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MACHINE CASTING OF FERROUS ALLOYS

H. R. Larson, et al

Abex Corporation

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H.R. Larson
B.A. Heyer
C.P. Biswas

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A pilot casting machine capable of evaluating rheocasting as well as more conventional casting techniques has been designed and is presently under construction. This machine is a bottom pouring furnace in which the transfer of the metal "slurry" to the mold will be accomplished by pressurizing the furnace chamber to 100 psi and retracting a stopper rod. The melting and casting operation will takeplace entirely under an inert atmosphere at low positive pressure to minimize slag formation.

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A DC rail propulsion unit and an AC multi-phase induction unit have been devised for levitation. But both of them require improvement for stronger levitation force. For surface stabilization of the liquid, a laboratory model of a rotating magnetic field with an ascending travelling wave has been built. But this unit also requires improvement to accomplish the required surface stabilization.

Among all the protective coatings of graphite studied so far, the most promising approach has been the formation of diffusion bonded metallic carbide on the graphite surface with an oxide layer on the final surface. Hot pressed silicon nitride and also boron nitride have performed well as permanent mold material.

FOREWARD

This report covers work done in the period 1 February 1974-30 June 1974 under the general title "Machine Casting of Ferrous Alloys". The work was sponsored by the Defense Advanced Research Projects Agency under ARPA Order No. 2267, Program Code No. 4D10. The work was carried out at the Abex Research Center, Valley Road, Mahwah, N.J. 07430, by the principal investigators, H.R. Larson, B.A. Heyer and C.P. Biswas. The work was accomplished under Contract No. DAAG46-73-C-0113 with Dr. E. Wright and Mr. F. Quigley at the Army Materials and Mechanics Research Center as the program technical monitor.

SUMMARY

An experimental casting machine has been designed and is presently under construction. The immediate objective of this machine is to study rheocasting and conventional casting with respect to processing and properties. The melting and casting operation will take place entirely under an inert atmosphere at low positive pressure to minimize slag formation. This is a bottom pouring furnace in which the transfer of the metal "slurry" to the mold is accomplished by pressurizing the furnace chamber to about 100 psi and retracting a stopper rod.

A DC rail propulsion unit and an AC multi-phase induction unit have been devised for levitation of molten metal. But, both of them require much stronger lift force for any practical casting machine. For surface stabilization of the molten metal, a laboratory model of a rotating magnetic field with an ascending travelling wave has been built. But, this unit also requires improvement to accomplish the required surface stabilization.

For permanent mold application, coated graphite and some ceramic materials have been studied. Among all the coating techniques studied, namely, plasma spraying, hot pressing, metallizing with subsequent diffusion annealing, the most promising approach has been the formation of diffusion bonded metallic carbide on the graphite surface with a plasma sprayed zirconia coating on the final surface. Among all the ceramic materials examined so far, hot pressed boron nitride and also silicon nitride have shown considerable promise.

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REPORT

This report presents the work done at the Abex Corporation during the period February 1, 1974 to June 30, 1974. This program was designed to develop a completely integrated furnace-valve-mold ferrous casting system that will produce quality castings (in the five to twenty-five pound class) at a higher speed and lower cost than is possible by present casting methods. Our efforts have been directed in three major areas.

I. Design and fabricate an experimental melting and casting unit capable of examining several casting process possibilities.

II. Determine the feasibility of a magnetohydrodynamic (MHD) valve using laboratory scale equipment.

III. Develop a mold coating for graphite or some other suitable mold material that will provide the properties required of a permanent mold in the automatic casting process envisioned.

I. Design and Fabrication of the Experimental Melting and Casting Unit.

The objectives and general design parameters for the Pilot Melting and Casting Unit were described in detail in the Interim Report covering the contract period 1 February 1973 through 31 January 1974. For convenient reference, the schematic drawing for the unit is included as Figure (1) in this report.

I. (continued).

Construction of the Experimental Casting Unit has proceeded to the point where, at this writing, final assembly of the paddle drive and plug actuator components is in progress.

Figures (2) through (5) are overall views of the apparatus. The pressure vessel, or melting chamber, is rigidly mounted on a steel framework at a level that provides sufficient clearance for the mold which will be positioned directly under the outlet. The latter is best seen in Figure (6). Manual access to the chamber (other than by unbolting the lid) is through the opening shown in Figure (6), immediately to the left of the name plate. In Figure (7), showing the rear of the chamber, the induction power access port can be seen, as well as the over pressure burst disc installation. The presence of this latter safety feature was considered an absolute necessity in view of the unlikely but possible contact of cooling water and molten metal. The disc is designed to burst at just over 100 psi, and will provide 1.77 square inches of escape area should the occasion arise.

The induction power access port provides power to a centrally positioned induction coil in the bottom of the melting chamber. This can be seen in Figure (8). The induction coil receives an alumina crucible equipped

I. (continued).

with an alumina bottom pouring nozzle. The crucible and nozzle are shown in Figure (9). The nozzle passes through the bottom of the coil frame and out of the chamber through the bottom outlet shown in Figure (6).

The bottom pouring feature is accomplished by the bottom plug also shown in Figure (9). The taper at the plug bottom fits the taper at the top of the alumina nozzle, thus providing a seal similar to that normally used in small, bottom-pour ladles.

The stirring required by the Rheocasting procedures is to be accomplished by the paddle assembly shown in Figure (9). The paddles shown are alumina. Additional paddles are being made by Norton Co. from silicon oxy-nitride. The rotation of the paddles is concentric with the bottom plug O.D., permitting totally independent operation of both.

The multi-component, water-cooled operating shaft for the paddles and bottom plug is shown out of the assembly in Figure (10). The shaft consists of a central solid non-rotating bar, which will activate the bottom plug, an axially located tube that provides the paddle drive, and a double-wall axial water cooling sleeve. Figure (1) best shows these details.

I. (continued).

The shaft will be mounted in two bearings mounted on a vertically movable support beam, and axially aligned exactly with the central axis of the crucible. Figure (11) shows the relationship among these components.

Vertical motion of the paddle assembly, required to move the paddles in and out of the crucible, is achieved by moving the support beam, guided by two guide bars, using the air cylinder shown in Figures (11) and (12). The upper end of the air cylinder shaft is rigidly fastened to the main frame, thus providing vertical motion of the entire support beam.

Rotational motion of the paddles will be provided by a motor attached to the rear of the support beam, as shown in Figure (13).

Independent, short vertical displacement of the curcible bottom plug will be provided by a manually operated locking lever device not shown here.

Operating procedures for the Experimental Casting Unit were detailed in the earlier report dated April 1974, and need not be repeated here.

II. Development of Magnetohydrodynamic (MHD) Valve.

Further experiments of both conduction and induction type MHD valves have been done. As reported earlier, Abex's work on MHD valving has demonstrated that some lift can be obtained from an MHD device to hold the bulk metal and to control its flow, but a much stronger lift force is required for any practical casting machine.

