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THE VACUUM CASTING FURNACE FOR THE PROCESSING REFABRICATION EXPERIMENT

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THE VACUUM CASTING FURNACE FOR THE PROCESSING REFABRICATION EXPERIMENT

By

G. L. SCHMIDT

Principal Workers

G. L. SCHMIDT
E. F. CARPENTER
E. G. KENDALL

ATOMICS INTERNATIONAL

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

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The author expresses appreciation to D. I. Sinizer, Project Engineer; J. R. Foltz, Technical Supervisor; E. G. Kendall, Responsible Engineer and Engineering Supervisor; and to the technicians, E. F. Carpenter, R. J. Sullivan, and G. Fulton, for their advice and assistance throughout the investigation. Recognition is afforded to D. J. Stoker, D. Zweng, and L. Manners for the conceptual design of the prototype furnace, and to B. H. Dixson for the conceptual design of the in-cell furnace. The enthusiasm and efforts of the above people made the following investigation a pleasant endeavor.

ABSTRACT

A full-scale prototype vacuum casting furnace was operated successfully in the Processing Refabrication Experiment (PRE) mockup with the aid of in-cell handling and viewing equipment. The operation included the removal and replacement of components of the furnace that would be affected by the high temperature processing of the irradiated metallic uranium fuel. The information and experience gained from the mockup operations have been translated into the conceptual design of an in-cell furnace for use in future hot cell facilities.

I. INTRODUCTION

A. BASIC APPROACH TO PROCESSING PROBLEM

The need to develop new fuel processing systems that might lead to reduced fuel cycle costs has led the AEC to support research on the high temperature decontamination of uranium metal fuels. The Processing Refabrication Experiment (PRE)[1] was a natural extension of this research effort.

Since high temperature processing methods lead to only partial decontamination, a development program, involving the remote decontamination and refabrication of the extremely radioactive fuel with full-scale equipment, was deemed necessary. This program was carried out in conjunction with the Sodium Reactor Experiment (SRE) and the related problems associated with the irradiated metallic uranium fuel obtained therefrom.

B. DESIGN CONCEPT OF PRE EQUIPMENT

With the SRE program as the design basis for the processing of the fuel material, the quantity and quality of the material to be handled had to meet the physical, metallurgical, and chemical specifications for recycling through the reactor. The total capacities of the associated equipment would be related throughout the process. However, the specific capacities or batch capacity would be different, for more efficient use of equipment and the optimum geometry. All process equipment would be designed for both operation and maintenance by remote techniques.[2] The major modifications would not be done in the process cell with the handling equipment installed. Modifications or major repairs would be accomplished in a maintenance cell specifically designed for this function.

Many of the PRE equipment units have counterparts in use by industrial processes. The major difference in design lies in the environmental condition resulting from the high level of radioactivity. The oxide drossing furnace and the vacuum casting furnace, required to remove the nonvolatile and gaseous fission products and the particulate matter, reconstitute the irradiated slugs and reshape them for suitable fuel elements, would be operated at high temperatures in an inert atmosphere process cell with a minimum of service from in-cell apparatus. Control of the atmosphere within the cell would be rigorous to provide adequate protection for supporting personnel and equipment.

C. FUNCTION OF THE VACUUM CASTING FURNACE

The vacuum casting furnace was designed to receive the decontaminated material in the form of a large ingot.[3] This ingot (formed during the oxide-drossing furnace operations) would be remelted, re-enriched, and cast into slugs which could be used to fabricate reactor fuel rods.[4] Following fabrication, the fuel rods would be assembled into a fuel element and recycled through the reactor.

II. DESCRIPTION OF EQUIPMENT

A. VACUUM FURNACE

The furnace and related components may be placed in four major groupings: (1) the vacuum shell and attached mechanisms, (2) the vacuum system, (3) the induction circuitry, and (4) the centrifugal drive system.

1. Vacuum Shell and Attached Mechanisms

The vacuum shell consisted of three main sections which contained the induction coil, the crucible and charge, and the mold centrifuge. Figure 1 shows a view of the assembled furnace as it was installed in the mockup cell.

The material used for fabrication of the shell, flanges, and portholes was type 304 stainless steel. The shell had an over-all height of 58-5/8 in. and an outside diameter of 42 in. The flanges were welded to the 1/2-in.-thick shell and were machined, after stress relief, to a surface finish of 64-125 RMS microinch. The vacuum seal was obtained by using an elastic seal, bonded to the top and bottom sides of a 3/16-in.-thick stainless steel ring. The sealing ring had dimensions which matched the large flanges of the shells, and had sufficient strength for removal and replacement with a remote handling device (see Figure 2).

The top section of the furnace contained the viewing ports, charging ports, crucible radiation shield, and a tank light.

Two guide holes were drilled through the face of the flange of the top section to aid removal and replacement by an overhead crane. These two 1-in.-diameter holes matched tapered pins that were attached to the top flange of the center section. As the top was lowered onto the center section, the pins engaged the holes and assured correct alignment.

The center section, shown in Figures 1 and 3, was attached to vertical members which supported the various components of the assembled furnace. The center section contained the power port, vacuum port, side port, crucible coil box, and the electrical and water connectors for the induction coil.

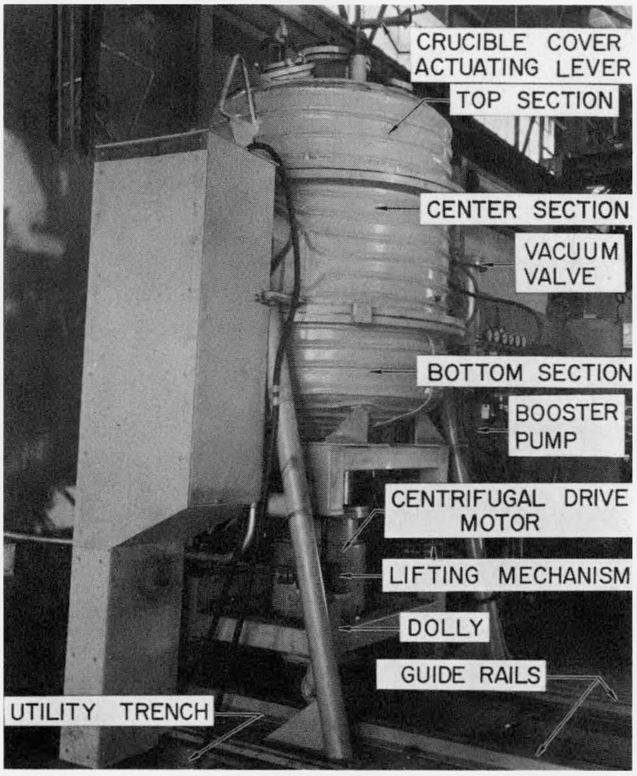

Figure 1. Vacuum Casting Furnace

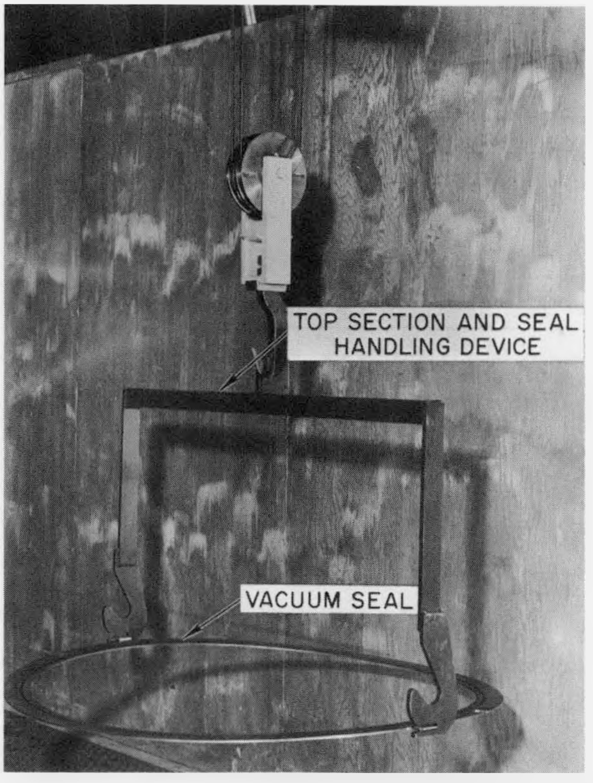

Figure 2. Vacuum Seal and Handling Yoke

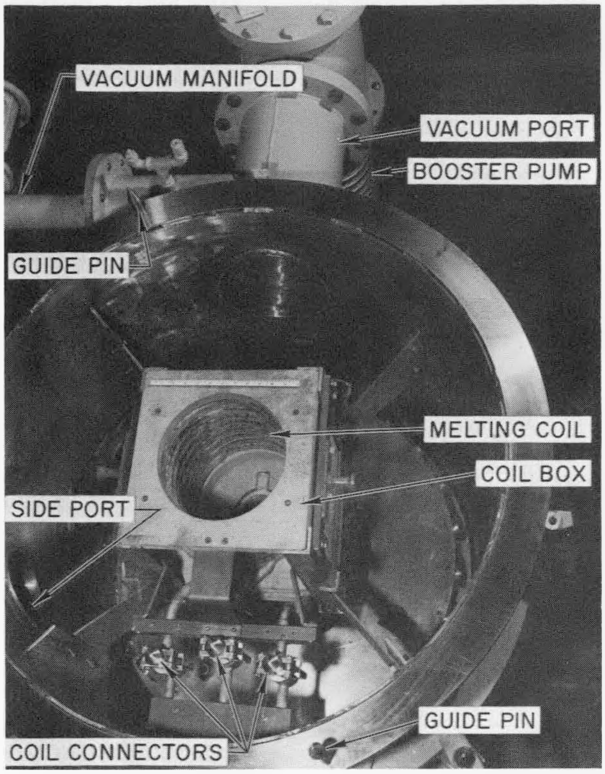

Figure 3. Internal Components of Center Section

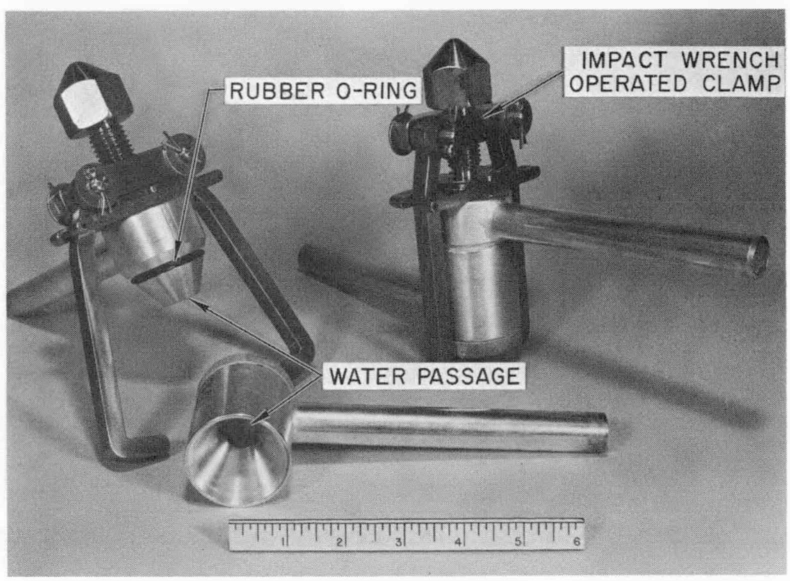

Figure 4. Coil Connectors

The female portions of the connectors were supported by an insulated blind flange which was secured to the 12 in. power port. Figure 4 shows the connectors, prior to attachment to the induction coil.

The supporting brackets for the crucible coil box, which are shown by Figure 5, were designed to permit the removal and replacement of the coil box

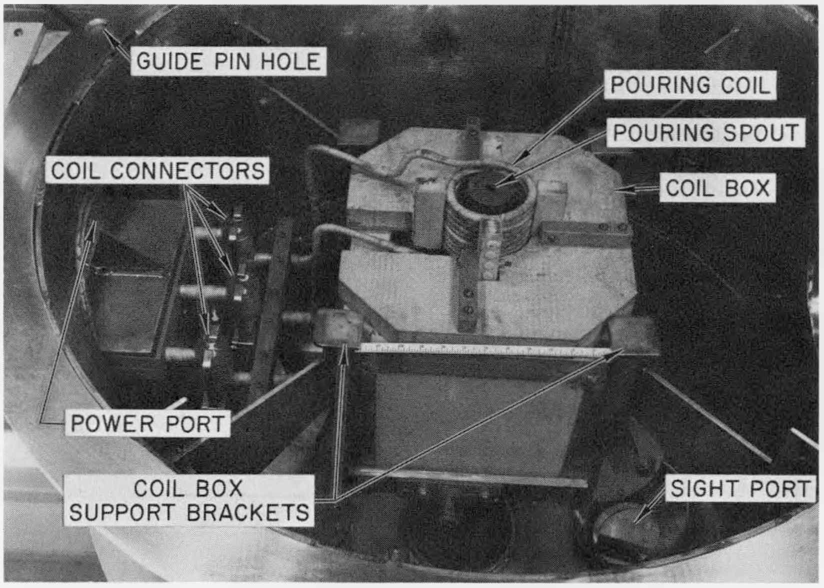

Figure 5. Bottom View of Center Section

by an overhead crane. The brackets were flared at the top to allow replacement if, during the lowering operation, some misalignment occurred between the coil box and the supporting brackets.

The vacuum booster pump and manifold were supported by the 10 in. vacuum port, located on the side of the middle section. The bottom flange of the middle section and the top flange of the bottom section had two tapered pins and matching holes, to insure alignment of the bottom section as it was raised into position.

The bottom section, shown by Figure 1, could be lowered and moved horizontally on a supporting dolly to allow handling of the mold centrifuge. The dolly was mounted on guide rails and was powered by a 1/4-hp gear head drive motor and chain mechanism attached to the dolly.

The vertical movement was accomplished by means of four worm gear jacks, secured to the dolly and driven by a gear head motor. Limit switches were installed which restricted the motion at the extreme position of travel.

2. Vacuum System

The vacuum system consisted of four major components. The shell was evacuated by a mechanical gas-ballasted fore pump, with a free air capacity of 280 cfm, backing a 10 in. oil booster pump. During standby operation of the booster pump, a fore pressure of less than 1500 microns was maintained, by means of a small auxiliary mechanical holding pump.

Operation of the vacuum pumping components and the pneumatically operated vacuum valves was controlled from the pump console. The three vacuum valves could be actuated to give various system arrangements for the most effective use of the pumping equipment.

3. Induction Circuitry

The charge inside the graphite crucible was heated by radiation and conduction of heat from the graphite crucible, which acted as a susceptor within the large induction coils.[5] The high frequency current supplied to the induction coil was obtained from a 50 kw, 3000 cps, 240 v, single-phase generator which was driven by a 75 hp, 440 v, three-phase ac motor.

A 500 mcm coaxial electrical cable conducted the high frequency current from the generator to a furnace control console, which was located adjacent to the operating face of the mockup structure. The furnace console, shown in Figure 6, incorporated all the metering and control components which were required to vary the power input to the graphite susceptor from 0 to 50 kw.

The high frequency current was conducted from the furnace console to the furnace power port by a three-conductor copper bus. The two outside 1/8 x 6 in. conductors were connected in parallel, and enclosed a 1/4 x 6 in. conductor. Because of the high transient voltages across the conductors, the latter was insulated with two layers of isomica tape to prevent arcing. The copper bus was located in a utility trench which ran from the base of the furnace console, under the mockup operating wall, to the supporting leg of the furnace structure.

