NASA CONTRACTOR REPORT

NASA CR-1764

CURVED PERMEABLE WALL INDUCTION TORCH TESTS

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • MARCH 1971

1. Report No. NASA CR-1764	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle CURVED PERMEABLE WALL INDUCTION TORCH TESTS		5. Report Date March 1971
		6. Performing Organization Code
7. Author(s) Charles E. Vogel		8. Performing Organization Report No. None
9. Performing Organization Name and Address TAFA Division Humphreys Corporation Concord, New Hampshire 03301		10. Work Unit No.
		11. Contract or Grant No. NAS 3-13226
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		

16. Abstract

An experimental program was conducted with permeable walls and solid-rod feed techniques to simulate these design features of the Gas Core Nuclear Rocket. A refractory oxide and sodium were chosen as the referenced materials for the permeable wall and solid-feed, respectively. An induction coupled arc-plasma consisting of vaporized sodium was successfully sustained inside of a permeable wall through which nitrogen was being introduced. Wall gas mass flows of from 1,500 to 5,000 times that of the solid-feed material were achieved. Mixing profiles of gas flow indicated that no recirculation was experienced during plasma operation.

17. Key Words (Suggested by Author(s)) Induction plasma heating; Propulsion systems; Gas concentrations	18. Distribution Statement Unclassified - unlimited

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified	46	$3.00

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

FOREWORD

The work described in this report was done by the TAFA Division of the Humphreys Corporation under NASA contract NAS 3-13226. Mr. Chester D. Lanzo of the Lewis Research Center Nuclear Systems Division was the NASA Project Manager.

TABLE OF CONTENTS

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By Charles E. Vogel

SUMMARY

An experimental program was conducted which included the design, materials selection, and operation of an induction plasma torch incorporating permeable walls and solid-feed techniques. This program achieved simulation of these design features of a Gas Core Nuclear Rocket. Several designs were investigated and experimental data obtained for each of these designs. A materials evaluation program resulted in a refractory oxide and sodium being chosen as the referenced materials for the permeable wall and solid-feed respectively. During actual laboratory testing it was found that extremely stable operation could be achieved with all of the gas flow in the torch being introduced through the permeable wall. Additionally, it was possible to sustain a plasma consisting entirely of vaporized sodium. This plasma ball was suspended inside of a permeable wall torch in which nitrogen was being introduced through the walls. The mass ratio of nitrogen to sodium obtained in these experiments was from 1,500/1 to 5,000/1. Mixing profiles of the gas flow with an argon core operating inside of an air cooled permeable wall revealed that no recirculation was experienced in this configuration when a plasma was present. During cold flow the amount of circulation was considerably less than that previously experienced in a coaxial flow torch. These mixing patterns coupled with the high mass ratios obtained during the solid-feed operation indicate that the current design for fuel containment in a coaxial flow Gas Core Nuclear Rocket is realistic.

INTRODUCTION

The design of the Gas Core Nuclear Rocket (GCNR) includes the provision for adding solid fuel material into the reactor cavity where it is vaporized and becomes a part of the fissioning ball of fuel. There is also provision for introducing the coolant-propellant gas through the walls of the reactor chamber where it is heated by radiation from the fissioning ball of fuel and then exhausted through a nozzle. (Figure 1) Previous work with the induction plasma simulator[1,2,3] has been limited to a coaxial flow gaseous core simulator where mixing and temperature distributions were studied at various core gas to propellant flow ratios, scale-up to 1,000 kW, and diameters up to six inches. This report describes experimental work which added the solid-feed and permeable wall features to the induction plasma simulator.

DESIGN CONSIDERATIONS

Solid-Feed

In an operating induction coupled plasma torch it has been found that a number of materials can be vaporized and subsequently ionized to form the plasma simulating the fuel of the GCNR. By properly selecting the materials and techniques for introducing them into the plasma, it is possible to gain information as to how the uranium can be fed into the GCNR. Three basic classes of materials, gases, salts, and metals, have been considered for these simulation studies. Different types of injection systems must be used for each of these different classes of materials and, therefore, the design of the system must take into account the kind of materials that are to be used. A more thorough discussion of the specific materials utilized in this program is included in a subsequent section of this report.

The introduction of gases into the plasma torch to form an arc-plasma ball is typically performed by utilization of a device called a gas mixer which is positioned in the torch base. This device has several sets of holes through which gas can be introduced either parallel to, perpendicular to, or swirling around the major axis of the torch. All of TAFA's standard production induction coupled plasma torches introduce gases through some combination of these holes. Figure 2 is a schematic drawing of a typical torch. In more sophisticated torch designs, a sheath gas flowing around the plasma ball can be introduced by including some sort of a separator within the torch around the plasma ball as shown in Figure 3. One of the advantages of this geometry is that one type of gas can be introduced into the plasma ball and a second type introduced around the plasma in a coaxial flow mode. A third design for gas injection into a plasma torch, which even more closely simulates the requirements of the GCNR, is shown in Figure 4. This design provides a water cooled probe inserted into the torch in such a way that the gas introduced through this probe is introduced directly into the plasma ball. Additional gases can then be introduced at other appropriate positions throughout the torch. Previous work conducted in support of the GCNR program has utilized both the standard gas mixer and the sheath type torch.[1,2,3] Recent studies have been made with the injection probe design and are described in the experimental procedure portion of this report.

For the introduction of salts into the plasma, an entirely new feed system had to be designed. Initially this consisted of a graphite rod with a small (approximately 1/8" diameter) hole drilled along its axis through which salts could be injected. Sufficient material to sustain a plasma could not be introduced in this way so a crucible was inserted near the base of the torch from which a sufficient quantity of salt could be vaporized. A typical torch with a crucible feed is shown in Figure 5. Rather large diameter crucibles were used (i.e. a 1 1/2" diameter crucible in a 3" diameter torch) so that large surface areas would be presented to the plasma and sufficient vaporization rates could be obtained.

Since the design of the GCNR and the ultimate goal of this development program is to introduce the plasma forming material in the form of a solid rod, several injection techniques for the introduction of solids to the plasma were designed. Initially a 1/8" diameter metal rod was inserted inside of a 1/4" diameter graphite rod and this assembly placed into the torch. The purpose of the graphite rod in this design was to contain the metal which would become molten prior to vaporization. It was recognized that some graphite would vaporize, but this did not seem detrimental to the goals of the test. A second design consisted of a larger diameter graphite rod, approximately 1/2" in diameter, in which a funnel-shaped cavity was made at the exit end. This rod also had a hole drilled through its entire length. The goal here was to feed the metal in the form of a small diameter rod up through the central hole into the funnel-shaped area where the material would become molten and then vaporize, forming the plasma inside of the torch. The funnel-shaped end provided a larger surface area for vaporization and thereby a larger feed rate of material into the plasma. A third design for metal injection was the utilization of a water-cooled copper probe which contained a central hole along its axis through which metal wire could be fed. The concept here was to maintain the metal below its melting point out to the end of the water cooled section and then have a small length exposed where melting and vaporization could occur into the plasma ball.

Permeable Wall

The conceptual design of the GCNR includes the provision for introducing the coolant-propellant gas through the wall of the reactor chamber in some manner. This may be through an open mesh, shutters, a permeable material, or perhaps some combination of these or other appropriate techniques. For the purposes of laboratory experimentation using the induction coupled plasma torch, a permeable wall was selected as the design technique to be utilized. By proper design it was possible to introduce at selected axial positions along the torch various amounts of gas flow through the wall or even different gases if so desired.

The initial model was a straight parallel wall device as shown in Figure 6. The goal of designing this device was to duplicate a standard torch, about which operating conditions are well known, except for the addition of the permeable wall. This simple configuration would serve as a material evaluation device before more complicated shapes were fabricated and also for obtaining gas mixing patterns within the torch that could be compared directly to mixing profiles previously obtained in a solid-wall coaxial flow torch.[3]

In the utilization of low electrically conductive materials (generally considered non-conductors) the design of the parallel wall torch was rather straightforward inasmuch as a cylinder of material could be simply inserted in the torch. When electrically conductive material was used, however, the design became much more complicated and required segmentation of the wall so that a complete electrical path was not existent around the circumference of the torch. Figures 7 and 8 illustrate the design and an actual photograph of such a segmented walled torch.

The design of a curved-permeable wall torch incorporated a cylinder, as previously described, which had curved inserts placed in each end. Figure 9 shows two configurations utilized. Because non-segmented graphite was used for the curved inserts, it was necessary to have sufficient spacing between them to prevent direct coupling to the induction coil.

MATERIAL SELECTION

Solid-Feed

A number of factors dictated the materials selected as solid-feed candidates. The ease of ionization, the boiling point, the liquidus range, the heat of vaporization, and the toxicity were all prime considerations. Table I lists the candidate materials and notes some of their properties which made them desirable for this application.

For the direct injection of gas into the plasma, argon was the obvious choice since it is one of the most readily ionized gases and considerable experience has been gained with argon in induction plasma torches. Sodium chloride was chosen for the salt injection technique primarily because of the ease of ionizing sodium. For the solid-feed system, zinc was chosen because of its low latent heat vaporization. Subsequently, with the completion of an adequate ventilation system sodium metal was employed. Aluminum, manganese, and 50/50 tin/lead solder were also tested, but none of these performed as well as the materials noted above. Obviously the induction plasma simulator has an additional electrical restriction not present in the GCNR. That is, the electrical conductivity and associated temperature of the arc-plasma region must be compatible with the available power supply. In the case of the tests conducted in this program the power supplies available limited materials selection to materials which would ionize relatively easily at low vaporization temperatures.

Permeable Wall

The primary material properties which must be evaluated for application as a permeable wall include the following: permeability, electrical conductivity, thermal stress, melting point, fabricability, and mechanical strength. Initially the degree of permeability required for successful operation was not known however TAFA has had considerable experience with the design and operation of permeable anodes used in dc plasma torches.[4,*] It was desirable to have low electrical conductivity inasmuch as the application was inside of an induction coil. The general category of ceramics rather than metals was therefore surveyed. Since it was known that the material would experience rather severe thermal stress loadings due to the large radiant load of the plasma on the one side and cool gas on the other, the resistance to thermal stress and the high temperature behavior were of primary concern. It was also desirable to find a material which could be readily fabricated into various shapes and would be able to withstand being held in a torch assembly with various seals.

While it is not surprising that no material was found that perfectly met the criteria as described above, a number of materials were found which met enough of the criteria to warrant testing. These materials included three different types: alumina, glass bonded silica, and a material known as AlSiMag** (this material is two parts MgO, two parts Al_2O_3 and five parts SiO_2). Table II lists the properties and suppliers of the specific materials evaluated. In addition graphite was considered as a candidate in spite of the electrical problems because of its superior qualities in all other aspects. The alumina and silica materials were available only as right circular cylinders with wall thickness of approximately 7/16". This is as thin a wall as the manufacturers can currently fabricate successfully. It was possible to purchase the AlSiMag material with a wall thickness down to 1/4" and graphite components were machined with wall thicknesses as thin as 1/8". The alumina and silica cylinders are fabricated as filter media and therefore the permeability is controlled by the manufacturer in the production of these pieces. In the case of the AlSiMag these parts are made as refractory bodies for various applications and no attempt is made to control permeability. This material had, however, been successfully used by Gruber Pfendor, and Eckert at the University of Minnesota in studying a transpiration cooled constricted arc.[5]

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*The anodes in these devices have been found to require extremely uniform porosity (as measured with micro pitot tube surveys of effluent gas) with pore sizes in the range of 10-50 microns and thicknesses governed by pressure drop and thermal considerations. By proper design the dc arc can be struck directly to the anode surface without erosion or overheating.

**Registered trademark, American Lava Corporation.

All of the AlSiMag material used in this program was in the form of right circular cylinders which had been ground on the o.d., however, both ground and unground i.d. cylinders were evaluated. Figure 10 shows a comparison of permeability between an unground and ground cylinder. As can be noted in this figure, no great change in permeability can be observed after grinding. There are however large differences in the permeability from cylinder to cylinder. Figure 11 shows a cylinder in which rather poor uniformity is noted. During operation of a cylinder with this flow distribution, the arc-plasma tended to move toward the area of low permeability. Figure 12 shows what is considered a satisfactory permeability map. In cylinders of this type a stable plasma centered in the chamber can be maintained. It therefore became necessary to map the permeability and select the individual cylinders used for this program. In addition to this selection based on permeability, there were definite changes in the operating characteristics of ground and unground cylinders and in torches which contained crucibles or baffles. A complete discussion of these observations is given in the experimental procedure portion of this report.

