GA–A25247

# Z-PINCH IFE

## Task 2 — IFE Power Plant Technology
## Load Production and Debris Removal

## Final Report

by

R. GALLIX, W.S. RICKMAN, and N.B. ALEXANDER

Prepared under
Contract No. 69070
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GENERAL ATOMICS

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# 1. PURPOSE

The purpose of this report is to present the work performed by General Atomics (GA) on Task 2, Z-IFE Power Plant Technology under contract No. 301600 to Sandia National Laboratories (SNL). This work consisted of a study to (1) develop a conceptual design for the baseline Z-Pinch IFE load, (2) provide conceptual solutions and cost estimates for the mass production of the loads and their insertion into the Replaceable Transmission Lines (RTL), and (3) provide conceptual solutions and cost estimates for the removal of the load debris. The Z-Pinch IFE load consists of a tungsten wire array assembly and a cryogenic target assembly. The latter includes a beryllium shell holding the layered solid DT fuel, surrounded by low-density carbon foam. The study is based on baseline dynamic hohlraum targets with a 3 GJ-yield fueling an nth-of-a-kind, 3600 MW(th)/1000 MW(e) power plant (Fig. 1) with ten reactor chambers, each operating continuously at 0.1 Hz (Fig. 2), as described in Refs. [1] and [2], and at the Z-Pinch IFE Workshop in Albuquerque, NM, on August 10–11, 2004.

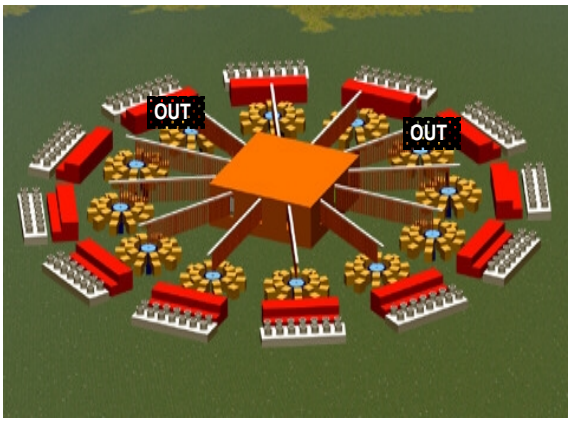



*Fig. 1. 3600 MW(th)/1000 MW(e) Z-IFE power plant.*

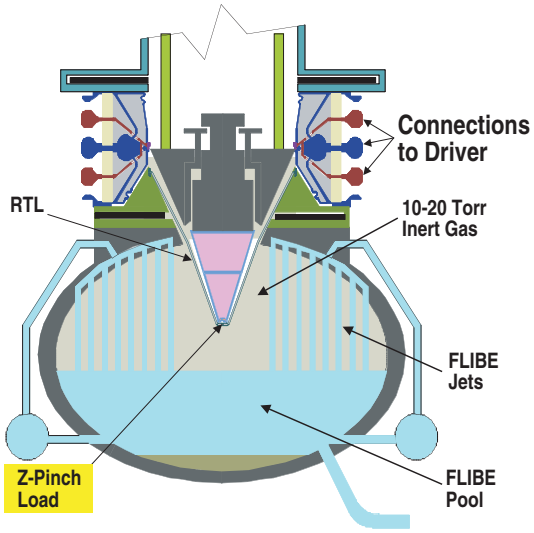



*Fig. 2. Typical Z-IFE reactor chamber.*

This document reports the results of the GA study that took place from May 26th to September 30th, 2004. It builds upon earlier work by GA on Z-Pinch IFE load production, notably in Refs. [3] and [4].

# 2. SUMMARY AND CONCLUSIONS

## 2.1. LOAD DESIGN

Figure 3 shows the schematic baseline load configuration specified by Sandia National Laboratory for the Z-Pinch IFE plant. We have turned this schematic configuration into a conceptual engineering design of the load (Fig. 4), based on the arrangement, dimensions and materials specified by the physics design.

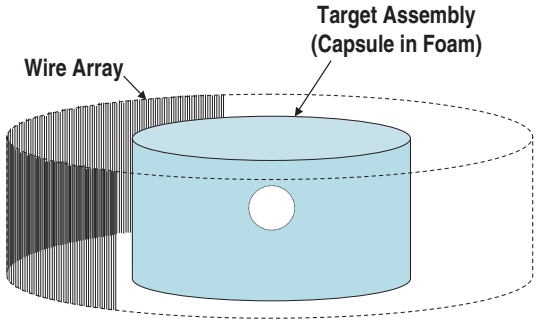



*Fig. 3. Schematic of the baseline Z-IFE load.*

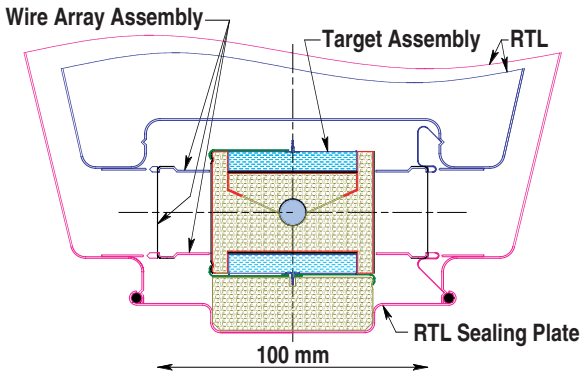



*Fig. 4. Conceptual design of the Z-IFE load in the RTL.*

The proposed conceptual design is intended to facilitate:

- Automatic mass manufacturing and handling of all load components and assemblies,
- Fuel layering (forming and maintaining until shot time a very uniform layer of solid DT ice at about 18 K on the inner wall of the beryllium shells located at the center of the cryogenic target assemblies),
- Automatic assembly in vacuum and at cryogenic temperatures,

- Compatibility with the RTL for load insertion under vacuum at 0.1 Hz, and
- Load production at minimum total cost.

## 2.2. LOAD PRODUCTION

Based on the proposed load design, we have developed a recommended conceptual process for load production, as summarized in Fig. 5.

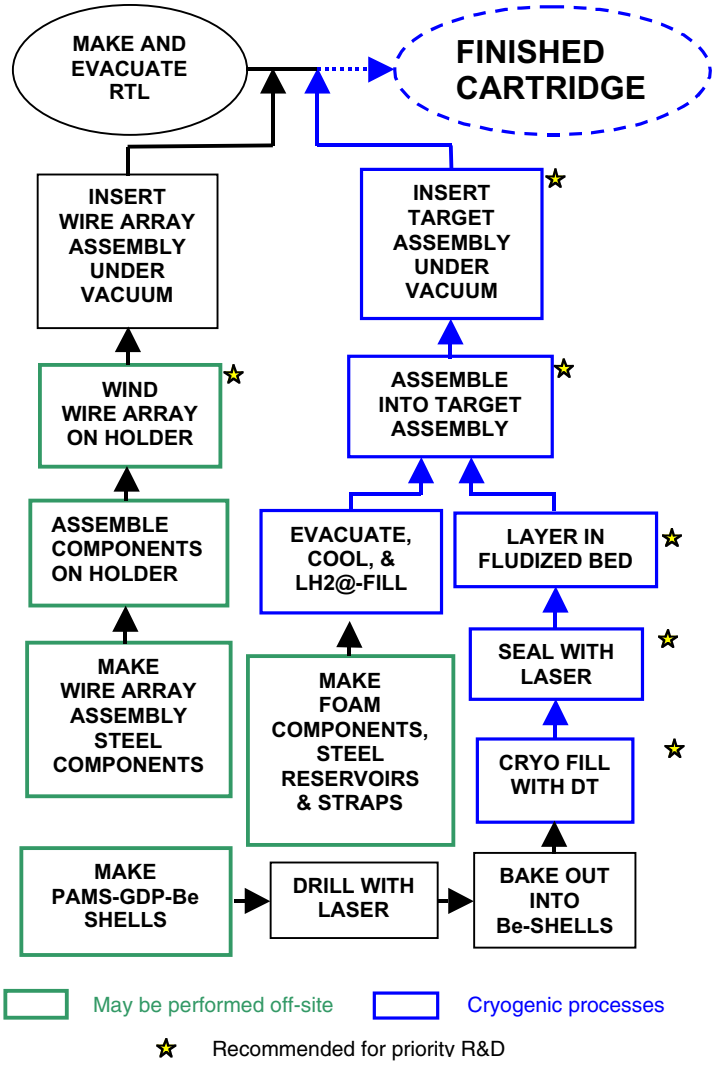



*Fig. 5. Synopsis of the load production process.*

Using chemical engineering analysis techniques, we have devised detailed sequences of necessary manufacturing operations. We have analyzed a commercial-scale load production facility designed to supply 86,400 wire array and target assemblies per day to the power plant. We have further assumed that the loads are made from new, commercially available materials. On this basis, we have prepared preliminary cost estimates for mass production of the loads. They are summarized in Table 1.

**Table 1. Cost Estimates for Producing One Z-Pinch IFE Load per Second for 30 Years**

| | | | Yearly Operating Costs, $M/yr | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | **Capital Cost, $M** | **Annualized Capital Cost, $M/yr** | **Labor** | **Materials** | **Maintenance** | **Utilities** | **Total Annual Costs, $M** | **Cost per Load, $** | |
| **Base Case** 1000 MW(e) power plant with all load components manufactured on-site | **327.1** | **40.9** | **9.1** | **16.8** | **19.6** | **3.5** | **90.2** | **2.86** | |
| ***Sensitivity Studies for the Base Case*** | | | | | | | | | |
| **Doubled Labor Costs** | 327.1 | 40.9 | 18.3 | 16.8 | 19.6 | 3.5 | 99.1 | **3.14** | **10% increase** |
| **Doubled Capital Costs** | 655.8 | 82.0 | 9.1 | 16.8 | 39.3 | 3.5 | 150.7 | 4.77 | **67% increase** |
| **Doubled Materials Costs** | 327.1 | 40.9 | 9.1 | 33.6 | 19.6 | 3.5 | 106.7 | 3.38 | **18% increase** |
| **Doubled Maintenance Costs** | 327.1 | 40.9 | 9.1 | 16.8 | 39.3 | 3.5 | 109.6 | 3.48 | **22% increase** |
| **Doubled Utilities Costs** | 327.1 | 40.9 | 9.1 | 16.8 | 19.6 | 7 | 93.5 | 2.96 | **3% increase** |
| **Alternate Case** 1000 MW(e) power plant with wire array assemblies, foam parts, and empty PAMS/GDP /Be shells pre-fabricated at an off-site facility that serves 10 power plants | 502.2 | 62.8 | 12.2 | 160.4 | 30.1 | 2.1 | 270.2 | | cost of off-site prefabrication facility that serves 10 power plants |
| | 50.2 | 6.3 | 1.2 | 16.0 | 3.0 | 0.2 | 27.0 | 0.86 | cost of off-site prefabrication facility apportioned to one power plant |
| | 157.5 | 19.7 | 6.3 | 0.9 | 9.5 | 3.5 | 39.9 | 1.26 | cost of on-site assembly facility at a single power plant |
| | **207.7** | **26.0** | **7.5** | **16.9** | **12.5** | **3.7** | **66.9** | **2.12** | **total** |
| | -36% | -36% | -17% | 1% | -36% | 6% | -26% | -26% | % change from Base Case |

Our study uses basic technology principles being developed in the laboratory, best engineering judgment, chemical engineering scale-up principles, and established cost estimating

methods. The conceptual design of the production facility includes process flow diagrams, equipment sizing and sketches, and solution storage tanks.

Our cost projections apply to an nth-of-a-kind load production facility, excluding R&D costs. Therefore, we assumed that a significant process R&D program would already have been successfully completed for each of the basic unit operations used in the load production facilities.

We first estimated the production cost per load, for the base case of a load production facility with a 30-year life, located next to the RTL production facility at the power plant. This cost estimate per load includes both the capital and operating costs for the production facility. We also estimated the production cost per load when many power plants will have been built, and cost reductions will be possible by prefabricating certain load components at a remote central production facility with a 30-year life, serving multiple power plants.

Table 1 displays the cost results. For the base case, the total production cost estimate is $2.86 per load, with the wire array assembly and the target assembly accounting respectively for about 16% and 84% of the total. However, the wire array assembly accounts for about 71% of the total material cost per load. The total cost could be reduced by 26% to $2.12 per load if the abovementioned components could be prefabricated at a central facility serving ten power plants.

## 2.3. LOAD DEBRIS REMOVAL

We have devised conceptual methods and prepared preliminary cost estimates for separating and removing the debris of the fired loads from the liquid Flibe coolant. In their end form, the load debris will consist of steel (removed with the RTL debris), beryllium (absorbed into the Flibe), hydrogen isotopes (removed in a vacuum degasser), and tungsten carbide particles. The latter can be removed by seeding and on-line slip-stream filtration, at an estimated total cost of 4.2 cents per load.

## 2.4. RECOMMENDED FUTURE TASKS

Based on this conceptual study, we have determined which aspects of the load design and production present the most uncertainties and risks. The latter are indicated in Fig. 5. As a result, we recommend that the following tasks be performed in priory to reduce the main uncertainties concerning the mass production of Z-Pinch IFE loads and their insertion into RTLs:

- Development and bench top demonstration of the proposed new wire array design and manufacturing process. This may have immediate beneficial applications to on-going Z-Pinch ICF research programs.
- Development and laboratory demonstration of the proposed batch process for the production of net-dimension, low-density, carbonized resorcinol formaldehyde (RCF) foam components.
- Determination of the mechanical and thermal properties of sample RCF foam components.
- Investigation of alternate Be shell manufacturing methods better suited to mass production than sputtering, e.g., Chemical Vapor Deposition.
- Development and bench top demonstration of the proposed batch processes for laser drilling, cryo-filling, and laser sealing of Be shells.
- Development and bench top demonstration of the proposed fluidized bed process for layering DT-filled Be shells.
- Development, prototyping, and testing of the mechanical and thermal design proposed for the target assembly.
- Development and bench top demonstration of the assembly process for the proposed target assembly design, especially automatic precision handling, assembling and sealing of delicate components at approximately 18 K in vacuum.
- Development and bench top demonstration of the proposed removable RTL sealing plate.

# 3. LOAD DESIGN

## 3.1. WIRE ARRAY ASSEMBLY

The wire array assembly (Fig. 6) consists of 300 parallel tungsten wires, evenly spaced to form a cylindrical array 100 mm in diameter by 30 mm in height. Each wire is a single filament 10 μm in diameter. The wires are held in place at each end by a split-ring wire retainer that presses them against the smooth edge of a 0.635 mm-thick ring plate.

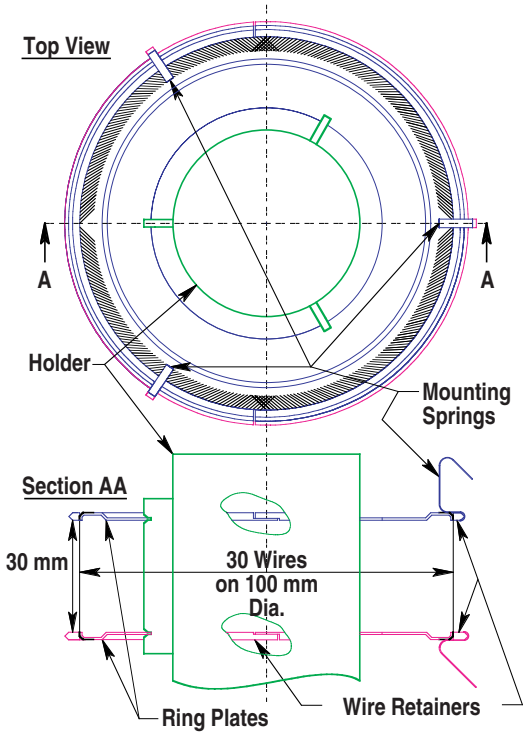



*Fig. 6. Conceptual design for the wire array assembly.*

During manufacturing and insertion of the wire array, described in Sections 4.2.1 and 4.2.5, the wire array is mounted on a holder with an expanding mandrel that engages the IDs of its two ring plates. Small indentations in the outer corners of the ring plates accurately locate the wires at assembly. Three mounting springs, with a 0.2 mm × 5 mm cross section, are clipped at 120° over the edge of each split-ring retainer; they are used to snap and keep in place the wire array in the tip of an RTL.

During the shot, the electrical current discharge jumps across the small gap between the RTL cathode and the split-ring wire retainer next to it, flows simultaneously through the 300 wires to the other retainer, and jumps across the small gap between the retainer and the RTL anode. To minimize cost and facilitate debris removal and disposal, cross sections are minimized, and the

same carbon steel used for the RTL is also used for the wire array's wire retainers, ring plates, and mounting springs. These can thus be recycled together with the much more massive RTL, at minimum additional cost.

## 3.2. TARGET ASSEMBLY

The target assembly (Fig. 7) is of the "dynamic hohlraum" type. At its center is a 330 μm-thick, 10 mm-diameter, DT-filled, beryllium capsule with an inner layer of frozen D-T.

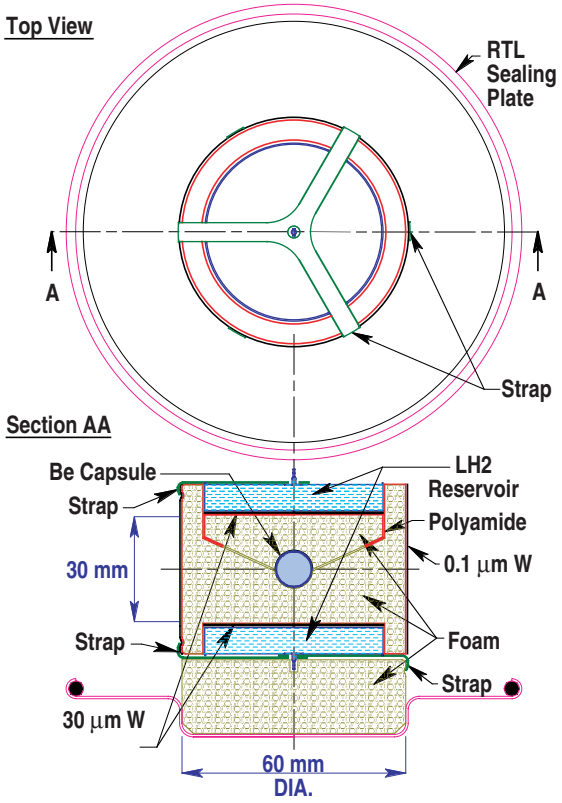



*Fig. 7. Conceptual design for the target assembly and the RTL sealing plate.*

The capsule is surrounded by a 60 mm-diameter, 30 mm-high cylinder of low-density (~10 mg/cc), open-cell, carbon foam. To allow placement of the capsule at the center of the foam cylinder, the latter is divided into a body and a plug, both partially coated with a film of polyamide. The side of the body is also coated with a 0.1 μm-thick, low-emissivity tungsten coating. The body and plug are assembled around the capsule and sealed together in a 3 Torr helium gas environment that remains trapped in the foam cylinder.