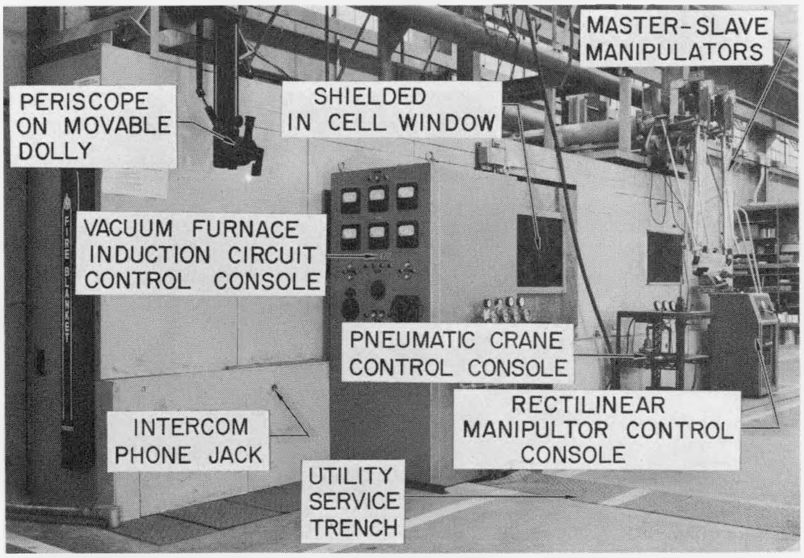

Figure 6. Operating Face of PRE Mockup

The three-conductor bus was reduced to two-conductor by a common connection from each of the outer conductors. The two conductors were extended vertically from the trench to a pneumatically operated shorting switch, located beneath the power port.

The three conductors carrying current to the induction coil were connected to the shorting switch, shown in Figure 7, through three connectors located within the furnace shell. The three conductors, which extended through the shell of the furnace, were secured to a laminated phenolic flange which served as a cover for the power port and an insulator between the conductors.

The three electrical connectors located inside of the furnace shell, as shown in Figures 3, 4, and 5 were designed to permit water cooling of the induction coil. This was accomplished by drilling a passage through the center of the connector. This passage could be attached to the hollow copper tubing of the induction coil and the power port conductors. A water-vacuum seal was maintained by an O-ring gasket, suspended in a square groove which was machined into the male portion of the connector. To insure the electrical connection, the male and female portions of the copper connector were silver plated. The two portions were forced together by a threaded clamp which could be actuated by an impact wrench supported from the crane hook.

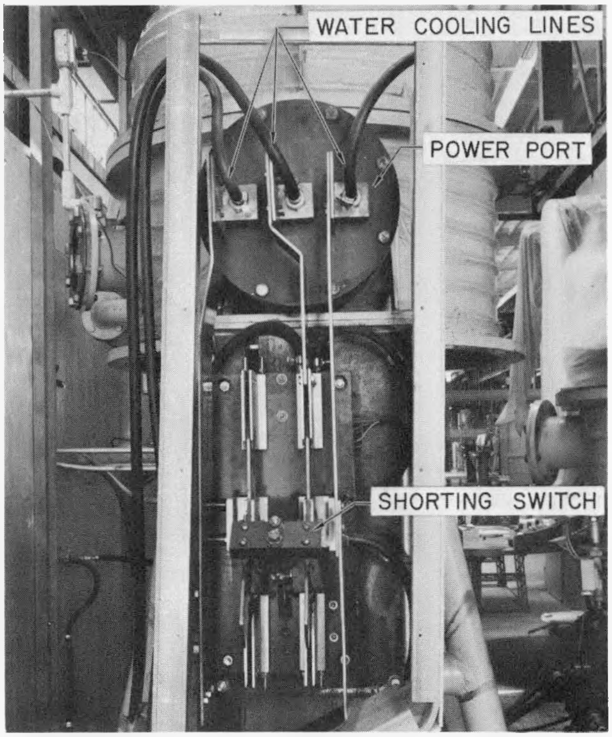

Figure 7. Induction Circuit Shorting Switch

The induction coil included a 10 in. ID coil, with eight turns of 7/8-in. diameter copper tubing, spaced evenly along the 11-in. length of the coil; and a 3-1/2 in. ID coil, with eleven turns of 3/8-in.-diameter tubing, which was flattened to give an eliptical cross section and spaced along a 4-in. length of coil. The large diameter coil surrounded the 7-in. OD graphite susceptor thermal insulating shield. The small coil was positioned under the large coil and surrounded the long cylindrical 3-in.-diameter graphite pouring spout which extended from the bottom of the crucible or susceptor. The coils are shown in Figures 3 and 5.

The two copper coils were insulated electrically with a silicone varnish and fiber glass tape. A series-connected circuit, which existed between the two coils, could be changed by the position of the shorting switch. During the melting portion of the furnace operation, the major portion of the electrical energy was induced by the large coil. This was accomplished by shorting the electrical path through the induction coil, by means of the shorting switch. The small coil was isolated from the circuit at the point of attachment to the large coil and also at the bus connection, located on the shorting switch.

After the charge was melted and sufficient superheat given to the molten metal, the shorting path of the coil circuit was opened, which allowed the electrical energy to be dissipated into the pouring spout and the susceptor. The pouring spout was then heated inductively by the small coil which melted the fusible plug.

4. Centrifugal Casting Unit

The centrifugal casting unit consisted of a 5 hp vertically mounted dc motor, a tube rectifier and control unit, a shaft-seal coolant pump, and the mold centrifuge.[4] A view of the unit is shown by Figures 1 and 8.

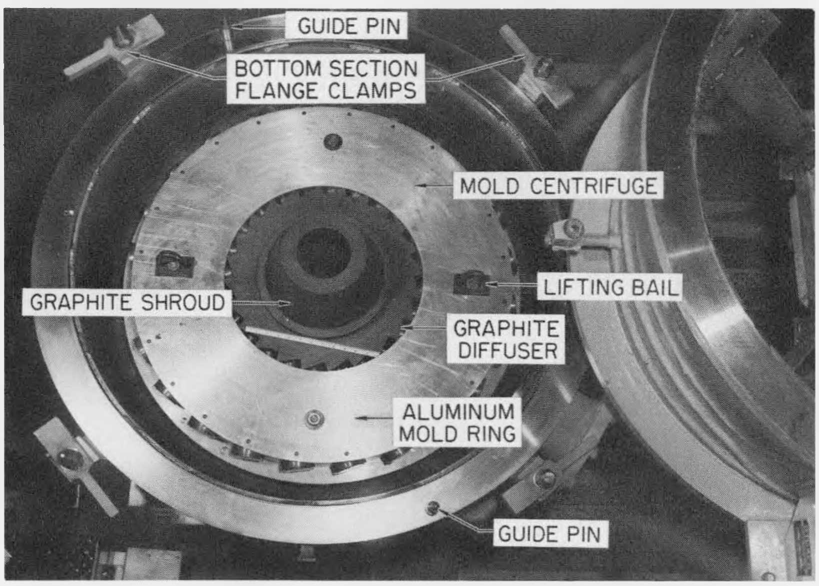

Figure 8. Mold Centrifuge and Bottom Section

The dc motor and control system was selected to provide some flexibility of design for various centrifugal mold configurations. The control characteristics reduced or eliminated the tendency for overspeeding or underspeeding during the pouring and casting of the molten metal.

A shaft-seal coolant pump was connected to the centrifugal casting unit to dissipate the heat from the section of the furnace adjacent to the rotating drive shaft. The coolant was a low viscosity lubricant which helped to reduce the gas leakage into the furnace through the shaft seal.

The mold centrifuge was located below the pouring spout of the graphite susceptor or crucible, and was contained within the bottom section of the furnace. The position of the centrifuge in the bottom section is shown by Figure 8. The centrifuge was supported on a turntable which was keyed to the rotating shaft projecting through the bottom of the furnace shell. The centrifuge contained the graphite shroud, cone, diffuser, 24 mold inserts, and the aluminum mold ring and mounting plate. The various components of the centrifuge are shown by Figure 9.

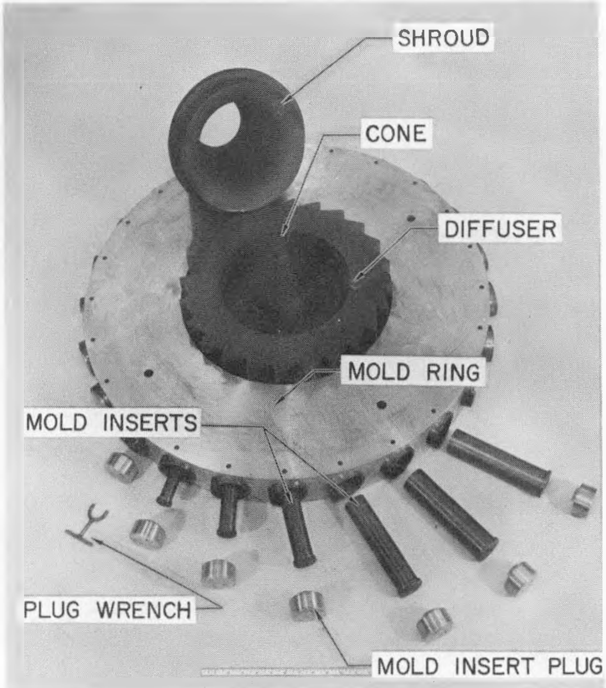

Figure 9. Mold Centrifuge Assembly

The mold centrifuge mounting plate was secured to the turntable by four bolts, spaced evenly about the circumference of the table. The alignment was insured, during remote removal and replacement of the assembly with the overhead crane, by three guide pins and four guide plates attached to the periphery of the turntable. The centrifuge was lifted from the table by a yoke which matched the crane hook and bail configuration of the aluminum mold ring. The indexing of the mold centrifuge and/or the turntable was accomplished by jogging or short power applications to the drive motor, or by applying a slight horizontal force with the crane hook tangentially at the circumference of the table or mold ring.

The mold ring was fabricated from an aluminum billet which was upset forged to give the approximate dimensions required for final machining. The finished ring was 4 in. thick, with an OD of 34 in. and an ID of 17-3/4 in. Twenty-four mold insert cavities were bored into the mold ring, with an angular offset between the centerline of the longitudinal axis of each insert cavity and the line normal to the axis of rotation of the table. The centerline of each mold insert cavity was bored tangent to a 7-1/2-in.-diameter circle circumscribed about the axis of rotation of the mold ring.

The mold inserts were fabricated to OD configurations of 1 in., 1-1/4 in., 1-1/2 in., 1-3/4 in., and 2 in., with all IDs bored to 3/4 in. The length of the 3/4-in.-diameter cavity was 8 in. The variation of the ODs permitted an analysis of the chilling or cooling characteristics which could be related to the mass of the mold insert. The mold inserts were held in position in the mold by a threaded plug, which was screwed into the mold ring after the diffuser and inserts were installed.

Two materials were used for fabrication of the mold inserts.[6,7] The first set of 24 inserts was machined from hard drawn commercial copper, and the second and third sets of 24 inserts were machined from ATZ grade graphite. The surfaces in contact with the molten metal were treated, for five of the centrifugal casts, with a magnesium zirconate wash.[8,9,10]

The shroud, cone, and diffuser were machined from ATZ grade graphite, to conform to the geometry of the mold ring and the mold inserts. The gating for each mold insert was a 1/2-in.-diameter hole, bored on a horizontal plane and perpendicular to the matching face of the diffuser and mold insert.

B. MOCKUP CELL

The mockup cell floor was 30 ft long and 10 ft wide. This area, shown in Figure 10, was closed along the operating face of the structure by a double-walled plywood partition which represented the 3-1/2 ft concrete wall in cross section. The control consoles and viewing equipment were located adjacent to this wall, representing the arrangement that might be expected in the cell designed for radioactive fuel processing. Heavy longitudinal members supported the crane and manipulator, which rolled on tracks along the length of the cell.

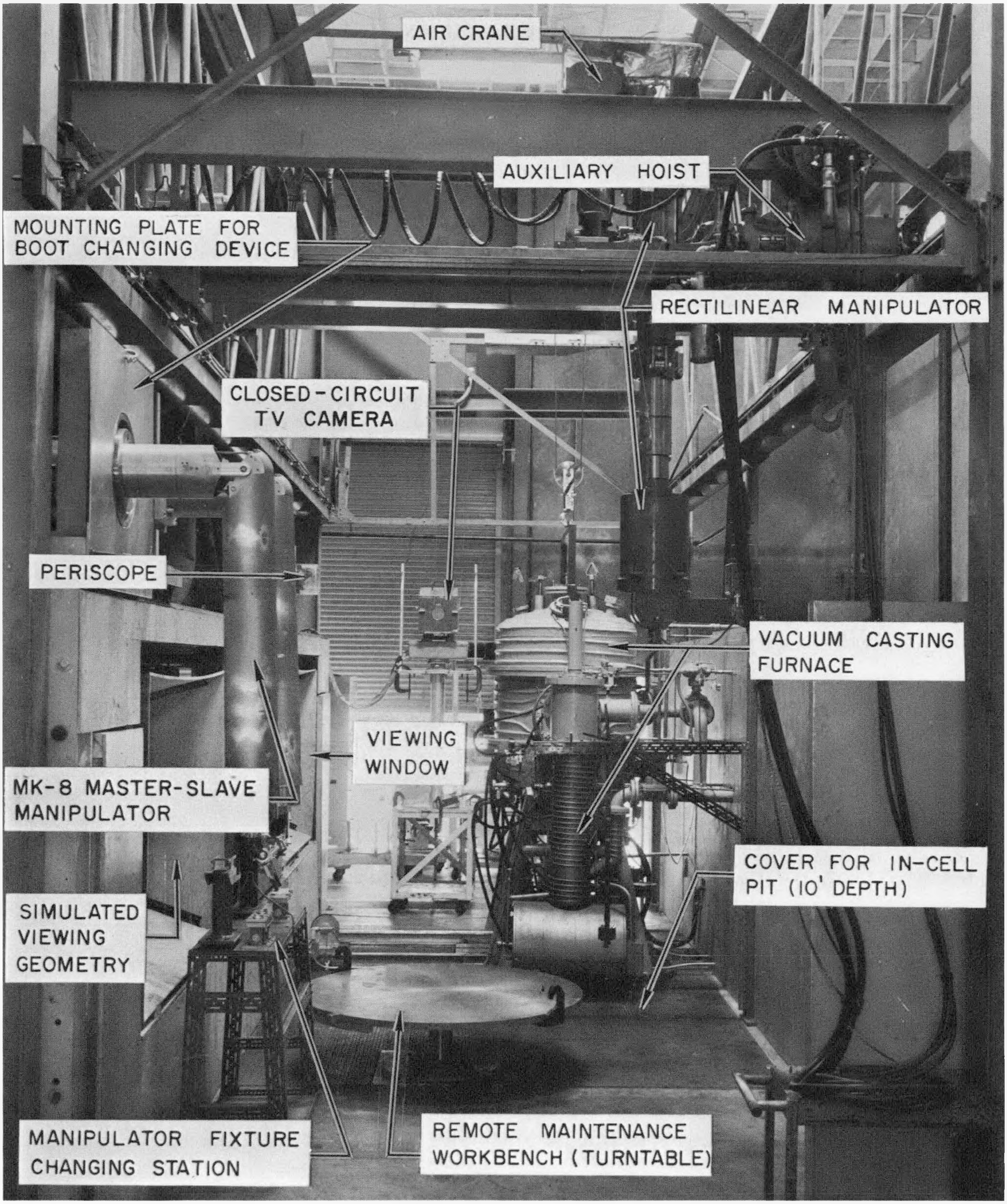

Figure 10. PRE Mockup (Interior View)

The utility services (water, electricity, and air) were supplied through two trenches which ran crosswise to the length of the cell in the vicinity of the vacuum casting furnace. No attempt was made, during the operating of the furnace, to connect or disconnect these services to the furnace by remote service equipment.