AUXILIARY EXPERIMENTAL EQUIPMENT

In addition to the various torch configurations defined in separate sections of this report, a power supply which operated at 4 MHz at plate powers up to 89 kW was available. A photograph of this equipment is shown in Figure 13. Gas flows were controlled by standard flow meters. Heat balance measurements were conducted by measuring water flow rates and temperature changes across all of the possible heat loss components in the system. The power available out of the torch was calculated to be the difference between measured electrical input and these measured losses. This technique has been repeatedly verified by the insertion of a calorimeter in place of the torch and conducting complete heat balances. Specific details of this procedure have been previously described and are included in Reference 1.

EXPERIMENTAL PROCEDURES

Solid-Feed

Initial experiments to evaluate techniques for inserting solid-feed material into the plasma were conducted in a clear, solid-wall torch. This permitted observation of the feed mechanism and the plasma ball. Experiments were conducted using zinc, aluminum, and a 50/50 tin/lead solder. The metal was introduced into the plasma as a 1/8" diameter wire inside of a 1/4" diameter graphite rod. In these initial tests no effort was made to continuously feed the material into the plasma. The end of the rod was positioned just into the plasma ball so vaporization would occur directly into the plasma. These tests revealed, as the material characteristics would indicate, that zinc vaporized and subsequently ionized more easily than the other materials tested; however, sufficient material could not be vaporized to sustain the plasma. Figure 14 is a photograph of the clear wall torch operating with this zinc metal wire feed.

In addition to the vaporization and ionization of metals, it seemed appropriate to consider a number of salts as materials that would easily vaporize and subsequently ionize to form the plasma. The best candidates for this would be materials that have low melting points, ionization potentials, and high conductivity as a plasma. Sodium chloride was chosen and subsequently used in actually operating a plasma torch. Since the results obtained with zinc and the initial tests with sodium chloride indicated that not enough material was being vaporized to sustain a plasma, a large diameter crucible was utilized so that more material would be available to the plasma. Figure 15 shows a photograph of the test setup of the clear wall torch with the crucible inserted inside and a second photo of this torch in operation with sodium chloride being vaporized from the crucible. It was possible with the configuration shown to sustain a plasma made essentially from the sodium chloride. The torch configuration utilized to demonstrate this consisted of a 1 1/4" o.d. graphite crucible in which the sodium chloride was placed. This crucible was positioned inside of a 1 1/2" i.d. quartz tube with the top of the crucible at the same axial position as the first turn of the induction coil wrapped around the quartz tube. A standard gas mixer was utilized in the base of the torch. The operational procedure consisted of igniting the torch while flowing argon through the gas mixer; subsequent to the attainment of steady operating conditions, nitrogen was introduced through the mixer as the argon was slowly turned off. It was observed during the switch over from argon to nitrogen that the argon plasma which was initially in the torch became much smaller and was centered about two inches above the crucible. Concurrently, a bright yellow glow could be seen forming on top of the crucible over the molten sodium chloride, which was the beginning of a sodium plasma. As more nitrogen was introduced and less argon was available, the sodium plasma increased in size until a crucial point was reached where the argon plasma went out and a bright yellow-orange sodium chloride plasma replaced it. Extremely stable operation in this mode was obtained at a plate power level of 6 kW with 100% nitrogen flowing around the sodium chloride plasma at flows up to the maximum permitted by this particular torch configuration (approximately 500 SCFH). In addition to running the torch in this mode with 100% nitrogen, successful operation was also obtained with 30% hydrogen in the nitrogen at 28 kW.

Several independent experiments and observations were made to confirm the fact that a sodium chloride plasma was formed. One of the first observations was that the typical yellow-orange color of sodium was obtained in the plasma when the switch was made from argon to nitrogen and subsequently with the addition of hydrogen. In addition, by observing the electrical meters on the induction power supply, it was apparent that there was a drop in the total power requirements as the sodium chloride became vaporized and contributed to the plasma. A specific experiment was performed to further confirm the fact that a sodium chloride plasma was formed. In this experiment an empty crucible was placed in the torch and standard operating procedures conducted. Initially when 100% argon was introduced to the torch a plasma was obtained as in previous runs, however, as nitrogen was being added the torch extinguished when only 6% nitrogen was present in the argon. In this experiment the yellow-orange color attributed to the sodium was not observed and the argon plasma simply was reduced in size as nitrogen was added until extinguishment occurred. In all of these experiments the torch configuration, total gas flows, and power were held constant so that the effect of the individual variables could be observed.

All subsequent experiments with solid-feed were conducted utilizing some sort of a permeable wall in conjunction with the solid-feed and are discussed in a separate section of this report entitled, "Experimental Procedures -- Combined Solid-Feed, Permeable Wall."

Permeable Wall

The goal of these experiments was to operate a torch which contained a curved, permeable wall through which gas could be injected. Initial experiments, however, were conducted with a simple cylinder of the permeable material inserted in a torch to gain operating experience and to provide a simple method for materials evaluation. A standard TAFA Model 66 torch was modified to allow the insertion of a permeable wall inside of the torch body to conduct these experiments. Figure 6 is a schematic of this torch configuration. The permeable material available for these initial tests were alumina and glass bonded silica. These cylinders were 1.75" i.d. by 2.5" o.d. and were placed inside of the quartz tube of the TAFA Model 66 torch which has a 3" i.d. The induction coil around this quartz tube has a diameter of 3.5". This torch geometry gives a load to coil diameter ratio of 0.35 (assuming a 1.25" diameter arc, which is estimated from observations made during operation). This low load to coil diameter ratio results in rather poor coupling efficiency (50%) as compared to higher load to coil ratios normally used. The effect of this ratio can be seen in Figure 12 of Reference 1. Nonetheless successful operation of this torch was achieved. A standard TAFA gas mixer was used in the base of the torch to provide a gas flow into the plasma ball and additional gas flow was provided through the permeable wall. The maximum ratio of wall to gas mixer flow was approximately four to one. It was observed that the permeable wall gas flow had a pronounced effect on the diameter of the plasma. As the wall flow was increased, the plasma diameter decreased and finally extinguishment could be obtained by squeezing the arc to a point where the coupling efficiency was too low to sustain operation. Plate power levels of from 8 to 36 kW were successfully used. It was observed that the operation of these torches was extremely stable over the entire range tested. This indicated that the basic design and operational procedure of the permeable wall torch was sound.

These initial tests, as noted earlier, were performed using rather thick walled alumina and silica tubes and were, therefore, highly subject to thermal stress cracking. In general, the alumina tubes tended to crack circumferentially at the axial position of the first turn of the induction coil. This is the point where the plasma is the hottest (see Figure 35 in Reference 3) and therefore the greatest stress is placed upon the wall. In an attempt to alleviate this problem, water-cooled segmented metal walls (see Figures 4 and 21 of Reference 3) were inserted inside of the permeable wall which extended axially up from the base of the torch above the first turn of the induction coil.

Unfortunately, this did not ease the problem but simply moved the position of the crack from under the first coil up to the position at the end of the metal wall which was the point of highest thermal stress in this configuration. Since no noticeable improvement in performance was gained with this metal wall, all subsequent experimentation performed with the permeable wall was conducted without any metal separator inside. In spite of the persistent cracking problem it was possible to successfully complete several experiments without failure. However, it was evident that some other material had to be found.

Testing of the glass bonded silica cylinders revealed a slightly different kind of a problem. While these cylinders did not seem to crack from thermal stress in the same way as the alumina cylinders, they did tend to spall immediately upon ignition of the torch. During the initial stages of the run small chips of material, which spalled off the i.d., were ejected from the exit of the torch. This phenomenon persisted until thermal equilibrium in the torch was reached. The loss of material was severe, amounting to approximately 1/8" of the wall thickness for each run. Apparently the cause of this difficulty was that the glass bonding material used in these cylinders was not capable of withstanding the temperature and/or the thermal gradients imposed upon the material. Discussions with the vendor failed to produce any improvement in the bonding material for these cylinders.

Because it was believed that silica would make an ideal material for this application, an extensive survey was made of various suppliers of silica materials. Small discs of permeable silica material are manufactured for use as filter media and it was hoped that someone would be able to fabricate this material in a shape compatible with the needs of this program. Several vendors indicated interest in the problem and conducted in-house reviews to determine whether or not they could meet the requirements. They have all concluded that the fabrication of such items is extremely difficult if not impossible with presently known processing techniques.

An AlSiMag material (known in the ceramic industry as Cordierite) was also evaluated. This material is made up of two parts MgO, two parts Al_2O_3, and five parts SiO_2. It has a very low thermal expansion coefficient and a high resistance to thermal shock. Since it is produced as a refractory material for a number of uses in the ceramic industry, there is no attempt on the part of the manufacturer to control the permeability, as noted in a previous section of this report under material selection. It was found that the permeability of this material did vary somewhat from piece to piece and even within a piece. It became necessary, therefore, to make permeability maps on each piece to evaluate the uniformity of the piece to determine if it were acceptable for testing purposes. If cylinders were used that had areas of low permeability compared to the remainder of the cylinder, it was observed that the plasma ball would be displaced off center inside of the torch toward that area of low permeability. This caused considerable coil to plasma arcing through the wall and subsequent failure of the wall at the point of arcing.

A second observation made concerning the AlSiMag material was that the surface glaze had to be ground off for successful operation. All of the pieces received from the vendor were ground on the o.d., however, not all of them were ground on the i.d. While grinding of the i.d. did not seem to make significant changes in the permeability maps, as noted in Figure 10, there was a significant difference in the operating characteristics of the torch. When unground i.d. surface cylinders were utilized, very unstable operation of the plasma torch was observed. The plasma ball would shift erratically inside of the cylinder and arcing would occur from the plasma to the walls of the torch; however, on cylinders that were ground, this phenomenon did not seem to be present. It was noted that in the glaze which was ground off there were a number of dark spots presumed to be contaminants left over from the extrusion process used to fabricate these cylinders. It seems reasonable to assume that this surface contamination raised the electrical conductivity of the surface of the cylinder and/or produced conductive gases which caused the erratic behavior of the plasma.

Since those characteristics of the AlSiMag material which created difficulties in successfully running a plasma torch could be defined, it was possible by the selection of only ground cylinders, which had relatively uniform permeability maps, to conduct reproducible and meaningful experiments.

One of the most important questions concerning the use of permeable walls was whether they improved the recirculation or mixing occurring within the plasma torch. Techniques previously developed for measuring concentration profiles in a binary induction plasma system were applied to measure the mixing within a permeable wall torch.[3] These experiments were performed utilizing the alumina cylinders. The torch geometry used in these experiments was kept as close as possible to the geometry of the system previously used for concentration profiles with the exception of the addition of the permeable wall. A comparison of the two torches used is shown schematically in Figure 16. The referenced earlier work revealed that rather gross recirculation occurred during cold flow; however, when a plasma was present virtually no recirculation was observed. The concentration profiles obtained in this work utilizing a permeable wall indicate that little recirculation is present during cold flow and again virtually none is observed when a plasma is present. Figure 17 shows the comparison of cold flows in a coaxial flow torch and in a torch containing a permeable wall. Figure 18 shows a comparison of the mixing of these two torches when a plasma is present. It can be noted that the 40 and 50% mixing lines in the cold flow region of the permeable wall torch do show a dip near the axis indicating some recirculation, however, this mixing is not nearly as pronounced as in the solid-wall torch.

Curved Permeable Wall

Three basic designs have been utilized in the construction and operation of curved, permeable wall torches. One consists of a segmented, graphite wall torch with solid curved inserts at each end to produce the curved configuration; the other two designs involve the utilization of a cylinder of AlSiMag which has two transpiration cooled graphite inserts at each end to produce the curved configuration. The only difference in the two AlSiMag graphite torches is the length of the parallel wall section of the AlSiMag material. Figure 19 is a photograph of the components of the curved graphite torch. Figure 9 shows the AlSiMag-graphite, curved, permeable torch.

The permeable, graphite wall torch was segmented into sixteen sections with gas passages the length of each section through which gas could be introduced into the torch chamber. Inside and at each end of this permeable cylinder, graphite inserts were placed to provide the curved wall configuration. Argon was introduced through a gas mixer at the base of the torch and was also introduced through the walls as the coolant. In the experiments conducted with this torch approximately 45% of the total gas flow was introduced through the permeable wall with completely successful operation. Table III itemizes the operating conditions and heat balance obtained for two typical runs made with this torch. Figure 20 is a photograph of this torch in operation.

The AlSiMag-graphite, curved, permeable wall torch was constructed in such a way as to permit individual gas control to each curved end section and to the cylindrical section at the middle of the torch. During the operation of this torch the gas flows were varied in these three sections until optimum operating characteristics were obtained. These optimum operating conditions are tabulated in Table IV. It can be noted in the drawing of this torch shown in Figure 9 that provision was made for the introduction of gas to a gas mixer at the base of the torch, however, it was found that this was not necessary and successful operation was achieved with all of the gas flow in the torch coming through the permeable sections.

