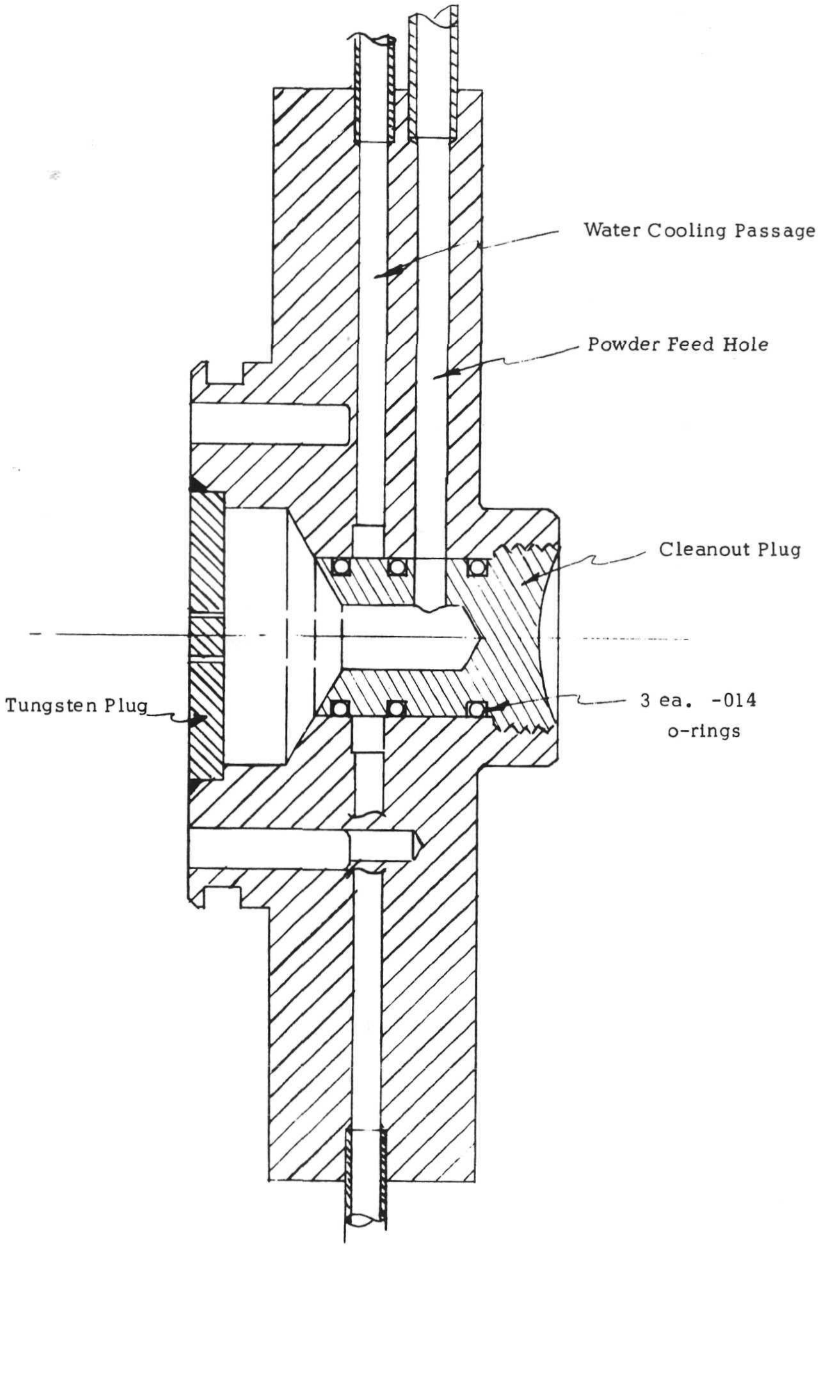

FIGURE 2 THRUSTER BASE DRAWING SHOWING MODIFICATION WHICH INCLUDES WATER COOLING, CLEANOUT PLUG AND SUBSTITUTION OF TUNGSTEN IN THE GAS INJECTOR (NASA DRAWING CF 353996)

