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EQUIPMENT FOR REMOTE INJECTION CASTING OF EBR-II FUEL*

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An injection casting process has been developed at ANL for the remote fabrication of EBR-II fuel pins. Over 16,000 castings have been made for the first core loading in a prototype furnace. Experience and knowledge from this production run has been used in the design of a furnace for the Fuel Cycle Facility in Idaho.

I. INTRODUCTION

Injection casting[1] is the method selected for the production of EBR-II fuel pins. This process has developed into a remote operation which is capable of producing precision castings with a random grain orientation. Injection casting uses pressurized gas to force molten metal into precision-bore, glass molds in the following way.

1. A shallow crucible of metal is melted in an evacuated furnace.
2. Tubular molds with top ends closed are employed. These molds are suspended vertically over the crucible with the open ends pointed toward the metal bath.
3. At a predetermined superheat, the crucible is raised, immersing the open tips into the metal bath.
4. The furnace is pressurized and differential pressure across the mold wall forces metal into the cavity.
5. When the metal has solidified, the crucible is lowered.

* Work performed under the auspices of the U.S. Atomic Energy Commission.

Two furnaces were designed and constructed during the development program to determine casting variables and handling techniques. The Model I furnace was used to prove the feasibility of injection casting, while the Model II furnace was a full scale pilot furnace used to cast 16,000 pins for EBR-II, Core I. A Model III furnace was designed for remote operation in the Fuel Cycle Facility (FCF) in Idaho.

II. FEASIBILITY OF INJECTION CASTING

The feasibility of injection casting was developed in a small, water-cooled furnace. As experimental equipment, its primary purpose was to explore and define various casting variables; e.g., casting temperature and pressure, pressurizing rate, molds, mold coating, etc. All remote handling features were intentionally left for later designs.

Molds

Vycor* glass was selected as the mold material because it is: (1) nonpermeable to pressurized gases, (2) resistant to severe thermal shocks, (3) commercially available in precision shape, and (4) dimensionally stable at high temperatures. Chemical reactivity with molten uranium, which may be prevented with a refractory protective coating, is the only property deleterious in application.

The precision-bore, EBR-II molds are made from Vycor tubes shrunk over a ground Hastalloy mandrel. One end is pinched closed to form a vacuum-tight seal. The excess Vycor at this end forms a flat rectangular shoulder which is used to vertically support the molds in a pallet.

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* Vycor is the trade name for high silica glasses from Corning Glass Works.

The open end is cut on a 30° angle to aid it in penetrating the dross on the molten metal bath.

The original mold specifications were: (1) bore diameter - 0.1475 ± 0.001"; (2) wall thickness - 0.040 ± 0.010"; (3) length - 17" ± 1/32"; and (4) warp - not to exceed 0.015" off center line of bore. Later, the length was increased to 18" and bore diameter was increased to 0.1480 ± 0.001". This was done to obtain better casting yields. The mold diameters were inspected with an air gage to ± 0.00005". The total rejection was less than 1 percent.

A coating is applied to the internal bore of each mold to prevent a metal-glass reaction. The most successful protective coating was 7-10 micron thoria in an alcohol suspension, but yttria and colloidal graphite were also used. The coating is applied by hand to the molds, using a swab-type applicator. A short length of 3 mm pipe cleaner, attached to a 1/8" diameter rod, is dipped into the slurry and inserted into the molds. After repeated application, the swab is removed with a smooth motion and the mold is inspected. The coating thickness and uniformity can be controlled by particle size and consistency of the mixture.

Although the coating is not bonded to the mold, only a small amount will flake loose during normal handling procedures. The large surface-to-volume ratio of the molds, however, does require a good drying operation to remove all vapors. This includes air drying for several hours and baking at 600°C from 4 to 6 hours.

Crucibles

Since the metal is not poured, the injection casting furnace uses a crucible of simple design (see Figure 1). Construction materials are limited, however, because the crucible is subjected to severe thermal and mechanical shocks. For this reason, graphite is used.

