N73-16691
NASA CR-2155

INDUCTION SIMULATION
OF GAS CORE NUCLEAR ENGINE

by John W. Poole and Charles E. Vogel

Prepared by
HUMPHREYS CORPORATION
Concord, N.H. 03301
for Lewis Research Center

1. Report No. NASA CR-2155	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle INDUCTION SIMULATION OF GAS CORE NUCLEAR ENGINE		5. Report Date February 1973
		6. Performing Organization Code
7. Author(s) John W. Poole and Charles E. Vogel		8. Performing Organization Report No. None
9. Performing Organization Name and Address Humphreys Corporation Concord, New Hampshire 03301		10. Work Unit No.
		11. Contract or Grant No. NAS 3-14416
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546		13. Type of Report and Period Covered Contractor Report
		14. Sponsoring Agency Code

15. Supplementary Notes

Project Manager, Chester D. Lanzo, Nuclear Systems Division, NASA Lewis Research Center, Cleveland, Ohio

16. Abstract

The goal of this investigation was the design, construction, and operation of an induction heated plasma device known as a combined principles simulator. This device incorporates the major design features of the gas core nuclear rocket engine such as solid feed, propellant seeding, propellant injection through the walls, and a transpiration cooled, choked flow nozzle. Both argon and nitrogen were used as propellant simulating material, and sodium was used for fuel simulating material. In addition, a number of experiments were conducted utilizing depleted uranium as the fuel. The test program revealed that satisfactory operation of this device can be accomplished over a range of operating conditions and provided additional data to confirm the validity of the gas core concept.

17. Key Words (Suggested by Author(s)) Induction heated gases Plasmas Radiofrequency heating High-temperature gases Gas core reactors		18. Distribution Statement Unclassified - unlimited	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 43	22. Price* $3.00

TABLE OF CONTENTS

SUMMARY

The goal of the work conducted during this investigation was the design, construction, and operation of an induction heated plasma device known as the Combined Principles Simulator (CPS). This device was designed to be a small scale inductively heated device which simulates as nearly as possible the major design features of the Gas Core Nuclear Rocket (GCNR).[1] This includes solid feed, propellant seeding, propellant injection through the walls, and a transpiration cooled, choked flow nozzle. The CPS consists of a nearly spherical chamber approximately eight inches in diameter constructed from a permeable material through which the propellant is introduced. Positioned at the inlet end are the solid feed and propellant seed devices. The exit end consists of a transpiration cooled, choked flow nozzle. This assembly is placed within a pressure shell. An induction coil surrounds the pressure shell and provides power to sustain a plasma ball in the center of the chamber. As in the GCNR, the hot plasma heats the seeded propellant which is exhausted through the nozzle to provide thrust. In the CPS the solid feed device injects sodium vapor into the plasma region over a range of feed rates. Additionally, a solid wire injector was designed and tested which will replace the sodium feeder in future work. A unique propellant seeding injector was designed which provides for uniform injection of solid particles along the inside of the permeable wall. The permeable wall is semi-spherical in shape and was constructed from AlSiMag 447.[2] This is a cordierite material which has relatively good thermal properties and is permeable at modest pressure differentials. The nozzle was fabricated from permeable graphite and was constructed in such a way that nearly uniform transpiration cooling could be obtained in spite of the severe pressure gradient through the nozzle.

This device was assembled and operated under a variety of operating conditions including pressures from 0.004×10^5 to 4.9×10^5 N/m^2; propellant gas flow from 9.8 to 28.2 g/sec; solid fuel injection rate from 0.0058 to 0.027 g/sec; and propellant to fuel ratios from 445 to 2700. Successful operation was achieved over nearly the entire range of operating conditions tested.

This device was designed and constructed for operation in the future at powers to 15 MW. During this design and construction phase, laboratory testing was conducted to 80 kW for system checkout.

INTRODUCTION

The Gas Core Nuclear Rocket has a number of unique design requirements. In recent years the TAFA Division of Humphreys Corporation has been involved in a number of programs to test and refine some of these features. The purpose of the work reported herein was to incorporate all of the individual items that have been investigated by TAFA into a single unit known as a Combined Principles Simulator (CPS). It was recognized that these various components were not fully developed or optimized but it was believed that by building such a device it would be possible to establish which areas were most critical and the operation of the device would reveal any unforeseen interactions between the components. The device was designed to operate at high powers, however, the work conducted during this study was limited to relatively low power to assess operation of the various components and indicate any required modifications.

A number of supporting experiments were performed to assist or confirm the design principles and materials selection consistent with the overall philosophy of assembling an operable unit with the technology as it was presently known. These experiments were conducted primarily as screening tests to help select materials or obtain more detail design information. Optimization was not attempted nor were exhaustive studies conducted in those areas where anomalies or unexpected results occurred.

It was a basic assumption in this work that future testing at high powers would be conducted on this device. Likewise, it was assumed that further development work would be done in those areas where incomplete information had to be used.

DESIGN OF THE COMBINED PRINCIPLES SIMULATOR

A. Basic Design Criteria

The basic design criteria of the CPS included: a permeable wall, a spherical or nearly spherical chamber, provision for solid feed, provision for propellant seeding, a transpiration cooled, choked flow nozzle, operation at 21.7×10^5 N/m^2, and operation at 15 MW.

Figure 1 is an assembly drawing of the CPS. A permeable wall roughly spherical in shape surrounds the plasma region and is contained within an outer pressure vessel. The fuel inlet-end flange provides for penetration of the solid fuel feed mechanism and injection of the seeding for the propellant gas stream. The nozzle-end flange supports the nozzle and provides for transpiration cooling and seeding flow to the nozzle. Adequate cooling and space for a large coil are provided for high power operation. The design details of these various components are discussed in subsequent paragraphs.

B. Pressure Vessel

In order to meet the design requirement of 21.7×10^5 N/m^2 in the chamber, the outer containment components of the CPS had to be designed to withstand even greater pressure to allow for the pressure drop through the permeable wall. Laboratory work indicated that this pressure drop would be approximately 8.0×10^5 N/m^2 at the anticipated wall gas flow rates. A cylinder of glass cloth laminant reinforced silicone plastic tubing was chosen for the center section of the vessel. This component had to be gas tight and electrically non-conductive. The end flanges were fabricated from 5 cm thick aluminum held against the cylinder by six 3.18 cm diameter G10 fiberglass reinforced epoxy tie bolts. The solid feed and propellant seeding device is positioned in the center of the inlet-end flange and the nozzle assembly is positioned in the center of the exit-end flange. The pressure within the vessel is controlled by the rate of introduction of propellant wall flow and the sizing of the exhaust nozzle throat.

This design provides for convenient assembly since the components can be added piece by piece to the exit-end flange. Since the fuel injection assembly can be easily removed from the top of the CPS, convenient inspection of the inside of the permeable wall between runs is possible. Figures 2, 3, and 4 show the Combined Principles Simulator in consecutive steps of assembly. Figure 2 shows the exit-end flange with the nozzle, tie bolts, and load coil for r.f. testing installed. Figure 3 shows the assembly after the permeable wall has been added. Note the wall heat sensor that is installed through the lower section. The completed assembly with the outer sleeve and inlet-end flange in place is shown in Figure 4. The coupling pieces for the solid-feed are conveniently added to the inlet-end flange.

All components of the pressure vessel were selected to provide a factor of safety of at least five at design pressures and temperatures. The only potential problem that can be anticipated is overheating of the outer wall because of insufficient gas flow through the permeable wall. Since the strength of the outer wall drops rather rapidly at elevated temperature, it is proposed that a temperature sensor be installed to monitor the outside temperature of the permeable wall prior to operation at high powers.

C.   Permeable Inner Wall

The permeable wall of the CPS serves as the confinement region for the plasma and is probably the most significant test item in the simulator. Since energy is coupled into the plasma from an electromagnetic field, the wall material must have a very high electrical resistivity. Due to the sudden increase in radiant heating upon establishment of a plasma, the material must have good thermal shock properties. Uniformity of permeability is necessary to avoid distortion of the plasma and to provide cooling of the entire wall.

A permeable silica should be the ideal material for the permeable wall due to its excellent electrical and thermal shock properties. Unfortunately, the one source of fused silica foam located during this program proved to have inadequate permeability to allow the necessary coolant flow.

This, coupled with the extremely low heat transfer coefficient of the foam, caused localized melting on the interior surface to occur during testing.

The permeable wall material used in the CPS constructed for this investigation was AlSiMag 447, a cordierite material obtained from the American Lava Company.[2] This material has a thermal expansion coefficient similar to silica and has appropriate electrical properties. The right circular cylinders of AlSiMag 447 used for laboratory tests were supplied without any discernable internal cracks. Unfortunately, cracking of the more complex shape for the CPS has become a very severe problem. The cracks are believed to be caused by stresses built up in the material during sintering due to non-uniform density in the green pressed shape. Repeated efforts by the supplier have failed to correct this problem. Figure 5 shows a typical wall failure. This failed during Run 16 along cracks that had been observed before the test. A number of tests have been run where no observable cracking took place and some operational data using this material in previous work is available.[3] In spite of these problems, the AlSiMag 447 cordierite material remains a reasonable choice for the permeable wall of the CPS and has been used for all meaningful tests.

D. Permeable Nozzle

Figure 6 shows the permeable graphite nozzle designed for use with the Combined Principles Simulator. The nozzle is segregated into three axial flow plenums so that the pressure in each plenum can be matched to the internal pressure to provide the appropriate flow pattern. The throat diameter of the current permeable nozzle was designed at 0.95 cm inches to provide chamber pressures slightly in excess of 4.46×10^5 N/m^2 using available power supplies in the TAFA laboratory.

E. Propellant Seeding

Since the ultimate design of the GCNR requires propellant seeding in the boundary layer to intercept the high

radiant energy from the fuel region, a continuing effort has been made in the TAFA simulator programs to refine the seeding system. The CPS shown in Figure 1 has provision for propellant seeding along the permeable wall and again at the entrance to the nozzle. The various problems involved in providing a radiation barrier have been approached from several directions during this study. The goal of this phase of the program was to provide approximately five percent by weight of seed material in the propellant flow.

TAFA's experience on previous programs has been that it is essentially impossible to force a seeded propellant flow through a porous membrane without generating blockages which disturb the flow uniformity. As a result, seeding injection has involved feeding a powder with a carrier gas stream through individual slots that exhaust into the plasma cavity. Even this scheme has its limitations, however, since the flow passages must be very carefully designed to avoid blockages or non-uniform injection. In order to avoid these problems the powder feeding slot at the inlet of the CPS was developed to feed the powder into the inner cavity in a uniform manner. This was accomplished by feeding the powder and carrier gas into a circular plenum which decreases in cross section uniformly from the entrance to the closed end. The exhaust from the plenum is a slot of appropriate size to keep the gas-seed mixture at constant velocity throughout the length of the plenum. The resulting flow pattern is a uniform sheet of gas and seed flowing out of the slot normal to the propellant flow. The current design includes two plenums, each extending π radians around the circumference of the feeder. This configuration has been operated inside of a clear quartz wall for observation and the powder pattern issuing from the feeder was very uniform. This technique could be modified by introducing additional powder feed points if denser concentrations of seed material are required. A similar propellant seeding system is provided for the protection of the nozzle.

F. Fuel Injector

The GCNR concept requires the introduction of the uranium fuel into the fissioning fuel region. Several techniques are being considered at the present time.

6

The CPS has been designed and equipped to simulate the uranium injection with two different types of solid feed devices. One introduces the fuel in wire form and the second as a vapor issuing from a heated injector tip that receives material in the solid form. The wire feed device is shown in Figure 7. This incorporates a simple variable speed motor drive propelling the wire between two rollers from a storage reel. Downstream from the drive wheels is a close fitting gas barrier which prevents leakage from the plasma chamber. Figure 8 shows the screw feed sodium extruder that is used as the second standard fuel source for the simulator. In this device sodium is extruded into a small chamber in a tungsten tip which is heated by the plasma. The resulting vapor is released through an orifice into the plasma chamber. Figure 1 shows this feeder in position. The electrical isolation and variable delivery speed features of these two devices are their most important requirements.

Early work with solid fuel as the source for the plasma gas was centered around the use of sodium chloride vaporized from a graphite crucible. Subsequently various metals, including sodium, contained in a crucible in the immediate vicinity of the plasma were tried. These techniques worked quite well when the device was exhausting vertically upward but obviously the problem of molten material dropping out of the holder would occur in the down firing position. Since it is envisioned that all future work with the CPS will utilize down firing of the propellant stream, the fuel injectors developed for this stage of the project had to be capable of operating downward.