Two 30 μm-thick tungsten disks and two carbon-steel reservoirs with 0.1 mm-thick walls are placed below and above the foam cylinder. The bottom surface of the lower reservoir and the top surface of the upper reservoir are given a finish with a 0.02 emissivity. The reservoirs are filled

with a total of 83 $cm^3$ of liquid hydrogen ($LH_2$) at atmospheric pressure, initially at 18 K. An unsealed pedestal of low-density foam thermally insulates the above subassembly from the RTL sealing plate. Three 0.1 mm-thick carbon-steel straps clinch together all of the above described the components into the finished target assembly.

The target assembly is located and mechanically supported by the removable RTL sealing plate. This necessary component of the RTL allows the target assembly to be inserted into the RTL under vacuum, inside the Load Insertion Station (LIS). An organic O-ring is captured at the edge of the sealing plate. Pushing the plate into place over the rim of the opening at the tip of the RTL compresses the O-ring against this rim. This makes a vacuum seal and holds the sealing plate in place on the RTL. When atmospheric pressure and vacuum are present respectively outside the RTL and in the RTL inner space, the resulting upward force on the plate further tightens the seal.

During the shot, the tungsten coating on the side of the foam cylinder provides the "First Strike Liner" and the tungsten disks below and above the foam cylinder reflect X-rays toward the center of the target assembly, as required by the physics design of the target.

Before the capsule is inserted into the target assembly, the DT is frozen and forms a smooth and uniform layer on the inside of the capsule, through a process known as beta layering. Previous studies performed on the injection of targets for IFE have determined that a filled and layered target must be maintained in the 18.0 K to 19.7 K-temperature range. Below 18.0 K, the DT gas in the center of the capsule has a lower pressure than required by the target designers, and experiments have shown that the solid DT layer becomes unacceptably rough. Above 19.7 K, the solid DT becomes very soft and the slumps, thereby destroying required target symmetry.

The above-described design of the target assembly is driven by this need to control the capsule temperature, from the time the target assembly is inserted into the RTL in the room temperature environment of the LIS, until the cartridge is inserted into one of the reactor chambers at 650°C and shot.

The higher thermal conductivity of the helium gas trapped inside the foam cylinder helps transfer the heat generated in the capsule by the beta decay of the DT to the $LH_2$ reservoirs, where it is absorbed. The low-emissivity of the outer surfaces of the target assembly and the low-conductivity of the foam pedestal in vacuum reduce the heat transferred from the RTL to the target assembly and absorbed by the reservoirs. The high sensible heat capacity of the $LH_2$ initially at 18 K in the reservoirs slows down the temperature rise of the DT layer above 18 K.

An earlier simplified analysis by GA of the heat up of a ZFE target during assembly and insertion (Ref. [5]) has been updated for the proposed target assembly design. The new results

show that the total time available to insert a target assembly into the RTL, transport the thus completed cartridge to a reactor chamber, insert the cartridge into the reactor chamber, and fire it, can be as much as 95 s before the capsule temperature rises from 18 K to 19.2 K. This time is divided into 87 s outside and 8 s inside the reactor chamber, with respective temperature increases of 0.2 K and 1.5 K. This should provide sufficient margin at this early stage of the Z-IFE power plant project, when compared with the nominal 10 s total cycling time between shots assumed for the design of each reactor chamber.

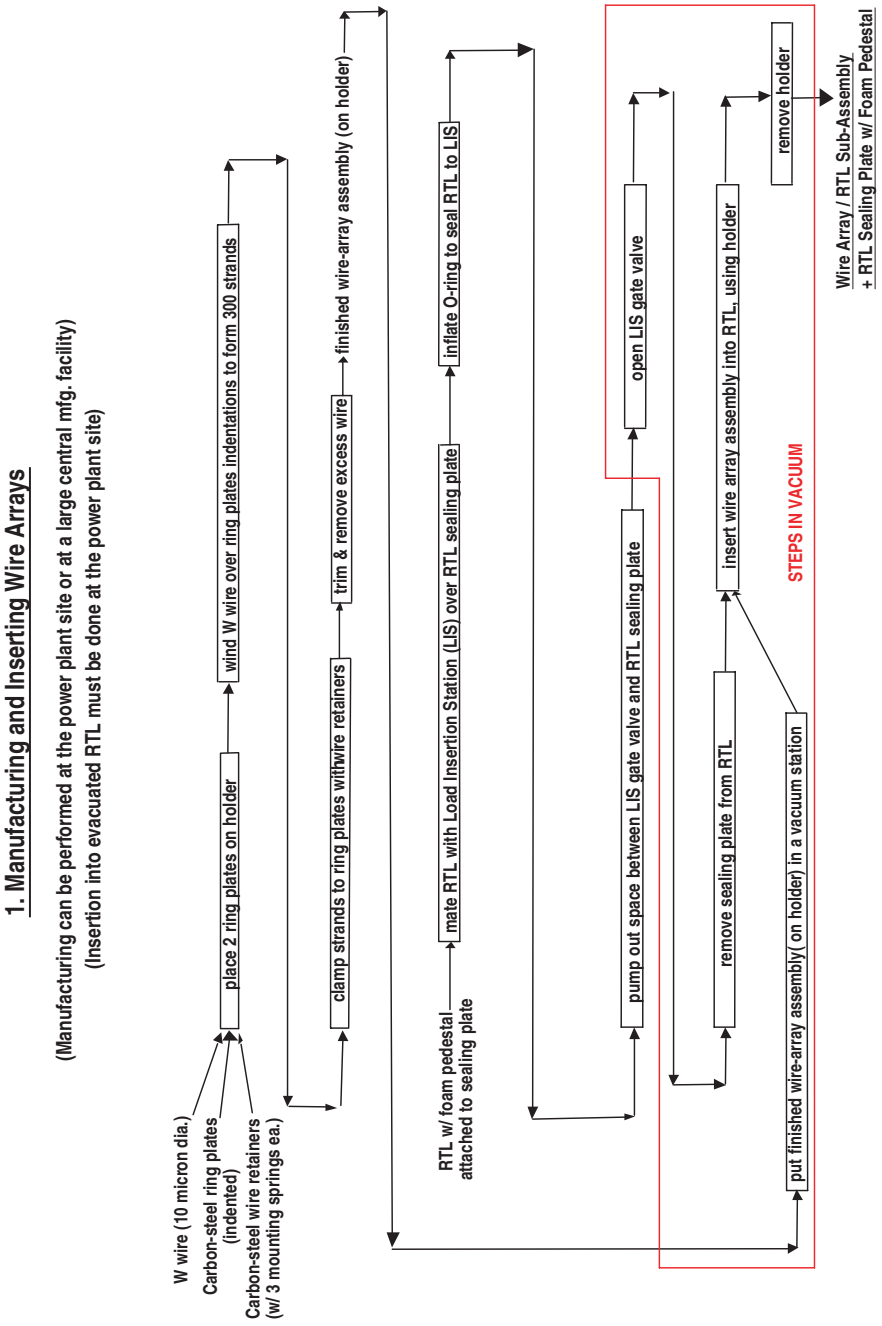
Although this analysis is believed to be a good estimate, several simplifying assumptions were used. It is recommended that in the next phase of this program, a finite element analysis, with temperature dependent material properties, be performed to verify these results.

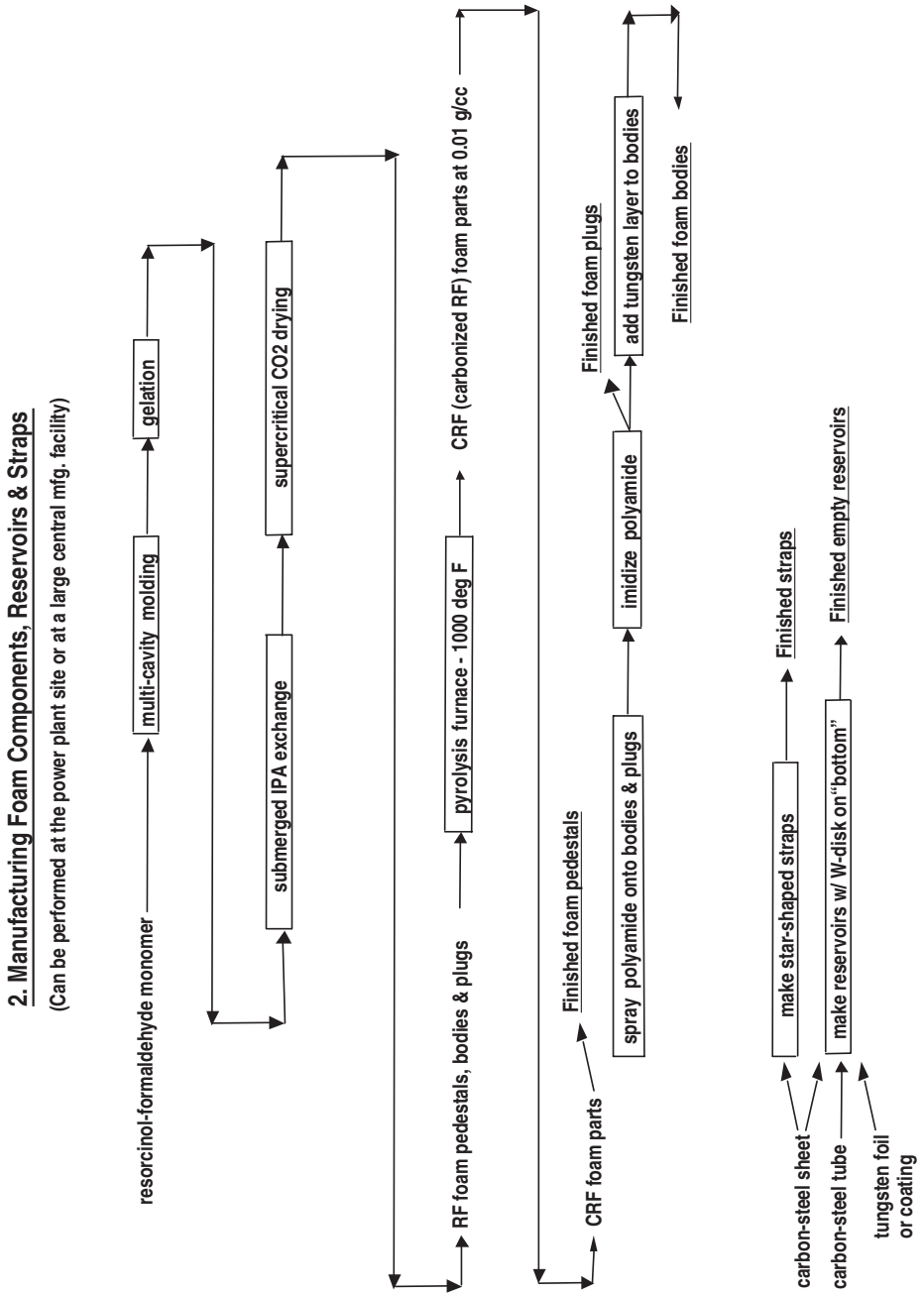
Finally, to minimize cost and facilitate debris removal, minimum quantities and number of types of materials are used for the load. The hydrogen reservoirs, as well as the straps holding the target assembly together, are made of thin stampings of the same carbon steel material as the RTL, so that they can be recycled with the RTL.

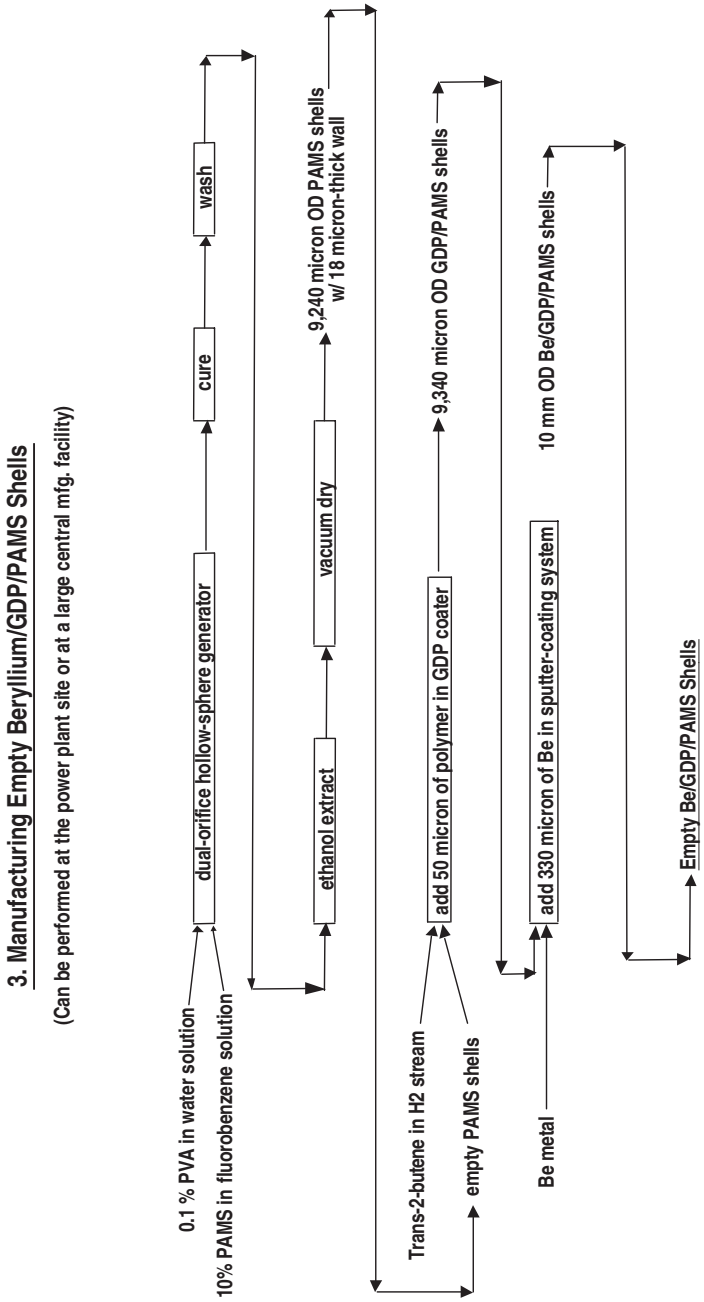
# 4. LOAD PRODUCTION

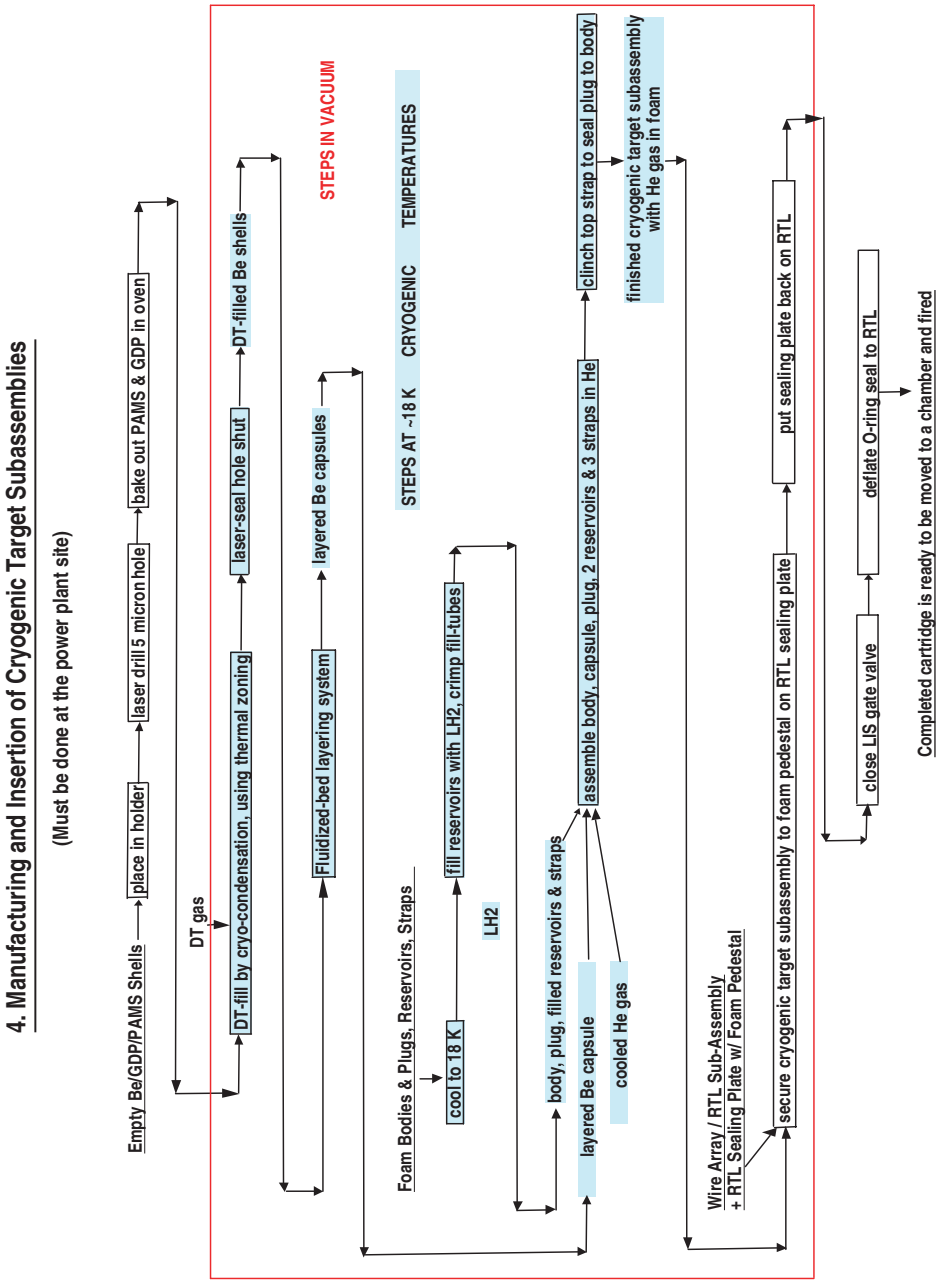
## 4.1. SUMMARY OF THE LOAD PRODUCTION PROCESS

The proposed process for the mass production of Z-Pinch IFE Loads is summarized in Fig. 5. Detailed flow sheets are given below.


