INL/MIS-21-64302-Revision-0

VTR Casting Furnace Conceptual Design

September 2021

Changing the World's Energy Future

Carl E Baily

Idaho National Laboratory

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TEV-3862
VTR Casting Furnace Conceptual Design

Technical Evaluation

TECHNICAL EVALUATION

Title: VTR Casting Furnace Conceptual Design

TEV No.: 3862 Rev. No.: 01 Project No.: N/A Date: 10/06/21

1.	Does this TEV involve a Safety SSC?	Yes	**Professional Engineer's Stamp** See LWP-10010 for requirements.
2	Safety SSC Determination Document ID	N/A	
3.	Engineering Job (EJ) No.	X	
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5.	Building	704	
6.	Site Area	MFC	

7. Introduction:

This TEV documents a conceptual design for a casting system to be used for development of fuel fabrication processes for the Versatile Test Reactor (VTR)

8. If revision, please state the reason and list sections and/or pages being affected:

9. Conclusions/Recommendations:

The final design is a single-crucible vertical pressure-vacuum induction furnace. The furnace will be installed in a glovebox in the Fuel Manufacturing Facility (FMF) to accommodate use of Plutonium bearing metal fuel alloys. The glovebox will accommodate two furnaces to allow for eventual higher throughput if general fuel production should be required in FMF.

CONTENTS

APPENDIXES

Title: VTR Casting Furnace Conceptual Design

TEV No.: 3862 Rev. No.: 01 Project No.: N/A Date: 10/06/21

PROJECT ROLES AND RESPONSIBILITIES

Project Role	Name (Typed)	Organization	Pages covered (if applicable)
Performer	Carl Baily	U720	See eCR 674172
Checker[a]	Denis Johnston	U720	See eCR 674172
Independent Reviewer[b]	NA	N/A	N/A
CUI Reviewer[c]	John Major II	M310	See eCR 674172
Manager[d]	Wesley Benjamin	U720	See eCR 674172
Requestor[e]	Steve Marschman	U600	See eCR 674172
Nuclear Safety[e]	Michael Bailey	U740	See eCR 674172
Document Owner[e]	Wesley Benjamin	U720	See eCR 674172

Revision 01

Project Role	Name (Typed)	Organization	Pages covered (if applicable)
Performer	Carl Baily	U720	See DCR 690495
Checker[a]	Denis Johnston	U720	See DCR 690495
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Manager[d]	Wesley Benjamin	U720	See DCR 690495
Requestor[e]	See previous*	U600	See DCR 690495
Nuclear Safety[e]	See previous*	U740	See DCR 690495
Document Owner[e]	Wesley Benjamin	U720	See DCR 690495

* Rev 01 for removal of OUO markings only, no alteration of content

Responsibilities

a. Confirmation of completeness, mathematical accuracy, and correctness of data and appropriateness of assumptions.

b. Concurrence of method or approach. See definition, LWP-10106.

c. Concurrence with the document's markings in accordance with LWP-11202.

d. Concurrence of procedure compliance. Concurrence with method/approach and conclusion.

e. Concurrence with the document's assumptions and input information. See definition of Acceptance, LWP-10300.

NOTE: *Delete or mark "N/A" for project roles not engaged. Include ALL personnel and their roles listed above in the eCR system. The list of the roles above is not all inclusive. If needed, the list can be extended or reduced.*

INTRODUCTION

This TEV describes the development of a conceptual design for a fuel casting system to be used in the development and demonstration of fuel designs for the new Versatile Test Reactor (VTR). This system will be installed in the Fuel Manufacturing Facility (FMF). The system will be in a shielded glovebox and will be used to melt fuel materials and injection cast these materials into fuel slugs, which will further be used to fabricate fuel elements for the VTR. This TEV covers only the injection casting system itself. Operations such as removing the castings from the injection molds, trimming of the castings, and installation of the castings into fuel element cladding are beyond the scope of the TEV. The conceptual design herein is principally concerned with the mechanical portion of the casting system and does not include details of the control or power supply systems.

DEFINITIONS AND ACRONYMS

The following definitions and acronyms are used throughout this document.

- Demolding – The process of removing the casting molds from the cast metal components.
- DOE – Department of Energy.
- EBR-II – Experimental Breeder Reactor II
- Casting Alloy – The mixed metal alloy used in the furnace to cast fuel slugs.
- Confinement Barrier/Boundary – The boundary separating different confinement zones.
- Confinement Zone – Confinement zones are areas established in a nuclear or radiological facility which have different potentials for experiencing airborne radioactive contamination. Confinement zones are typically designated as Primary, Secondary or Tertiary Confinement Zones. See the DOE Air Cleaning Handbook for more information.
- Criticality – ‘nuclear criticality” where enough fissile material is collected under the proper conditions and geometry to create a self-sustaining fission reaction.
- Crucible – The “cup” in which the feedstock is melted as part of the casting operation.
- FMF – Fuel Manufacturing Facility
- FFTF – Fast Flux Test Facility
- Feedstock – Materials which will be received into the system to create the casting alloy. This may consist of pre-mixed alloy, or elemental materials which would be mixed and homogenized in the furnace upon melting.
- Casting Heel (or simply “Heel”) – residual casting alloy and scrap remaining in the crucible after the casting process has been completed.

- HEPA – High Efficiency Particulate Air
- INL – Idaho National Laboratory (Also referred to herein as "the Laboratory".
- Molds - The individual glass or quartz tubes into which the alloy will be cast into slugs.
- Melt – The molten casting alloy.
- MFC – Materials and Fuels Complex
- Pallet – The combination of a pallet frame and molds which is used for a single casting operation.
- Pallet Frame – A frame which is installed into the furnace and which holds an array of individual molds through the casting process.
- Pallet Elevator – The part of the furnace which holds the pallet, and which allows the pallet to be inserted into the melt and then withdrawn after casting.
- Primary Confinement Zone - Area where high levels of airborne radiological contamination is expected during normal operations.
- Primary furnace/accumulator system – This includes the furnaces, accumulator tank, and the piping system which connects them.
- Slugs – Cast elements produced by the injection casting process
- Secondary Confinement Zone – Area where high levels of airborne radiological contamination could be generated during normal operations or as a result of a breach of a primary confinement barrier.
- Susceptor – The material which couples to the magnetic field created by the induction furnace, and in which heat is thereby generated. The crucible and casting alloy may form part or all of the susceptor.
- Suspect Exhaust – Ventilation systems which service primary and secondary confinement areas and in which airborne radiological contamination does or could occur.
- Tertiary Confinement Zone – Area where airborne contamination is not expected during normal facility operations. Secondary and tertiary boundaries may be common, as in a single-structure envelope.
- VTR – Versatile Test Reactor

BACKGROUND

The proposed VTR will utilize uranium-plutonium-zirconium (U-Pu-Zr) metallic fuel similar to that which was used in EBR-II and FFTF. The VTR Fuel Casting System will be used to develop and demonstrate the fuel designs for this new reactor. Fuel development and demonstration will include all equipment necessary to create VTR fuel elements from receipt of the elemental metals and alloys through final inspection and acceptance of a reactor-ready fuel element.

The furnace and pressure systems described herein will be used in development of the fuel casting process.

Metallic fuels have been produced at MFC (formerly Argonne National Laboratory – W) since the early 1960s. These fuels have been principally manufactured using injection casting systems. The basic injection casting process is still being used at MFC for casting experimental materials, and the systems used are very similar to those early casting systems.

The general injection casting process flow is as follows:

- The alloy components are melted and mixed in a vacuum furnace, in a pressure-controlled argon atmosphere.
- The furnace is evacuated
- Multiple high temperature glass (quartz glass or Vycor™) molds, closed at the top and open at the bottom are simultaneously dipped into the molten metal. Molds are held in a special fixture in an array referred to as a “pallet”.
- The furnace is quickly pressurized with argon gas to force the metal upwards to fill the molds. Furnace power is turned off and a cooling gas flow is introduced into the mold area.
- After a pre-determined time (chosen to ensure the metal in the molds has become solid, but before the pool of metal in the furnace solidifies), the molds are withdrawn from the molten metal pool.
- Once the furnace has cooled, the molds are removed from the furnace. Molds will be later broken to remove the glass from the metal fuel slugs. The mold breaking (or “demolding”) process is outside the scope of this TEV.

The intended VTR fuel composition is 70% uranium, 20% plutonium and 10% zirconium (referred to as U-20Pu-10Zr). INL has produced injection cast fuels of this composition, but at much smaller batch and slug sizes than will be needed for the VTR fuel elements. The current fuel design will require casting pins of roughly .190-inch diameter and 19.75 inches length, in batches of 135 pins. Based on INL experience with anomalies at the ends of the elements (such as hot tears), molds will be up to 22 inches in length and will support up to 135 pins.

INITIAL CONCEPT DEVELOPMENT

In the mid-1980s, INL built the Fuel Manufacturing Facility (FMF) to fabricate metallic U-Zr fuel for the EBR-II reactor. This facility contained what was referred to as the "FMF cold line", since it was used with un-irradiated or 'cold' uranium fuels. The nature of this fuel material was such that only limited radiological confinement was needed, and most operations could be performed by hand using radiological hoods and tables. This facility fabricated fuel for both EBR-II and FFTF until the mid-1990s when the EBR-II reactor was shut down. The cold line furnace was a horizontal chamber vacuum induction furnace with two crucibles mounted on an extendible slide. Two vertical columns were fitted with pallet elevators which inserted and removed the molds. This system was decommissioned and removed from the facility in 2011.