Combined Solid-Feed, Permeable Wall

Subsequent to performing experiments with the solid-feed and with the permeable wall these two principles were combined into a single torch. In addition the design feature of a curved wall was added. Once again the initial experiments performed combining these principles was performed with a solid-feed made of a 1/8" diameter wire inserted inside of a 1/4" diameter graphite rod. This rod was positioned inside the torch in such a way that the end of the rod was just inside of the plasma ball. No gas mixer was used in these experiments and the torch was ignited by simply passing argon through the permeable wall. Zinc was used as the solid-feed material in these experiments and it was apparent from the color of the exit plume that zinc was being vaporized and was contributing to the plasma. However as in the earlier experiments sufficient zinc could not be vaporized to fully sustain the plasma. If for example nitrogen were introduced in addition to the argon coming through the wall, torch extinguishment would occur.

Because of the highly successful operation previously obtained using sodium chloride as a solid-feed material, a permeable wall was constructed utilizing an AlSiMag wall and a crucible containing sodium chloride. It was known that sodium chloride would attack the AlSiMag material and cause failure, however, because large quantities of gas would be being passed through the AlSiMag it was decided to attempt this experiment. Figure 21 is a photograph of this torch in operation. It was possible with this configuration to obtain several minutes of steady-state operation before the attack of the sodium chloride on the AlSiMag material caused wall failure. This experiment clearly demonstrated that a plasma could be sustained being feed virtually entirely from a solid material with the entire gas flow being introduced through a permeable wall.

Subsequent to installing adequate ventilation and safety equipment in the laboratory the experiment previously defined utilizing sodium chloride in an AlSiMag permeable wall torch was reproduced using sodium metal. Because chlorine tends to inhibit the formation of a plasma, it was believed that a smaller diameter crucible of sodium could be utilized in these experiments. A series of runs were conducted in an attempt to optimize the diameter of sodium being presented to the plasma. Figure 22 shows the two designs for the sodium injection probes that were used. It was found that when 1/16" diameter sodium feed was used it was impossible to sustain operations without the presence of argon in the torch. However, when the 5/32" diameter sodium feed system was used it was possible to sustain operation with powers as low as 8 to 10 kW with only nitrogen being introduced through the permeable wall. It is of interest to note that when the 1" diameter crucible was used that once again a sodium plasma with nitrogen flow through the wall could not be sustained. These results indicate the ease of ionizing sodium and the existence of a sodium plasma but demonstrate that too much sodium is as detrimental as too little sodium. It is believed that the reason for too much sodium being detrimental is that the large quantity of sodium vapor tends to reduce the temperature of the plasma to the point where the conductivity isnot sufficient to sustain operation.

The operating procedure followed in conducting these sodium plasma experiments was to ignite the torch with a standard dc arc starter while flowing argon through the wall. Subsequent to obtaining an argon plasma, nitrogen was added through the wall as the argon flow was reduced and finally turned off. This procedure confirmed the presence of a sodium plasma since a nitrogen plasma could not be sustained at these power levels without the presence of sodium. Additionally, during several experiments the argon flow through the wall was completely turned off before any nitrogen flow was begun. Even in this condition, with only sodium being vaporized from the injection probe and no gas flowing through the wall, the plasma continued to be sustained. The power requirements were identical during this mode of operation as well as when nitrogen flow was being sustained through the permeable wall.

Several runs were made in an attempt to get quantitative information as to the nitrogen sodium mass flow ratios. These experiments were conducted with the 5/32" diameter sodium injection probe. A sodium consumption rate of approximately 0.1 grams/min. was experienced while flowing 500 SCFH of nitrogen through the wall. This yields a mass flow ratio of 2720 to 1 of nitrogen gas to sodium. It must be recognized that since the sodium flow rate was so low and the experiment was performed over short periods of time of one to two minutes that small errors in the computation of sodium flow would greatly affect this ratio. It is believed, however, that the measurement of sodium consumption was at least within a factor of two in either direction, therefore, it is safe to assume that the mass flow rate obtained was no lower than 1,500 to 1 and probably no higher than 5,000 to 1. This range is extremely encouraging in relation to the goals of GCNR.

During the course of conducting these varied experiments, it was observed that if a crucible were placed in a permeable wall torch it was possible to produce a rather stable plasma inside of permeable walls which had rather varied permeability maps. This phenomenon was observed whether the crucible contained some material contributing to the plasma or not. It can be concluded therefore that the presence of a baffle plate, which is essentially what the crucible was in these experiments, produces some smoothing of the velocity profile around the baffle thereby centering the arc. This effect was so pronounced that permeable walls which had rather poor permeability maps and would not achieve stable operation without a crucible could be run quite easily if a crucible were installed. The tendency for the plasma ball to move toward the area of low permeability could still be observed; but, the erratic behavior and arcing was virtually eliminated by the presence of the crucible or baffle plate.

CONCLUSIONS

The goal of this program to support a plasma from a solid-feed inside of a permeable wall torch has been demonstrated. Specific conclusions which support or supplement this are as follows.

1. A permeable wall can be cooled from gas being passed through it while an induction coupled plasma is operating inside of the wall.

2. An arc-plasma comprised of a vaporized solid can be successfully sustained.

3. By combining the two operations noted above, it is possible to achieve a mass flow through the wall some 1,500 to 5,000 times that of the vaporizing solid feeding the plasma.

4. Mixing profiles of the gases in a permeable wall torch indicate no recirculation. These mixing patterns coupled with the high mass ratios noted in No. 3 above indicate that the current design for fuel containment in a coaxial flow gas core nuclear rocket is realistic.

REFERENCES

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

2. Thorpe, M.L., "Radio-Frequency Plasma Simulation of a Gas Core Reactor," Journal of Spacecraft and Rockets, Vol. 6 - Number 8, August 1969.

3. Dundas, P.H., "Induction Plasma Heating: Measurement of Gas Concentrations, Temperatures, and Stagnation Heads in a Binary Plasma System," NASA CR-1527, February 1970.

4. TAFA Bulletin LP19, "Transpiration Cooled Plasma Torch," January 1969.

5. Gruber, G.G., Pfender, E., and Eckert, E.R.G., "Experimental Study of a Transpiration-Cooled Constricted Arc," University of Minnesota, ARL 68-0023, February 1968.

TABLE I

SOLID-FEED MATERIAL CANDIDATES

Material	Molecular Weight	Melting Point ^{o}C	Boiling Point ^{o}C	Latent Heat of Vaporization KgCAL/g-Atom	Ionization Potential Volts
Aluminum	26.97	659	2500	69.6	5.96
Lead	207.21	327	1740	42.5	7.38
Nickel	58.71	1455	2910	89.4	7.61
Tin	118.75	232	2750	64.7	7.30
Zinc	65.39	419	907	27.3	9.36
Iron	55.85	1539	3070	81.3	7.83
Sodium Chloride	58.44	801	1465	40.7	
Sodium Hydroxide	40.00	320	1390	34.5	
Potassium Hydroxide	56.11	400	1330	30.9	
Sodium	22.99	97.5	883	24.1	5.12
Potassium	39.102	62.3	760	18.9	4.32

TABLE II

PERMEABLE MATERIALS CANDIDATES

Material	Permeability SCM-AIR/Ft^2/1 1/2"/2"(H_2O)	Thermal Expansion ^oC (25-300^oC)	Supplier
Alumina	3	10.2×10^{-6}	Ferro Corp.
	3	10.2×10^{-6}	Norton Co.
Glass Bonded Silica	3		Ferro Corp.
AlSiMag 447*	Variable**	1.7×10^{-6}	American Lava Corp.
Graphite	Variable	12×10^{-6}	National Carbon

*Cordierite (2 parts Alumina, 5 Silica, and 2 Magnesia; AlSiMag is the registered trademark of American Lava Corp.)

**Varies within a piece. See Figures 10, 11 and 12.

TABLE III

OPERATING CONDITIONS, CURVED, GRAPHITE, PERMEABLE WALL TORCH*

	Run A	Run B
Plate Power (kW)	33.3	32.6
Power Distribution (%)		
Power Supply	26.1	26.9
Coil	2.7	1.9
Load**	71.2	71.2
Flow Through Gas Mixer (Argon-SCFH)	337	456
Flow Through Wall (Argon-SCFH)	284	350

*3" Diameter wall in 16 evenly spaced segments.

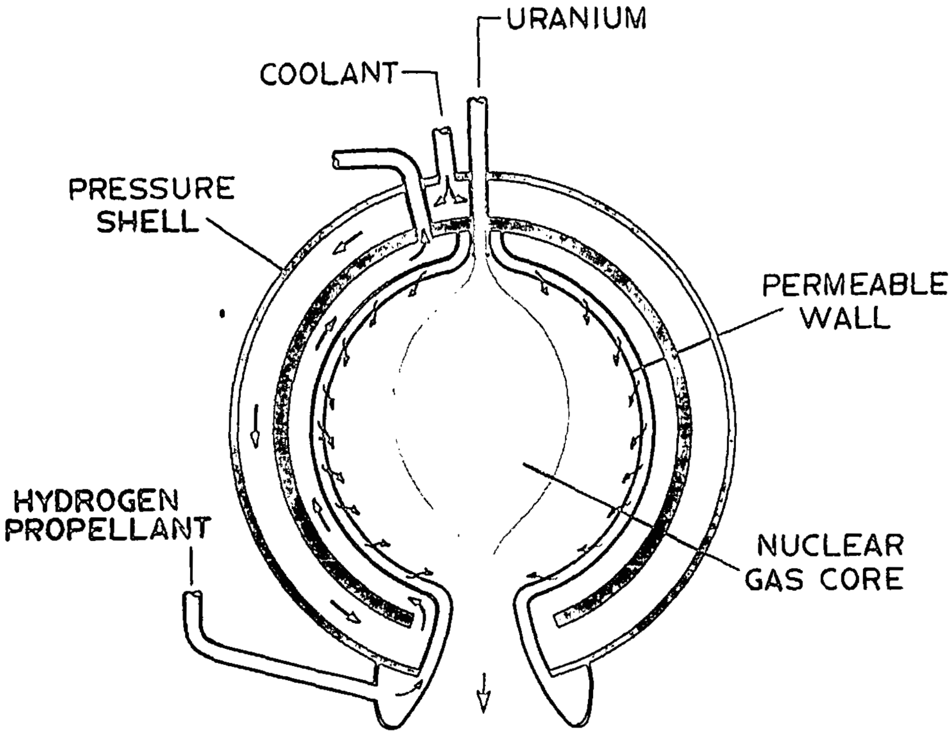
**This includes power in the plasma plus any that may have been absorbed in the graphite wall. An independent study of the segmented wall indicated that over 50% of this power was in the plasma.

TABLE IV

OPTIMUM OPERATING CONDITIONS
CURVED PERMEABLE WALL*

Argon Flows (SCFH)	
Rear Curved Section	170
Side Wall	1200
Exit End Curved Section	85
Mixer	0
Power (kW)	30

*Configuration was AlSiMag cylinder with permeable, curved graphite inserts at each end.