C. MOCKUP CELL SERVICE EQUIPMENT

The in-cell equipment, which was used to observe and to perform transporting, handling, and operating tasks associated with the investigation and development of the vacuum furnace, was developed during the same period. The viewing and handling devices were operated, to analyze the particular characteristics of each device, by operators who had to become acquainted with the service equipment, the vacuum furnace and associated components, and the mockup cell complex. Some in-cell equipment and operating consoles are shown by Figures 6 and 10.

1. Viewing Window

The PRE-prototype high density lead-glass window was located in the middle of the mockup cell operating face.[11] This location was approximately 5-1/2 ft to the right of the centerline of the furnace shell, as viewed by the operator through the window. This window was used by the operators for direct viewing of the handling equipment and the furnace.

The operator's side of the window was 36 in. in length and 24 in. in height. The in-cell side of the window was 48 in. in length and 36 in. in height. The centerline of the viewing window was 4 ft 10 in. from the floor level. The maximum viewing angle with minimum distortion was sixty degrees, at a position of view 1 ft from the operator's side of the window. With this geometry, the major portion of the front side of the furnace, and all the right side, could be viewed by the operator. The maximum height from which a downward view could be obtained was approximately 5 ft 6 in. from the floor level. The components, shown in Figure 3, which were located inside of the middle section could not be viewed through the shielded window. A mirror, installed behind and above the furnace, let the operator see the crucible and connectors, from his position in front of the cell face.

After the bottom section of the furnace was lowered, to clear the guide pins, and moved forward, to permit removal of the mold centrifuge, the top surface of the bottom section flange and the vacuum seal could be observed. The mold centrifuge, when in position on the turntable, could not be seen through the window.

2. Periscope

The periscope was mounted on a movable dolly which was supported by the 3-1/2 ft simulated concrete wall. The in-cell prism or vantage point was located 9 ft 3 in. above the cell floor, and could be elevated or lowered 7 in. from this position.

Magnifications of 2 x and 10 x were possible, with a field of view of 15 degrees and 3 degrees for the respective magnifications. The focus, at 2 x, was from zero to infinity; and, at 10 x, was from 3 ft to infinity. The scan for the periscope was 180 degrees, and was controlled by the position of the eyepiece.

The location selected for the periscope along the operating face of the mockup wall, for viewing of the furnace operation, was directly in front of the furnace. From this location, scanning of the components attached to the top section and to the operator's side of the furnace was possible.

The internal components of the center section and the bottom section could be viewed, after the top and bottom sections were moved out of the assembled position. Movements of the crane and the rectilinear manipulator could be followed throughout the length of the mockup cell.

3. Closed-Circuit Television

The television camera, which was used for auxiliary viewing of the vacuum furnace and service equipment operations, was located on a pedestal which could be moved to various viewing positions within the mockup cell. The camera was equipped with drive motors and remote controls for scanning through an angle of 140 degrees horizontally, and 120 degrees vertically. The focusing of the camera gave adequate resolution of viewed objects, from a distance of 3 ft to 25 ft. To prevent damage to the camera pickup tube, the depth of field was from 3 ft to 8-1/2 ft, for close viewing, and from 10 ft to 23 ft, for distance viewing.

The television monitor had a 7 in. by 8 in. rectangular viewing tube incorporated into the camera control and monitor control panel. The assembly was attached to a movable stand which gave some flexibility to the position and viewing arrangement for the operator of the crane.

4. Cell Lighting

The in-cell area of the mockup was illuminated by 3 luminaires, each of which contained a 3 kw mercury vapor lamp. The luminaires were positioned 26 ft above the cell floor, and at the 1/3, 1/2, and 2/3 stations along the length of the cell complex. With this configuration, a luminaire was above the centerline of the furnace and above the centerline of the viewing window.

The six mercury vapor tubes gave a light intensity of 350 ft-candles, measured at any location within the cell complex 1 ft from the floor.

5. In-Cell Crane

The pneumatic 2-ton in-cell crane was the principle means for transporting or moving the furnace components and special tools required for the remote operation of the furnace.

The rate of travel, for all directions of motion of the crane, was varied during the development of the furnace. Early in the program, the speed for the vertical motion was 9 fpm, but was dependent upon load for a given manifold pressure of 100 psi. Traverse speeds were 4 fpm, along the length of the cell, and 9 fpm, across the cell. Modifications during the program resulted in a speed for the vertical motion of 13 fpm, and 12 and 9 fpm, for the logitudinal and transverse directions, respectively.

The crane hook was modified to provide greater stability for the special handling grapples and yokes. The geometry of the lifting portion of the hook was designed to give a locking action between the crane hook and the yoke or component to be moved. The locking action reduced the pendulum motion about the axis of the hook, which is inherent with crane operations. The modified hook is shown in Figure 11.

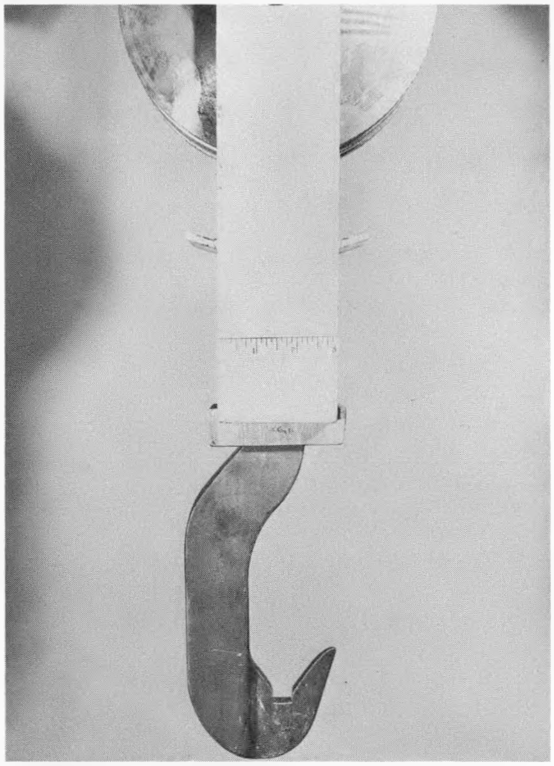

Figure 11. Modified Crane Hook

6. Rectilinear Manipulator

The rectilinear manipulator[12] was installed in the cell mockup to provide additional dexterity, when required by the remote operations associated with development of the process equipment. The manipulator was considered a secondary supporting service, when remote operations with the crane were impractical. The reliability and relative capacity of the crane and the manipulator influenced the choice of equipment for in-cell handling.

7. Intercom Set

An intercommunication system was incorporated into the operating face of the mockup cell wall. The intercom was used extensively, during the remote operation of the furnace, to help coordinate the motions of the crane, handling devices, and manipulators. Three stations were provided, along the face of the cell, with "y" extension cords plugged into each station. Six headsets and microphones could be used during observation and operation of the equipment in the cell.

8. Special Handling Devices and Tools

All major components were designed to receive a suitable remote handling auxiliary device for transporting or operation. Special yokes, bails, and grapples were devised to perform each remote operation. In the PRE mockup, the special handling devices were stored on a special storage rack in the simulated cell. Each device was selected and carried, by the crane hook, from the storage rack to the component to be transported. After reaching the component, the device was engaged with the bail of the component by the crane and transported to a preselected location. The device was released from the component by lowering and moving the crane hook, and was then transported back to the storage rack.

Removal of the water-cooled induction coil and coil box required the use of a clamping device attached to the induction coil connector. The clamping action of the connector was obtained by means of a threaded shaft which extended perpendicular to the mating faces of the connector. This shaft was fitted with a tapered nut which was rotated by an pneumatic impact wrench. The impact wrench was controlled from a remote station outside of the cell complex, and was transported in-cell by the crane. Views of the components, suspended from the crane hook by their lifting devices, are shown in Figures 2, 12, 13, 14, 15, and 16. All grapples developed for the PRE program were designed for use with two lifting bails. Lifting the grapple by one bail locked the grapple jaws. Lifting by the second bail released the grapple jaws.

D. INSTRUMENTATION

During the development and remote operation of the furnace, information was collected which could be used to improve the design of the furnace to be installed in the PRE hot cell.

The melt temperatures, during melting and casting of the copper-nickel alloy charge, were obtained by thermocouples immersed in the molten charge and susceptor walls, and by viewing the charge with an optical pyrometer. The data from the thermocouples were recorded by a multiple-channel potentiometer

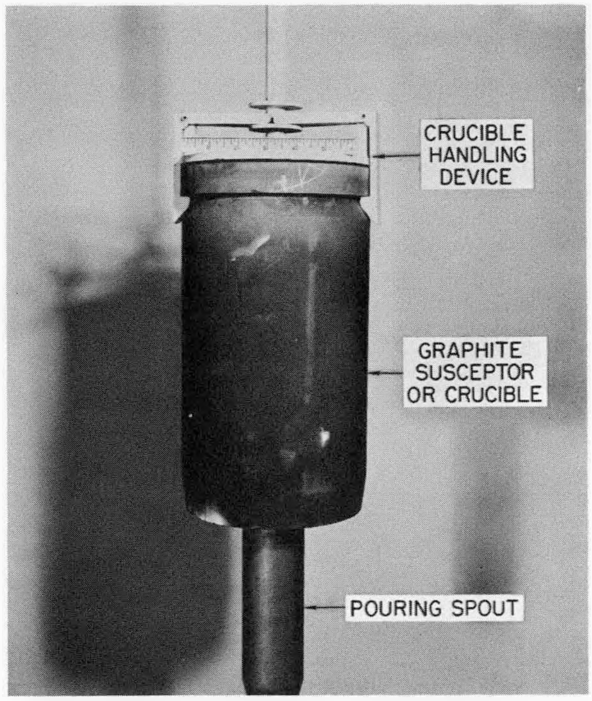

Figure 12. Graphite Crucible and Pouring Spout

recorder. The optical pyrometer measurements were made by viewing through a sight port on the furnace top, by viewing an image reflected in a mirror placed above the light port, by viewing through the periscope, and by viewing through the shielded window.

The changes in temperature and mass flow of the cooling water were obtained by immersion thermometers and pressure gauges installed in the cooling lines.

The temperatures of strategic positions inside the furnace shell were obtained by thermocouples. The temperature of the shaft seal coolant was obtained by an immersion thermometer, located in the reservoir of the coolant pump.

The pressures inside the furnace shell were measured by two thermocouple gauges. One thermocouple gauge was installed in the vacuum roughing line leading to the mechanical pump, and the other was installed on the vacuum fore line leading to the booster pump and to the mechanical pump. The range of the first thermocouple gauge was 0 to 20 millimeters of mercury. The range of the second gauge was 0 to 1000 microns of mercury.

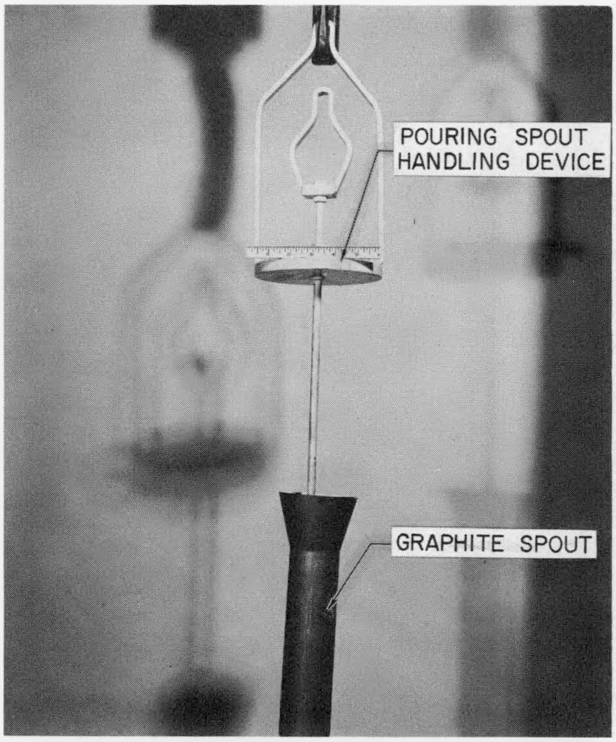

Figure 13. Pouring Spout and Handling Device

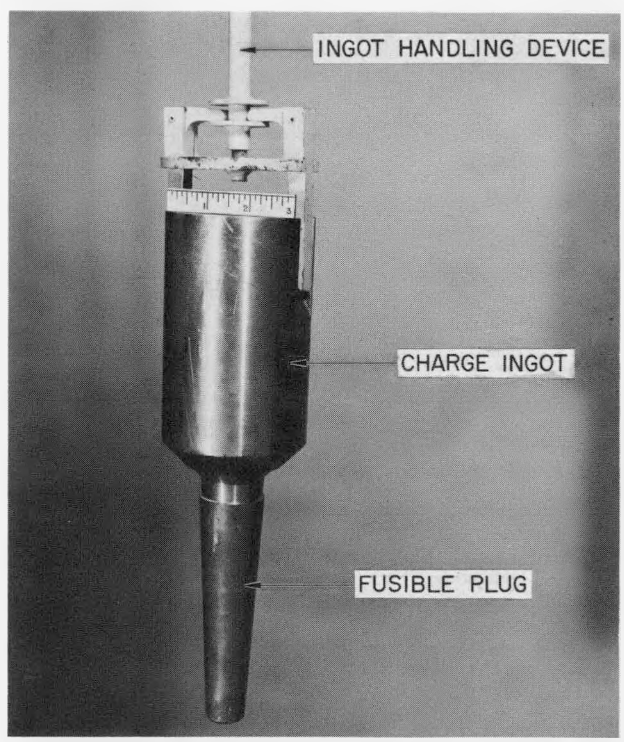

Figure 14. Change Ingot and Handling Device

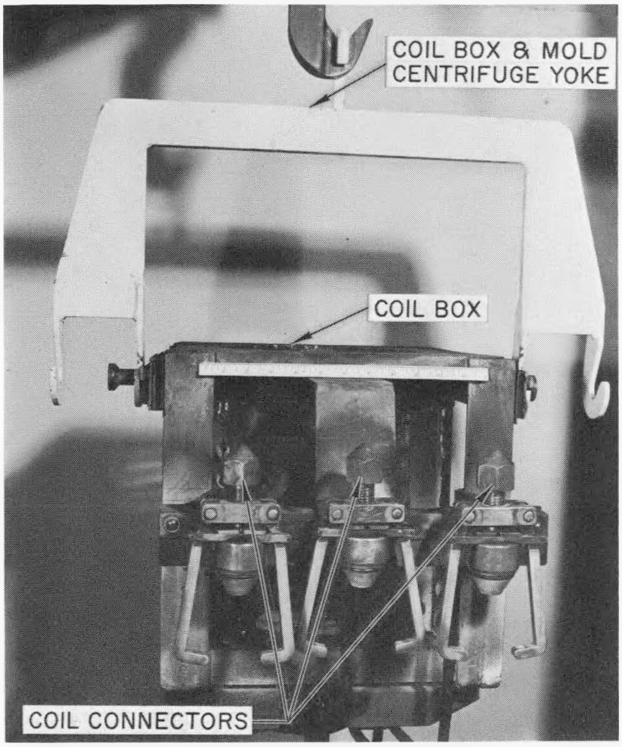

Figure 15. Induction Coil Box and Handling Yoke

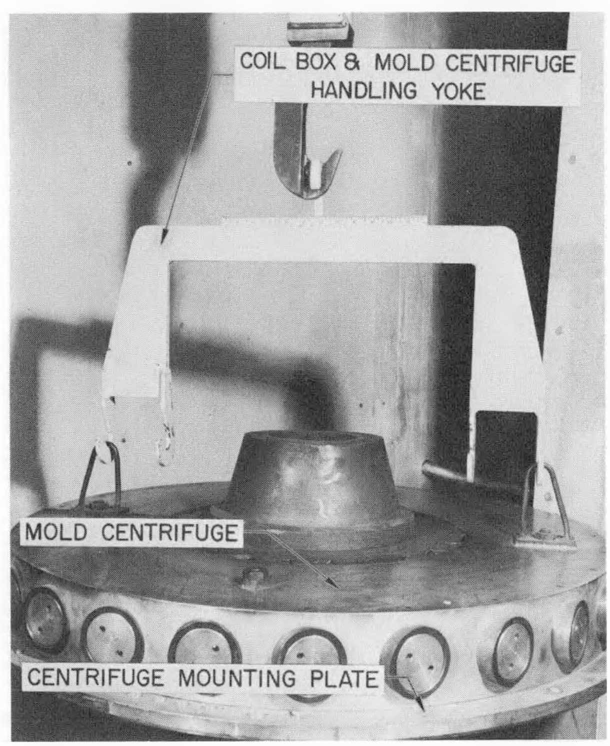

Figure 16. Mold Centrifuge and Handling Yoke

The rotational speed of the mold centrifuge was transmitted to the dc drive motor control unit by a small ac generator which was geared to the rotating shaft of the drive motor.