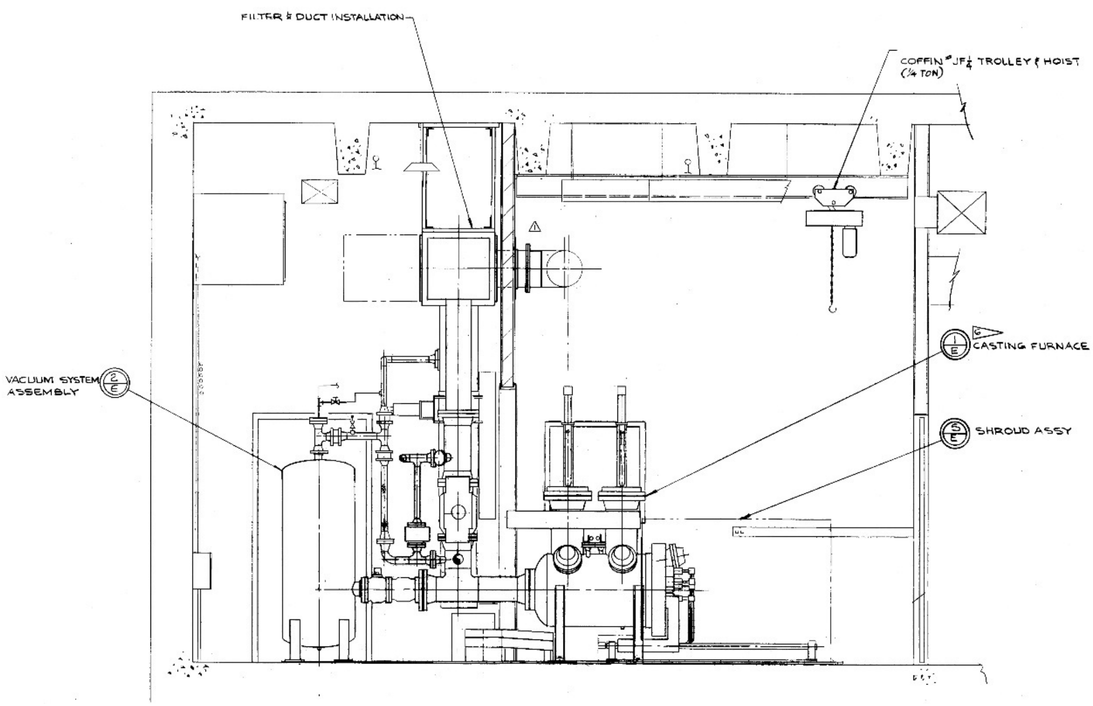

Figure 1 - FMF Cold Line Casting System

The initial concept was to essentially duplicate the FMF Cold Line furnace system, with modifications necessary to support fabrication of U-Pu-Zr fuels. Due to the presence of Pu, all operations would need to be performed inside primary confinement systems (gloveboxes). The furnace and its associated atmosphere systems would also be part of the primary confinement boundary. Another issue is direct radiation dose due to the presence of Pu isotopes. This necessitates provision of biological shielding and minimizing the need to directly handle fuel materials. The extent of shielding required will be dependent upon the exact nature of the source materials used for element fabrication.

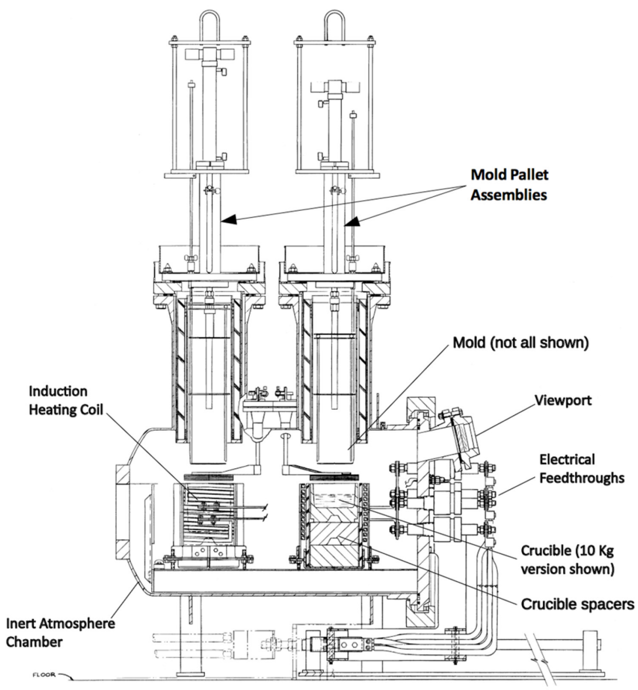

Figure 2 - FMF Casting Furnace Cross-Section

While this concept could be fit into the space available, there were several problems that became apparent as the conceptual design progressed.

- The glovebox required to accommodate the furnace was quite large. The glovebox not only requires enough vertical space to accommodate pallet removal, but it also requires horizontal space of roughly twice the shell length to allow the horizontal opening lid and crucible tray system. Since this lid and tray are located near floor level, the glovebox must also extend to the floor, at least in this area.

- In discussing the concepts with glovebox designers at INL, it was noted that multi-part glovebox shells are HIGHLY discouraged for Pu gloveboxes, due to the need for large bulkhead seals along with the potential for leakage and difficulty with repair that those seals bring. A single-shell glovebox design would be simply too large to bring into the facility, as the access doors are 6 feet wide x 7 feet tall.

- The design includes a large accumulator tank and several mechanical joints and valves which would by necessity be outside the glovebox. These components would all need to be part of the safety-significant confinement boundary or would need to be located in their own confinement boundary structures.

FINAL CONCEPTUAL DESIGN

The final conceptual furnace design uses two independent vertical vacuum induction furnaces instead of a single two-crucible horizontal design. This arrangement has several benefits with respect to the need to provide primary confinement for the system, and to perform many of the operational tasks inside a glovebox enclosure.

- The individual furnaces can have an internal volume much smaller than the horizontal furnace design. This also allows use of much smaller accumulator tanks and gas system components. These components are sufficiently reduced in size that all mechanical pressure joints and valves in the primary furnace and pressure system can be located inside the glovebox confinement boundary.
- The two furnaces are fully independent. If one furnace is out of service for maintenance or repair, the other furnace can remain operational.
- Since all openings are on the top of the furnace, the furnace can be located below the glovebox floor. The inherent size of the glovebox is much smaller. The large horizontal door and high-power electrical disconnects are not required.

This orientation does have some disadvantages. The crucibles will not be directly accessible, and visibility will be limited. There is also not room for the simple round rotatable thermal shutters used in the cold line furnace. These issues both exist in a fuel casting furnace located in the FCF argon cell, and some of the design features of that furnace were used in the conceptual design.

The final conceptual design was developed primarily to establish general layouts and configuration of the system. The cold line induction coil, coil insulation systems and crucible designs were used as a baseline, with both stretched to increase the crucible volume from the 20 kg cold line design to the desired 30 kg size. These features established a baseline for determining a feasible size and layout for the furnace. It is noted that the actual coil design may be significantly different, as it will involve specialized electromagnetic and thermal analyses by the furnace designer.

Functional and Operational Requirements

System functional and operational requirements are detailed in FOR-489[1].

Molds and Pallets

[1] FOR-489, VTR Fuel Development Casting System

The furnace will be used to injection cast fuel alloy into molds as shown in the following figure.

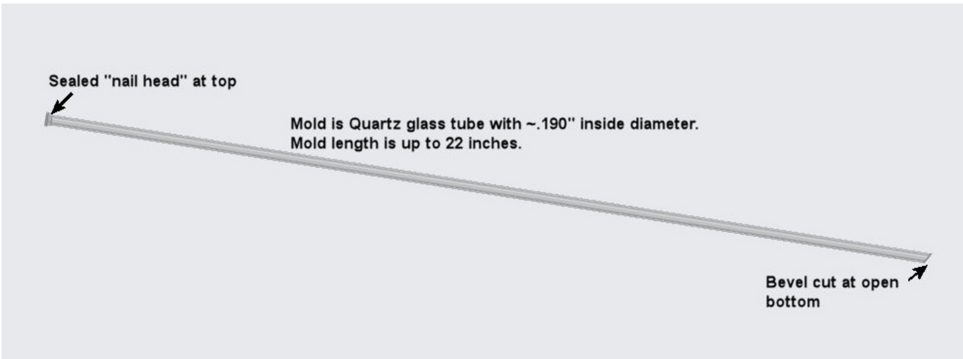

Figure 3- Injection Casting Mold

These molds are very similar to molds previously used in the INL casting furnaces, but are longer to produce the longer fuel slugs which will be required for the VTR fuel design. The molds will be internally washed with a zirconia solution to facilitate separation of the mold from the cast slug.

To achieve the required throughput, the molds are placed in a frame and each casting operation will mold up to 135 fuel slugs. The array of molds for each casting operation is referred to as a "pallet".

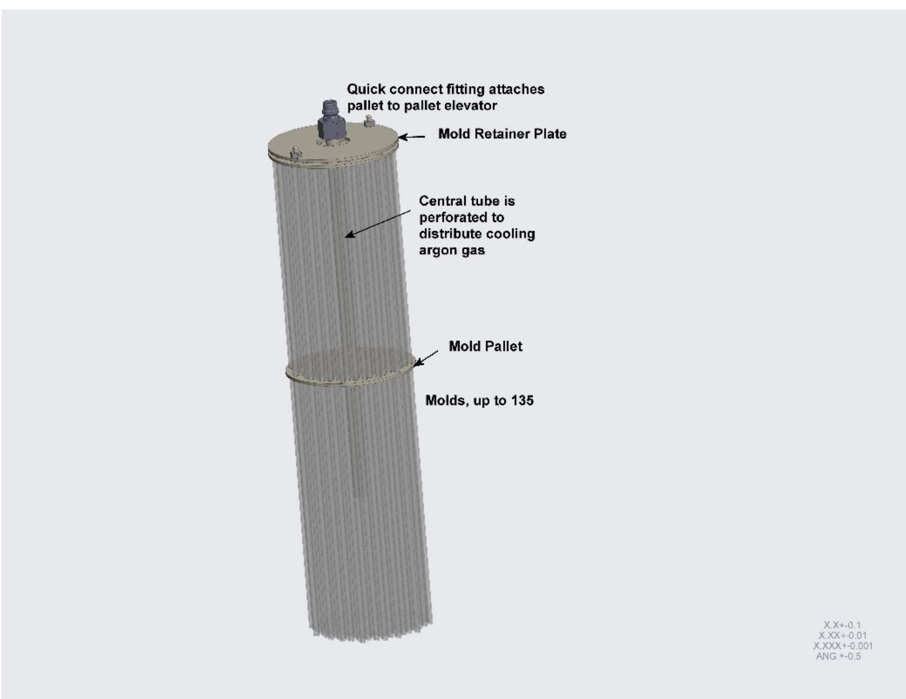

Figure 4- Mold Pallet

The pallet frames are single-use and are disposed of after each casting operation. By varying the pallet frame design, the furnace will be able to accommodate significant variations in mold size, number and length. This flexibility will be valuable in supporting development of the casting process and any variations identified in the final fuel slug design.