(Figure 1)

The crucible is a right cylinder with the internal wall and bottom tapered slightly to aid in removal of the metal heel left after casting. A protective coating on the graphite is necessary to minimize carbon contamination in the melt. A mixture of -300 mesh zirconia and thoria powders mixed with water was successfully used. This 5 w/o zirconia - 95 w/o thoria coating was applied by a spray gun and air dried before use.

Early Casting Results

The early casting experiments were divided into the three following groups to find relationships between casting variables and pin quality.

1. The temperature range for casting fissium alloy was examined while the pressure and pressure rate were kept relatively constant.
2. Various casting pressures were tested in the determined temperature zones.
3. Different pressurizing rates were explored over the other two regions.

The range of the casting conditions are given in Table I.

TABLE I

CASTING CONDITIONS - MODEL I FURNACE

	Temperature Range	Pressure Range*	Valve Opening**
Condition 1	1250 to 1400°C	75 psia	90°
Condition 2	1275 to 1350°C	25 to 75 psia	90°
Condition 3	1275 to 1350°C	25 to 75 psia	30 to 60°

* The pressures are given for the accumulator tank before casting. The furnace and tank volumes are nearly equal, so the final pressure is approximately 1/2 of the given value.

** The gas flow into the furnace is controlled by a 3/4" ball joint valve, which has an inscribed dial graduated in degrees. The valve opening gets larger as the indicator goes from 0° to 90°.

Condition 1 produced a maximum casting length of good quality in the temperature range between 1290°C and 1330°C. Above this range the total length was longer, but the castings had defective surfaces, especially, near the bottom. The castings from lower temperatures were usually too short. Almost all castings had some internal porosity, but this condition was particularly aggrevated at higher temperatures.

The most favorable results obtained by Condition 2 showed that lower casting pressures could be used. The length of good pins did not increase an appreciable amount, but the surface defects were reduced. The internal void now became the predominate defect. A combination of high temperature and pressure would produce almost a full length hollow casting.

When the third condition was also allowed to change, the variables were systematically varied and the results were compared with the other conditions. By this method the yield of acceptable castings were increased to approximately 90 percent. The furnace was used to produce several batches of test specimens with the condition maximized to varify results and the feasibility of injection casting.[2]

III. PROTOTYPE FURNACE

When the Model I furnace produced favorable results, the prototype furnace was designed and constructed. The basic design modifications were: (1) increased furnace capacity, (2) advanced fixtures and components for remote control operation, (3) installation of some radiation resistant materials, and (4) the elimination of water-cooled components.

Space was made available where the prototype, EBR-II equipment could be installed and tested. This facility included equipment to cast, process, inspect, jacket, bond, and assemble fuel elements. The casting furnace was installed on an elevated platform behind a carriage-mounted, hot-cell window to simulate cave conditions. Utility equipment - vacuum pumps, accumulator tank, power supply, etc. - was located underneath the platform. An overhead crane and General Mills manipulator were provided to operate and replace components.

Components

The prototype furnace is shown in Figure 2. The internal components are positioned and aligned with the furnace base in the following order: (1) crucible actuating cylinder, (2) furnace pan, (3) induction heater assembly, (4) crucible pedestal, and (5) mold support stand. Three hairpins are used to guide the bell over the internal components and onto the furnace base. An expandable metal ring clamps the bell and base together on an O-ring seal. A sight glass in the furnace bell provides a means for comparing metal temperature readings between an optical pyrometer and a crucible thermocouple. The casting capacity is approximately 6 times larger than the original 30 mold, Model I furnace.

(Figure 2)

A gas circulating system is installed with the prototype furnace to increase the solidification rate of cast pins. Previously, the gravid molds were cooled only by radiant heat loss. Elimination of the water-cooled bell and larger furnace capacity, however, made internal gas cooling necessary. The system uses a turboblower to circulate argon gas through the mold pallet after casting.