Conductive Levitation.

It was reported previously that a conduction cell was built in which an electromagnet capable of producing 4,000 gauss field and also a circular cross section tube with round insertable multiple electrodes were used. The test of this apparatus indicated that the levitation was not strong enough and also the levitation force was non-uniform in the liquid due to the discrete electrodes. Therefore, modifications were made - a pair of long rail electrodes in combination with a pair of long electromagnetic poles were used to form a rail propulsion device. This is shown schematically in Figure (14). The molten metal is confined in the space between two conductive rail bus bars contacting the liquid and two magnetic poles. When the current and the magnetic field are applied, the liquid experiences propulsion force along its entire length.

II. (continued).

The electrodes are made hollow and are cooled by the circulation of suitable coolant. The electrodes can be made of the same metal as the liquid in which case the electrodes become consumable but the extent of their melting can be controlled by controlling their cooling rate. The electrodes can also be made of any conductive material of higher melting temperature in which case a conductive coating on the electrode can be used. Alternating current may be used in place of a steady current provided the phase relationship between rail current and magnetic field is time invariant. If the cross section of the nozzle is made uniformly tapered toward the exit end, the magnetic field will be more concentrated near the exit end thus providing a surface stabilizing action on the terminal liquid surface.

Figures (15) and (16) show our laboratory model of rail conduit hinged to the bottom of a furnace through a cylindrical gate valve. The conduit can be set at different angles with the furnace so that both pouring up and pouring down are possible. In our experiment with liquid Woods Metal a metallostatic head of about 5" was supported by applying 150 amp current and 1 kilo-gauss field. It was calculated that 10 amperes per cm^2 per gm per cm^3 per kilo-gauss is required to balance any conductive medium against gravity.

II. (continued).

Therefore, a much stronger current and magnetic field are required in our model rail device to hold a vertical column of any practical importance. An additional induction device will be used to stabilize the metal-air interface. Work is in progress to improve this conduction device and resolve some of the thermo-mechanical problems that will be encountered in the practical application of this device.

It should be noted that the above rail propulsion device can also be used for molten metal conveyance as an alternate to the existing linear induction motor devices.

Inductive Levitation

Inductive levitation relies upon the coupling of energy from a primary coil into the melt as a one-turn secondary. It has been established in our previous work that for a successful levitation it is necessary to generate a large gradiant of the magnetic field because the levitational force is proportional to and in the direction of the negative gradient of this field. This gradient field can be achieved by the divergent end effects in an induction coil. But this diverging magnetic field, while necessary, is not sufficient for the stable

II. (continued).

operation of the MHD valve which must be a servo system. By combining paired static levitation coils in a polyphase linear stator, wherein the molten charge in the nozzle will be a liquid rotor, we obtain an MHD valve system adapted to treatment by servo theory.

The arrangement is shown in Figure (17) where coils are stacked axially to comprise a travelling wave stator coil of a linear motor. Interference with spatial wave length caused by coil dimensions in the stator system was solved by using mu-metal flux concentrators in our experimental model. Each coil is comprised of a mu-metal cup-core flux concentrator completely filled with a coil, except for a central bore. The mu-metal cores, when stacked, nest together to form a low reluctance magnetic path and an aligned bore. Coils, available in sets of three, have 15 turns of 1/8 inch copper tubing or 150 turns of No. 18 enamelled wire. A 3-phase automobile alternator was modified and used as the power source. Unfortunately, only 225 volt-amperes could be generated by this alternator in each coil type. The coils were connected across A, B and C phases respectively for 3-phase levitation or an A, -B and C connection for a partial, derived 6-phase connection. The latter connection gives most efficient pumping.

II. (continued)

Because of the power limitation of our 3-phase generator and the inability to tune the equipment, levitation only sufficient to raise solid conductors was achieved. When an iron core was added to the stator, very strong levitation and propulsion of aluminum tubing was obtained. Our model has a 150 to 1 turns ratio or a 15 to 1 turns ratio depending on the coils used. Since the molten charge is one shorted turn, the induction efficiency is very low. A practical MHD valve without iron flux concentrators must, from the standpoint of spatial frequency dimensioning, be a single layer solenoid. The fundamental problem is that of satisfying the contradictory requirements of making the volts - per-turn in a single layer primary sufficiently high to ensure sufficient eddy current induction in the melt for efficient levitation forces. This requires tuning the levitation coils to resonance and having sufficient "Q" value such that the loading by the melt does not reduce the volts-per-turn below an efficient levitational value (unloaded volts/turn = IZ = QIWL, wherein coupling with charge lowers the Q). The proper tuning of the coils is now in progress.

Another method of levitation is also under investigation. The model is shown in Figure (18). This

II. (continued)

model combines a rotating field with an ascending travelling wave. A vortice pump is not the object here. Under slip conditions the levitational forces on a liquid would be static and hopefully will stabilize the lower suspended surface. Lovell(1) first suggested the rotating levitational field and Wroughton(2) et al described its use for levitational melting and in connection with surface stabilization stated: "The resultant rotative fields, if multiple phase power is used, conserves energy by reducing the effect of the weak spot or "hole" in the magnetic field through which the molten metal sometimes tends to be discharged....effective rotation due to the phase differences will tend to prevent discharge of molten metal from the field when it is operated just above the value needed for discharging the melt in order to conserve energy." In the case of our model as applied to the MHD valve, the rotating field is the 3-phase equivalent of the single-phase ferrite stabilizer suggested earlier as our stabilizing approach. This stabilizer has circular symmetry, the rotation of which will provide an induced surface tension reinforcing field which will smear the lower surface with 'wiping' forces. The surface will probably not rotate due to friction with the nozzle wall.

II. (continued)

Some levitation has been achieved with this device but the work is still in progress to accomplish better surface stabilization.

III. Development of Permanent Mold Material.

We have selected both graphite and some ceramic materials for possible permanent mold application.

Graphite.

The following graphite coatings were evaluated during this reporting period:

(a) Graphi-bond 551-R.

(b) Diffusion bonded carbide coating with refractory oxide layer on the final surface.

(c) Diffusion bonded carbide coating with diffusion bonded oxide layer on the final surface.

A detailed discussion of the coatings and test results are given below:

(a) Graphi-bond 551-R Coating. This is a proprietary coating made by Aremco Products, Inc., N.Y. This material is a graphite base adhesive (heat cure) that can presumably withstand temperatures up to 5400°F in a reducing atmosphere. The coating was applied by brush in a thin coat and cured at 250°F for 3 hours.

The evaluation of the coating was done by pouring ferrous alloys between 2500°F and 2700°F. After about eight castings the coating started to appear spongy indicating that either oxidation or reaction with the metal has started.