Overall Furnace Design.

As noted, the conceptual furnace design is a single crucible vertical vacuum induction furnace.

There are some significant design limitations which arise from the need to install the furnace system into a glovebox:

1. The overall size of the glovebox flange is limited due to the need to be able to reach the centerline of the glovebox. In practice, the floor width should not exceed 38 inches. This is further reduced by the need for structural supports under the glovebox floor and the need for some clearance between the furnace flange and glovebox structure. A flange diameter of 30 inches is a practical maximum for a conventional glovebox configuration.

2. The furnace must be short enough to be installed under the glovebox floor, since it must be possible to install or remove the furnace without lifting the entire glovebox. The furnace must also clear the glovebox support structure during installation or removal. The conceptual design assumes a glovebox support structure height of 38 inches, which is relatively typical and provides acceptable ergonomics for work in the glovebox. Assuming that the structure will use 3-inch structural tubing, the furnace height must be reducible to less than 35 inches.

3. Installation of the pallet elevator and pallet requires raising the pallet elevator sufficiently for the pallet to clear the furnace using an internal hoist in the glovebox. The overhead space is limited due to the need to be able to transfer the glovebox shell into the facility through doors with a maximum height of less than 7 feet. Even using a conceptual low-profile hoist, this requirement necessitated incorporation of a well into the furnace shell design to provide sufficient overhead space.

4. It is highly desirable to design the furnace such that all mechanical seals are located inside the glovebox confinement boundary. Due to the nature of the materials being cast, even very small leaks outside of this confinement boundary present a hazard to the operating personnel in the facility. Since the furnace internals (core) will be radiologically contaminated, the core is required to be removed into the glovebox for repair or refurbishment.

5. Crucible installation and removal will be through the elevator opening. Special tools will be needed for this operation. Visibility for this operation will be poor to non-existent.

6. Most commercial induction furnaces use water cooling for the induction coils. Water cannot be used inside the confinement boundary of this system due to nuclear criticality issues and the potential severity of consequences if water were to contact the molten fuel alloy.

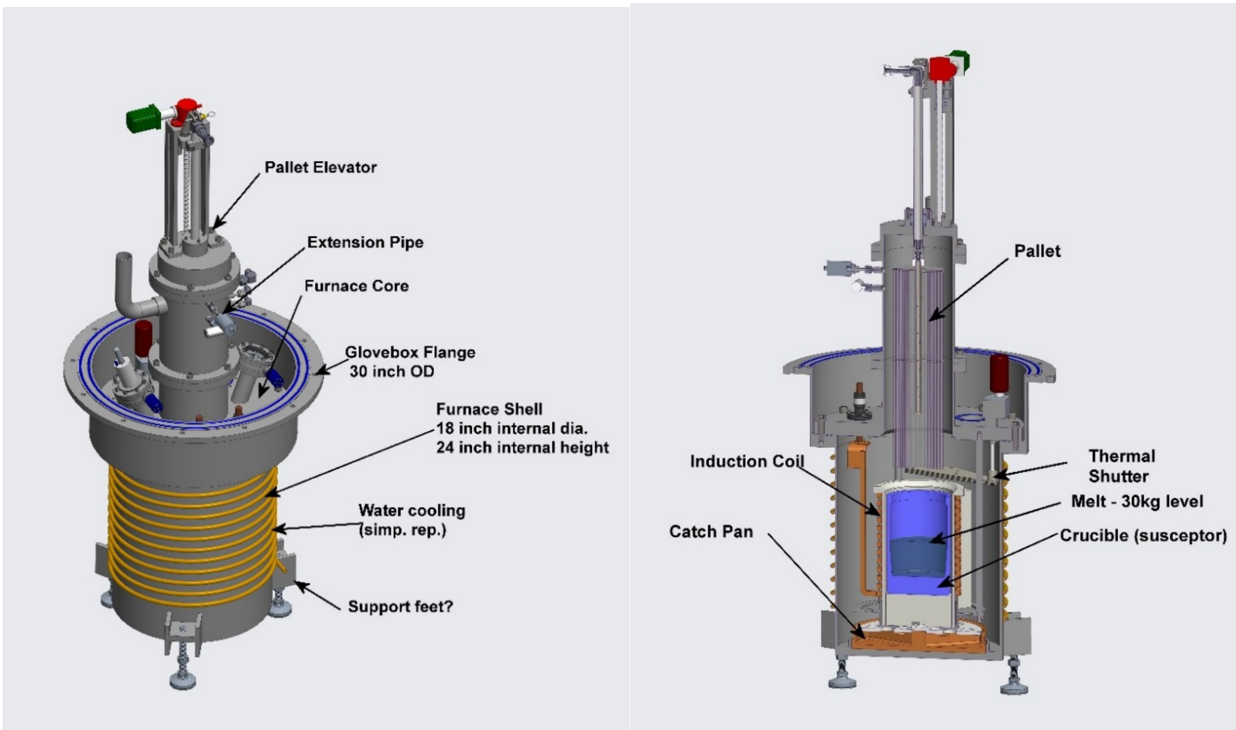

Figure 5 - Conceptual Casting Furnace

The furnace shell bolts to a flange which is built into the floor of the glovebox. It provides both the confinement boundary and the pressure boundary for the process. The furnace's internal volume has been minimized to the extend practical, since this also allows smaller components to be used in the pressure/vacuum system which will be attached to the furnace. The 18-inch shell size is driven both by the need to provide space for the thermal shutters and the need to provide connections for the 3-inch pressure system piping. It is noted that the assumption of 3-inch piping size for the pressure system is conservative (based on the significantly larger FCF casting furnace). It is noted that, if determined necessary as the design progresses, a significantly larger shell could be accommodated with reconfiguration of the vessel flange and perhaps a necked vessel design. This would increase the volume of the vessel, however.

The seal on the glovebox flange is a double o-ring design. This seal is a critical one, as it is a part of the glovebox confinement boundary and therefore needs to meet the same seal performance requirements as the general glovebox boundary seals. A port would be provided which connects to the interstitial area between the o-rings to allow leak testing. This port would be plugged when not in use.

The furnace will operate over a pressure range between 30 psig and full vacuum. It is recommended that the furnace be designed with an allowable working pressure of at least 100 psig, to eliminate the potential for over-pressurization due to failure in the pressure control system (as the maximum gas supply pressure in the facility is ~85 psig). With this potential eliminated, the only potential over-pressure source would be from heating of the gas inside the furnace. This process is sufficiently slow that it could be mitigated using a relatively small pressure relief device.

Water cooling of the furnace shell is anticipated since a water-cooled induction coil design cannot be used for this furnace. Based on INL fuel casting furnaces which use solid-coil designs, it is anticipated that significant heat will be radiated to the furnace shell to cool the coils. A set of copper tubing coils are shown on the conceptual design as a very simple representation of the potential need for cooling, since the actual extent and configuration of the cooling system will not be known until thermal analysis of a more complete design has been performed.

The extension pipe attached to the upper glovebox flange is removed during furnace installation/removal to reduce the height of the furnace and allow it to be moved into place below the glovebox. The overall height is necessary to provide room for the pallet and elevator to be installed with the bottom of the molds in the proper position above the crucible.

The "feet" on the furnace shell are intended primarily as a method to raise the shell into position under the glovebox to be bolted to the flange on the glovebox. If the glovebox shell is not sufficiently robust to support the weight of the furnaces, the feet may be used to support the furnaces. It is noted that, if used to support the glovebox, the feet may need to incorporate some compliance elements (springs or similar) to avoid applying excess stress to the glovebox floor due to thermal expansion of the shell during heating of the furnace. An alternative support leg design could also be used which would support the flange area directly (instead of being mounted on the furnace shell).

Pallet Elevator

The pallet elevator is used to hold the fuel mold pallet and provides a mechanical drive to lower the molds into the melt and to withdraw them afterward. The elevator is mounted to the extension pipe, which is in turn mounted to the furnace flange.