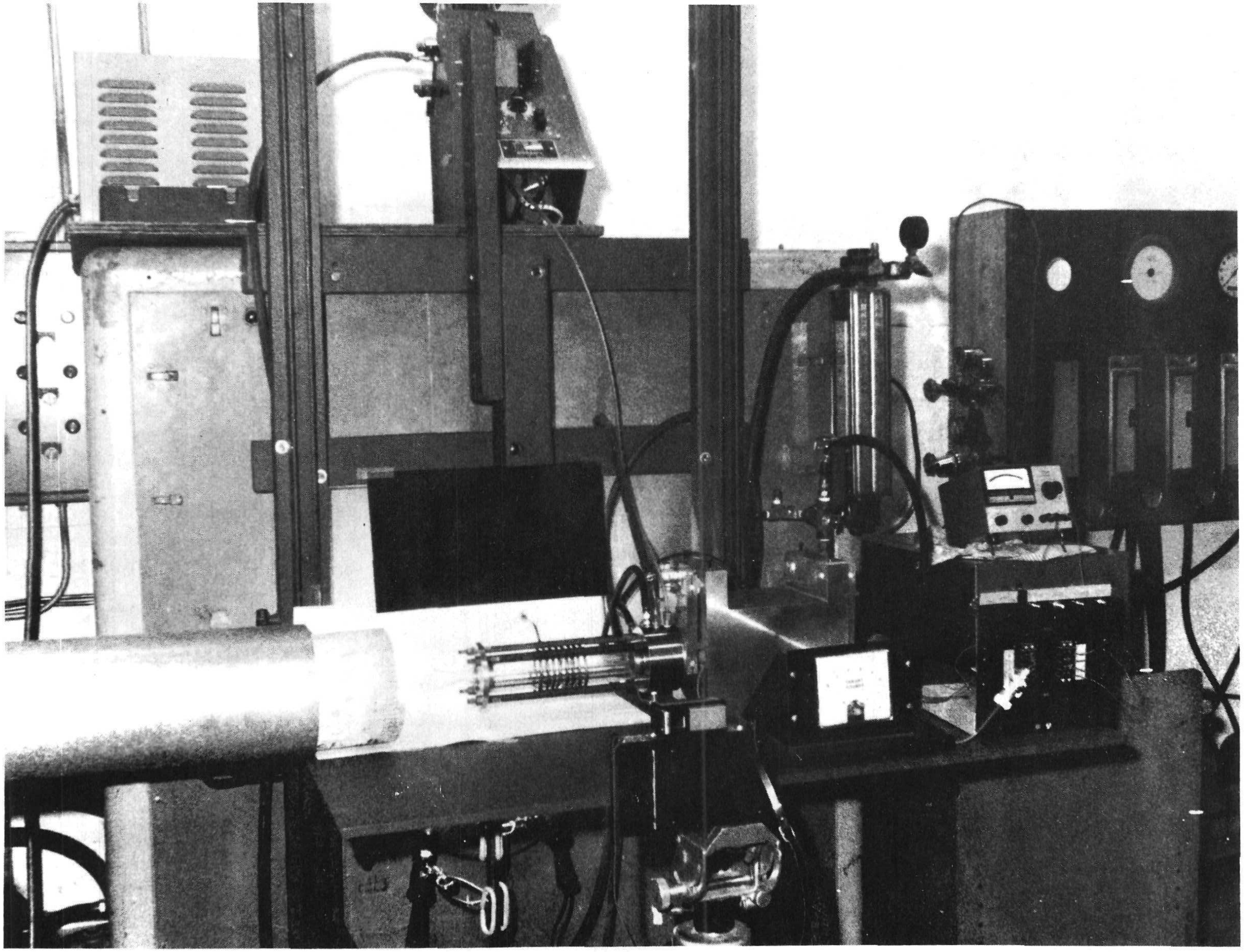

FIGURE 3 EXPERIMENTAL SETUP

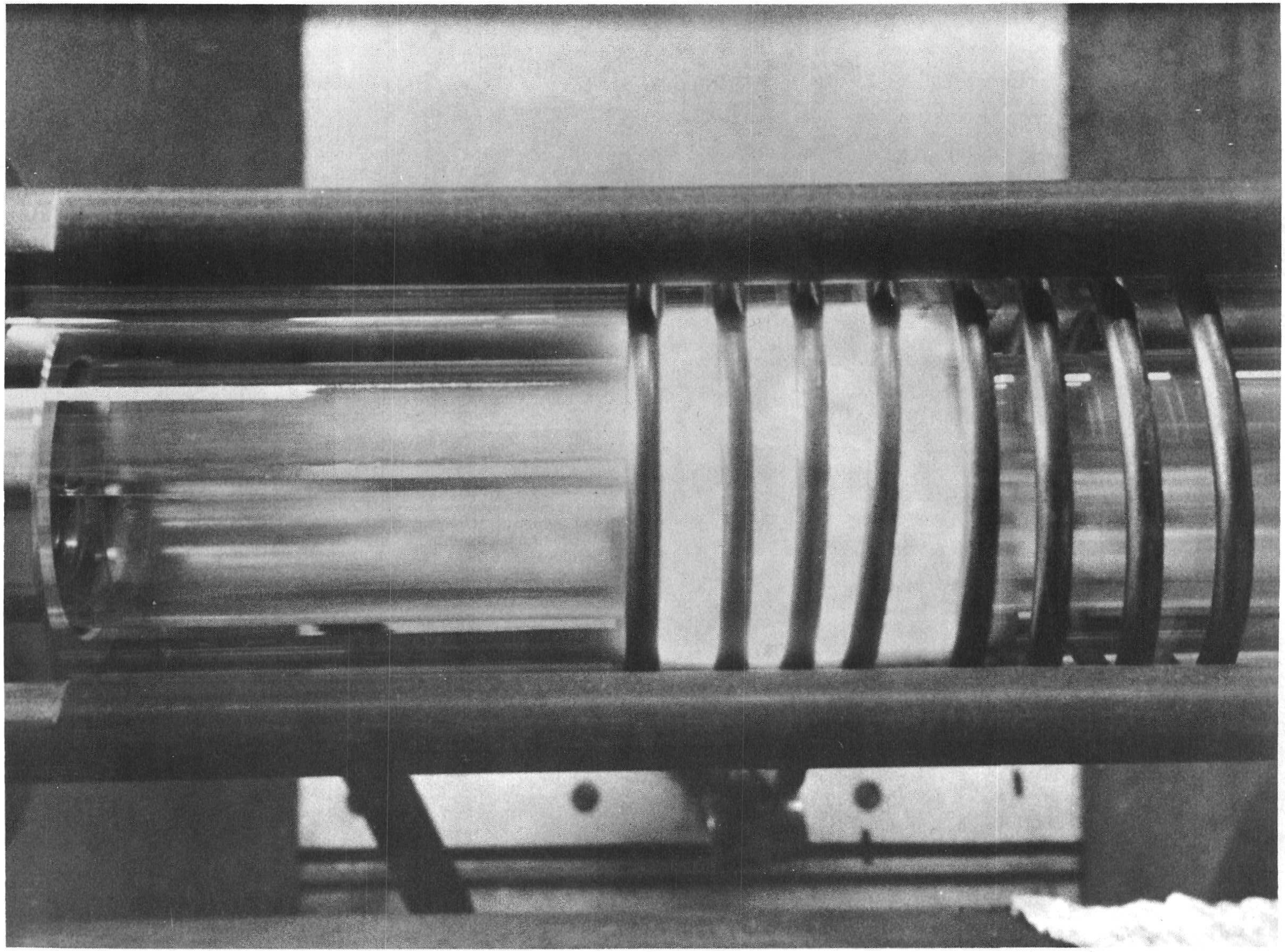