III. OPERATION

A. NONREMOTE STATIC CASTING

After the furnace was moved into the mockup, and the utilities, controls, and induction circuitry connected, a 25 lb charge of a Cu-Ni 70-30 w/o alloy was melted and statically cast. The Cu-Ni alloy was used as the charge throughout the investigations. The melting point of 1130°C matched that of uranium metal within ±25°, and the induction heating characteristics were similar. Information was thus obtained on the melting, casting, and remote handling of uranium, without the problems associated with contamination or environmental factors.

The first melts were made to determine, by remote techniques and equipment, the effectiveness and suitability of a fusible plug for future operations of the furnace. Pouring hole diameters of 3/4 and 1 in. were used. Fusible plugs of 1-in. diameter, with a length of 1-1/2 and 3-3/8 in. were tried. The power input was varied to determine the time required to heat the charge to melting temperatures. After several melts and pours were conducted with the fusible plug, an effort was made to improve the control of the melting and casting cycle and to improve the quality of the cast ingot. The energy input to the furnace and the time required for melting and casting were established.

The electrical power supplied to the furnace was programmed for uniform heating without severe shock to the susceptor and thermal insulation. During the 50 min melt cycle, power input to the main coil was varied during each successive 10 min period. During the first 10 min, the power input was 15 kw. During the succeeding 10 min periods, power inputs were 25, 30, 35, and 40 kw, respectively. A power input of 30 kw to the pouring coil was used to melt the fusible plug. A typical test sheet is shown by Table I.

The molten charge was cast into a graphite mold placed beneath the pouring spout. The mold had the same configuration as the susceptor and the fusible plug combined. It was possible to use the cast ingot as the new charge, without machining it to the desired configuration. Figure 14 shows the shape of the ingots that were cast statically.

TABLE I

SAMPLE TEST SHEET

Charge Material: Cu-Ni 70-30 w/o
Charge Weight: 22.75 lb

Time Start: 13:14
Time Finish: 14:06

Date: 7-21-58
Operator: E. F. Carpenter

Time After Start (min)	Generator Current (amp)	Generator Voltage (v)	Field Current (amp)	Field Voltage (v)	Power Input (kw)	Power Factor	Capacitor Setting	Transformer Setting	Furnace Pressure (μ)	Remarks
2	77	205	3.8	130	15	0.98	8	5	290	
4	75	210	4.0	120	15	0.98	8	5	295	
6	75	210	4.0	130	15	1.0	8	5	325	
8	75	210	4.0	130	15	1.0	8	5	400	
10	75	210	4.0	130	15	1.0	8	5	550	
12	95	270	5.4	165	25	1.0	8	5	700	
14	95	270	5.4	165	25	1.0	8	5	750	
16	95	270	5.4	168	25	1.0	8	5	800	
18	95	270	5.4	168	25	1.0	8	5	900	
20	95	270	5.4	168	25	1.0	8	5	875	
22	104	300	6.0	185	30	1.0	8	5	800	
24	103	300	6.0	185	30	1.0	8	5	775	
26	103	300	6.0	185	30	1.0	8	5	780	
28	103	300	6.0	185	30	1.0	8	5	800	
30	103	300	6.0	185	30	1.0	8	5	800	
32	110	320	6.4	200	35	1.0	8	5	850	
34	110	330	6.5	205	35	1.0	8	5	>1000	Charge began to melt
36	110	330	6.5	205	35	1.0	8	5	>1000	
38	110	330	6.5	205	35	1.0	8	5	>1000	
40	110	330	6.5	205	35	1.0	8	5	>1000	
42	112	360	7.0	220	40	1.0	8	5	900	
44	112	360	7.0	225	40	1.0	8	5	900	
46	112	365	7.0	225	40	0.99	8	5	900	Centrifuge Started
48	112	365	7.0	225	40	0.99	8	5	900	
50	112	365	7.0	225	40	0.99	8	5	900	Shorting Switch Energized
52	83	405	7.0	255	30	0.99	0	5	900	Power supplied to pouring coil during last 2 min.

NOTE:
(1) Booster pump removed
(2) Centrifugal cast – 140 rpm
(3) Mod III Susceptor and Spout Used

Temperatures were measured with thermocouples and with an optical pyrometer, during the initial melts, to establish some reference for control. As more melts were made, the use of the optical pyrometer was eliminated, in favor of programming the energy input to the furnace. After the metal had been recycled several times, the amount of slag and degassing was reduced, which made consistent control by the energy input method practical. Establishing the feasibility of melt control without temperature instrumentation represents significant progress in operating criteria for the PRE hot facility.

Several methods were used to insulate the crucible from the water-cooled induction coil. The first consisted of a series of shells of stainless steel and graphite which were enclosed in a stainless steel can. The can and shells containing the graphite susceptor were placed inside the induction coil during the melting operation. The shells and the can were slotted to reduce eddy current heating by the induction coil. The assembled view of this configuration is shown by Figure 17.

The second method of insulating the induction coil was a combination of a cylindrical refractory liner and a stainless steel shell to support the refractory liner during remote removal and replacement.

A third method of coil insulation consisted of a refractory liner, cast in two sections, which occupied the space between the susceptor and the coil. The two sections eliminated breakage due to thermal stresses, and made removal easy if breakage should occur. The two sections, shown in Figure 18, were held together at the top and bottom by stainless steel wires. These wires were formed into lifting bails, for use in handling by the crane.

B. NONREMOTE CENTRIFUGAL CASTING

After sufficient melts were made to establish the control for pouring, the first centrifugal cast was made, using a speed of rotation of 400 rpm. The mold inserts were fabricated from graphite. The furnace was operated by direct personnel contact.

The melts and centrifugal casts which followed were made with an energy input of 1.1 kwh/lb and a rotational speed of 140 rpm.

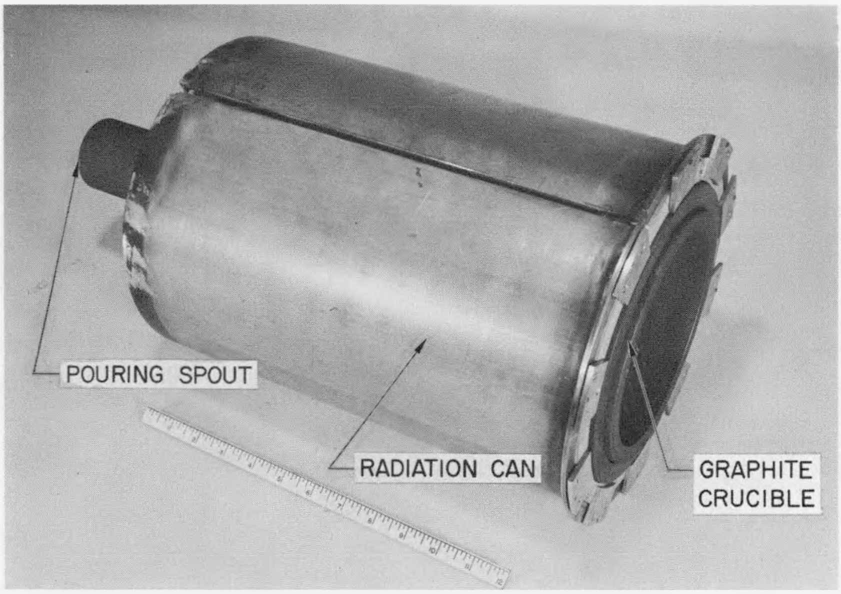

Figure 17. Crucible and Thermal Radiation Can

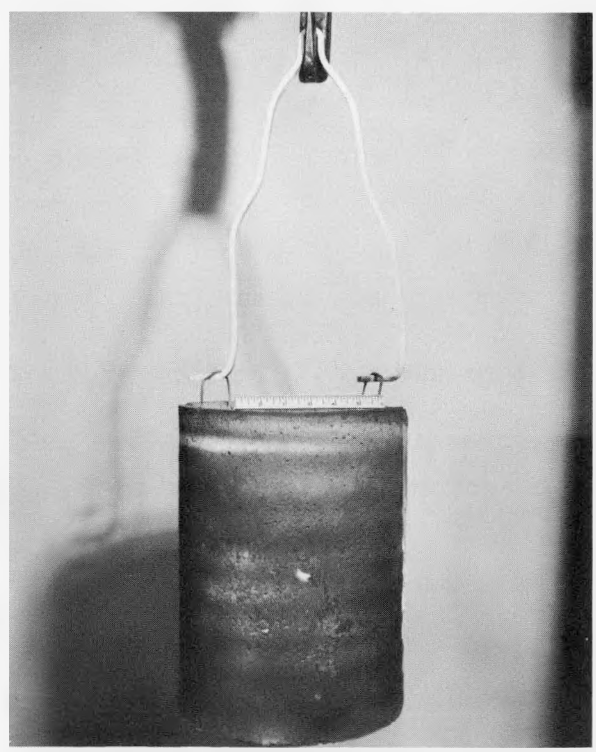

Figure 18. Refractory Liner - Thermal Radiation Shield

During several of the centrifugal casts, a window was installed on a side port of the middle section. This permitted observation of the pouring spout, the molten stream of metal as it left the pouring spout, and the action of the diffuser during the pouring operation.

C. EQUIPMENT MODIFICATION

The nonremote operation of the furnace during the checkout operations revealed design features which would require modification before remote operation suitable for the PRE facility could be demonstrated. Modifications to the crucible and thermal insulation shields were discussed previously. The modifications which were made to the shield permitted installation and removal by the crane. The guides and supporting members for the coil box were increased in width and length to compensate for misalignment of the crane by the operators, during installation of the coil box.

The split crucible covers, which were previously operated by hand from above the top section of the furnace, were incorporated into a single cover which made operation with the crane possible.

The four large flange clamps, that were secured to the bottom section and designed for operation by an impact wrench suspended from the crane, were removed. This elimination was possible because a vacuum seal could be made by controlling the upward travel of the bottom section lifting mechanism.

After several centrifugal melts were made which indicated that the dynamic balance was not seriously affected after the molten metal had entered the mold, the securing bolts and aligning pins for the mold centrifuge were eliminated.

The graphite shroud was removed to provide a better view of the pouring and casting operation. The splatter during pouring, which was expected, was eliminated by reducing the height of the graphite cone located in the center of the mold centrifuge.

The crucible or graphite susceptor was modified to facilitate removal and replacement of the pouring spout by the crane. The first modification was made to evaluate the use of a tapered flange on the spout which matched a similar taper inside the crucible, as shown in Figure 12. The second modification was made to improve the geometry of the ingot charge and the susceptor to obtain better handling, heat transfer, and mold characteristics. This configuration is shown by Figure 19. Figure 20 shows the third configuration, which is described in Section IV.

The furnace-shell cooling-water service connections, pressure gauges, flow indicators, and temperature instrumentation were removed from the furnace.

D. REMOTE OPERATION

1. Trial Handling

Some handling experience was obtained by the operation of the furnace and the in-cell service equipment during the nonremote checkout. The modifications which were made were tested to reveal any interference or misfitting of the components. After a check of the modified components for misfitting, the mockup cell structure was closed off to operator viewing, except through viewing equipment which would be used in the PRE hot cell complex.

With the necessary handling devices and service equipment located within the cell, the operational cycle was simulated. The time for each component to be removed and/or replaced was recorded for each of the operational cycles. Table II indicates the viewing equipment used and the time required to perform the operations involved with the major components of the furnace.

The furnace was disassembled for servicing and inspection of the induction coil box, graphite susceptor, pouring spout, and the refractory liner. After the inspection, the components were replaced and the charge was loaded. The top section was replaced and the mold centrifuge was installed. Following the installation of the centrifuge, the bottom section of the furnace was moved into position and the reassembly was completed.

2. Melting and Casting

The furnace was evacuated, and the charge was melted and poured. After the cast slugs had cooled sufficiently, the furnace was disassembled and the components removed for replacement or inspection. The viewing equipment installed in the mockup cell was used to observe the moving of the components by the crane.