III. (continued).

(b) Diffusion Bonded Carbide Coating with Refractory Oxide Coating on the Final Surface. As discussed in the previous report, one of the techniques to produce a permanent coating on graphite was to convert the graphite surface to metal-carbides so that the subsequent ceramic coating will have a better adherence. The carbide conversion was accomplished by depositing a thin metallic layer on the graphite surface and forming the carbide by diffusion annealing. The following three carbides were selected:

(1) Chromium carbide
(2) Titanium carbide
(3) Molybdenum carbide

(1) Chromium Carbide. The chromizing of the graphite samples was done by pack metallizing technique at the Chromalloy Research, N.Y. After diffusion annealing at 2000°F for 1 hour in a vacuum furnace, the graphite surface was examined by x-ray diffraction analysis and was found to be chromium carbide ($Cr_{23}C_6$). A top coating of 4 layer graded MgO-ZrO_2 (applied by plasma spray) using NiAl as the bond coat on the carbide surface survived 50 cycles of dip test at 2350°F, whereas a single layer of MgO-ZrO_2 coating started to fail after about 40 cycles.

III. (continued)

The sample with four layer graded coating was later dip tested in liquid steel at 2950°F, but after about 3 cycles the coating started to fail. The failure seemed to have occurred through melting of the coating. It is highly probable that NiAl melted partially because the melting point of stoichiometric NiAl is only 2980°F and the NiAl powder contains some off-stoichiometric composition with a lower m.p. In dip test the specimen surface normally reaches the liquid bath temperature (2950°F). However, it was decided to evaluate this coating by pour test since dip test is a severe test and in actual casting condition the maximum temperature that the graphite mold wall reaches is substantially less than that of the liquid metal.

Studies are also being made to see if the castings can be made against the chromized surface without using the plasma sprayed top coating. Although $Cr_{23}C_6$ is dissolved in liquid steel to some extent, the fact that the metal next to the mold surface solidifies immediately on contact with the mold wall (except in the gating area) may cause negligible amount of mold erosion.

III. (continued).

For pour test evaluation, small pig molds of graphite with about 5"x3"x2" mold cavity were made and the entire surface was chromized by the pack metallizing technique. An x-ray diffraction analysis revealed that $Cr_{23}C_6$ was already formed on the graphite surface by the metallizing treatment. Therefore, no diffusion annealing was done for these molds. One mold was given a coating of MgO-ZrO_2 with a bond coat of NiAl, whereas the other mold was given a four layer graded MgO-ZrO_2 using NiAl as the bond coat. During plasma spraying some problems were encountered - an excessive amount of coating material was found to accumulate around the corners leading to a non-uniform coating in these areas. Liquid steel was poured in the mold cavity at around 3000°F and after about 3 castings the coating started to spall around the corners in both the molds. The coating seemed to have separated at the NiAl - $Cr_{23}C_6$ interface. It is possible that during plasma spraying of one side of the cavity the adjoining sides received some "overspray" which is normally not very adherent and this resulted in a failure of the coating in these areas.

(2) Titanium Carbide. Titanizing was done by pack metallizing technique at the Chromalloy Research, N.Y. In

III. (continued).

our previous titanizing process the formation of some TiN occurred on the surface along with TiC. Therefore, this time several experiments were run to minimize this TiN formation. Although the extent of formation was reduced, the amount of TiN present in the surface layer was still substantial. Since TiN has a very high melting point we considered its presence to be not harmful. An x-ray diffraction analysis showed that there was no residual titanium present on the surface layer and therefore no diffusion annealing was performed on these specimens.

Two specimen molds were made, one was coated with $MgO-ZrO_2$ using NiAl as a bond coat and the other with four layer graded $MgO-ZrO_2$. The plasma spraying was done carefully so that no additional deposit from "overspray" is formed. The coating in both the molds still looks good after several castings poured at around 3000°F.

(3) Molybdenum Carbide. It was reported previously that a single layer $MgO-ZrO_2$ coating on molybdenum carbide surface survived 50 cycles of dip test. The molybdenum was deposited by plasma spraying and molybdenum carbide was formed by diffusion annealing at 2000°F for 1 hour in a vacuum furnace. These specimens were later dip tested in liquid steel at around 2950°F. The coating

III. (continued)

started to fail after about 3 cycles. This failure appeared to be due to melting of the bond coat NiAl. It was decided not to further evaluate this coating because (a) after 50 cycles of dip test at 2350°F this coating did not look as good as the chromium carbide coating system did and (b) the conversion of molybdenum to molybdenum carbide on the graphite surface seemed to be extremely difficult by diffusion annealing technique and no successful pack metallizing process exists for molybdenum so far.

(c) Diffusion Bonded Carbide Coating with Diffusion Bonded Oxide Layer on the Final Surface. On the basis of thermodynamic considerations, titanium was selected as the coating material. The pure titanium powder was plasma sprayed to a thickness of about 0.01" on the graphite surface and the carbide-oxide layers were formed by diffusion annealing the specimen in a controlled oxidizing atmosphere. By this a diffusion bonded titanium carbide layer is formed at the graphite surface and a diffusion bonded titanium oxide layer on the final surface. This work is still in progress.

Ceramic Materials.

The following ceramic materials were evaluated during this reporting period:

Ceramic Materials - (continued).

(a) Boron nitride (from Carburundum Co.)
(b) Boride "Z" (" " ")
(c) Silicon nitride (from Norton Co.)
(d) Modified ZRBSC-D(" " ")

All the above materials were evaluated by pouring ferrous metals in the temperature range of 2400°F to 2700°F in open ended cylindrical sand molds using these specimens as chill plates. No preheating of the specimens was done. The Boron nitride showed some good results - although is showed slight reaction with the metal, it did not crack at all in a total of 16 castings. The Boride "Z" showed some cracking and reaction with the metal. The silicon nitride, however, showed an extremely slow reaction with the metal before it shattered into pieces during the eighth casting indicating its insufficient thermal shock resistance. Some more tests are planned for SiN preheated to 1000°F.

ZRBSC-D is a hot pressed ceramic material of zirconium boride and silicon carbide that is capable of withstanding high temperatures. The thermal shock resistance of this material is presumably very good, but it has been demonstrated in other work that the material shows some reaction with the ferrous metals. Therefore, two different modifications were made to reduce the mold-metal reaction, (1) mixing of $CaO-ZrO_2$ with ZRBSC-D, (2) hot pressing a surface layer of $CaO-ZrO_2$ on ZRBSC-D.

Ceramic Materials - (continued).

Three different proportions of CaO-ZrO_2, 29, 19 and 13 vol. pct., were tried to reduce the mold-metal reaction without impairing the thermal shock resistance property. Circular discs of 4" dia. and 3/4" thick were made. On examining these samples it was found that the disc with 29% CaO-ZrO_2 was very seriously crazed cracked probably due to significant shrinkage because of reaction of the zirconia with the balance of the mix. However, all the discs cracked immediately after the metal was poured suggesting their very poor thermal shock resistance for our application.