FIGURE 4 INDUCTION ARC SHOWN OPERATING IN ANNUAL SPACE BETWEEN WALLS OF TANGENTIALLY SLOTTED THRUSTER MODEL

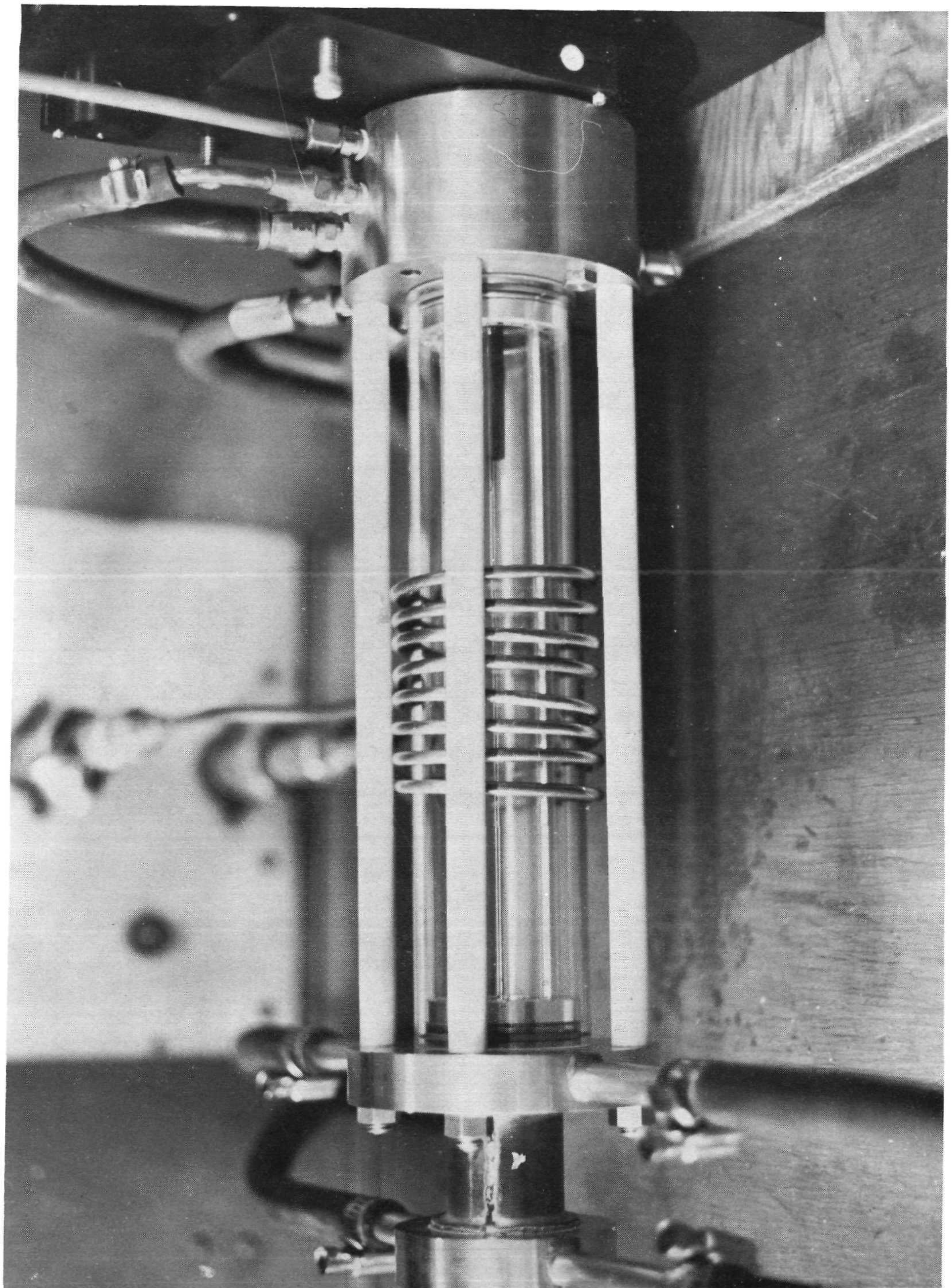