Figure 19. Graphite Crucible and Pouring Spout, Second Configuration

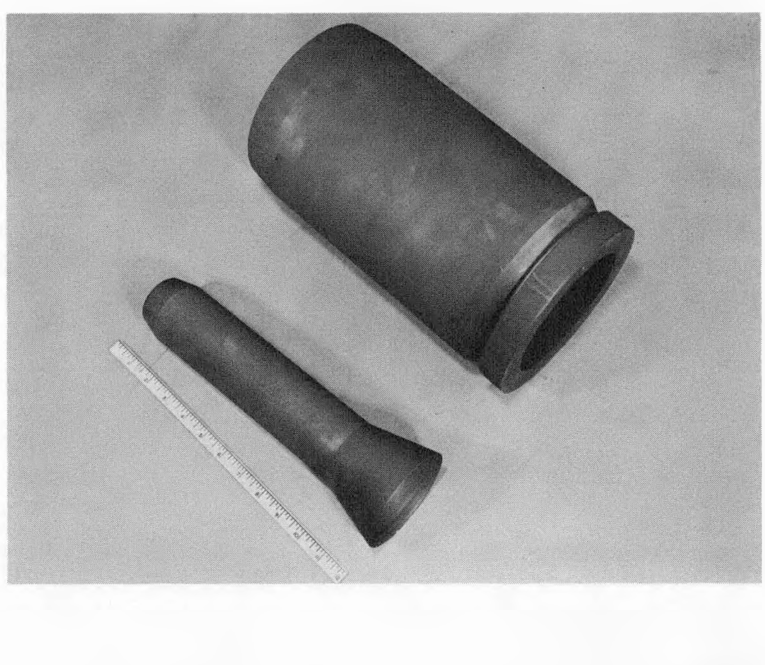

Figure 20. Graphite Crucible and Pouring Spout, Third Configuration

TABLE II

REMOTE OPERATION TABULATIONS

Test No.	Top Section Remove (min)	Top Section Replace (min)	Connectors Loosen (min)	Connectors Tighten (min)	Coil Box Remove (min)	Coil Box Replace (min)	Charge Load (min)	Bottom Section Remove (min)	Bottom Section Replace (min)	Mold Centrifuge Remove (min)	Mold Centrifuge Replace (min)	Viewing Equipment TV	Viewing Equipment Periscope	Viewing Equipment Window
1	40	30	-	-	25	25	20	-	-	25	15	X	X	X
2	33	-	-	-	23	9	19	5	-	15	-	X	X	X
3	33	15	-	-	10	15	20	1	1	-	-	X	X	X
4	27	23	-	-	13	10	-	1	1	14	13	X	X	
5	12	-	-	-	10	12	-	1	1	5	13	X	X	
6	12	8	13	13	8	9	15	1	1	7	8		X	X
7	11	7	8	9	7	9	17	1	1	9	7	X	X	X
8	8	8	-	-	-	-	13	1	1	7	8	X	X	X
9	11 & 7	13 & 7	10	6	5	5	8	1	1	9	7		X	X
AVERAGE TIME (min):	19.4	13.8	10.3	11.3	12.6	11.8	12.5	1.6	1.0	11.3	10.7			

AVERAGE TOTAL TIME:

Remote Handling	157 min
Pump Down	10 min
Melt & Pour	60 min
Cooling of Castings	180 min

AVERAGE CYCLE TIME:
407 min or 6.8 hr

IV. RESULTS

The investigation of the operational characteristics of the vacuum casting furnace with a simulated in-cell environment revealed engineering design features which were not evident, prior to the in-cell operation. The limitations of the viewing equipment, the dexterity of the handling equipment, and the technique of the operators were analyzed and evaluated as an integrated operation.

A. HANDLING OF FURNACE COMPONENTS

The handling characteristics of the components were influenced by the particular design of each component and the equipment used for handling. Because of the extensive use made of the crane, its characteristics affected all of the components. The sensitivity of control and hook geometry of the crane became important factors.

For the large components of the furnace, i.e., top section, coil box, and mold centrifuge, close alignment of less than 1/2 in. was required between matching parts. A time delay of 1 to 3 sec in crane response, and the difficulty of controlling crane location within 1 to 2 in., made installation a trial and error operation. Some improvement of this condition was effected by making the coil box guides larger, which allowed greater misalignments to be tolerated. The geometry of other components of the furnace made modifications to improve this condition impractical.

The suspension of the hook and sheave on the crane affected the removal and replacement of the furnace components. The orientation of the crane hook, the bails of the handling devices and/or the bails on the furnace components were fixed to point in one direction to eliminate the need for orienting the hook. This orientation in one direction, with an angular displacement of ±2 degrees from that position, aided alignment of components that required indexing to each other. The open part of the crane hook was directed toward the operating face of the cell mockup to provide the best possible viewing, while engaging the hook.

The lifting bails and the hook were designed to give a "locked on" attachment during the transporting of furnace components. The special design of the hook, shown in Figure 11, resulted in plane, rather than point, contact between the hook and the bail. This feature reduced the pendulum action of the components with respect to the crane hook, and improved the handling of the smaller components.

The crane hook rotated about the axis of the pulley shaft during vertical motion. This rotation caused misalignment of guides and guide pins during installation of the furnace components. The amount of rotation varied with the weight of the object that was lifted and the distance between the center of gravity of the object and the axis of the pulley. Rotation caused a displacement of 1/2 to 1 in. at the end of the hook with the crane unloaded.

In the PRE mockup, one lighting fixture was installed directly above the vacuum furnace. Because of the elevation of the light fixture above the bridge of the crane, the crane blocked the light from this fixture when the light was most essential for viewing. Operation of the crane under the light fixture for long periods, and the proximity of the crane to the light, caused some radiant heating of the bridge components. It became apparent in mockup operation that, wherever possible, lights should not be installed in the PRE facility directly above process equipment.

The positioning of the furnace components was affected by the location of the viewing equipment and the available lighting. The television camera line-of-sight was perpendicular to the operator's line-of-sight through the window or the periscope. This setup augmented the operator's depth perception. Components inside the furnace were scanned by the periscope, which was at a higher elevation. For close examination or critical alignment, the periscope was used at the higher magnification. Molten metal inside the crucible was observed with the periscope and a mirror located above the viewing port.

Temperatures of the susceptor were read by an optical pyrometer from outside the mockup, both through the periscope and through the shielding window. For comparative purposes, temperatures were read through the furnace viewing port by an optical pyrometer. The information obtained is shown by the curves in Figure 21. The difference in the apparent temperatures indicates the losses incurred through the various viewing devices.

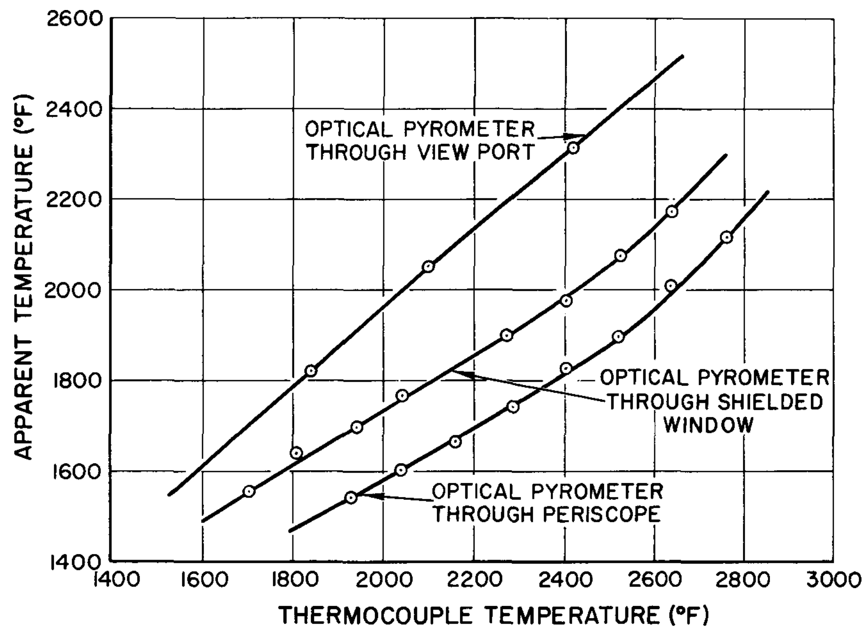

Figure 21. Temperature Comparison Curves

The average time required to complete a cycle of removal and replacement of the furnace components in mockup operations was 2.6 hr. Improvements made on the handling equipment, relocation of the viewing equipment with respect to the furnace, modification or elimination of some of the guides and guide pins, and operating experience reduced the time required for each remote operation by more than 100%.

The average total time required for the assembly of the furnace, melting and pouring, cooling of the cast slugs and crucible, and furnace disassembly was 6.8 hr. Of this, 3 hr were required for cooling, and 1 hr for melting and pouring. The remainder was for pump-down, checkout, assembly and disassembly.

B. PROCESS CHARACTERISTICS

The excessive amount of slag included in the Cu-Ni alloy ingots, which were produced by the oxide drossing furnace operation, affected the melting and casting, and the quality of the cast slugs. Severe degassing of the ingots, during the first melting in the vacuum furnace, caused agitation of the molten charge and excessive splattering of metal about the interior of the furnace. The accumulation of splatter, in proximity to the melting and pouring coils, resulted in a grounded induction circuit. The operation had to be discontinued until the source and magnitude of the condition were determined.

Agitation of the melt by gas evolution during melting had the effect of washing or eroding the fusible plug, resulting in premature pouring of the molten charge. The agitation was reduced after the metal had been degassed by melting and pouring several times. The control of the pouring portion of the operation was improved by increasing the length of the fusible plug and incorporating a shoulder in the spout pouring hole. The spout configuration which gave the best pouring characteristics is shown by Figure 20. The fusible plug section was 6-3/8 in. long, with a diameter of 1 in. The time required to melt the longer plug, after the pouring coil was energized, was between 3 and 4 min. A full stream of metal from the spout, as the plug was melted, and a well defined completion of the pour, demonstrated the effectiveness of the fusible plug method of valving the molten metal. The time required for the pour to begin and the metal to be distributed to the individual molds was less than 4 sec for a 22.5 lb charge.

The surface quality of the cast ingots and slugs was improved by additional superheat, by a longer period of degassing, and by treatment of the molds. The energy, per pound of furnace charge, to obtain a temperature of 2700°F, was 1.0 kwh. Treatment of the mold inserts with a magnesium zirconate wash, followed by 4 hr of degassing at a pressure of 25 microns and a temperature of 1500°F, eliminated the small surface defects which were characteristic of the untreated mold inserts. The first centrifugal cast is shown by Figure 22. The last centrifugal cast, using the improved techniques developed in the mockup program, is shown by Figure 23.

The addition of superheat gave more fluidity to the melt, which reduced the amount of residual metal left on the graphite parts of the mold centrifuge. The metal residue represented an average of 5% of the charge. Residue was removed from the graphite cone by upsetting the cone. Removal of the residue

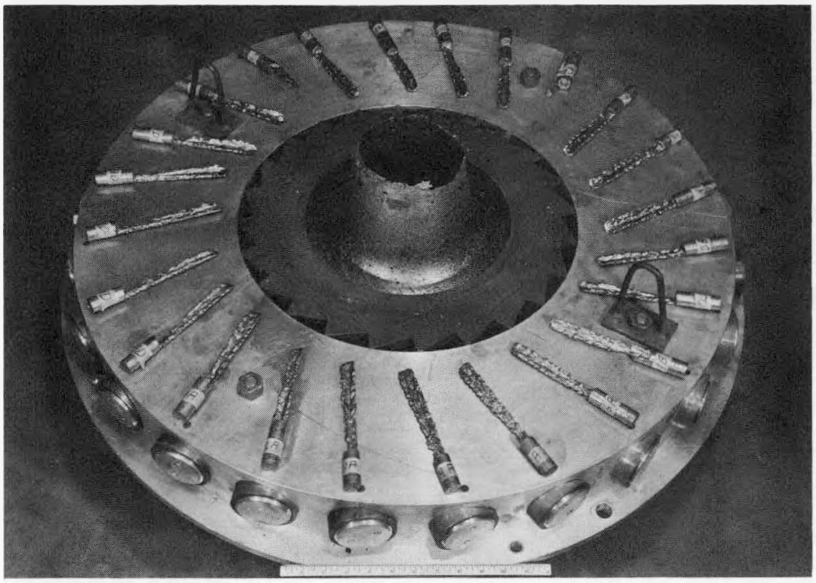

Figure 22. Mold Centrifuge and Cast Slugs After First Casting

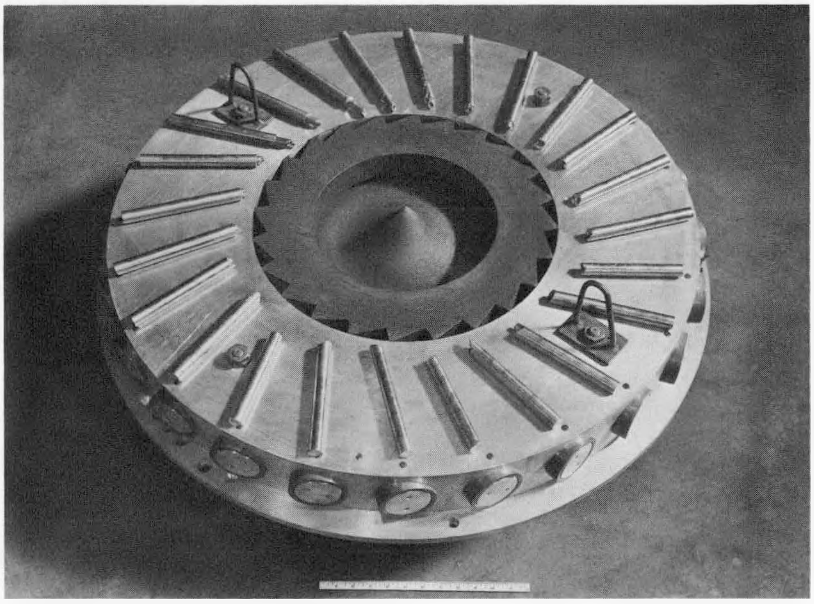

Figure 23. Mold Centrifuge and Cast Slugs After Last Casting

attached to the diffuser was more difficult. No attempt was made to perform this operation with remote handling equipment.

A comparison was made between the mold inserts which were fabricated from copper and those fabricated from graphite. The surface quality and density of the slugs which were cast into the graphite molds were superior to those cast in copper molds. The surface defects on the slugs cast in copper molds indicated that too rapid solidification resulted in cold shuts and flaws. The variation in the mass of the mold inserts was indicated by the surface quality of the cast slug. The copper inserts with the smallest outside diameter and with the least mass produced the slugs with the best surface condition. The mass of the graphite molds did not influence the surface quality as noticeably as the mass of the copper molds.[6] Removal of the cast slugs from the copper molds was difficult, because little shrinkage or diametral variation existed between the mold cavity and the slug after the slugs had cooled to room temperature.

The problems associated with crucible breakage, and subsequent leakage of molten metal around the induction coil, during remote operation were experienced during the investigation of the vacuum casting furnace. The first leakage occurred during the evaluation of a stainless steel thermal radiation shield. The Cu-Ni alloy welded to the steel shield, which required disassembly of the crucible coil box before removal was possible. The second and third leakage occurred when a refractory thermal radiation shield was installed around the susceptor. The molten metal solidified at the base of the susceptor, but did not become welded or attached because the refractory shield captured the leakage.

A cracked or broken susceptor was detected by a variation in the control panel instrumentation readings. A grounded induction circuit indicated contact between the molten metal and the induction coils.

During the checkout tests on the pumping equipment, back-diffusion of the oil from the booster pump occurred when a cooling-water flow switch failed to cut off power to the boiler heating element. The overheated oil vapors condensed on the inner surface of the furnace shell and internal components. Some difficulty was encountered in removing the viscous oil from the inner surfaces and components. The condition was further complicated by the method used to weld the large flanges to the shells. The inner weld was not continuous around the flanges on the inside of the furnace, which left cracks in which the condensed oil was entrapped. Some of this trapped oil was driven out during each of the tests which followed, and continued to cause a cleaning problem. No attempt was made to remove the condensed oil with remote equipment.

The cumulative condensation of volatile material (from 15 successive melts) on the cooled surfaces of the induction coil and coil connectors caused a corona discharge across the connectors and the induction coil. The discharge was eliminated after the condensed material was removed from the water-cooled surfaces. No attempt was made to remove the condensate with remote cleaning equipment.

