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**FLAME HEATED THERMIONIC
CONVERTER RESEARCH**

**Report No. 1
First Quarterly Report
(1 July 1961 to 30 September 1961)
Contract No. DA-36-039 SC-88982**

**Department of the Army Task No. 3A99-09-002-04
U. S. Army Signal Research & Development Laboratory,
Fort Monmouth, New Jersey**



ATOMICS INTERNATIONAL

A DIVISION OF NORTH AMERICAN AVIATION, INC.

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**FLAME HEATED THERMIONIC
CONVERTER RESEARCH**

**Report No. 1
First Quarterly Report
(1 July 1961 to 30 September 1961)**

**By
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R. L. McKISSON
R. G. HOFF**

**Power Sources Division Technical Guidelines for PR & C
No. 61-ELP/D-4623 dated 23 December 1960**

Department of the Army Task No. 3A99-09-002-04

**Object: To develop the technology required for portable
flame heated thermionic power sources.**

ATOMICS INTERNATIONAL

**A DIVISION OF NORTH AMERICAN AVIATION, INC.
P.O. BOX 309 CANOGA PARK, CALIFORNIA**

**CONTRACT: DA-36-039 SC 88982
ISSUED: APRIL 2, 1962**

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PURPOSE

The purpose of this procurement is to investigate the various problems encountered in the design and construction of generators capable of producing power from 5 to 200 w. These problems cover the selection of suitable materials for thermionic diode envelopes and heat ducts where high temperatures and corrosive gases are encountered; the design of a fossil fuel burner capable of providing the required temperatures and thermal watts; the establishment of design parameters for thermionic generators of various power levels from 5 to 200 w; and the construction of a sample generator, rated at 100 w output, to demonstrate feasibility of design approach.

PROGRAM OUTLINE

Task A - Thermionic Converter Development

1. Construct converters for testing, with or without protective coating, as required.
2. Study the basic performance characteristics of diodes designed for use in the 100-w Thermionic Generator program. Use electron beam heating of the cathode.
3. Using the same equipment as for Number 2, operate diodes for up to 1000 hr to determine lifetime characteristics for the diode itself.
4. Operate converters during prototype testing.

Task B - Heat Source Development

1. Develop aspirated regenerative burners. Propane fuel will be used for screening tests, but the perfected burner will function on regular gasoline.
2. Develop temperature controls for anode, cathode, and cesium reservoir.
3. Develop the 100-w thermionic generator prototypes, including integration of combustion chamber, converters, electrical conversion, and control equipment. This includes the design of generators and the analysis of test results.

4. Perform environmental tests on a perfected thermionic generator.
5. Design converters for 5 to 200 w power levels at 6, 12, and 24 v dc, and analyze performance expectations.

Task C - Materials Development and Evaluation

1. Perform corrosion tests on molybdenum and molybdenum alloys coated with molybdenum disilicide in a stagnant air environment at temperatures up to 1500°C.
2. Perform corrosion tests on silicon carbide base refractories and other related materials in oxidizing, neutral, and reducing flames at material temperatures up to 1700°C.
3. Determine permeability of gases through molybdenum or molybdenum alloy thimbles coated with a superior anticorrosion coating, as determined by (1) above. Identify the gas diffusing through. In the standard test, the outside end of the thimble shall be heated to 1500°C by contact with the silicon carbide refractory, which in turn is heated with a gas flame.
4. Investigate methods and materials for welding or brazing molybdenum to molybdenum, and molybdenum to steel.

Task D - Electrical Component Development

1. Develop voltage control circuits for:
 - a) Voltage conversion equipment, or
 - b) For series-connected diodes (include a failed diode locator).

Task E - Project Coordination and Reports

1. Coordinate the various parts of this contract.
2. Write three quarterly technical reports and one final technical report.

A program schedule of the preceding tasks is given in Appendix III.

OTHER PROGRAMS

The following programs at Atomics International are related to the present contract:

- 1) Company sponsored research on flame heated thermionic converters
- 2) Atomic Energy Commission sponsored research on cesium vapor diode construction operation and application
- 3) Office of Naval Research sponsored research on the basic physics of thermionic converters

ABSTRACT

TASK A - CONVERTER DEVELOPMENT

A nominal 150 w(e) electrically heated thermionic converter is being constructed. Such a large converter has not been made previously at this laboratory, but no unusual difficulties have been encountered.

TASK B - HEAT SOURCE DEVELOPMENT

Two lines of development have been followed, in perfecting a furnace for heating thermionic diodes. One line of development has used laboratory compressed air and propane to attain thermionic temperatures and heat fluxes in a small combustion bed of zirconia chips. A furnace of this sort, called the demonstration furnace, has operated successfully many times. Using this furnace, a workable protective coating system for molybdenum was discovered (See Task C). The furnace is troubled with blockage of the fuel line due to coking, and with high heat losses, high stack losses, and a short lifetime for the furnace internals.

The other line of development concerns furnaces employing aspirated air. These are now being sized to heat a converter like the one being built in Task A. Three designs were tested, each one better than the last. The best so far would heat a diode to 700°C with a heat flux of 9.5 w/cm². A temperature of ~1500°C, and a heat flux of ~20 w/cm², are required.

TASK C - MATERIALS DEVELOPMENT

An apparently satisfactory protection scheme for molybdenum metal in a flame environment was discovered. The molybdenum metal is protected by a MoSi₂ coating. The MoSi₂ coating is protected from flame erosion by a thin barrier of SiC base refractory.

Evaluation of MoSi₂ base coatings is well underway. One molybdenum wire, coated with a 0.0025-in. thick layer of Durak-B, withstood 1750°C in still air for 211 hr before the run was inadvertently terminated.

TASK D - ELECTRICAL DEVELOPMENT

A survey of all possible inversion schemes was completed. Two methods appear to be practical for converting the output of one diode (1/2 v) to 12 v dc.

One of these is a solid-state converter. At $1/2$ v input, this converter is $\sim 50\%$ efficient, and weighs 0.2 to 0.3 lb/watt of output. The other is a novel type of motor-generator. It would operate as a hermetically sealed unit, with no possibility of radiating any radio noise. From preliminary designs, we estimate that it will be 75% efficient and weigh 0.08 to 0.10 lb/watt of output.

PUBLICATIONS, LECTURES, REPORTS, AND CONFERENCES

W. R. Martini attended the International Heat Transfer Conference, held at Boulder, Colorado, August 28 to September 1, 1961. It was sponsored by a large number of technical societies from both the U. S. and the United Kingdom. Over 500 registrants from all over the world were present. Papers were submitted on all phases of heat transfer. Information pertaining to the following fields of inquiry was obtained, which is proving a direct benefit to the progress of the work under this contract:

- 1) Gas conduction at low pressures
- 2) Heat transfer from flames
- 3) Heat transfer in regenerators
- 4) Natural convection heat transfer near the critical point.

TECHNICAL PROGRESS

TASK A - THERMIONIC CONVERTER DEVELOPMENT

Work Previous to Contract

A furnace and a thermionic diode were constructed to demonstrate the fact that a thermionic diode heated with a flame can produce electricity. A vacuum diode, which operates at a lower temperature and produces a much lower power density, has previously been heated by a flame. However, it is believed that this is the first time that a cesium vapor diode has been so heated. The furnace built for this test is shown in Figure 1. This furnace requires propane and compressed air, both at about 1 psig pressure. They are metered into the furnace through the manifold at the top of the furnace. The gases are then preheated in the furnace, using an economizer type heat exchanger. The bottom part of the 21-in. long heat exchanger is shown in the cutaway in Figure 2. As shown, air passes down through the inside of the heat exchanger tube, and fuel passes down through a tube concentric with the heat exchanger tube. The gases mix in a bed of broken zirconia chips (-6 +8 mesh). Burning takes place in this bed at a temperature of 1700 to 1900°C. Exhaust gas from the heat exchanger passes up the outside of the heat exchanger tube, and preheats the air and fuel to some extent. The furnace is approximately 8 in. in diameter by 30 in. long, and weighs approximately 40 lb. Four percent of the chemical energy released in the combustion chamber is conducted across a thin wafer of silicon carbide into the cathode of the thermionic converter. A higher percentage of the heat could be utilized if more converters faced onto the same combustion chamber, or if a more efficient insulation were used in the furnace. The cathode is a molybdenum thimble, coated on the outside with Durak-B, a molybdenum disilicide base coating. This coating allows the diode to function properly at 1500°C while exposed to air. Electrons are emitted to the anode from the cathode surface, which is the inside end of the thimble. The sides of the thimble are 0.010 in. thick, to approximate an optimum lead wire for the cathode proper. The anode surface is positioned only a few mils away from the cathode surface, and collects heat from the cathode by radiation, gas conduction, and electron bombardment. The anode assembly is made of copper, in order to conduct the heat away from the anode surface to the anode boss while maintaining the temperature of the

anode surface at 600 to 700°C. The cathode and anode were joined by a flange, so that the converter could be more easily dismantled. The temperature of the cesium reservoir was regulated with an auxiliary electric heater. A change in temperature of the cesium reservoir of only 1 or 2°C made a noticeable change in the performance of the thermionic converter. This sensitivity is characteristic of all cesium vapor diodes.

The best performance obtained during this series of experiments is given in Table I. The heat flow down the cathode thimble and the anode bar was computed, using the measured temperature of the cathode, anode, cathode flange, and anode boss, along with the dimensions of the converter and the handbook values for the thermal conductivity of molybdenum and copper. The electric

TABLE I
FUEL-FIRED THERMIONIC DIODE PERFORMANCE
(Run No. 6)

Temperatures	
SiC wafer above cathode	1530°C
Anode	710
Anode boss	430
Cathode flange	440
Cesium reservoir	330
Heat flow down cathode thimble	24.2 watts
Heat flow down anode bar	65
Electric power generated	<u>3.86</u>
Total power into diode	93.06
Heat flux into diode	32.7 w/cm ²
Efficiency = $\frac{3.86}{93.06} =$	4.15%

power generated was measured, using an optimized load resistance. The relatively low diode efficiency indicated in Table I is probably due to poor spacing between anode and cathode surfaces. Uncertainties in the thermal expansion coefficients for both molybdenum and copper make the actual spacing difficult to predict. The best performance obtained from the diode, indicated in Figure 3,

shows that a maximum of approximately 4 w were obtained at 1/2 v output. The diode operated for 10 hr before it failed as a result of corrosion from the outside (See Task C).

Work on Contract - Phase 1

Construction of a nominal 150-w electrically heated thermionic converter is well under way. In design, this diode is substantially a copy of the thermionic diode studied under the AEC Contract at Atomics International. However, the cathode area is 13 times greater. This diode, shown in Figure 4, is 2 in. in diameter by 8-1/4 in. long, and has 84 cm² of cathode emitter area. The spacing between the anode and cathode is 12 mils when operating, and 10 mils when cold. The molybdenum cathode is heated by electron bombardment from the tungsten foil filament which is positioned inside of the cathode. The circuit used to heat the cathode is also shown schematically in Figure 4. The filament is heated by 100 amp at 20 v alternating current, and the center tap of the filament transformer is made 200 v negative, with respect to the molybdenum cathode, by a filtered dc power supply. The heater circuit is designed to deliver up to 4 kw to the molybdenum cathode.

One innovation in the diode is the use of four insulating spacers. These spacers prevent the bottom of the molybdenum cathode from coming closer than 4 mils to the anode surface. The spacer is cut from a sapphire rod, in such a manner as to allow only a rounded contact to touch the molybdenum thimble. The sapphire spacers are held in place by steel set screws which are seal-welded to make the assembly vacuum tight.

A unique type of variable load will be used to test this diode. As shown in Figure 4, the load consists of two concentric steel tubes. Water flows through the central tube for cooling. Mercury can be added to or removed from the annulus between the tubes, in order to short across between the inner and the outer tubes. The chief resistance is the inner tube; the outer tube acts as a container and a return lead. Although not shown, the test circuitry will also have provision for passing a current through the diode, in order to strike the arc at relatively low temperatures.

All the parts for the diode have been fabricated, and assembly of the diode is about 30% complete. The assembly of test equipment is about 50% complete.

TASK B - HEAT SOURCE DEVELOPMENT

Results of Work Previous to Contract

Since the contract proposal was written, a considerable amount of work has been accomplished toward the development of a heat source. Analysis of the thermodynamics of air-propane or air-octane flames show that an overall heating efficiency of 30% is possible without the use of an economizing heat exchanger to reduce stack heat loss.

Experimental development has followed along two general approaches. One approach used compressed air and propane, which burned as it passed through a bed of broken zirconia chips. The bed was adjacent to a silicon carbide heat sink, standing in for a diode. The best performance from a number of experiments is as follows:

Heat flux to heat sink	75 w/cm ²
Combustion intensity	72 w/cm ³
Heating efficiency	43%
Temperature at hot end of heat sink	1300°C

As a result of this general approach to furnace development, the demonstration furnace was constructed and operated as described in the previous section.

The other general approach to diode heating uses a jet pump, powered by compressed propane, to draw the requisite combustion air through the economizing heat exchanger and the combustion chamber. Before the demonstration furnace was constructed, the theory of the jet pump, as it applies to our problem, was worked out. Nine experiments were carried through, using the jet pump principle; the ninth one was the most successful, and will be described briefly here (See Figure 5). The furnace was easily lighted by temporarily placing a damper in the inlet cone. The burner operated without trouble for 165 min. At this point, all temperatures had leveled out, and there seemed to be no reason to continue the experiment. Pertinent measurements are summarized in Table II. Even though the heating system, illustrated by Experiment No. 9, is much simpler than the system chosen for the demonstration furnace, it was not used because we could not be sure of being able to heat a diode to 1500°C while transferring heat to the diode at the rate of 33 w/cm². Consequently, the propane-compressed air burner was chosen, because of its reserve capacity. Nevertheless, for portable applications, the aspirated burner would be preferred.

TABLE II
PROPANE-ASPIRATED AIR EXPERIMENT No. 9

Heat Balance	
Heat Sink	125 watts
Stack loss	15
Insulation loss	140
Unaccounted for (by diff.)	95
Total Chemical Energy Input	375
Heating Efficiency	33%
Heat flux to heat sink [*]	16 w/cm ²
Heating intensity [†]	9.3 w/cm ³
Observed Temperature of heat sink	1100°C
Air-fuel ratio	0.88

*Assuming that the heat transfer area is the bottom of the hole

†Flame volume assumed to be 1-1/4 in. in diameter by 2 in. long

Work on Contract

Phase 1 - Furnace Development

Two distinctly separate lines of experimentation have been undertaken, in connection with developing a suitable furnace. One employed compressed air and propane, and used the demonstration furnace previously described to heat a dummy diode which had the same thermal and material characteristics as the real diode. Most of the experimental work was accomplished on this, previous to the contract. However, the task of analyzing and reporting this work has been done on the contract. Although the demonstration furnace functioned adequately, its size and weight is obviously not practical for a portable thermionic power supply. Therefore, a series of smaller, lighter weight furnaces have been built and tested, on a scale required to heat the diode shown in Figure 4 by a gasoline or propane-fired furnace.

Dummy Diode Runs

The dummy diode runs were started in advance of the testing program for the thermionic diode, in order to check out the demonstration furnace, which

was used for both testing programs. The runs were also successful in evaluating some methods of protecting molybdenum metal from destructive oxidation in a flame at 1500°C, in determining the suitability of materials of construction at high temperatures, in investigating the problems of injection of fuel into high temperature furnaces, and in measuring the heat balance for the demonstration furnace. Figure 6 is a sketch of the demonstration furnace, as it was used in Dummy Diode Runs No. 1 to 5. In Dummy Diode Runs No. 1 to 4, the furnace was substantially the same; however, the combustion chamber was somewhat different in each run. For Dummy Diode Run No. 5, the furnace was entirely rebuilt and modified, so that the insulation heat loss and the heat loss from the stack gases could be more readily measured. Each of the five runs will be described briefly in the following sections.

Run No. 1

In this run, the molybdenum nail was exposed directly to the combustion chamber made up of zirconia chips (-4 +6 mesh), as shown in Figure 7. The nail was heated to 950°C for 2.8 hr, and to between 1400 and 1500°C for 1.1 hr. The test was terminated when waxy needles of MoO_3 plugged the observation hole in the bottom of the dummy diode.

The dummy diode assembly after Run No. 1 is shown in Figures 8 and 9. Molybdenum trioxide crystals from the corrosion of the top of the nail had deposited around the lower leg of the nail and the upper section of the copper boss. The shape of the pits in the top of the molybdenum nail suggest that the molybdenum disilicide coating (Durak-B) corroded through at certain points where the jets of flame, flowing between the zirconia chips, passed directly over the surface. Once a hole in the coating developed, rapid oxidation of the underlying metal progressed in all directions, undermining the coating and developing hemispherical cavities. The dummy diode functioned according to design. When the temperature of the bottom of the nail head was observed to be 1500°C and the temperature of the copper boss was observed to be 524°C, the temperature of the top of the molybdenum nail was computed to be 1520°C. The heat transferred away from the nail head by conduction was computed to be 52.9 w and, by radiation, it was 27.1 w (emissivity = 0.9). Thus, the total heat transferred from the end of the nail is 79 w or 28 w/cm^2 . This heat flux is close to the 32.7 w/cm^2 observed in fuel-fired thermionic diode Run No. 6 (See Table I).