The currently used technique for uranium fuel injection is to introduce the uranium wire through a boron nitride tip into the core of the plasma. A small quantity of chlorine gas is passed around the wire to form uranium chlorides that vaporize at temperatures of about 873°K. This is significantly below the vaporization temperature of about 4073°K for uranium. If chlorine is not used, this high melting point and vaporization temperature for uranium prevents the formation of a vapor in the plasma device. In the GCNR the high temperatures during operation will circumvent this problem, however, the injection of chlorine does suggest an ignition technique at lower temperatures.

In summary, two modes of fuel injection are available for the Combined Principles Simulator. One injects a metal in wire form with the addition of chlorine to produce a low temperature metal chloride. The second feeder is designed primarily for operation on sodium and utilizes a chamber heated by the plasma in which vapors are formed prior to injection into the plasma region. The latter device has been used for tests at pressures up to 4.9×10^5 N/m^2.

G. Instrumentation

The instrumentation utilized in this work was designed to accomplish four basic goals: 1) complete heat balance on the system, 2) measurement of thrust, 3) measurement of the propellant to fuel injection ratio, and 4) measurement of the fuel retention within the simulator. The detailed procedures used in some of these measurements has been previously reported.[3] Figure 9 is a photograph of the thermometer and flowmeter panel adjacent to the CPS test stand. The various parts of the instrumentation system are described in the following paragraphs.

The heat balance measurement is accomplished in the conventional manner of noting temperature rise and cooling water flow rate. Variable area type water flowmeters and bi-metallic spring type temperature sensors are used to make the required measurements. The heat balance includes flow and temperature rise measurements on the following five water cooling circuits.

1)   Oscillator in the r.f. power supply

2)   Coil and tank capacitors in the r.f. power supply

3)   Inlet flange of the CPS including seeding injector and fuel injector

4)   Nozzle seeding ring

5)   A water cooled insert used in place of the permeable transpiration cooled nozzle for checkout runs

8

There is also a water cooled calorimeter for measuring the heat flux on the permeable wall. The d.c. plate power to the oscillator is taken as the input power to the system. The oscillator and coil circuit losses are manually recorded during each of the test runs but the remaining measurements are permanently recorded by photographing the instrument panel. The photographic recording also includes the chamber pressure and the voltage drop across the oscillator coil.

The thrust measurement is made by the instrument shown in Figure 10. This is a vane arrangement which is inserted into the exhaust jet of the nozzle. Sensing is accomplished by a Revere Electronics precision strain gauge* load cell coupled to a Sargent millivolt recorder for readout. The system is calibrated in the operating position by using standard weights. Good electrical isolation and grounding practices have been established and the recording of this measurement can be made without r.f. interference that has been experienced in previous efforts to use this same load cell.

For the sodium fuel injection rate measurement, a mechanical counter records the rotations of the sodium feed drive which can be converted into total volume of material. Run time is measured by a watch and recorded manually by the instrumentation operator. Since the weight per unit volume and the diameter of the feed passage are known, the delivery rate of sodium is a straightforward calculation. Many of the early runs with the device were plagued with r.f. feedback into the variable speed d.c. drive which resulted in the drive operating at full speed whenever the power supply was turned up to high voltage. A scheme whereby the pickup on each of the return leads from the d.c. motor is shunted to ground through capacitors has eliminated this problem and the d.c. drive now operates reliably at any preset speed.

A calculator program has been written to combine all of the heat balance and thrust measurement inputs and to provide all of the desired run data in appropriate form as outputs. Thirty-nine individual inputs are used in the

---

*Revere Electronics Precision Load Cell, Model USPI-.05-A.

program for each of the runs made. Not all of these inputs are used on each run but are included in the program to maintain consistency. The outputs from the program include percent hydrogen in the propellant, propellant to fuel ratio, thrust, and enthalpy of the gas at the nozzle throat as determined by the heat balance and as determined by the critical flow calculation assuming the propellant to be all nitrogen.

Spectral absorption, emission, x-ray radiography, and electrical response have been investigated as possible techniques in determining the amount of fuel retention in the plasma. Of these, the two most promising are radiography and careful monitoring of the electrical response.

The x-ray radiography technique involves exposing film by x-rays and examining the resultant film by a densitometer. Exposure times are on the order of 1-1/2 minutes. For visual discrimination on the film there must be at least two percent difference in density between the area being examined and the background. Figure 11 shows the result of a calculation of absorption for various fuel loadings. It can be noted that at about three grams of uranium or greater, sufficient absorption would be experienced to make radio-graphy attractive. A simple perfect gas thermodynamic calculation for the fuel region, assuming uranium vapor at 6000°K, reveals that in order to achieve the indicated uranium loading a pressure of 3×10^5 to 5×10^5 N/m^2 is required. Several radiographs were made of an operating plasma at 1×10^5 N/m^2 to demonstrate the technique. Since the pressure was not sufficiently high, quantitative data could not be obtained from the photographs, however, some discrimination was observed which indicated that meaningful data can be obtained by this technique at elevated pressures.

Initial examination of the electrical response of the system indicated that too much variability was present to make meaningful measurements. Subsequently, with refinement of the wire feed technique, the electrical measurements were stabilized and may be adequate for this measurement. Present practice is to optimize the position of the end of the wire feed device and the wire feed rate by observing the electrical response. Either too rapid or too slow

a feed rate causes instabilities and a resultant increase in r.f. current.

H.   Test Facility

The plasma tests described in this report were conducted using a Lepel 189 kW r.f. power supply located in the NASA test bay at TAFA. A special rack with heavy duty supports was constructed to support the CPS in the coil and the fuel feed device on a shelf above. The exhaust from the device is downward from the test area into a transite lined 15.24 cm diameter pipe that exhausts through a vent in the roof. A special flowmeter and thermometer panel was constructed to provide for more satisfactory photographic recording of the data during each run. The overall layout of the facility is shown in Figure 12. The power supply is operated from a station just outside of the doorway that is apparent in this photograph.

I.   Safety

The safety equipment utilized during the runs on this contract included several new items. The mechanical positioner for ignition shown in Figure 13 was designed specifically for the CPS program. With the boom mounted on the top and with the graphite rods pointed downward, the ignitor is appropriate for testing work on devices exhausting vertically upward. With the boom on the bottom and the graphite rods pointed upward, the device is appropriate for atmospheric pressure start of the CPS. In both cases the operator need touch only the frame of the ignitor which is completely grounded and offers complete protection against electrical shock.

Transparent barriers are positioned around the CPS to prevent accidental contact with the coil. Additionally, a flashing red light is energized whenever the r.f. power supply is on to visually alert all personnel in the area. A 3/4 inch thick plexi-glass explosion barrier is positioned between the CPS and the operators during pressure tests or at any other time there is a possibility of rupture.

A hydrogen purge system designed to automatically purge the hydrogen feed lines in case of plasma extinguishment during a run has been installed. This system is wired to shut off the hydrogen and purge the system with nitrogen if the r.f. power supply goes off or if the manual purge switch is depressed. The system is also interlocked so that hydrogen can be fed into the torch only when the r.f. power supply is operating. With this group of safety items, it is felt that the high frequency operation of the CPS is completely safe.

LABORATORY TESTS

A. Propellant Seeding Studies

A new approach to propellant seeding was taken during this program based on the assumption that the introduction of hardware into the wall of the nuclear rocket for seeding injection would be very difficult. This work involved an investigation of seed material introduction in the form of a gas. The idea was to inject a gas, such as methane, through the permeable wall which would dissociate into hydrogen and carbon as it was exposed to the radiation from the plasma. The hydrogen atoms present would add to the propellant flow and the carbon would provide an ideal interceptor for the radiation and produce the desired heating of the propellant gas stream.

Operation of a clear wall device at approximately 20 kW with an argon-nitrogen plasma was established and then a few percent of methane was introduced into the gas flow. During argon-nitrogen plasma operation the bright colored arc zone was approximately one inch in diameter and eight inches long. When the methane was introduced, the radiating region completely filled the torch and the visible light intensity as recorded on a photographic light meter increased by a factor of seven. A similar series of tests was run using a metal wall to qualitatively measure the radiation from the arc. The heat balance measurements showed that the heat transmitted to the metal wall went up when methane was introduced.

The surprising result with methane led to an investigation of the effectiveness of propellant seeding with

12

solids in protecting the wall. This was accomplished using the test specimen holder shown in Figure 14. In this case, 6.35 cm diameter samples of AlSiMag 447 wall material were mounted in a water cooled fixture so that they could be transpiration cooled and subjected to a high heat flux plasma flame. By viewing the test from the side, it was possible to observe how the flow through the permeable sample kept the test flame away from the wall. With no seeding present, it was found that the surface of the ceramic did not start to melt until the visible ionization zone of the plasma came in contact with the material. Further tests were conducted with the addition of powder seeding intro- duced across the face of the permeable wall in a configuration shown in Figure 15. A dense cloud of finely divided tungsten powder was used as the seed material. Unexpectedly the test sample melted directly behind the seeding stream whereas the other parts of the sample were not affected. Evidence of melting of the sample can be seen in the photograph (Figure 15). As shown in Figure 16, it was noted that the seeding flow became brillantly radiative during the experi- ment, as had been the case with the earlier tests with methane in the plasma. Another series of tests were con- ducted using carbon particles as the seed. Similar results were obtained inasmuch as when a dense cloud of material was injected the seeding flow appeared brighter than the plasma flame. When the amount of seeding material being injected was reduced, the seeding flow took on a cooler, more characteristic yellow color for carbon.

These observations indicate that the radiation level may become increased by the introduction of a dense seeding cloud of particles. It is apparent that there are a number of unanswered questions in this area and additional study is required to understand and control the observed phenomena.

B. Uranium Plasma Tests

One of the goals of this study was to operate a uranium plasma. A number of experiments utilizing depleted uranium powder and uranium wire 0.274 cm in diameter were conducted in which an attempt was made to vaporize the metal directly into the plasma. In one series of experiments,

pieces of wire approximately 1.91 cm long were inserted into
a boron nitride holder located so that the tip of the holder
was in a plasma operating in a vertically upward position.
It was possible to heat the uranium sufficiently to obtain
melting but as soon as melting took place the material tended
to run down over the edge of the boron nitride holder and
no apparent vaporization took place. This experience can be
attributed to the fact that there is a large liquidous regime
for uranium metal. The melting point is reported at
approximately 1405°K whereas vaporization does not occur
until 4091°K.[4]

In order to obtain a molten pool of uranium metal which
could be brought up to the vaporization temperature another
series of experiments was conducted in which uranium powder
was held in a graphite crucible. The crucible was positioned
inside of a plasma device so that the bottom of the work coil
provided some direct heating to the crucible and additional
heat was provided to the uranium by the radiation and con-
vection from the plasma. In this case it was impossible to
deliver sufficient energy to the uranium to cause melting.
In an attempt to get more energy into the metal, a d.c. arc
was established between the surface of the uranium and a
carbon electrode held over the top of the crucible. This
provided sufficient additional energy to cause melting and
some vaporization of uranium to occur. Unfortunately, as
soon as melting occurred at the foot of the d.c. arc, the
arc would shift away from the hot spot, most often to the
edge of the crucible, resulting in cooling of the uranium
and subsequent cessation of melting and vaporization.

Since uranium chloride has a sublimation temperature of
just over 873°K, a series of tests to determine if a uranium-
chlorine reaction could be used to vaporize the uranium wire
fuel was conducted. The first tests were made in a clear
wall device as shown in Figure 17. The uranium wire was
held in a boron nitride holder and an argon plasma established.
Chlorine was then introduced near the uranium and vaporization
occurred. Figure 18 shows the argon plasma operating with
the uranium wire in position. Figure 19 shows the plasma
during chlorine injection and vaporization of the uranium.
These two photographs are somewhat misleading inasmuch as
the uranium plasma does not look as bright as the argon
plasma. This observation is in error since the uranium

14

plasma radiates significantly greater than argon. The difference in the photographs is due to the selected aperture and shutter speed of the camera.

A series of tests was made to substantiate the presence of uranium in the plasma generated by the above technique. Figures 20-22 show appropriate portions of spectrometer traces generated by looking at a spot less than 1 cm in diameter in the center of the plasma. Figure 20 shows the trace of an argon plasma operating at 19 kW plate power with a boron nitride fuel holder installed. Figure 21 shows an argon-chlorine plasma at the same spectrometer settings and with the power at 19.3 kW. It can be noted that the chlorine does not produce any significant lines in this portion of the spectrum. The two strong calcium lines come from an impurity in the boron nitride that is vaporized by the chlorine. Figure 22 shows an argon-chlorine-uranium plasma at 18.9 kW. A multitude of uranium lines are apparent with both neutral and ionized species represented. The spectrometer sensitivity has been reduced to 40 percent of the previous setting for this trace and it is apparent from the increased continuum and uranium lines that a high level of ionized uranium was present in the plasma.