FIGURE 5 RADIALLY SLOTTED INNER WALL INSTALLED IN THRUSTER

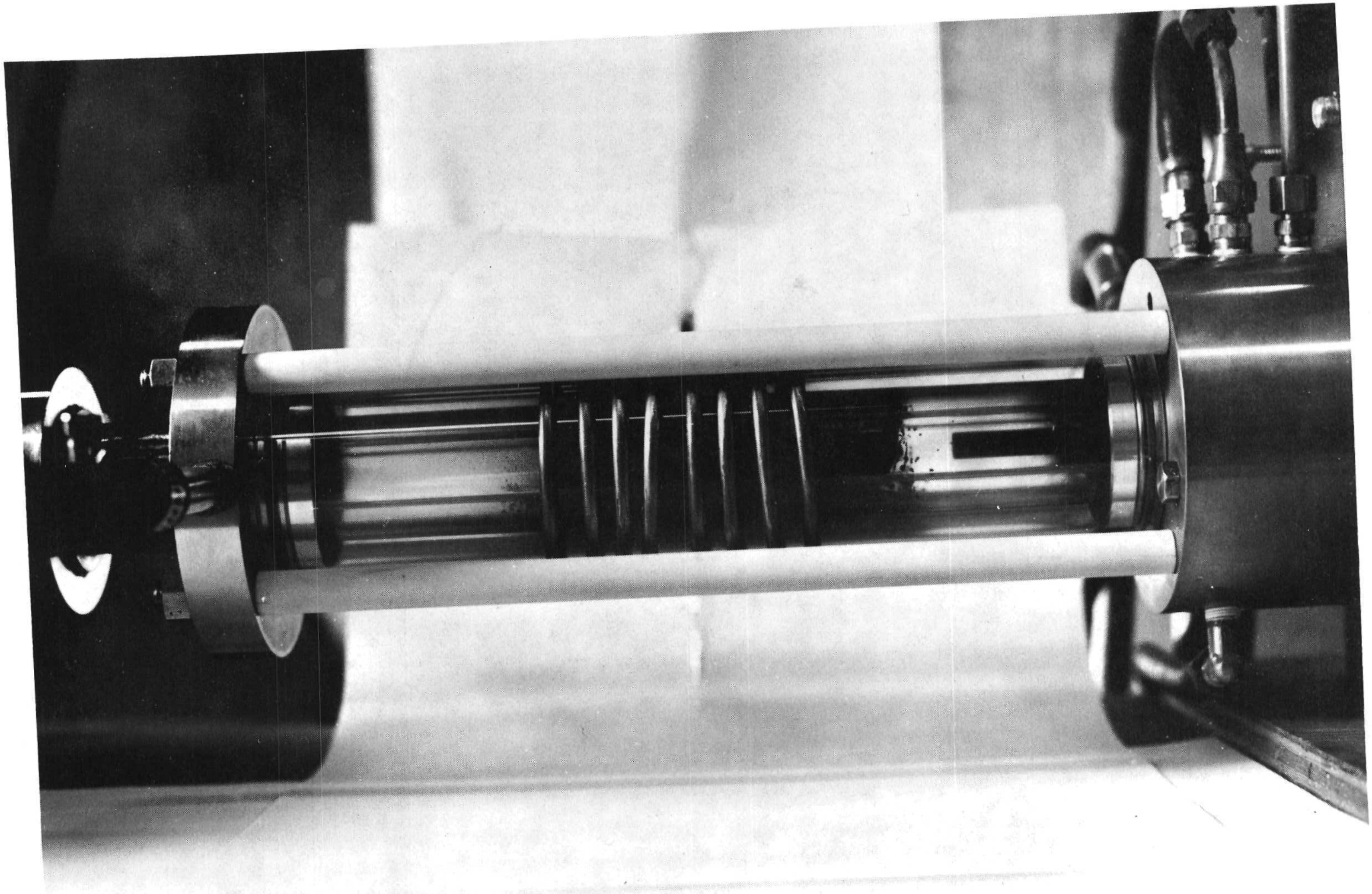

FIGURE 6 PHOTOGRAPH