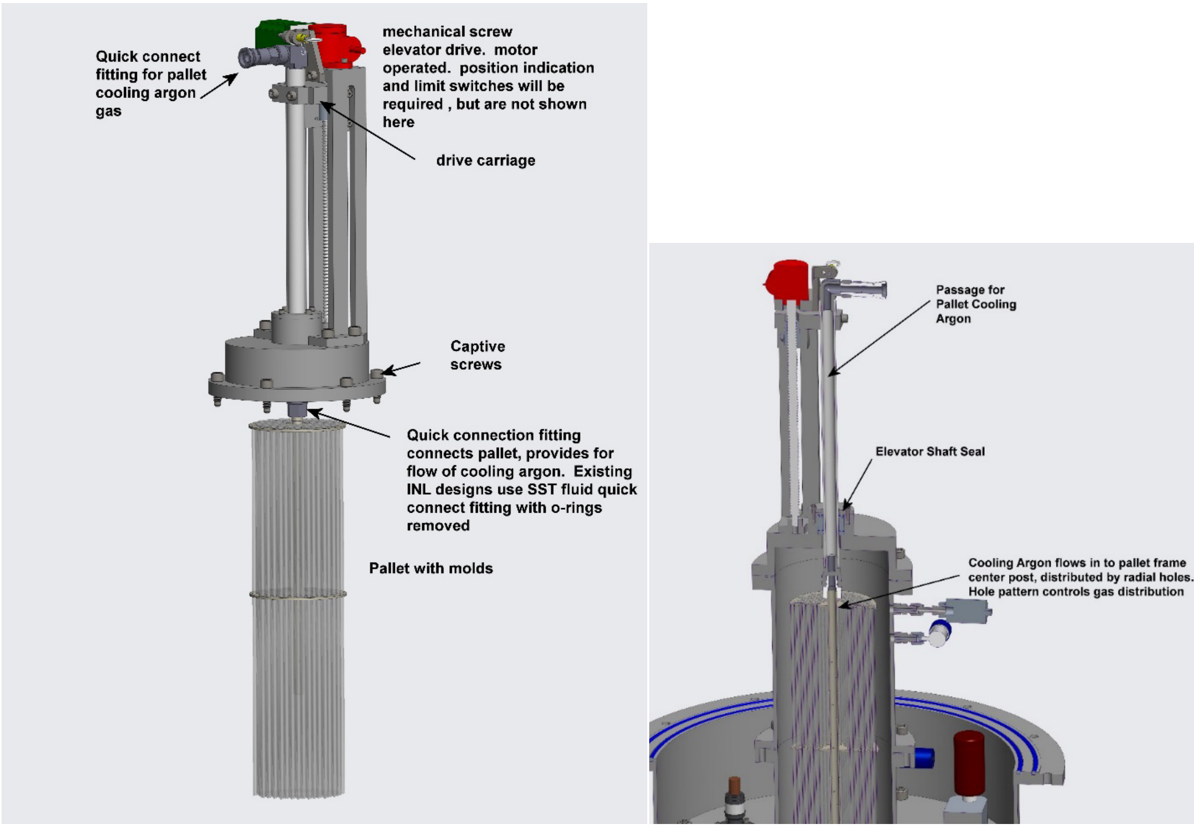

Figure 6 - Pallet Elevator Details

The pallet elevator system uses a central pipe which passes through a dynamic seal and connects to the mold pallet. This pipe provides a passage for pressurized argon gas, which is used to cool the molds after casting. The central pipe is connected to a drive mechanism which raises and lowers the pallet during the casting process. The conceptual design uses a mechanical acme screw drive mechanism. This system would be fitted with limit switches and a position indicating system which are not shown. The elevator system should operate at a speed which will allow full travel in approximately 15 seconds or less.

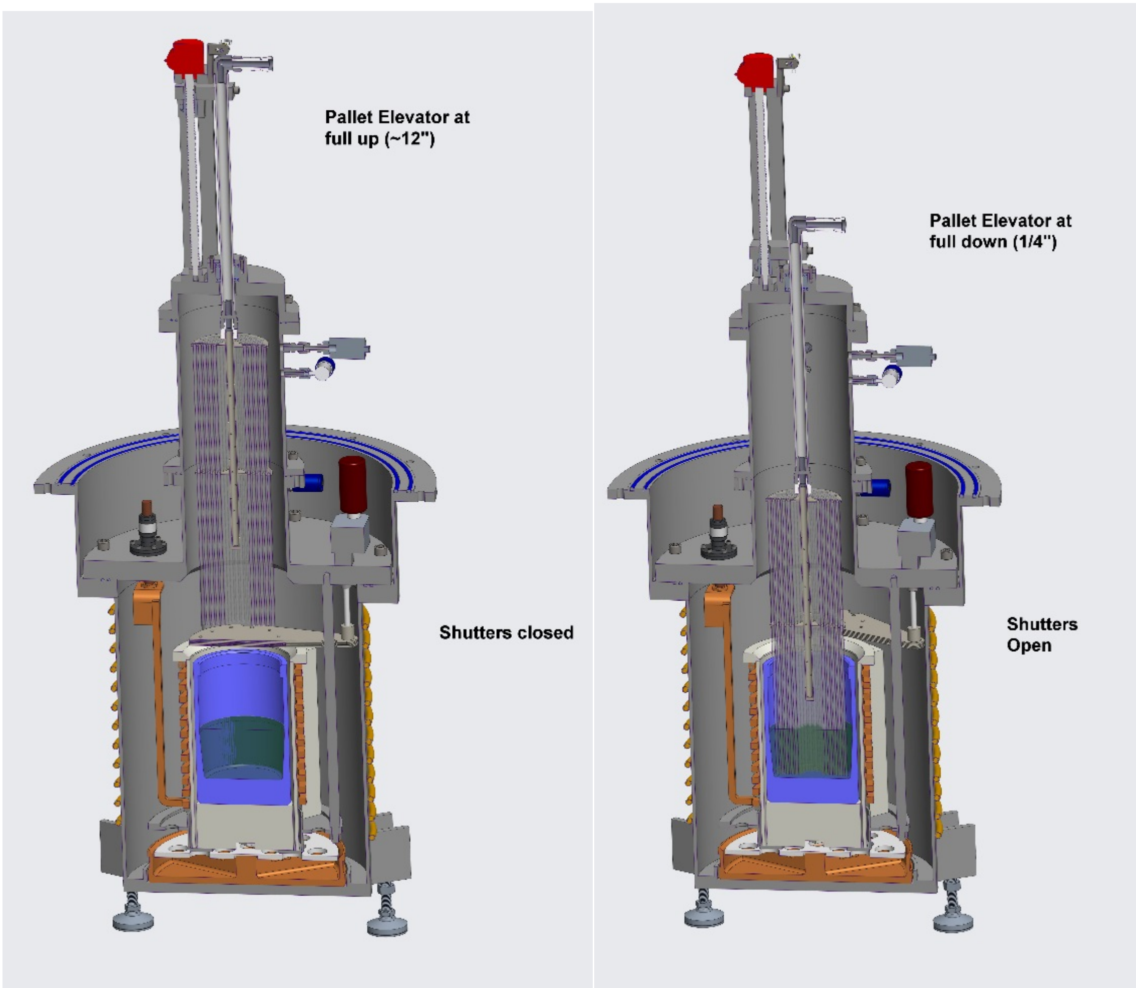

Figure 7 - Operation of Pallet Elevator

Internal Configuration of Furnace

The furnace core consists of the furnace top closure flange, heating coils, coil insulation package and thermal shutters. The core encompasses essentially all the internal furnace components which would be expected to require periodic maintenance or replacement.

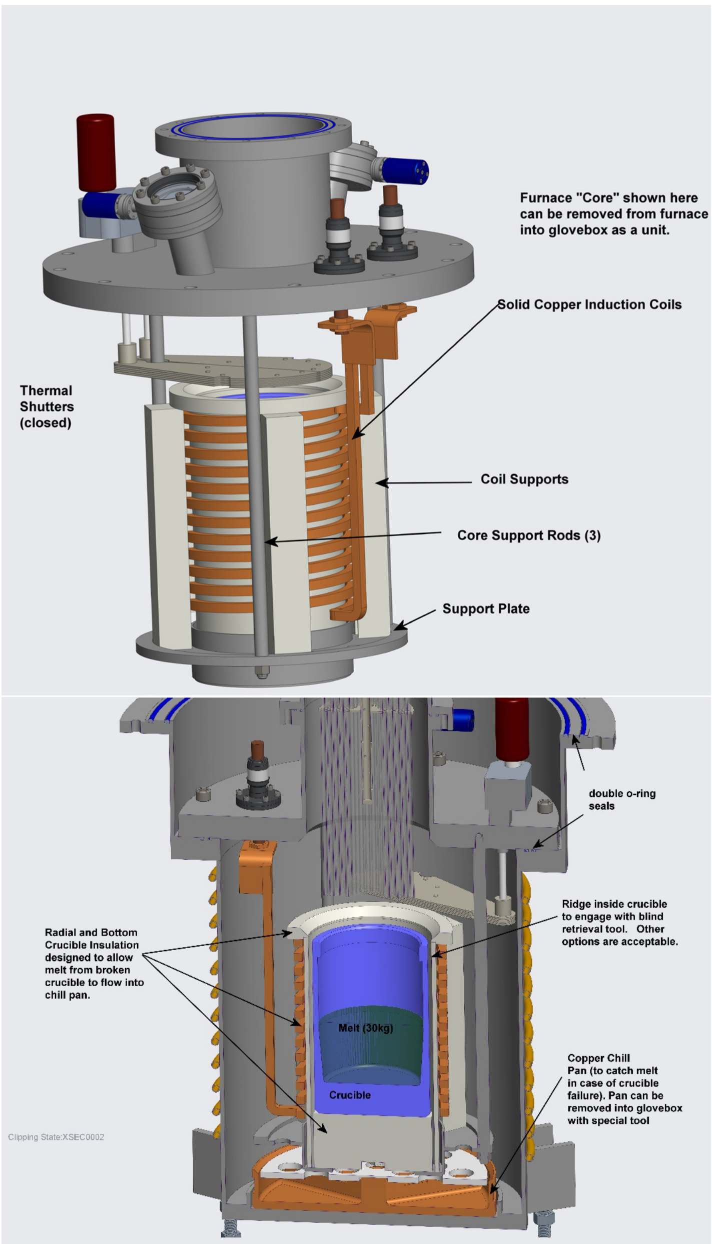

Figure 8 - Internal Details of Furnace

The coil, crucible and insulation are suspended from the closure flange by support rods. The furnace core is intended to be removed into the glovebox to allow maintenance and replacement of the internal furnace components. Except for the closure flange, all core components are sized to allow them to be transferred through the 15-inch bag out port in the glovebox in case they require replacement.

The closure flange, and the flanges which attach the extension pipe and elevator to the furnace, and the gas system connection to the furnace all use the same type of double o-ring seal that is described for the flange which connects the furnace to the glovebox floor. In this case, there is much less concern with leakage, and use of the double o-ring design is not as important. This design is used here simply because it was used several previous INL furnaces and demonstrated good service in pressure-vacuum conditions and because the double o-ring is a "worst case" design with respect to the size of the sealing area. It is noted that many of the later INL furnace designs use single element seals, with no significant issues noted.