SCHEMATIC OF GAS CORE NUCLEAR ROCKET

FIG. 1

STANDARD TAFA MODEL 56 TORCH

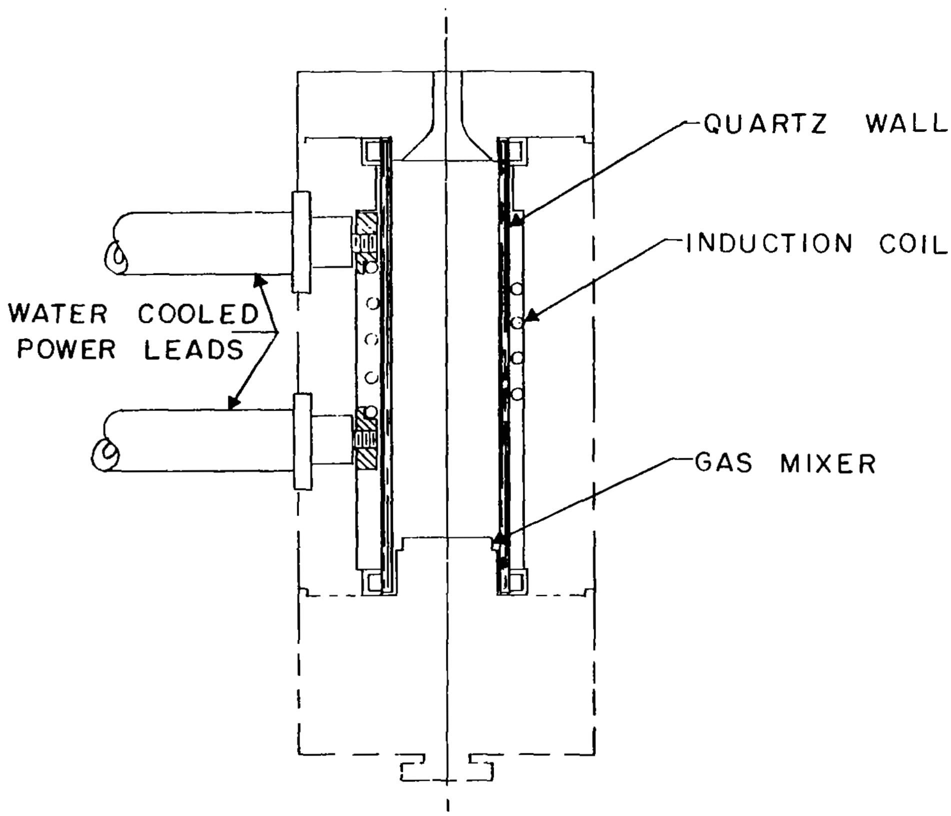


FIG. 2

COAXIAL FLOW TORCH

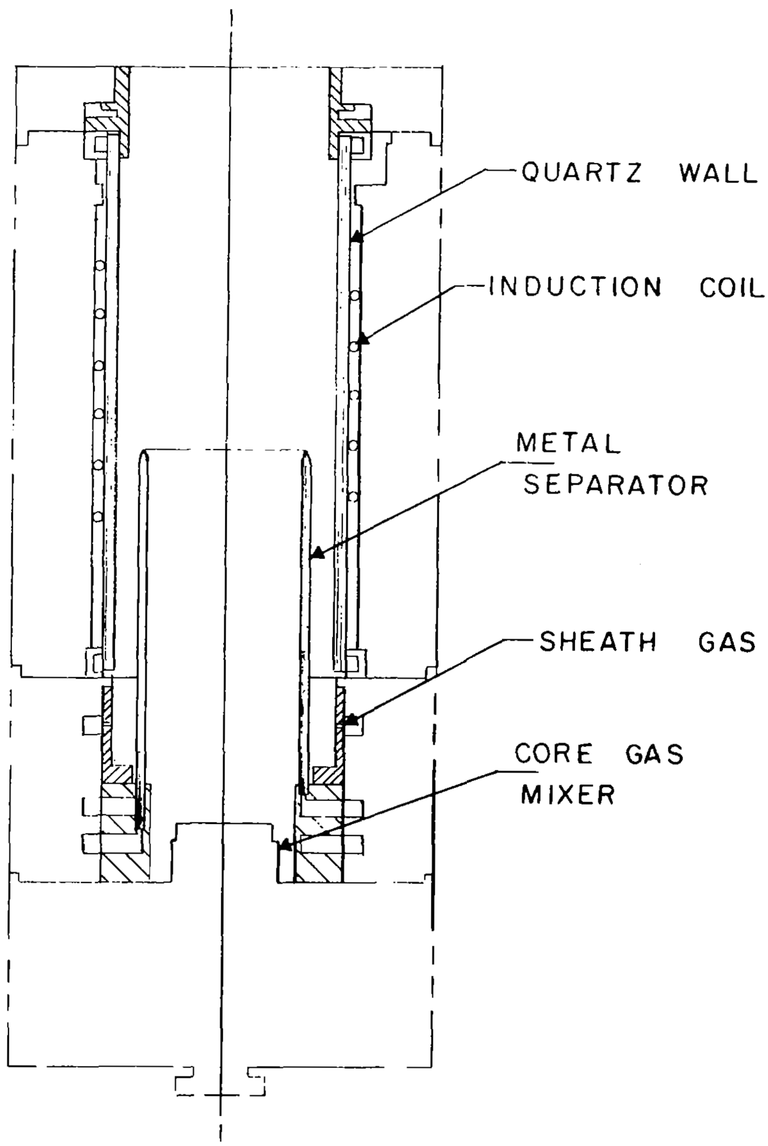


FIG. 3

PERMEABLE WALL TORCH
WITH GAS INJECTION PROBE

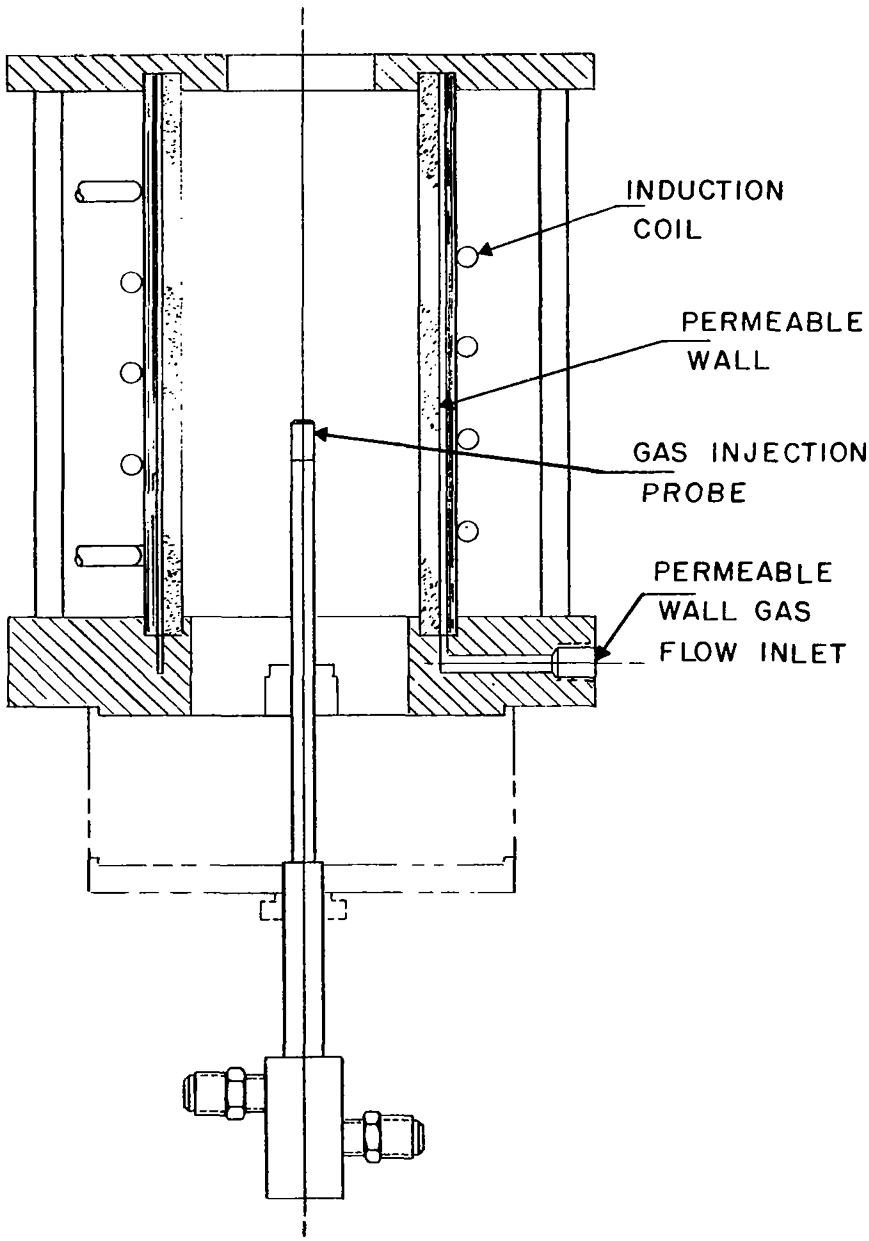


FIG. 4

QUARTZ WALL TORCH
WITH
CRUCIBLE FOR SALT FEED

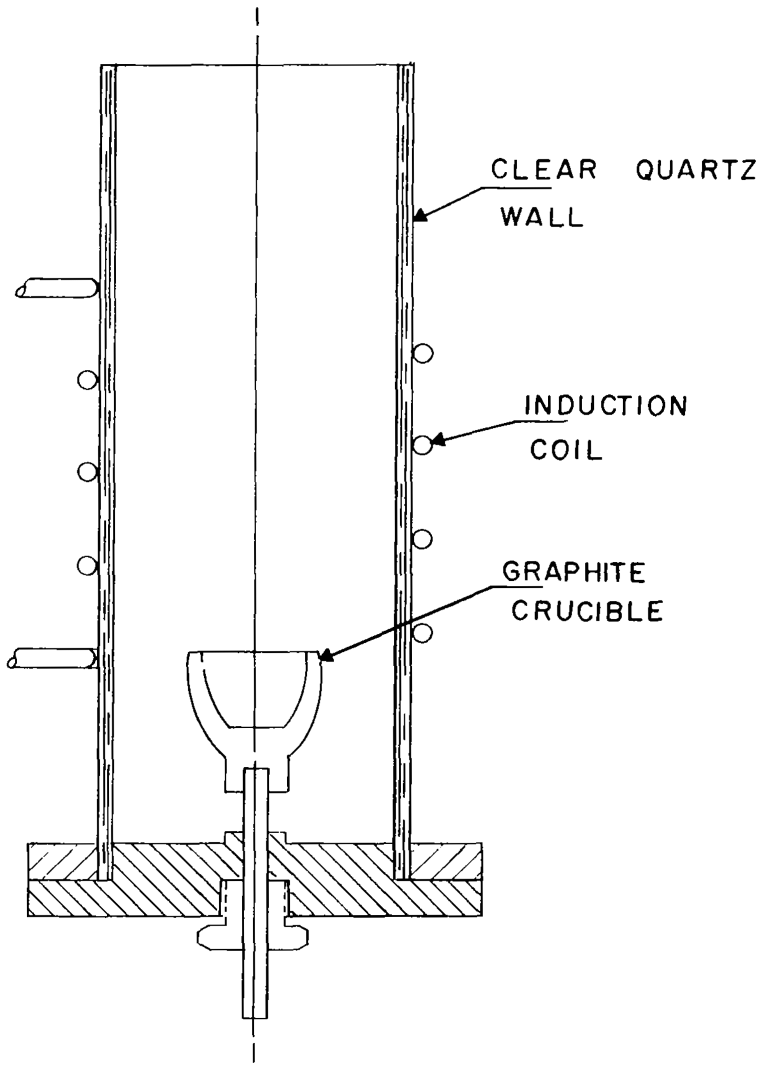


FIG. 5

PERMEABLE WALL TORCH

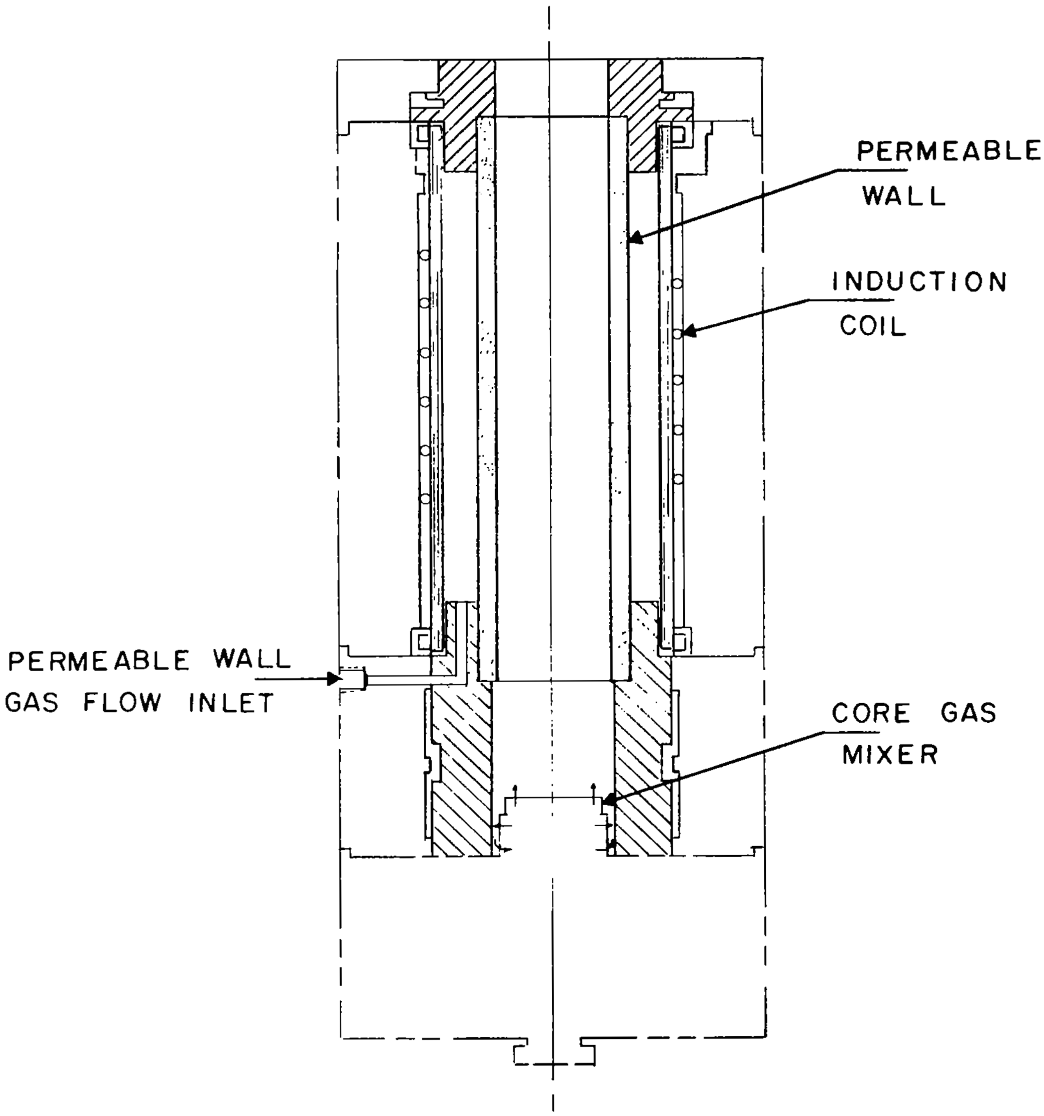


FIG. 6