Since mixing of zirconia was contributing to the poor thermal property, attempts were then made to hot press a thin layer of graded CaO-ZrO_2 on the ZRBSC-D surface. A three layer graded coating of increasing CaO-ZrO_2 content (each layer about 0.003" thick) was originally planned to compensate the difference in the thermal expansions of the substrate and zirconia, but this could not be accomplished by Norton's existing facilities. Instead, just one layer of CaO-ZrO_2 of about 0.03" thick was hot pressed on ZRBSC-D substrate.

Problems were encountered in selecting the hot pressing temperature because of a large difference in this temperature for CaO-ZrO_2 and ZRBSC-D. However, the problems were finally resolved and two hot pressing temperatures were selected. When cooled to room temperature after hot press-

Ceramic Materials - (continued).

ing, the samples showed numerous cracks in the zirconia surface layer probably because of difference in the thermal contractions of the substrate and the surface layer. The surface layer was ground off from the substrate and an x-ray diffraction analysis of the ground surface layer showed some preferential diffusion of ZrB_2 into this layer. During the surface grinding operation it was noticed that the bond between the substrate and the surface layer was very good in some areas and poor in others. However, considering the difficulties encountered in hot pressing operation and the cracking problem in the surface layer, this concept was abandoned for making permanent molds.

Therefore, among all the ceramic materials tested so far the Boron nitride produced the best results, but the material and processing costs were considered to be extremely high. Silicon nitride shows some promise, if preheating will ameliorate the poor thermal shock resistance.

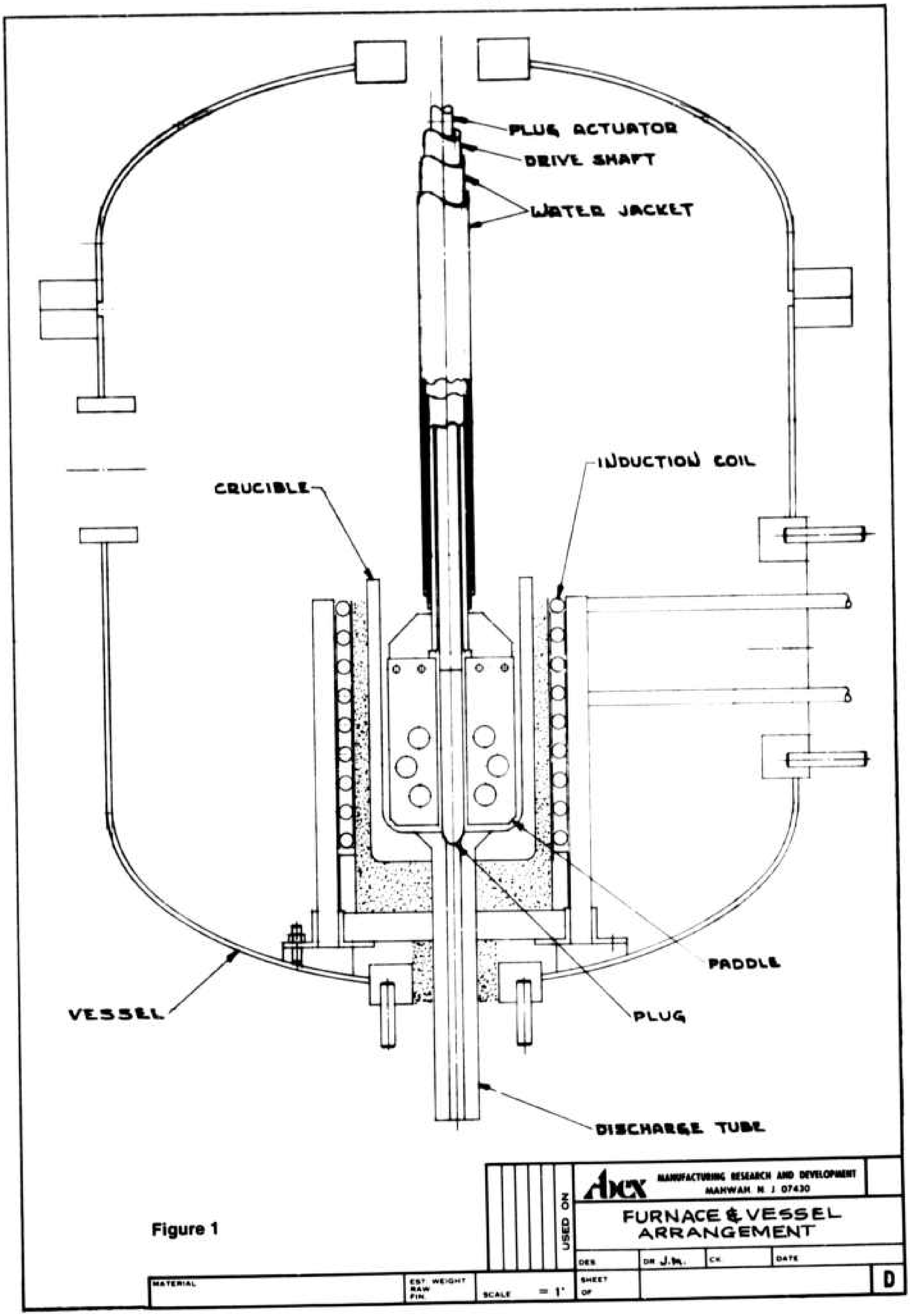
PLUG ACTUATOR
DRIVE SHAFT
WATER JACKET
INDUCTION COIL
CRUCIBLE
PADDLE
PLUG
VESSEL
DISCHARGE TUBE
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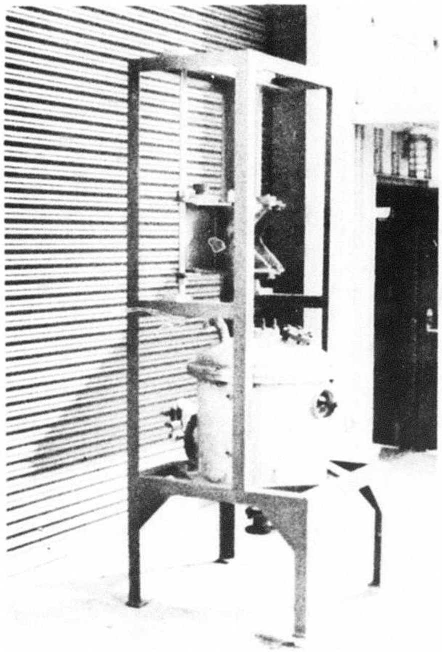
Figure 1