Additional tests have been run with iron wire and chlorine reacting in a plasma to produce an iron vapor plasma. In this case the plasma is cool enough so that there is no apparent continuum radiation.

C. Combined Principles Simulator Tests

A total of 35 runs have been made with the CPS constructed for this study. Twelve of these runs include heat balance and electrical measurements and are reported in Table I. A large number of additional tests were run in checking out various auxiliary items and have been discussed in other parts of this report.

Because there is no requirement to operate the CPS at subatmospheric pressures and because normal plasma ignition is accomplished at one atmosphere, all initial experiments with the CPS were conducted utilizing an

ignition technique at one atmosphere. A number of difficulties were experienced during ignition in the early phases of testing the device. The characteristic pressure pulse experienced during ignition and resultant disturbance to the electrical characteristics resulted in cracked permeable walls and electrical difficulties. Attempts to appropriately mount the permeable wall to provide for cushioning and expansion helped alleviate the problems but it became apparent that some ignition technique would have to be utilized that would minimize the pressure pulse. It was also desirable that the ignition technique developed be compatible with planned future testing of this device on a low frequency power supply.

The technique developed consists of reducing the pressure in the CPS to approximately 0.004×10^5 N/m^2. A small flow of argon is used to balance the vacuum pumping rate and maintain a dynamic system at the set pressure. A glow discharge is then generated within the torch cavity by utilizing the two aluminum end plates as electrodes and the r.f. power is coupled into the glow discharge. The flow of gas through the permeable wall is then increased and the power to the end plate electrodes and vacuum pump shut off. As the pressure approaches one atmosphere the coupling on the nozzle which is attached to the vacuum pump is removed and operation is established at one atmosphere. For tests in excess of one atmosphere, the gas flow is simply increased and the nozzle provides an orifice which restricts the flow and causes a pressure buildup within the device.

Subsequent to ignition the CPS has been operated over a wide range of operating modes. Power, pressure, feed rate of the fuel simulating material and different gases have been utilized. Table I is a compilation of the data acquired during the significant test runs.

In reviewing Table I, it can be seen that the CPS can be operated over a wide range of operating parameters. Additional work needs to be done to optimize the various components in the system but it is apparent that the basic concept of a plasma being fueled from a solid feed source and suspended in a chamber in which gas is flowing through the walls and being exhausted through a choked flow nozzle has been demonstrated.

16

CONCLUSIONS

The principle goal of this program to design, construct, and operate an induction heated device which includes the unique design principles of the Gas Core Nuclear Rocket has been accomplished. All of the experience gained in prior work which examined various components has been brought to bear on the design and operation of this device.[5-8] Operation over a range of conditions has not presented any insurmountable problems. While additional work needs to be conducted to optimize various components, it is believed that the successful operation of this device has confirmed the validity of the basic design principles involved.

REFERENCES

1. Ragsdale, Robert G.; and Willis, Edward A. Jr.: Gas-
    Core Rocket Reactors - A New Look. NASA TM X-67823,
    1971.

2. American Lava Corporation: Mechanical and Electrical
    Properties of AlSiMag Ceramics, Chart No. 691.

3. Thorpe, M.L.: Induction Plasma Heating: System
    Performance, Hydrogen Operation and Gas Core Reactor
    Simulator Development. NASA CR-1143, August 1968.

4. E. H. Sargent & Co.: Table of Periodic Properties of
    The Elements, Catalog Number S-18806, 1964.

5. Poole, John W.; and Vogel, Charles E.: Induction
    Torches and Low Frequency Tests. NASA CR-2053,
    May 1972.

6. Vogel, Charles E.; Poole, John W.; and Dundas, Peter
    H.: Radiation Measurements and Low Frequency and High
    Pressure Investigations of Induction Heated Plasma.
    NASA CR-1804, May 1971.

7. Poole, John W.; and Vogel, Charles E.: Induction Plasma
    Nozzle Tests. NASA CR-1765, April 1971.

8. Vogel, Charles E.: Curved Permeable Wall Induction
    Torch Tests. NASA CR-1764, March 1971.

TABLE 1

CPS TEST SUMMARY

	Run No.											
	18	23	24	25	26	28	29	31	32	34	35A	35B
	1.83 cm Nozzle	.98 cm Nozzle										
Run Duration - sec	118	71	46	50	47	36	40	34	61	70	169	169
D.C. Power - kW	113.0	96.52	129.61	130.86	107.48	114.66	107.68	109.67	109.67	119.64	107.18	124.62
R.F. Amps	-	120	100	130	120	-	180	170	160	110	105	140
Top Argon Flow - g/sec	2.45	.59	.59	0	0	0	0	0	0	5.94	2.52	2.08
Wall Flow - g/sec	18.10	10.77	15.20	15.20	10.77	10.77	10.77	13.74	12.27	9.87	17.38	28.23
Total Propellant Flow - g/sec	20.55	11.36	15.79	15.20	10.77	10.77	10.77	13.74	12.27	15.81	19.90	30.31
Fuel Flow (Sodium) - g/sec	.0164	.0313	.0316	.0409	.0126	.0265	.0136	.0267	.0275	.0058	.0142	.0142
Propellant: Fuel Ratio	1214	363	500	371	857	406	790	514	445	2708	1398	2128
Power Supply Losses - kW / Percent	57.29 / 50.7	26.02 / 27.0	47.81 / 36.9	51.32 / 39.2	42.12 / 39.2	37.72 / 32.9	32.45 / 30.1	27.19 / 24.8	28.95 / 26.4	46.05 / 38.5	48.25 / 45.0	43.86 / 35.2
Coil Loss - kW / Percent	3.43 / 3.0	2.31 / 2.4	1.62 / 1.3	1.26 / 1.0	1.08 / 1.0	1.08 / 0.9	2.52 / 2.3	3.06 / 2.8	1.98 / 1.8	2.70 / 2.3	1.80 / 1.7	3.60 / 2.9
Torch Top - kW / Percent	3.83 / 3.4	1.79 / 1.9	2.53 / 2.0	1.69 / 1.3	1.56 / 1.5	1.69 / 1.5	2.70 / 2.5	1.70 / 1.5	1.09 / 1.0	3.04 / 2.5	1.94 / 1.8	2.67 / 2.1
Nozzle Ring - kW / Percent	.83 / 0.7	.77 / 0.8	1.12 / 0.9	1.21 / 0.9	.78 / 0.7	.92 / 0.8	.37 / 0.3	.27 / 0.3	.16 / 0.1	.58 / 0.5	.89 / 0.8	2.46 / 2.0
Nozzle - kW / Percent	2.10 / 1.9	2.74 / 2.8	2.99 / 2.3	2.83 / 2.2	3.29 / 3.1	3.29 / 2.9	1.10 / 1.0	1.57 / 1.4	1.11 / 1.0	2.36 / 2.0	3.00 / 2.8	3.95 / 3.2
Total Measured Losses - kW / Percent	67.49 / 59.7	33.63 / 34.8	56.06 / 43.3	58.31 / 44.6	48.83 / 45.4	44.70 / 39.0	39.13 / 36.3	33.80 / 30.8	33.34 / 30.4	54.74 / 45.7	55.80 / 52.1	56.84 / 45.4
Energy to Gas - kW / Percent	45.47 / 40.3	62.88 / 65.2	73.54 / 56.7	72.59 / 55.4	58.65 / 54.6	69.95 / 61.0	68.54 / 63.7	75.86 / 69.2	76.38 / 69.6	64.91 / 54.3	51.31 / 47.9	68.09 / 54.6
Heat Balance Enthalpy - kg-cal/g	528	1319	1111	1138	1300	1549	1519	1316	1483	980	615	536
Critical Flow Enthalpy - kg-cal/g	1747	982	1008	1110	1918	1125	1125	634	1241	729*	832*	737*
Torch Pressure - $\frac{N}{cm^2}$	3.1	10.3	18.6	18.6	15.2	10.3	10.3	10.7	14.1	15.2	23.4	38.6
Thrust - g	932	932	599	-	966	832	732	1165	1299	1265	2531	3796
Specific Impulse - sec	45	82	38	-	90	77	68	85	106	80	127	125
Wall Heat Sensor - $\frac{W}{cm^2}$	134	-	54	56	93	83	-	35	-	42	111	-

*Calculated assuming all nitrogen propellant flow.

19

PROPELLANT SEEDER
PROPELLANT GAS INJECTION
SOLID ROD SEEDING ASSEMBLY
WATER COOLING
WALL LOADING SPRINGS
PERMEABLE WALL
FIBERGLASS REINFORCED EPOXY OUTER WALL
TIE BOLTS
RADIO FREQUENCY INDUCTION COIL
WALL HEAT FLUX CALORIMETER
SUPPORT FRAME
NOZZLE COOLANT DUCTS
FIBER OPTIC ASSEM
WATER COOLING RING
NOZZLE PROTECTION SEEDER
NOZZLE INSERT (TRANSPIRATION COOLED)
REMOVABLE CALORIMETER
(FOR USE DURING CHECKOUT WITH LARGE I.D. NOZZLE INSERT)
EXHAUST THROTTLING VALVE PORT
VIEWPORT

0 5 10 15 20 25 30

SCALE: CM.