GRAPHITE SEGMENTED WALL TORCH

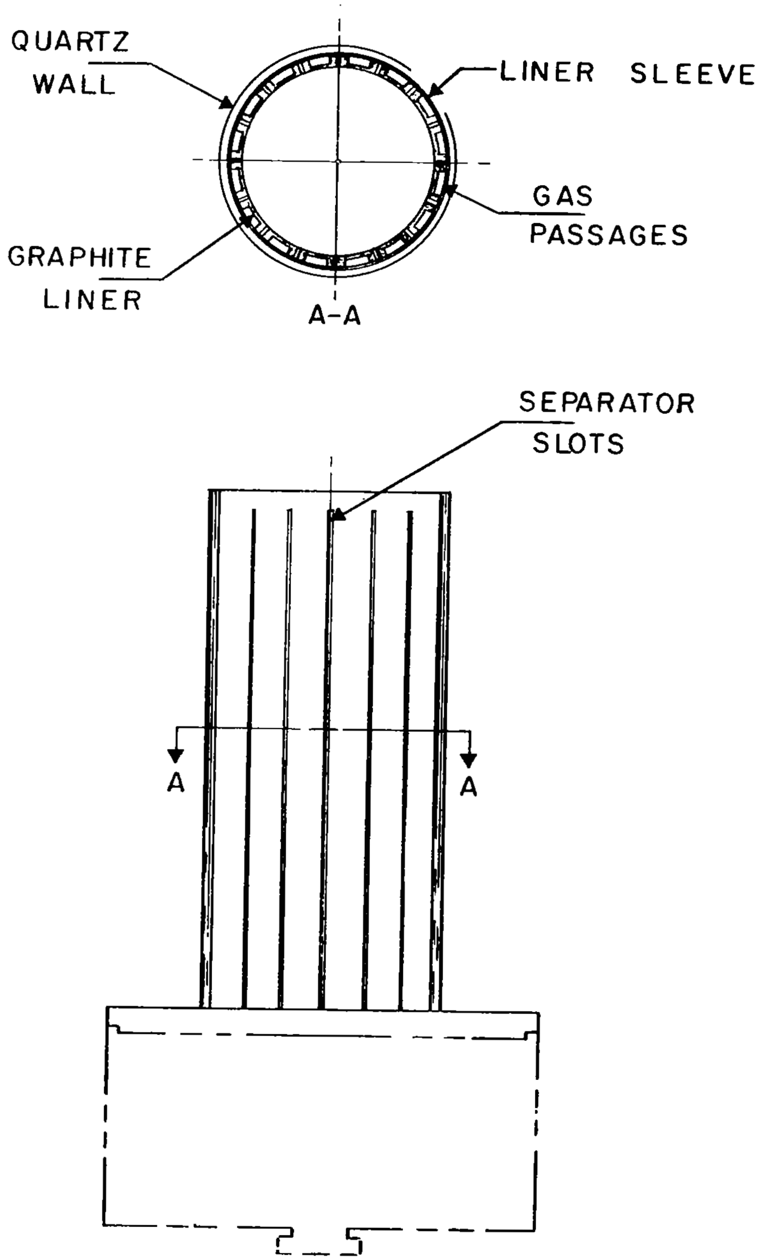


FIG. 7

SEGMENTED WALL TORCH

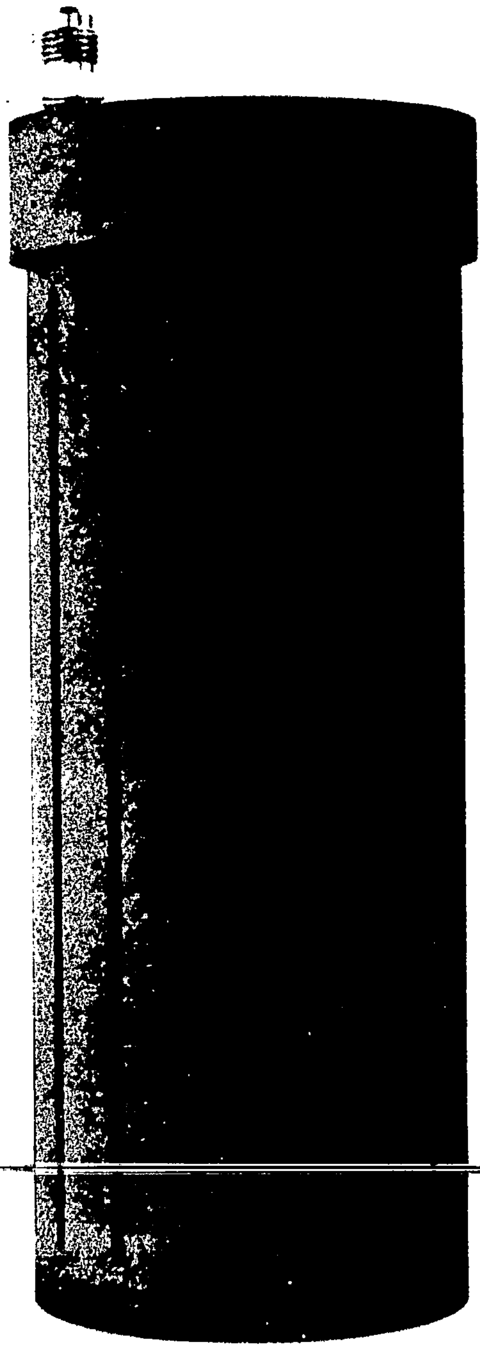


FIG. 8

CURVED PERMEABLE WALL TORCH

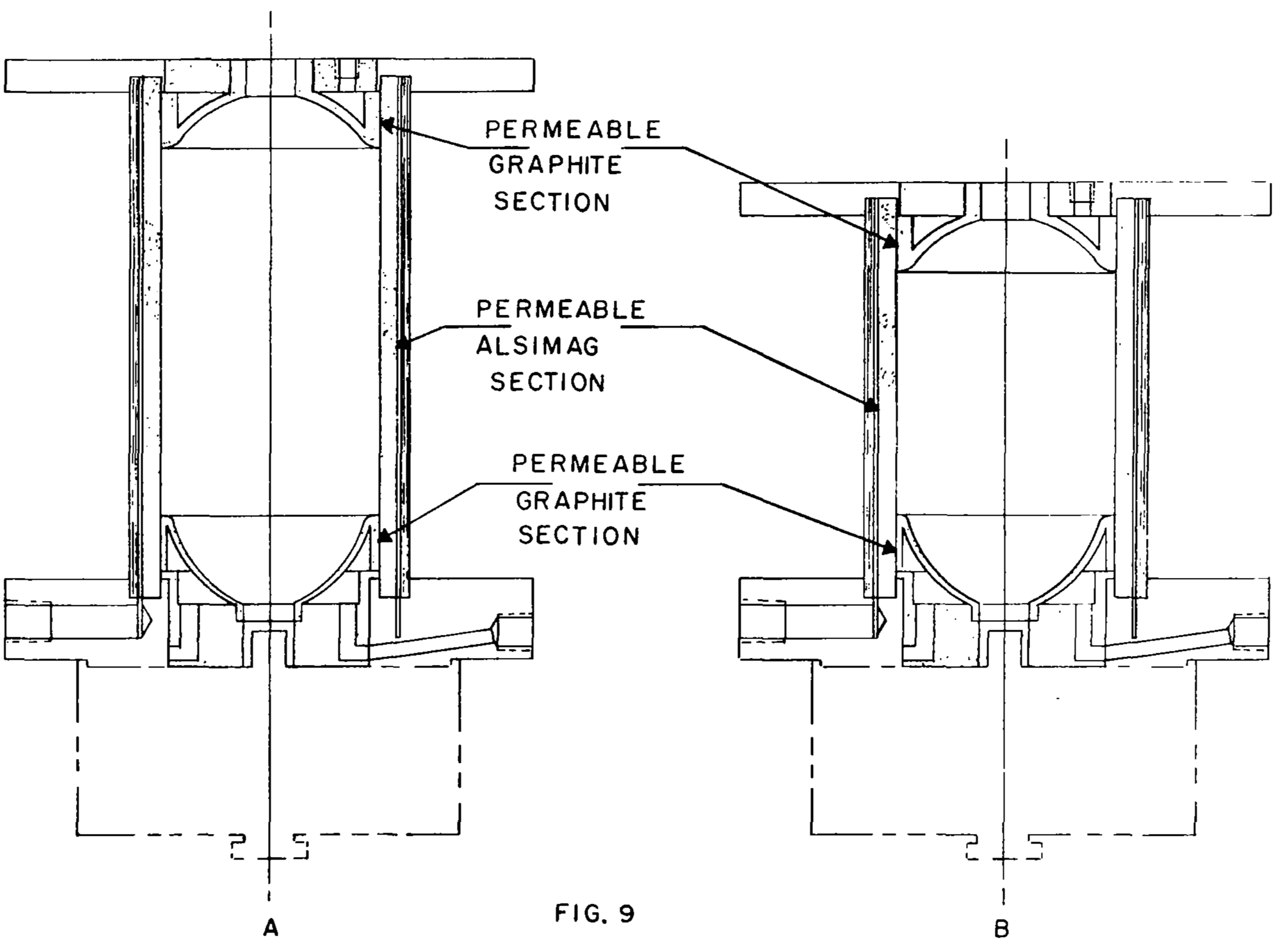
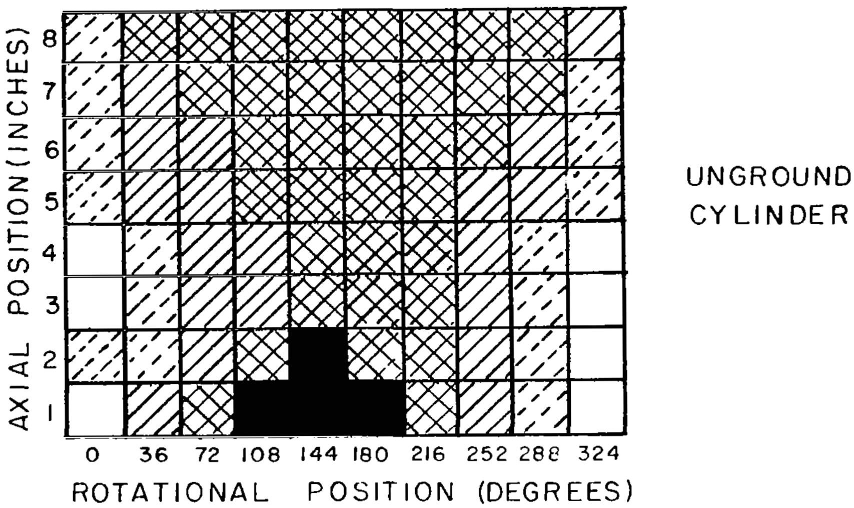
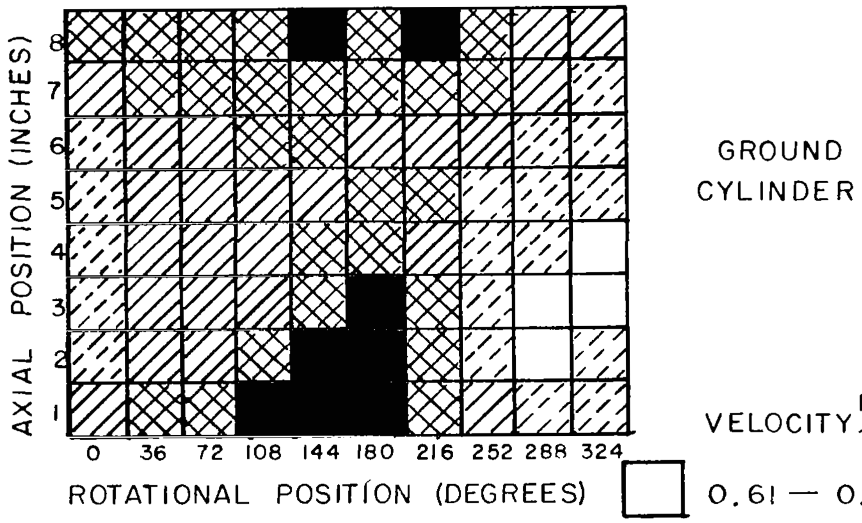


FIG. 9

PERMEABILITY MAPS
COMPARISION OF GROUND/UNGROUND CYLINDERS





MAT'L: ALSIMAG 447

SAMPLE: 8" LONG x $3\frac{1}{4}$" I.D. x $3\frac{3}{4}$" O.D. CYL.