<u>Casting Conditions and Results</u>

Three different casting methods were used with the prototype furnace. The first method was similar to established conditions from the Model I furnace. At 1340°C the furnace was pressurized with the mold tips submerged in the superheated metal. After a 10 second delay the crucible metal was lowered and allowed to cool. When the gravid molds were removed for an inspection, metal was only found in the mold tops. This indicated that metal had filled the molds, but dripped out when the crucible was lowered too soon. To correct this problem, a series of melts were made using various casting temperatures and mold immersion times. The best conditions produced only a 68% yield of acceptable castings over 15-1/2" long. However, many of the rejected castings were near the acceptable length, so 18" molds were ordered. With this additional mold length, a yield of 76% was achieved.

The second method was approximately the same as the first except the gravid molds were cooled by circulating the casting gas over them. The gas was cooled and circulated by installing a heat exchanger and turboblower in a closed system with the furnace and accumulator tank. After the furnace was pressurized for casting, the gas was drawn through the system and directed toward the mold pallet. This provided enough cooling to increase casting yields to 80%.

The third casting method was used with the 18" molds. For this method an immersion thermocouple with a graphite protection tube was placed in the mold pallet to record metal temperatures. When the crucible was raised to submerge the molds, a high speed recorder traced the cooling curve of the metal. The crucible was held in the raised position until the liquidus arrest was observed (approximately 1080°C). Then, the crucible was lowered. By this method casting yields were increased to 83%. The last two casting methods are summarized in the following table.

TABLE II

CASTING PARAMETERS - MODEL II FURNACE

	17 inch molds	18 inch molds
Charge Weight (kg)	9 - 12	9 - 12
Casting Temperature (°C)	1300	1315
Initial Pressure (mmHg)	60 - 100	60 - 100
Pressurizing Rate (psi/sec)	10	10
Final Pressure (psia)	27	27
Timer #1* (sec)	4	5
Timer #2** (sec)	11	277
Crucible Retraction Temp (°C)	1250	1050
Pin Cooling (scfm)	30	0

* Indicates time delay between mold tip submersion and pressurizing of furnace.

** Indicates time delay between mold tip submersion and crucible retraction.

Approximately 16,000 normal and enriched uranium fuel pins were cast in the prototype furnace. Of these, 12,900 were inspected, processed, and jacketed for EBR-II service. The knowledge acquired from this production run was used to design the Model III furnace for hot-cell operation.

V. HOT CELL FURNACE

The injection casting furnace for remote operation (Figure 3) in the Fuel Cycle Facility is designed for sequential assembly with modular replacements. A straight, vertical motion with a manipulator or crane is used to fit or detach each subassembly. The furnace shell and internal components are convection cooled and designed so that any areas with seals will not go above 200°C during a normal cycle.

(Figure 3)

Furnace Shell

The furnace shell is comprised of a 26" diameter base and bell made from mild steel with an electroless , nickel protective coat. Two locating arms, extending from the base, position the furnace shell to cell feed thrus. Vacuum, pressure, and electrical bridges connect the base to separate service feed-thrus by metal freeze seals and braided copper cable. A porous metal filter in the vacuum bridge prevents fine radioactive dust from migrating through the pipe and feed-thrus into the subcell, vacuum-pressure system. Mineral insulated cable conducts current from the electrical bridge into the furnace chamber.

Three hairpin guides are used to position the bell over the internal components into the furnace base. The bell is sealed to the base by a liquid metal freeze seal. Four 3,000 watt heaters are used to melt the freeze seal. These resistance heaters are connected in a parallel circuit to prevent one or two burned out elements from disrupting furnace operation.

<u>Furnace Components</u>

The furnace base is designed for two induction spindles and a crucible actuator which are positioned by a pan and bushing plate. The induction spindles - 10^6 circular mil, mineral insulated cables - support the heater assembly and conduct current to it. The crucible actuator, a gas cylinder with cast iron piston rings, is used to provide a 12" vertical movement for lifting the crucible. The actuator is connected to a gas line by a metal freeze seal in the base bottom.