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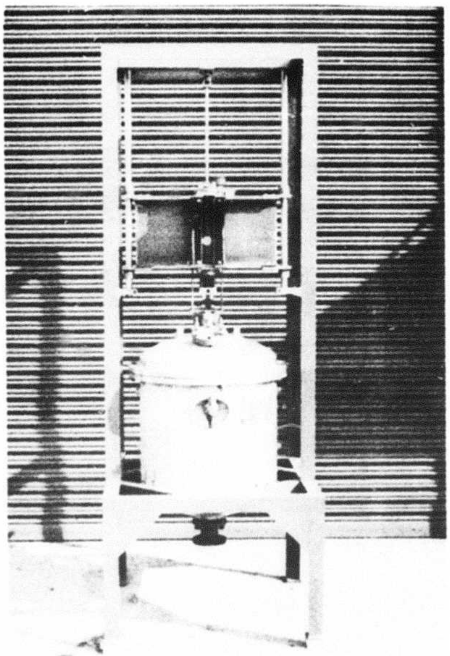

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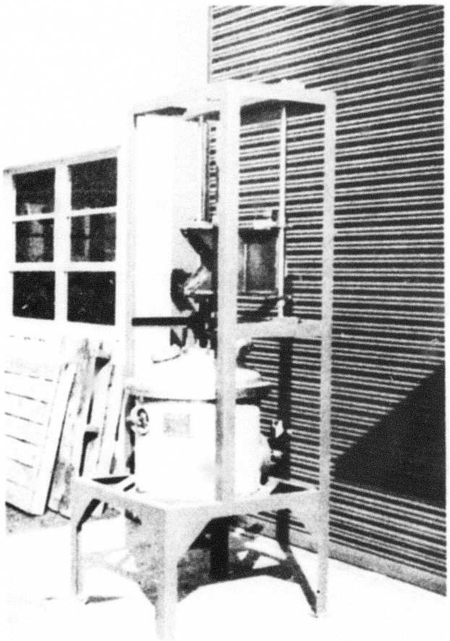

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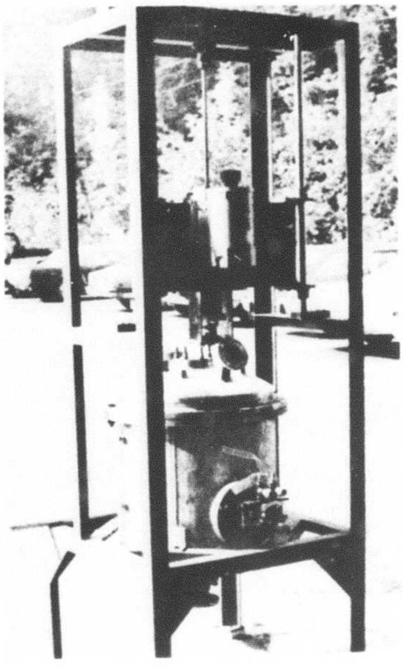

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Figures (2)-(5)

The ARPA Experimental Melting and Casting Unit

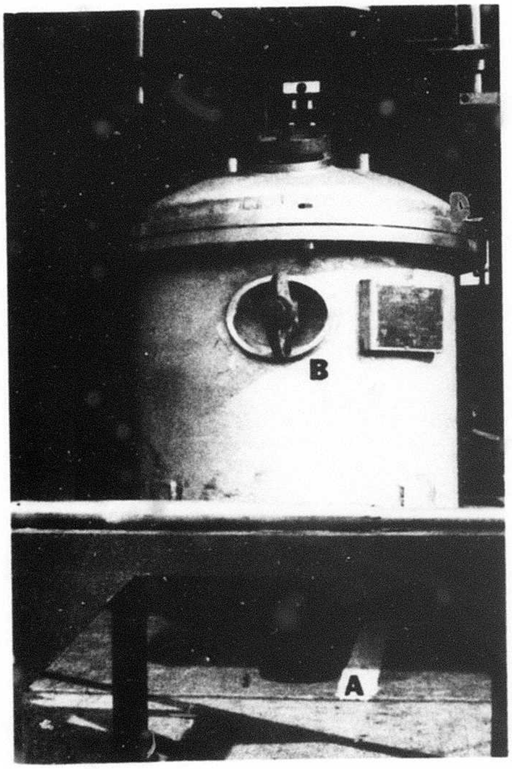

Figure (6)

Front View of Casting Unit

A Outlet

B Access Port

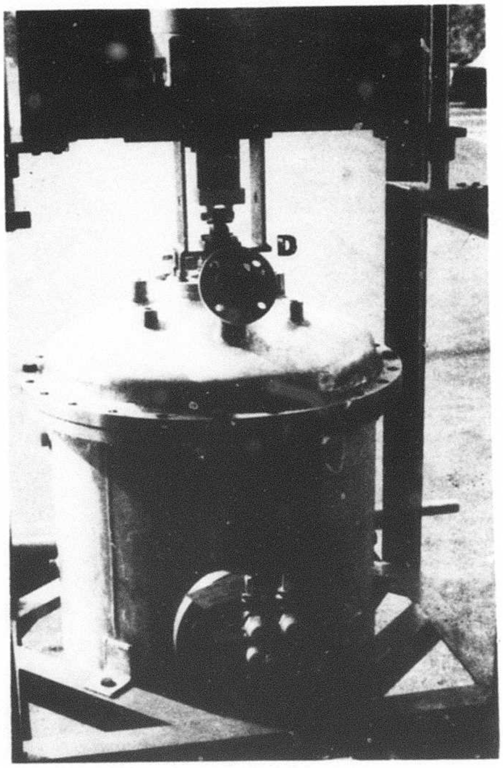

Figure (7)

Rear View of Casting Unit

C Induction Power Port

D Burst Disc Fixture

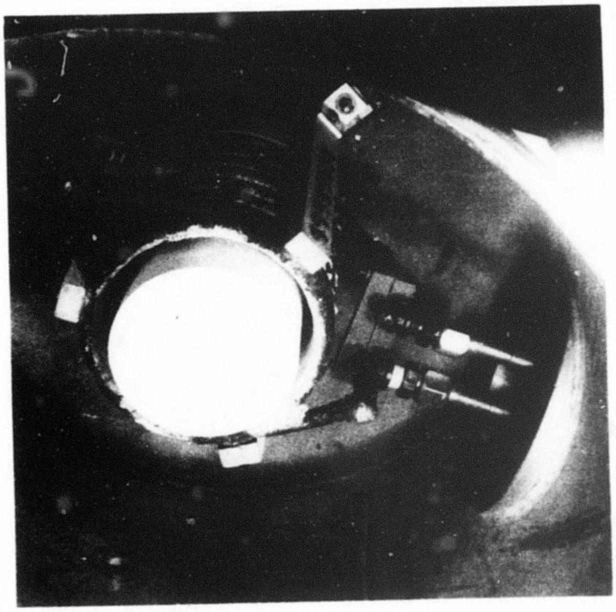

Figure (8)