The closure flange is recessed approximately 8 inches below the glovebox flange. This configuration provides enough overhead room to allow the pallet elevator, with the pallet attached, to be raised clear of the furnace for loading and unloading.

The graphite crucible is based on an existing INL "20 kg" crucible, extended to provide additional room for up to 30 kg of material. The crucible both contains the molten fuel, and acts as an inductive susceptor for the induction heating process. It is noted that the actual maximum fuel loading is anticipated to be 22 kg.

The induction coil is based on the FMF cold line furnace coil, modified to provide a different connection to the induction feedthroughs (the original connection used horizontal buss-bars). Additional turns were added to extend the coil to match the taller crucible. This previous furnace coil used ½ inch square copper bar for this coil. No analysis of this coil design has been performed and the coil geometry should be considered as a general representation only.

Crucible insulation (base and radial) is based on the general geometry of the previous furnace, as are the ceramic coil supports. Radial insulation was a high alumina refractory in the FMF cold line furnace. The base insulation was a high zirconia ceramic with three thin alumina or zirconia felt disks cast in place. Crucible supports and separators were fired "Lavite Lava Grade A" which appears to be an alumina silicate ceramic material. It is expected that details would be similar for the new furnace, with updated materials.

Conceptual power feedthroughs are a commercially available solid copper bar ceramic feedthrough with a ¾ inch diameter conductor rated for 800 amps current at 8000 Vdc by MPF Products Inc. These were chosen based on the original power supply specifications for INL furnaces of similar capacity, which specified power inputs of 800V, 3-10 kHz, 25 kW and 600A. It is anticipated that the overall power of the new furnace would be approximately the same as the cold line furnace. To allow for use of induction mixing, multiple frequencies may be required, with one frequency used for heating, and a different frequency used for inductive mixing.

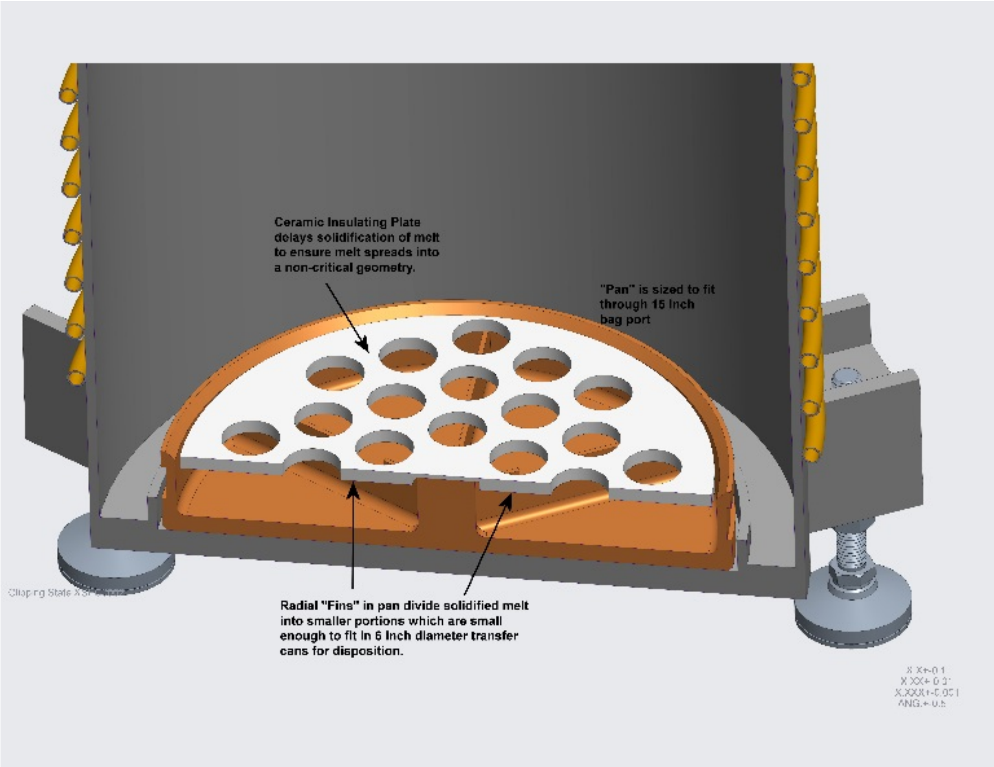

Figure 9- Catch Pan

A copper catch pan is provided inside the furnace to protect the furnace shell in case of failure of the crucible while it contains molten fuel material. Ferrous alloys are subject to very rapid attack when in contact with uranium alloys at temperatures at or above 800ºC, due to formation of uranium-iron eutectic, which is molten above this temperature. The copper pan will contain any molten fuel material which escapes the crucible. The fins are intended to divide the molten metal into smaller, more easily handled pieces. A ceramic insulating plate is intended to allow the metal to distribute into the pan instead of forming a large "lump" immediately under the source of leakage. This lump would be difficult to separate into portions which could be packaged for disposition.

It is noted that copper and uranium form a eutectic alloy with a solidus temperature of 950°C. Because of this, the copper catch pan must be sufficiently massive to ensure that the melt cools below this temperature quickly to avoid eutectic penetration of the pan. Thermal analysis would be required to ensure the pan remains intact after collecting the melt.

Thermal shutters are used to minimize radiant heating of the pallet and upper portions of the furnace during heating operations. These are configured in a "butterfly" arrangement, which is similar to the arrangement used in the FCF hot cell casting furnace.

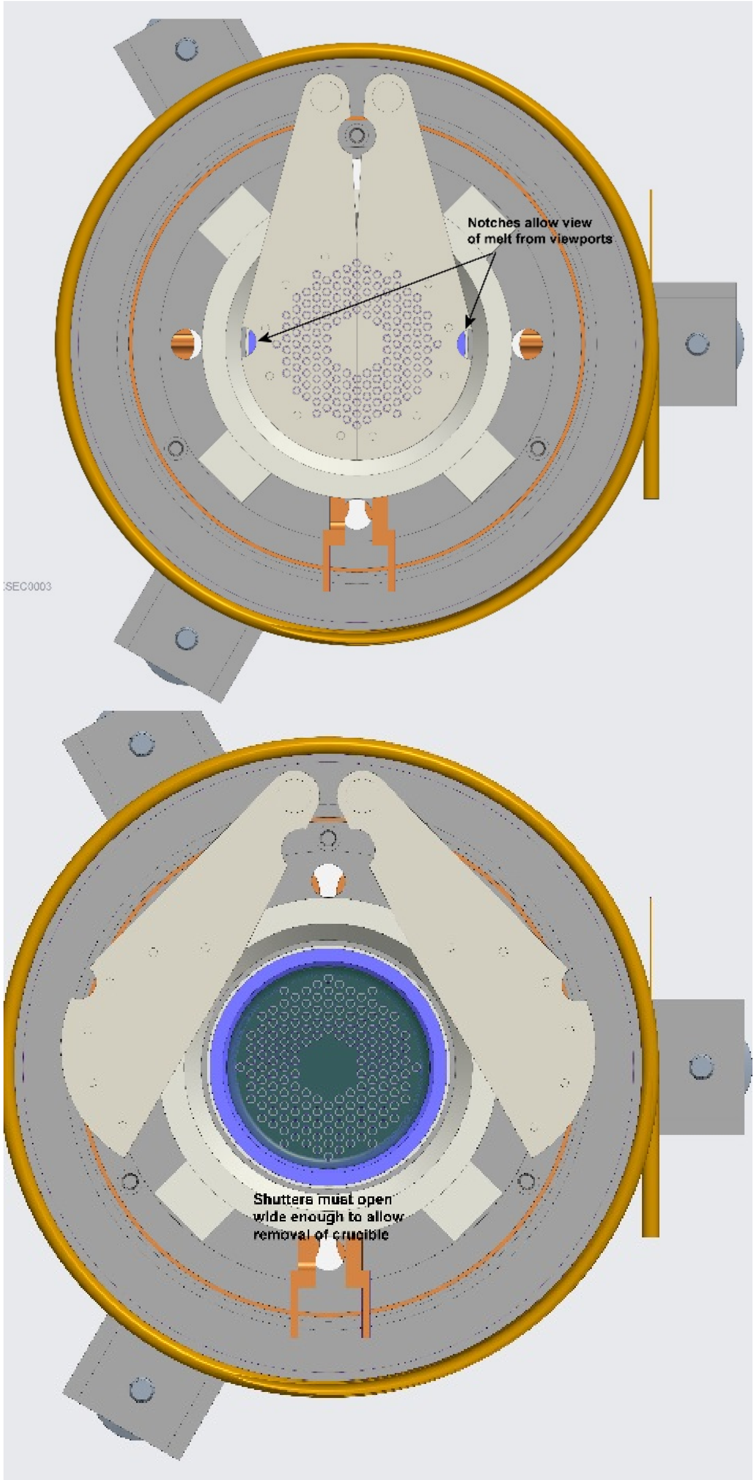

Figure 10 - Operation of Butterfly Shutter

The butterfly design allows use of a smaller furnace shell than a single round shield. While the operating mechanism has not been detailed, it is expected that it would incorporate a set of sector gears which would synchronize the shutter operation. A small actuator would be connected to one shaft to drive the shutters open and shut. The actuator should be removable from the shafts to allow for repair or replacement without removing the furnace core from the furnace.

Additional External Furnace Details

The furnace design incorporates two windows which allow viewing of the crucible and contents. The windows will also accommodate installation of pyrometers and/or video cameras for determining melt temperature and for investigating melt behavior.