COMBINED PRINCIPLES SIMULATOR

| DATE: 5/18/71 | DRAWING NO. 49·22 |

FIG. 1

20

COMBINED PRINCIPLES SIMULATOR
PARTIAL ASSEMBLY SHOWING BASE AND COIL

FIG. 2
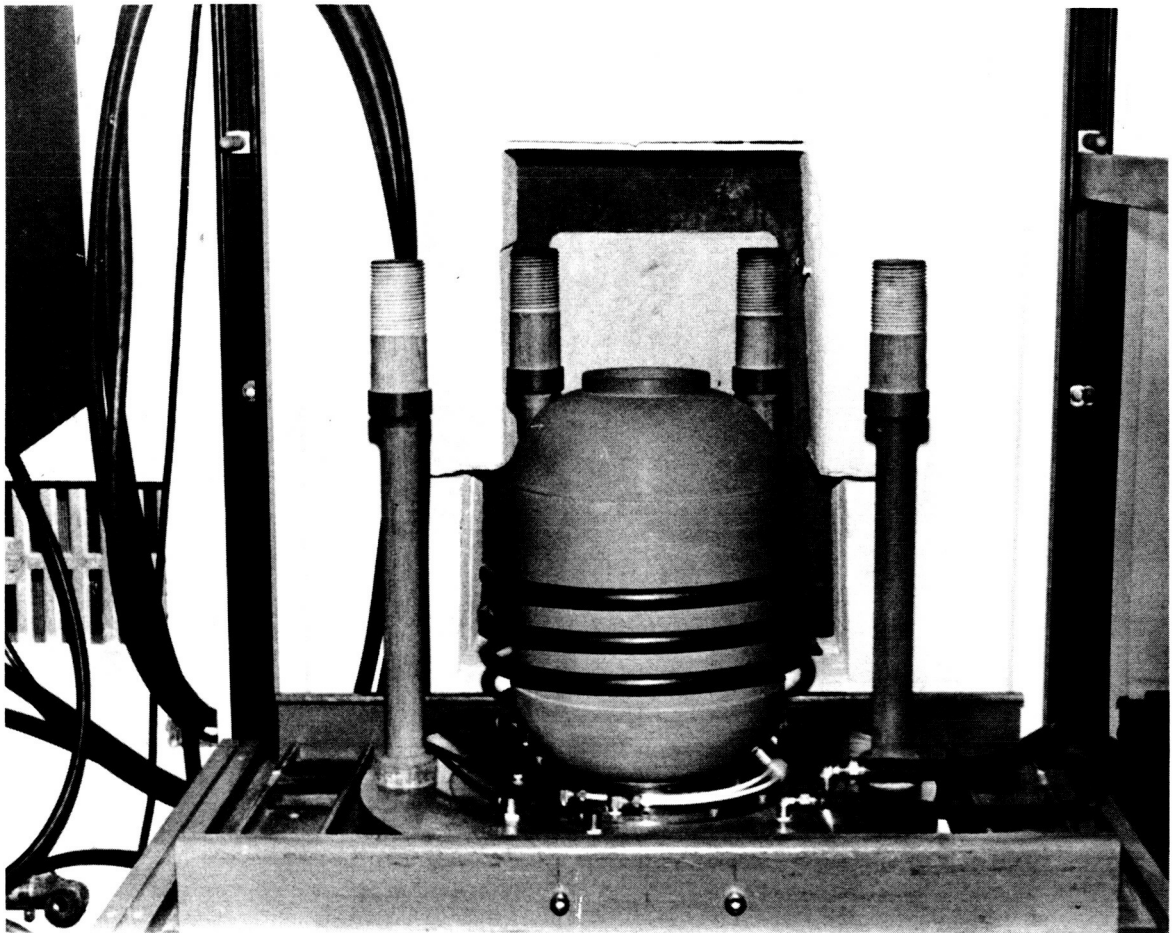
COMBINED PRINCIPLES SIMULATOR

PARTIAL ASSEMBLY SHOWING PERMEABLE WALL

FIG. 3
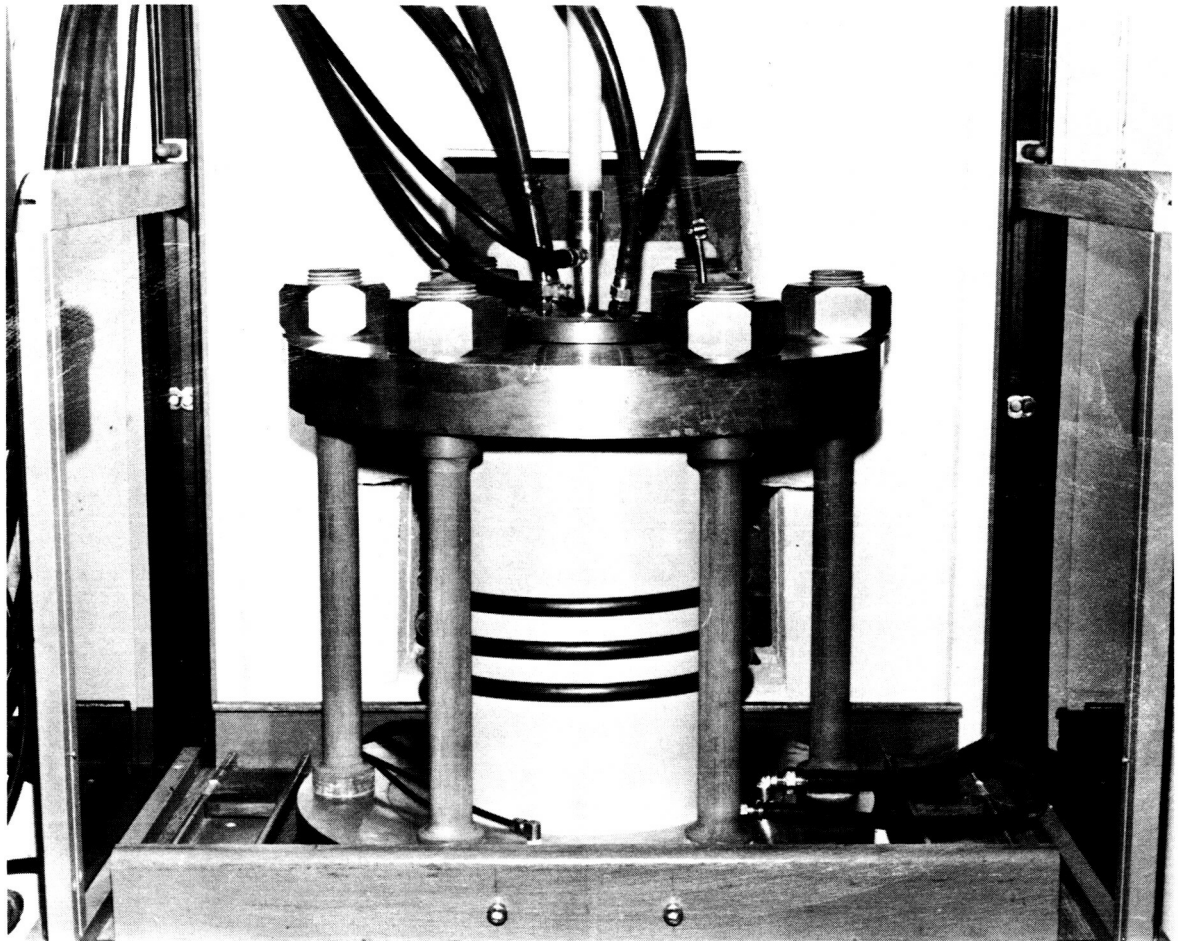
COMBINED PRINCIPLES SIMULATOR

COMPLETE ASSEMBLY

FIG. 4

COMBINED PRINCIPLES SIMULATOR
TYPICAL FAILURE OF PERMEABLE WALL

FIG. 5
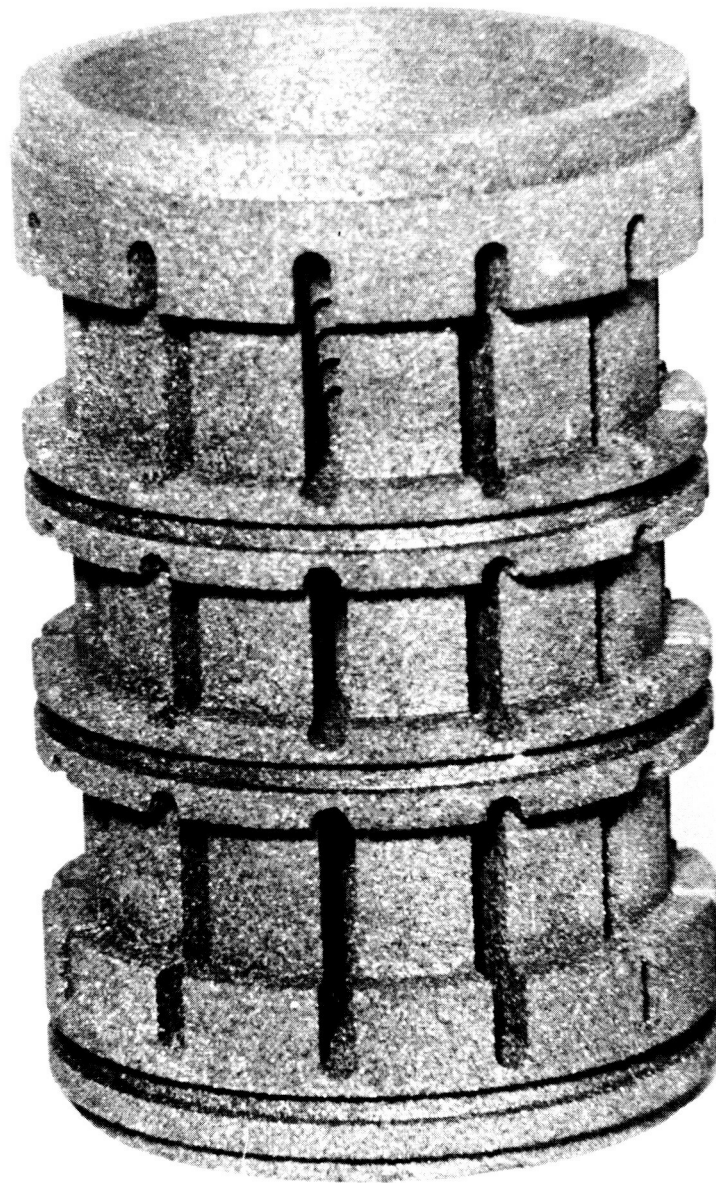
COMBINED PRINCIPLES SIMULATOR
PREMABLE GRAPHITE NOZZLE
FIG.6
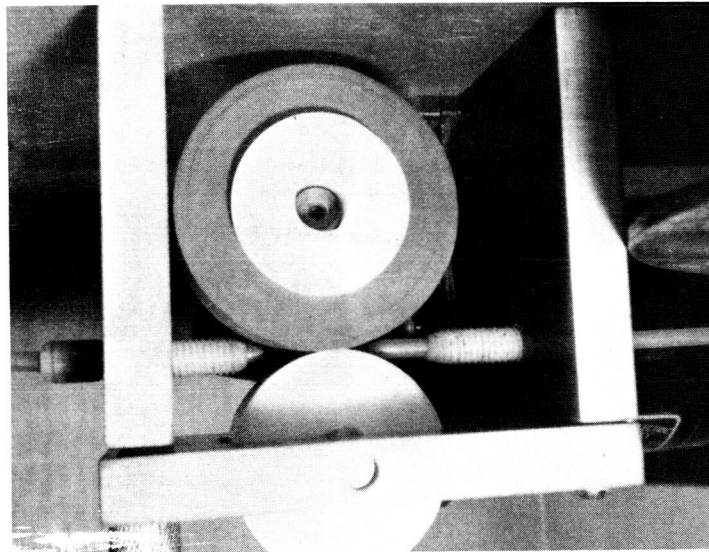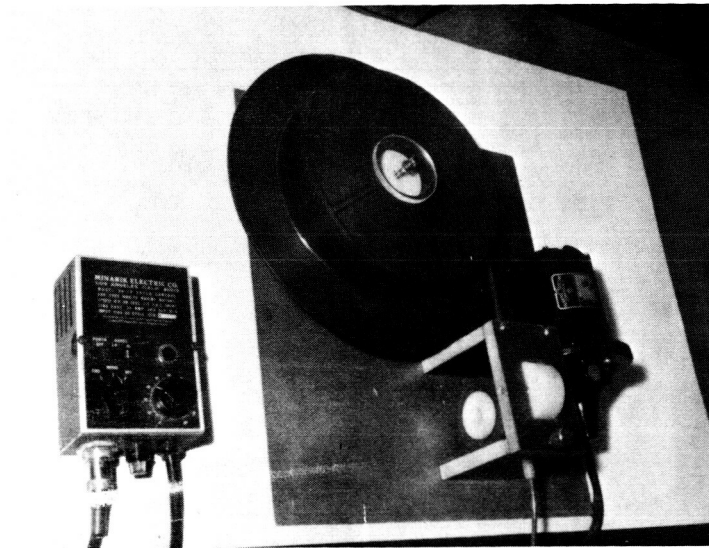
WIRE FEED MECHANISM
FOR
COMBINED PRINCIPLES SIMULATOR