SHOWING POWDER DEPOSITION ON RADIALLY SLOTTED WALL AFTER COLD FLOW OPERATION

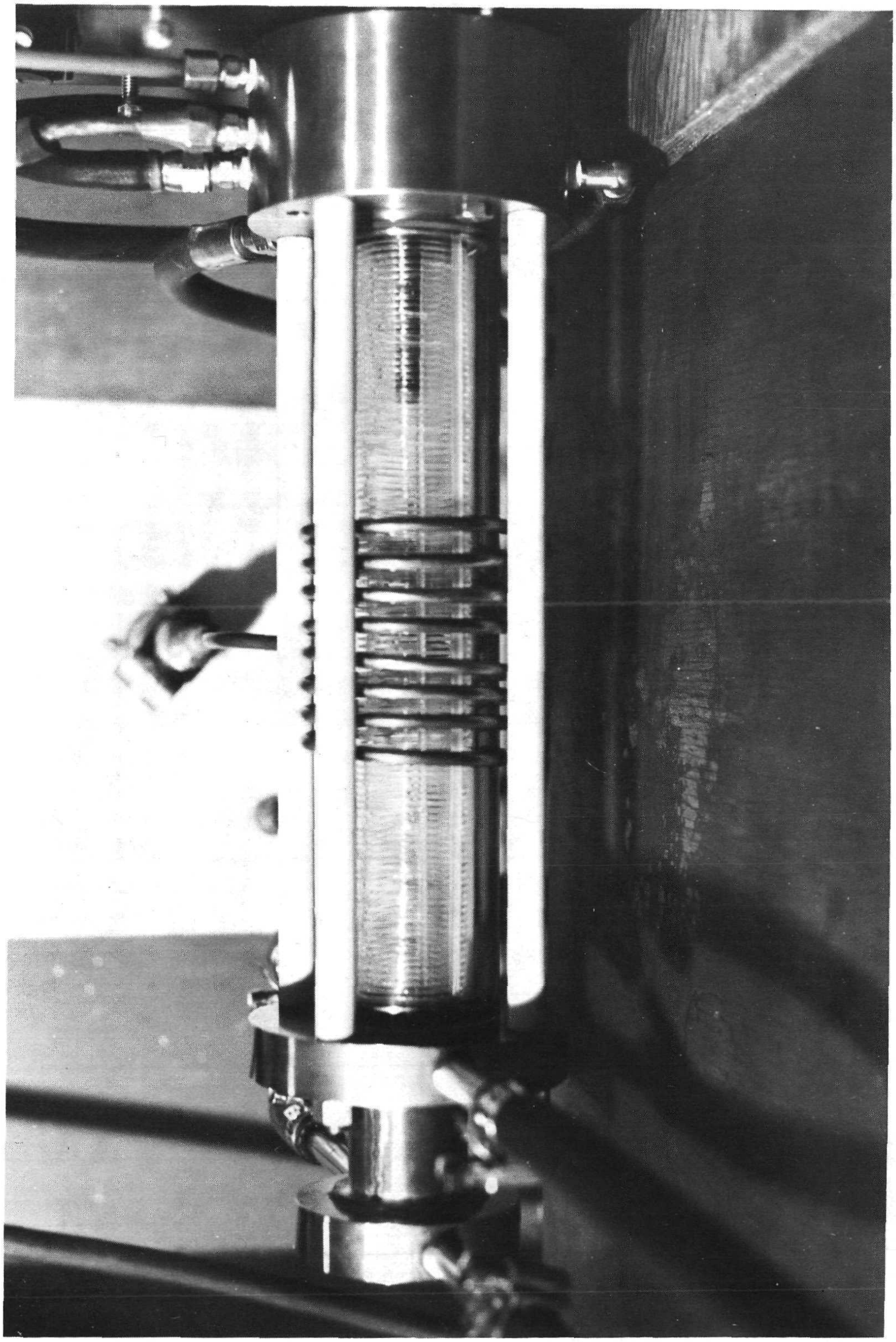