IDENT.: G-2

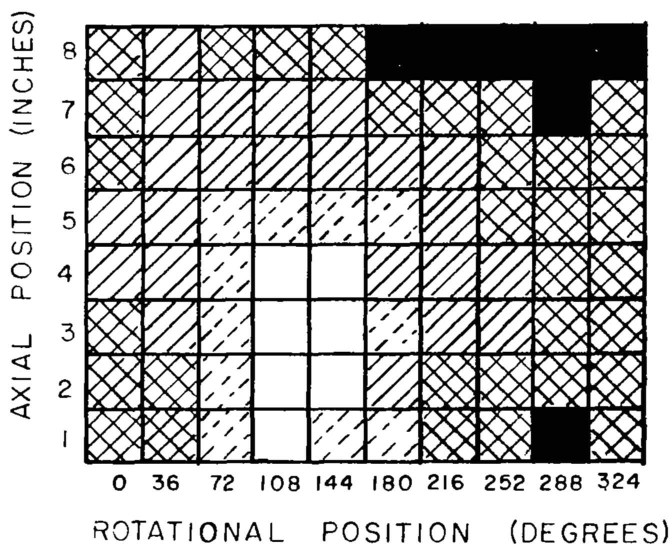
PERMEATING GAS: ARGON

PRESSURE DIFFERENTIAL: 70 P.S.I.

TEMPERATURE: 70°F

FIG. 10

PERMEABILITY MAP
NON-UNIFORM CYLINDER



VELOCITY FT./SEC.

0.61 – 0.75
0.76 – 0.90
0.91 – 1.05
1.06 – 1.20
1.21 – 1.35

MAT'L: ALSIMAG 447

SAMPLE: 8" LONG x $3\frac{1}{4}$" I.D. x $3\frac{3}{4}$" O.D. CYL.

IDENT.: G-1

PERMEATING GAS: ARGON

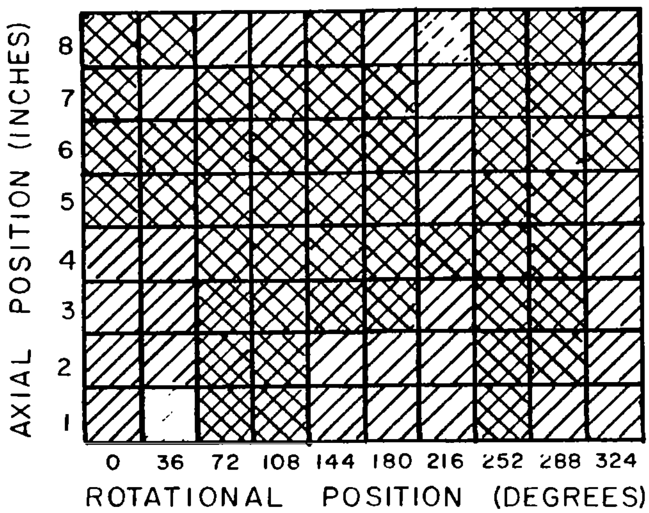
PRESSURE DIFFERENTIAL: 70 P.S.I.

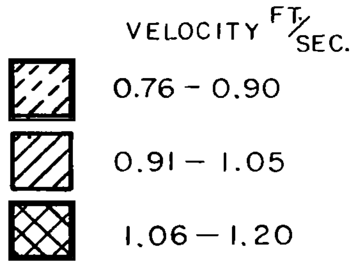
TEMPERATURE: 70° F

FIG. 11

PERMEABILITY MAP

UNIFORM CYLINDER





MAT'L: ALSIMAG 447

SAMPLE: 8" LONG x $3\frac{1}{4}$" I.D. x $3\frac{3}{4}$" O.D. CYL.

IDENT.: M-2

PERMEATING GAS: ARGON

PRESSURE DIFFERENTIAL: 70 P.S.I.

TEMPERATURE: 70°F

FIG. 12

89 KW POWER SUPPLY

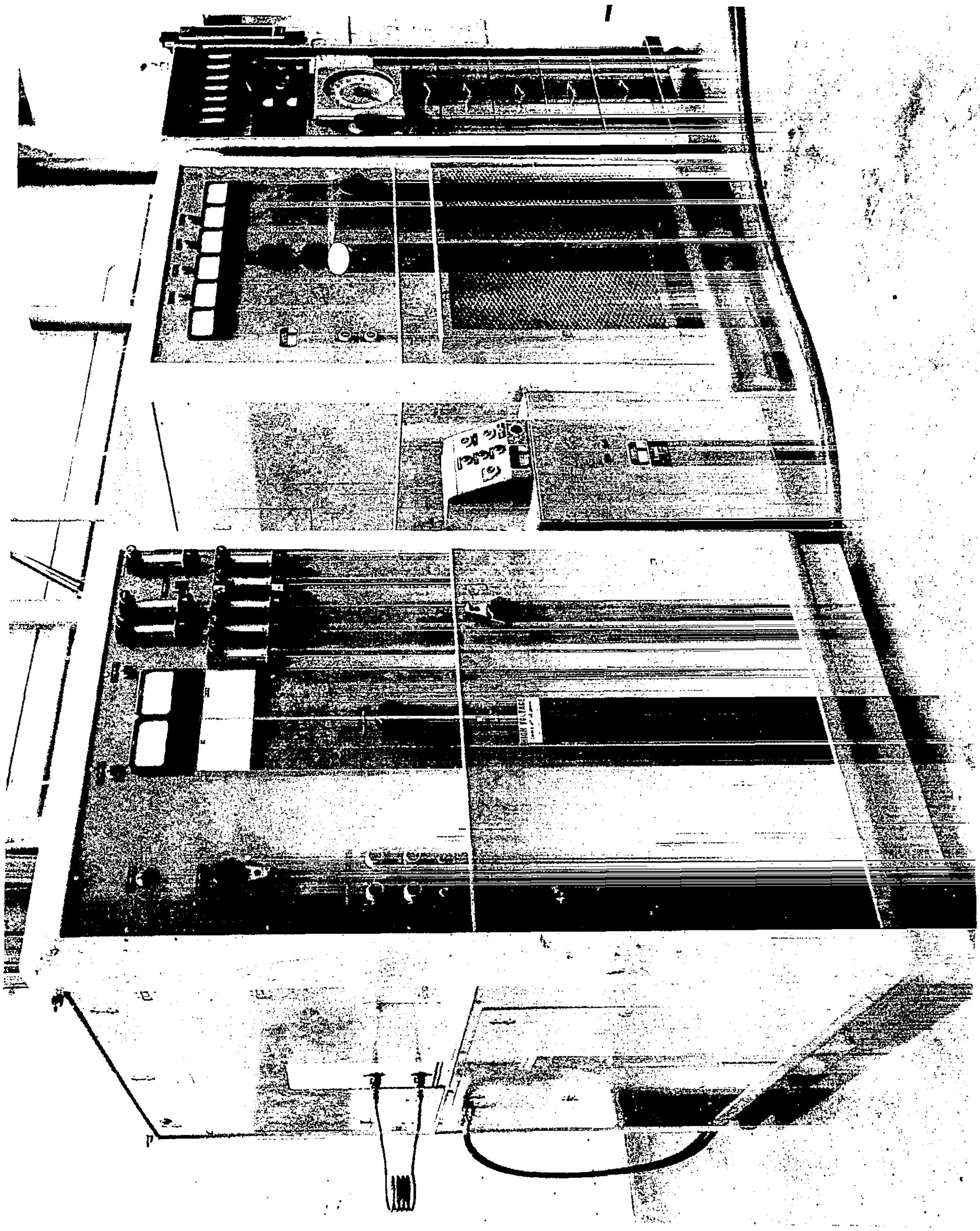
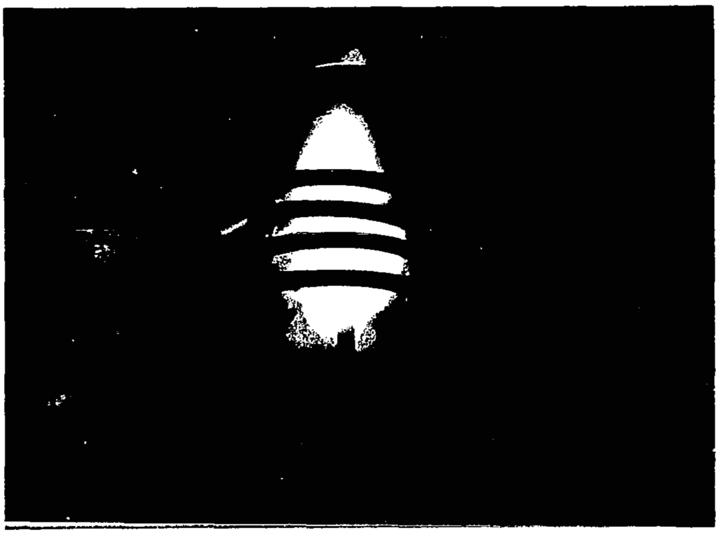


FIG. 13

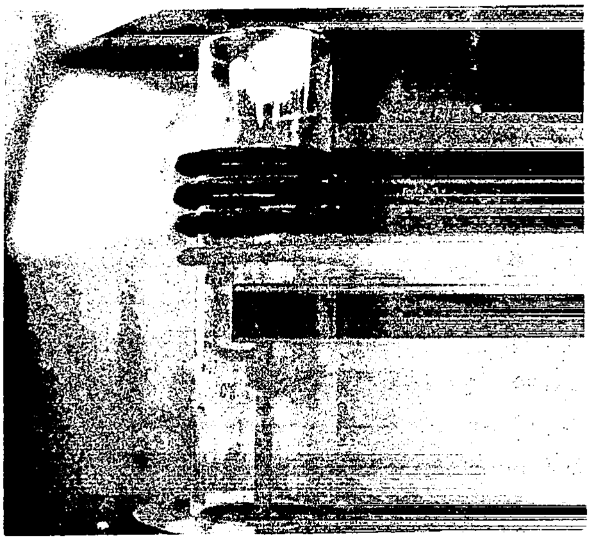
ZINC METAL SOLID-FEED



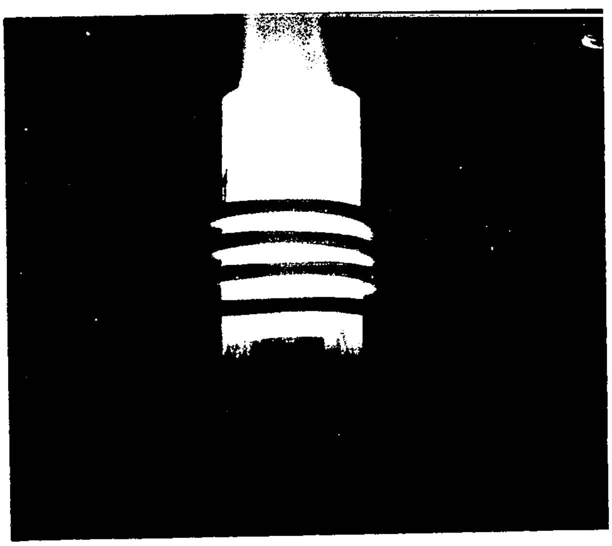
CLEAR QUARTZ WALL TORCH OPERATING WITH ZINC METAL SOLID-FEED, ZINC IS $\frac{1}{8}$ DIA. WIRE IN THE CENTER OF $\frac{1}{4}$ DIA. GRAPHITE ROD