FIG. 7
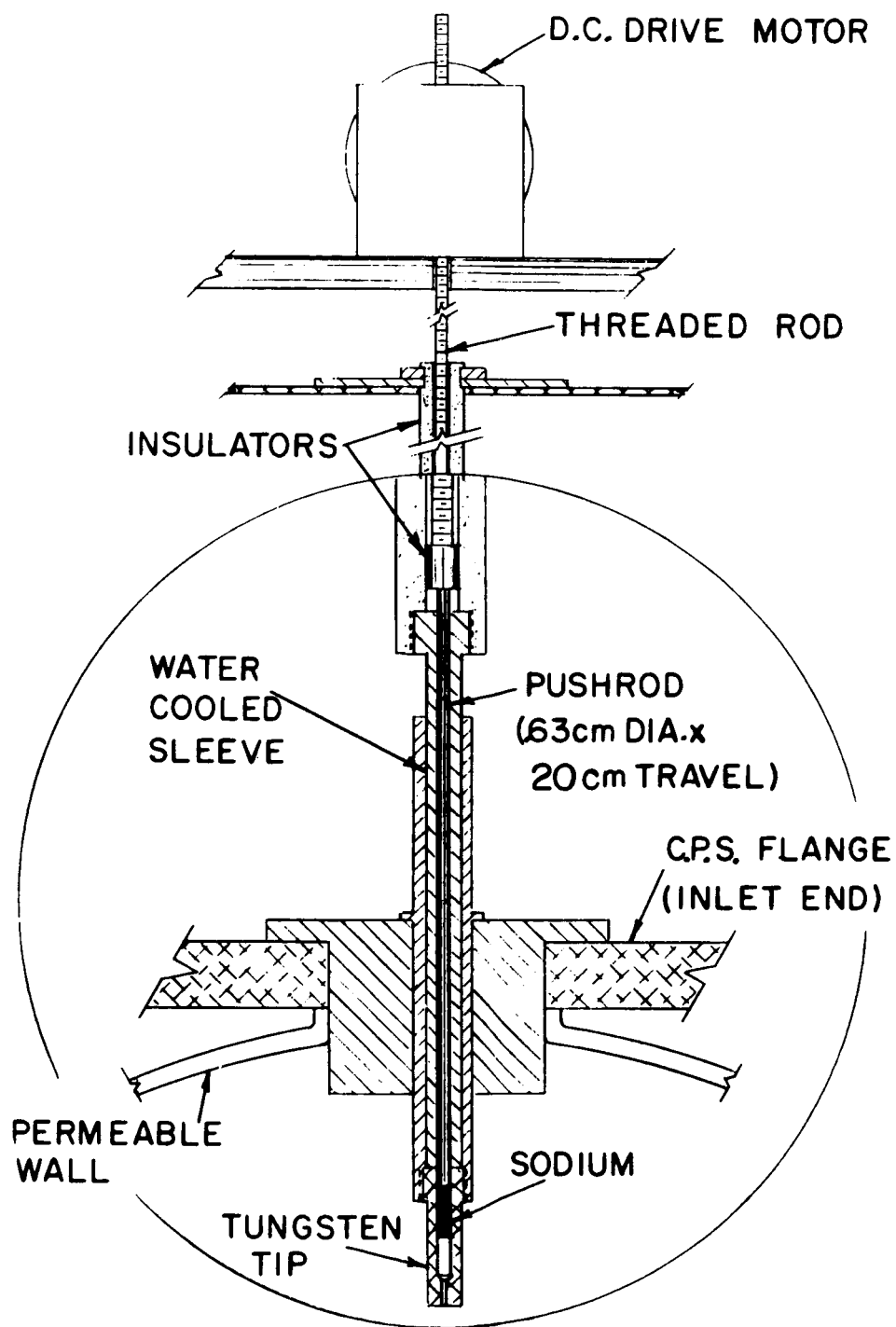
SODIUM FEED DEVICE
FOR
COMBINED PRINCIPLES SIMULATOR

FIG.8
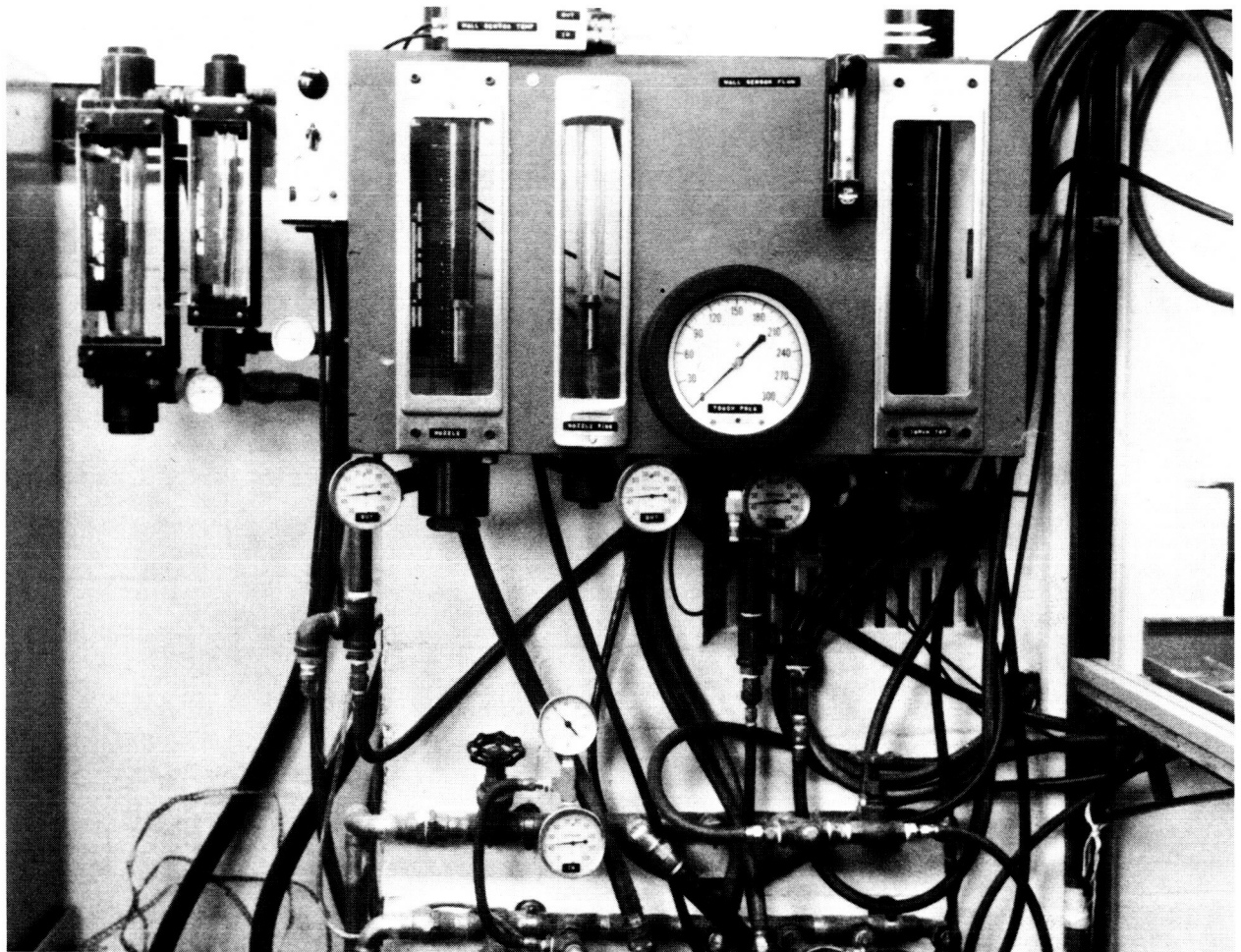
FLOWMETER PANEL

FOR

COMBINED PRINCIPLES SIMULATOR TEST

FIG. 9
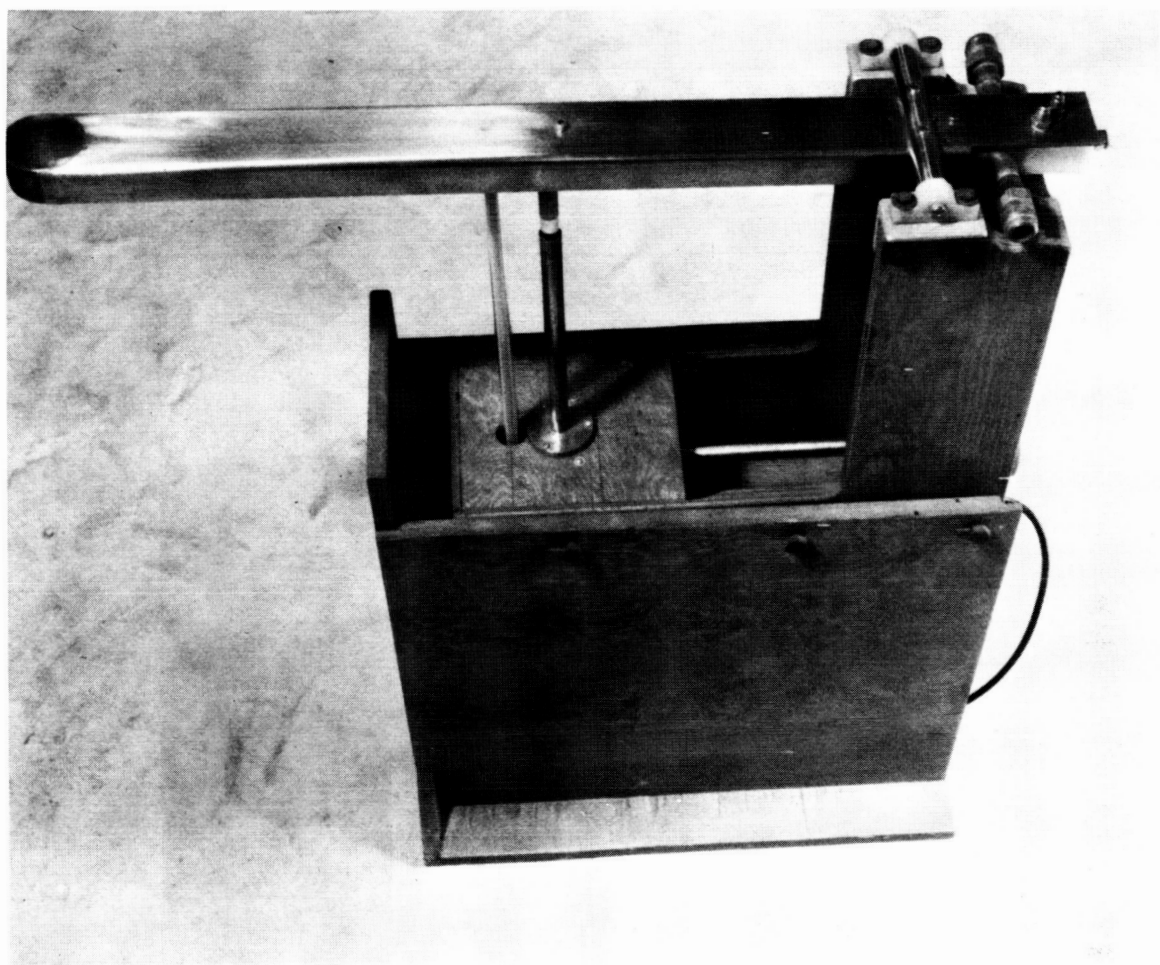
THRUST MEASURING DEVICE
FOR
COMBINED PRINCIPLES SIMULATOR

FIG.10
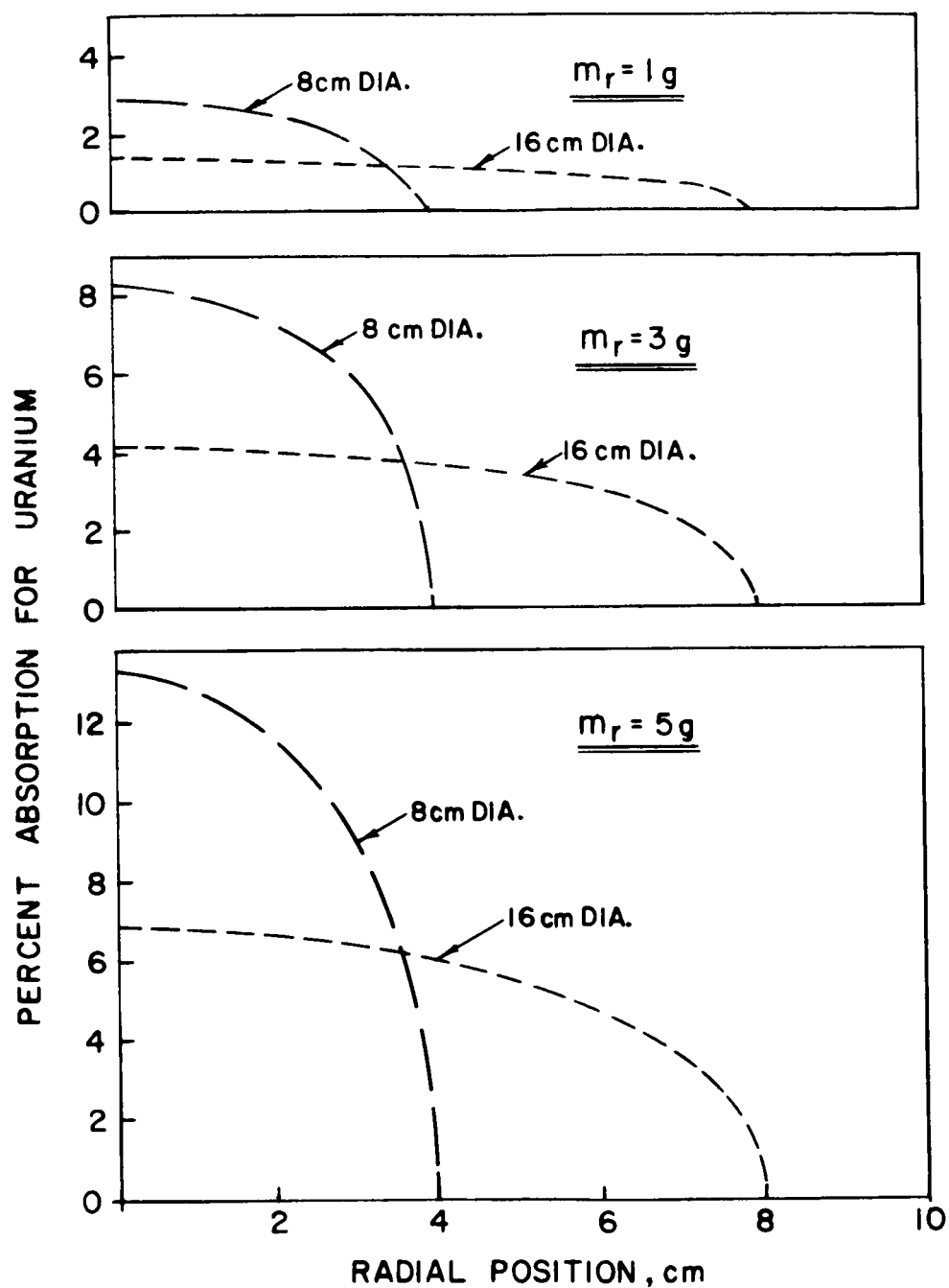
CALCULATED X–RAY ABSORPTION FOR VARIOUS URANIUM MASS RETENTION VALUES (m$_r$) FOR THE COMBINED PRINCIPLES SIMULATOR AS A FUNCTION OF RADIAL POSITION