1. Manufacturing and Inserting Wire Arrays
(Manufacturing can be performed at the power plant site or at a large central mfg. facility)
(Insertion into evacuated RTL must be done at the power plant site)
W wire (10 micron dia.)
Carbon-steel ring plates (indented)
Carbon-steel wire retainers (w/ 3 mounting springs ea.)
place 2 ring plates on holder
wind W wire over ring plates indentations to form 300 strands
clamp strands to ring plates withwire retainers
trim & remove excess wire
finished wire-array assembly (on holder)
RTL w/ foam pedestal attached to sealing plate
mate RTL with Load Insertion Station (LIS) over RTL sealing plate
inflate O-ring to seal RTL to LIS
pump out space between LIS gate valve and RTL sealing plate
open LIS gate valve
remove sealing plate from RTL
insert wire array assembly into RTL, using holder
remove holder
put finished wire-array assembly( on holder) in a vacuum station
STEPS IN VACUUM
Wire Array / RTL Sub-Assembly
+ RTL Sealing Plate w/ Foam Pedestal


2. Manufacturing Foam Components, Reservoirs & Straps
(Can be performed at the power plant site or at a large central mfg. facility)
resorcinol-formaldehyde monomer
multi-cavity molding
gelation
submerged IPA exchange
supercritical CO2 drying
RF foam pedestals, bodies & plugs
pyrolysis furnace - 1000 deg F
CRF (carbonized RF) foam parts at 0.01 g/cc
Finished foam pedestals
CRF foam parts
spray polyamide onto bodies & plugs
imidize polyamide
Finished foam plugs
add tungsten layer to bodies
Finished foam bodies
carbon-steel sheet
make star-shaped straps
Finished straps
carbon-steel tube
make reservoirs w/ W-disk on "bottom"
Finished empty reservoirs
tungsten foil or coating


3. Manufacturing Empty Beryllium/GDP/PAMS Shells
(Can be performed at the power plant site or at a large central mfg. facility)
0.1 % PVA in water solution
10% PAMS in fluorobenzene solution
dual-orifice hollow-sphere generator
cure
wash
ethanol extract
vacuum dry
9,240 micron OD PAMS shells w/ 18 micron-thick wall
Trans-2-butene in H2 stream
empty PAMS shells
add 50 micron of polymer in GDP coater
9,340 micron OD GDP/PAMS shells
Be metal
add 330 micron of Be in sputter-coating system
10 mm OD Be/GDP/PAMS shells
Empty Be/GDP/PAMS Shells


4. Manufacturing and Insertion of Cryogenic Target Subassemblies
(Must be done at the power plant site)
STEPS IN VACUUM
STEPS AT ~18 K
CRYOGENIC
TEMPERATURES
Empty Be/GDP/PAMS Shells
place in holder
laser drill 5 micron hole
bake out PAMS & GDP in oven
DT gas
DT-fill by cryo-condensation, using thermal zoning
laser-seal hole shut
DT-filled Be shells
Fluidized-bed layering system
layered Be capsules
Foam Bodies & Plugs, Reservoirs, Straps
cool to 18 K
fill reservoirs with LH2, crimp fill-tubes
LH2
body, plug, filled reservoirs & straps
layered Be capsule
cooled He gas
assemble body, capsule, plug, 2 reservoirs & 3 straps in He
clinch top strap to seal plug to body
finished cryogenic target subassembly with He gas in foam
Wire Array / RTL Sub-Assembly
+ RTL Sealing Plate w/ Foam Pedestal
secure cryogenic target subassembly to foam pedestal on RTL sealing plate
put sealing plate back on RTL
close LIS gate valve
deflate O-ring seal to RTL
Completed cartridge is ready to be moved to a chamber and fired

## 4.2. DETAILED DESCRIPTION OF THE PROCESS

### 4.2.1. Wire Arrays Assemblies

A pair of carbon-steel ring plates are placed and held 30 mm apart on a mechanical holder with an expanding mandrel [Fig. 8.(a)]. Fine tungsten wire (10 μm in diameter) is wound around the pair of ring plates from a spool on a winding arm. The holder is rotated 1.2° on its axis after each turn of the winding arm, placing a pair of strands in one of 300 pairs of matching indentations in the ring plates. After 75 turns of the winding arm, the first half of the array has been wound [Fig. 8.(b)]. The holder is then rotated once by 90° on its axis and the winding arm makes another 75 turns to wind the second half of the array, again with the holder rotated 1.2° on its axis after each turn of the winding arm.

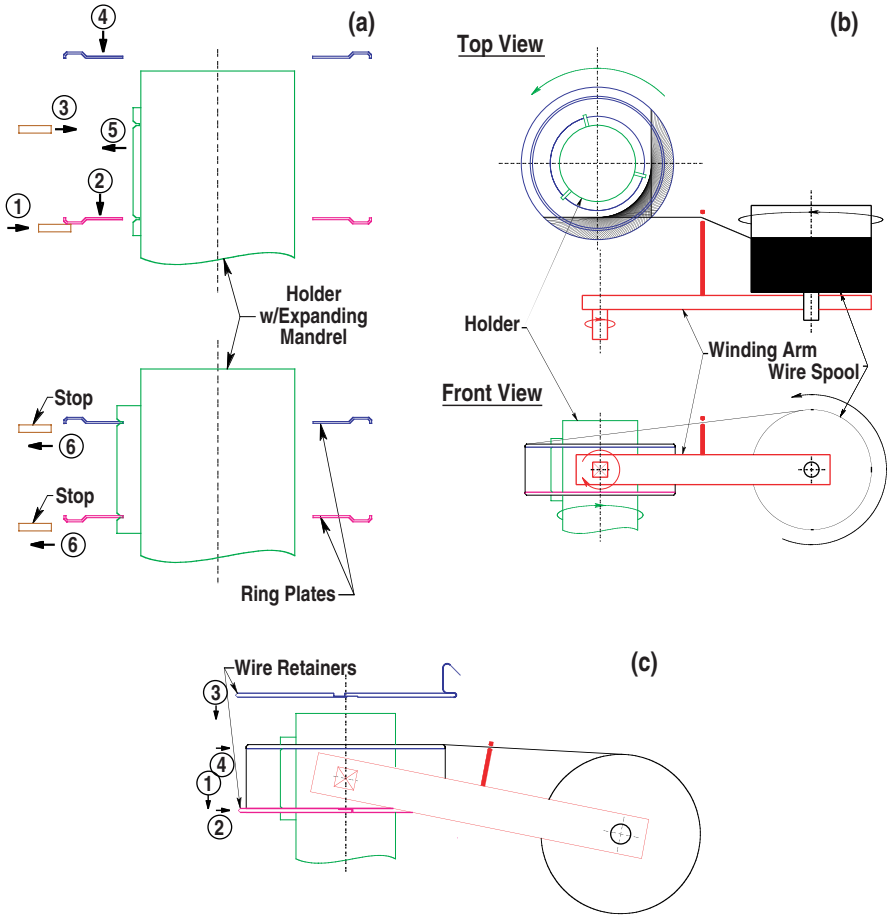



*Fig. 8. (a) Putting two ring plates on a wire array holder, (b) Winding tungsten wire onto the ring plates, and (c) Securing the wires to the ring plates.*

The 300 strands are then clamped to the rings by means of two carbon-steel, split-ring, wire retainers, each with three carbon-steel mounting springs clipped at 120° over the edge of the ring plate [Fig. 8(c)]. Both ends of the wire and the lengths of wire crossing over the ring plates are cut off and removed. Each finished wire array assembly is retained on its holder until it is inserted into the tip of an RTL as explained in section 4.2.5.

The wire array assemblies on holders can be manufactured in the cartridge production facility at the power plan site and stored there in vacuum stations at room temperature. Alternately, they can be manufactured away from the power plan site and shipped in batches to the cartridge production facility at the site to be stored in the same vacuum stations. In both cases, at the site, they will be transferred, at 0.1 Hz under vacuum, from the vacuum stations to each of the ten operating evacuated Load Insertion Station (LIS).

### 4.2.2. Foam Components, Reservoirs and Straps

The foam components of a target assembly comprise a pedestal, a body and a plug. An aqueous solution of resorcinol-formaldehyde monomer is injected and allowed to gel for two days in precision molds with multiple cavities in the final shapes of the foam components (Fig. 9). The gelled parts are removed from the molds and repeatedly washed and rinsed for three days in an increasingly strong isopropyl alcohol (IPA) solution to remove water, followed by supercritical $CO_2$ drying for four days to remove the IPA, which is soluble in both water and supercritical $CO_2$.

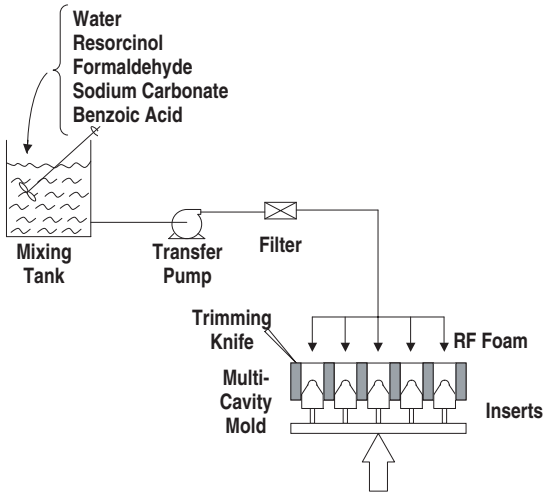



*Fig. 9. Basics of casting and gelling foam bodies.*

The washed resorcinol-formaldehyde parts are placed for one day in a 1000° F furnace to carbonize them and drive off volatile hydrocarbons, leaving solid carbonized resorcinol-formaldehyde foam (CRF) components with a density of 10 mg/cc. A polyamide coating is

sprayed onto part of the body and the plug assemblies, then imidized. A 0.1 mm-thick tungsten layer is sputter-coated on the polyimide film on the side of the body.

Both $LH_2$ reservoirs of the target assembly are identical. They are assembled from stamped, 0.1 mm thick, carbon-steel "bottoms" and "tops" joined together. A short fill-tube fitting of the same material is previously joined to each reservoir "top". The "top" surface of the reservoirs is given a finish with an emissivity of 0.02. The 30 mm-thick tungsten disks attached to the "bottom" of the reservoirs can be punched out of tungsten foil. Alternately, a 30 mm-thick layer of tungsten can be sputtered on the "bottom" of the reservoirs.

The star-shaped straps that clinch the reservoirs to the foam plugs, bodies and pedestals are stamped out of 0.1 mm thick, carbon-steel.

All of the above components can be manufactured and stored in the cartridge production facility at the power plan site. Alternately, they can be manufactured away from the site, then shipped to the site for storage at room temperature in the cartridge production facility. There, the foam pedestals will be attached to the RTL sealing plates as part of the RTL assembly process; and the remaining components will be transferred from storage into cooling stations.

### 4.2.3. Empty Beryllium/GDP/PAMS Shells

Hollow poly-alpha methyl styrene (PAMS) spherical shells are formed by a dual-orifice, hollow-sphere generator in a micro-encapsulation column. A 10% solution of PAMS in fluorobenzene flows through the outer orifice and a dilute (0.1 wt%) aqueous solution of poly-vinyl alcohol (PVA) flows through the inner orifice [Fig. 10(a)].

The hollow PAMS shells flow into a tank where they are cured for a specified time period. During this curing period, the PAMS shells slowly solidify as the solvent is removed through their thin wall.

The cured PAMS shells are washed in water after curing is complete. They are then contacted counter-currently with increasingly strong aqueous solutions of ethanol to remove the water from their interior.

Following ethanol extraction of the bulk of the water, the PAMS shells are vacuum dried to yield empty shells with an outside diameter of 9240 mm and a wall thickness of 150 mm.

The PAMS shells are moved to a glow-discharge polymer (GDP) coater where a 100 mm thick polymer coating is applied to their outer surfaces, making spherical GDP/PAMS mandrels with a very smooth and accurate outer surface [Fig. 10(b)].

A 330 mm thick layer of Beryllium is subsequently sputtered by physical vapor deposition (PVD) onto the outer surface of the GDP/PAMS mandrels, producing 10 mm OD Be/GDP/PAMS shells [Fig. 10(c)].

Batches of Be-GDP-PAMS shells can be manufactured in the cartridge production facility at the power plan site. Alternately, they can be manufactured away from the site, and then shipped to the cartridge production facility at the site. In both cases, the Be/GDP/PAMS shells in their holders will be stored on site until they are laser drilled.

### 4.2.4. Cryogenic Target Subassemblies

The following operations take place in the cartridge production facility at the power plant site.

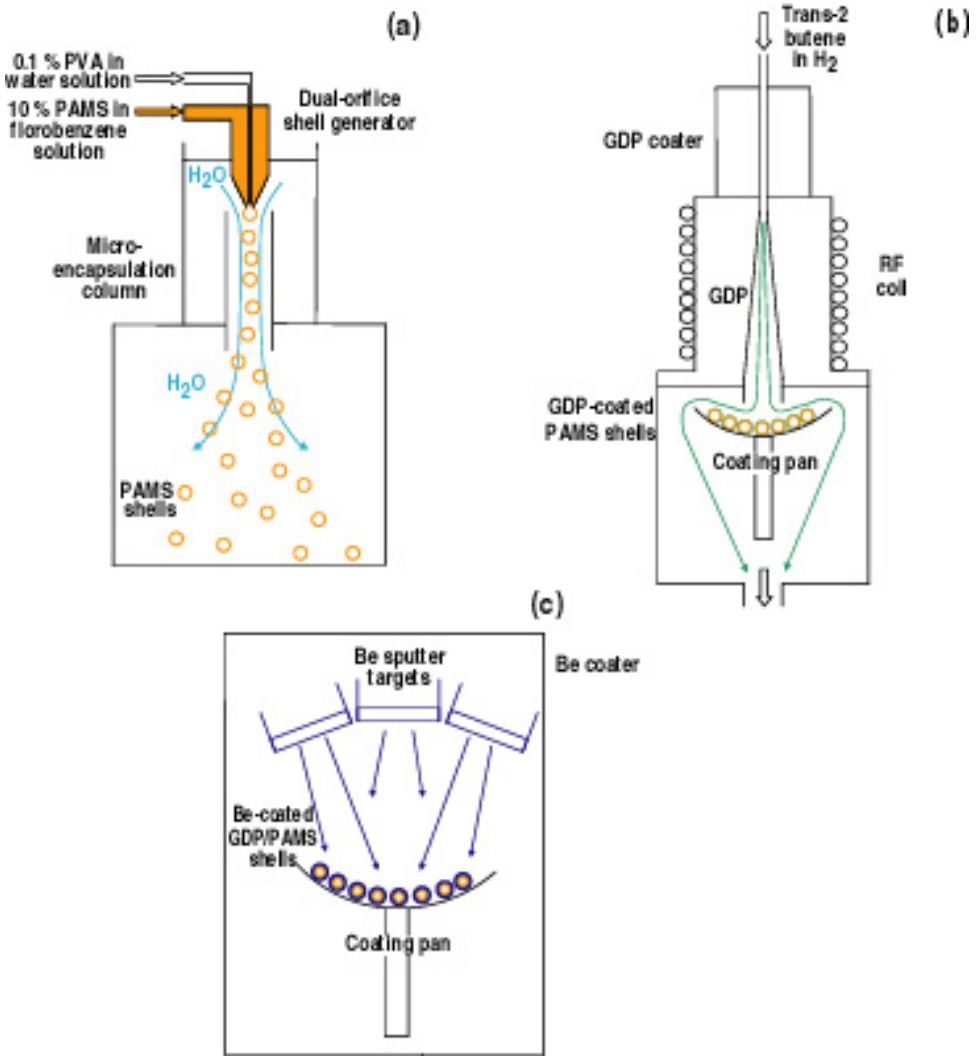



*Fig. 10. (a) Basics of making spherical PAMS shells, (b) Basics of coating GDP on PAMS shells, and (c) Basics of coating beryllium.*

A batch of Be/PAMS/GDP hollow shells is arrayed in a multi-shell holder that holds the shells between a dimpled lower platen and a dimpled and perforated upper platen. The holder is set on a first fast-moving X-Y stage. A vertical laser beam passing through the perforations of the upper platen drills a 5 µm-diameter hole through the top wall of each shell, after the X-Y stage has moved the shell under the laser beam [Fig.11(a)]. The batch of drilled Be/PAMS/GDP shells in its holder is first placed in an oven, where the PAMS and GDP inner coatings are baked out through the holes, then taken out and cooled to room temperature.

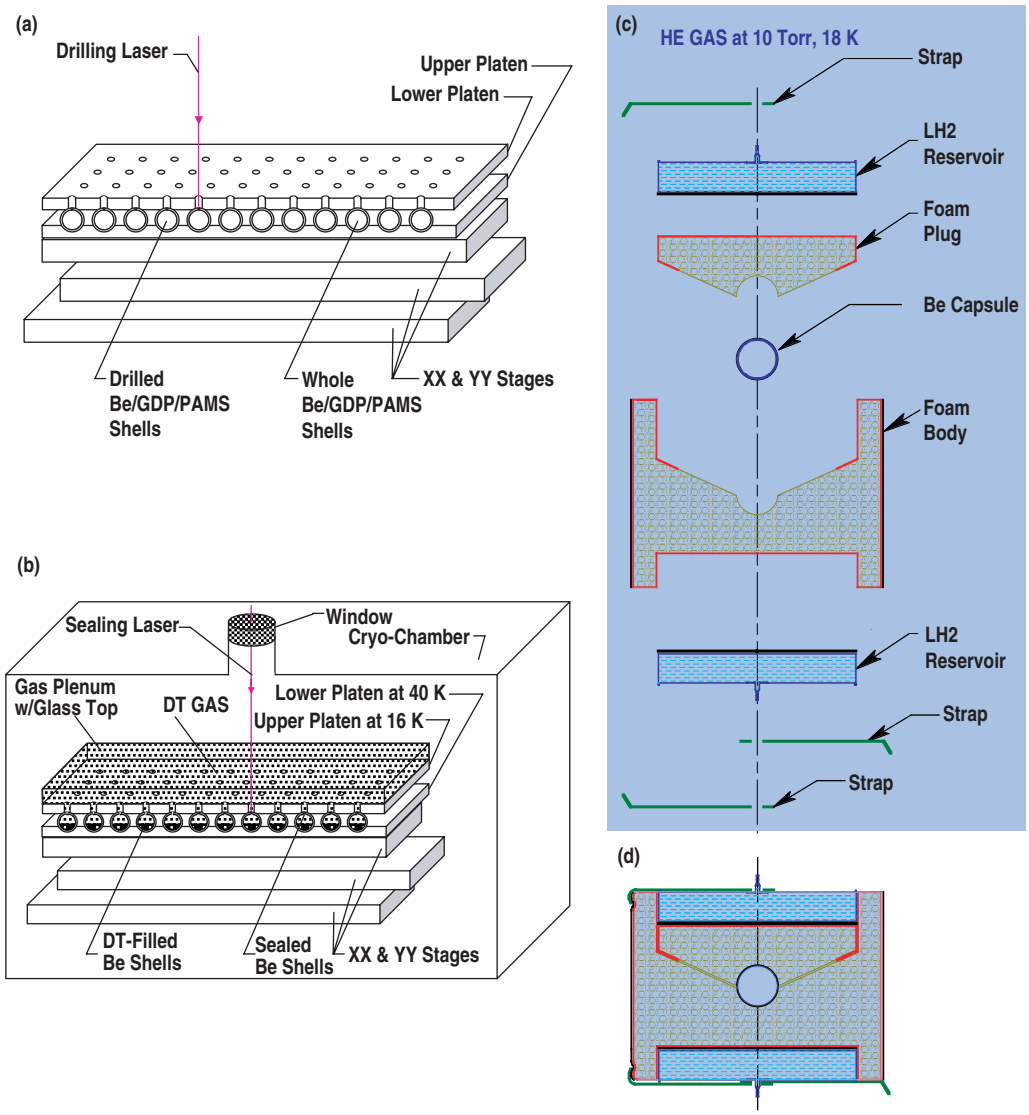



*Fig. 11. (a) Concept for drilling beryllium shells, (b) Concept for cryo-filling and sealing beryllium shells, (c)Putting together a target subassembly, and (d) Completed target subassembly.*

Figure 11(b) shows how the, now empty, Be shells are filled with DT. The same holder, still holding a batch of drilled Be shells with their holes up, is first mounted on a second fast-moving

X-Y stage. A gas plenum with a glass top is fitted and sealed over the top edge of the upper platen of the holder. The stage, the holder with it gas plenum, and the shells are placed at room temperature inside a cryo-condensation chamber with a window at the top. The underside of the dimpled and perforated upper platen of the holder makes a seal with each shell around its top hole.