A pedestal on the actuator ram centers the crucible on zirconia insulation bricks in the induction heater assembly. A molybdenum sheath screws into the pedestal and extends through the insulation bricks into the crucible bottom. This tube protects a thermocouple used to record the crucible temperature. Two spike connectors between the thermocouple and lead wires furnish a disconnect for the moveable crucible thermocouple.

A molybdenum coil supplies induction current to the crucible. The coil is made from 3/8" diameter rod which has been wound to 7-1/2 turns with a 9" O.D. A reflector shield, coil spacers, and the coil fit into a lava form supported by re-enforced lava plates (see Figure 4). Four tie-rods through the plates fasten the assembly together. Two of these rods are used as handles for moving the assembly by manipulator.

(Figure 4)

Two counterbalanced doors attached to the top plate of the heater assembly reduce radiant heat losses from the crucible. The doors are hinged with counterweights to prevent them from damaging the assembly when the doors are opened by the rising crucible during casting.

The mold pallet is held suspended over the crucible in a pallet stand. The stand is constructed of two cylindrically shaped sections made from 1/8" stainless steel sheet. The upper section is shaped to accept a mold pallet. The bottom of this section is bolted to a larger cylinder, which is used as a hollow support column. The column fits around the induction heater assembly and rests on the furnace base.

A removable plate is bolted to the bell top on a copper-asbestos gasket. This plate is equipped with a lifting handle, mold heater brackets, and electrical receptacles. Resistance heaters for degassing and preheating the molds are attached to the plate brackets. Electrical connections to the heaters are made through the receptacles with ceramic insulated wires. Lead wires join to the receptacles by quick-disconnect fittings.

<u>Subcell Equipment</u>

Auxiliary equipment for the injection casting furnace is located in a subcell beneath the working area. Major items of equipment includes a heat exchanger, turboblower, accumulator tank, vacuum pumps, control valves, and monitoring instruments (see Figure 5). Because high level radiation is expected, the equipment is arranged for quick removal and replacement.

(Figure 5)

The induction power source is an exception. It is located in a space adjacent to the subcell where maintenance can be performed without risk of radiation to personnel. The source is a 10,000 cycle, 220 volt, motor-generator set, which is water cooled. Induction power is conducted to the furnace by 10^6 circular mil, mineral insulated cable.

The two vacuum pumps are individually shrouded to contain pump leakage. Cooling air is drawn through a filtered inlet across the pumps and piped to a ventilation system. The pump exhaust is filtered through a ceramic element to a suspect stack.

The pressure and circulation system for casting and cooling the fuel pins is also located in the subcell. An accumulator tank supplies the pressurized argon gas and contains the turboblower for circulating it. This two-stage blower is flanged to the tank for quick replacement. The compressed gas is cooled by a heat exchanger which is positioned up-stream from the tank unit. In the furnace the gas is channeled to flow up the outside of the pallet stand and down through it.