FIGURE 7 STACKED WAFER WALL INSTALLED IN THRUSTER SYSTEM

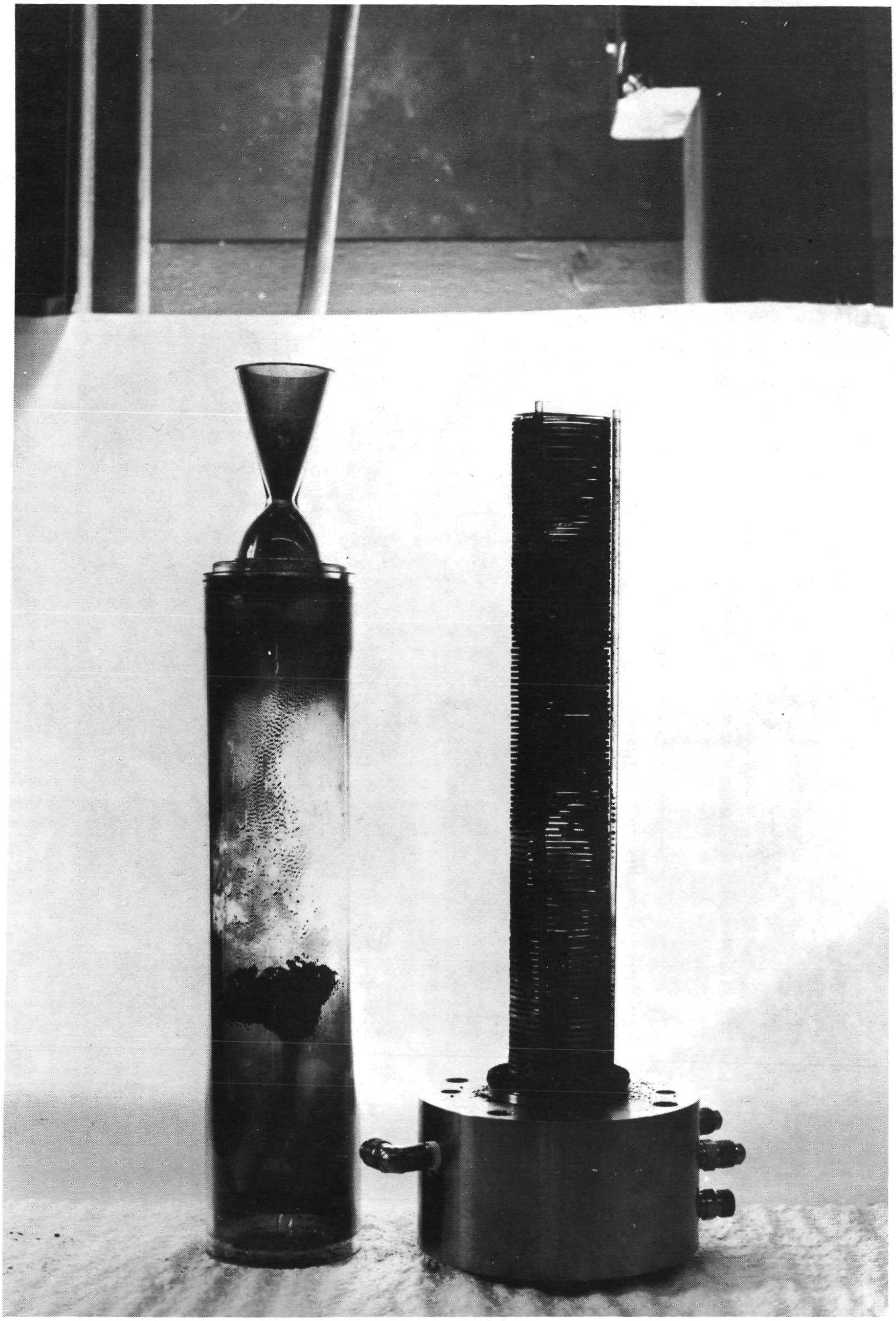

FIGURE 8 PHOTOGRAPH SHOWS POWDER DEPOSITION