FIG. II
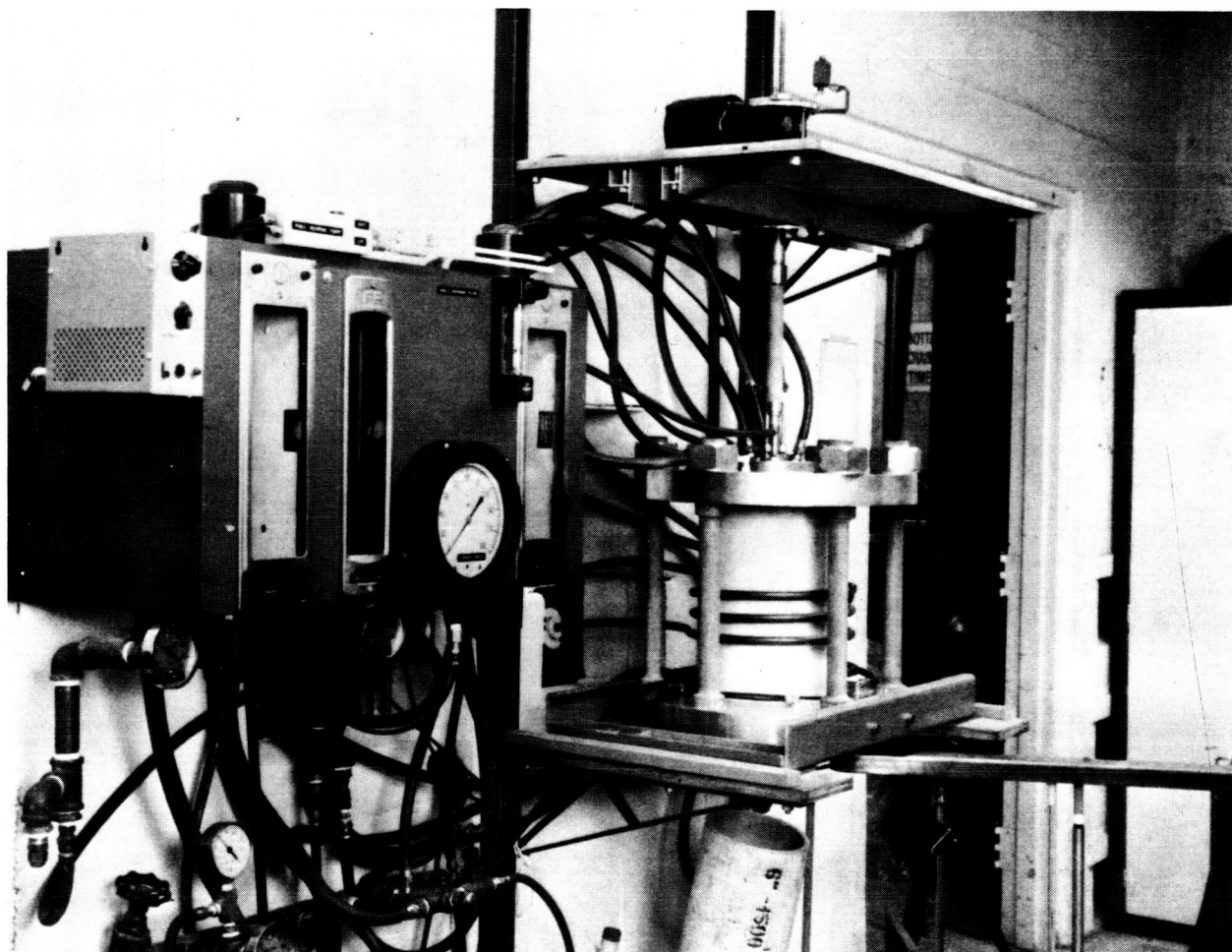
TEST FACILITY
FOR THE
COMBINED PRINCIPLES SIMULATOR
(With Safety Shield Removed)

FIG. 12
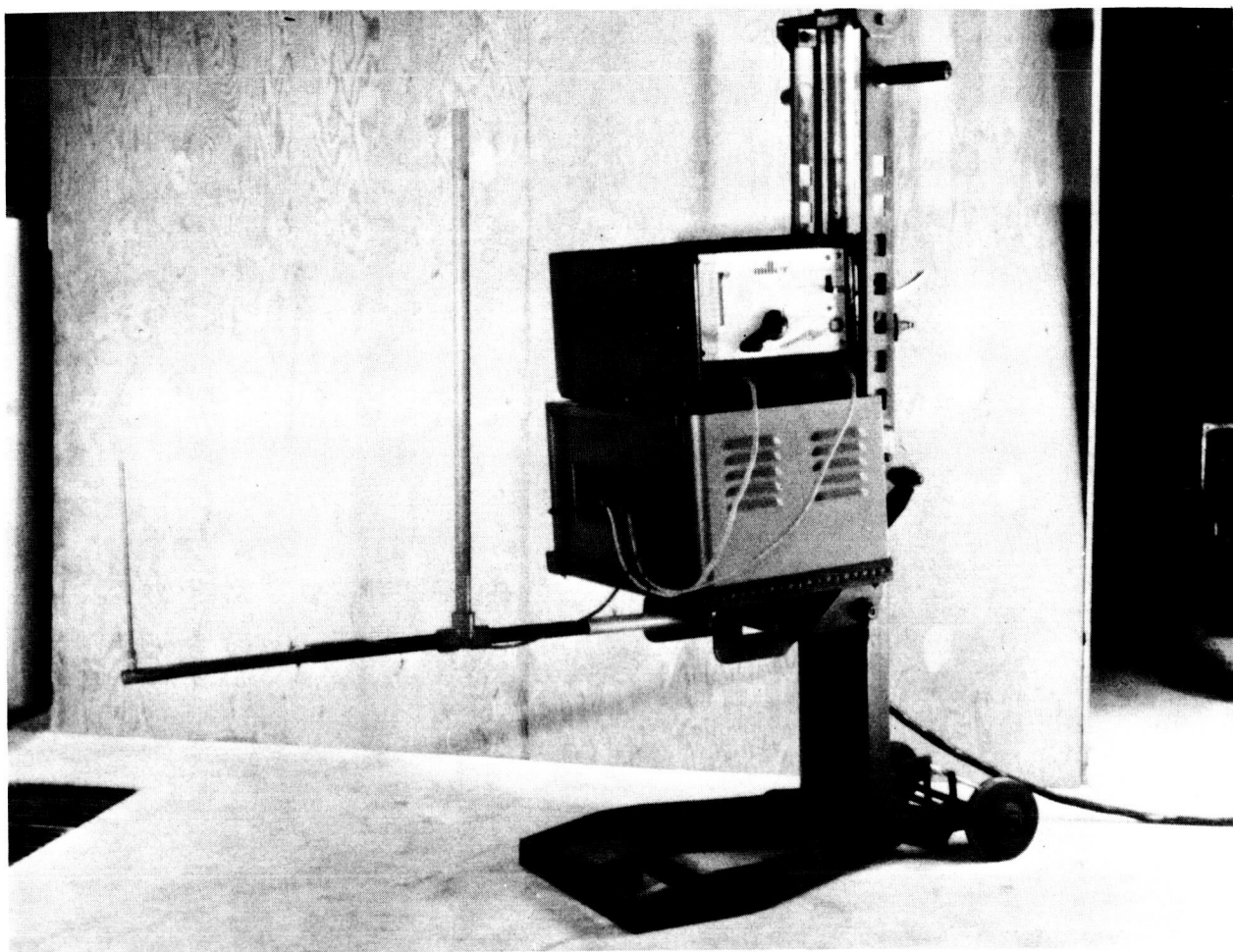
PORTABLE D.C. IGNITOR

FIG. 13
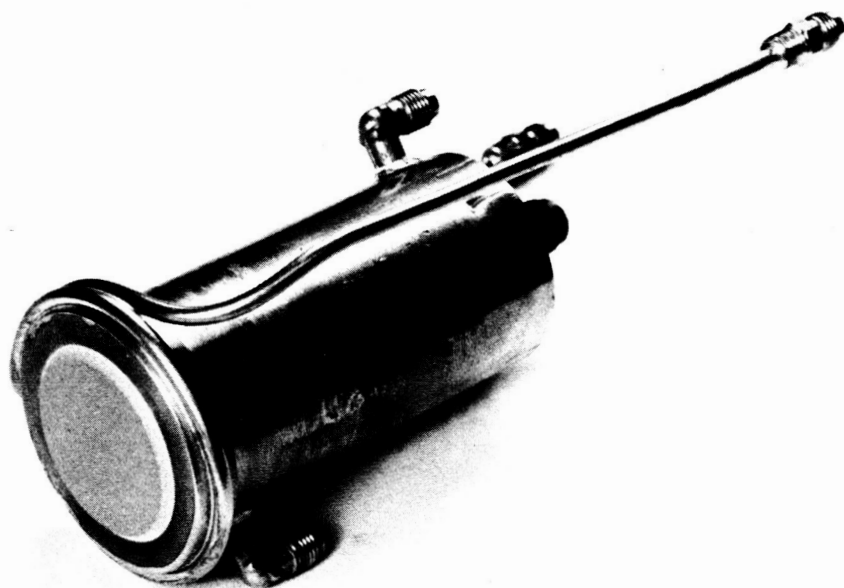
WATER COOLED TEST FIXTURE
WITH PERMEABLE SAMPLE IN PLACE

FIG. 14
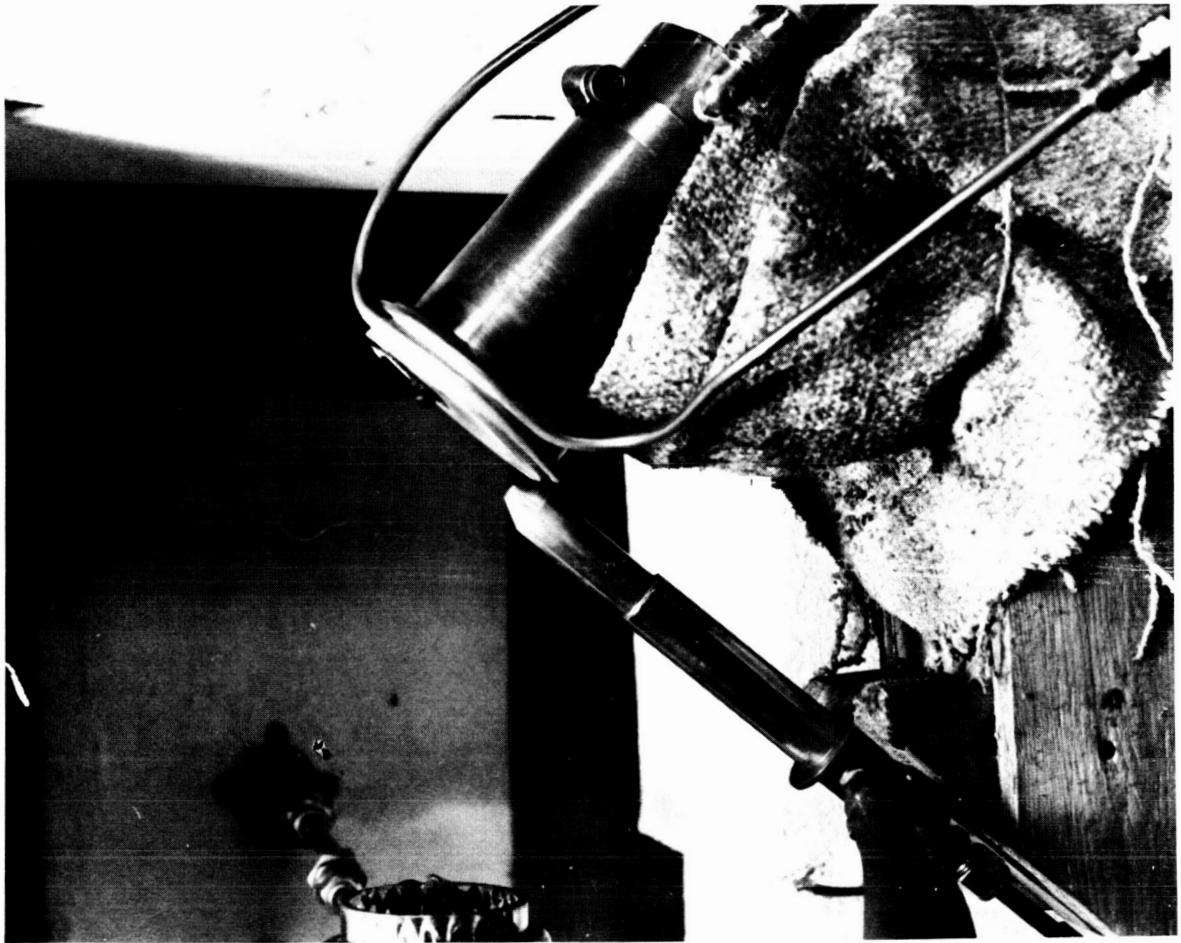
PROPELLENT SEEDING TEST ASSEMBLY AFTER TEST
(SOME MELTING OF PERMEABLE SAMPLE CAN BE NOTED)