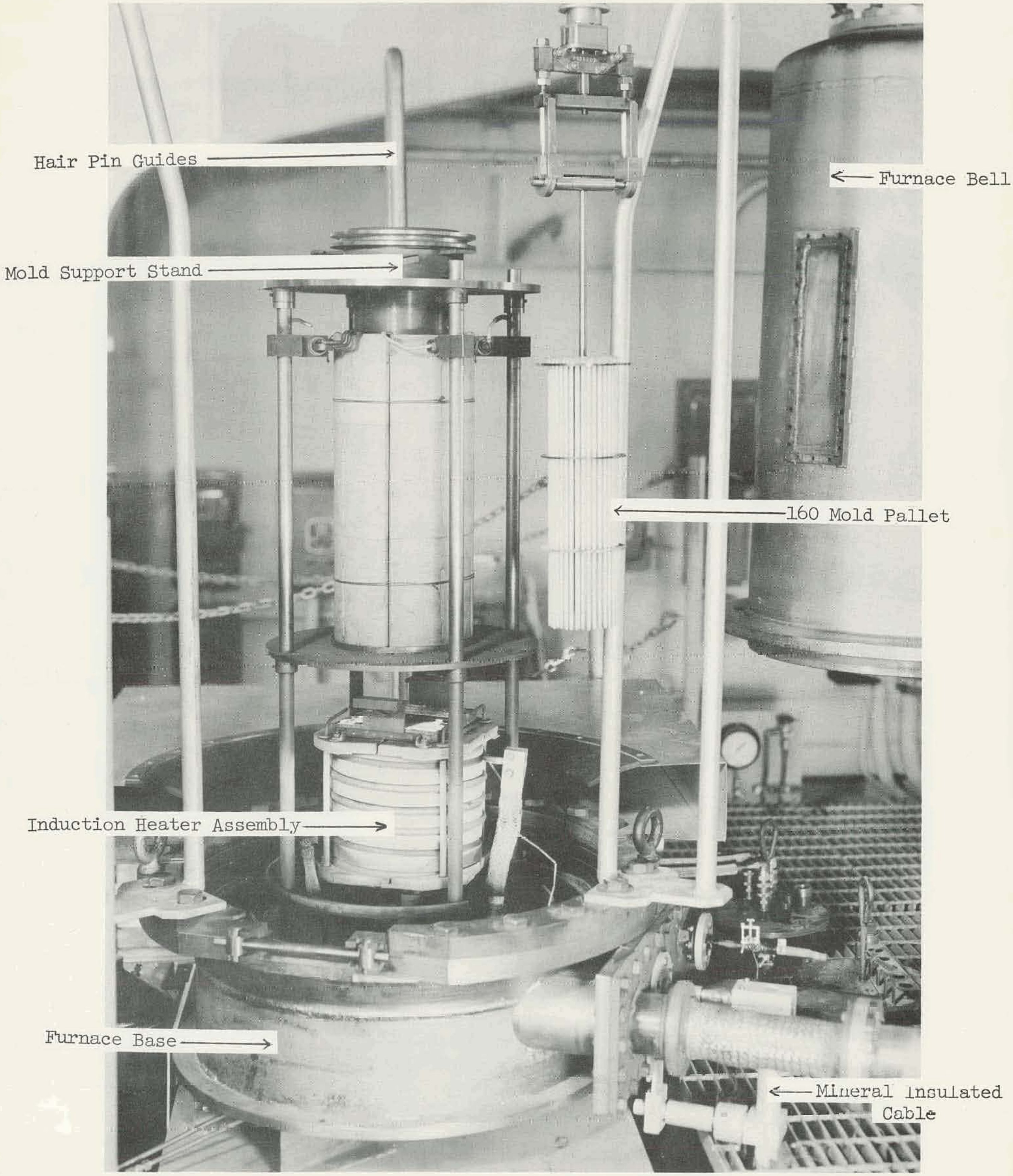
Ball joint valves with air cylinder actuators are used to regulate the pressure systems. Four-way, solenoid valves control the actuators while position indicators on the valve stems are used for visual assurance of correct performance.

REFERENCES

1. Shuck, A. B.; U.S. Patent No. 2952056 (Sept. 13, 1960)

2. Yaggee, F.L.; Ayer, J.E.; and Jelinek, H.F.; Injection Casting of Uranium-Fissium Pins, Nuclear Metallurgy (Vol. IV), Nov. 6, 1957 (IMD Special Report Series)