Run No. 2

In Run No. 2, a 0.1-in. thick flame barrier of Norton oxide-bonded silicon carbide was placed on top of the dummy diode to prevent erosion of the molybdenum. Silicon carbide was used because it has good thermal conductivity and a high melting point. Also, the presence of SiO gas from the silicon carbide might suppress evaporation of the molybdenum disilicide coating. The combustion bed was similar to that used in Run No. 1 (See Figure 7). Run No. 2 was concluded when the flow of fuel and air was blocked, due to the formation of a clinker of pyrolysed propane. The silicon carbide wafer had been eroded somewhat, and the end of the heat exchanger tube had flared out and melted a small amount (See Figure 10). The molybdenum nail was undamaged, and was reused in Run No. 3.

Run No. 3

As shown in Figure 7, the combustion chamber of Run No. 3 was substantially the same as that used in Run No. 2, with the exception of the injection of propane into the preheated air. This occurred 6 in. above the combustion bed, after both the flow of propane and air had been calmed. This arrangement for fuel injection proved to be no better, because the furnace also failed, due to pyrolysis of the propane and oxidation and melting of the stainless steel. The bottom of the heat exchanger tube was also badly melted, probably due in part to fluxing with stainless steel oxides. The silicon carbide wafer was corroded, and had cemented itself into the furnace. However, the top of the molybdenum nail was not corroded, and appeared to have been bonded to the silicon carbide wafer, at temperature, with the oxide binder of the silicon carbide brick. On the side of the nail head, two cavities were observed. The nail head lost 0.1 g, and had been heated for 8.3 hr at $1500 \pm 50^\circ\text{C}$ and for 8.2 hr at $1400 \pm 50^\circ\text{C}$.

Run No. 4

In this run, we tested an alternate type of protection for the molybdenum cathodes. It is Astroceram, manufactured in the form of a castable paste by the American Thermocatalytic Corp. According to the vendor, it has the following properties:

Maximum Service Temperature	2900°C
Thermal Conductivity	23.2 BTU/ft ² (°F/in.)
Thermal Expansion	5 x 10 ⁻⁹ in./°F
Tensile Strength	10,000 to 20,000 psi
Compressive Strength	80,000 to 150,000 psi
Porosity	0 to 0.2%
Hardness	8 to 9 mohs

The above description gives this material a thermal conductivity only one-half that of a silicon carbide brick, and a thermal expansion coefficient 50 times less than that of fused quartz!

The coating was applied to a coated molybdenum nail, as shown in Figure 7. The wax was placed on the nail before it was cast into the cement, to allow for the calculated expansion of the molybdenum. Apparently, however, the air drying of this coating is not sufficient, because the cement shrinks upon firing. The cement appeared to shrink down upon the molybdenum nail head and then shrink still further, causing cracks to open up in the coating. The cracks allowed serious corrosion of the molybdenum nail head, similar to that shown in Figure 9.

Run No. 5

As mentioned previously, the demonstration furnace was rebuilt before Run No. 5 was conducted, because the zirconia insulation had been badly cracked and the Fiberglas (PF-105) had melted back badly. We felt that a new zirconia brick combustion chamber and Cerafelt insulation in all the space between the brick and the steel shell would give the best insulation possible for the demonstration furnace. To measure the heat losses from the furnace, a copper cooling coil was wrapped around the outside of the steel container, and also around the copper boss of the dummy diode. The temperature rise and the flow rate of the water flowing through this coil were recorded. Also, as shown in Figure 6, a large number of thermocouples were installed, in order to measure the effectiveness of the insulation and to measure more accurately the gas temperature leaving the furnace. Since, in Run No. 3, the end of the dummy diode had been protected but the sides had been corroded, a silicon carbide crucible was made to fit over the end and the sides of the molybdenum nail in Run No. 5. The crucible was made in this laboratory, using Norton No. 1130 cement. The

cement was mixed with 10 to 15% water, to which had been added 10 to 20% of ethyl silicate to act as a binder. The mixture was tamped into a greased mold. After the mixture had set, it was removed from the mold, dried, and fired to 1100°C. The product had considerable strength, and appeared to be resistant to thermal shock.

Run No. 5 was operated for approximately 5-1/2 hr. It was planned to obtain a steady-state heat balance at various temperatures. Therefore, a high temperature was not obtained in this run. A bad crack apparently developed, half way up the heat exchanger tube, which allowed a considerable amount of short-circuiting of air. Even though the furnace apparently already had begun to deteriorate, a fairly reliable set of measurements was made, from which a heat balance was computed (See Table III). Notice that there seems to be a 400°C temperature drop between the combustion chamber and the molybdenum nail head.

TABLE III
DEMONSTRATION FURNACE PERFORMANCE DUMMY DIODE
(Run No. 5)

Combustion chamber temperature	1500°C
Molybdenum nail head temperature	1100
Stack gas temperature	920
Maximum temperature of Cerafelt insulation (4 in. from bottom of furnace)	900
Air-gas ratio	1-1/4
Air supply pressure	1.1 in. Hg
Propane supply pressure	1.4 in. Hg
Chemical Energy Input	2100 watts
To dummy diode	170
Through insulation	594
Up stack	850
Unaccounted for	486
Heat flux to dummy diode = $170/2.85 =$	60 w/cm^2
Resistance to corrosion of dummy diode assembly	
Time at 1000 to 1100°C	3-1/2 hr
Weight loss of SiC crucible	0.1 gm
Weight gain of Mo nail	0.01 gm

The 23% of the chemical energy input still unaccounted for was probably escaping through the uncooled Transite end plates at the top and bottom of the furnace. Also, the stack gas is somewhat hotter than the fire brick duct which surrounds the thermocouples. Therefore, the temperature measurement of the stack gas is probably low. It appears probable that the heat loss through the insulation is about the same as the heat loss out the stack.

Note also, in Table III, that the molybdenum nail only showed a slight gain in weight, due to the pickup of some binder from the silicon carbide crucible surrounding it. However, the silicon carbide crucible had disintegrated considerably, considering the short time at a relatively low temperature. There are many types of silicon carbide base ceramic bodies, and a fairly resistant formulation must be employed.

The alumina tube that supplied the propane to the combustion bed was plugged with pyrolysed propane 8-1/2 in. from the bottom. The plug was 2 in. thick.

Analysis of the temperature measurements shows that the Cerafelt insulation in the top of the furnace was performing with an effective conductivity near that claimed by the manufacturer. However, in the bottom of the furnace, its effective thermal conductivity was approximately 0.02 w/cm-°C, twice that claimed by the manufacturer. This large value might be due to the flow of purge air or combustion gases through the insulation.

Notice that the required pressure to supply air and propane to the furnace is quite substantial (See Table III). The pressure drop through a cold furnace at the same flow would be about 0.3 in. of mercury.

Observations on Demonstration Furnace

This demonstration furnace has been employed for a total of five dummy diode runs, as well as seven diode runs. It has been extremely quiet in operation, and has almost always been able to attain thermionic temperatures for a number of hours before deterioration of the internal parts becomes serious. Even with 40 lb of insulation and a 20-in. long economizer heat exchanger, the heating efficiency of the furnace is, at most, 8%. This fact should point up the great difficulty in obtaining a respectable heating efficiency at a high diode temperature in a furnace with a practical size and weight for portable applications.

Pyrolysis of the propane to form a plug is a phenomenon that contributed to the downfall of all of the runs mentioned in this report. There appears to be an awkward temperature at which plugging takes place. Below this temperature, little reaction occurs; and above this temperature, the gas has already pyrolysed to more stable products. For instance, in Run No. 5, both ends of the alumina tube were clean, but a plug had formed not far from the cold end of the tube. More work must be done to determine the maximum safe temperature at which various fuels can be injected into the combustion chamber. Due to the nonvolatile constituents in regular gasoline, the effect of coking is expected to be even more serious in gasoline-fueled devices.

Propane-Aspirated Air Runs

Propane-Aspirated Air Experiments No. 10, 11, and 12 were conducted during this report period. A photograph of the experimental setup for Experiment No. 10 is given in Figure 11. Experiments No. 11 and 12 had a very similar experimental setup. In this series of experiments, three furnace arrangements and three heat exchanger tubes were used. Sketches of these are shown in Figure 12. In all three arrangements, a quartz fuel tube conducts high pressure propane to the nozzle which directs the jet of propane into the mixing tube at the bottom of the heat exchanger assembly. The jet in the mixing tube constitutes a jet pump which pumps the requisite combustion air through the heat exchanger assembly and the combustion chamber. In all three arrangements, the silicon carbide crucible is surrounded by a thin layer of bubble zirconia insulation, and then by a hollow cylinder which is water cooled. The 1/4 in. thickness of bubble zirconia grain has been found to have the same thermal resistance as a thermionic diode. That is, if the silicon carbide crucible were to be heated to 1500°C, the heat flux in the crucible would be approximately 20 w/cm². At lower crucible temperatures, the heat flux is proportionately lower.

Arrangement "A" (See Figure 12) differs from the other arrangements, in that a hat-like structure with vertical fins on the inside of the hat surrounds the heat exchanger tube. The outside of the hat is insulated. The incoming air is first preheated by passing over the fins in the hat structure, and then the air is further preheated by passing down through a central tube in the heat exchanger assembly to the jet pump at the bottom. The flue gases pass up through the annulus, and lose heat both inwardly and outwardly. In other words, both the

TABLE IV
RESULTS OF PROPANE-ASPIRATED AIR FURNACE EXPERIMENTS

EXPERIMENT		10			11										12	
RUN		1	3	1	2	3	4a	4b	4c	4d	4e	4f	4g	4h	4i	1
Arrangement (See Figure 12)	A	A	A	B	A	C	C	C	C	C	C	C	C	C	C	B
Heat Exchanger (See Figure 12)	1	1	1	2	2	2	2	2	2	2	2	2	2	2	2	3
Air-gas ratio	0.79	0.79	0.80	0.79	0.79	0.79	1.48	1.42	0.815	0.82	0.82	0.825	0.835	0.87	1.65	0.96
Fuel Energy (w)	885	950	1270	1180	1190	350	420	540	500	470	430	390	290	150	575	575
Heat Input (w)	630	680	910	840	850	350	420	400	380	350	320	300	230	150	545	545
Heat Output (w)	240	230	340	330	290	220	290	250	240	240	230	220	190	115	480	480
Heating Efficiency (%)	37	34	38	39	34	64	68	62	64	67	70	73	81	74	88	88
Fuel Efficiency (%)	27	24	27	28	24	64	68	46	48	50	52	56	66	74	83	83
Flame-crucible heat flux (w/cm ²)	7.5	7.2	10.6	10.2	8.9	6.8	9.0	7.8	7.5	7.5	7.2	6.8	5.9	3.6	14.9	14.9
Projected emitter heat flux (w/cm ²)	4.7	4.6	6.8	6.5	5.7	4.4	5.7	5.0	4.8	4.7	4.5	4.3	3.8	2.3	9.5	9.5
Heating intensity (w/cm ³)	40	43	58	53	54	22	27	25	24	22	20	19	15	9.5	34	34
Crucible Temperature (°C)	400	270	430	420	460	350	410	370	350	340	320	310	260	170	710	710
Propane fuel pressure (psig)	60	122	125	125	128	30	40	50	45	40	35	30	20	5	60	60

inside and outside surfaces of the annulus of the heat exchanger transfer heat to the incoming combustion air. In Arrangement "B", the heat exchanger tube is merely insulated with Cerafelt insulation and Fiberglas (PF-105).

In Arrangement "C", an inlet diffuser for the combustion air, and an exit diffuser for the exhaust gas, are attached to the heat exchanger tube, and the heat exchanger tube is thoroughly insulated, as shown in Figure 12.

The results of Experiments No. 10, 11, and 12 are summarized in Table IV. The arrangement and the heat exchanger employed in each experiment, and each run of each experiment, are indicated.

The quantities shown have been computed in the following manner: The air-gas ratio was computed from the analysis of the stack gas obtained by an Orsat gas analyzer. Well known stoichiometric relationships for the burning of propane in air were used to obtain the curves given in Figure 13. Usually, the percentage carbon dioxide is taken as the most accurate measurement, and the percentage of oxygen or carbon monoxide is used to determine whether the air-gas ratio is greater or less than one. The fuel energy is obtained from the propane flow rate, as measured by a calibrated rotameter, assuming that complete combustion takes place and releases 490 kcal/gm-mol of propane. The actual heat input is the same as the fuel energy when the air-gas ratio is greater than one. For ratios less than one, incomplete combustion occurs, and all the chemical energy contained in the fuel is not released. The amount released is obtained from well-known thermodynamic relationships, and is shown in Figure 13. The heat output is simply the heat taken up by the cooling water. The temperature rise and the flow rate of the water were measured. The heating efficiency is the heat output divided by the heat input. The fuel efficiency is the heat output divided by the fuel energy. The flame-crucible heat flux is the heat output divided by 32.2 cm^2 , which is the inside surface area of the silicon carbide crucible. The projected emitter heat flux is the heat output divided by 50.5 cm^2 , which is the projected cathode surface area, 1-1/4 in. in diameter by 2 in. long. The heating intensity is the heat input divided by 15.8 cc, the internal volume of the silicon carbide crucible. The crucible temperatures was measured by a thermocouple touching the crucible from the outside. The propane fuel pressure was usually measured at the pressure reducer, since the pressure drop through the supply line is negligible.

The data in Table IV are plotted in the following figures to show some interesting relationships. In Figure 14, the silicon carbide crucible temperature for all runs has been plotted against the projected emitter heat flux. Note that the data correlate on a straight line, as expected. If this line is extrapolated, it will pass through 1500°C and 20 w/cm^2 , the goals for this furnace development program. This means that we have the right thickness of insulation between the crucible and the cooling jacket. In Figure 15, the silicon carbide crucible temperature is plotted against the fuel efficiency for all runs, since one would like to attain thermionic temperatures with as high a fuel efficiency as possible, in order to reduce the size of the fuel tank required. Note that, for most experiments, the fuel efficiency drops off rapidly with increasing crucible temperature. Note that, in Experiment No. 12, we have attained a higher heating efficiency along with a higher crucible temperature. Since the fuel pressure for Experiment No. 12 was only 60 psig, a higher fuel pressure may lead to a new high in crucible temperature at a somewhat lower heating efficiency. In Figure 16, measurements, using only Arrangement "C" and Heat Exchanger Assembly 2, are considered (Runs No. 3 and 4 of Experiment No. 11). The fuel pressure in this run is plotted against the air-gas ratio. Notice that these data fall on two curves, the upper curve is for combustion at the bottom of the crucible, and the lower curve is for combustion at the entrance to the mixing tube. When combustion takes place at the entrance of the mixing tube, the temperature of the gas passing through the tube is much higher, and therefore less of it can pass through for a given energy input from the fuel jet. It is interesting that the air-gas ratio changes very little when the flame is at the entrance to the mixing tube, even though the fuel flow varies over a factor of 4. In Figure 17, both the fuel energy and the heat output are plotted as a function of fuel pressure for Experiment No. 11, Runs No. 3 and 4. Note that the fuel energy (which is directly proportional to the fuel flow rate) increases linearly with fuel pressure. However, the heat output varies very little with fuel pressure. This may be due to the fact that, when the flame is at the entrance to the mixing tube, it is quite well insulated from the silicon carbide crucible. Experiment No. 12 was constructed, combining the mixing tube with the crucible, in order to get more direct heating of the crucible by the flame during all modes of operation.

In all the propane-aspirated air tests to date, the motive power for the furnace was supplied by a jet of high pressure propane gas. The nozzle has

been made by drawing down abruptly a quartz tube and then grinding off the drawn-down portion until the proper orifice size was reached, in order to pass the desired quantity of propane. Since the nozzle was so fine (approximately 0.005 in.) we were concerned whether the laws governing adiabatic flow nozzles still applied, and whether we would have to construct a convergent-divergent nozzle in such a very small size. Accordingly, eight nozzles were tested. Their throat diameters, ranging from 0.006 to 0.014 in., were constructed from brass and from quartz tubing. The flow rate of propane through these nozzles, as a function of fuel pressure, was observed. Also, the thrust exerted by the nozzle was measured on a force-balance especially constructed for the purpose. Above 10 psig, all orifices agreed within $\pm 5\%$ of the theoretical equation for choking flow (Equation 1).*

$$w = \sqrt{\frac{k}{R} \left(\frac{2}{k+1} \right)^{\frac{k+1}{k-1}} \frac{A_t p_o}{\sqrt{T_o}}} \quad \dots (1)$$

where

w = mass flow rate

A_t = throat area of nozzle

p_o = upstream absolute pressure

$k = C_p / C_v$ = ratio of specific heats
= 1.13 for propane

T_o = upstream absolute temperature

R = gas constant

The data for choking flow were examined to determine whether the nozzle diameter had an effect in addition to that predicted by Equation 1. Scatter of the data prohibited observing any additional effect. The thrust for a simple convergent nozzle is given by Equation 2. The thrust for a convergent-divergent nozzle with the optimum exit section is given by Equation 3.