FIG. 14

SODIUM CHLORIDE SOLID-FEED



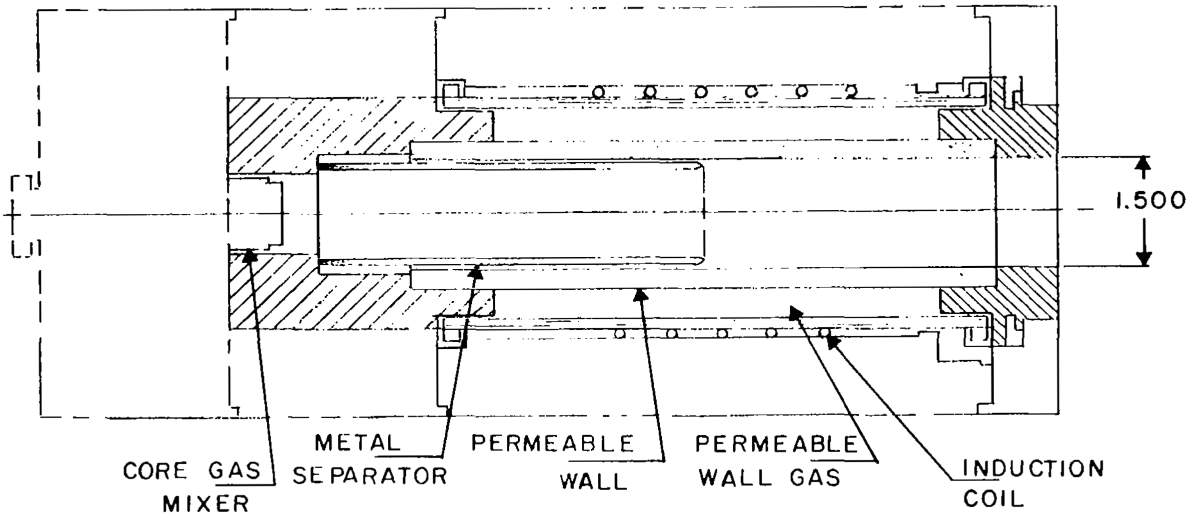
EQUIPMENT SET-UP FOR SOLID VAPORIZATION FROM A CRUCIBLE



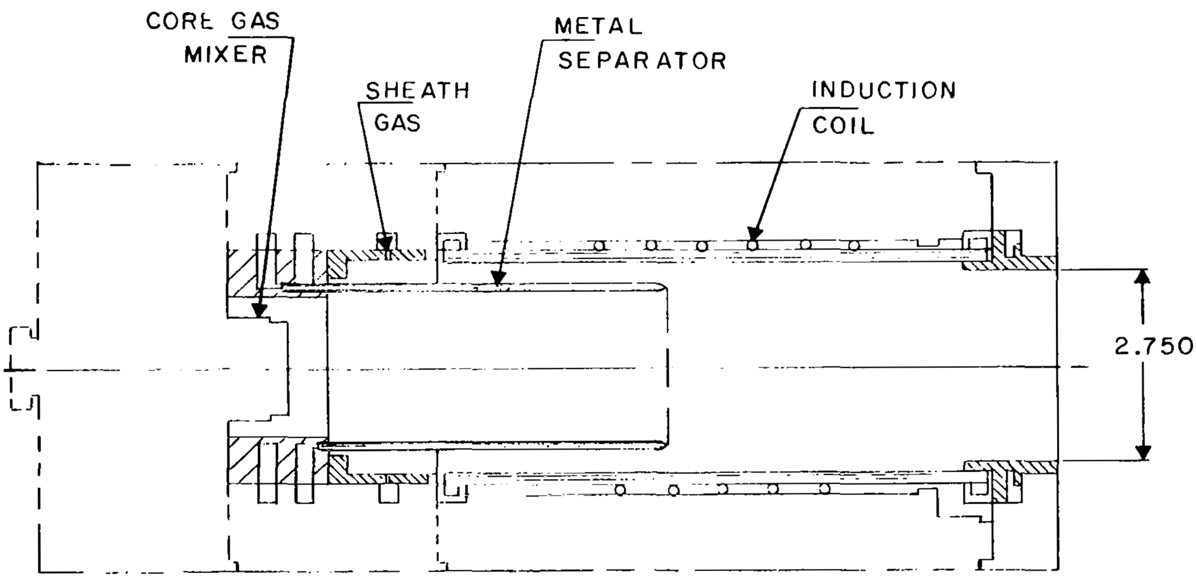
OPERATION WITH SODIUM CHLORIDE IN CRUCIBLE