Induction Coil With Crucible in Place

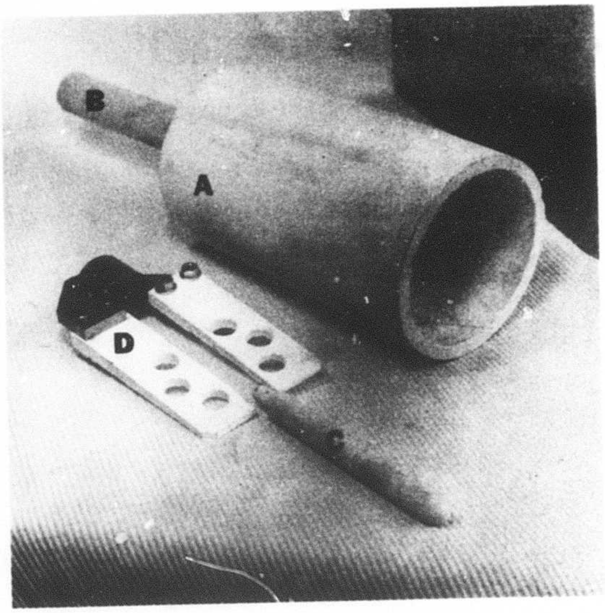

Figure (9)

Refractory Components of Casting System

A Alumina Crucible
B Bottom Nozzle
C Bottom Plug
D Paddle Assembly

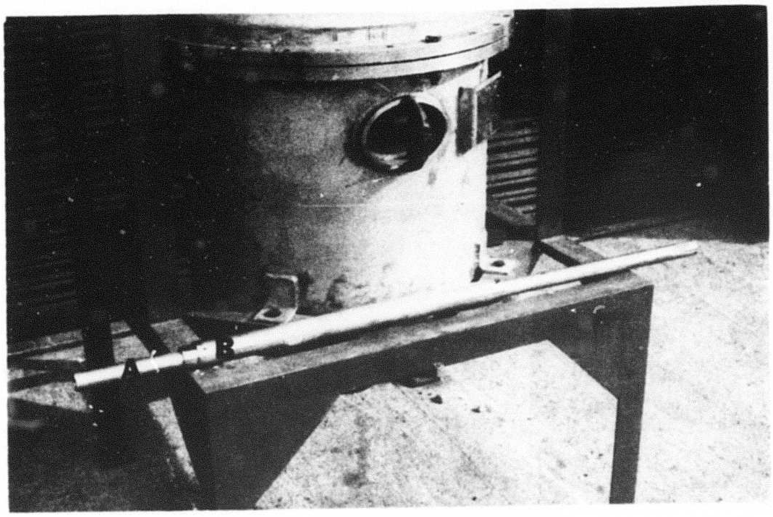

Figure (10)

Multiple-Function Shaft

A	Paddle Drive
B	Cooling Jacket (Note: Plug Actuating Bar Not Shown)

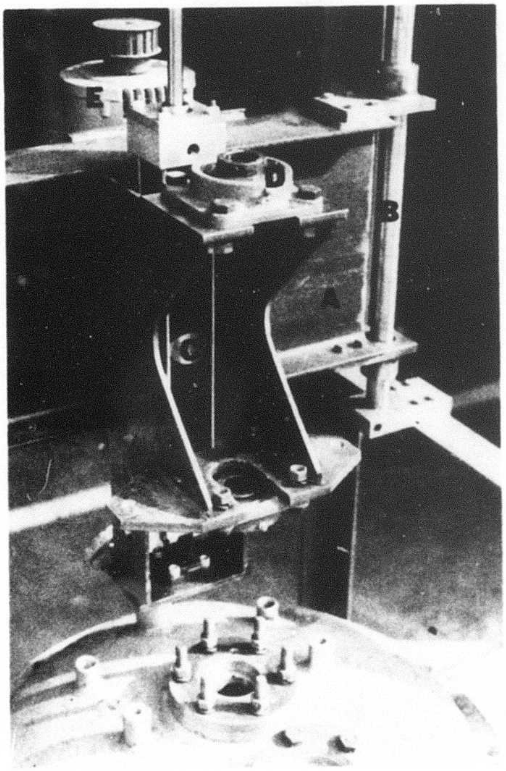

Figure (11)

Shaft Actuating Assembly

A	Support Beam
B	Guide Bars
C	Air Cylinder
D	Shaft Bearings
E	Paddle Drive Motor

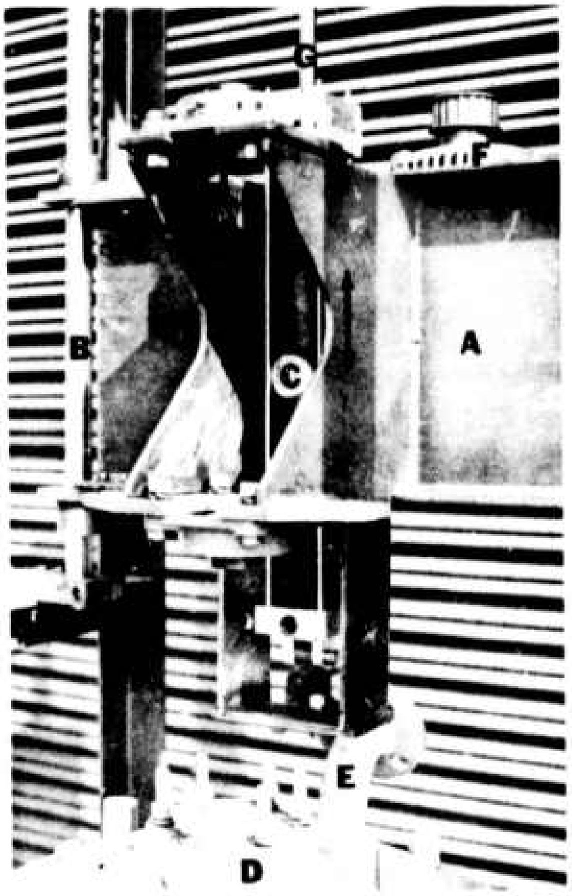

Figure (12)