*See A. H. Shapiro, "Compressible Fluid Flow," Vol. 1, Ronald Press, page 85 to 103.

$$\tau_{\text{conv.}} = 2p_o A_t \left[\left(\frac{2}{k+1} \right)^{\frac{1}{k-1}} - \frac{p_a}{p_o} \right] \quad \dots (2)$$

$$\tau_{\text{max.}} = p_o A_t k \left[\frac{2}{k-1} \left(\frac{2}{k+1} \right)^{\frac{k+1}{k-1}} \right]^{1/2} \left[1 - \left(\frac{p_a}{p_o} \right)^{\frac{k-1}{k}} \right]^{1/2} \quad \dots (3)$$

where, in addition

$\tau_{\text{conv.}}$ = thrust for a convergent nozzle

$\tau_{\text{max.}}$ = thrust for an optimum convergent-divergent nozzle

p_a = pressure of surroundings (absolute)

The thrusts measured experimentally agreed well with Equation 2. Equations 2 and 3 were evaluated for a k value of 1.13 and upstream pressures up to 125 psig. At 60 psi, one could obtain 6% more thrust by using a convergent-divergent nozzle over a simple convergent nozzle. At 125 psig, one could obtain 12% more. Thus, the trouble of constructing an extremely small convergent-divergent nozzle does not appear to be worthwhile for propane gas. For gasoline, the k value would be even closer to unity, and the advantage of using a convergent-divergent nozzle would be even less.

Phase 3 - Thermionic Generator Design and Comparison

Some design work was undertaken on a 25-diode, series-connected power source, capable of producing 100 w of electric power at 12 v. This generator used as a basis of design the thermionic diode illustrated in Figure 2. Also, some estimates have been made on how a single thermionic diode, similar to that shown in Figure 4, could be incorporated into a portable gasoline-fired thermionic power source. Both of these studies are incomplete, and will be reported at a later time.

TASK C - MATERIALS DEVELOPMENT AND EVALUATION

Results of Work Previous to Contract

Subsequent to the preparation of our proposal, tests at this laboratory, plus additional searching through the literature, have shown that, although platinum

and rhodium stand up satisfactorily in a gas flame environment, they are permeable to oxygen. Englehard Industries protects molybdenum by first flame spraying it with alumina and then applying a platinum cladding. This protection scheme, although workable, has been abandoned in favor of the molybdenum disilicide coatings. In fact, a comprehensive review of the work on the protection of molybdenum has been carried out, and molybdenum disilicide coatings have been singled out as most suitable for our purposes. Three types of coated molybdenum were tested to some degree. The first was a vapor-deposited coating of silicon. The second was the Durak-B coating, applied by the Chromizing Corporation. The third was a coating applied by another research effort at Atomics International. Although the manufacturer of the Durak-B coating says that Durak-B will protect molybdenum for an nominal 100 hr at 1500°C, we found protection times of only 10 to 20 hr in our rather high velocity flame. The 100-hr life refers to a quiet air environment. Accordingly, we were not very surprised when, in the preliminary runs of the demonstration furnace, we discovered that a 2-mil coating of Durak-B over molybdenum was corroded through in the places where the high velocity gases from the combustion chamber impinged upon the coating. We also found that a silicon carbide wafer interposed between the combustion chamber and the molybdenum was attacked, but that it served to protect the molybdenum. In two cases, a silicon carbide wafer protected the end of a molybdenum bar to such a degree that failure or pitting occurred on the side, while the end was still well protected. One such failure is shown in Figure 18. This caused the loss of our first demonstration diode. Note that, although a deep cavity developed in the thicker end section of the cathode thimble, a small hole in the wall of the cathode sleeve allowed air to fill the diode.

During the fabrication of the demonstration diode, it became apparent that leaktight joining of molybdenum to molybdenum and molybdenum to another metal is difficult. All molybdenum thimbles made by joining molybdenum tubes to end caps by Heliarc welding or Aquadag^{*} welding failed, due to brittle fracture. The demonstration diode was finally fabricated by machining the cathode thimble from a single piece of metal.

^{*}Aquadag welding is performed by painting a suspension of carbon in water (Aquadag) on the mating surface of joint to be welded. The joint is heated, just to the eutectic temperature for Mo-C. The eutectic forms, fuses, and bonds the two pieces together.

Work on Contract

Phase 1 - Molybdenum Coatings

A device for testing the performance of coated molybdenum rods has been constructed, and is shown schematically in Figure 19. The sample is electrically heated, using a Variac and stepdown transformer power supply. The adjustments are made manually, and the sample temperature is observed with a Leeds and Northrup optical pyrometer. The samples are heated continuously to failure through the use of a current detector circuit which is actuated by the current in the low voltage sample circuit. When the sample burns out and there is no current in its circuit, the timer motor circuit is opened to stop the timer. In this way, we are able to run the tests continuously until burnout. In addition, the timer can be set to turn off the Variac power at a predetermined time, so that a test of a fixed duration can be run. Variations in the line voltage have thus far not been troublesome, and, if necessary, can be eliminated through the use of a constant voltage power supply.

This apparatus is being used to test the performance of the Durak-B coating produced by the Chromizing Corp. and a variety of coatings produced by a proprietary NAA process. The purpose of the present series of tests is to establish the useful service lives of the various coatings as a function of operating temperature and environment. In addition, the causes of failure of these samples are being sought.

The first series of samples was exposed at a nominal 1500°C, and it was found that the sample failures occurred 3/4 to 1 in. from the clamps, rather than at the center of the sample. This was unexpected, because the sample temperature in the region of the break was only 1200 to 1300°C. Similar behavior was observed from a sample (No. 376) heated to a nominal 1700°C. In order to prevent the failures occurring at this point, short lengths of quartz tubing were slipped over the ends of the wire to cover the sensitive areas. The function of the tubes is merely to prevent the free movement of air past the 1200 to 1300°C zone. This measure was found to be successful, and our failures are now occurring at the centers of the samples.

In addition to these observations, post-test metallographic and microscopic examinations have been made. These studies have generally shown: (1) that the "core" diameter (i. e., the diameter of the molybdenum phase beneath

the coatings) decreases with increasing exposure time at 1500°C; (2) the complexity of the surface layers increases with time; (3) the KHN (Knoop Hardness Number) of the core metal immediately adjacent to the coating is generally lower than the average value of the core; and (4) the hardness of the core decreases (as expected) with increased exposure time. The third item poses the question of whether silicon from the case has diffused into the molybdenum to form a layer of solid solution with a lower hardness than the base molybdenum.

Tables V and VI summarize the data obtained to date. Examination of Table V shows that the samples heated without the quartz end protectors failed in a nominal 50 hr, regardless of the test temperature. In some cases, there were areas of incipient failure in addition to the actual failed zone. In all cases, the temperature of the samples at the failure point was from 1200 to 1300°C. The reason for these low-temperature failures is not immediately apparent. However, it does seem that the cause may be the nature of the coating at 1200°C. At higher temperatures, the developed silica coating is obviously glassy, and is presumably moderately fluid. Therefore, the coating is capable of sealing itself relatively easily. As the temperature is lowered, the viscosity of the silica coating increases, and one can imagine that, at 1200°C, it can no longer flow enough to seal itself. In addition, there is a slow transition of glassy silica to cristobalite at this temperature. One can therefore postulate that this combination of low viscosity and the transition produces a very brittle coating after a few hours at 1200°C, and its degree of protection is markedly less than that of the coating at 1500 to 1750°C.

One rather obvious potential solution to this difficulty is to attempt to increase the fluidity of the coating used in the 1200 to 1300°C region. This presents a problem, in that any agent which would mix with the silica-base coating to produce a suitable viscosity at 1200°C would almost certainly produce a too-fluid coating at 1500°C. Therefore, if one uses this technique, one must tailor the coating composition to match the expected service temperatures. Although this may at first seem to complicate the material protection problem, the service life of sample No. 396 is sufficiently encouraging that a tailored coating might be quite feasible.

Sample No. 395 shows a negligibly small service life, but a similar sample, No. 396, showed 211 hr service, and would probably have gone many more

TABLE V
SUMMARY OF CORROSION EXPERIMENTS ON DURAK-B COATED MOLYBDENUM SAMPLES

Sample No.	Nominal Coat Thickness. Test Environment	Nominal Temperature (°C)	Corrected Temperature (°C) [†]	Time (hr)	Core Diameter (in.)	Core Hardness KHN (50 gm)	Remarks
359	0.0015 in., Air	1500	1570	43.8			Failed 1 in. from center
360	0.0015 in., Air	1500	1570	47.8			Failed 5/8 in. from center
366	0.0015 in., Air	1500	1570	15.8	0.0576		Terminated - poor electrical contact
367	0.0015 in., Air	1500	1570	29.0	0.0580	250 ± 28	Failed at center, but had a region of incipient failure 3/4 in. from center
369	0.0015 in., -	-	-	-	0.0610	355 ± 32	As-received sample
376	0.0015 in., Air	1700	1785	49			Failed 1 in. from center
377*	0.0015 in., Air	1750	1840	16.5			Failed at center
378	0.0015 in., Air	1500	1570	9.0	0.0583	249 ± 27	Terminated - poor electrical contact
379	0.0015 in., Air	1500	1570	49.5	0.0574	235 ± 11	Failed 1 in. from center
384	0.0015 in., Argon	1500	1570	7.5			Timed heating, precoated for 30 min at 1500°C in air
385	0.0015 in., Argon	1500	1570	4.0	0.0606	280 ± 15	Timed heating, no precoat
387	0.0025 in., -	-	-	-	0.0590	275 ± 27	As-received sample
395*	0.0025 in., Air	1700	1785	0.1			Sample failed during heatup
396*	0.0025 in., Air	1750	1840	211			Run inadvertently terminated

*Sample run with quartz end protectors

†Temperatures are corrected for $\epsilon - 0.6$

TABLE VI
SUMMARY OF CORROSION EXPERIMENTS ON PROPRIETARY NAA COATED SAMPLES

Sample No.	Coating, Test Environment	Nominal Temperature (°C)	Corrected Temperature (°C) [†]	Time (hr)	Remarks
834	Si-Sn, Air	1750	1840	11	Failure 1 in. from center
835	Si-Sn, Air	1500	1570	60	Failure 1 in. from center
838	Si-Zn, Air	1500	1570	28.1	Failure 3/4 in. from center
842	Si, Air	1500	1570	0.7	Failure at center
845	Si, Air	1500	1570	9.2	Failure 1-1/4 in. from center
903*	Si-B-C, Air	1750	1840	0.7	Failure at center
904*	Si-B-C, Air	1500	1570	2.0	Failure occurred at center when sample temperature was raised after a 2 hr exposure at 1500°. Sample reached 1735°C. maximum.

*Sample run with quartz end protectors

†Temperatures are corrected assuming $\epsilon = 0.6$

hours. The difference in their behavior is ascribed to the fact that No. 396 was preoxidized at 1300, 1500, 1600, and 1710°C, for a total of about 4 hr, before the final adjustment of its nominal 1750°C temperature was made. Sample No. 395 was heated to temperature in about 10 min; and, from its performance, we conclude that the protective coating simply did not have time enough to form. We have now adopted the more leisurely pretreatment used on No. 396 for all of our samples.

At present, only a few of the samples tested have been examined metallogically. However, some interesting information has been developed from those we have examined. Representative photomicrographs are shown in Figures 20, 21, 22, 23, and 24.

Figure 20 shows the edge of Sample No. 369, an as-received nominal 0.0015 in. Durak-B coated molybdenum wire sample. The diamond shapes are indentations in the polished metal, made for the purpose of measuring hardness. The coating thickness is 0.00128 in., and its hardness is 1150 KHN (50 gm). Just inside the core (0.00041 in.), the hardness is 310 KHN (50 gm); and, within the core, it averages 355, with an average deviation of 32 KHN (50 gm). Note the uniformity of the coating and the deep cracks.

Figure 21 shows the edge of Sample No. 387, an as-received nominal 0.0025 in. Durak-B coated molybdenum wire sample. The coating is made up of an outer case, 0.00262 in. thick, and a 0.00021 in. inner interfacial layer, for a total coating thickness of 0.00283 in. The hardness of the outer portion of the coating is 1300 KHN (50 gm), but the inner parts are softer, 510 KHN (50 gm). Just inside the core (0.00039 in.) the hardness is 225 KHN (50 gm), with an average core hardness of 275 and an average deviation of 27 KHN (50 gm).

Figure 22 shows the edge of Sample No. 366, a 0.0015 in. Durak-B coated sample heated 15.8 hr at 1500°C in air. Note the thin glassy outer layer and the two inner layers. The glassy layer is 0.00060 in. thick, the outer case layer is 0.00185 in. thick, and the inner layer is nominally 0.00055 in. thick. The outer case layer does not show well in this photograph, but it consists of columnar crystals oriented radially.

Figure 23 shows the edge of Sample No. 367, a 0.0015 in. Durak-B coated sample heated 29 hr at 1500°C in air. In this sample, the expected outer glassy

layer does not appear. There are two, and perhaps three, case layers: a thin outer layer with no discernible crystal structure, 0.00018 in. thick; an intermediate layer showing the columnar structure, 0.00140 in. thick (perhaps these two are really only the columnar layer with a poorly defined outer shell); and an inner layer with no clearly defined crystal structure, 0.00060 in. thick. The hardness of the columnar layer is 1130 KHN (50 gm), and that of the inner layer is >1800 KHN (50 gm). The hardness of the core just inside the case is 198 KHN, with an average core value of 250 and an average deviation of 28 KHN (50 gm).

Figure 24 shows the edge of Sample No. 379, a 0.0015 in. Durak-B coated sample heated 49.5 hr at 1500°C in air. In this sample, four layers are observed. The outermost is a glassy layer, about 0.001 in. thick. The outer case layer, which does not show any well-defined crystal structure, is 0.00070 in. thick. The intermediate case layer, having the columnar structure, is 0.00085 in. thick, and the inner case layer is 0.00070 in. thick. The hardness of the outer case layer is 1530 KHN (50 gm); that of the columnar-crystal layer is 1030 KHN (50 gm); and that of the inner layer is 1450 KHN (50 gm). The hardness of the core metal, 0.00047 in. from its outer interface, is 248 KHN (50 gm) and the average in the core is 235 ± 11 KHN (50 gm). This sample is the only one of those examined which shows a higher hardness value at its outside edge than the average core value. This aspect of the hardness profile will be investigated further in subsequent samples.

Figures 25 and 26 summarize the trend of core hardness, and of core diameter with exposure time, respectively.

Figure 25 shows the expected trend of molybdenum core annealing with exposure time. Figure 26 shows the effect of silicon diffusion into the molybdenum core (i. e., the movement of the interface between the "case" and the core). Although no further analysis of these data has been attempted to date, we plan to attempt to characterize these time-dependent factors, using additional experimental data.

Examination of Table VI shows that the NAA-coated samples thus far tested have significantly shorter service-lives in air than do the Durak-B coatings. As additional samples become available, they will be evaluated.

An attempt to measure the emissivity of our coated samples has been made, so that we can correct the observed pyrometer temperature. Our

preliminary results indicate the emissivity at $0.65\text{-}\mu$ wave length for the Durak-B sample surfaces to be 0.45 to 0.5. The manufacturers report the emissivity to be 0.75 to 0.77. Because of the uncertainty, we are presently using an arbitrary value of 0.6, and the corrected temperatures in Tables V and VI have been computed on this basis. A more refined measurement technique is being set up, and a more reliable value will be sought.

Phase 2 - Flame Erosion of SiC

As mentioned previously, silicon carbide has shown promise as secondary protection for our molybdenum cathodes, and we are attempting to determine which of the various carbide compositions is the most satisfactory. A possible alternative has also come to our attention. It is Astroceram, which is available as a castable paste from the American Thermocatalytic Corporation. The manufacturers report that the product is useable to 2900°C and has good strength at elevated temperatures. Its thermal conductivity is quoted as $0.033\text{ w/cm-}^{\circ}\text{C}$.

A small part-time effort is being directed toward becoming familiar with the capabilities of cast and rammed bodies of these materials. Thus far, the results are only moderately encouraging. The Astroceram bodies thus far prepared have been fragile and tend to crack. However, rammed products are superior to cast products.

In addition to these investigations, a brick furnace, for use in testing refractories to 1725°C , has been assembled. The furnace uses preheated air and propane, burning in a zirconia pebble bed. The exhaust gases are used to preheat the incoming air. This furnace is capable of heating a sample to 1500°C in its exhaust gas stream, but higher temperatures can only be attained by installing the sample in the combustion zone. Presumably, the sample enters into a surface combustion process, and the heat liberated takes the sample to the higher temperature.

Two samples of Carborundum Company silicon carbide have been exposed in this furnace. The first, Sample No. 824, was "Refrax" composition No. 3330. It was exposed for 1 hr at 1700°C in an oxidizing flame and lost 0.389 gm. This loss rate is $93\text{ mgm/cm}^2/\text{hr}$. The second sample, No. 833, was "Carbofrax" composition No. A978. It was exposed for 5 hr at temperatures above 1500°C . During about 1-1/2 hr of that time, the temperature was 1700°C . Although there was considerable difficulty in maintaining a stable temperature, the sample

performed significantly better than did No. 824. Sample No. 833 gained 0.0065 gm, and showed an average weight gain of $+0.3 \text{ mgm/cm}^2/\text{hr}$. Additional tests are in progress.

Phase 4 - Molybdenum Welding

The welding we are investigating comprises the Heliarc welding of a rhenium-plated molybdenum cap. An alternate method is the use of a rhenium-molybdenum alloy filler to be fused into the molybdenum-molybdenum joint. One weld of the rhenium-plate type has been attempted, but it was unsuccessful, in that the tube overheated and drew away from the fusion area. Some areas of the weld appeared quite satisfactory, and further welding attempts are scheduled.