ON STACKED WAFER WALL AFTER COLD FLOW OPERATION

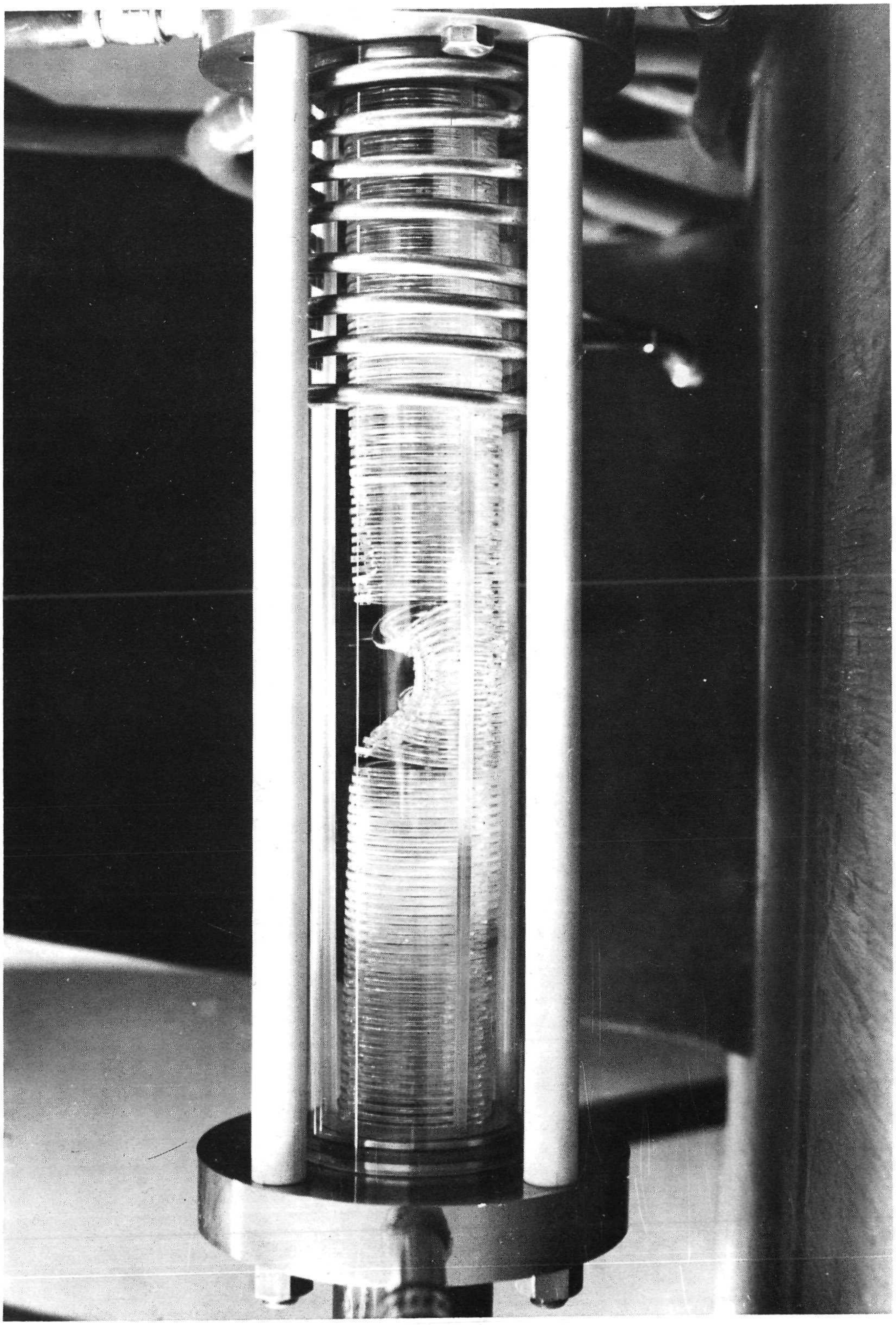

FIGURE 9 CLOSE-UP OF WAFER THRUSTER INNER WALL SHOWING MELTING AFTER HOT FLOW RUN

NASA-Langley, 1974 —— 16 L-7718

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