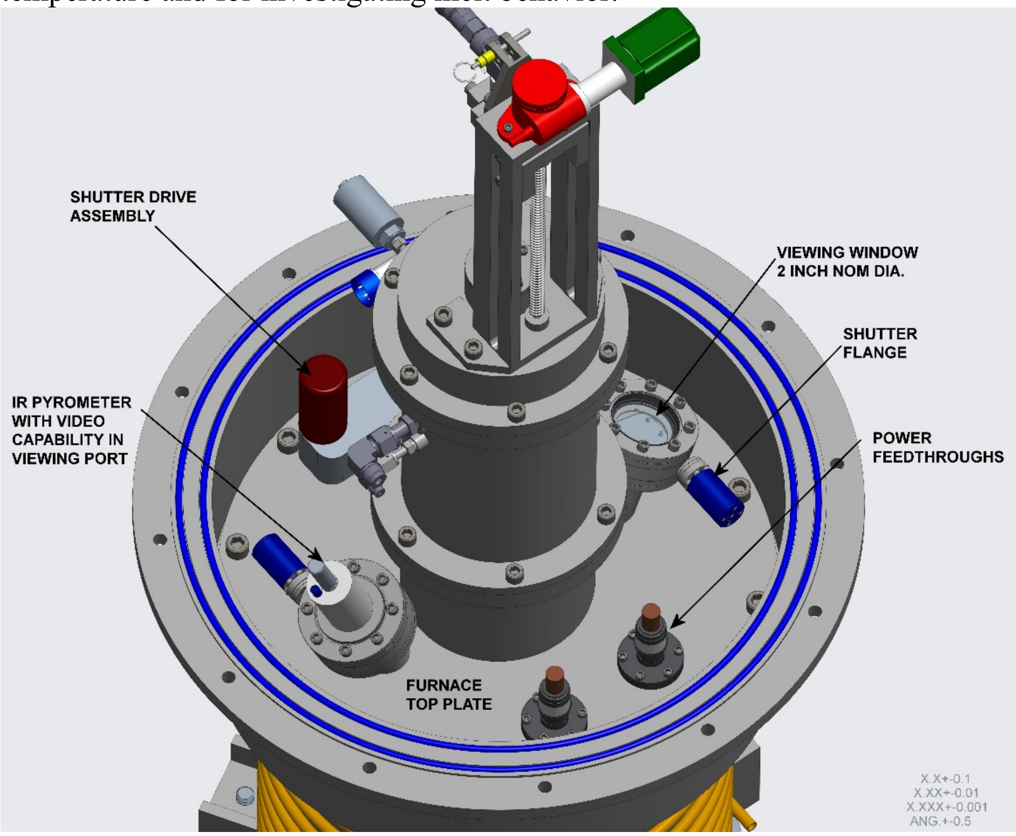

Figure 11 – External Configuration (Top)

The windows are fitted with shutters to prevent deposition of fumes and other contaminants on the windows during operation, and to reduce heating of the windows when not in use. Windows of 2-inch nominal diameter are shown in this conceptual design. Conflat style vacuum windows are shown in the conceptual design. Due to limitations on positive pressure for vacuum windows, it is likely that a different style of window would be specified in the final design, but the Conflat design should be representative. It is also noted that the Conflat window is larger than required for the IR video pyrometer shown.

Note that pressure system connections are not shown in this view but are shown in a later view during discussion of the glovebox installation details.

Casting Process

The following conceptual casting process has been developed, based on INL experiences with various fuel casting systems.

1. The pallet elevator is removed from the furnace.
2. Casting alloy is placed into the crucible and the crucible is placed into the furnace. Alloy may be pre-mixed or may consist of individual pieces of metal selected to create the desired alloy mixture.
3. The pallet is connected to the pallet elevator and the pallet elevator is re-installed into the furnace. The pallet cooling argon supply is connected to the pallet elevator. Pallet power and instrumentation/control (I&C) wiring is connected.
4. The furnace thermal shutters are closed.
5. The furnace is evacuated to ~50 milliTorr and checked for leakage. Any leakage is corrected.
6. Furnace pressure is increased to a controlled heating pressure. Heating pressure will range from a very rough vacuum (400 Torr) to a positive pressure up to 30 psig (42.2 psia).[2]
7. A pressure accumulator tank is charged to the necessary pressure to provide the desired casting pressure in the furnace during injection casting[3].
8. Furnace heating commences. The crucible and contents are heated to melt the casting alloy.
9. When the casting temperature is reached, the furnace will remain at temperature for a specified period to allow for mixing of the alloy (~30 minutes).[4]
10. The furnace is evacuated to less than 1 Torr.

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[2] Recent INL practice has been to hold pressure at approximately 450 Torr to suppress release of volatile elements such as cesium. Additional research identified that some furnaces at FCF were held at even higher pressures, up to 30 psig, to suppress "corona effects", particularly at higher frequencies.

[3] Based on recommended equations from Argonne experience with the cold line furnaces, a casting pressure of approximately 16 psig is estimated. To allow for process development, casting pressures of up to 30 psig may be desirable. The size of the accumulators in this conceptual design provides approximately the same internal volume as the furnace system. Accumulator pressure for this design would be approximately double the desired casting pressure.

[4] Based on discussion with furnace manufacturers, heating will be more efficient if an induction frequency is chosen that provides most of the inductive heat generation in the susceptor. For mixing, a different (generally lower) frequency provides better coupling with the alloy, which creates turbulence in the alloy.

11. The thermal shutters are opened. (They may be opened earlier if needed to pre-heat the molds).

12. The pallet elevator lowers the pallet down to lower the molds into the melt.

13. The fast-acting ball valve between the accumulator tank and furnace is rapidly opened to pressurize the furnace and force the melt into the molds. To allow the molds to fill before the alloy begins to solidify, the target pressure should be achieved within approximately 1 second.

14. Furnace power is secured.

15. Mold cooling argon flow is initiated. The furnace is vented to maintain a positive pressure in the furnace (~5-15 psig) as the molds cool.

16. Once the melt has cooled sufficiently (just above the cast material solidus temperature), the pallet elevator withdraws the pallet upward from the crucible. The timing of this operation will be identified during development of the casting process.

17. Thermal shutters are closed.

18. Once sufficiently cooled, the pallet elevator and pallet are removed from the furnace.

19. The pallet and filled molds are disconnected from the elevator and transferred to the demolding glovebox.

20. The crucible with remaining casting heel is removed.

21. The pallet elevator is replaced on the furnace.

Casting System Installation in Glovebox

To match the capacity of the cold-line furnace, two furnaces will be installed in the glovebox. A vacuum pump is installed under the glovebox and will be used to evacuate the furnaces when required by the casting injection process.

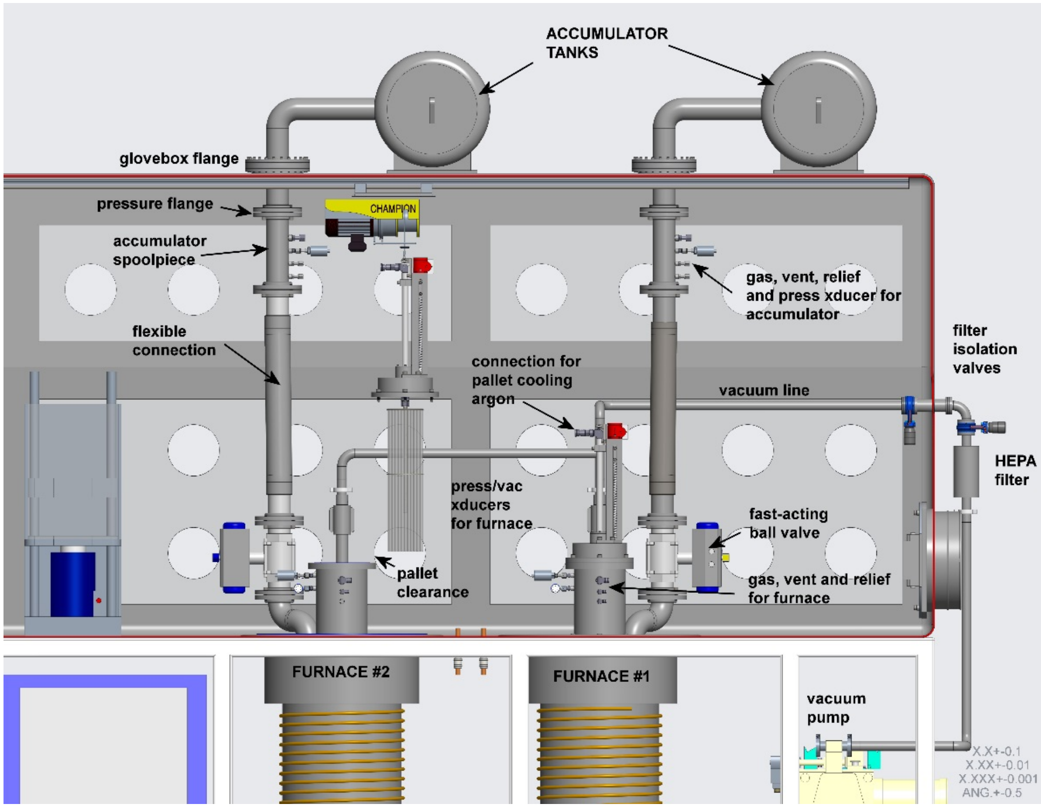

Figure 12 - Casting System Arrangement

The vacuum system consists of a single vacuum pump which is connected to both furnaces. Each furnace is provided with a vacuum solenoid valve to isolate the vacuum system when it is not needed for that furnace, and to avoid exposing the vacuum system to significant positive pressure. Furnace power and controls are shown below the glovebox. This location is desirable to reduce the total facility footprint, but it may not ultimately be practical. It is possible that this location could be used for the power matching capacitor bank system for the furnaces, with other portions of the power supply located remotely if required.