TASK D - ELECTRICAL COMPONENT DEVELOPMENT

Phase 1 - Voltage Transformation

Various means were considered for transforming the $1/2 \text{ v}$ power produced by a thermionic diode to the 12 v required by Signal Corps equipment. The most attractive transformation devices appear to be the homopolar dynamotor and the solid-state converter. These devices produce no radio noise, are reasonably efficient, and can be built with only a slight extension of existing technology.

If all diodes are heated by the same furnace, insulation between diodes is a serious problem. Most solid insulators break down, and also the flame is a fair conductor of electricity. Also, the cathode temperature, anode temperature, and cesium reservoir temperature of each diode must be carefully adjusted, so that the power generated in one diode is not dissipated in the next. In series connected diodes, the electron emission of the cathode is a function of the cathode temperature and the cesium reservoir temperature. Each cathode must emit the same number of electrons, and each converter must be adjusted to add to their energy.

In series connected diodes, the reliability of the system is in one way greatly decreased and in another way considerably enhanced. For instance, if a single diode of the 24-diode array has nine chances out of ten of lasting 500 hr without failure, then the entire array has 0.9^{24} , or one chance in 13, of lasting

for 500 hr. However, if the failed diode can be quickly located and shorted across, the remaining array of 23 can continue to operate with only 4% loss of power.

Vibrator-commutator type converters were ruled out, because of radio noise and contact maintenance problems.

For the future, a pair of oscillated diodes appears very attractive. In this case, two diodes would be alternately oscillated in and out of conduction to produce alternating current whose voltage can then be raised directly by a transformer. Insulation of the cathodes from each other is unnecessary, since the cathodes can be connected electrically.

In this scheme, each diode could develop full power if it ran full time. When it is shut off, heat loss across the interelectrode space and out the cathode lead still continues. Nevertheless, the power source, as a whole, may be lighter and more reliable. In the future, more work will be done to evaluate this concept.

Homopolar Dynamotor

This approach uses the 1/2-v diode output to run a small homopolar motor. This motor, in turn, drives a permanent magnet alternator that generates an ac voltage which, when rectified and filtered, produces the required 12 v dc. A homopolar motor is used because, unlike most dc motors, no commutation is required. Current flows continuously, hence no sparking occurs which might cause radio noise. The permanent magnet alternator requires no brushes or slip rings, hence is also quiet, reliable, and efficient.

Figure 27 is a drawing of the dynamotor. The homopolar motor portion consists of two metal disks mounted on a shaft, two toroidal permanent magnets, and two mercury slip rings. The discs have radial slots cut through them, in the area that passes through the magnetic poles, in order to prevent spiraling of the electric current in the disk. The magnets establish an axial magnetic field of opposite polarity across the outer portion of each disk. Current enters one disk via the mercury slip ring on the perimeter. This current flows radially inward to the shaft, through the shaft to the other disk, and then radially out to the slip ring on the perimeter of the other disk. This radial current flow is at right angles to the axial magnetic field for every position of the rotor;

hence, a continuous current develops a continuous torque as the rotor turns. There is no need to commutate or alternate current flow in the armature. Use of mercury slip rings minimizes resistive and frictional losses, and eliminates any tendency for sparking. Since no shaft protrudes from the housing, the unit can be completely sealed to keep out dirt and prevent mercury oxidation. Centrifugal force and surface tension hold the mercury in place, so the unit can be operated in any position.

The homopolar motor is quiet, light, reliable, and can be efficient. It is, however, limited to low dc voltages, and has not been widely used because sources of low-voltage high-current dc power have not been previously available.

The alternator portion would consist of a permanent magnet mounted on the shaft and stationary coils mounted on a surrounding laminated iron yoke. No slip rings are necessary, since the voltage is induced into the stationary coils by the rotating permanent magnet. Alternators of this type are commercially available, and have proven very successful. Conversion of the ac voltage produced to dc requires rectification and filtering. Silicon rectifiers and the use of high frequencies make conversion of ac to dc a comparatively easy chore.

A detailed performance calculation for the dynamotor described above is given in Appendix II. It is expected to have the following approximate characteristics:

Diameter	4-1/2 in.
Length	5-1/2 in.
Weight	11.5 lb
Speed of rotation	12,000 rpm
Input current	400 amp
Input voltage	1/2 v
Dynamotor efficiency	70%

Solid-State Converters

Conventional transistorized inverters used for changing 6 or 12 v dc to 110 v ac are not immediately applicable, since the available 1/2 v starting voltage is too low. Silicon transistors and controlled rectifiers have a minimum 0.6 v drop in forward conduction at 30% of rated current. Those made of germanium have a 0.2 to 0.3 v drop under similar conditions. Little or no power thus remains to be transformed.

To avoid this low voltage limitation, various companies are now developing solid-state converters, using a comparatively new device called the tunnel diode. Those made of germanium have a volt-ampere characteristic, wherein current through the diode increases as the driving voltage decreases from 0.35 v down to 0.05 v. Such a response is called negative resistance, and can be used to drive an oscillator, which, with a transformer, would convert low voltage dc to ac at the desired 12 v.

Solid-state converters have several attractive features. They have no moving parts. They are rugged, reliable, and quite efficient. The following figures were obtained from the Hoover Company, a manufacturer of low voltage uncontrolled converters:

6 v input	90% efficiency
1.5 v input	75% efficiency
0.5 v input	50% efficiency

Values may have to be reduced for voltage control.

A device capable of supplying 100 w at 12 v dc output from a 1/2 v dc input would be quite large and heavy. The Hoover Company estimates such a device would measure 8 in. by 12 in. by 14 in., and would weight between 20 and 30 lb.

The solid-state converter is thus the heavier of the two converters at the present time. In the future, however, tunnel diodes of larger current capacity might become available, making the solid-state converter the lighter of the two. Development of such a converter is being left to those companies which have capabilities in this field, and which are already deeply engaged in its development. When and if such a converter is developed, it will be purchased and incorporated into the power package.

CONCLUSIONS

1. No unusual problems have been encountered in the scaleup of internally heated thermionic diodes.
2. Thermionic temperatures and heat fluxes are readily obtained, using a combustion bed of zirconia chips to burn compressed air and propane. So far, however, such a furnace has a low efficiency, a relatively short life-time, and cannot be made portable.
3. Compact furnaces, employing aspirated air, have already been tested which will produce half the heat flux at half the temperature above ambient needed for thermionic diodes.
4. So far, protection of molybdenum metal by the Durak-B coating has been found to be the best in still air.
5. Although the use of silicon carbide to protect the coated molybdenum from flame erosion has been proved out in a number of diode heating tests, the most practical type of silicon carbide body to use is not as yet determined.
6. At the present state of the art, the cost of a thermionic diode is high, and its reliability is relatively low. Also, it would cost almost as much to make the large diode as it would a small one. Therefore, a single diode portable power source appears to be more practical. However, a more thorough investigation of the problem must still be undertaken.
7. Practical converters for single diode power sources can be constructed, using tunnel diodes or a special type of motor generator set.

PROGRAM FOR NEXT QUARTER

TASK A – CONVERTER DEVELOPMENT

The construction of the 150 w(e) thermionic generator will continue. Measurement of its characteristics and, if possible, a life test will be undertaken.

TASK B – HEAT SOURCE DEVELOPMENT

Development of small aspirated-air furnaces will continue. Adaption of these furnaces to gasoline fuel will be attempted. An experiment to determine the coking and plugging temperature for propane and regular gasoline will be undertaken. Building and testing of a rugged temperature control for the cesium reservoir will be undertaken.

TASK C – MATERIALS DEVELOPMENT

Evaluation of coatings for molybdenum metal will continue. Besides the tests in still air, a series of tests in carbon monoxide will be tried. Additional data on flame erosion of silicon carbide base refractories will be obtained. An apparatus for testing the permeability of molybdenum metal coated with molybdenum disilicide will be constructed.

TASK D – ELECTRICAL DEVELOPMENT

No work is being planned in this area.

PERSONNEL ASSIGNED TO PROJECT

		Hours Worked During First Quarter
D. H. Adair	Sr. Mechanic	444.7 hours
E. V. Clark	Research Engineer	383
R. P. Forslund	Research Engineer	378
R. G. Hoff	Sr. Research Engineer	476
W. R. Martini	Project Engineer	469
R. L. McKisson	Project Engineer and Supervisor	169

APPENDIX I
FIGURES

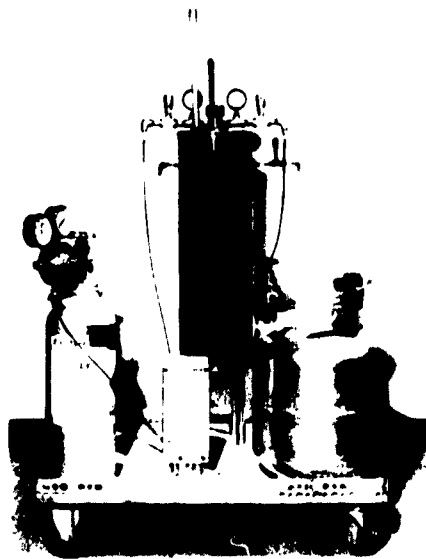
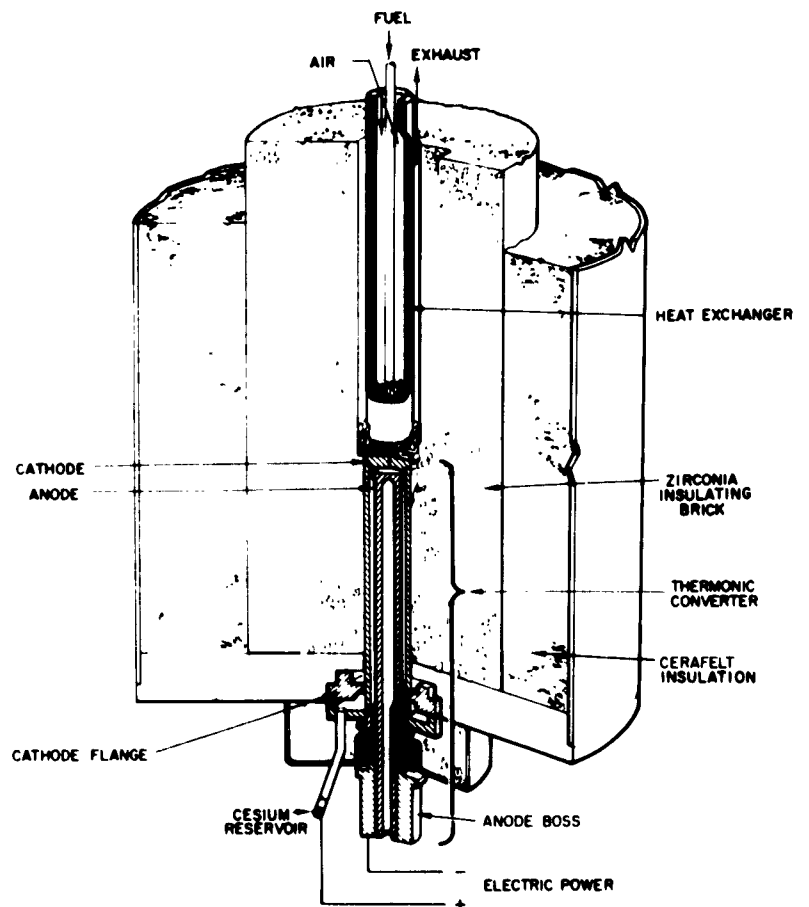


Figure 1. Demonstration Furnace

Figure 2. Cutaway of
Demonstration
Furnace



AI-6815

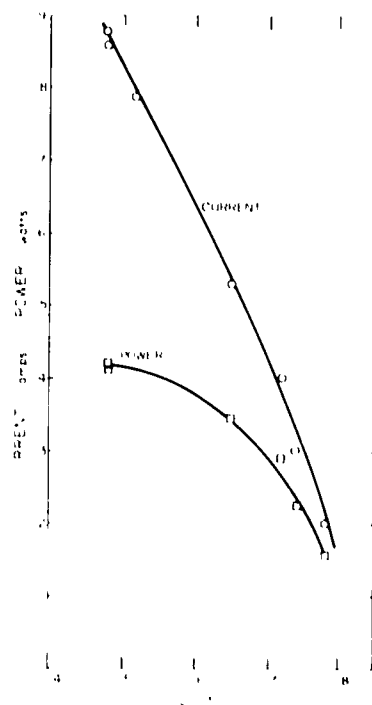
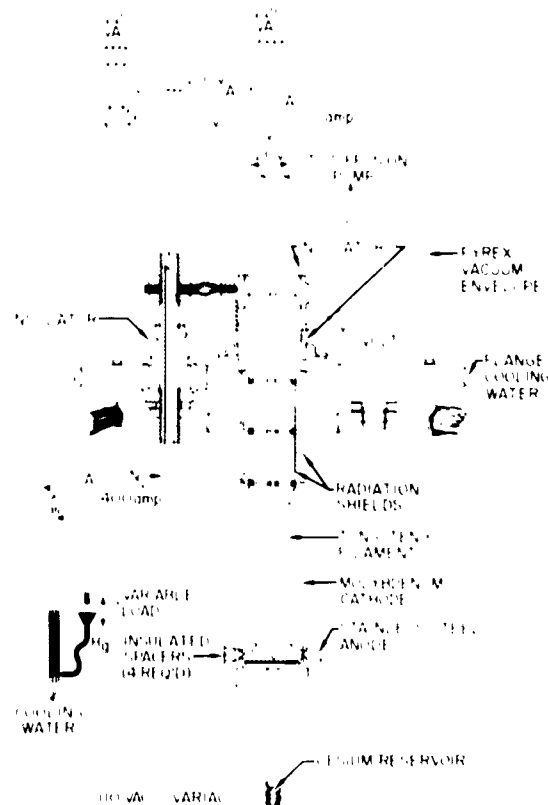


Figure 3. Diode Characteristics
From Fuel Fired Diode Ex-
periment No. 6
(Cesium Temperature 325 to 322°C,
Anode Temperature 728 to 732°C,
Cathode Temperature 1536 to 1551°C)