Shaft Actuating Assembly

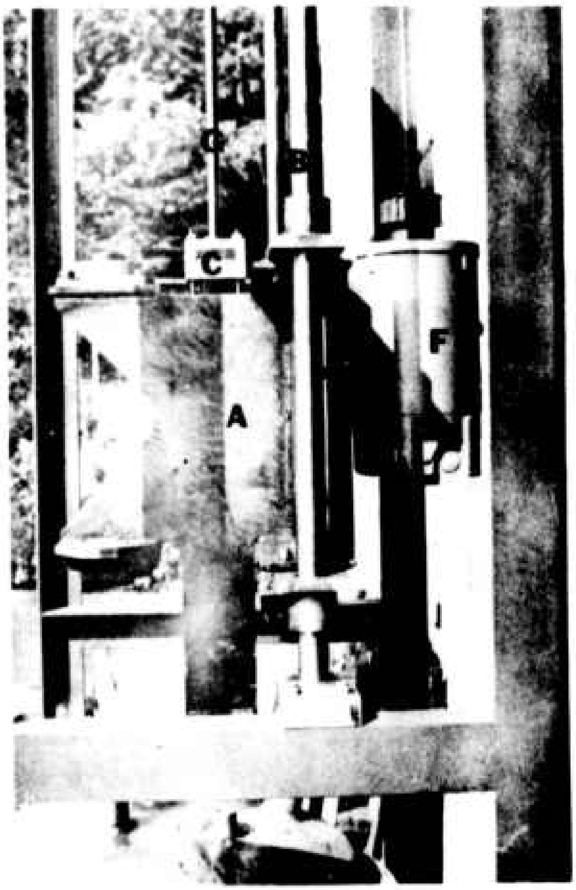

Figure (13)

Shaft Actuating Assembly

A	Support Beam
B	Guide Bars
C	Air Cylinder
D	Casting Chamber Access
E	Burst Disc Fixture
F	Paddle Drive Motor
G	Fixed Air Cylinder Shaft