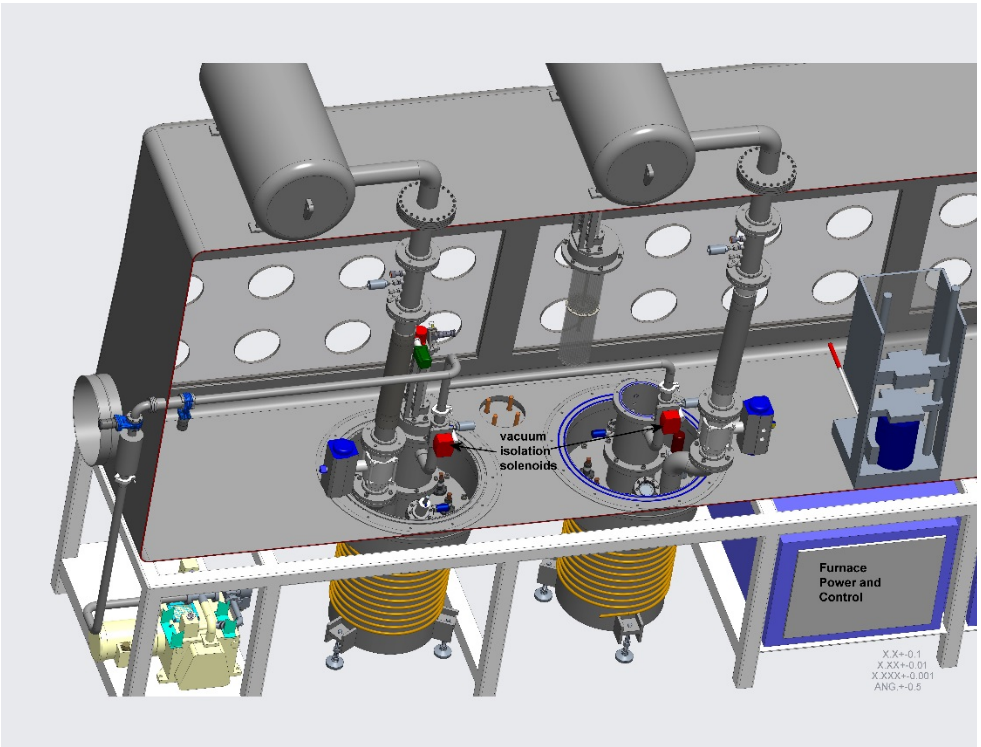

Figure 13 - Oblique Overhead View of System

To quickly pressurize the casting furnaces during the injection casting operation, each casting furnace is provided with an argon accumulator tank. Once the furnace contents are melted and mixed, the furnace is evacuated. The molds are dipped into the molten alloy and the accumulator (which has been pressurized with argon to a pre-determined pressure) is connected to the furnace by opening a quick-acting ball valve. The furnace and accumulator equalize pressures at the desired casting pressure within one second.

Earlier designs used a single accumulator tank and fast acting valve, with piping and valves allowing this tank to serve either furnace. Use of two independent accumulator systems provides significant benefit by reducing the complexity of the piping and operations inside the glovebox. In addition, the potential for connecting the accumulator to the wrong furnace is eliminated.

Furnace System Piping and Instrumentation Layout

The conceptual system layout is shown below.

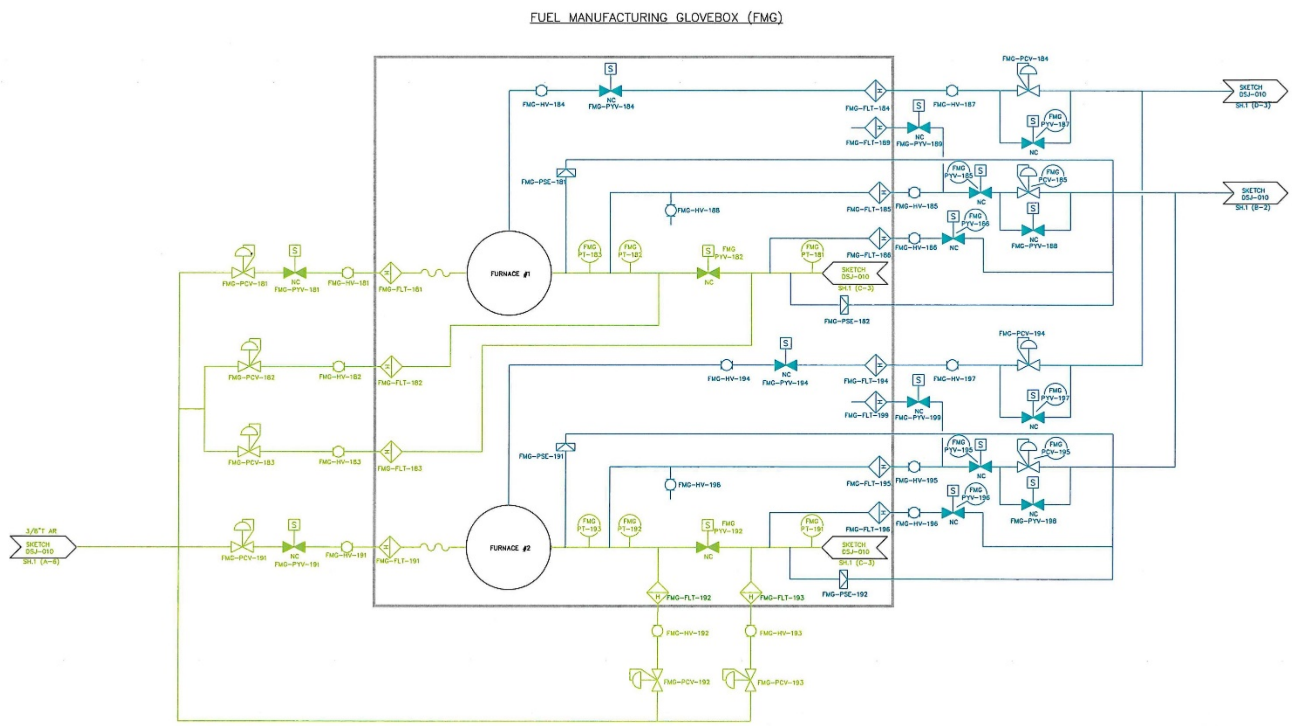

Figure 14 -Conceptual P&ID

For static positive pressure control of the furnace, and for charging the accumulators, argon regulators on the gas supplies would be used. It is anticipated that these would be electronically adjustable to allow the control computer system to set pressures. When pallet cooling is initiated, control of furnace pressure would shift to a back-pressure regulator on the vent line to suspect exhaust. A bypass valve is provided for each back-pressure regulator to provide for fully venting the furnace after operation. For operation at pressures below atmospheric, the vacuum system would be used with a vacuum regulator to allow a controlled negative pressure to be established. Each back-pressure regulator is provided with a bypass valve to support full-vacuum operation. A solenoid-controlled valve is provided on each furnace vent line to allow the furnace to be vented into the glovebox to equalize pressure with the glovebox. A manual vent valve is provided to keep the furnace vented to the box when the control system is not active.

General Control System

In general, the control system for the casting system will be as fully automated as practical. For initial process development, the system will allow all significant casting parameters (such as heatup rates, dwell, pressures etc.) to be adjusted to create a “recipe” for the fuel alloy being cast. Once developed and verified, the recipe would be used to automate the casting process. Once the furnace is ready for casting (the crucible is loaded with material and the elevator installed (with an empty pallet attached) the casting process would proceed without operator intervention until the system is ready to be opened and the pallet containing the cast elements removed.

A comprehensive data acquisition system would be provided to record all system parameters during the casting process. This both provides quality assurance data for the casting run, but allows troubleshooting if problems are encountered or if an excessive number of flawed castings are noted during further processing.

To ensure that the system and facility operators are protected in the event of system failures or unexpected occurrences. The control systems will be designed to fail to a safe condition. Generally, in the event of a significant failure or fault (including manual initiation of “emergency stop”), the system will fail with the following status:

- The pallet shall be in the raised position
- Thermal shutters shall be closed
- Furnace power shall be de-energized
- Pressure and vacuum sources shall be secured
- The accumulator tank shall be vented.
- The furnace will be vented to a low positive pressure and then equalized with the glovebox atmosphere.

After this safe condition is established, operator action will be required to re-initiate system operations.