Figure 4. 200 w(e) Thermionic Converter



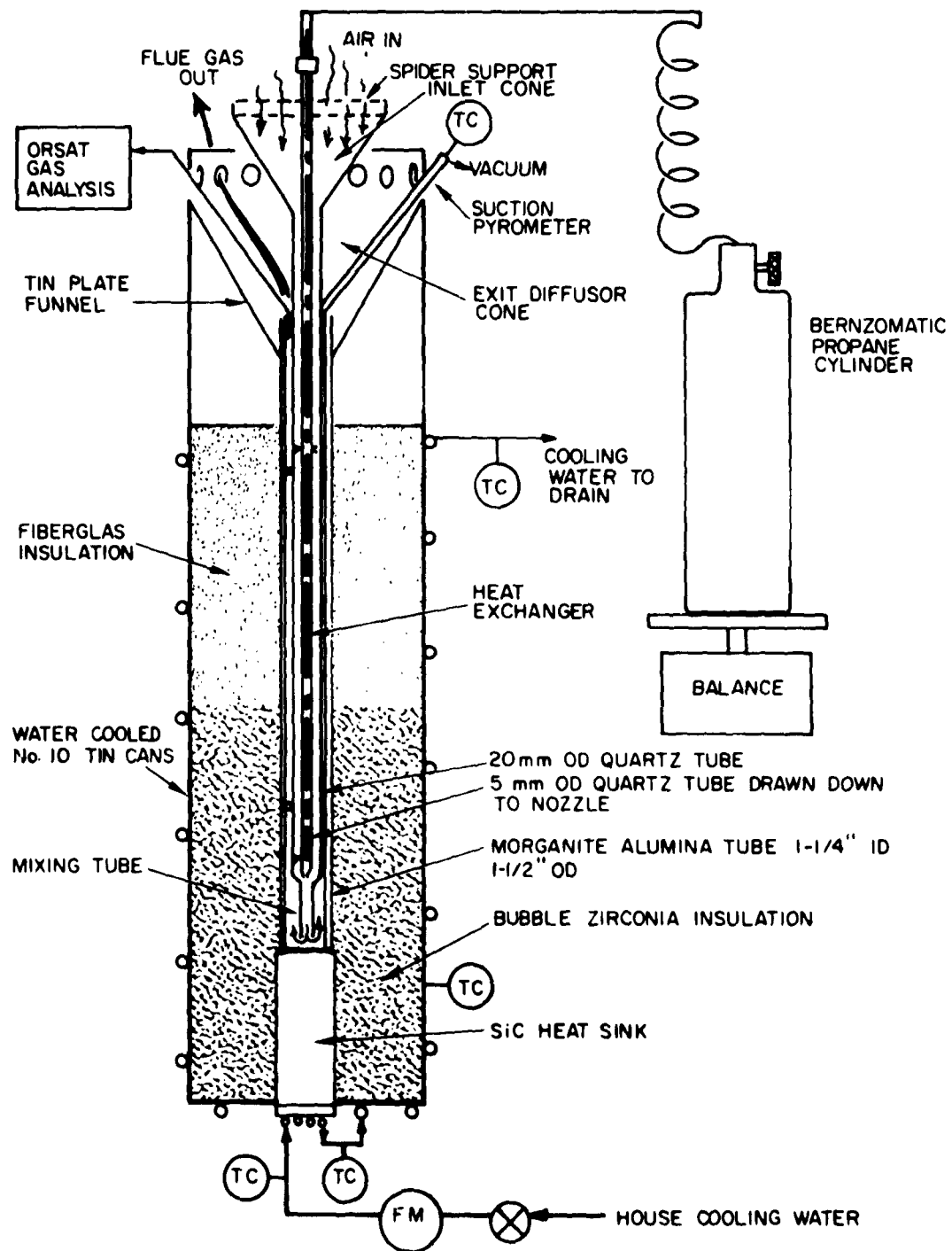


Figure 5. Propane - Aspirated Air Burner Test No. 9

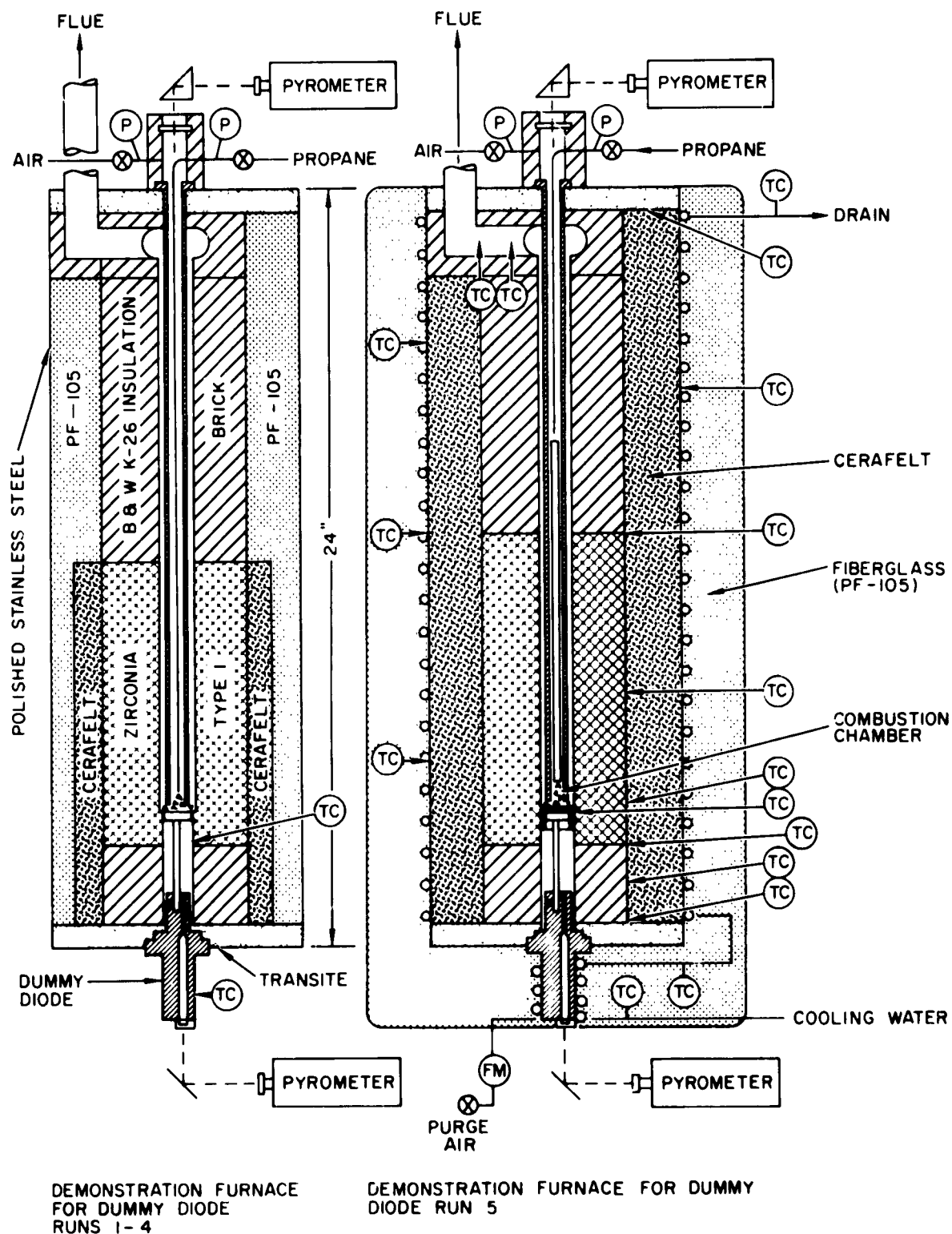


Figure 6. Schematic of Demonstration Furnace for Dummy Diode
Runs No. 1 Through 5

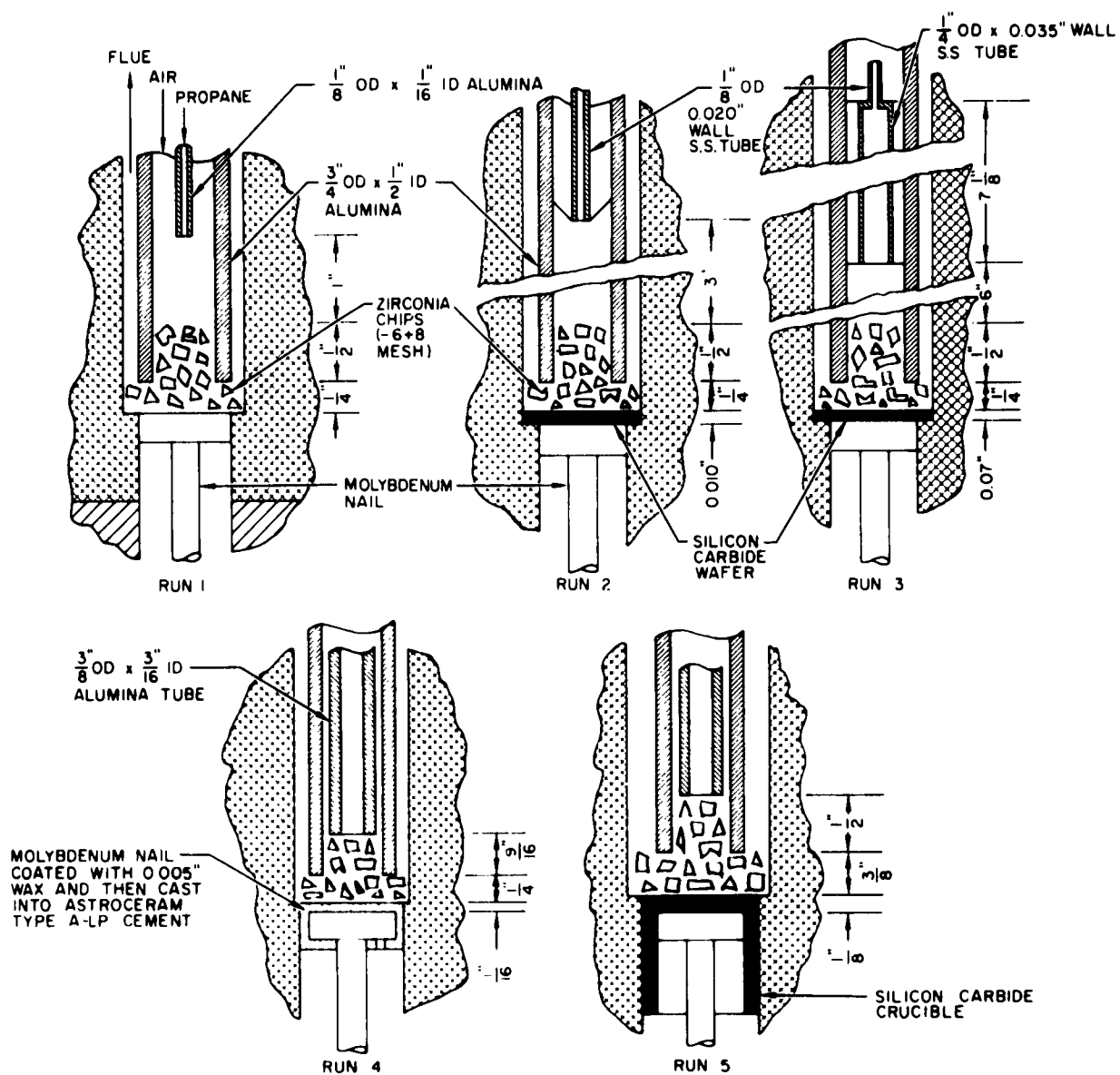


Figure 7. Combustion Chamber Details for Dummy Diode
Runs No. 1 Through 5

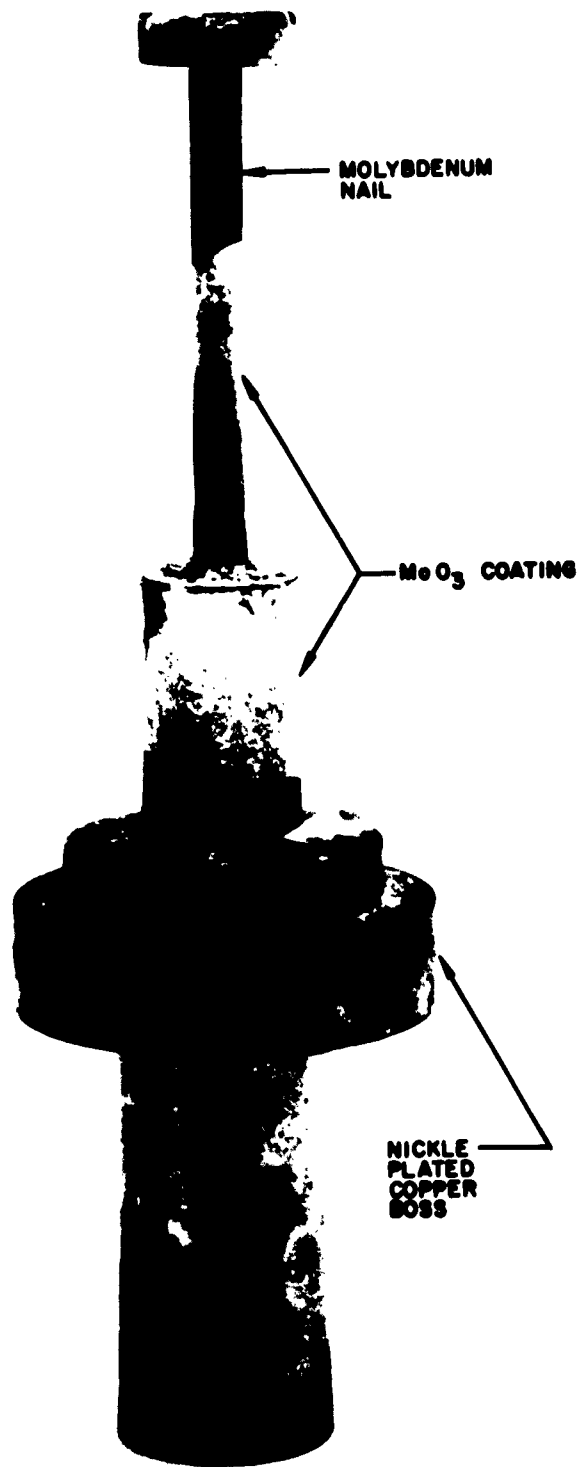


Figure 8. Dummy Diode
Assembly After Run No. 1
(Side View)

Figure 9. Dummy Diode
Assembly After Run No. 1
(Top View)



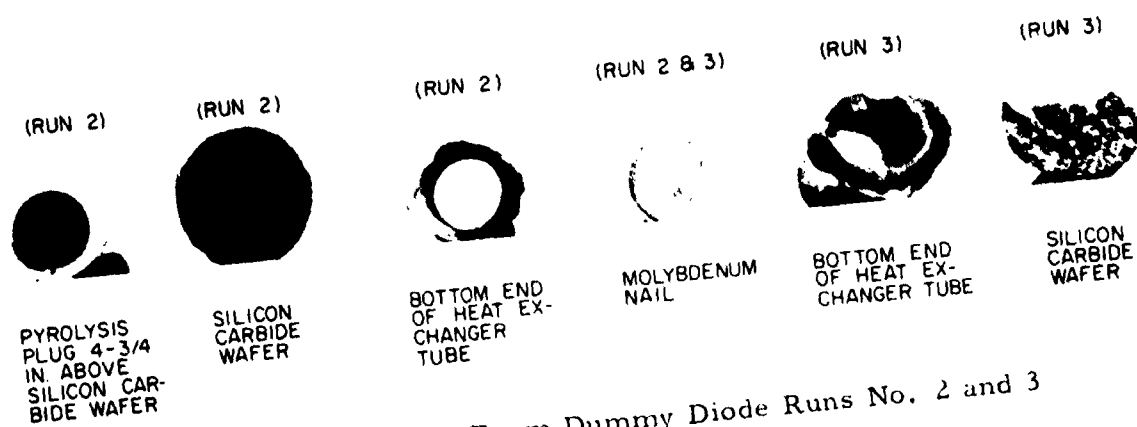


Figure 10. Remains From Dummy Diode Runs No. 2 and 3

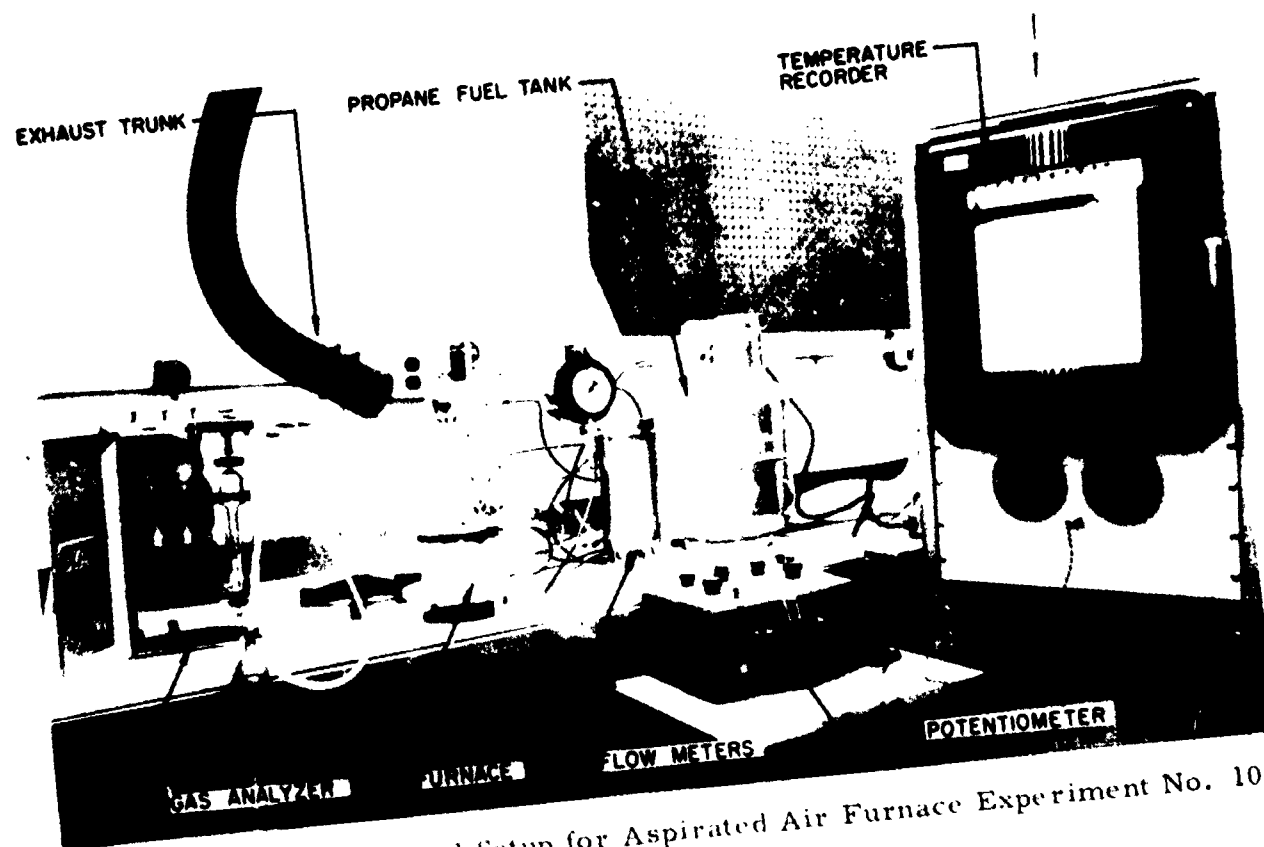
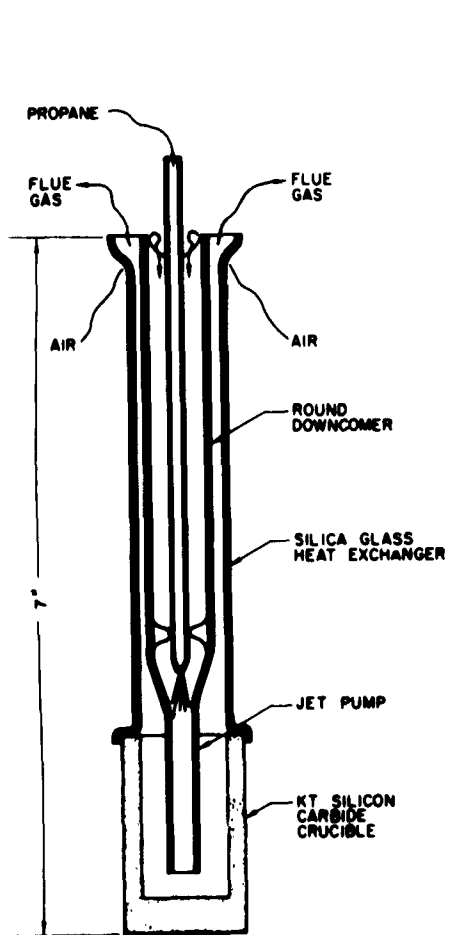
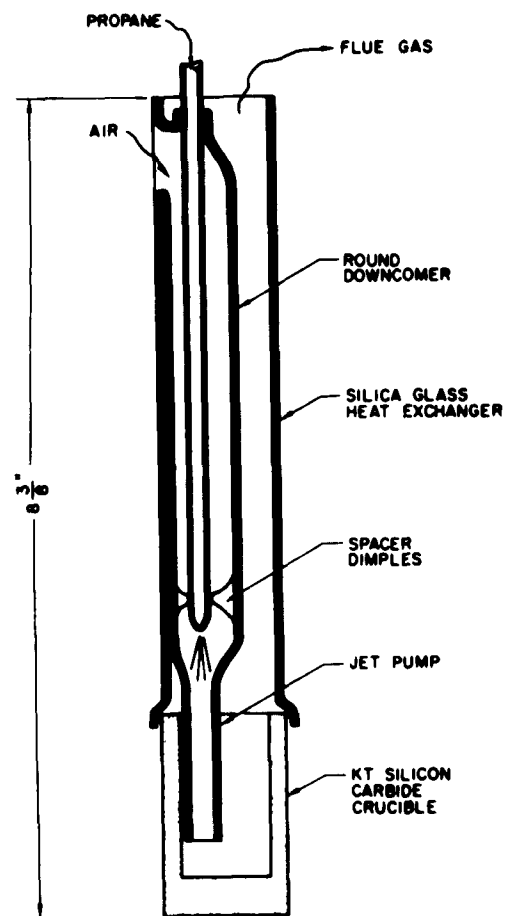