The chamber and the gas plenum are evacuated and the lower and upper platens of the shell holder are cooled respectively to about 16 K and 40 K, imparting similar temperatures by contact conduction respectively to the bottom and top regions of the shells. DT gas at about 300 Torr is fed into the plenum above the top platen of the holder, through the upper platen's perforations and the shell holes, and into the shell cavities. The DT gas inlet at the top of the plenum is then valved off. A portion of the now fixed mass of DT gas in the chamber plenum condenses as a liquid in the colder, bottom region of the shell cavities, while the holes at the top of the shells remain free of liquid and open. The time necessary for the desired mass of DT to condense inside every shell will be determined by experiments, and by monitoring the drop in DT gas pressure in the plenum.

To rapidly seal the shells at this time, a different laser beam, shining through the top window, the glass top of the gas plenum, and the platen's perforations, quickly melts a spot and seals the hole at the top of each shell after the X-Y stage has moved it under the laser beam, thus trapping the desired mass of DT in each Be shell.

Next, large batches of DT-filled and sealed Be capsules are placed and held for several hours in fluidized-bed cryogenic tanks filled with Helium gas at 18 K for beta layering. The minimum dwell time necessary to produce a DT ice layer with the desired uniformity and smoothness on the inside wall of the capsules will be predetermined by experiment. After that time, the capsules are transferred at 0.1 Hz from the layering tanks to the first section of the cryogenic target subassembly station.

In parallel, large batches of foam bodies, foam plugs, reservoirs, and straps at room temperature are fed into the cooling stations, where they are evacuated, cooled to 18 K, the reservoirs are filled with $LH_2$ at 18 K through their fill tubes, and the tubes are crimped and trimmed off into stubs. These components are then transferred from the cooling stations to the cryogenic target subassembly stations.

Each cryogenic target subassembly station contains Helium gas at 10 Torr and 18 K. It receives and assembles the layered capsules, cooled foam bodies, foam plugs, reservoirs, and straps into target subassemblies. To make each target subassembly, two bottom straps, a bottom $LH_2$-filled reservoir with its tungsten disk, a layered Be capsule, a foam plug, a top $LH_2$-filled reservoir with its tungsten disk, and a top strap are stacked up in that order [Fig. 11(c)]. The

bottom and top straps are then clinched to the foam body, sealing 10 Torr He gas inside the foam cylinder [Fig. 11(d)]. The resulting sealed target subassemblies at 18 K are then transferred under vacuum, at 0.1 Hz, to each of the ten operating evacuated Load Insertion Stations (LIS).

### 4.2.5. Load Insertion into an RTL

The load insertion operations take place at 0.1 Hz in each of the ten operating evacuated Load Insertion Stations (LIS) that serve the ten operating Reactor Chambers. The LIS are part of the central cartridge production facility at the power plant site. This section describes a first attempt at a conceptual design to carry out these operations continuously and automatically. The arrangement of a LIS, and its step-by-step operation, are presented below and illustrated in Figs. 12–17.

A load consists of a wire array assembly, a foam pedestal, and a cryogenic target subassembly. The LIS receives each wire array assembly on its holder from an on-site vacuum station, via a loop conveyer operating at room temperature in a vacuum duct. To reduce the complexity of the insertion operations in the LIS, we assume that the foam pedestal is pre-attached elsewhere to the sealing plate that closes the tip of the RTL, so that it arrives at the LIS already inside each evacuated RTL. The target subassemblies are assembled at 18 K in an on-site cryogenic target subassembly station. They are brought to the LIS via a similar loop conveyer, operating in a second vacuum duct, which is fitted with a helium-cooled inner radiation shield at 18 K. The LIS handles the load components by means of robotic manipulators that are powered and controlled from outside the LIS via mechanical and electrical feed-throughs.

At the start of a load insertion cycle, an evacuated RTL at room temperature is brought above the LIS, and then lowered onto the LIS, so that the tip of the RTL mates with the deflated O-ring on top of the LIS (Fig. 12). The O-ring is inflated to seal off the space between the LIS gate valve and the RTL sealing plate. This space is evacuated and the LIS gate valve is opened.

A first robotic manipulator handles the sealing plate at the bottom of the RTL. It consists of a horizontal arm at the top of a vertical shaft that can be translated vertically and pivoted about its axis. An end-effector is mounted on the arm to grab, remove, hold, replace, and release the RTL sealing plate. The arm swing under the RTL seal plate, reaches up, grabs the sealing plate by its boss, pulls the plate down off the RTL, lowers it to the bottom of the main LIS chamber, and swings it out of the way of the vertical path of the wire array (Fig. 13).

A second robotic manipulator handles the wire array assembly. It consists of a vertical shaft that moves up and down, through gaps in the wire array conveyer and through the LIS main chamber along the vertical axis of the RTL. A mandrel-type end-effector is mounted at the top of the shaft to grab, hold, and release a wire array holder, and to free the wire array from its holder.

The vertical shaft passes through the conveyer from below, lifts a wire array holder off its conveyer and up through the chamber, inserts it into the RTL opening until the six mounting springs of the wire array snap into the two locating grooves in the tip of the RTL. With the wire array thus mounted in the RTL, the manipulator contracts the mandrel of the holder to uncouple it from the wire array (Fig. 14), lowers the empty holder, and puts it back on the wire array conveyer.