Figure 1. Thoria Coated Graphite Crucibles (6" O.D.) Neg. 106-3310



Neg. 106-4827

Figure 2. Prototype Casting Furnace

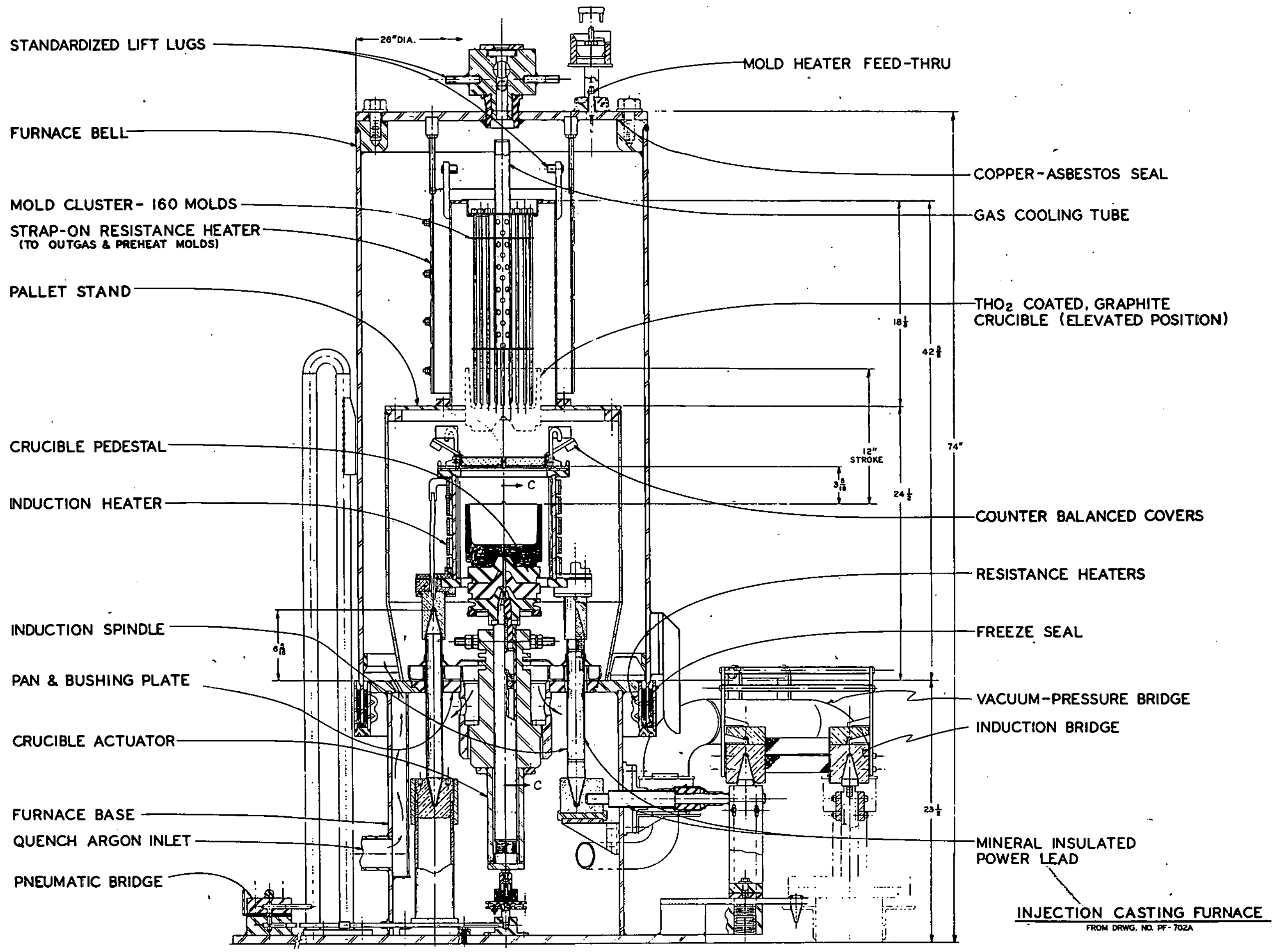