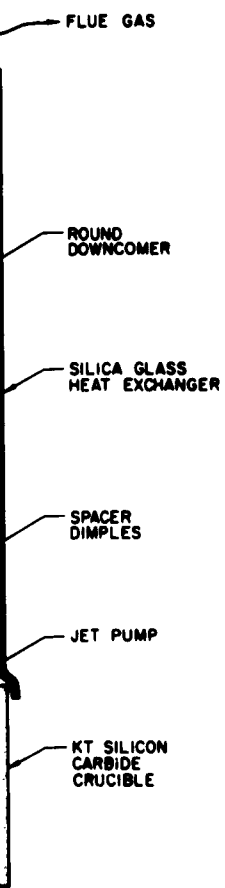
Figure 11. Experimental Setup for Aspirated Air Furnace Experiment No. 10



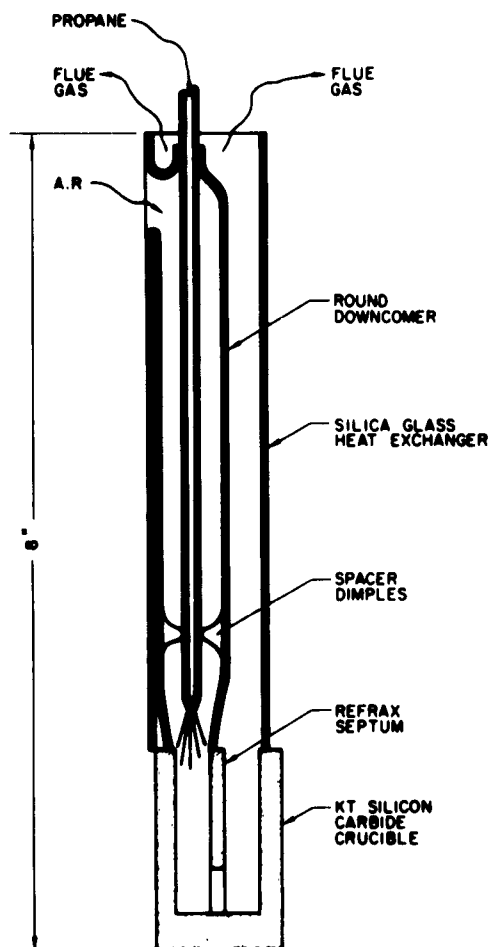
a. Heat Exchanger Assembly 1



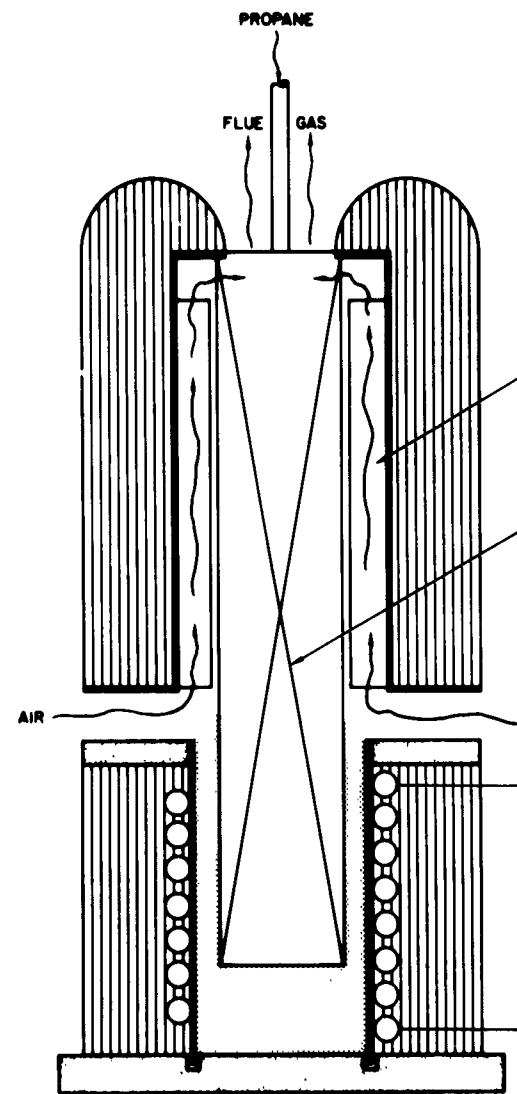
b. Heat Exchanger Assembly 2



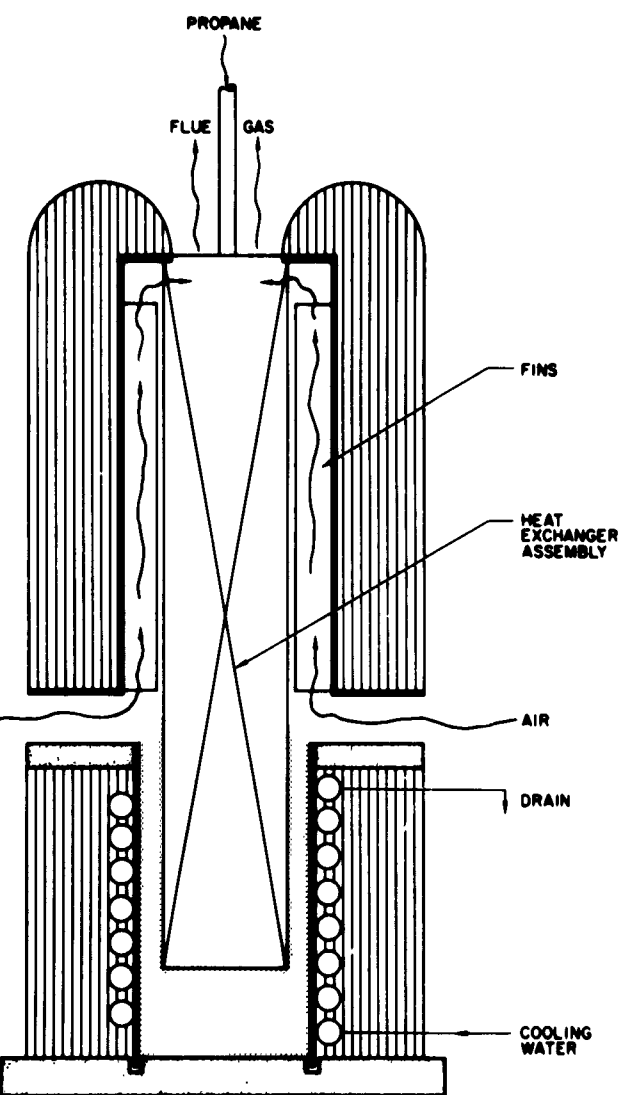
Heat Exchanger Assembly 2



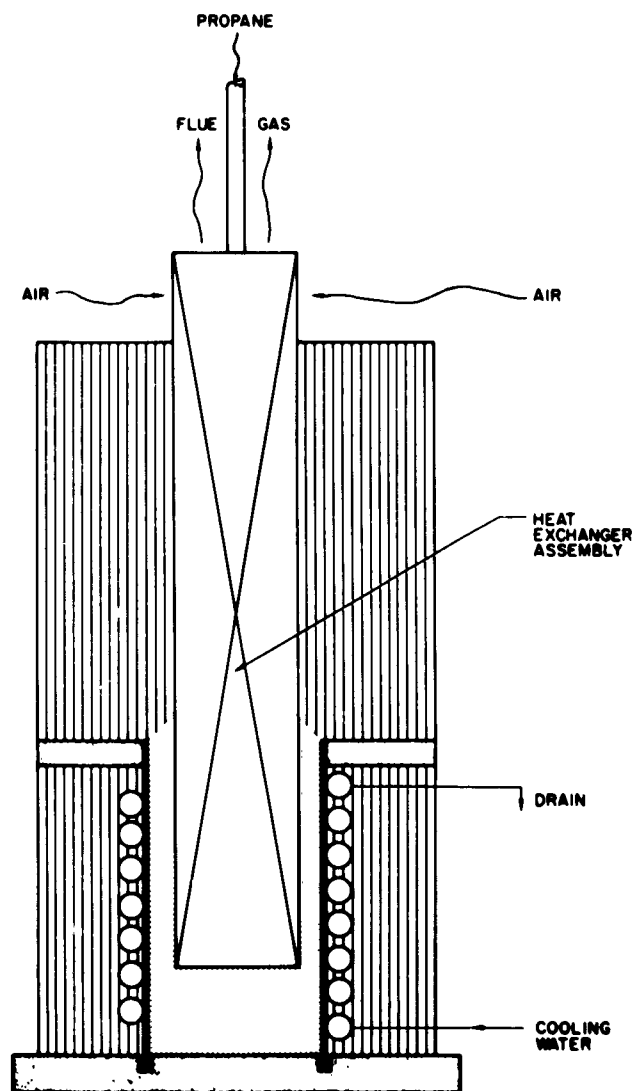
c. Heat Exchanger Assembly 3



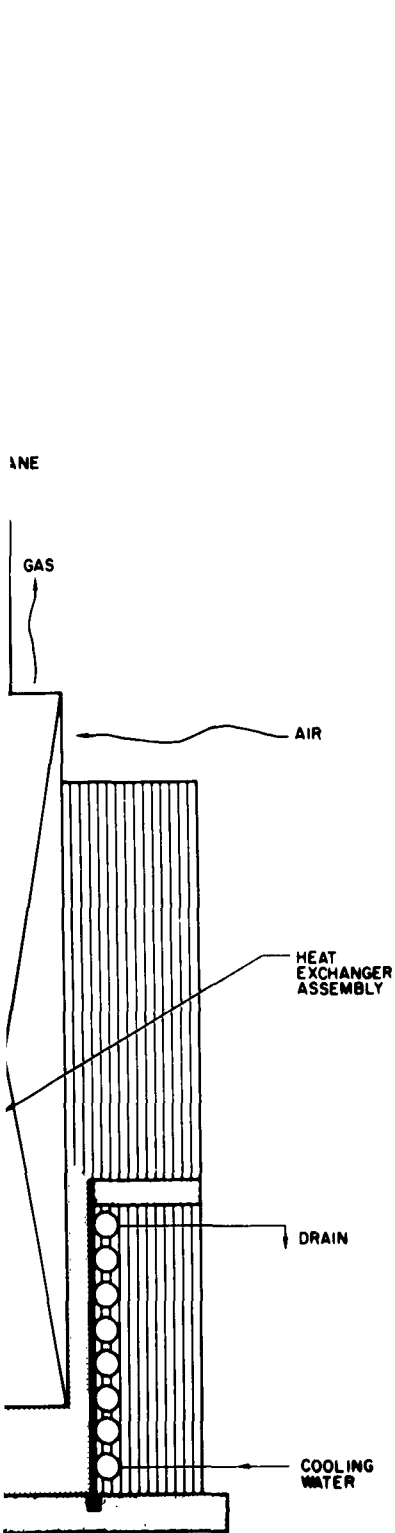
d. Arrangement A



d. Arrangement A

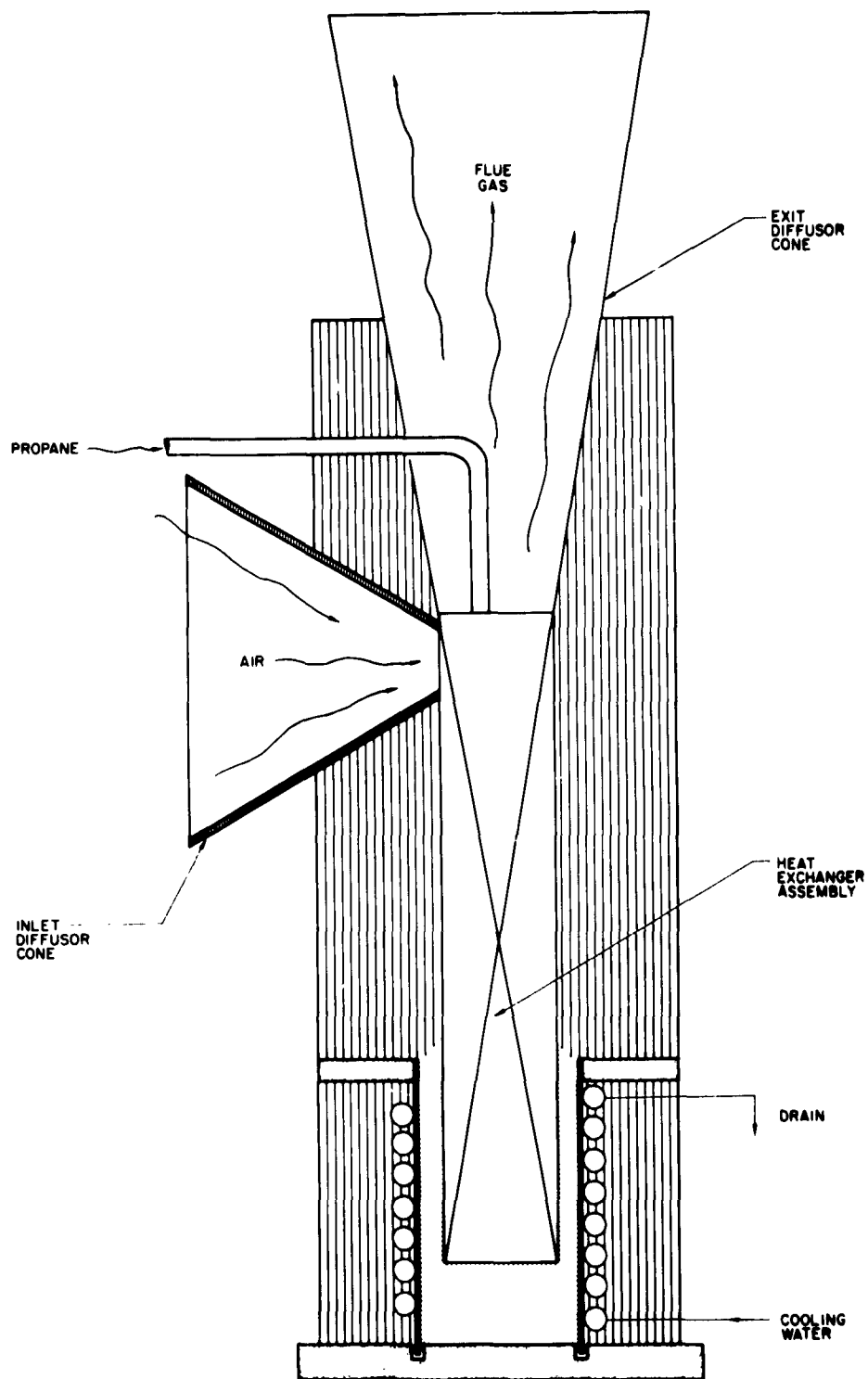


e. Arrangement B



Arrangement B

4



f. Arrangement C

Figure 12. Furnace Arrangements and Heat Exchanger Assemblies for Propane-Aspirated Air Runs No. 10 to 12