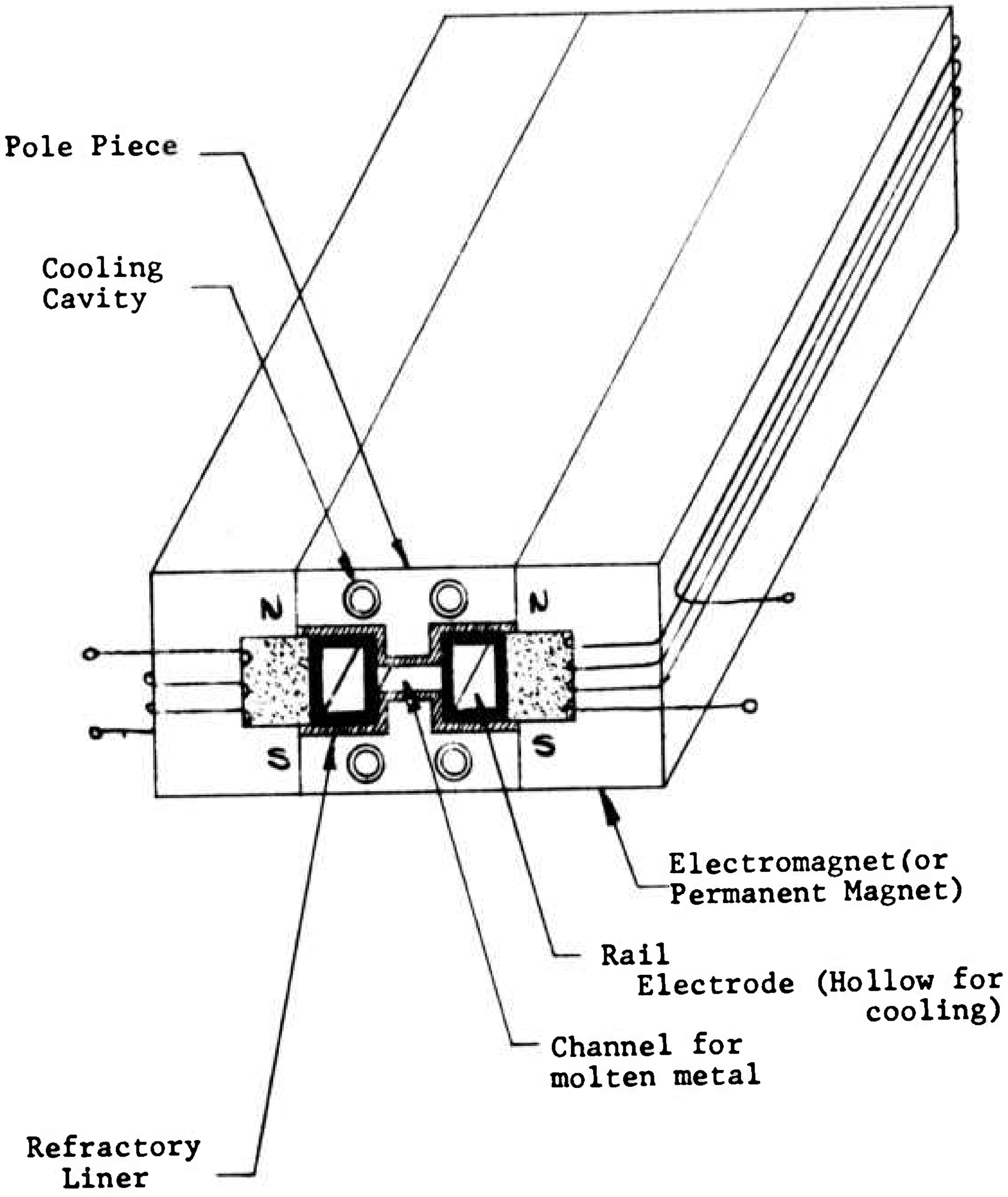

Figure 14. Rail Propulsion Conduit and Valve

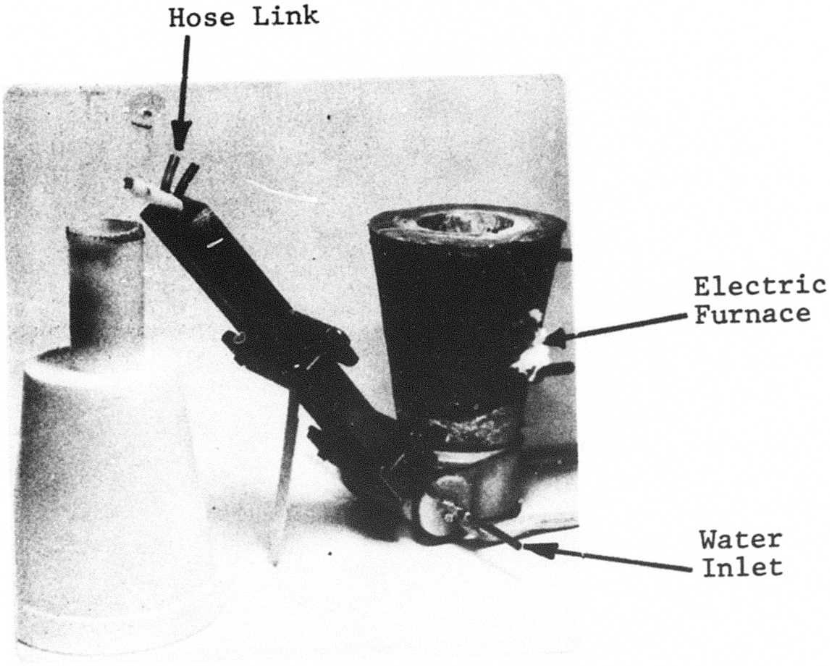

Figure 15. Rail Propulsion Conduit Adjusted to Pour Up

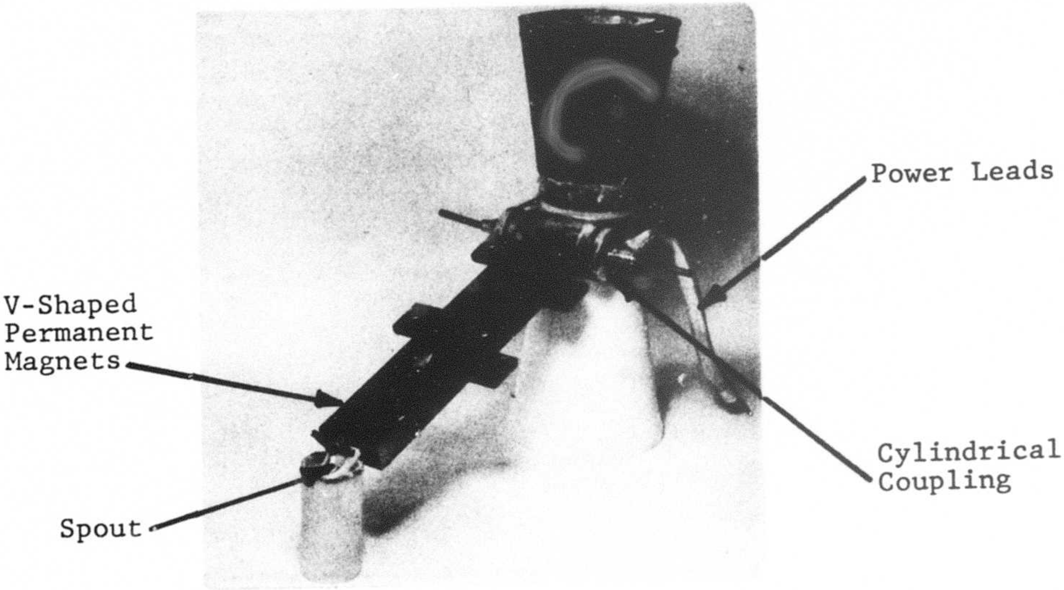

Figure 16. Conduit Used as Valve for Gravity Pouring.

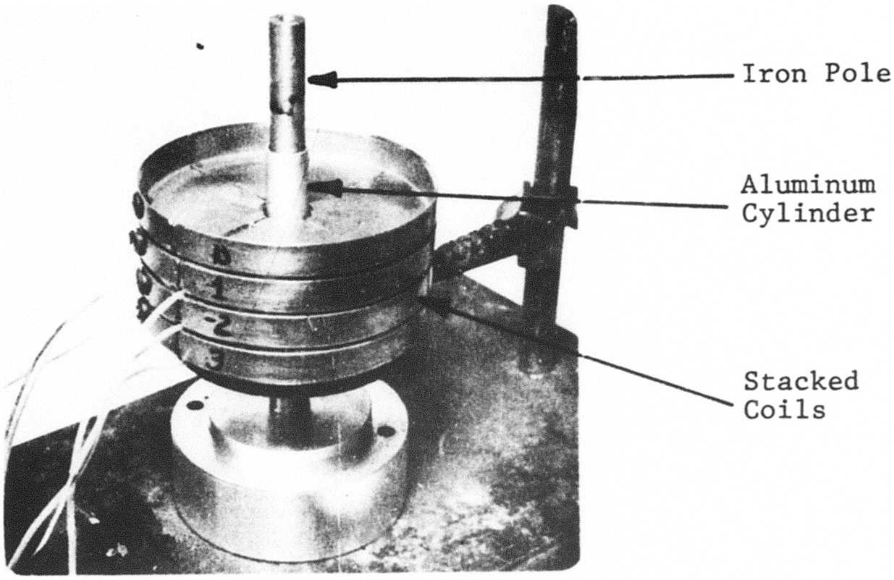

Figure 17. Polyphase Levitation Pump With Mu-Metal Flux Concentrators

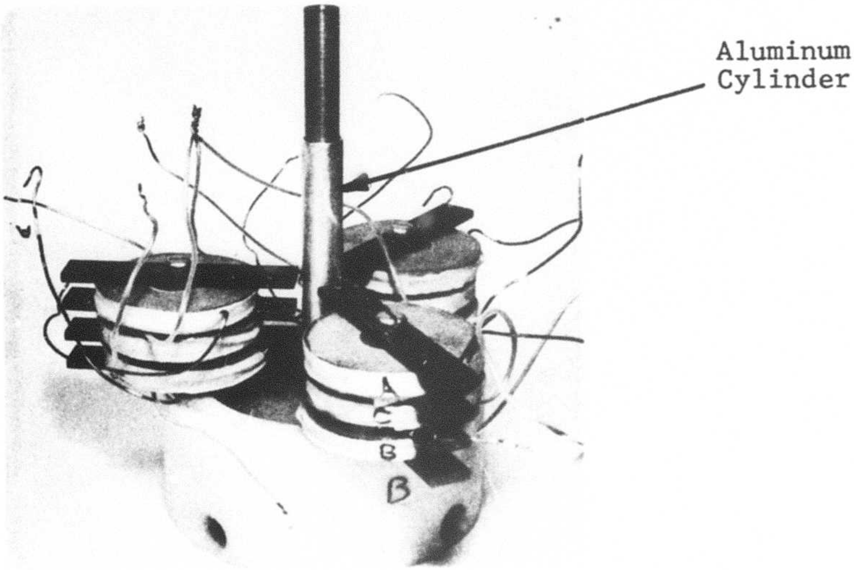

Figure 18. Three-Pole, 3-Phase Levitator Having Lift and Rotation

References

(1)Lovell - U.S. Patent 2,566,221 (1951)

(2)Wroughton, et al - U.S. Patent 2,686,864 (1954)

FUTURE WORK

I. Furnace.

- (1) Assemble and operate the pilot casting unit.
- (2) Evaluate both conventional and rheocasting processes.
- (3) Study the properties of rheocast metal.
- (4) Establish the process parameters.
- (5) Evaluate the materials of construction in the casting unit and the mold.
- (6) Testing of the MHD valve should it become a feasible device.

II. MHD Valve.

- (7) Study MHD conduction device with rail electrodes.
- (8) Study multi-phase induction device for stronger levitation.
- (9) Study AC rotating field for stabilization of liquid surface.

III. Mold Material.

- (10) Evaluate the diffusion bonded carbide coating on graphite.
- (11) Evaluate the diffusion bonded carbide-oxide coating on graphite.

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