Figure 3. Hot Cell Furnace

Neg. 106-5743

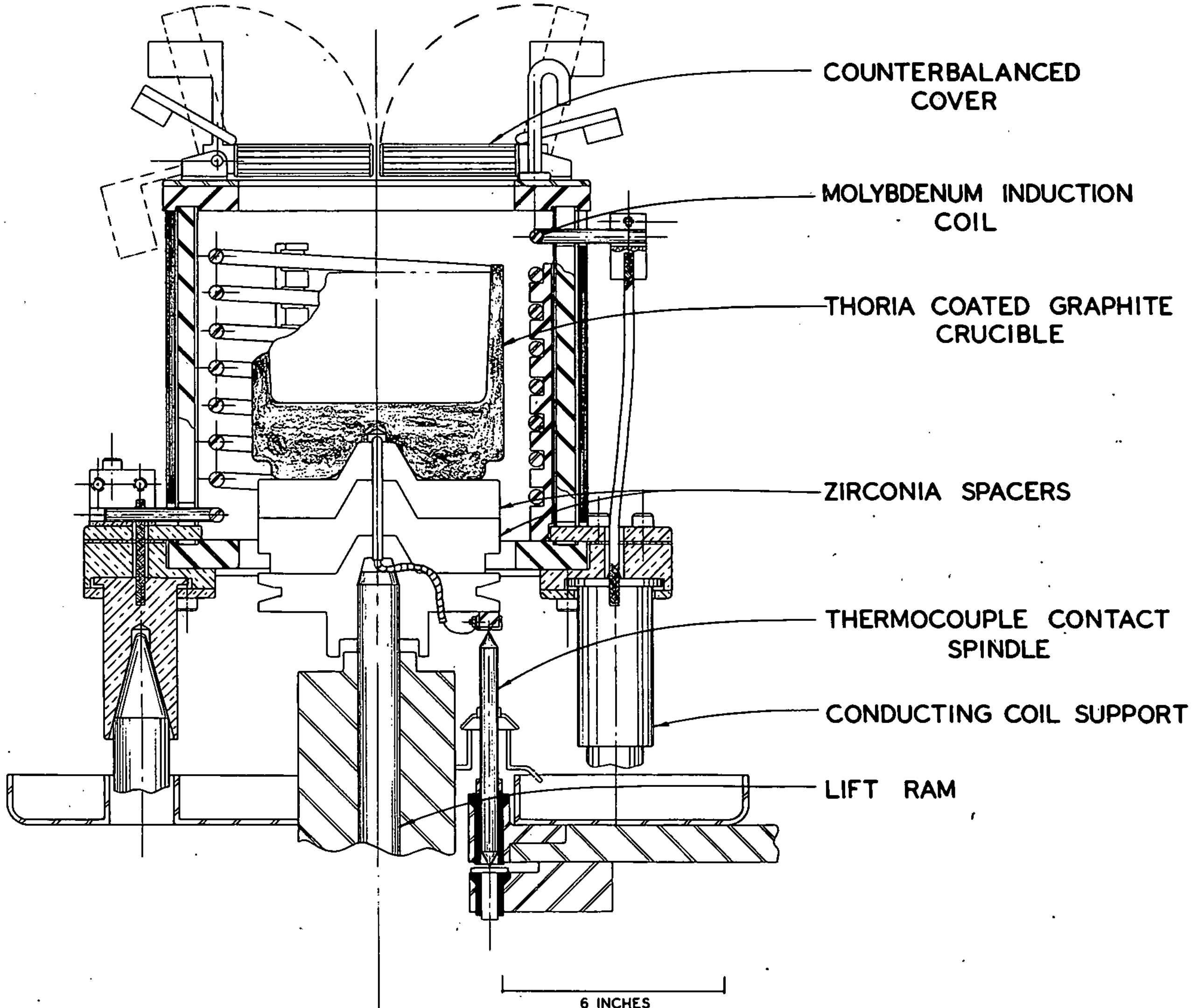


Figure 4.

MOLYBDENUM COIL INDUCTION MELTING ASSEMBLY.