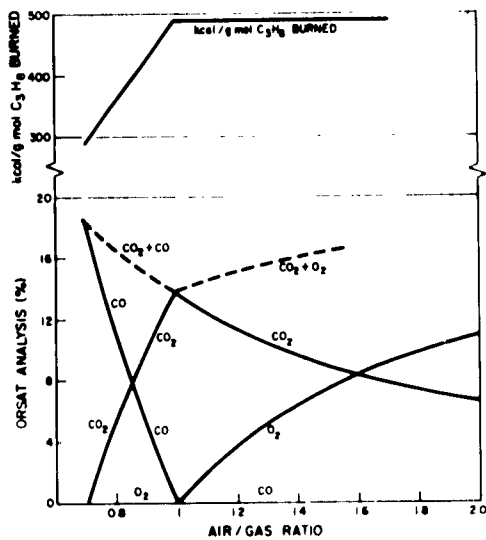


Figure 13. Propane Burning Data

Figure 14. Relationship Between Heat Flux and Crucible Temperature

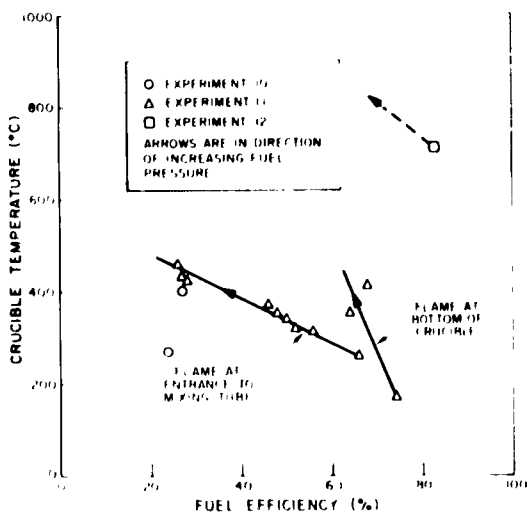
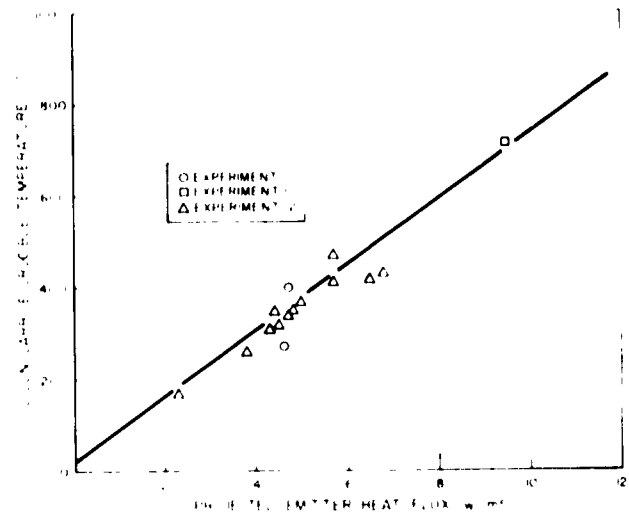


Figure 15. Crucible Temperature as a Function of Fuel Efficiency (Experiment No. 11, Runs No. 3 and 4)

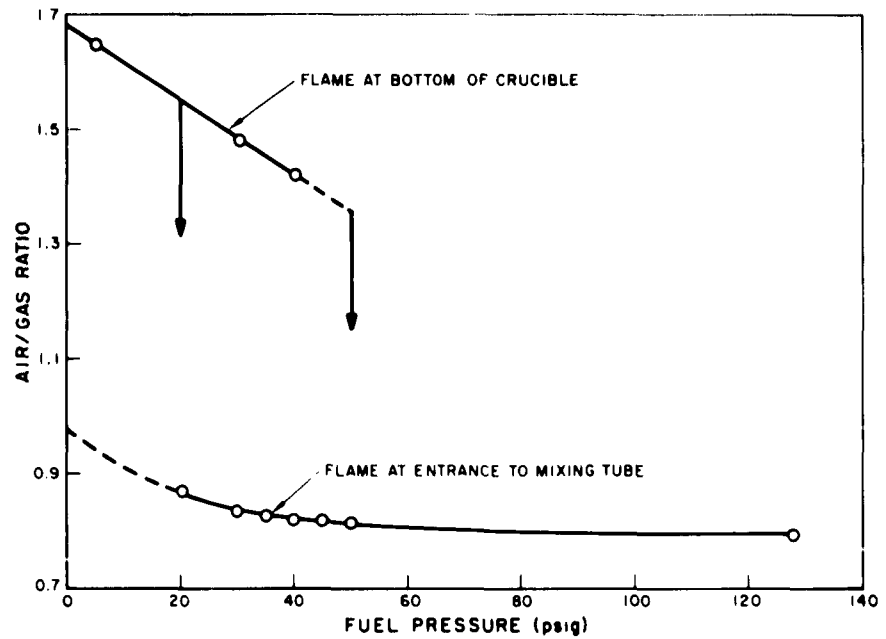


Figure 16. Two Modes of Operation for Experiment No. 11, Runs No. 3 and 4

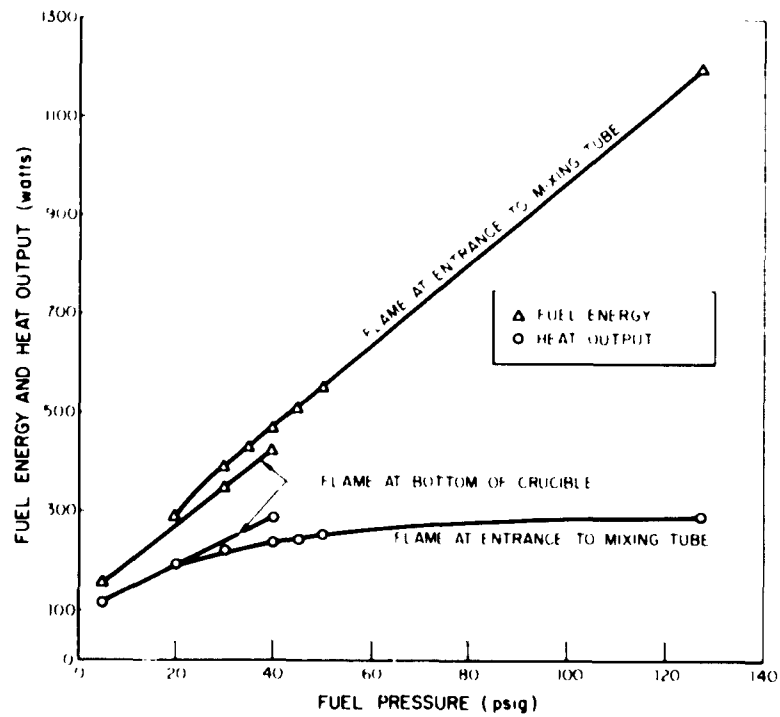


Figure 17. Fuel Energy and Heat Output as a Function of Fuel Supply Pressure (Experiment No. 11, Runs No. 3 and 4)

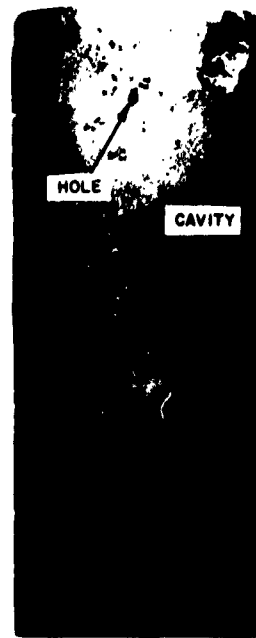


Figure 18. Corrosion of Demonstration
Diode After Fuel Fired Diode
Experiment No. 6

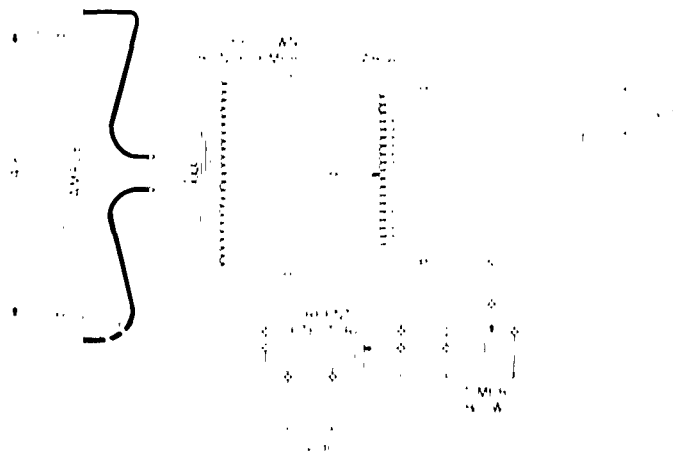


Figure 19. Corrosion Test Apparatus

As-Received Durak-B Coated Molybdenum Samples

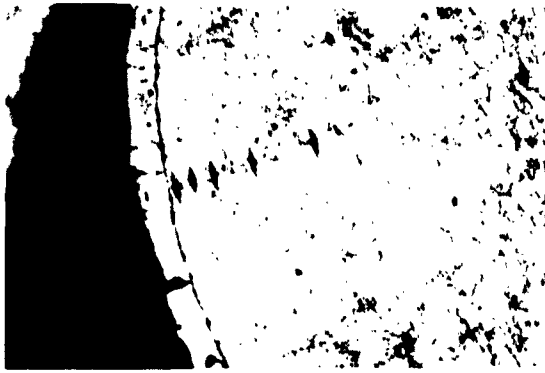


Figure 20. Outer Edge, Sample No. 369
(0.0015 in.)



Figure 21. Outer Edge, Sample No. 387
(0.0025 in.)

Durak-B Coated Molybdenum Samples Heated in Air at 1500°C

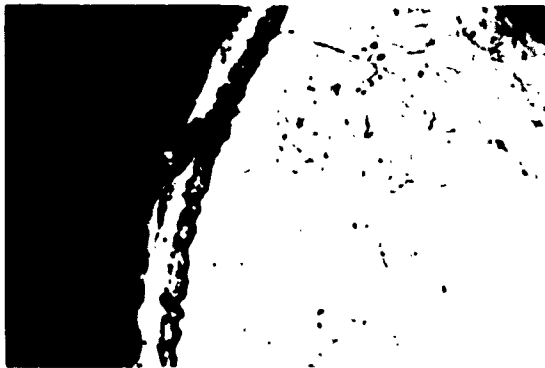


Figure 22. Sample No. 366 (0.0015 in.)
(Heated 15.8 hr)

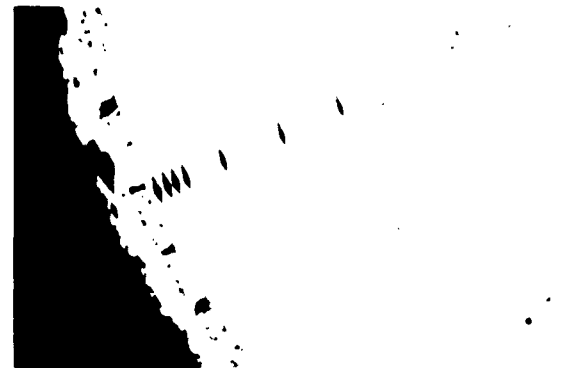


Figure 23. Sample No. 367 (0.0015 in.)
(Heated 29 hr)



Figure 24. Sample No. 379 (0.0015 in.)
(Heated 49.5 hr)

(All photomicrographs - 120x)

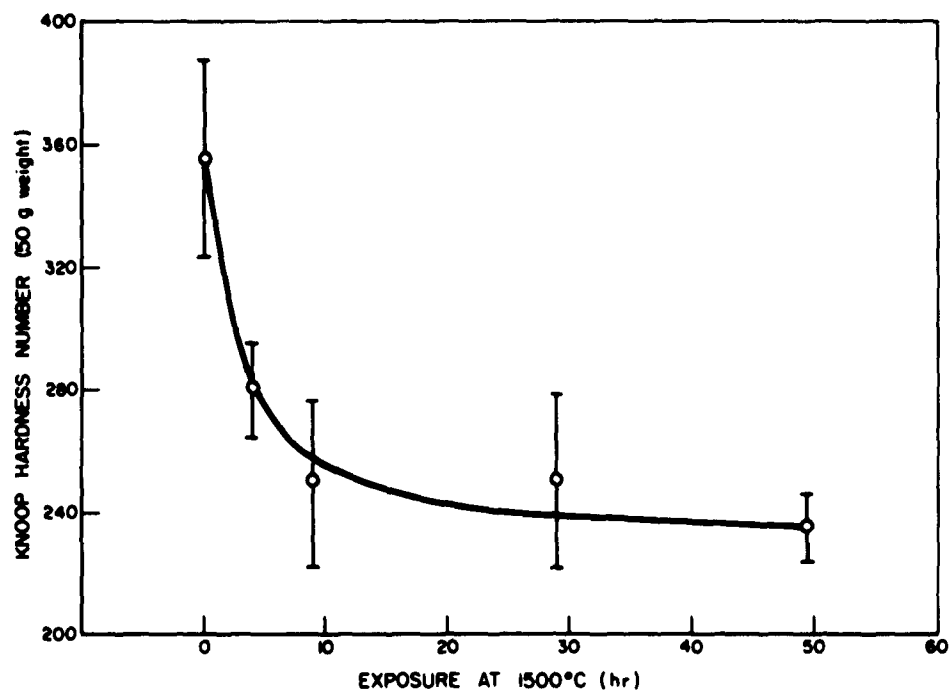


Figure 25. Core Hardness vs Exposure Time

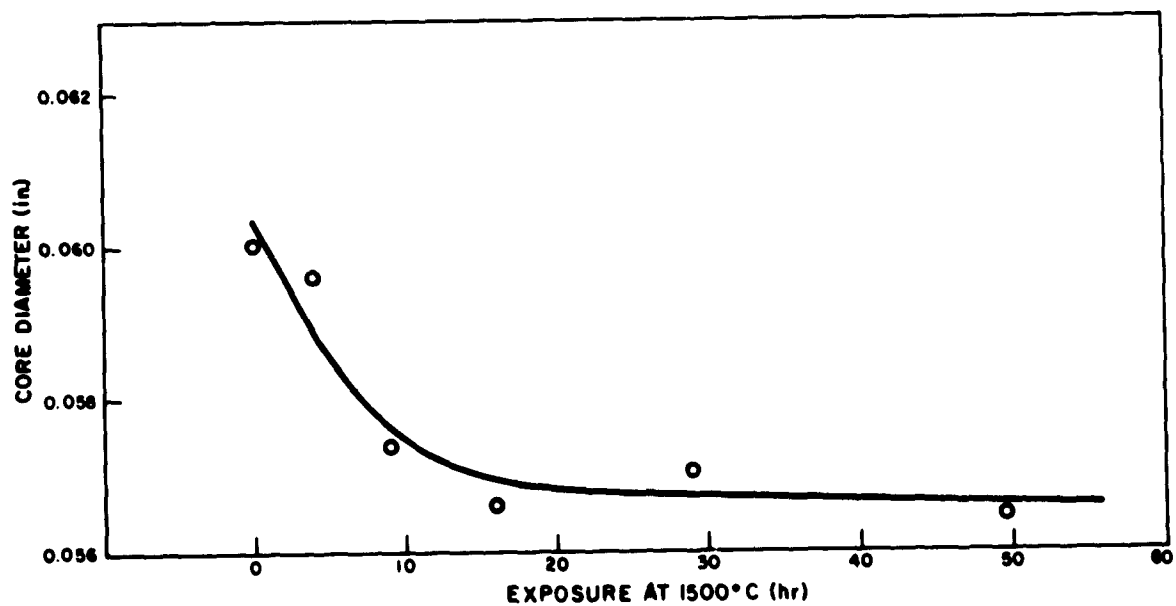


Figure 26. Core Diameter vs Exposure Time

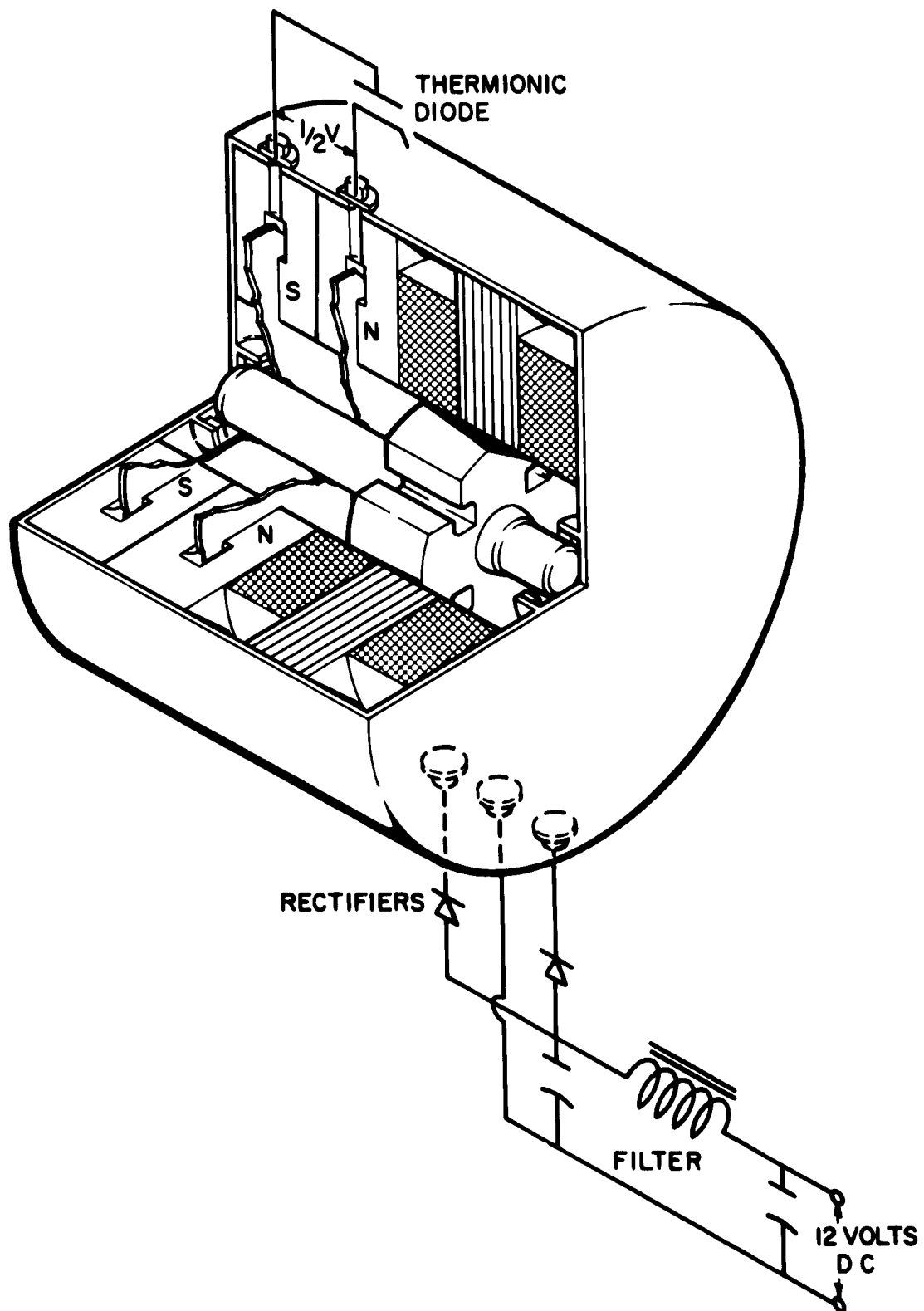


Figure 27. Homopolar Dynamotor

APPENDIX II

DESIGN OF A HOMOPOLAR DYNAMOTOR

INTRODUCTION

One method of converting low voltage power from a single thermionic converter to high voltage power is the use of a homopolar motor to drive directly a rotating permanent magnet alternator. This device is described briefly in the text, and is illustrated in Figure 27. In this appendix, the design of the motor is outlined and the generator is specified. Also, an estimate of overall performance and weight is made.