FIG. 15
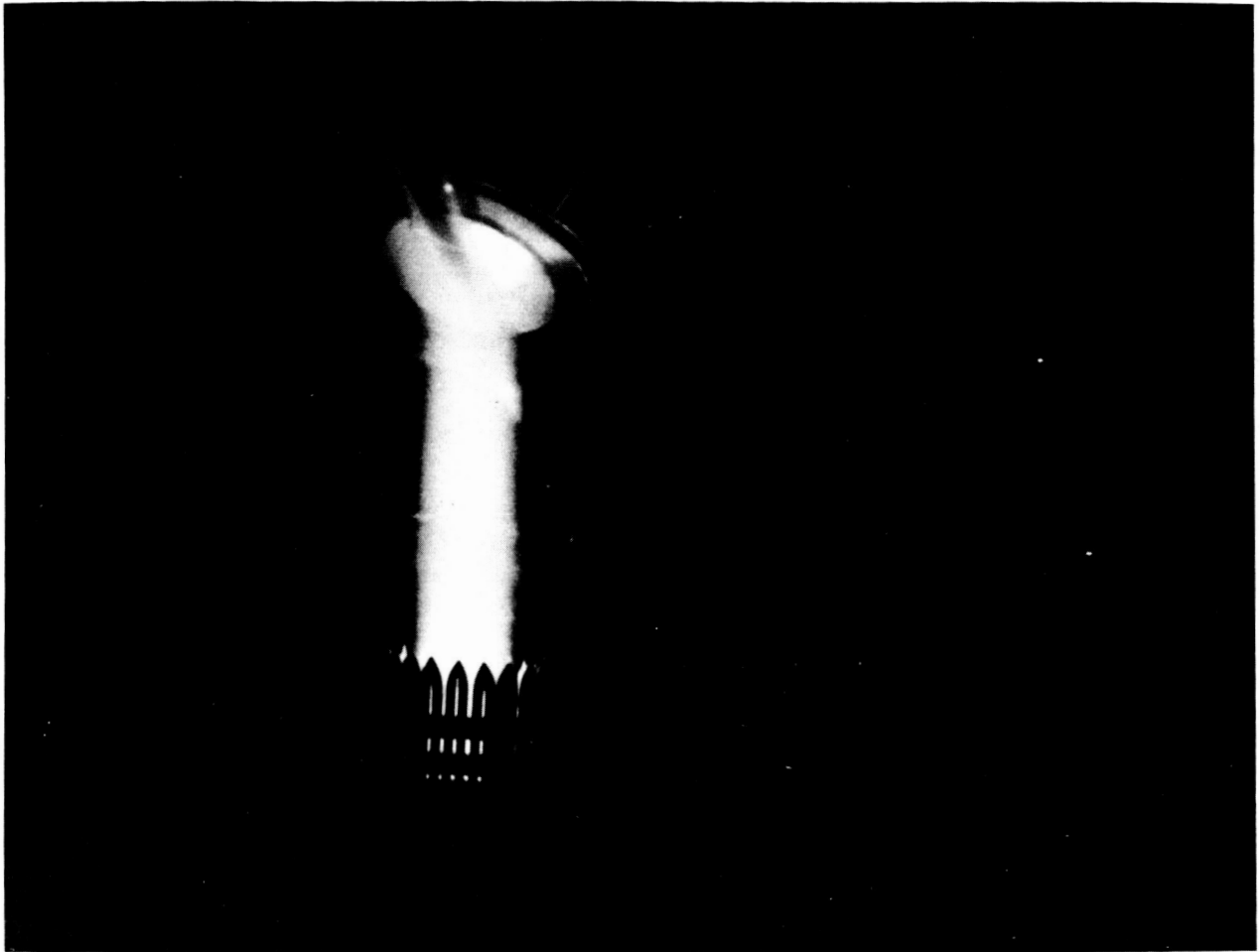
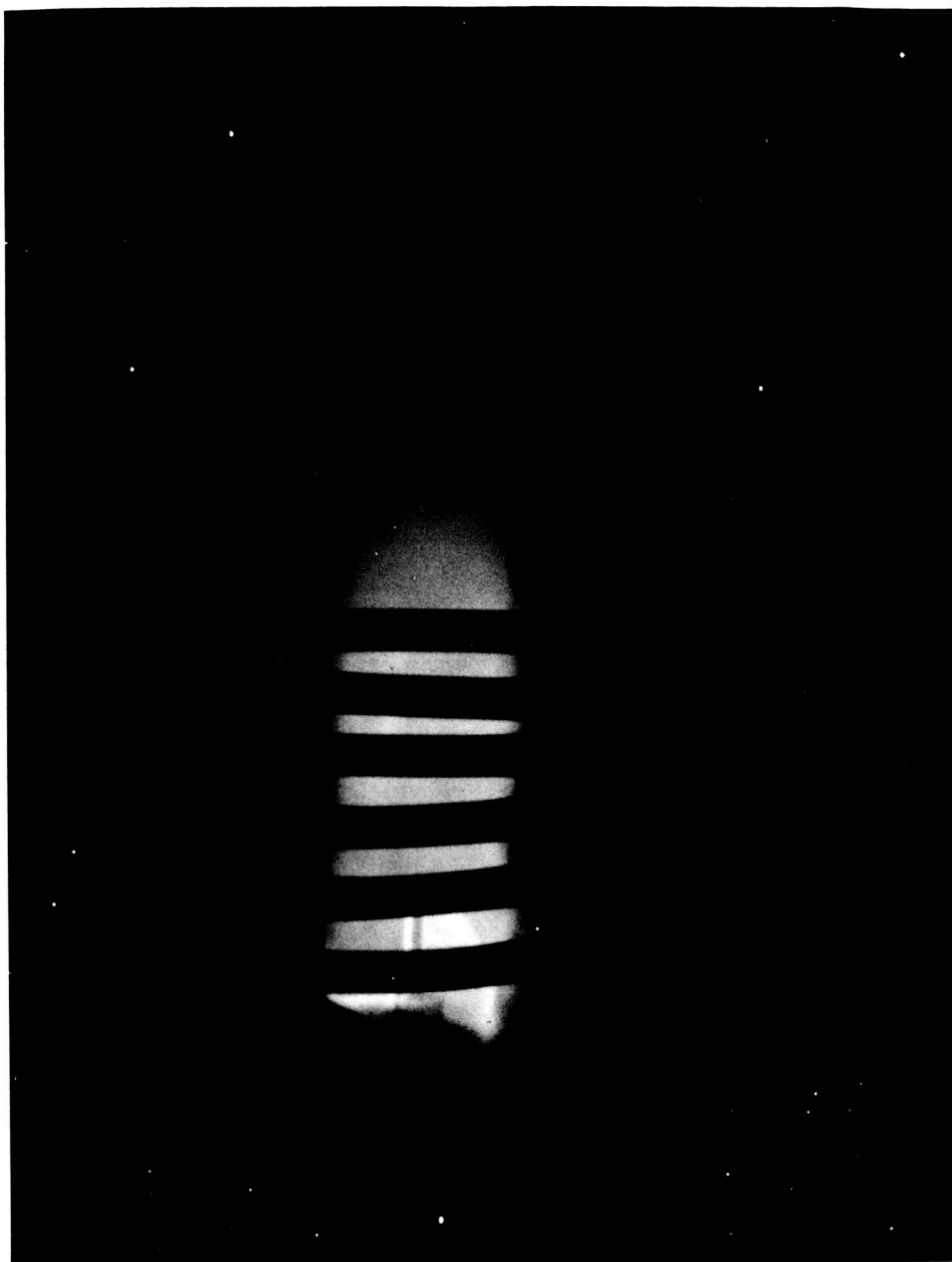PROPELLENT SEEDING TEST WITH TUNGSTEN

FIG. 16
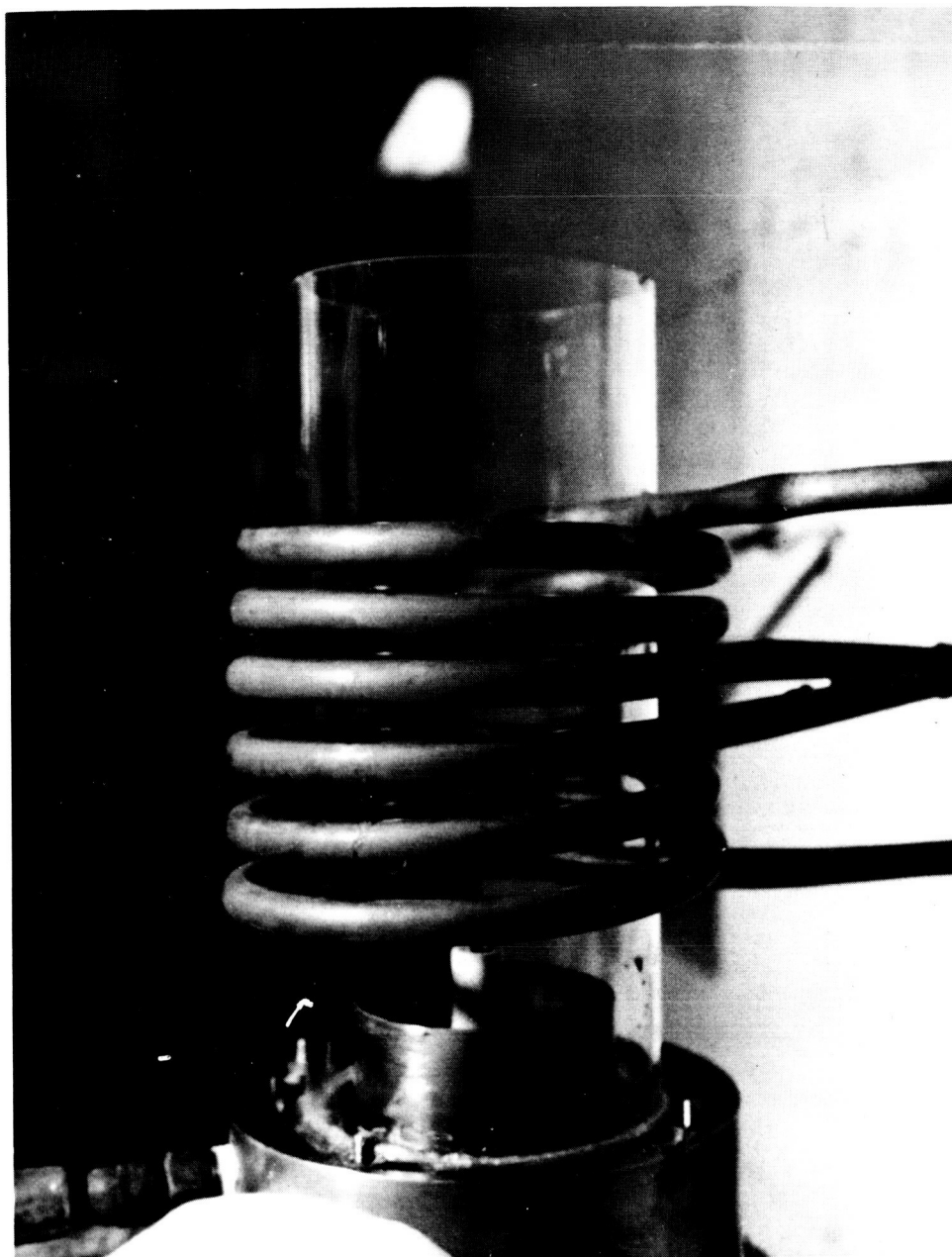
URANIUM   PLASMA   TEST   DEVICE