FIG. 15

COMPARISON OF PERMEABLE WALL AND CO-AXIAL FLOW TORCHES USED FOR GAS CONCENTRATION PROFILE MEASURMENTS



PERMEABLE WALL TORCH



COAXIAL FLOW TORCH

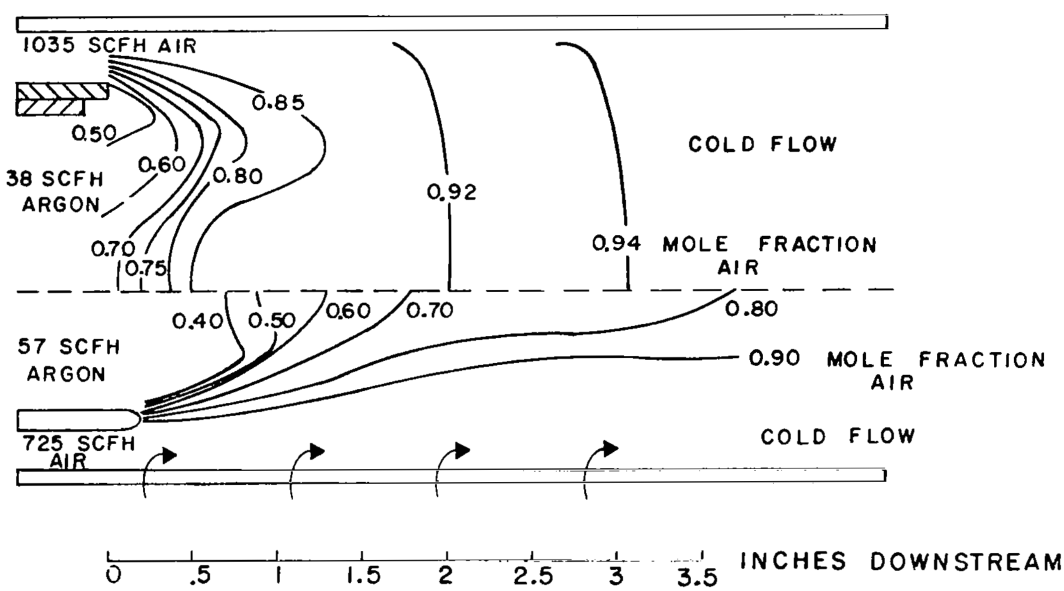
FIG. 16

COLD FLOW MIXING MAPS

COAXIAL FLOW COMPARED TO PERMEABLE WALL

MIXING MAP WITH COAXIAL FLOW

AIR/ARGON MASS RATIO = 19.7



MIXING MAP WITH PERMEABLE WALL

AIR/ARGON MASS RATIO = 17.7

FIG. 17

MIXING MAP WITH PLASMA
COAXIAL FLOW COMPARED TO PERMEABLE WALL

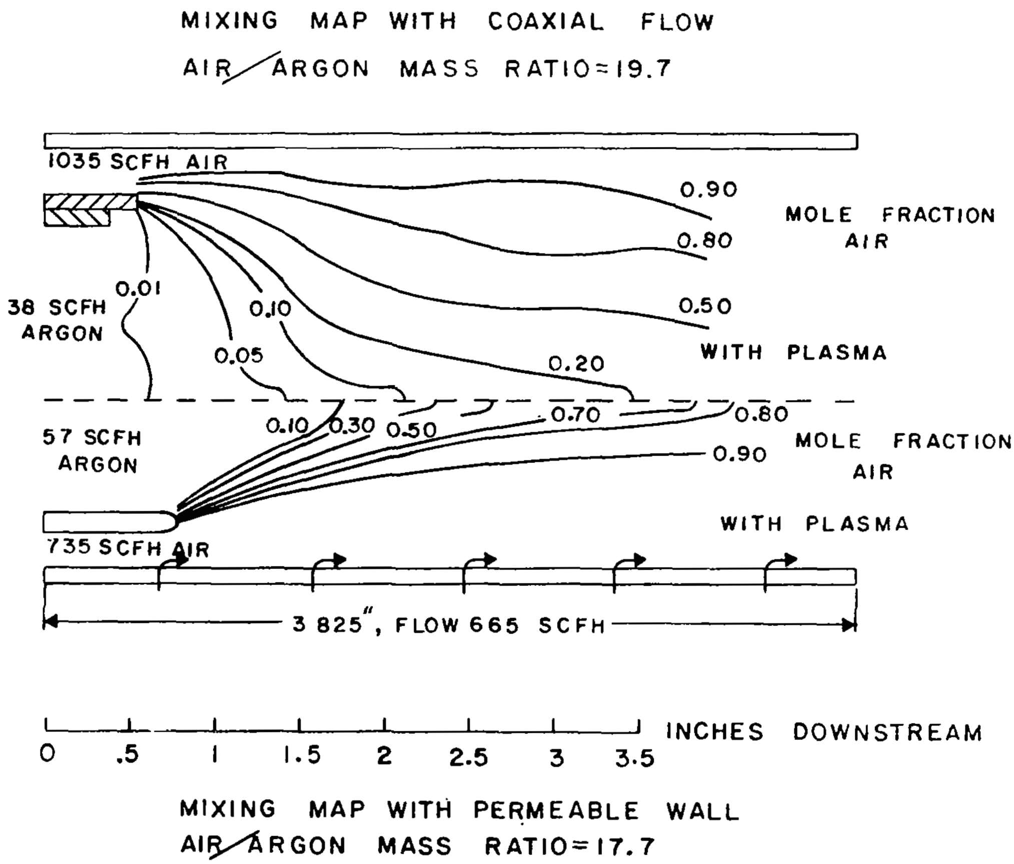


FIG. 18

COMPONENTS FOR CURVED SEGMENTED GRAPHITE PERMEABLE WALL

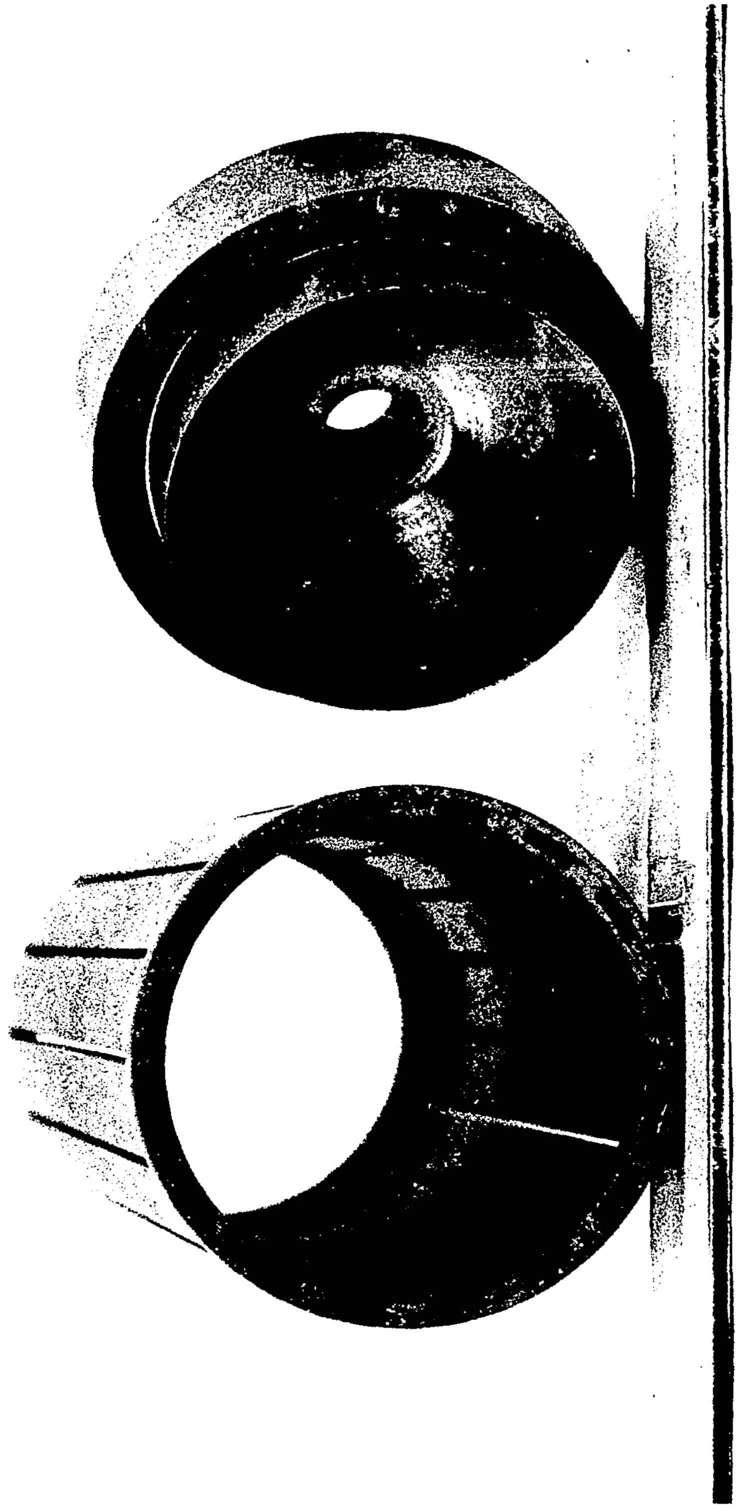


FIG. 19

CURVED SEGMENTED GRAPHITE PERMEABLE WALL TORCH IN OPERATION

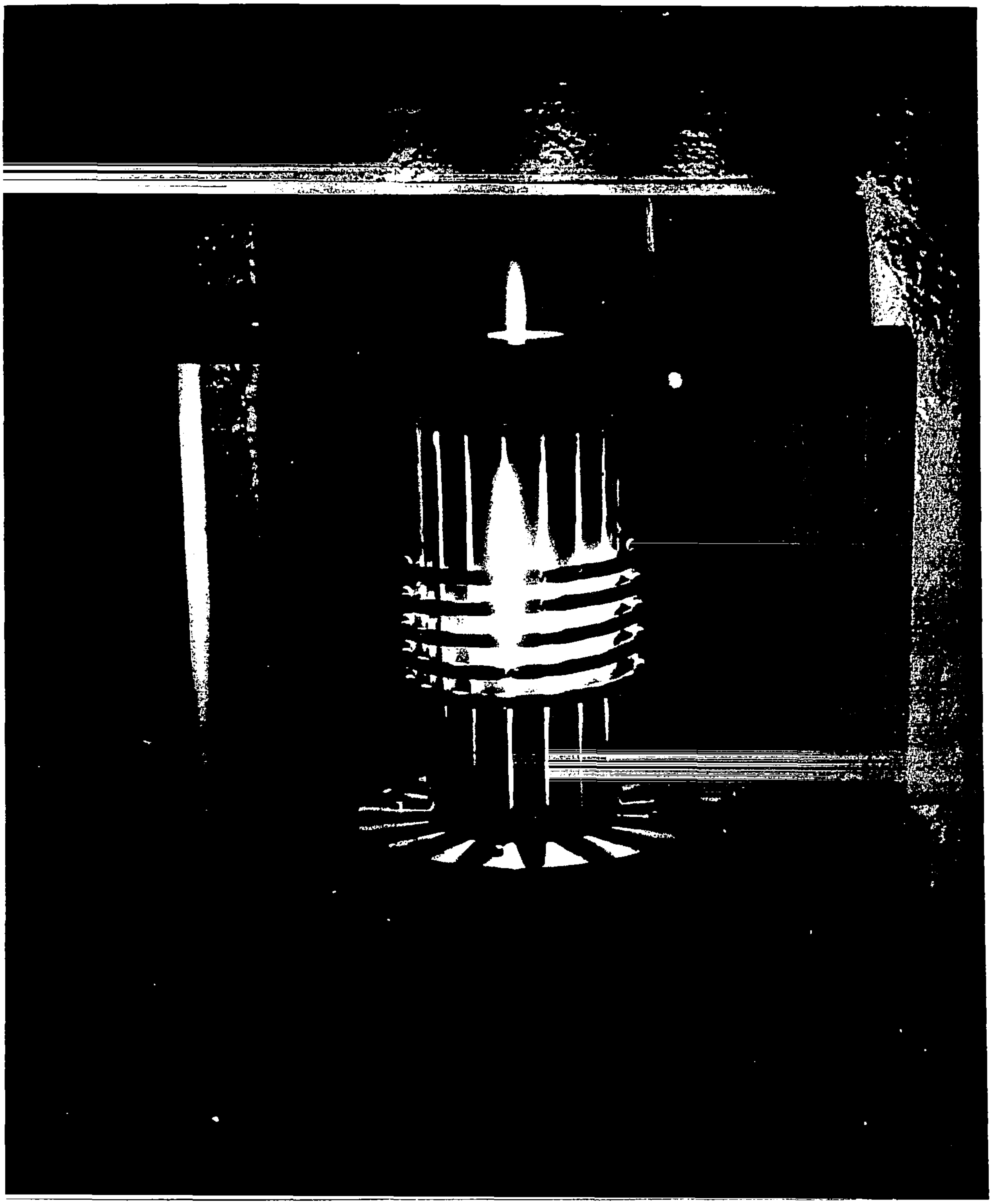


FIG. 20

PERMEABLE WALL (ALSiMAG) TORCH OPERATING WITH NaCL SOLID FEED

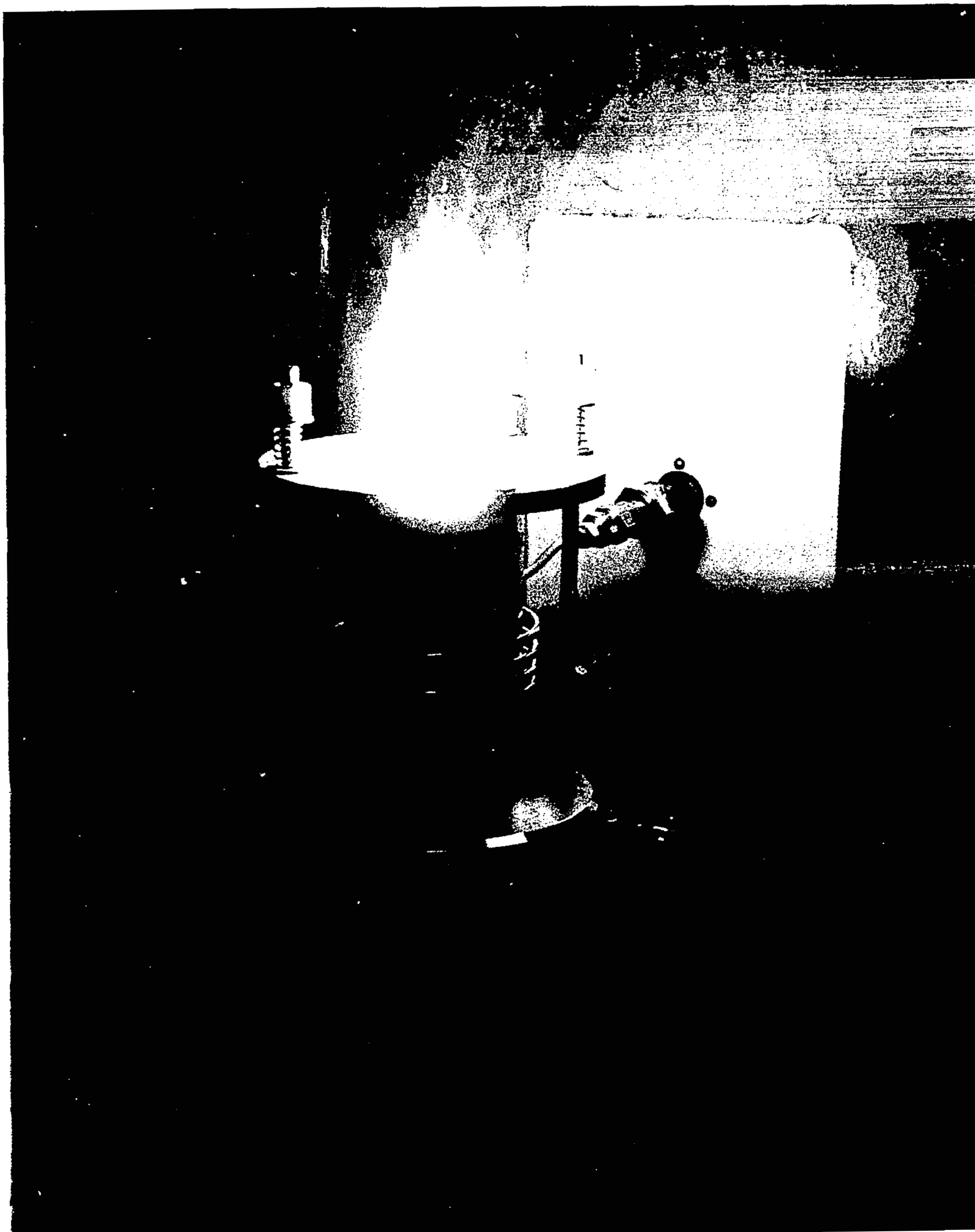


FIG. 21

PERMEABLE WALL TORCH
WITH SODIUM INJECTION PROBES

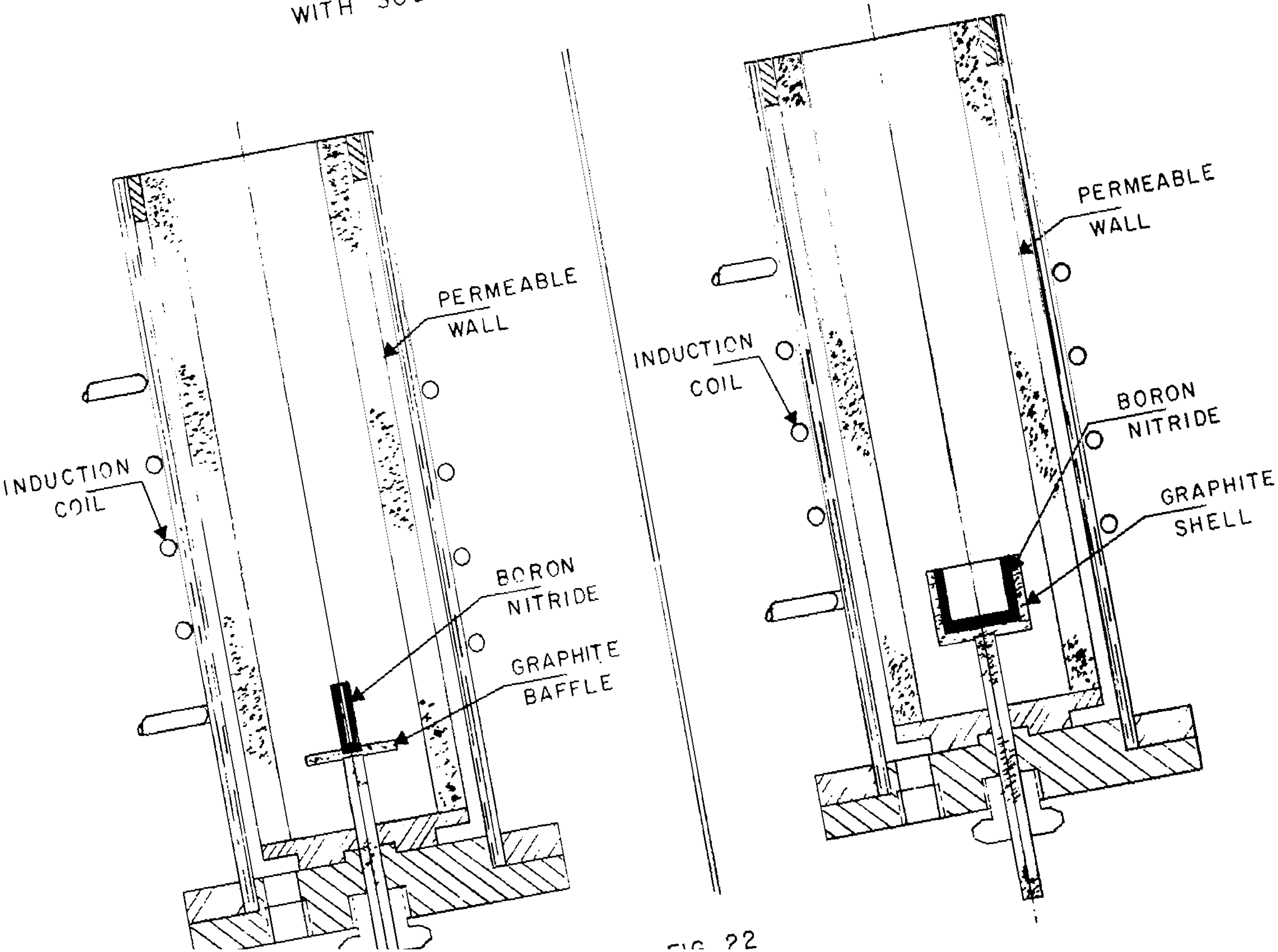


FIG. 22