FROM DRWG. NO. PF-111-134

Neg. 106-5444

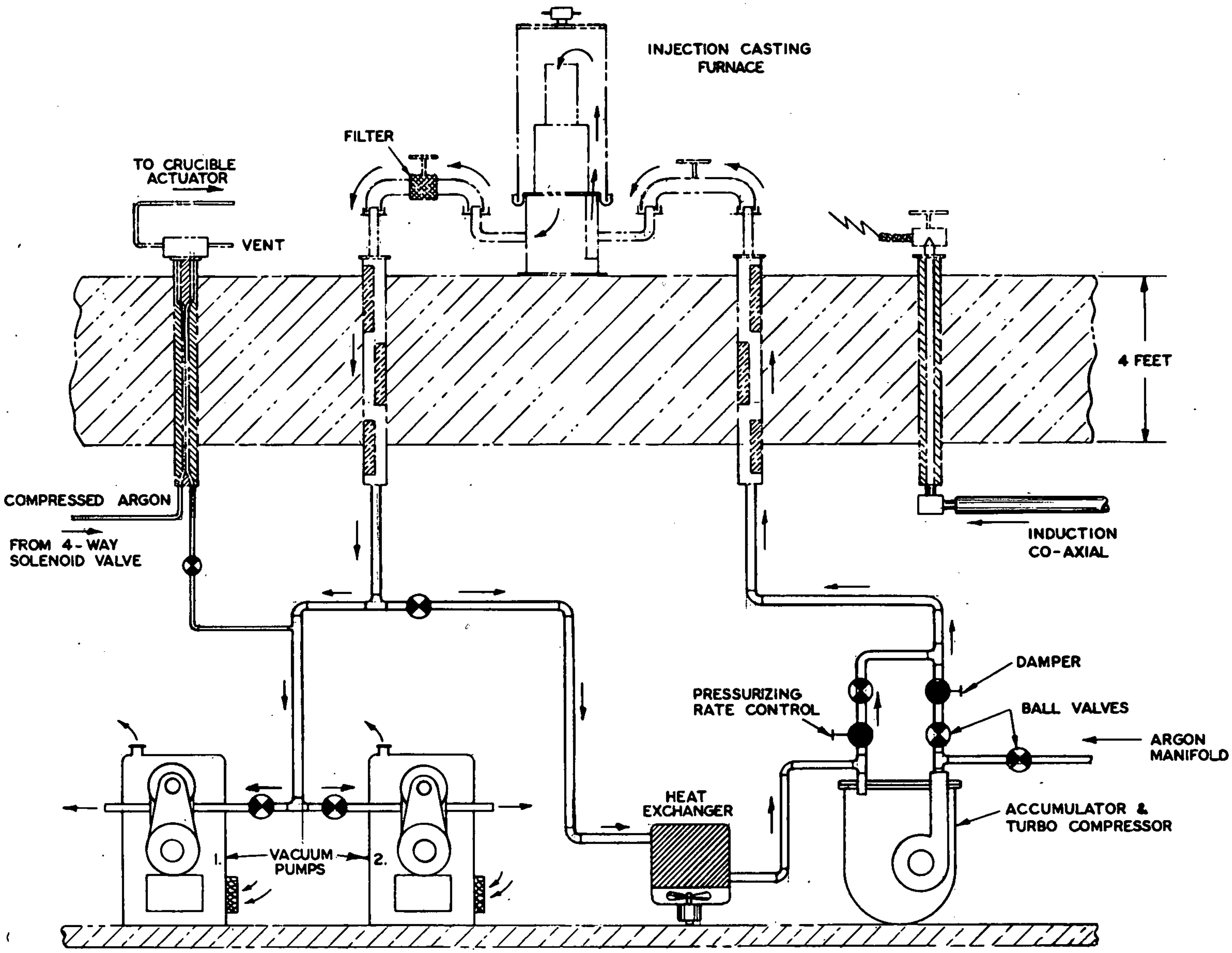


Figure 5. SUBCELL EQUIPMENT

PF-100-332

Neg. 106-5980