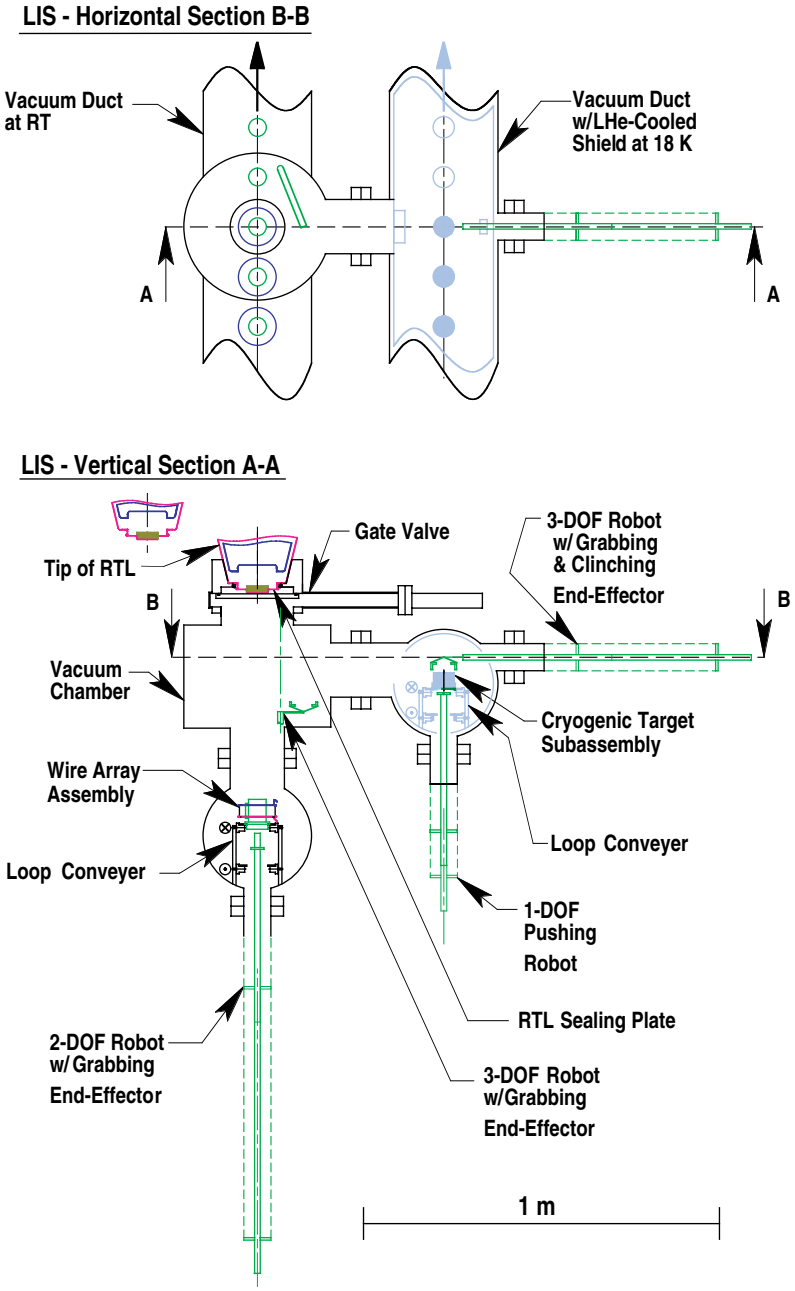



*Fig. 12. Receiving the RTL.*

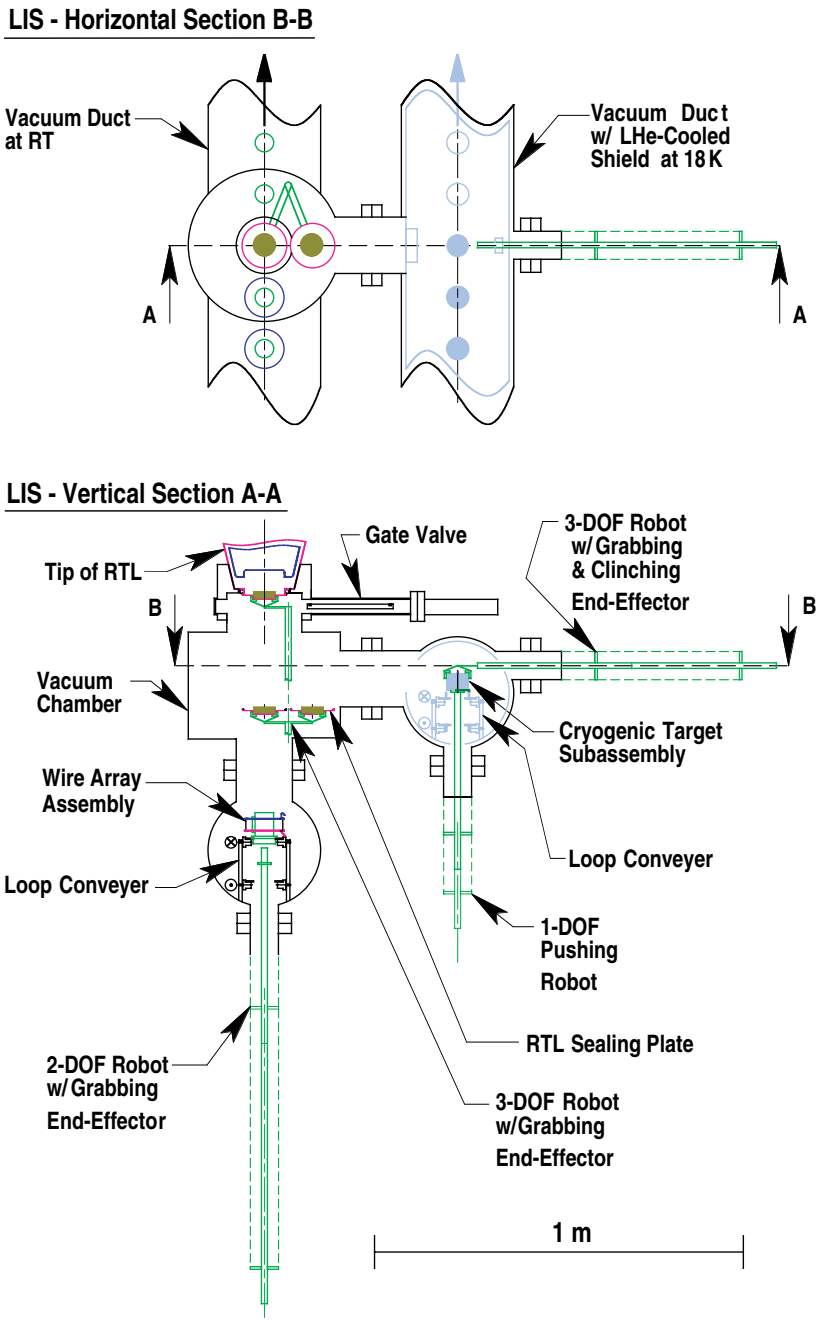



*Fig. 13. Removing the RTL sealing plate.*

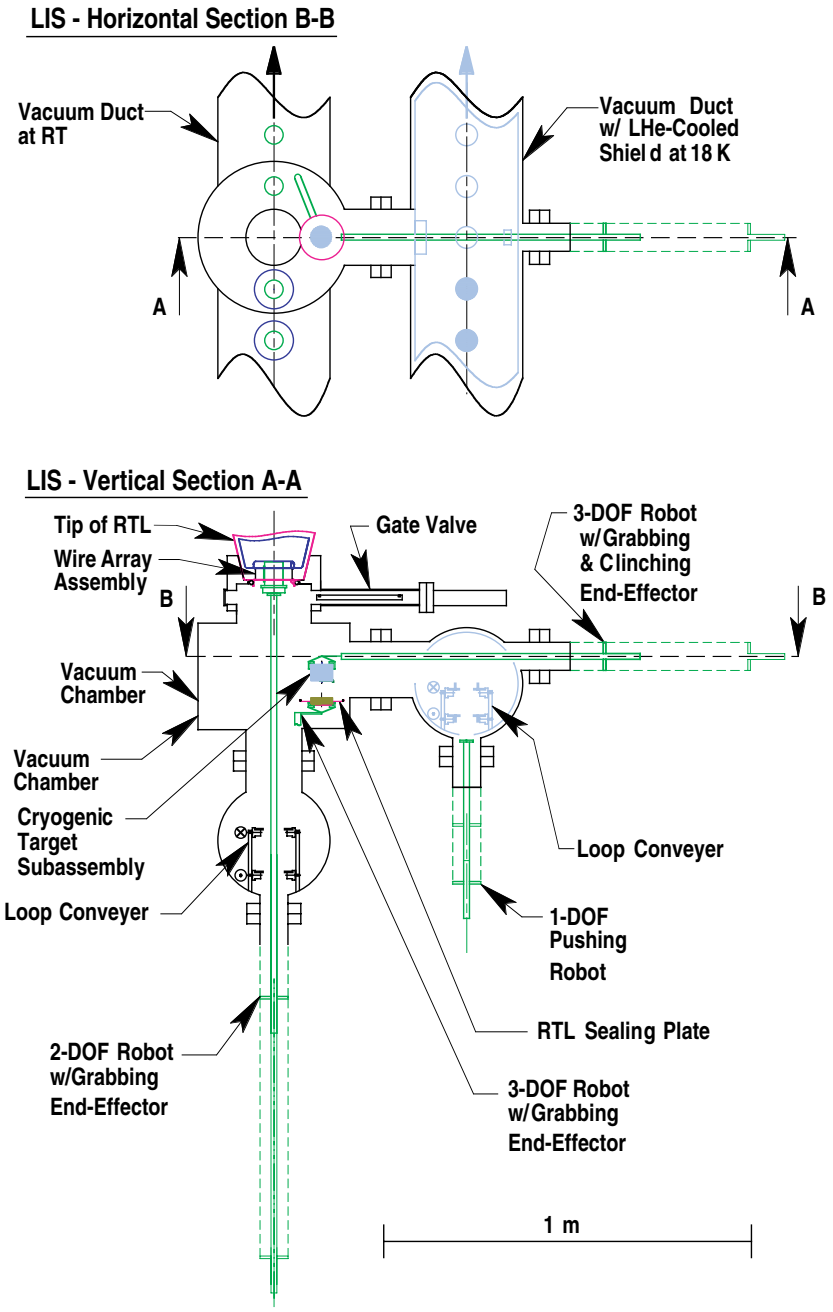



*Fig. 14. Inserting the wire array into the RTL.*

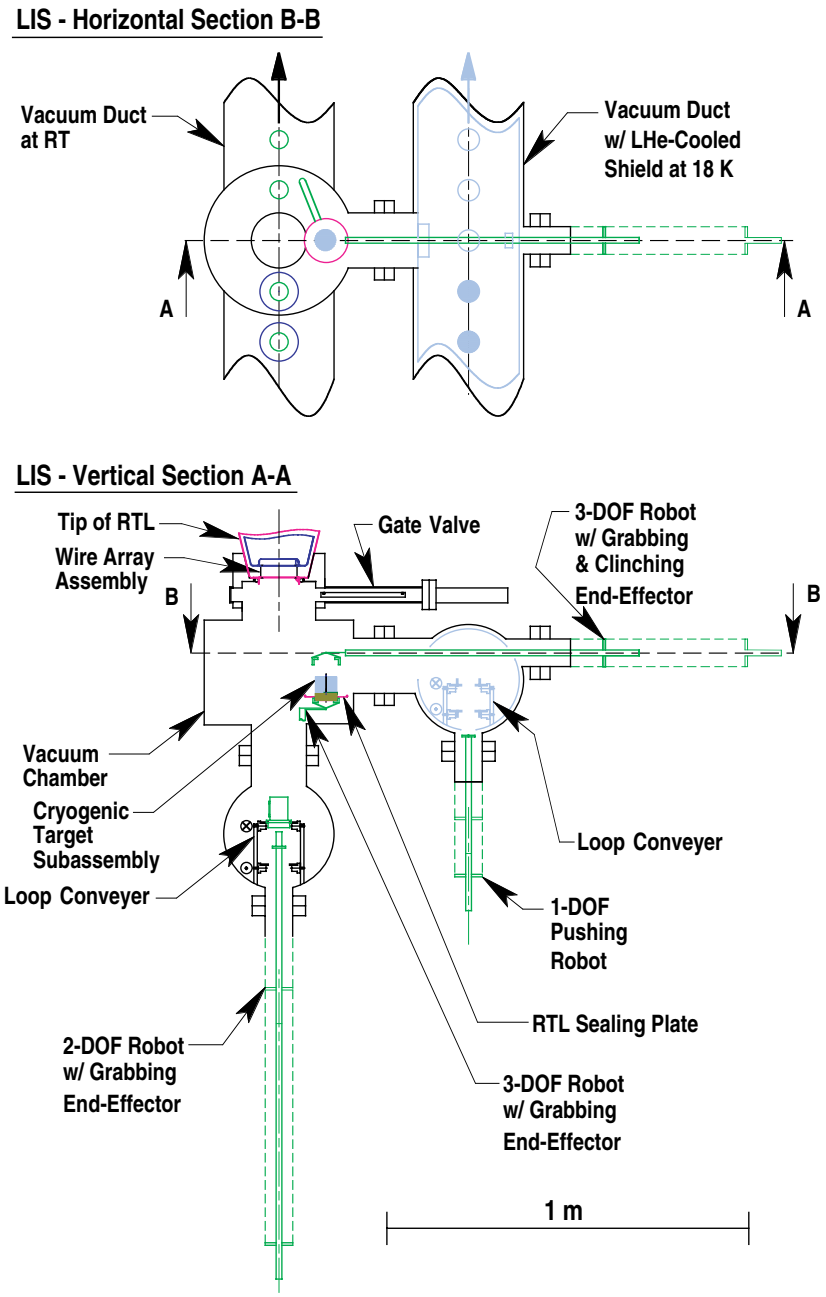



*Fig. 15. Mounting the cryogenic target assembly on the RTL sealing plate.*

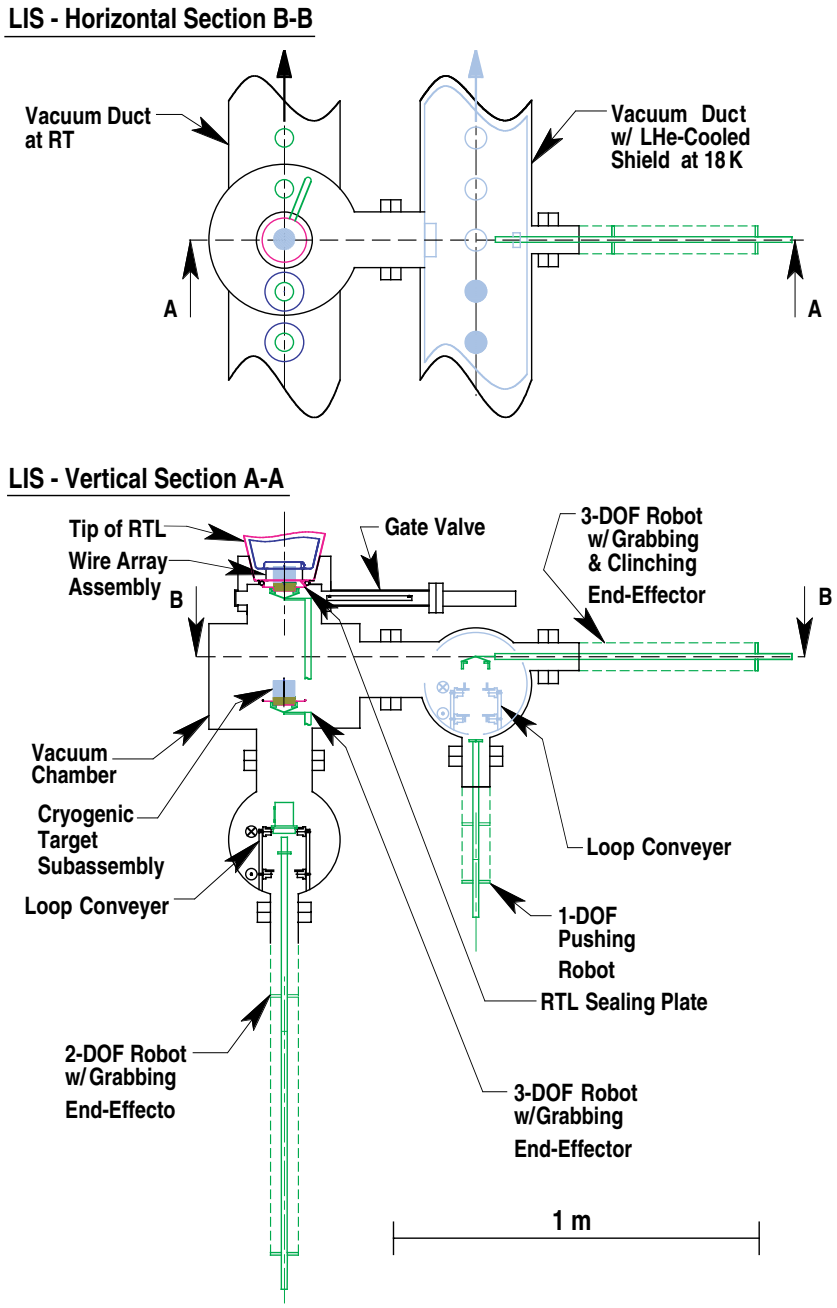



*Fig. 16. Inserting the target assembly and closing the RTL.*

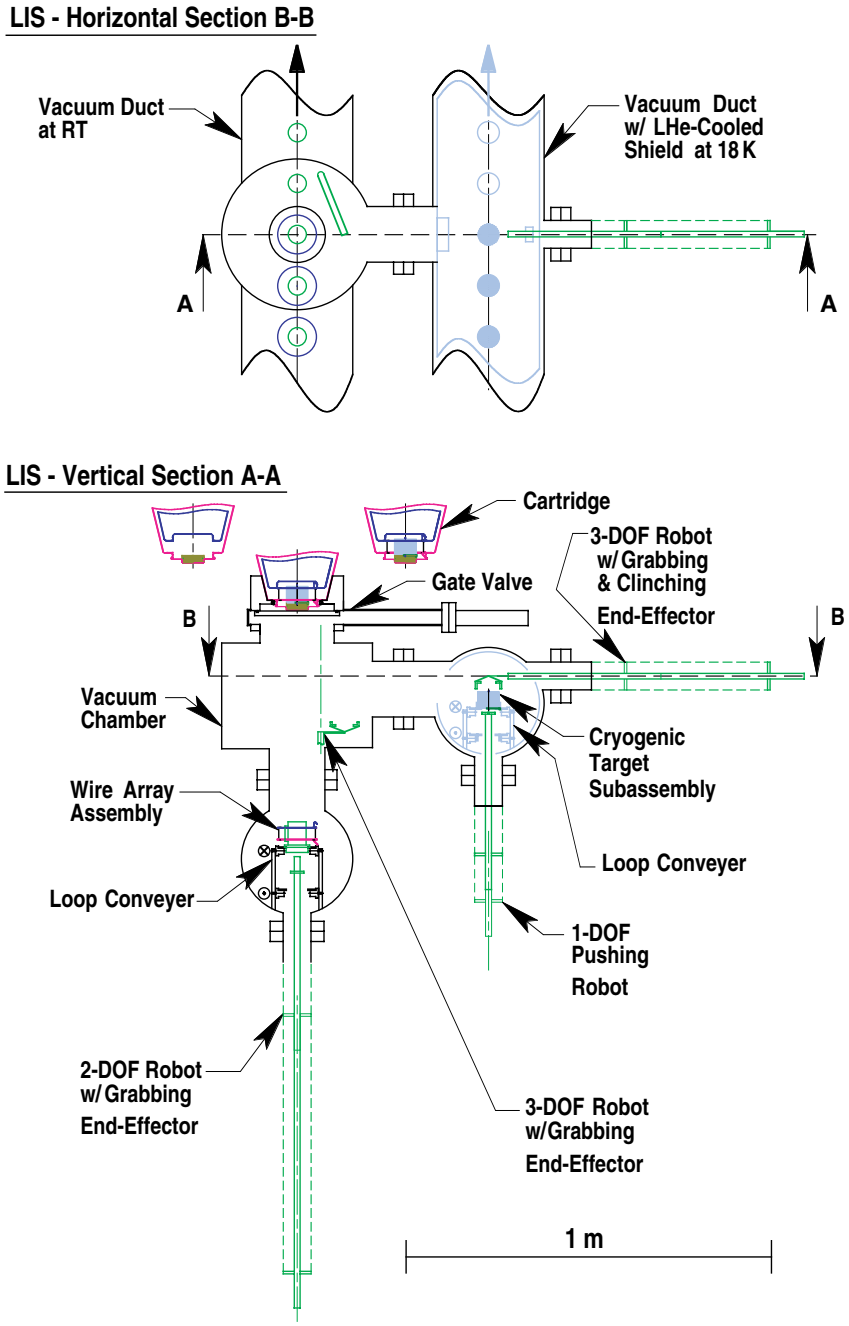



*Fig. 17. Releasing the cartridge.*

A third and a fourth robot manipulators handle the cryogenic target subassembly. The third manipulator consists of a vertical shaft that moves up and down through openings in the vacuum duct and its 18 K shield and through gaps in the cryogenic target subassembly conveyer. This manipulator pushes a subassembly up off the conveyer, lets the fourth manipulator grab the subassembly (Fig. 13), and goes back down out of the duct.

The fourth manipulator consists of a horizontal shaft with a double-function end-effector. It grabs the cryogenic target subassembly off the third manipulator, moves it into the vacuum chamber, above the foam pedestal mounted on the sealing plate (Fig. 14), lets the sealing plate manipulator bring the plate up, clinches the three ends of the strap at the bottom of the subassembly onto the top of the foam pedestal, and releases the subassembly. The fourth manipulator, now empty, lets the plate manipulator bring the plate back down (Fig. 15), and moves back to its original position with its end-effector above the cryogenic target subassembly conveyer. This completes the assembly of the cryogenic target assembly together and its mounting on the RTL sealing plate.

The sealing plate manipulator then swings the plate, with the attached target assembly, back under the RTL opening, raises it back up through the RTL opening, and pushes it over the rim of the RTL opening, sealing back the RTL (Fig. 16). This ends the insertion of the load into the RTL and completes their assembly into a cartridge. The sealing plate manipulator then moves its end-effector back down to its original position at the bottom of the LIS chamber.

The LIS gate valve is closed, the space between the gate valve and the RTL sealing plate is vented, and the LIS O-ring is deflated, releasing the cartridge. The cartridge is moved up and off the LIS (Fig. 17), and then rapidly transported to one of the ten operating reactor chambers to be shot. At the same time, the next RTL is brought to the LIS and the load insertion cycle to be repeated.

## 4.3. PROCESS MODELING AND COSTS

### 4.3.1. General Assumptions

We have prepared preliminary cost estimates for mass production of the loads on the following basis:

- Load conceptual design described in Section 3.
- Conceptual process for mass production of loads described in Section 4.1.
- Commercial-scale load production facility supplying 86,400 wire array and target assemblies per day to one power plant.

- Loads are made from new, commercially available materials.
- Nth-of-a-kind load production facility, excluding R&D costs.
- Load production facility with a 30-year life.
- Cost estimate per load includes both the capital and operating costs of the load production facility.
- Base case: complete load production facility integrated with the central RTL/cartridge production facility at the power plant.
- Alternate case: certain load components prefabricated at a remote central production facility serving 10 power plants, with assembly and insertion of loads at one power plant.

### 4.3.2. Modeling Approach

#### *4.3.2.1. Calculation Approach and Equations*

This work uses basic technology principles being developed in the laboratory, best engineering judgment, chemical engineering scale-up principles, and established cost estimating methods. The conceptual design and costing of the production facility includes process flow diagrams, equipment sizing and sketches, and solution storage tanks. Recycle and beneficial reuse of liquid process effluents are designed into the facility.

Statistical sampling of load component batches will be performed at every process step to avoid unnecessary further processing of off-spec components.

Finished load components will be sampled (100% QC in a final flow-through step) and stockpiled (potentially at a central facility serving multiple power plants) to assure a reliable supply backlog of several days of on-spec components.

We used chemical engineering modeling techniques and Excel spreadsheet calculations to obtained the cost estimates. This approach is intended to provide guidance on process development needs (and subsequent research directions), and to serve as a standardized method of comparing process costs for future evaluations.

#### *4.3.2.2. Cost Estimation*

The cost estimates for the production of loads include both capital and operating costs. The capital costs are broken down into purchased equipment, engineering/contingency, building/auxiliaries, and piping/electrical/instrumentation. The operating costs are broken down into operating staff, consumable materials, utilities, and waste disposal. Sampling and inspection equipment and staffing costs are included at all stages of load production. The costs of new and novel equipment have been estimated using engineering judgment.

### *4.3.2.3. Financial Calculations*

Load production facility capital costs are treated as an annual expense. Design and construction costs are typically paid for by a combination of the following sources:

- Debt (bonds)
- Preferred dividend stock
- Common equity stock.

Standard financial treatment (Ref. [6]) results in a levelized "fixed charge rate" of expressing the annual expense of repaying the design and construction cost to these sources. The fixed charge rate is calculated by using inputs such as interest rates, stock returns, tax rates, depreciation schedules, etc. For a 30-year facility with typical financial assumptions, the fixed charge rate is calculated to be 12.5 % per year, as shown in Table 2 below:

**Table 2. Calculation of Fixed Charge Rate for a 30-year Nuclear Facility**

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| **nuclear plant fcr for utility parameters** | | | idc yrs = | 3.26 | | | |
| fixed charge rate computation | | | toc = | 780 | | | |
| per necdb published september 1988 | | | idc = | 220 | | | |
| project and financial input parameters | | | tcc = | 1000 | tax depreciation sch | | |
| | | | | | | oper yr | depr % |
| | book life, yrs | 30 | capitalization | | | ====== | ====== |
| | levelization period, yrs | 30 | debt | 50.0% | | 1 | 5.000% |
| | constant $ ref year | 2002 | preferred stock | 10.0% | | 2 | 9.500% |
| | comm operation year | 2040 | common equity | 40.0% | | 3 | 8.550% |
| | | | return on capitalization | | | 4 | 7.700% |
| tcc = | total capital cost, nom m$ | 1000.00 | debt interest | 7.0% | | 5 | 6.930% |
| idc = | afudc, nom m$ | 219.54 | preferred dividend | 8.0% | | 6 | 6.230% |
| | tax depre portion, nom m$ | 877.72 | common equity return | 9.0% | | 7 | 5.905% |
| | total capital cost, const m$ | 225.29 | | | | 8 | 5.905% |
| | | | avg cost of money | 7.90% | | 9 | 5.905% |
| | annual inflation rate | 4.00% | real avg cost of money | 3.75% | | 10 | 5.905% |
| | federal income tax rate | 34.00% | tax-adjusted cost of money | 6.62% | | 11 | 5.905% |
| | state income tax rate | 4.00% | real cost of money | 2.52% | | 12 | 5.905% |
| | effective income tax rate | 36.64% | | | | 13 | 5.905% |
| | annual property tax rate | 2.00% | | | | 14 | 5.905% |
| | annual replacement rate | 0.50% | | | | 15 | 5.905% |
| | | | | | | 16 | 2.945% |
| | | | | | | | 100.000% |

## Table 2 (continued)

yearly revenue streams

| | | | | | | | | | revenue req'mts (million $) | | cashflow | return on |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | rate | return | book | tax | i tax | i tax | prop | intrm | | | nom m$ | investmt |
| year | base | on cap | depr | depr | defer | curr | tax | repl | nom $ | 2002 | ====== | |
| ====== | ====== | ====== | ====== | ====== | ====== | ====== | ====== | ====== | ====== | ====== | -1000 | ====== |
| 2040 | 1000.0 | 79.0 | 33.3 | 43.9 | 5.4 | 22.4 | 20.0 | 5.2 | 165.3 | 35.8 | 117.7 | -88.23% |
| 2041 | 961.3 | 75.9 | 33.3 | 83.4 | 19.8 | 7.0 | 20.0 | 5.4 | 161.5 | 33.6 | 129.1 | -57.70% |
| 2042 | 908.1 | 71.7 | 33.3 | 75.0 | 16.8 | 8.7 | 20.0 | 5.6 | 156.2 | 31.3 | 121.9 | -37.02% |
| 2043 | 858.0 | 67.8 | 33.3 | 67.6 | 14.0 | 10.1 | 20.0 | 5.8 | 151.2 | 29.1 | 115.2 | -23.97% |
| 2044 | 810.7 | 64.0 | 33.3 | 60.8 | 11.6 | 11.4 | 20.0 | 6.1 | 146.4 | 27.1 | 108.9 | -15.48% |
| 2045 | 765.8 | 60.5 | 33.3 | 54.7 | 9.3 | 12.5 | 20.0 | 6.3 | 142.0 | 25.3 | 103.1 | -9.72% |
| 2046 | 723.1 | 57.1 | 33.3 | 51.8 | 8.3 | 12.5 | 20.0 | 6.6 | 137.8 | 23.6 | 98.7 | -5.64% |
| 2047 | 681.5 | 53.8 | 33.3 | 51.8 | 8.3 | 11.4 | 20.0 | 6.8 | 133.7 | 22.0 | 95.4 | -2.64% |
| 2048 | 639.9 | 50.6 | 33.3 | 51.8 | 8.3 | 10.4 | 20.0 | 7.1 | 129.6 | 20.5 | 92.2 | -0.38% |
| 2049 | 598.3 | 47.3 | 33.3 | 51.8 | 8.3 | 9.3 | 20.0 | 7.4 | 125.6 | 19.1 | 88.9 | 1.35% |
| 2050 | 556.7 | 44.0 | 33.3 | 51.8 | 8.3 | 8.3 | 20.0 | 7.7 | 121.5 | 17.8 | 85.6 | 2.70% |
| 2051 | 515.1 | 40.7 | 33.3 | 51.8 | 8.3 | 7.2 | 20.0 | 8.0 | 117.5 | 16.5 | 82.3 | 3.75% |
| 2052 | 473.5 | 37.4 | 33.3 | 51.8 | 8.3 | 6.1 | 20.0 | 8.3 | 113.5 | 15.4 | 79.0 | 4.60% |
| 2053 | 431.9 | 34.1 | 33.3 | 51.8 | 8.3 | 5.1 | 20.0 | 8.7 | 109.5 | 14.2 | 75.7 | 5.28% |
| 2054 | 390.3 | 30.8 | 33.3 | 51.8 | 8.3 | 4.0 | 20.0 | 9.0 | 105.5 | 13.2 | 72.4 | 5.83% |
| 2055 | 348.7 | 27.5 | 33.3 | 25.8 | -1.2 | 12.5 | 20.0 | 9.4 | 101.5 | 12.2 | 59.6 | 6.22% |
| 2056 | 316.6 | 25.0 | 33.3 | 0.0 | -10.7 | 21.1 | 20.0 | 9.7 | 98.5 | 11.4 | 47.6 | 6.49% |
| 2057 | 294.0 | 23.2 | 33.3 | 0.0 | -10.7 | 20.6 | 20.0 | 10.1 | 96.5 | 10.7 | 45.8 | 6.73% |
| 2058 | 271.4 | 21.4 | 33.3 | 0.0 | -10.7 | 20.0 | 20.0 | 10.5 | 94.6 | 10.1 | 44.1 | 6.93% |
| 2059 | 248.7 | 19.7 | 33.3 | 0.0 | -10.7 | 19.4 | 20.0 | 11.0 | 92.6 | 9.5 | 42.3 | 7.10% |
| 2060 | 226.1 | 17.9 | 33.3 | 0.0 | -10.7 | 18.8 | 20.0 | 11.4 | 90.7 | 9.0 | 40.5 | 7.24% |
| 2061 | 203.5 | 16.1 | 33.3 | 0.0 | -10.7 | 18.3 | 20.0 | 11.8 | 88.8 | 8.4 | 38.7 | 7.37% |
| 2062 | 180.9 | 14.3 | 33.3 | 0.0 | -10.7 | 17.7 | 20.0 | 12.3 | 86.9 | 7.9 | 36.9 | 7.48% |
| 2063 | 158.3 | 12.5 | 33.3 | 0.0 | -10.7 | 17.1 | 20.0 | 12.8 | 85.0 | 7.5 | 35.1 | 7.57% |
| 2064 | 135.7 | 10.7 | 33.3 | 0.0 | -10.7 | 16.5 | 20.0 | 13.3 | 83.2 | 7.0 | 33.3 | 7.65% |
| 2065 | 113.1 | 8.9 | 33.3 | 0.0 | -10.7 | 16.0 | 20.0 | 13.9 | 81.4 | 6.6 | 31.5 | 7.72% |
| 2066 | 90.5 | 7.1 | 33.3 | 0.0 | -10.7 | 15.4 | 20.0 | 14.4 | 79.6 | 6.2 | 29.8 | 7.77% |
| 2067 | 67.8 | 5.4 | 33.3 | 0.0 | -10.7 | 14.8 | 20.0 | 15.0 | 77.8 | 5.8 | 28.0 | 7.82% |
| 2068 | 45.2 | 3.6 | 33.3 | 0.0 | -10.7 | 14.2 | 20.0 | 15.6 | 76.0 | 5.5 | 26.2 | 7.86% |
| 2069 | 22.6 | 1.8 | 33.3 | 0.0 | -10.7 | 13.7 | 20.0 | 16.2 | 74.3 | 5.2 | 24.4 | 7.90% |
| | | | 1000.0 | 877.7 | 0.0 | 402.4 | | | nom $ | 2002 | | |
| | | | | | | | | | ====== | ====== | | |
| | | | | | | pv sum @ startup, m$ | | | 1620.9 | 327.9 | | |
| | | | | | | capital recovery factor | | | 0.0775 | 0.0479 | | |
| | | | | | | **fixed charge rate** | | | **12.56%** | 6.97% | | |