The pouring spouts were eroded by the slag which remained at the entrance to the pouring hole. The amount of slag which remained after each melt was dependent upon the number of cycles for the particular charge and the original ingot material. Figure 24 shows the amount of slag that remained after the

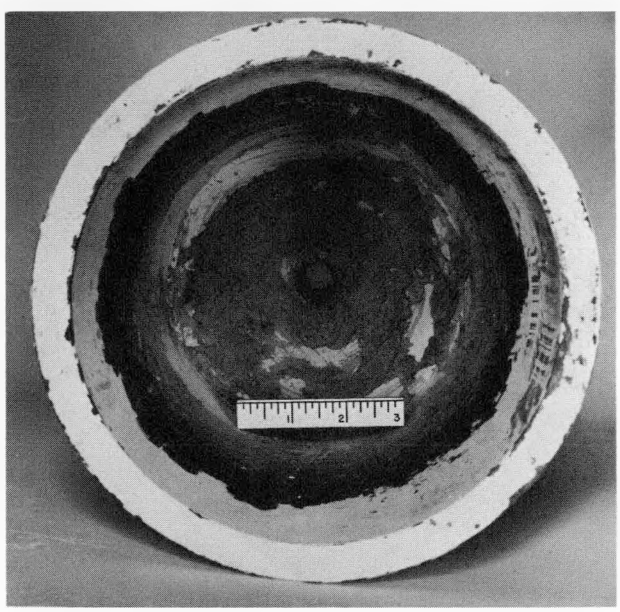

Figure 24. Graphite Crucible with Slag Formation

first melting of the charge. The maximum weight of slag was 2.25 lb, for a 26.4 lb charge. The number of tests made with each susceptor and spout is shown by Table III.

One of the refractory shields was used for 13 tests before replacement was necessary. The shields were easily removed and replaced with the crane. Fracture of a shield resulted after severe splattering of the charge, which required removal of the susceptor before the shield could be replaced. The number of cycles for each thermal radiation shield evaluated is shown by Table III.

Vacuum seals on the large flange were made and broken remotely 100 times to evaluate the effectiveness of the bonded seal. Of these, 20 cycles were made during melting operations with water cooling on the shell. Twenty-three were made with no cooling on the shell. Some sticking was indicated after the first 20 cycles of operation. No seal lubricant was used for these tests. Pressures of 30 microns mercury absolute were obtained, with a leakup rate of 3 microns per minute. The rotating-shaft seal gave no indication of leakage even after the 100 cycles were completed.

The maximum temperature obtained from thermocouples placed 4 in. from the inner surface of the top section was 150°C. This gave an indication of the effectiveness of the thermal radiation shields and the crucible cover during operation of the furnace. The heat energy dissipated to the cooling water during the checkout operations supported the data obtained from the thermocouples inside the vacuum shell. The percentage of the energy input dissipated through each section is tabulated in Table IV and plotted in Figure 25.

TABLE III

MELTING AND CASTING DATA

Test No.	Weight Of Charge (lb)	Total Energy Input (kwh)	Energy Input (kwh/lb)	Total Cycle Time (min)	Time to Melt Fusible Plug (min)	No. of Melts Made With Susceptor	No. of Melts Made With Shield	Remarks
2	25.5	19.6	0.77	43	10	2	-	Insufficient superheat to pour with pouring coil
3	25.0	15.2	0.62	30	4	1	1	
6	25.0	23.7	0.95	51	-	2	1	Fusible plug melted out without pouring coil
7	24.0	23.2	0.97	52	5	1	1	Centrifugal cast - 400 rpm
8	27.0	19.7	0.73	46	3	2	1	
9	26.5	20.2	0.77	48	-	3	2	Fusible plug melted out without use of pouring coil
11	25.0	25.2	1.01	58	4	3	2	Used longer fusible plug and Mod II Susceptor
12	23.3	25.0	1.09	58	3	1	3	
13	28.5	25.0	0.89	70	10	2	1	Corona discharge occurred Induction coil grounded
14	22.8	23.0	1.01	50	4	1	1	Centrifugal cast - 140 rpm
15	28.5	22.0	0.79	50	6	2	2	
16	25.25	18.5	0.73	44	-	3	3	Severe outgassing of charge Excessive splatter Fusible plug melted without use of coil
17	22.25	21.5	0.97	49	4	4	1	
18	24.25	22.0	0.91	50	4	1	2	
19	26.25	23.0	0.88	52	4	2	3	
20	22.0	19.8	0.90	45	4	3	4	
21	24.25	22.0	0.91	50	3	4	5	Centrifugal cast - 250 rpm Operated remotely
22	23.0	22.6	0.98	48	3	5	6	Centrifugal cast - 150 rpm Operated remotely
24	22.75	21.5	0.94	49	3	1	1	Centrifugal cast - 150 rpm No water cooling on furnace
25	25.0	23.2	0.95	52	2	2	2	
29	22.5	25.0	1.11	56	4	2	3	Used Mod II susceptor Centrifugal cast - 140 rpm
34	21.75	28.0	1.28	60	3	1	8	Centrifugal cast - 140 rpm
38	23.25	25.0	1.08	54	3	2	12	Centrifugal cast - 140 rpm
39	22.75	25.1	1.1	52	3	2	13	Centrifugal cast - 140 rpm
40	22.5	25.1	1.11	52	3	3	1	Centrifugal cast - 140 rpm
42	23.75	25.1	1.05	52	3	5	3	Centrifugal cast - 140 rpm

NOTE:
Test No. 1 and 23 were not completed because of grounded induction circuit indications.
Test No. 4 and 5 were made to make a comparison of temperature measuring equipment.
Test No. 10 was made to test new stainless steel radiation shield configuration.
Test No. 26, 27, 28, 30, 35, 36, 37, and 41 were made to melt and shape charge and fusible plug for Mod III susceptor.
Test No. 31 and 32 were discontinued because of cracked susceptors.
Test No. 33 was made to check new susceptor for thermal damage and for possible cracks.

TABLE IV

ENERGY TRANSFER TABLE

	Average Energy Distribution at Various Values of Power Input		
	15 kw	25 kw	30 kw
Losses to Furnace Components (%)*			
Top Section	3.9	5.5	6.0
Center Section	3.35	3.87	4.28
Bottom Section	6.07	3.89	2.69
Melting Coil	19.1	22.2	26.7
Pouring Coil	5.4	4.3	4.2
Energy To Charge (%)†	-	-	13.6
Energy Accountable (%)	-	-	57.0
Energy Unaccountable (%)	-	-	43.0

* $Q = MC_p\Delta T$ (for each coolant channel)
† $Q = MC_p\Delta T$ (for 23 lb Cu-Ni 70-30 w/o charge and a temperature increase from 68 to 2140°F)

Where

M = weight of water or charge (lb)
C_p = specific heat (Btu/lb-°F)
ΔT = temperature change (°F)

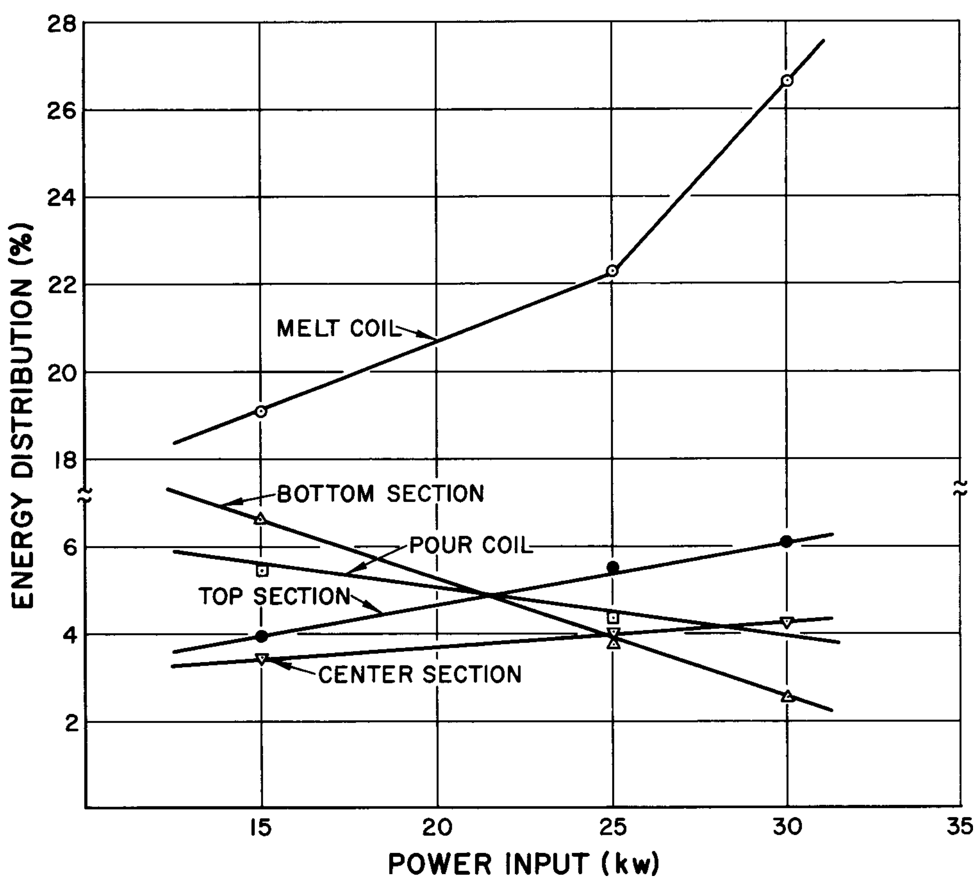

Figure 25. Heat Transfer Curves

V. DISCUSSION OF THE RESULTS

A. EQUIPMENT HANDLING

The reliability and capacity of the in-cell crane, compared to mechanical manipulators for handling of the furnace components, dictated that maximum use be made of this piece of equipment over all others. Other types of handling equipment must therefore perform the role of secondary or auxiliary equipment. The design or development of operations, either process or routine maintenance, will be based on the characteristics or limitations of the in-cell crane. The characteristics of the crane thereby become important to the over-all performance of the cell operations.

The sensitivity of control of the crane, and the design of the remote operation feature of the furnace components (i. e., guide, guide pins, and matching or interlocking parts), should be coordinated to obtain the best combination. Control should be sensitive enough in all directions to give responses to movement that are less than those required to match the furnace components. If guide pins are used to match two components, the maximum misalignment which can be compenstaed by the guide pins should be greater than the smallest incremental movements of the crane.

Suspension of the crane hook, and the components of the furnace on the crane hook, became factors which affected the over-all operation of the vacuum furnace. The actions of the hook during normal nonremote operation present no difficulty because of the proximity of the operator. The hook can be engaged by hand, if necessary. The condition that exists within the cell under remote operation precludes this solution. A misalignment of an inch or less between the hook and a bail, due to rotation of the hook, requires that the crane be moved before engagement can be made. To obtain an orientation of ±1 in. with the crane hook, prior to engagement with the bails, using the remote viewing equipment, was demanding of the operator's depth perception.

The rate of travel of the crane affected the operation of the furnace. A horizontal rate of travel below 4 fpm wasted time, while a rate above 10 fpm caused excessive pendulum action of the component on the hook. This resulted in more time wasted waiting for the hook or component to stop swinging.

A vertical rate of travel of 9 fpm permitted satisfactory placement of furnace components. Since the distance traveled in the vertical direction is short, little time can be conserved by an increase of this rate. Damage to furnace components or misfitting, as a result of the increased rate of travel, offset the advantage gained by the small amount of time that was gained.

The location of the special handling equipment (i. e., yokes and grapples) relative to that of the furnace components, and the number required, affected the remote operation. An effort was made to reduce the number of yokes required for handling furnace components. However, because of the geometry of the furnace shell and the location of bails, only a few could be combined. A more critical analysis of the special handling equipment, prior to the fabrication of the furnace, would have reduced the number required from 5 to 2 items. This could have been done by locating the bails on each component to be handled to correspond with the geometry selected for the handling device. This reduction would eliminate the travel of the crane through the cell complex for the single purpose of obtaining another yoke. Also, the racks and space required for the storage of the handling devices would be reduced, which would allow more space between process components or reduce the over-all length of the cell.

The furnace was operated remotely without the use of the viewing window. The television camera and the periscope were used throughout this operation. The time required for completion of the operating cycle was reduced during this program. A simplification of the guides and guide pins, and improved operating techniques, obtained by additional operating experience and operating equipment, were the contributing factors for the reduction of the cycle time. The advantages of viewing from more than one position were revealed during the operation without the use of the window.

B. PROCESS CHARACTERISTICS

The fusible plug, having a length of 1-1/2 in. and a diameter of the pouring hole of 1 in., used for the checkout tests did not give reliable control over the pouring cycle. Before the metal could be heated to the desired superheat, erosion and melting of the plug occurred. The location of the shorter plug, at the base of the crucible, did not permit sufficient heat transfer to keep the plug solidified. Because the pouring hole was the same diameter as the shank of the plug, as the top portion of the plug became molten, the plug slipped out of the spout. A reduction in diameter of the pouring hole below the bottom surface of the plug prevented the plug from sliding out and increased the time before pouring occurred.[4]

The amount of time for the initiation and completion of the pour into the centrifugal mold did not indicate a need for an enlarged pouring hole. The residual metal which was left clinging to the surfaces of the mold was in excess of that reported by other investigators.[4] Complete elimination of the metal which becomes attached to the diffuser seems unlikely. The amount of metallic uranium that solidifies and remains attached to the diffuser may be reduced by increasing the superheat given to the charge, prior to pouring. The increase of superheat would give a longer period of time before the molten metal in contact with the cold surfaces of the diffuser became solidified. Because of the longer period of time, more of the charge would reach the mold cavity before solidification. Surface quality of the cast slugs would be improved in a similar manner.

The method and control of the melting and pouring of the charge in the graphite crucible, by establishing power input for a given period of time, would be advisable for the in-cell furnace operation.

The limited cycle life of the crucible and pouring spouts was caused by the excessive slag and severe splattering which occurred during the first melting of the oxide drossing ingot. Several crucibles were broken because of expansion of the charge during heatup. Similar trouble would not be encountered during melting and casting of the uranium charge because of the change in geometry of the ingot. The ingot geometry for the uranium charge is shown by Figure 14. The work of other investigators indicated that longer cycle life can be expected.[7] Crucible fracture can be detected from the control console by the ground meter, which indicates metal in contact with the induction coils and by variation in power factor. Corrective action can be taken to prevent severe damage to internal components of the furnace.

The refractory liners that were used to insulate the graphite crucible from the water-cooled induction coils proved effective, and were easily removed and installed by the crane. A refractory liner to retain the molten charge, if crucible failure occurred, was demonstrated to be superior to a metal liner. The molten charge which became welded to the metal liner made complete disassembly of the coil box mandatory. For similar conditions, during operation with the refractory liner installed, the metal did not stick to the refractory and removal was easier.

Eliminating the water cooling for the furnace shells improved the remote handling of the furnace components. The additional operations that would be encountered, during remote connecting and disconnecting of the water service, would make maintenance operations more difficult. Possible elimination of water cooling of the induction coils has been discussed by other investigators.[3,13]

C. PROBLEMS REQUIRING FURTHER INVESTIGATION

Information on methods of melting and casting uranium metal has been reported by the investigators listed previously. The successful production of sound castings of various sizes indicated that the major problems related to the processing of irradiated material are those of remote operation and maintenance of the furnace with in-cell equipment.

1. Casting of a Uranium Charge

No uranium was melted or cast in the PRE program because of the possibility of contaminating the adjacent equipment and operating area. The melting and casting of uranium were simulated with a copper-nickel alloy. However, melting and casting of uranium itself is necessary, to develop operating information applicable to the PRE hot cell operation.

The energy required to heat the uranium charge to pouring temperatures can be estimated from data collected by other investigators. However, it cannot be calculated accurately enough to determine the control required for remote operation of a particular furnace. The variations in geometry of the susceptor, induction coils, thermal insulation shields, and the electrical circuitry of the induction system govern the operating cycle of each furnace configuration enough to require that melts and pours be made with cold material, before operation with hot material in-cell would be advisable.