Furnace Connection Details

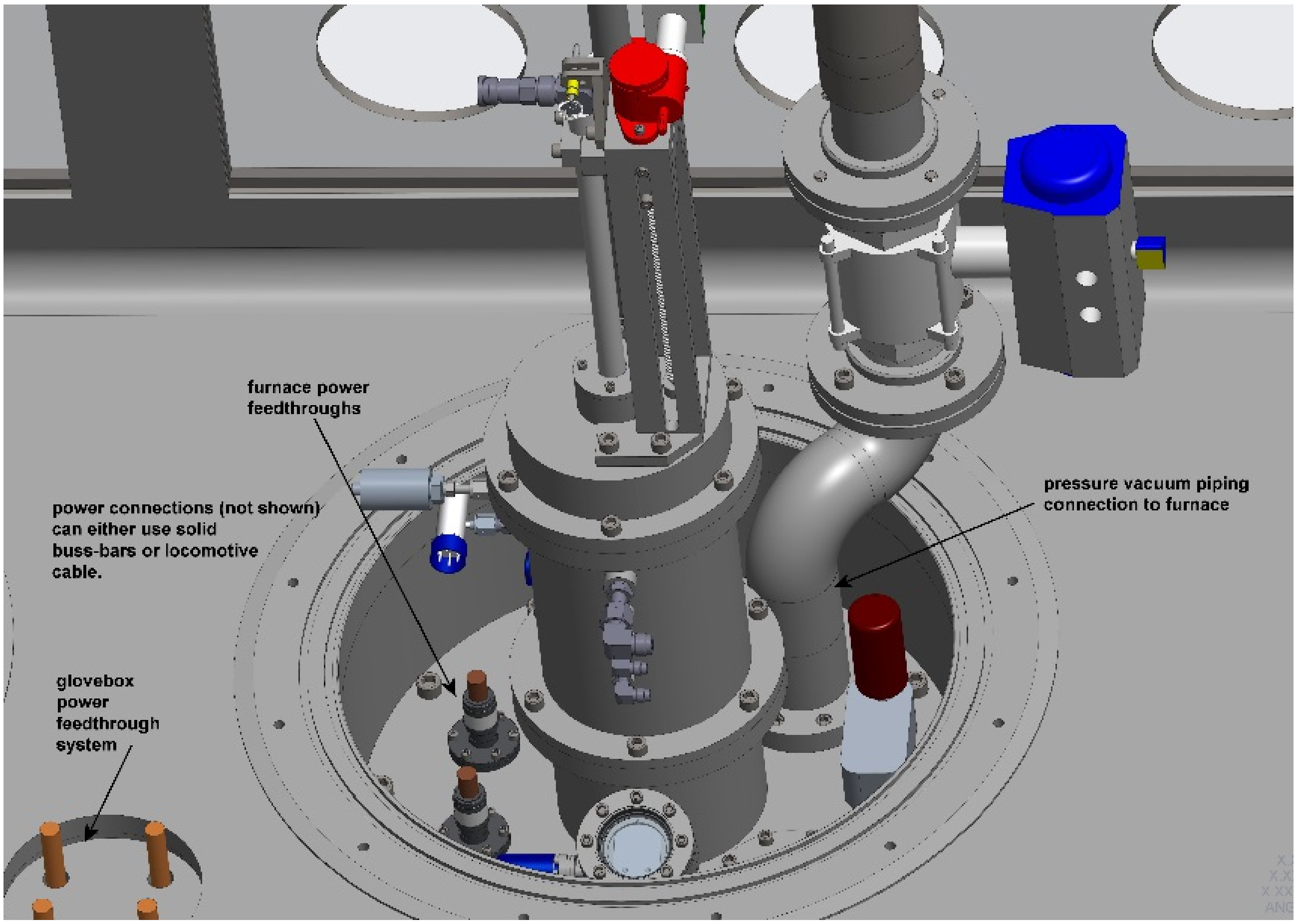

Figure 15 - "Front" side overhead view of furnace

The piping systems inside the glovebox are offset toward the back side (in the above view) to allow clearance for use of the glovebox hoist in loading and unloading the furnace, as well as for maintenance operations such as furnace core removal. Also shown in the above view is the clearance provided between the pallet and top of the furnace (on the left-hand furnace).

The pressure piping and fast acting ball valve are connected directly to the upper flange of the furnace. To maximize available working floor space in the glovebox, power connections for both furnaces are provided in a single power feedthrough on the glovebox floor. It should be noted that protective guards will be needed to ensure that the operators cannot inadvertently come into contact with electrical connections either inside or outside of the glovebox.

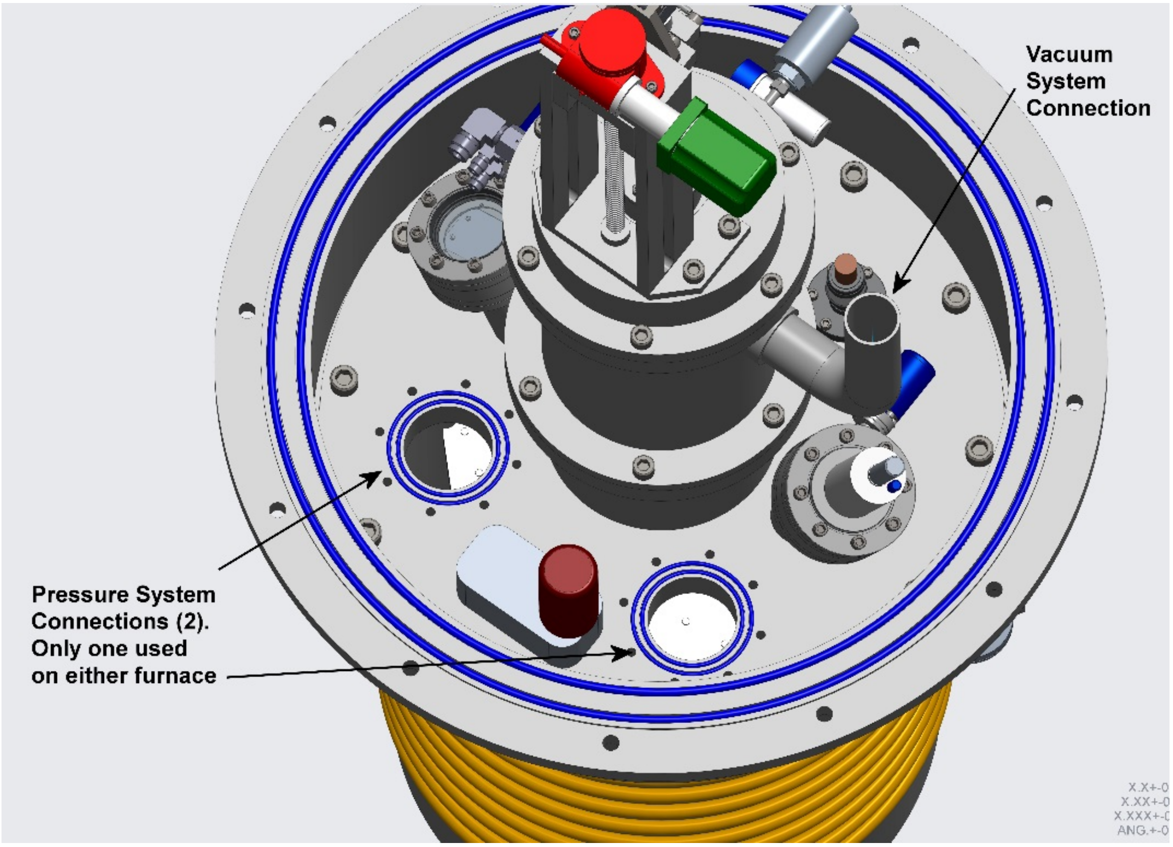

Figure 16 Main Pressure and Vacuum Connections

Due to the use of a single electrical penetration, the glovebox cores had to be installed in a mirrored configuration so that the electrical furnace feedthroughs were closer to the glovebox penetration. To accommodate the need to offset the pressure system piping for pallet handling without requiring that each furnace be completely unique, two pressure connections are provided. The un-used penetration on each furnace will be closed by a blind flange. For the vacuum system, the penetrations were placed on the extension pipe which can be installed in either orientation.

Installation of the pressure system to the extension pipe was considered, but this would expose the relatively hot molds directly to the cold argon flow during injection molding. This would almost certainly result in mold failures and casting failures due to overcooling of molds and was therefore rejected.

Design for Installation and Removal

During the life of the system, it is anticipated that replacement of an entire furnace would be necessary at least once. In addition, it is possible that a furnace could be damaged in some accident in a manner which would require its removal. To accommodate these possibilities while allowing continued operation on the remaining furnace, the conceptual design is arranged to allow a furnace to be removed and the glovebox to be operated in a single-furnace configuration.

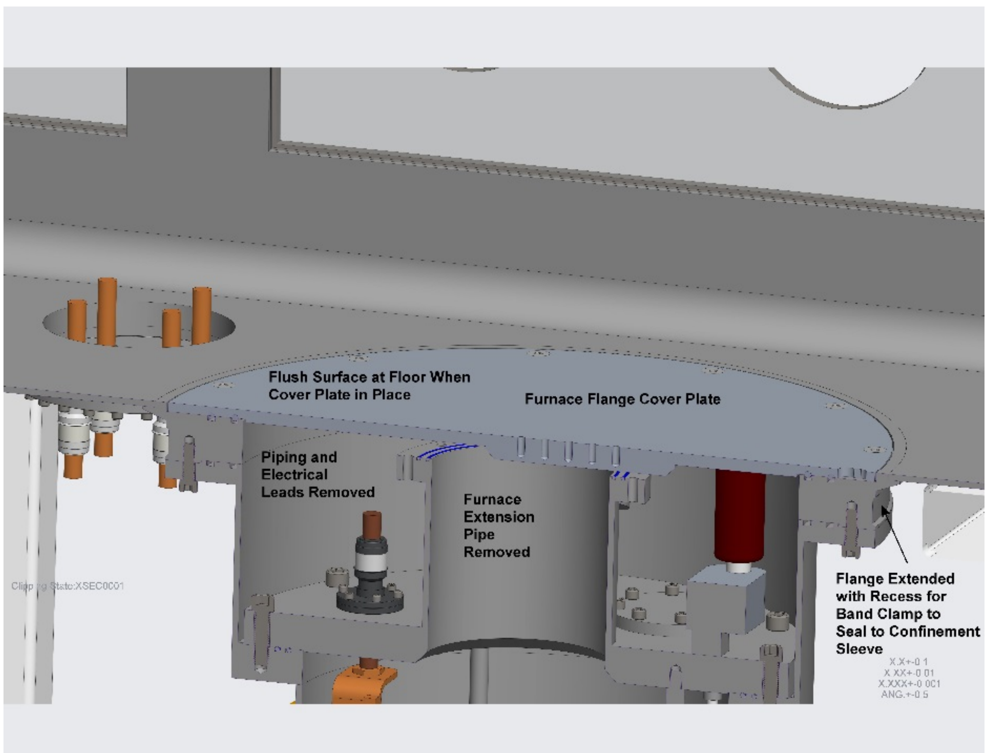

Figure 17- Furnace Installation/Removal

To accommodate total removal of the furnace, it is designed to be short enough to be removed from the glovebox with the furnace core installed. To ensure a robust confinement boundary while the furnace is not installed, a flange cover is provided, and would be kept inside the glovebox when not in use. This would also allow the system to be operated for an extended period with only a single installed furnace. The glovebox flange is configured to allow attachment of a radiological sleeve, which would be part of an overall confinement system to be developed by INL for use in the eventuality that the furnace would need to be installed or removed. The furnace cover is flush with the glovebox floor when installed to allow it to be used without restriction as part of the working surface of the glovebox.

Appendix A

Engineering Inputs

The initial engineering inputs are described in the body of the TEV. Essentially, the intent was initially to duplicate the previous FMF Cold Line furnace system with modifications and confinements to make it suitable to process Pu based metal fuel. The furnace system was required to fit into the facility along with additional glovebox systems (outside the scope of this TEV) required to develop the fabrication process for VTR fuel elements. It was also desired that the facility arrangement be designed such that it would not preclude eventual installation of additional production capacity. FOR-489 *VTR Fuel Development Casting System* was developed concurrently with the conceptual design. This document contains current engineering inputs for the further development of the design.