### 4.3.3. Cost Estimates For The Base Case

All load production and insertion operations are conducted at the power plant site.

*4.3.3.1. Technical Specifications and Assumptions*

- Basic Assumptions for Be capsule Production

| | | | |
|---|---|---|---|
| 9240 | micron PAMS shell outside diameter | | |
| 150 | micron thick PAMS wall | | |
| 910 | mg/cc final PAMS density | | |
| | | | |
| 100 | microns — GDP thickness | | |
| 0.67 | mass ratio of GDP/PAMS | | |
| 3.0 | mass ratio of trans-2-butene to GDP | | |
| | | | |
| 86400 | shells per day total production (on-spec) – 1 Hz | | |
| 25 | overall rejection rate, percent | | |
| 5 | ratio of outer water to final shell volume | | |
| 0.11 | ratio of PAMS to solvent | | |
| 8 | hours of shells per contactor | | |
| 40 | per cent fill on contactor | | |
| 1.0 | ratio of contactor diameter to lenght | | |
| | | | |
| 1.0 | per cent PVA in outer water | | |
| | | | |
| 1.0 | turn over per hour of contactor vapor space | | |
| 0.0013 | density of $N_2$ at ambient conditions, g/cc | | |
| | | | |
| 365 | Days per year operation | | |
| 8760 | Hours per year operation (24/7) | | |
| | | | |
| 5 | shifts to cover 24/7 + vacations, etc. | | |
| | | | |
| 5 | stages of contacting | | |
| 5 | stages contacted countercurrently | | |
| | | 25.00 | reject rate multiplier |
| 10.0 | % reject rate at droplet forming stage | 25.00 | baseline reject rate |
| | | | |
| 8 | % reject rate at ethanol exchange stage | | |
| 5.0 | % reject rate at $CO_2$ drying stage | 25.27 | overall reject rate |
| 0.0 | n/a | | |
| 5.0 | % reject rate at DT filling stage | 2.862 | total costs |

- Calculated Parameters for PAMS/GDP Shell Production

| | |
|---|---|
| 0.03892 | volume of each PAMS shell wall, cc |
| 0.03542 | mass of each shell wall, g |
| 115621 | total shells produced per day |
| 4818 | total shells produced per hour |
| 170.6 | mass flow of shells (PAMS only), g/hr |
| 0.00 | mass flow of initiator, g/hr |
| 0.11 | ratio of PAMS to solvent (fluorobenzene) |
| 1551.2 | mass flow of solvent, g/hr |
| (note that minor qtys of PVA & PAA will be added to reduce adherence between shells) | |
| 0.374 | inner water volume, cc/shell |
| 1801.4 | inner water flow, g/hr |
| 1801.4 | inner water flow, cc/hr |
| 0.413 | volume of each shell, cc |
| 1988.9 | volume of shells produced, cc/hr |
| 9944.6 | volume of outer water, cc/hr |
| 9944.6 | mass flow of outer water, g/hr |
| 95468.6 | contactor initial fill volume, cc |
| 238671.5 | contactor initial total volume, cc |
| 67.2 | contactor diameter, cm |
| 67.2 | contactor length, cm |
| 99.4 | PVA usage, g/hr |
| 143203 | vapor space in contactor, cc |
| 143203 | $N_2$ usage, cc/hr |
| 192.8 | $N_2$ usage, g/hr |
| 42201614 | total number of targets produced per year (usable and unusable) |
| 31536000 | total number of targets produced per year (usable) |
| 341.3 | g/hr – trans-2-butene usage rate |
| 4000 | kg/yr – trans-2-butene usage rate |
| 573 | volume of waste per contactor, liters |
| 1718 | volume of waste per day from contactor, liters |
| 1.72 | tons per day of waste liquids from contactors |
| 627 | tons per year of waste liquids from contactors |
| 1 | number of fresh rinses (i.e. not recycled) |
| 1.34 | number of reject targets/usable targets |

- Target Assembly Production Rates for Assumed Reject Rates

| Processing Step | Reject Rate (%) at this Process Step | Cumulative Production Multiplier (for this process step) | Shells Produced per Hour | Shells Rejected per Hour (integrated average over long time periods) | Fraction of Initially-Formed Shells Entering this Unit Operation |
|---|---|---|---|---|---|
| Shell form/cure | 10 | 1.338 | 4818 | 482 | 1.000 |
| Ethanol exchange | 8 | 1.204 | 4336 | 347 | 0.900 |
| Vacuum dry | 5 | 1.108 | 3989 | 199 | 0.828 |
| DT Fill | 5 | 1.053 | 3789 | 189 | 0.787 |
| Layer & Inject | 0 | 1 | 3600 | 0 | 0.747 |
| | | | | **overall % reject rate =** | **25.3** |

### *4.3.3.2. Capital Cost Calculations*

- Equipment Cost Assumptions for Load Production

| | |
|---|---|
| 12.5 | % capitalization rate |
| 6 | % maintenance (as % of installed capital) |
| 30 | total days of processing per batch (in contactors) – this will be subject of much R&D effort! |
| 8 | hours of shells per batch |
| $ 20,000 | cost per contactor |
| 90 | calculated number of contactors |
| $ 25,000 | cost per shell generator |
| 3 | shell generators needed |
| $ 187,349 | cost for each contactor counter-current tank sequence |
| $ 500,000 | vacuum dryer (10 required) |
| $ 1,000,000 | GDP coater (10 required) |
| 40 | % benefits (added to salary for personnel costs) |
| $ 400 | per metric ton aqueous waste disposal costs |
| $ 1,000,000 | Be sputtering system (10 required) |
| $ 750,000 | shell bake-out system (10 required) – includes laser drill & multi-shell holder |
| $ 1,250,000 | DT filling system (10 required) –cryo-condensation (includes laser seal & multi-shell holder |
| $ 4,375,000 | cryo-layering system (fluidized bed type) |
| $ 2,000,000 | wire-array forming equipment |
| 5,000 | kw usage (includes cryogenic cooling systems for $LH_2$-reservoir filling and various processing steps |
| $ 0.08 | cost per kw/hr |
| $ 13,560,000 | CRF foam mfg equipment (see below for details) |
| $ 10,000,000 | target subassembly machinery – robotically places capsule in foam cylinder body – installs plug & seals subassembly |
| $ 2,000,000 | load insertion station |

**DETAILS OF FOAM MANUFACTURING – EQUIPMENT CAPITAL COSTS FOR 1 Hz PRODUCTION**

| | |
|---|---|
| $ 60,000 | mix tank (chemicals are loaded out directly from five gallon drums) |
| $ 3,000,000 | casting molds and mixture manifolds for filling molds and exchanging IPA (note that this is a five-day process for gelation & IPA exchange so 3x432,000 pieces are in work) (3 pieces of CRF per assembly – cylinder & plug & pedestal) |
| $ 6,000,000 | supercritical $CO_2$ chambers and pressure reduction components (16 in parallel at $375000 each) |
| $ 4,500,000 | Pyrolysis furnaces – 3 each – batch vacuum system – inventory = 34,560 x 3 = 103,680 pieces |
| | Gelation – 2 days<br>IPA exchange – 3 days<br>Supercritical $CO_2$ drying – 4 days<br>Pyrolysis – 1 day at 1000°C |
| 1.91 | g/assembly organics (foams) |
| $ 10 | $/lb for organics (foams) |
| 6 | cm foam diameter |
| 5 | cm foam length (cylinder plus pedestal) |
| 127.17 | cc foam volume |
| 15 | mg/cc foam density |
| 1.91 | g per foam assembly |
| 80,502 | Kg per year RF components |
| 1 | |
| $ 0.008 | Cost per polyimide sleeve (formed *in-situ*) |

- Mass and Energy Balance for Production of PAMS shells

| | **Stream Number:** | 1 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | **Stream Name:** | PAMS-solvent Feed (solvent is fluorobenzene) | Inner Water to Shell Generator | Outer Water to Shell Generator | Raw Shells to Contactor | Inert Gas to Contactor | Shells to Cure Contactor | Cured Shells | EtOH to Contactor | Net Spent Liquid Discharge from EtOH Cycle | EtOH-filled shells to Drying |
| | Temperature, °C | 25 | 25 | 25 | 25 | 25 | 85 | 85 | 25 | 25 | 25 |
| | Temperature, °K | 298 | 298 | 298 | 298 | 298 | 358 | 358 | 298 | 298 | 298 |
| | Pressure, atm | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| **Liquids** | PAMS | 170.63 | | | | | | | | | 141 |
| | Solvent | 1551.18 | | | 1551.18 | | 1551 | 1551 | | | |
| | Water | | 1801.42 | 9944.64 | 11746.07 | | 11746 | 11746 | | | |
| | Polyvinyl Alcohol | | | 99.45 | 99.45 | | 99 | 99 | | | |
| | polymerized PAMS | | | | 170.63 | | 171 | 171 | | | |
| | Ethanol (EtOH) | | | | | | | | 10740 | | 1492 |
| | Mixed liquid waste | | | | | | | | | 10740 | |
| **Gases** | $N_2$ | | | | | 192.83 | | | | | |
| **Total, g/hr** | | 1721.8 | 1801.4 | 10044.1 | 13567.3 | 192.8 | 13567.3 | 13567.3 | 10740.2 | 10740.2 | 1632.9 |

- Tanks for Production of PAMS Shell

**Tank Calculations**

Each countercurrent contacting station will require 5 tanks. There is 1 station required.

The tank volume is sufficient for 1 week of batch operations, which will reduce the coupling of unit operations and hereby increase system availability

95.5 = the fill volume of each contactor (in liters)

2005 = the total volume required for each tank (in liters)

2506.05 = tank volume (with head-room allowance)

4 = L/D of vertical cylindrical

3.71 = height of tank, M

0.93 = diameter of tank, M

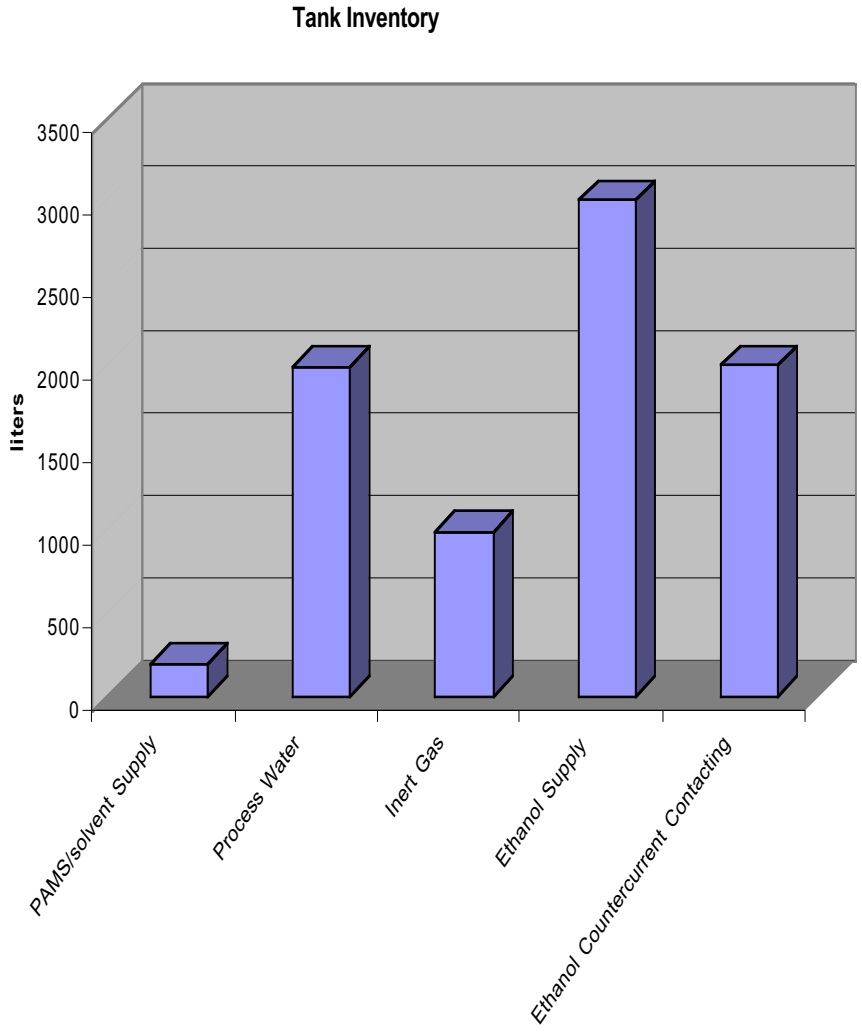
there are 5 of these tanks to provide a 5-step rinse

1.5 weeks storage in supply tank

3007 liters in storage tank

**Tank Matrix**

| System | Tank Volume, liters | Number of Tanks | Notes |
|---|---|---|---|
| PAMS/solvent Supply | 200 | 1 | |
| Process Water | 2000 | 1 | |
| Inert Gas | 1000 | 1 | nitrogen |
| Ethanol Supply | 3007 | 1 | |
| Ethanol Countercurrent Contacting | 2005 | 5 | |
| Total Tanks | | 9 | |



- Capital Costs of Equipment and Balance-of Plant

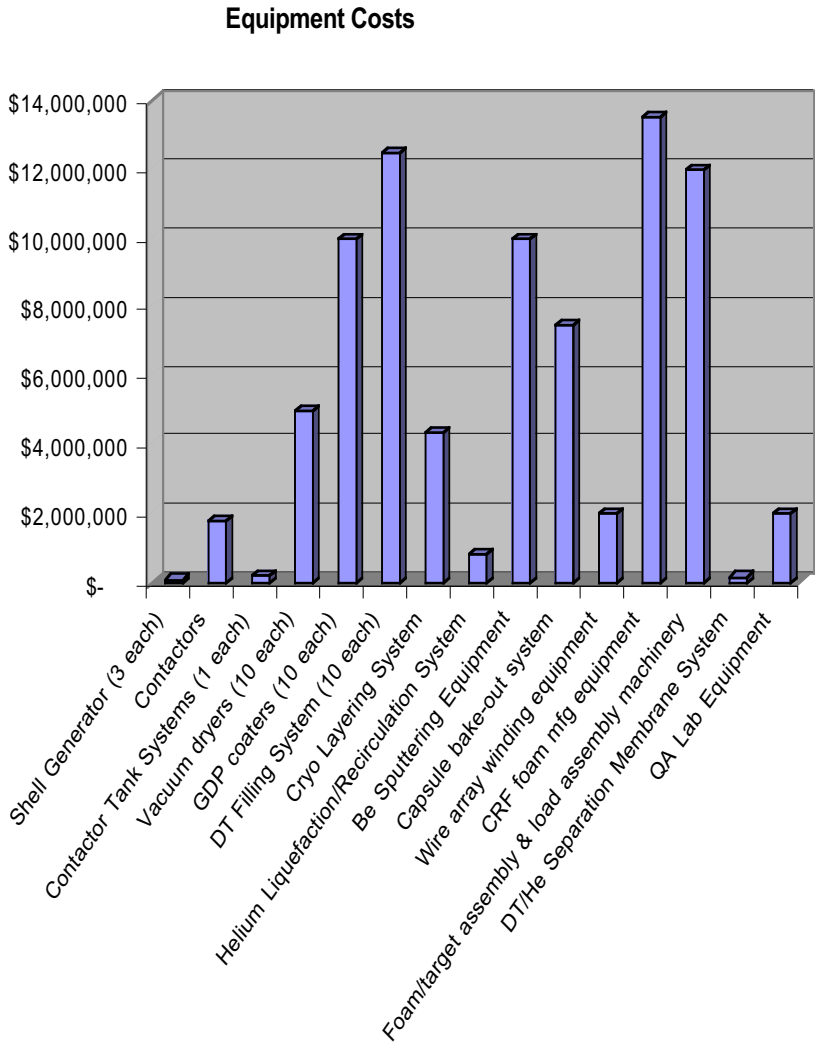
| | base price for processing at nominal (25% overall) reject rate | throughput multiplier based on actual reject rate | nominal reject rate at this stage (25% overall taken to be nominal) | cost multiplier based on 0.6 exponent scaling | projected costs for facility at stated reject rate |
|---|---|---|---|---|---|
| Shell Generator (3 each) | $ 75,000 | 1.34 | 1.34 | 1.001 | $ 75,041 |
| Contactors | $ 1,800,000 | 1.34 | 1.34 | 1.001 | $ 1,800,973 |
| Contactor Tank Systems (1 each) | $ 187,349 | 1.34 | 1.34 | 1.001 | $ 187,450 |
| Vacuum dryers (10 each) | $ 5,000,000 | 1.34 | 1.34 | 1.001 | $ 5,002,702 |
| GDP coaters (10 each) | $ 10,000,000 | 1.34 | 1.34 | 1.001 | $ 10,005,404 |
| DT Filling System (10 each) | $ 12,500,000 | 1.05 | 1.02 | 1.019 | $ 12,738,425 |
| Cryo Layering System | $ 4,375,000 | 1 | 1 | 1.000 | $ 4,375,000 |
| Helium Liquefaction/Recirculation System | $ 800,000 | 1 | 1 | 1.000 | $ 800,000 |
| Be Sputtering Equipment | $ 10,000,000 | 1 | 1 | 1.000 | $ 10,000,000 |
| Capsule bake-out system | $ 7,500,000 | 1 | 1 | 1.000 | $ 7,500,000 |
| Wire array winding equipment | $ 2,000,000 | 1 | 1 | 1.000 | $ 2,000,000 |
| CRF foam mfg equipment | $ 13,560,000 | 1 | 1 | 1.000 | $ 13,560,000 |
| Foam/target assembly & load assembly machinery | $ 12,000,000 | 1 | 1 | 1.000 | $ 12,000,000 |
| DT/He Separation Membrane System | $ 150,000 | 1 | 1 | 1.000 | $ 150,000 |
| QA Lab Equipment | $ 2,000,000 | 1 | 1 | 1.000 | $ 2,000,000 |
| **Total Process Equipment Cost** | **$ 81,947,349** | | | | **$ 82,194,994** |