A centrifugal mold which would form cast slugs of reactor quality, and would incorporate the requirements of remote stripping and mold preparation for the uranium metal, was not investigated. Information on mold design and mold treatment indicates that slugs of reactor quality can be produced without difficulty by centrifugal casting. The tasks associated with remote handling of the irradiated slugs and the components of the mold by in-cell equipment should be demonstrated with cold material prior to installation and operation within the process cell.

2. Remote Decontamination and Maintenance

The tasks associated with remote decontamination of the furnace shells and components were not performed. The normal buildup of the more volatile materials on the inner surfaces of the vacuum shells would require periodic attention within the process cells. The geometry which seemed most suitable, from the viewpoint of remote decontamination or routine housekeeping, was adopted in the conceptual design of the in-cell furnace. The optimum geometry for ease of remote decontamination and operation should be investigated.

In the PRE concept of remote maintenance, a defective component is removed by means of the crane, manipulator, and impact wrenches; and is replaced with a spare which permits continuation of the process. The maintenance tasks which could be performed on the defective component, to restore it to usefulness, have not been investigated. The PRE maintenance cell, for inspection and repair of malfunctioning and repairable items, would contain handling equipment with more manipulative dexterity than would be necessary in the process cell. The decision to repair a component would be based on a study of the economics of repair or safe disposal.

VI. CONCEPTUAL DESIGN OF THE VACUUM CASTING FURNACE FOR THE PRE FACILITY

A. GENERAL

From the information gained by this investigation, a conceptual design of the in-cell furnace is proposed. The design attempts to solve the remote handling problems associated with maintenance of the components of the furnace. The components which were demonstrated to be remotely maintainable in this investigation have been modified to improve this property. The components which could not be handled or maintained during the investigation are redesigned for remote handling, based on the experience gained by in-cell operation of the original furnace.

The concept used throughout the design was that each major component of the furnace should be removable with the crane. Because some of the components are located in positions inaccessible to the crane (i. e., under the furnace shell, below the drive motors, or behind the furnace), alternate methods of approach were devised. An alternate method would permit removal of components or groups of components until the item to be serviced could be lifted by the crane hook. Several different approaches to the maintenance of each component would thus be possible. Failure of one method of removal would make alternate approaches necessary.

B. FURNACE DESCRIPTION

An assembled conceptual view of the furnace is shown by Figure 26. An exploded view is shown in Figure 27. The top section is free of any external viewing ports, wipers, actuation mechanisms, or cover ports. Lifting bails are provided for transportation about the cell. The flanges and vacuum seals are similar to the mockup furnace. The height of the top section was increased to permit elevation of the induction coils, crucible, and pouring spout. With the top section removed, the increased elevation permits direct viewing of these components.

The radiation shield is mounted to a fixed support which is attached to the top section of the furnace. When the top section of the furnace is installed, the shield is properly located, relative to the crucible. Because of the splatter and collection of solidified material, some maintenance of the radiation shield will

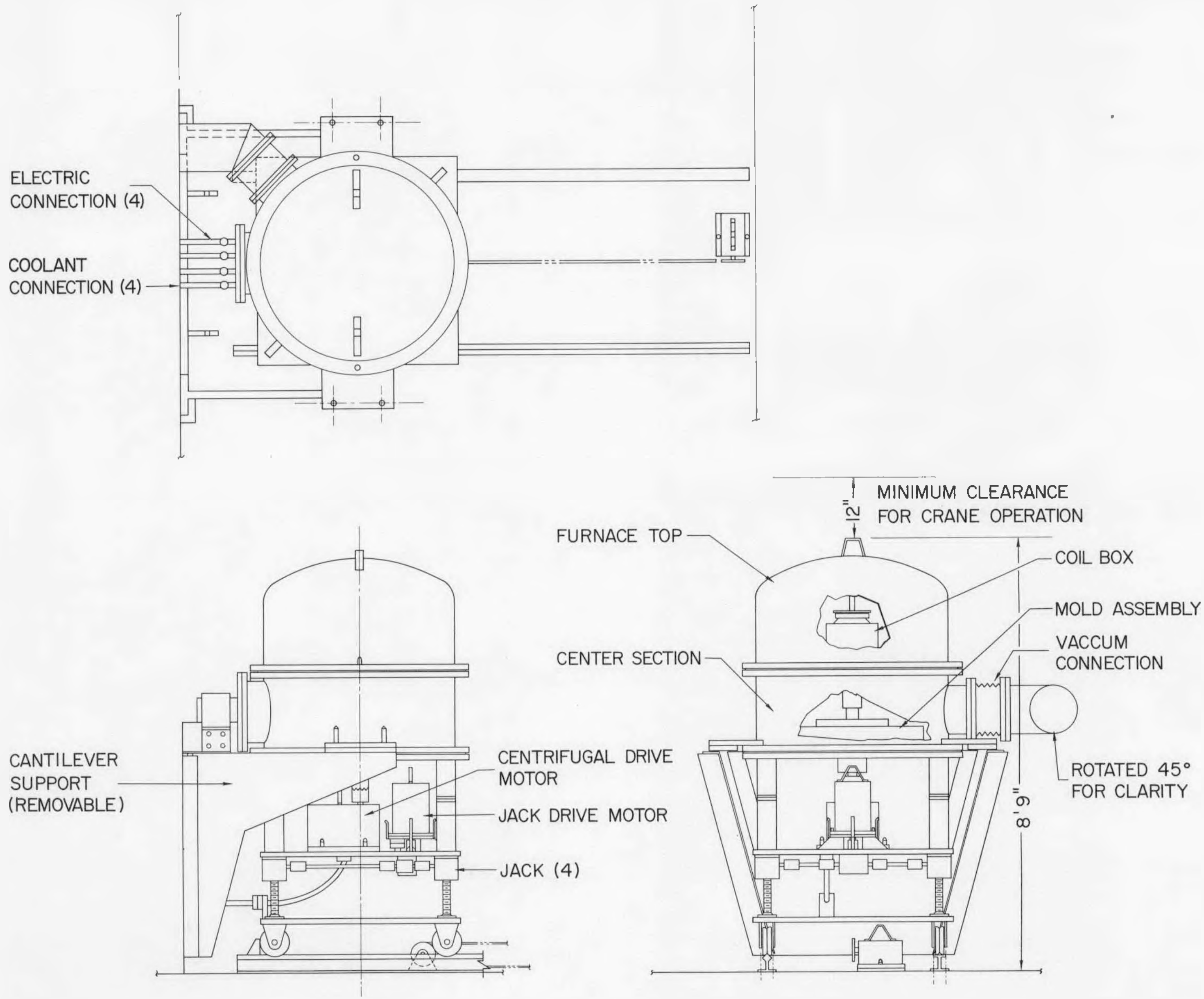

Figure 26. Conceptual Design of PRE In-Cell Vacuum Casting Furnace - Assembly

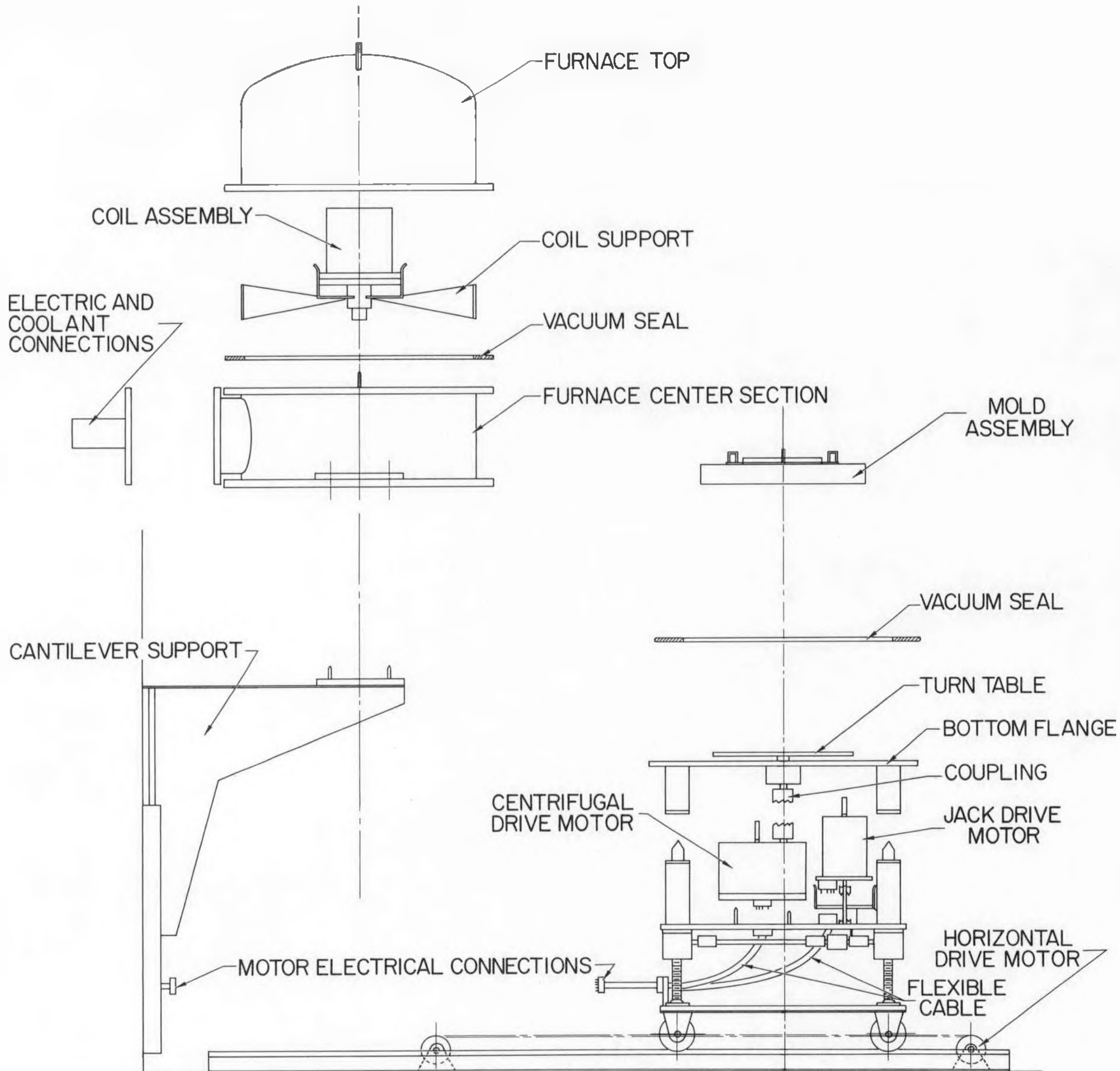

Figure 27. Conceptual Design of PRE In-Cell Vacuum Casting Furnace - Exploded View

be required. In-cell maintenance would dictate that the shield be designed for removal and replacement with remote equipment.

The interior surfaces of the top, middle, and bottom sections were designed free of small cracks or cavities which might result from noncontinuous welds or attachment of support brackets by bolt fasteners. Removal of particulate matter or condensed vapors from the molten charge during remote decontamination or routine housekeeping would be simplified by making all parts of the shell interior as accessible as possible.

The support designed for the center section was a cantilevered structure, attached to the cell walls by a slotted and tapered plate. The plate, which would be fixed to the cell wall by large screw fasteners, could be detached when it was necessary to remove all in-cell components. The plate was designed for removal and replacement by the crane. The cantilevered structure was designed to be removed by the crane, after removal of the center section.

Brackets, extending outward from the center section, rest on the cantilevered supports shown in Figures 26 and 27. The brackets were designed to align the furnace center section to the supports. Tapered pins on the section mate with holes drilled through the brackets. The brackets would provide the main support for the center section, internal components, and the top section.

The center section, shown in Figure 28, was designed with two large flanges which matched the large seals and flanges of the top and bottom sections. The large upper flange contains two aligning pins of different lengths, for location of the vacuum seal and top section. The induction coil, refractory liner, susceptor or crucible, charge, and pouring spout are supported by brackets attached to the inner surface of the shell by tapered slots. The brackets were designed for removal by the crane.

Ports for electrical connections and vacuum piping are included in the design of the center section. The high frequency bus, which protrudes from the cell wall through the utility service fixture, is connected to the power port by clamps operated by an impact wrench. These clamps are shown in Figure 4. A similar set of connections inside the furnace shell was designed to permit removal and replacement of the induction coils without removal of the insulated power port

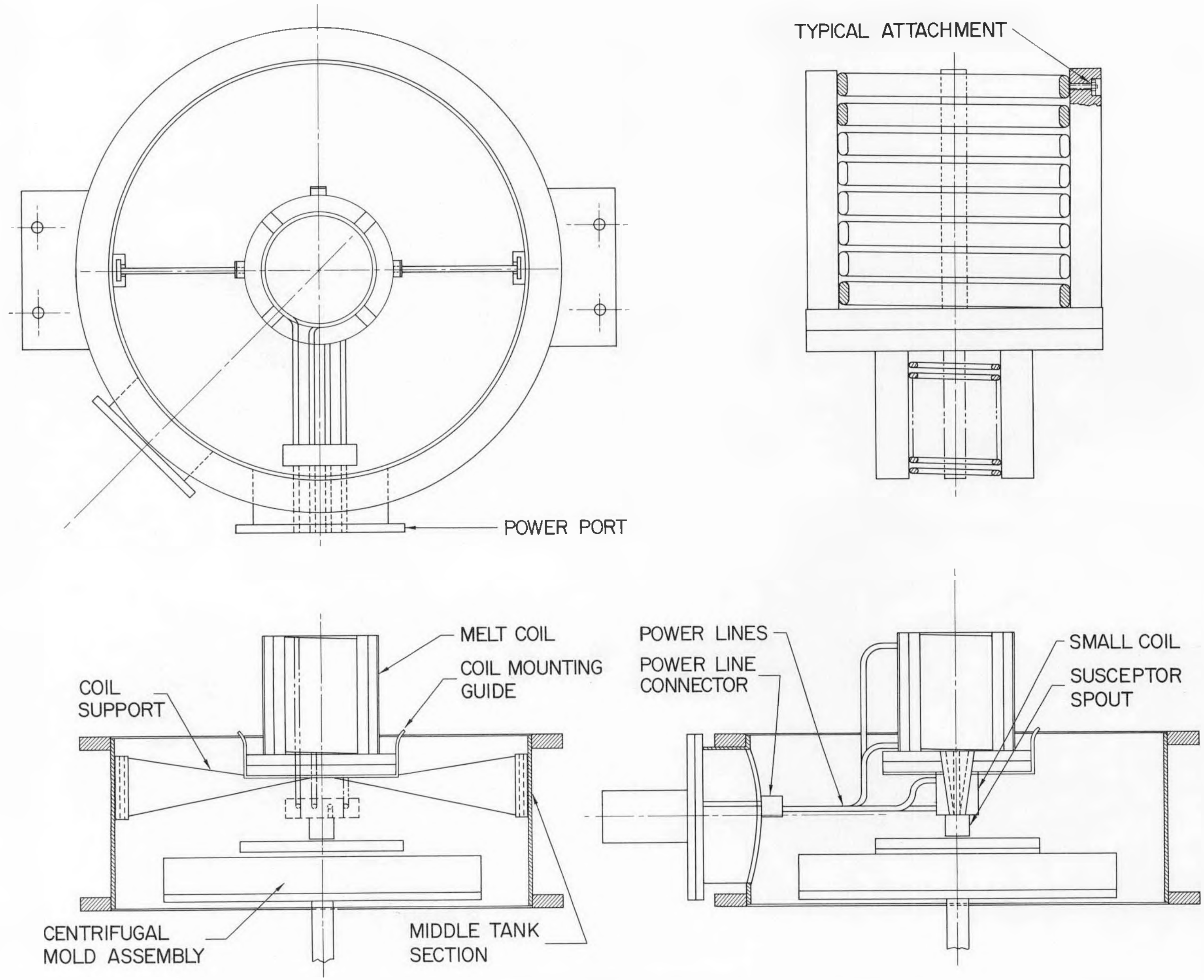

Figure 28. Conceptual Design of PRE In-Cell Vacuum Casting Furnace - Center Section

flange. The power port flange is sealed in place by crane-actuated clamps. The vacuum piping is connected to the center section by the crane-operated vacuum manifold flexible connector shown by Figure 29. The piping connection leading out of the cell to the pumping and filtering equipment is of similar design.