FIG. 17
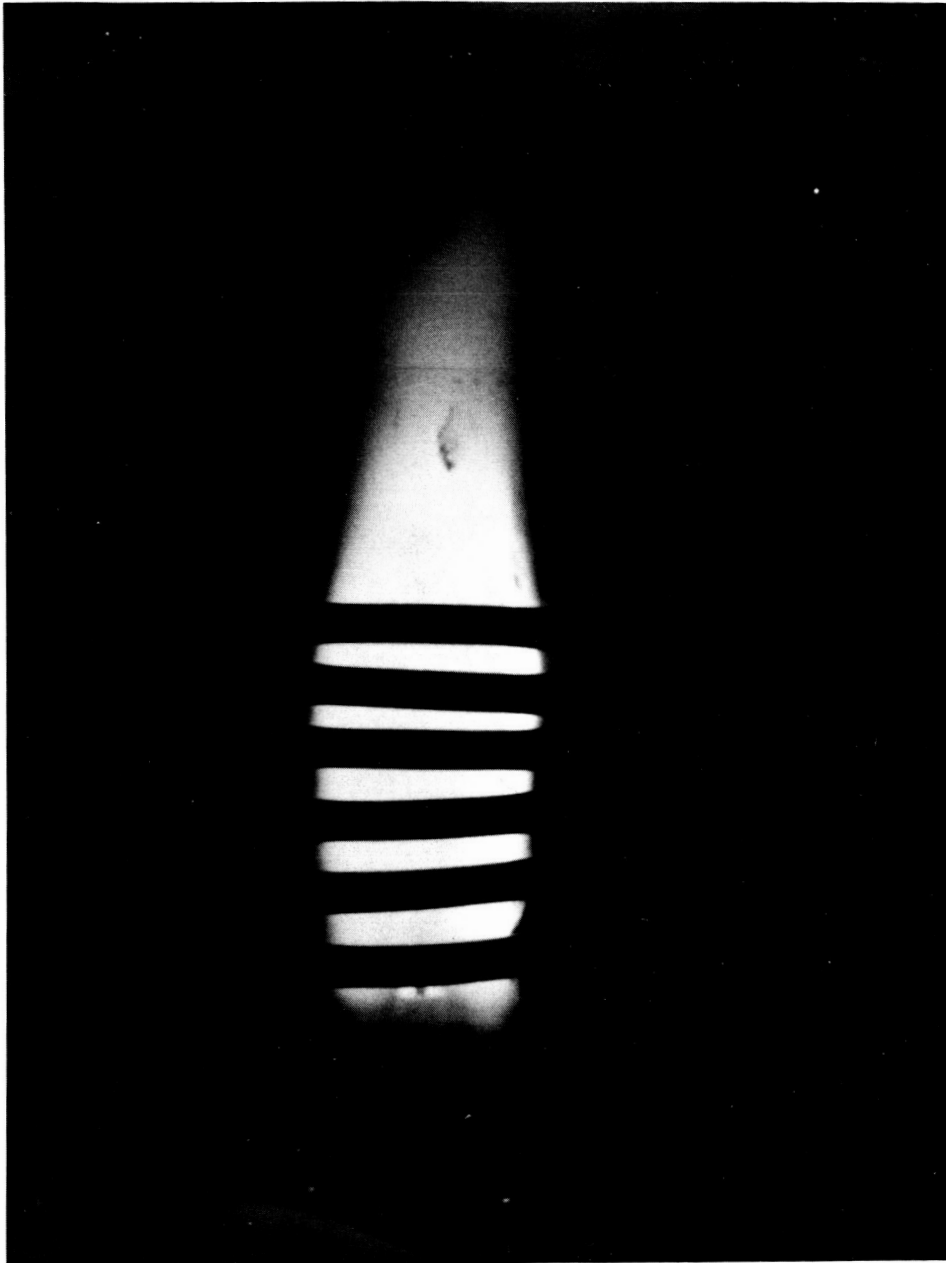
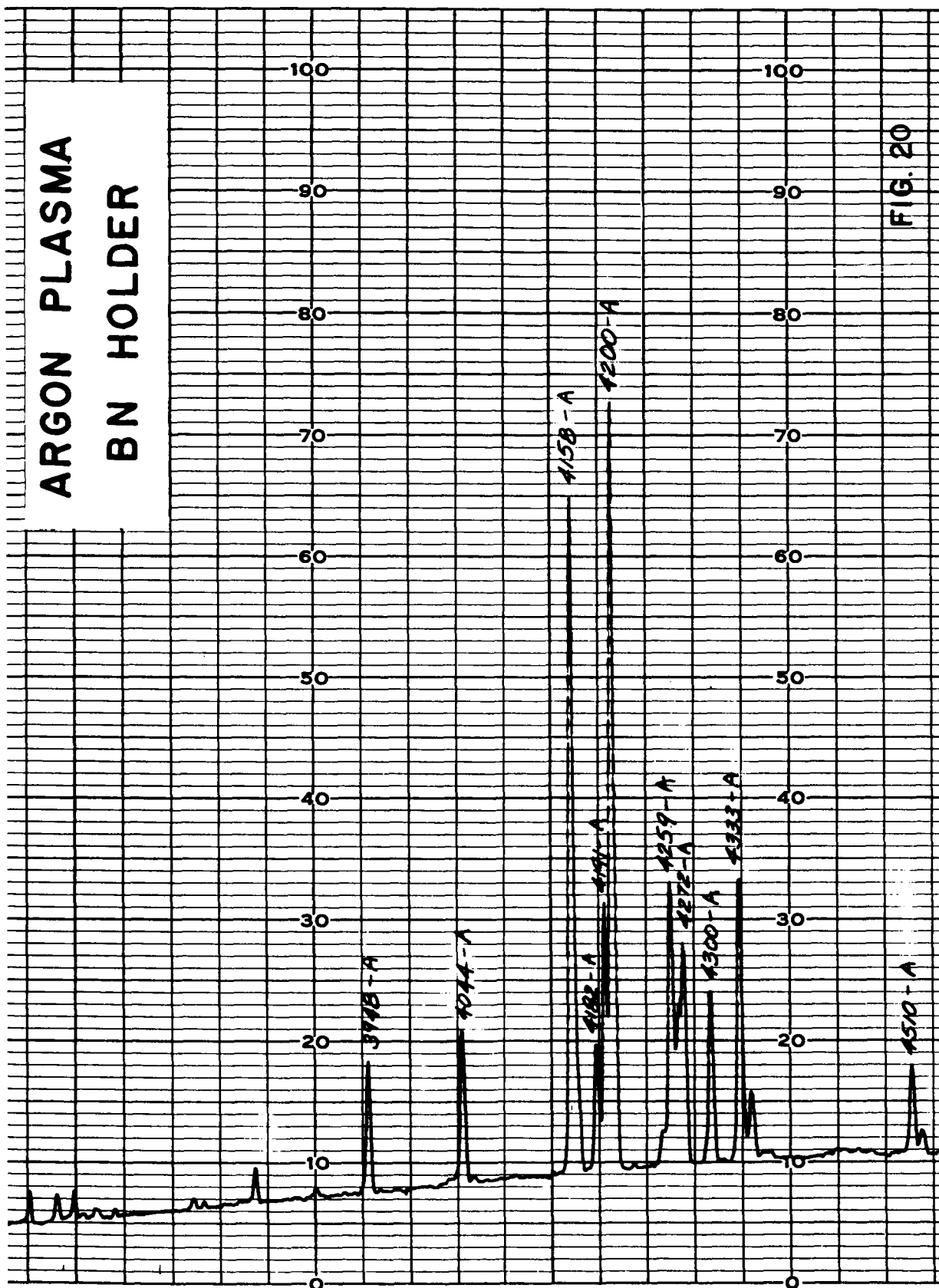URANIUM PLASMA TEST DEVICE
OPERATING WITH ARGON

FIG.18

URANIUM   PLASMA   TEST   DEVICE
OPERATING   WITH   URANIUM

FIG. 19

ARGON PLASMA BN HOLDER

3748-A
4044-A
4158-A
4182-A
4171-A
4200-A
4257-A
4272-A
4300-A
4333-A
4510-A

FIG. 20

A-CL PLASMA
BN HOLDER

3934 - Ca
3968 - Ca
4158 -1
4200 -1
3840 A
1044 -A
4102 -1
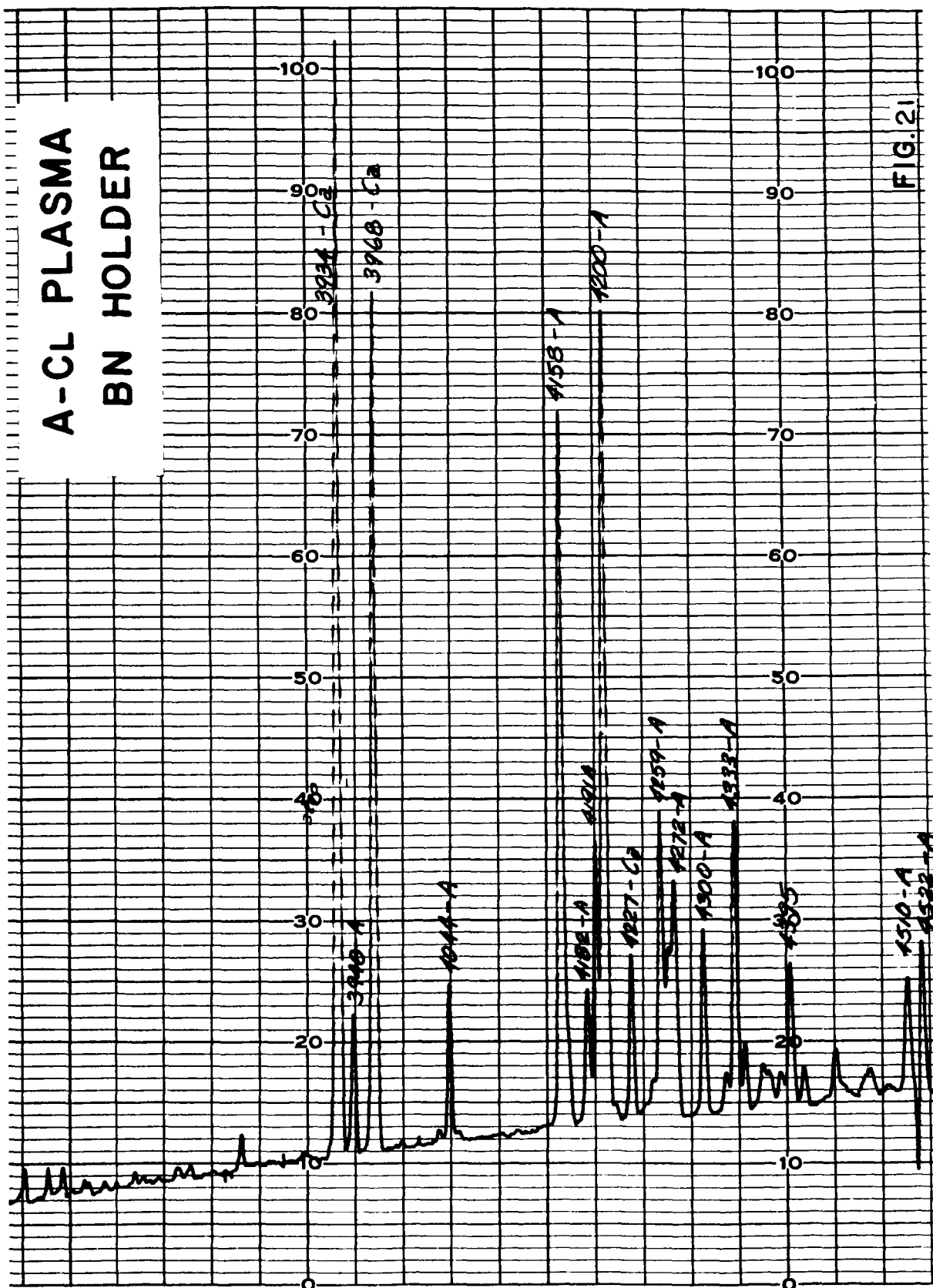4071 - Ca
4132 -1
4159 -A
4272 -1
4300 -A
4332 -A
3935
4510 -A
4522 -A

FIG. 2.1

40

A-CL PLASMA

URANIUM IN BN HOLDER

FIG. 22