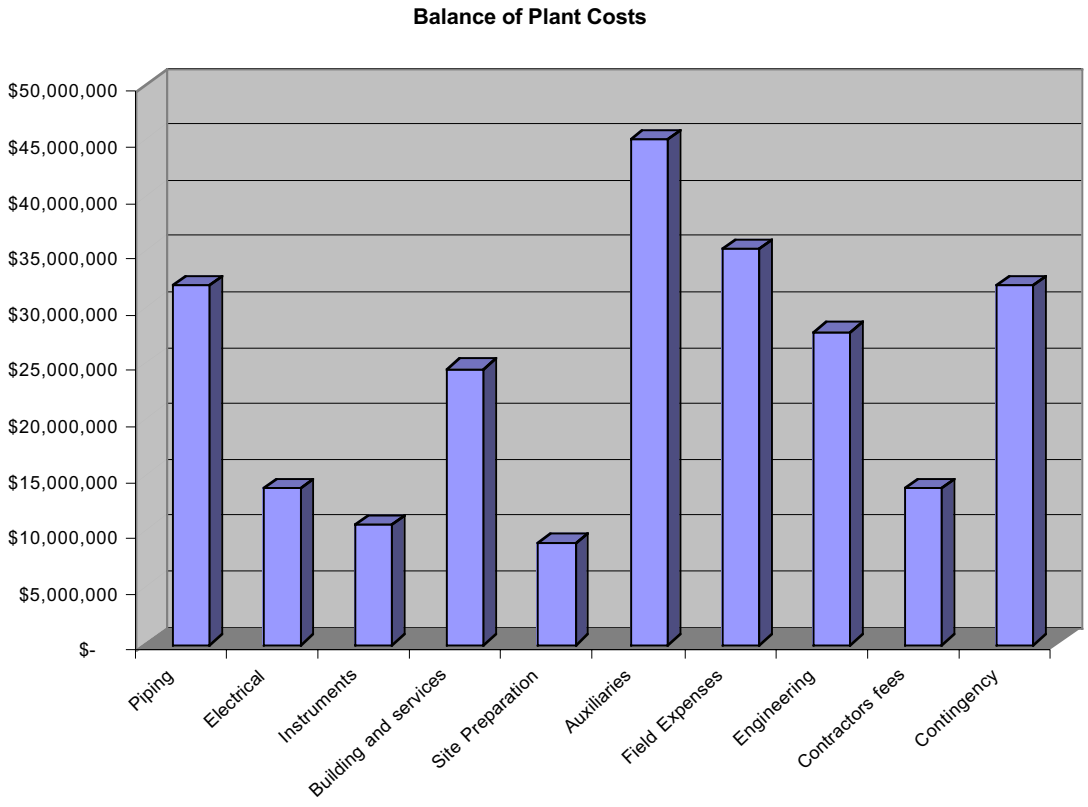
**Factored Balance of Plant Costs (from Miller's Method)**

| | |
|---|---|
| Piping | $ 32,056,048 |
| Electrical | $ 13,973,149 |
| Instruments | $ 10,685,349 |
| Building and services | $ 24,658,498 |
| Site Preparation | $ 9,041,449 |
| Auxiliaries | $ 45,207,247 |
| Field Expenses | $ 35,343,848 |
| Engineering | $ 27,946,298 |
| Contractors fees | $ 13,973,149 |
| Contingency | $ 32,056,048 |

**Total Installed Capital Cost** **$ 327,136,078**

**Annualized Cost of Capital Investment** **$ 40,892,010**


Equipment Costs
$14,000,000
$12,000,000
$10,000,000
$8,000,000
$6,000,000
$4,000,000
$2,000,000
$-
Shell Generator (3 each)
Contactors
Contactor Tank Systems (1 each)
Vacuum dryers (10 each)
GDP coaters (10 each)
DT Filling System (10 each)
Cryo Layering System
Helium Liquefaction/Recirculation System
Be Sputtering Equipment
Capsule bake-out system
Wire array winding equipment
CRF foam mfg equipment
Foam/target assembly & load assembly machinery
DT/He Separation Membrane System
QA Lab Equipment

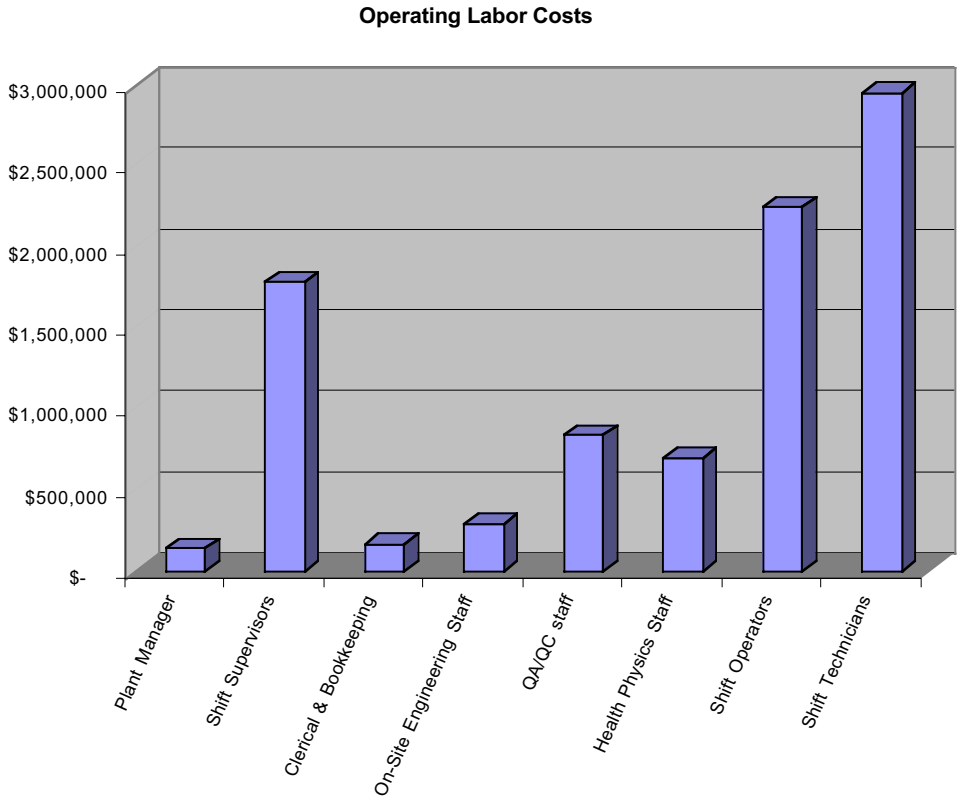

Balance of Plant Costs
$50,000,000
$45,000,000
$40,000,000
$35,000,000
$30,000,000
$25,000,000
$20,000,000
$15,000,000
$10,000,000
$5,000,000
$-
Piping
Electrical
Instruments
Building and services
Site Preparation
Auxiliaries
Field Expenses
Engineering
Contractors fees
Contingency

### *4.3.3.3. Operating Cost Calculations*

- Labor Costs of Operating Staff

| **Position Title** | **Staff per Shift** | **Number of Shifts** | **$/yr salary** | **Total Cost (including factor for reject rates - see right) also adjusted for radioactive operations (see below)** | reference reject rate (reference staffing costs are based on this) | Actual reject rate at this process stage for this case | multiplier using 0.6 exponent to account for adding staff to cope with higher than projected reject rates (25% overall is the expected level) |
|---|---|---|---|---|---|---|---|
| | | | | | | | |
| Plant Manager | 1 | 1 | $ 100,000 | $ 140,076 | 1.34 | 1.338 | 1.00 |
| Shift Supervisors | 3 | 5 | $ 85,000 | $ 1,785,965 | 1.34 | 1.34 | 1.00 |
| Clerical & Bookkeeping | 4 | 1 | $ 30,000 | $ 168,091 | 1.34 | 1.34 | 1.00 |
| On-Site Engineering Staff | 3 | 1 | $ 70,000 | $ 294,159 | 1.34 | 1.34 | 1.00 |
| QA/QC staff | 3 | 5 | $ 40,000 | $ 840,454 | 1.34 | 1.34 | 1.00 |
| Health Physics Staff | 2 | 5 | $ 50,000 | $ 700,378 | 1.34 | 1.34 | 1.00 |
| Shift Operator - Contactor Area | 1 | 5 | $ 40,000 | $ 280,151 | 1.34 | 1.34 | 1.00 |
| Technician - Contactor Area | 2 | 5 | $ 30,000 | $ 420,227 | 1.34 | 1.34 | 1.00 |
| Shift Operator - CRF area | 2 | 5 | $ 40,000 | $ 560,314 | 1.11 | 1.11 | 1.00 |
| Technician - CRF area | 4 | 5 | $ 30,000 | $ 840,470 | 1.11 | 1.11 | 1.00 |
| Shift Operator - Wire Array Area | 1 | 5 | $ 40,000 | $ 280,000 | 1.11 | 1.11 | 1.00 |
| Technician - Wire Array Area | 2 | 5 | $ 30,000 | $ 420,000 | 1.11 | 1.11 | 1.00 |
| Shift Operator - Fill/Layer Area | 2 | 5 | $ 40,000 | $ 570,681 | 1.02 | 1.05 | 1.02 |
| Technician - Fill/Layer Area | 3 | 5 | $ 30,000 | $ 642,017 | 1.02 | 1.05 | 1.02 |
| Shift Operator - Target Assembly Area | 2 | 5 | $ 40,000 | $ 560,000 | n/a | n/a | n/a |
| Technician - Target Assembly Area | 3 | 5 | $ 30,000 | $ 630,000 | n/a | n/a | n/a |
| | | | **Annual labor operating costs =** | **$ 9,132,982** | | | |
| | | | **Multiplier for operating costs during radioactive operations =** | **1** | | | |

| | |
|---|---|
| Plant Manager | $ 140,076 |
| Shift Supervisors | $ 1,785,965 |
| Clerical & Bookkeeping | $ 168,091 |
| On-Site Engineering Staff | $ 294,159 |
| QA/QC staff | $ 840,454 |
| Health Physics Staff | $ 700,378 |
| Shift Operators | $ 2,251,146 |
| Shift Technicians | $ 2,952,714 |



- Costs of Consumable Materials

**Steel Usage**

| | |
|---|---|
| Reservoirs | |
| 7.872 | g/cc – density of AISI 1006 carbon steel |
| 7 | mm, reservoir height |
| 60 | mm, reservoir diameter |
| 2 | reservoirs per load |
| 0.1 | mm thick steel in reservoir walls |
| 1.0 | grams of steel in reservoir side walls |
| 4.4 | grams of steel in reservoir ends |
| 5.5 | grams of steel per reservoir |
| **11.0** | **grams of steel per 2 reservoirs (in one load)** |
| Wire Array End Plates | |
| 114 | mm, outside diameter of ring plate |
| 60 | mm, inside diameter of ring plate |
| 0.63 | mm, thickness of ring plate |
| **73.2** | **grams of steel per pair of ring plates** |
| **84.1** | **grams – total weight of AISI 1006 carbon steel per load** |
| 1.00 | dollars per pound – fabricated cost of steel components |
| 2.20 | dollars per kg – fabricated cost of steel components |
| **0.185** | **dollars per load – steel component cost** |

**Tungsten Usage**

| | |
|---|---|
| Wire Array | |
| 40 | mm W wire lengths (include. 5 mm extra at each end) |
| 300 | number of wires per array |
| 10 | micron wire diasmeter |
| 19.3 | g/cc W density |
| 0.018 | grams of W per wire array |
| Foam Coating | |
| 60 | mm, foam body OD |
| 30 | mm, foam body height |
| 0.1 | microns, foam W coating on side |
| 30 | microns, foam W coating on ends |
| 0.011 | grams of W on foam side |
| 3.273 | grams of W on foam ends |
| **3.3** | **grams of W per load** |
| 6.75 | dollars per pound – cost of tungsten components<br>ref.: UCRL-1D-143228 Jan. 19, 2001 – R.W. Moir [Flibe coolant cleanup and processing in the HYLIFE-II inertial fusion energy power plant] |
| 5.00 | dollars per pound – wire forming costs |
| 10.00 | dollars per pound – foam coating costs |
| 0.085 | dollars per load – tungsten wire cost |
| 0.121 | dollars per load tungsten foam coating materials cost |
| 62.572 | dollars per kg – average cost per load |
| **0.207** | **dollars per load – total tungsten costs** |

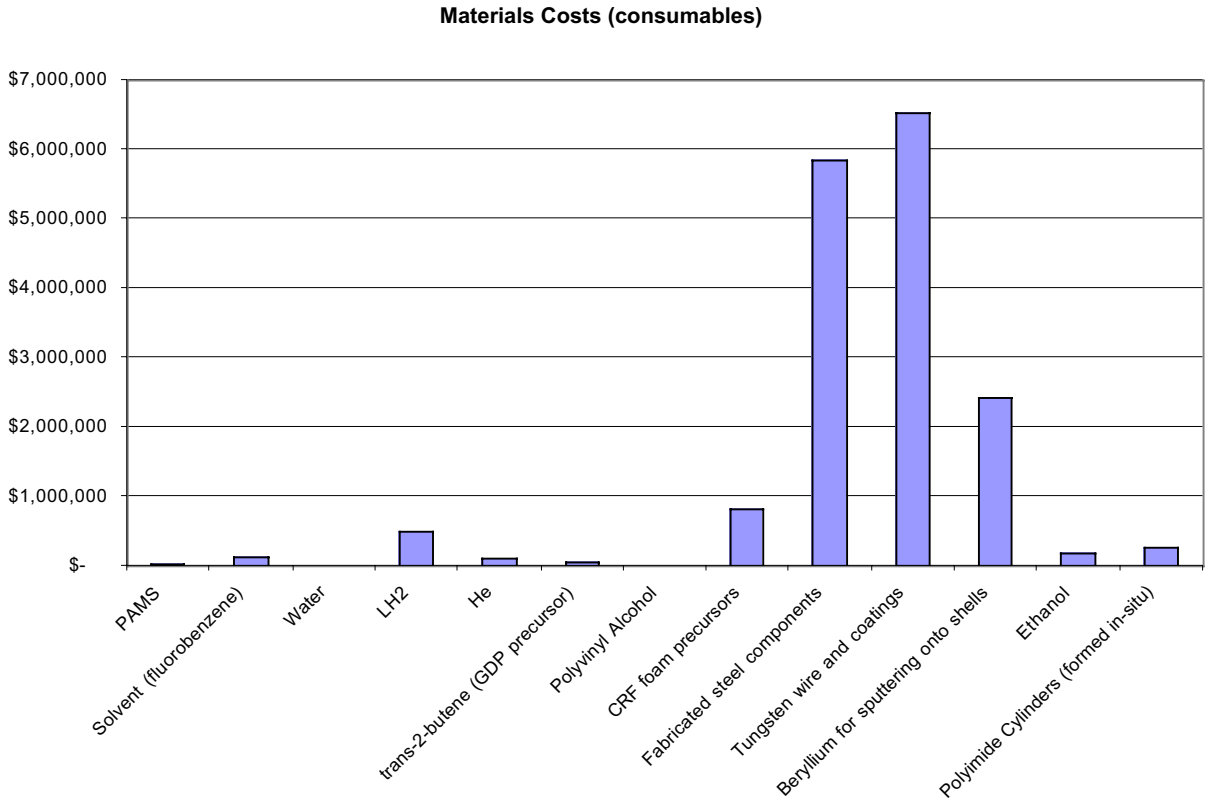
**Be Usage**

| | |
|---|---|
| 10 | mm, capsule OD |
| 330 | micron, shell Be thickness |
| 1.000 | cm, shell OD |
| 0.934 | cm, shell ID |
| 0.048466 | cc, volume of metal shell wall |
| 1.85 | g/cc, Be density |
| 100 | % Be purity in shell (no Cu) |
| **0.090** | **grams of Be per shell** |
| 390.00 | dollars per pound – cost of beryllium for sputtering<br>ref.: US Geological Survey – 40 years trend chart for US Be metal price |
| **0.077** | **dollars per load – beryllium component cost** |

## Materials Costs (consumables)

| Chemical | Kgs/yr | $/kg | $/yr |
|---|---|---|---|
| PAMS | 1495 | 10.00 | $ 14,947 |
| Solvent (fluorobenzene) | 13588 | 10.00 | $ 135,883 |
| Water | 102896 | 0.10 | $ 10,290 |
| LH2 | | | $ 500,000 |
| He | | | $ 100,000 |
| trans-2-butene (GDP precursor) | 4000 | 10.00 | $ 40,005 |
| Polyvinyl Alcohol | 871 | 10.00 | $ 8,712 |
| CRF foam precursors | 80502 | 10.00 | $ 805,017 |
| Fabricated steel components | 2653247 | 2.20 | $ 5,837,144 |
| Tungsten wire and coatings | 104119 | 62.57 | $ 6,514,969 |
| Beryllium for sputtering onto shells | 2828 | 859.03 | $ 2,428,970 |
| Ethanol | 94084 | 2.00 | $ 188,169 |
| Polyimide Cylinders (formed in-situ) | | | $ 252,288 |