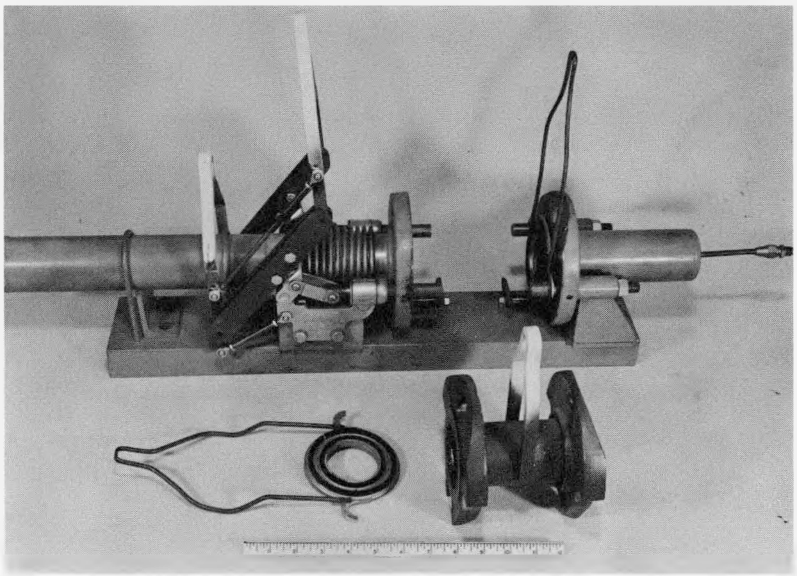

Figure 29. Vacuum Manifold Flexible Connector

Water cooling to the induction coils is carried through the electrical conductor to the connection outside the furnace shell. From the connectors, a utility jumper pipes the water to the utility fixture. However, the use of solid, uncooled coils would eliminate this equipment. Water cooling of the furnace shells was eliminated by information obtained from this investigation.

The bottom flange of the furnace is supported by a lifting dolly, shown in Figure 27, which rolls from beneath the center section on two rails secured to the cell floor. The drive motor and mechanisms that position the lifting dolly for removing and replacing the mold are located between the rails and are secured by aligning pins attached to the cell floor.

The lifting dolly contains the centrifugal drive motor and coupling, the jack drive motor, the rotating vacuum seal attached to the bottom flange, and the turntable on which the centrifugal mold is placed. The bottom flange is a reinforced flat plate that improves the line-of-sight viewing of the mold centrifuge,

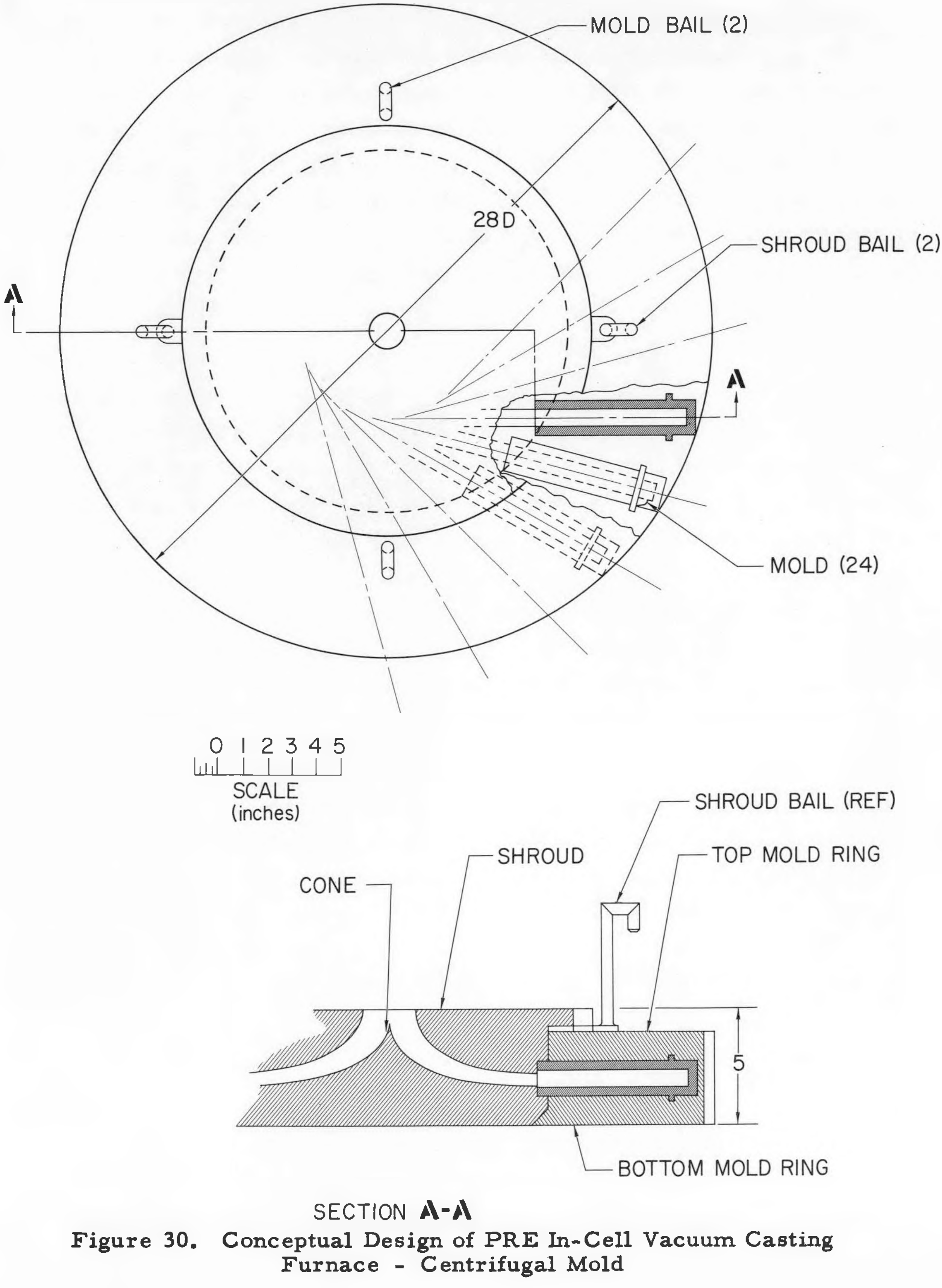

Figure 30. Conceptual Design of PRE In-Cell Vacuum Casting Furnace - Centrifugal Mold

during installation on the mounting plate. By eliminating the dished lower section, the removal of particulate matter by remote equipment is simplified. Because the life of the rotating seal is limited, removal and replacement of the seal would be performed in the maintenance cell, by equipment having more dexterity than the process cell crane. The bottom flange, turntable, and rotating seal are removed or replaced, as a subassembly, with the crane. The conceptual separation of these units from the lifting dolly and the centrifuge drive shaft is shown in Figure 27. The conceptual centrifugal mold assembly is shown in Figure 30. Remote assembly and disassembly techniques for the centrifugal mold require further development.

The lifting dolly may be removed as an assembled item, or may be broken down into components for removal from the process cell. The centrifugal drive motor and the jack drive motor can be removed from the lifting dolly and replaced separately. The electrical connections are designed so that lifting a motor disconnects it. Replacing the motor remakes the electrical connection. Aligning pins provide the correct matching of the electrical and mechanical connections that is required. The electrical supply and control circuits to the motors are made through pins on the motors and sockets on the movable dolly. Similar connectors would be used to complete the circuits from the dolly to the utility service port on the face of the cell structure.

Lateral movement of the lower section, in and out of position under the middle section of the furnace, is accomplished by a drive motor and chain linkage. The chain linkage and drive motor were designed as a unit, to be removed or replaced with the crane. Electrical circuit connections are similar to those for the drive motors of the lifting mechanism and centrifuge. The lateral movement motor and chain drive the movable dolly, by contact with a pawl attached to the chain. No fasteners are used to secure the dolly to the chain drive mechanism. This would simplify removal and replacement of the dolly on the guide rails. The conceptual design of the installation is shown by Figure 27.

Correct positioning of the bottom flange under the middle section is obtained by limit switches installed on the chain linkage and drive motor assembly.

Correct location of the chain linkage and drive motor assembly on the cell floor between the rails is established by guide pins and matching sleeves.

C. REMOTE MAINTENANCE

1. Radiation Effects on Furnace Materials

The remote operation of the furnace to process irradiated metallic fuels is mandatory because of the intensity of the radiation present in the fuel. Adequate shielding is provided to reduce the intensity of the radiation to tolerable limits for the operating personnel outside the cell, but it is impractical to consider in-cell shielding to attenuate radiation by local in-cell shielding to levels which would not cause damage to the various components of the furnace.

From calculations made on radiation intensities expected from a 50 kg processed ingot, as viewed sideways along the perpendicular midplate, after 300 days in pile operation at 20 Mw, the intensities were shown to vary from 3×10^4 r/hr, at a distance of 2 in. for a 10-day cooling period, to 1.5×10^3 r/hr, at a distance of 24 in.

The damage to organic materials, as a result of exposure to this radiation source, may be predicted. From information obtained on damage to elastomers, a 25% damage was indicated for a dosage of 2.6×10^7 roentgens.[15]

For the design geometry of the vacuum casting furnace, a damage of 25% would result to the unshielded elastomer seal in a field of 3.6×10^3 r/hr, at a distance of 12 in., after 300 days of exposure. Because the seals are shielded by the adjacent copper conductor and connectors, extended life may be expected in the PRE hot facility. Replacement of the seals because of damage in normal operation would seem to be more probable than replacement due to radiation damage.

Radioactive damage to the seal coolant, in proximity to the processed ingot, would result after an exposure to the field for a period of 3000 days. The amount of damage expected for the low viscosity organic lubricant would be a 10 to 18% increase in the viscosity. Under normal operating conditions, the lubricant would be replaced prior to this time.

The damage to the steel structure would be insignificant and would not affect operation of the in-cell furnace.

2. Servicing of Components

The top section of the furnace is designed for removal and replacement during routine operation with the in-cell crane. The maintenance of this part of the furnace would be associated with removal and replacement of the radiation shield. One design option would be to support the radiation shield from a blind flange, which would be placed over a port located on the center of the top section. To maintain a vacuum seal, a flange seal and fasteners would be required. Removal of the blind flange, with the radiation shield attached, could be accomplished with the in-cell crane.

The center section of the furnace and the internal components are designed for removal and replacement with the in-cell crane. The crucible and the grapple used for servicing are similar in design and operation to those used during the mockup program. The refractory shields are serviced in a manner similar to the mockup components. The melting and pouring coils are serviced independently. This feature requires the installation of an additional connector, but will permit more flexibility during servicing operations. The same yoke that will be used for the top section, large vacuum seals, center section, and mold centrifuge will be used for the induction coils.

If removal of all components within the furnace center section should be required, the support brackets for the crucible and induction coils may be removed, after the crucible and induction coils have been removed. The complete removal of all components within the center section would permit removal of the mold centrifuge without removal of the bottom section. The possibility that this method would be used for removal of the mold centrifuge is highly unlikely. However, the design does permit it, if needed.

The vacuum manifold connections are made by the in-cell crane, with the aid of a flexible connector shown in Figure 29. This connector has a lever and cam locking mechanism which is attached to an expandable or flexible pipe section. It can be placed between two rigid pipe sections by the in-cell crane. Once in position, the connector can be expanded until a vacuum seal is made.

The flange seals, which are located between the rigid pipe section and the expandable connector, can be serviced with the in-cell crane also. A similar manifold connection of smaller size, shown in Figure 28, has been remotely operated in the PRE mockup.[16]

The large vacuum manifold is designed for removal and replacement with the in-cell crane. Servicing with the in-cell crane is accomplished by locating and fixing the position of the manifold with guide pins attached to the cell connection and the furnace connection.

The induction coil connector, located outside the furnace, may be disconnected by the in-cell crane to permit removal of the assembled or disassembled center section. After the connectors to the vacuum manifold and induction circuits have been broken, the center section may be lifted from the cantilevered support brackets. Guide pins attached to the support brackets insure correct placement during servicing operations. The removal of the complete center section will permit disassembly of the lower section, if some unforeseen malfunction should occur which would make operation of the lifting and lateral movement mechanism impossible. With this flexibility of design, the lower section may be serviced in all positions that may be encountered by the in-cell crane. For additional convenience in servicing, the large support brackets may also be removed by the in-cell crane.

VII. CONCLUSIONS AND RECOMMENDATIONS

A. COMPONENT HANDLING

The in-cell crane should be considered the primary piece of equipment used for transporting, lifting, and operating functions within the process cell. The rate of travel, control sensitivity, and suspension characteristics of the crane influenced the remote operation of the furnace. Design of in-cell process equipment should be coordinated with that of the in-cell handling equipment.

Remote removal and replacement of furnace components were performed successfully with the crane. The conceptual design of the in-cell process furnace includes the modifications which were revealed by the operations that have been completed.

Special handling devices were needed to transport the furnace components. The number of devices required could be reduced by designing each device for use in more than one operation. The components of the furnace should be designed with the same concepts for handling. Fewer operations will be required of the crane by the reduction of the devices used in-cell, and more space will be available for other equipment.

The location of the lighting and viewing equipment should be established from the operational requirements of the in-cell equipment. A light installation directly above the furnace was ineffective because of interference by the crane, during removal and replacement of the furnace components.

The location of the periscope in front of the furnace, with the in-cell vantage point on a horizontal plane above the top of the center section, was most effective. The most suitable location for the shielded window would be adjacent to the furnace, but not directly in front of it. The television camera should be located above the uppermost component of the furnace, and on the centerline of the cell. The distance from the furnace to the television camera should permit good resolution of guide pins, bails, yokes, and grapples. Viewing of the crane, by the television camera, during transfer of furnace components throughout the cell, should be possible.

B. PROCESS CHARACTERISTICS

The fusible plug method of valving the molten metal from the crucible into the centrifugal mold was demonstrated successfully. The pouring control, which depended on the successful cooling and melting of the fusible plug, was sufficient to permit degassing, enrichment, and mixing operations to be performed in the process cell. The energy input to the furnace, and subsequently to the charge, was programmed to give the desired amount of superheat to the molten charge before casting. Temperature instrumentation to the molten charge was not required.

Water cooling of the vacuum shells was eliminated. The natural rubber elastomer seals, which were bonded to the stainless steel rings for remote handling, were not affected by the elimination of the water cooling to the furnace shells. Temperatures of 150°C were recorded in the vicinity of the seals during operation of the furnace.

The damage to the vacuum seals and rotating seal coolant, by the radiation field associated with the processing of the irradiated fuel, would not be sufficient to alter their effectiveness.

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