PRIMARY ASSUMPTIONS

Assume a power input of 400 amp at 1/2 v dc. Assume 5% of the input power to be expended as resistance losses in the current leads, brushes, and armature. The allowable total resistance must then be:

$$P_A = I_A^2 R_A \quad R_A = \frac{10 \text{ w}}{(400 \text{ amp})^2} = 62.5 \mu \text{ ohms} .$$

(This assumption will be checked later.)

DESIGN OF RING MAGNETS

The cross section of the ring magnets used in this design is given in Figure A-1. In order to determine the flux between the pole pieces, the leakage for this configuration must be determined. Maynard¹ gives a generalized formula for the leakage factor for the same arrangement of magnets and soft iron as viewed in cross section. However, Maynard's formula is for a magnet assembly of any length. The ring magnets in this design can be thought of as being made from long magnet assemblies by bending into a ring so the two ends meet. Thus, the flux leakage from the ends is eliminated. Also, since the two ring magnets are put into the motor so as to repel each other, flux leakage on one side of the ring magnet would also be eliminated. On the other hand, since the ID of the ring magnet is 3.4 cm and the OD is 9.4 cm, convergence of magnetic flux at the air gap near the ID of the ring magnet would tend to increase flux leakage. As an approximation, therefore, the leakage factor was computed from the Maynard formula, using an effective length of 60 cm, the circumference of the ring magnet. The formula that applies to this case is:

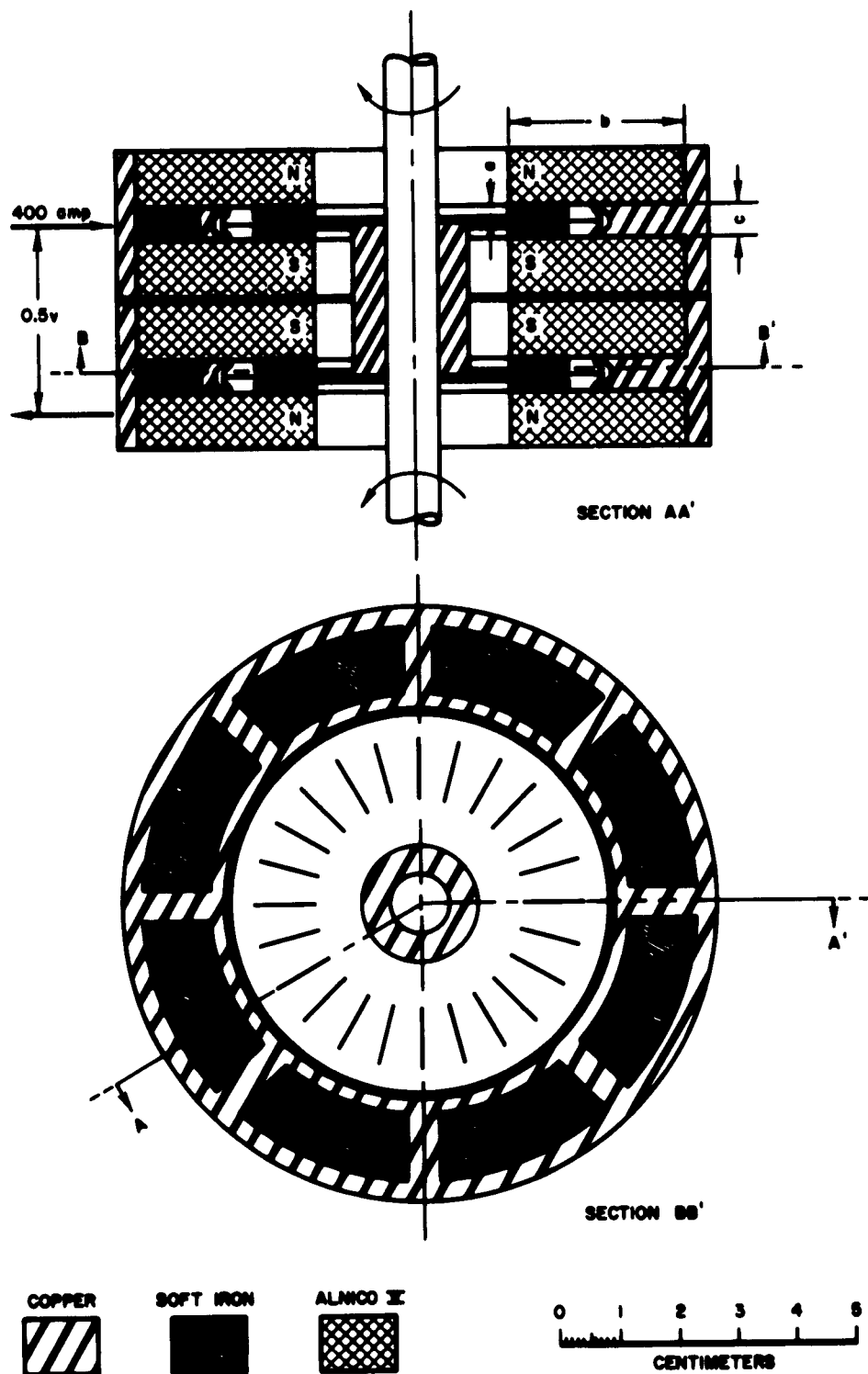


Figure A-1. Design of Homopolar Motor

AI-6815

$$\sigma = 1 + \frac{L_g}{A_g} \left(1.7 U_a \frac{a}{a + L_g} + 0.64 b \sqrt{\frac{U_b}{c} + 0.25} + 0.33 U_b \right) \quad \dots(1)$$

where:

σ = Leakage factor, ratio of flux produced by magnet to flux in air gap

L_g = Length of air gap parallel to flux = 0.1 cm

A_g = Cross sectional area of air gap at right angles to flux = 1 cm x L

L = Effective length of magnetic assembly

U_a = Perimeter of pole piece = 2 cm + 2L

a = Length of one pole piece = 0.2 cm

b = Length of one magnet = 3 cm

c = Length of return iron = 0.5 cm

U_b = Perimeter of magnet = 2 cm + 2L

When evaluated as a function of L, Equation 1 becomes:

$$\sigma = 1.2924 + \frac{0.384}{\sqrt{L}} + \frac{0.2924}{L} + \frac{0.204}{\sqrt{L^3}} - \frac{0.0547}{\sqrt{L^5}} + \dots \quad \dots(2)$$

If Equation 2 is now evaluated around the assumed effective length of 60 cm, it is seen below that the leakage factor varies little with effective length, L.

$\frac{L}{\text{cm}}$	σ
10	1.45
30	1.37
60	1.35
100	1.34

Knowing σ , the area of magnetic material required is given by:

$$A_m = B_g A_g \sigma / B_d \quad \dots(3)$$

where, in addition

A_m = area of magnet at right angles to direction of magnetization
(cm^2) = 1 cm x L

B_g = Flux density in air gap (gauss)

σ = Leakage factor = 1.35

B_d = Flux density in magnet at operating point (gauss)

Substituting known values in Equation 3 gives:

$$B_g = B_d / 1.35 \quad \dots(4)$$

The flux density in the air gap, B_g , is also given by:

$$B_g = \frac{L_m \mu_v H_d}{L_g r_f} \quad \dots(5)$$

where:

L_m = Length of permanent magnet material in direction of flux = 6 cm

μ_v = Permeability of a vacuum = 1

H_d = Magnetomotive force per unit length of magnet

r_f = Reluctance factor = 1.16 (this is assumed and will be checked later)

By substituting known values and Equation 4 into Equation 5, one obtains:

$$\frac{B_d}{H_d} = 70 = p \quad \dots(6)$$

Thus the permeance, p , of this magnet is 70.

Using the magnetic characteristics of Alnico V,

$B_d = 12,200$ gauss

$H_d = 175$ oersteds.

And, from Equation 4, $B_g = 9,050$ gauss.

The reluctance factor was computed, assuming 4 joints in the magnetic circuit, each with an effective air gap of 0.0015 in. It was found to be 1.16, as assumed. Note that the high flux density is obtained by using Alnico V magnets that are not air stabilized. That is, from the time the magnets are magnetized until they are fixed in the ring magnet assemblies, they must have keepers on them at all times.

From the above calculation, it is apparent that the flux at the air gap is only weakly dependent upon the size of the ring magnet, as long as its cross section is not affected. Thus, if one had a requirement for a certain power and shaft speed, one could tailor the size of the ring magnet to fit.

The force exerted on a conductor passing between the poles of a magnet is given by:²

$$F = B_p \lambda I / 10 \quad \dots (7)$$

where:

F = Force on conductor (dynes)

λ = length of conductor in magnetic field (cm) = 1

I = Current flowing through conductor (amp) = 400

The force on each of the two rotors is therefore:

$$F = 9050(1)(400)/10 = 362,000 \text{ dynes}$$

The force on the rotor is only generated if the rotor is slotted as shown in Figure A-1. Assume 190 w of energy are available to turn the two rotors at 200 rps, so as to drive a two-pole permanent magnet generator at 400 cps. The distance of the hub of the rotor from the center of the air gap is given by the formula

$$190 \times 10^7 = 2(362,000)(200)(2\pi r)$$

$$r = 2.08 \text{ cm}$$

A radius of 2.2 cm is used in Figure A-1. Thus, with a somewhat larger radius, a somewhat smaller rotational speed would result when 190 w of mechanical energy are developed.

ELECTRICAL RESISTANCE LOSSES

Several different attempts were made to design the current leads, the brushes, the rotor discs, and the connecting hub. The resistance of each design was estimated, using handbook values for the specific resistance of copper, soft iron, and mercury or NaK at a temperature of 100°C. Thus, the homopolar motor is designed for relatively high temperature operation. As mentioned under the primary assumptions, the resistance of the motor must be less than 60 μ ohms. The resistance of the current path for the homopolar motor design given in Figure A-1 is itemized as follows:

	Resistance (μ ohms)
Outer Copper Bands	17.0
Copper Spokes	0.7
Inner Copper Bands	2.4
NaK Brushes	0.6
Rotors	3.3
Hub	<u>2.4</u>
Total	26.4

The resistance for mercury brushes would be 1.8 μ ohms, so that it matters little which type of liquid metal brush is used, as far as resistance is concerned.

Also note that by far the largest resistance is in the outer copper bands. Here, the electric current was assumed to enter at one point, split, and flow, on the average, 1/4 of the way around the band. If the current is collected in reverse order, the resistance of the copper band is equivalent to a piece of copper with an area twice the band (2 cm²) and a length of 1/2 the band circumference (~15 cm). Thus, the resistance of massive current leads between diode and converter will represent an important power loss, when dealing with such extremely low voltage power.

MECHANICAL LOSSES

The rotor of the homopolar motor is retarded by the viscous drag of the liquid metal brushes and by any bearing losses that may be incurred. The viscous drag of the liquid metal brush was computed, using the viscosity of mercury or NaK at 100°C, a shear thickness between moving and stationery

part of 0.1 cm, and a shear area governed by the thickness of the rotor of 0.07 cm. Using these numbers, a brush power loss for NaK of 0.25 w was computed. For mercury, 0.84 w would be lost. Thus, the brush power loss, no matter what brush is used, is almost negligible. The bearing loss for this motor was computed, using the formula found on page 8-122 of Reference 2. Two journal bearings, 1/4 in. in diameter by 1/4 in. long, lubricated with light machine oil, were assumed. The computed loss for both bearings is 2.2 w.

Windage losses are difficult to calculate. Approximate formulas are given in handbooks for the windage loss for different types of motors. These formulas do not apply, because of the thinness and smoothness of the rotor. It was assumed that the bulk of the windage loss is accounted for by the viscous drag of the air between the pole pieces and the rotor. The clearance is 0.015 cm. Using the dimensions from Figure A-1, a rotor turning at 200 rps, and the viscosity of air at 100°C, a windage loss of 0.2 w is computed.

OVERALL COMPUTED EFFICIENCY

Losses for the homopolar motor are summarized as follows:

<u>Loss</u>	<u>Watts</u>
Resistance	4.2
Mercury Brushes	0.8
Bearings	2.2
Windage	<u>0.2</u>
Total	7.4

Because of the novelty of this motor, there are probably other losses in addition to those already mentioned. Assume that all losses account for no more than 20w, giving a motor efficiency of 90%. General Electric Company³ is advertising homopolar (acyclic) generators producing 10,000 amp at 300 v at greater than 98% efficiency. High efficiencies are therefore possible.

MOTOR WEIGHT

The heart of the motor which is shown in Figure A-1 is estimated to weigh 6.4 lb. With a case and bearings, a weight of 9 lb would be conservative.

PERMANENT MAGNET GENERATOR

Although the homopolar motor is of special design, the permanent magnet generator is constructed from commercial parts. The R. E. Phelon Company offers a standard magnetic rotor to fit onto a 1.40-in. diameter shaft; it is 2.608 in. in diameter by 1.127 in. long. The standard field coil which surrounds the rotor is 3.74 in. in diameter. This generator will easily produce 150 to 200 w of dc power, when associated with a suitable rectifier.

The TKM Electric Co. of Rochester, New York, has available a 2-1/2 lb permanent magnet generator which is 3-3/16 in. in diameter by 3-1/16 in. long, and which will generate up to 300 w of three-phase electric power, when connected directly to the homopolar motor designed above. The efficiency for the generator is 79% at unity power factor.

MOTOR-GENERATOR COMBINATION

The homopolar motor described in this appendix could be connected on the same shaft with the TKM generator. The total weight would be about 11.5 lb, and the overall electrical efficiency would be about 70%. This combination would invert low voltage dc power to high frequency ac power at any desired voltage. Since direct current is required, a rectifier must be used. Nevertheless, for electrical power conversion for the output of a single thermionic diode, the homopolar motor-generator appears to be better than other known conversion methods. From calculations, it appears to have a lower weight and a higher efficiency than solid-state converters.

REFERENCES

1. C. A. Maynard, "Analysis and Design of Permanent Magnet Assemblies," Machine Design 29 (April 18, 1957) pp 122-43
2. A. E. Knowlton, Standard Handbook for Electrical Engineers, 8th Edition, Section 2-43
3. "Acyclic Unit Generates Direct Current Directly," Chem. Eng. (November 27, 1961) p 58

APPENDIX III **PROGRAM SCHEDULE**

GFY 1962

J A S O N D J F M A M J

Task A THERMIONIC CONVERTER

1. Converter Design and Construction	X	X	X	X	X							X	X	X
2. Basic Performance									X	X				
3. Life Testing												X	X	X

Task B HEAT SOURCE

1. Aspirated Burner	X	X	X	X	X	X								
2. Fan Powered Burner									X	X	X	X	X	
3. Temperature Control									X	X	X	X	X	
4. Prototype Construction and Operation													X	X
5. Conceptual Design and Analysis									X	X	X			
6. Environmental Testing														

Task C MATERIALS

1. Mo Corrosion	X	X	X	X	X	X	X	X	X	X	X	X	X	X
2. SiC Corrosion		X	X					X	X	X	X	X	X	X
3. Gas Permeation									X	X	X	X	X	X
4. Metal Fabrication Techniques	X	X												

Task D ELECTRICAL COMPONENTS

X	X								X	X
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Task E PROJECT COORDINATION AND REPORTS

X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
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