**Annual materials costs = $ 16,836,393**

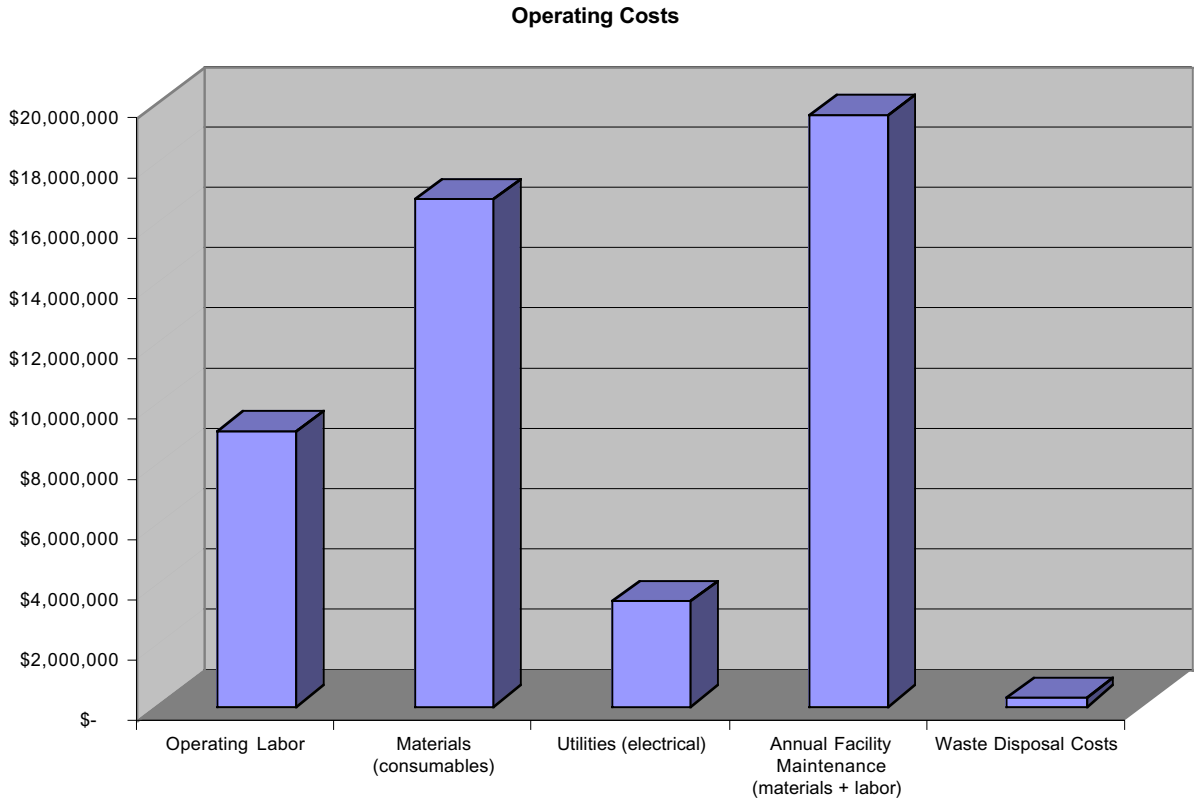


- Operating Costs

**Operating Cost**

| | | |
|---|---|---|
| Operating Labor | $ | 9,132,982 |
| Materials (consumables) | $ | 16,836,393 |
| Utilities (electrical) | $ | 3,504,000 |
| Annual Facility Maintenance (materials + labor) | $ | 19,628,165 |
| Waste Disposal Costs | $ | 250,891 |

**Total Annual Operating Costs = $ 49,352,431**

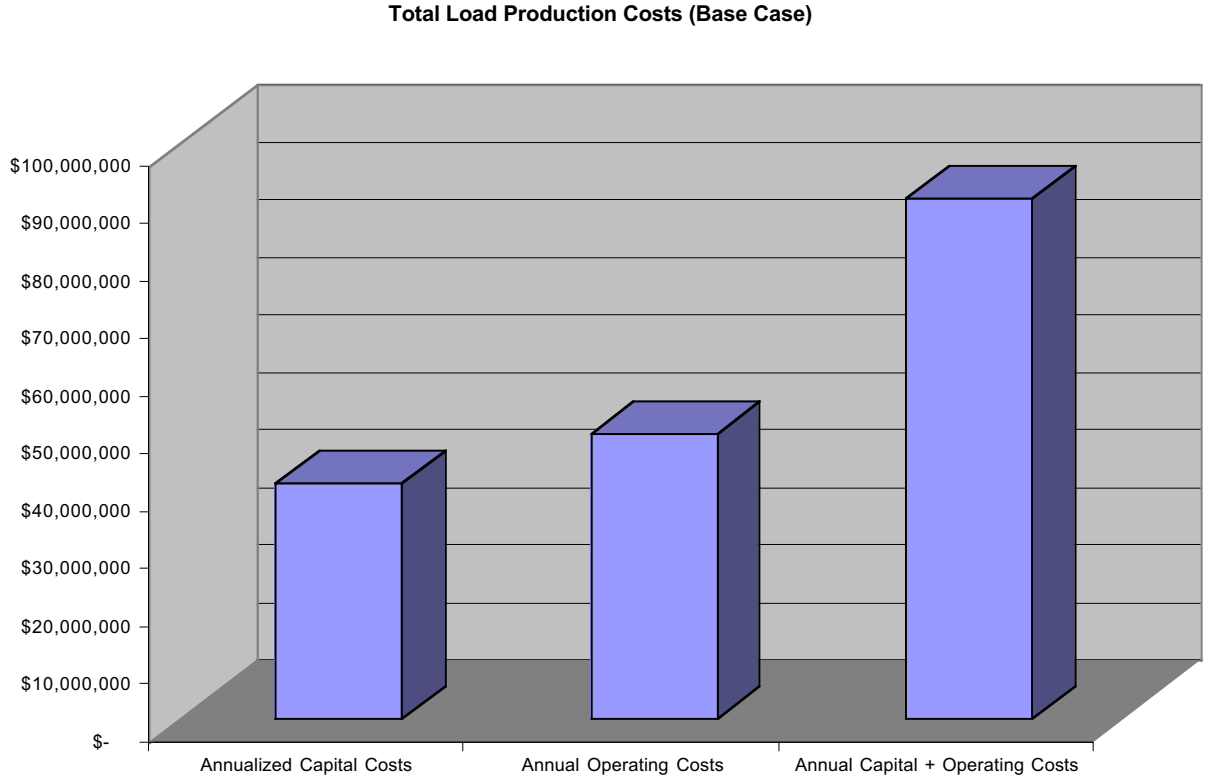


### 4.3.3.4. Total Cost Summary for the Base Case

**Total Load Production Costs (Base Case)**

| | |
|---|---|
| Annualized Capital Costs | $ 40,892,010 |
| Annual Operating Costs | $ 49,352,431 |
| **Annual Capital + Operating Costs** | **$ 90,244,441** |

**Cost per Inserted Target = $ 2.862**



#### *4.3.3.5. Cost Sensitivity Study for the Base Case*

As shown in Table 1, doubling the cost elements has the following consequences on the cost per load:

| | | |
|---|---|---|
| Labor Cost x 2 | → | Cost per Load x 1.10 |
| Capital Cost x 2 | → | Cost per Load x 1.67 |
| Materials Cost x 2 | → | Cost per Load x 1.18 |
| Maintenance Cost x 2 | → | Cost per Load x 1.22 |
| Utilities Cost x 2 | → | Cost per Load x 1.03 |

This show that the cost per load is very sensitive to the capital costs, but much less to the maintenance, material, labor, and utilities costs, in decreasing order.

### 4.3.4. Cost Estimates for the Alternate Case

The wire array assemblies (on holders), the empty PAMS/GDP/Be shells, and the foam components are assumed made at an off-site prefabrication facility that serves 10 power plants. All other load production and insertion operations are still conducted at the power plant site. The method used in Section 4.3.3 is used again in turn for the off-site and on-site facilities, and the corresponding costs elements are summed to obtain the new costs per load for the alternate case.

As shown in Table 1, the economies of scale achieved by making the abovementioned components off-site at a much larger facility would afford a substantial 26% reduction in the total cost per load. Looking at each cost element on a per load basis, we see that the capital and maintenance costs would be reduced by 36%, the labor costs would be reduced by 17%, the material costs would increase by 1% , and the utilities costs would increase by 6%.

# 5. LOAD DEBRIS REMOVAL

This section describes conceptual design solutions and gives a cost estimates for separating and removing the debris of the fired target and wire array assemblies from the primary coolant (liquid Flibe).

## 5.1. SUMMARY

1. Isotopes of hydrogen (D+T+H) from the fusion chamber become gases ($H_2$ and/or $CH_4$) – all are removed in vacuum degasser.
2. For subsequent recovery of tritium, tritiated $CH_4$ can be converted to $H_2$ + C via pyrolysis.
3. W from both the wire array & CRF foam coatings enters the Flibe as a solid (W and/or WC). It can be grown onto the large surface area of seed particles of W & WC (instead of depositing on the lower surface area of the walls).
4. Carbon particles will partially react to form $CH_4$ and WC – any surplus residual carbon will form carbon particulates.
5. WC seed particles plus carbon (if any) are removed from the Flibe using a slipstream continuous filter, such as a sintered metal or sintered ceramic filter.
6. Beryllium from the target becomes part of the Flibe molten salt inventory.
7. Steel enters the Flibe and is removed together with the RTL steel, using techniques being developed by others.
8. Total cost for seeding WC and removing it via on-line slipstream Flibe filtration is estimated to be 4.2 cents per load.

## 5.2. OVERALL ISSUE

Insoluble solids from the target and wire array assemblies enter the Flibe loop with resultant potential for:

1. plugging of nozzles in the tritium vacuum disengagers and/or the main reactor blanket jets.
2. plateout of insoluble solids on Flibe loop equipment and piping surfaces.

## 5.3. ASSUMPTIONS

1. Carbon and tungsten are ejected from the load as atoms/ions after the fusion reaction is ignited.
2. The favored molecular species for tungsten at the Flibe loop temperatures is tungsten carbide, which will initially exist in the Flibe as individual molecules, along with unreacted atoms of carbon and/or tungsten.
3. There are 2,500 tonnes of Flibe in the loop, recirculating at 167,450 kg/sec – or 85 $m^3$/s. This is based on HYLIFE-II where the Flibe flow rate was 7.1 $m^3$/s from each of 12 pumps for a total of 85 $m^3$/s for a similar, Flibe-cooled, 1000 MW(e) plant per Ref. [7].
4. The HYLIFE-II reactor design for the vacuum disengager used 400 μm holes to produce 400 μm droplets. However, for turbulent jet discharge, spray nozzles can be designed with internal openings ten times larger than the average droplet size, such that the opening for producing a 400 μm droplet could be 4000 μm. Therefore, we propose using a 4000 μm hole to produce 400 μm droplets, because this would tolerate far more plate out and fouling before the nozzles would require maintenance or replacement, thus reducing operating costs.

## 5.4. PROCESS

1. Seeding with new, fine powder of tungsten carbide (WC) will provide high surface area nucleating sites for individual WC molecules to deposit on, rather than on the surfaces of the Flibe loop equipment and piping (note that this seeding nucleation technique is a long-standing, basic principle used on a mass production basis in the crystallization industry).
2. As the WC particles grow, they are removed from the system with solid-liquid separation devices (some Flibe will be removed with the WC particles). See Ref. 8. These filters will be placed in a side-stream recycle cleanup loop off the main Flibe loop of each reactor.
3. The removed WC particles will not be recycled.

## 5.5. CALCULATION APPROACH

1. Calculate the mass flows of the insoluble solids and determine resultant concentration increases in the Flibe loop; determine whether there is an excess of carbon or tungsten.
2. Calculate the deposition rate on the Flibe loop walls by assuming that deposition is proportional to the surface area of either (a) the tungsten carbide powder, or (b) the Flibe loop equipment and piping surfaces.
3. The Excel calculation spreadsheets are given below.

LOAD MATERIALS INPUT INTO FLIBE

| | |
|---|---|
| 85 | m3 per second - Flibe recirculation flow |
| 3.3 | g tungsten per load |
| 1 | Hz, load injection frequency |
| 3.3 | g/sec tungsten injected via load |
| 1.63 | g/sec carbon from CRF foam |
| 0.27 | g/sec hydrogen from CRF foam |
| 2.00 | mole ratio of hydrogen to carbon in chamber |
| 0.814 | g/sec - carbon entering chamber that is not converted to CH4 |

therefore much of the carbon could be converted to CH4 by the remaining hydrogen
subsequent calculations will assume that is the case

| | |
|---|---|
| 0.26 | mole ratio of tungsten to remaining carbon in chamber (assuming that hydrogen is effective in converting 75% of C to CH4) |
| 1.00 | mole ratio of tungsten to carbon in tungsten carbide |

therefore all of the tungsten could be converted to tungsten carbide in the Flibe loop
subsequent calculations will assume that is the case

| | |
|---|---|
| 1.086 | g/sec - mass flow of CH4 in/out of Flibe |
| 3.52 | g/sec - mass flow of tungsten carbide into Flibe |
| 15.6 | g/cc - density of tungsten carbide |
| 0.225 | cc/sec - volumetric flow of tungsten carbide into Flibe |
| 0.00 | g/sec - mass flow of tungsten into Flibe (i.e no free tungsten is left - it is all combined with carbon) |
| 19.3 | g/cc - density of tungsten |
| 0.000 | cc/sec - volumetric flow of tungsten into Flibe |
| 0.225 | cc/sec - total volumetric flow of tungsten compounds into Flibe |
| 19469 | cc/day - total volumetric flow of tungsten compounds into Flibe |
| 7106147 | cc/yr - total volumetric flow of tungsten compounds into Flibe |
| 7.1 | m3/yr - total volumetric flow of tungsten compounds into Flibe |

## REQUIRED AMOUNT OF WC SEED

estimate surface area of heat transfer piping

| | |
|---|---|
| 1970 | kg/m3 - Flibe density |
| 167450 | kg/sec - Flibe mass flow rate |
| 545 | watts/m2-deg C - assumed heat transfer coefficient (=100 Btu/hr-ft2-dg F) |
| 2500 | MW - assumed gross thermal rating of HYLIFE-2 - to produce 1000 MW(e) |
| 625 | deg C - avg Flibe temperature |
| 315 | deg C - avg steam temperature (evaporative section) |
| 310 | deg C - avg temp difference across pipe walls |
| 14,797 | m2 - resultan t area of heat transfer surface in overall plant |
| | most of surface area in any power plant loop is in the heat exchangers |
| 2 | ratio of total surface area in loop divided by heat transfer area (conservatively high) |
| 29,595 | m2 - resultant area of all surfaces in overall plant Flibe loop |
| 100 | - surface area multiplier for fine particles to capture most of the tungsten carbide |
| 2,959,455 | m2 - required surface area of tungsten carbide seed material to prevent surface fouling |
| 0.5 | micron - assumed particle size of tungsten carbide seed material |
| 7.85E-13 | m2 - surface area of each tungsten carbide seed particle |
| 1.0205E-12 | g - mass of each tungsten carbide seed particle |
| 0.77 | m2/g - surface area of tungsten carbide seed particle |
| | |
| 2,500,000 | kg, mass of Flibe in loop |
| 3,847 | kg, required mass of tungsten carbide seed material in Flibe loop |
| | |
| 1539 | wt-ppm - required concentration of tungsten carbide seed particles in Flibe loop |
| | |
| 1.0 | wt% WC in Flibe is assumed to be the steady-state maximum allowable |
| 25000 | kg WC - maximum allowable in Flibe |
| 87.7 | average days worth of WC that can be in the Flibe |
| | (which is the average seed replacement time) |
| 16,015 | kg/year seed usage at this seed replacement rate |
| 20 | kg/minute Flibe flow through slip-stream filters to result in calculated WC removal rate |
| | |
| 3.52 | g/sec - mass addition to seed particles from hohlraum tungsten carbide |
| 8756 | sec to grow particles by a diameter factor of 2 |
| 0.10 | days to grow particles by a diameter factor of 2 |
| 0.439 | g/sec - seed feed rate to replenish particles (to keep particle size to a factor of 2 larger than feed) |
| 13,857 | kg/yr - usage of tungsten carbide seed material |

therefore, two independent methods both indicate similar tungsten seed addition rates
at ~15% of the load usage of tungsten, which can be provided either by regrinding filtrate
or by purchasing fresh tungsten powder (15% of tungsten costs = 3 cents per load for using new tungsten)

104,069 kg - annual usage of tungsten in target/load fabrication (for reference)

WC BUILDUP AND REMOVAL

285 kg/day tungsten carbide (from wire arrays and foam coatings)
0.01828 m3/day tungsten carbide (from wire arrays and foam coatings)
2500000 kg Flibe inventory
1269 m3 Flibe inventory

0.00144 volume % tungsten carbide in Flibe after 1 day
144 ppm tungsten carbide added to Flibe after 1 day

this means that it will take many days for the tungsten carbide particle concentration to build up to levels that could cause problems in the nozzles

therefore, slipstream filters could be installed off the main Flibe loop to continuously remove tungsten carbide particles

19.8k g/minute Flibe flow through slip-stream filters to result in calculated WC removal rate

a sintered-metal filter system (cleanable on-line) is estimated to cost ~$450,000, which would be ~$1.8 million installed cost (or $0.23 million annualized capital cost)
operating costs are estimated to be no more than $0.15 million (labor, utilities & maintenance)
total annual costs are therefore $0.38 million, or 1.2 cents per load

the cost of WC seed has already been calculated to be 3 cents per load

In summary, the total cost of seeding and removing tungsten from the Flibe loop (including other suspended solids) is estimated to be ~4.2 cents per load

## 5.6. RESULTS

1. An initial Flibe seeding with 1500 ppm of WC particles will keep the reactor surfaces clean of depositions.
2. An additional 15 ppm of WC will be added to the Flibe every day, from the wire array assemblies (W wires) and from the target assemblies (W coating on foam cylinders and W disks on reservoirs).
3. A small slipstream filtration system will maintain the WC surface area in the Flibe at a sufficient level.
4. The required amount of WC seed is about 15 tonnes per year, as compared with the 104 tonnes per year of W needed for load production.

The total cost for seeding WC and recovering WC via on-line slipstream Flibe filtration is estimated to be 4.2 cents per load.

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