LA-UR-91-0430

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Submitted to: American Nuclear Society Meeting

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Concepts for Fabrication of Inertial Fusion Energy Targets

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Abstract

Future inertial fusion energy (IFE) power plants will have a Target Fabrication Facility (TFF) that must produce approximately 500,000 targets per day. To achieve a relatively low cost of electricity, the cost to produce these targets will need to be less than approximately \$0.25 per target. In this paper the status on the development of concepts for a TFF to produce targets for a heavy ion fusion (HIF) reactor, such as HYLIFE II, and a laser direct drive fusion reactor such as Sombraero, is discussed. The baseline target that is produced in the HIF TFF is similar to the close-coupled indirect drive target designed by Callahan-Miller and Tabak at Lawrence Livermore Laboratory. This target consists of a cryogenic hohlraum that is made of a metal case and a variety of metal foams and metal-doped organic foams. The target contains a DT-filled CH capsule. The baseline direct drive target is the design developed by Bodner and coworkers at Naval Research Laboratory. HIF targets can be filled with DT before or after assembly of the capsule into the hohlraum. Assembly of targets before filling allows assembly operations to be done at room temperature, but tritium inventories are much larger due to the large volume that the hohlraum occupies in the fill system. Assembly of targets cold after filling allows substantial reduction in tritium inventory, but this requires assembly of targets at cryogenic temperature. A model being developed to evaluate the tritium inventories associated with each of the assembly and fill options indicates that filling targets before assembling the capsule into the hohlraum, filling at temperatures as high as possible, and reducing dead-volumes in the fill system as much as possible offers the potential to reduce tritium inventories to acceptable levels. Use of enhanced DT ice layering techniques, such as infrared layering can reduce tritium inventories

significantly by reducing the layering time and therefore the number of capsules being layered. Current processes for fabrication of ICF capsules can most likely be easily scaled up to produce capsules at rates needed for an IFE plant.

I. Introduction

Over the past decade, a number of design studies have been performed to examine the feasibility of inertial fusion energy (IFE) as a means of energy production. Costs of electricity in the Osiris and Sombraero studies (1), as well as the HYLIFE-II study (2) were determined to be less than \$0.07/kW-h.

In each of the concepts studied, targets need to be fabricated at rates of approximately 5-10 Hz, at costs approximating \$0.25/target. This is a significant challenge given the complexity and precision required for the targets. K. R. Schultz, et al. (3) recently described in detail the requirements for production of IFE targets. In the present paper, we present the status on the development of concepts for HIF and direct drive fusion energy concepts that meet these requirements. We discuss three options for filling and assembly of HIF targets, which consider DT filling of the capsule before and after assembly of the target. We discuss the advantages and disadvantages associated with each approach. We then describe a model that is being developed to calculate the minimum tritium inventories that will be required for each of the target fabrication approaches. We present some initial results from this model.

We present concepts for the manufacture of some target materials and assembly of target components. Target production processes for HIF targets are based

on the close-coupled target design developed by Callahan-Miller and Tabak (4). This target requires an injection rate of 6 Hz for the HYLIFE-II conceptual plant design for a net electric power of 1 GWe. The direct drive target design is the design that has recently been described by Bodner et al. (5). Such a target requires an injection rate of 6.7 Hz for the Sombrero plant design with a net power of 1 GWe.

II. Target Designs and Materials

Figure 1 shows the design of the HIF close-coupled target. The target materials can be categorized into the following types of materials:

- DT (solid or gas)
- CH polymer (capsule)
- Fe Foam
- Al Foam
- Other metal foams
- Metal-doped CH foam
- Hohlraum (full density metal)
- Deuterium gas

Figure 2 shows the direct drive target design. This target consists of a thin CH polymer capsule that contains an inner layer of CH foam. The capsule wall contains gold.

III. Options for Filling and Assembly of Targets

Before considering how these materials will be manufactured, it is important to consider the overall target fabrication process and evaluate whether targets should be filled with DT before or after they are assembled. Figure 3 shows three options that need be evaluated with respect to the sequence of target assembly and filling for the HIF target.

The path labeled "Temperature Shimmed Hohlraum" (TSH) involves manufacture of target materials followed by diffusion filling of the target capsule before assembly of the targets. The capsule is then assembled into the target while the target is cold. The DT ice layer is then formed while the capsule is in the hohlraum. In this scenario, the conditions in the hohlraum must be created such that the capsule exists in a spherically symmetric thermal environment. Such an environment is required for formation of a spherically

symmetric DT ice layer. This spherically symmetric environment can be formed either by designing the hohlraum so that heat transfer out of the capsule from beta decay of tritium results in a spherically uniform thermal profile, or a temperature distribution can be imposed on the external surface of the hohlraum that causes the thermal profile around the capsule to be spherical. Once a smooth and uniform DT ice layer is formed on the capsule interior surface, the target can be injected into the target chamber.

The TSH approach allows filling of the capsule in a minimum fill volume by eliminating placement of the entire hohlraum in the fill volume, and this allows the capsule to be filled with lower tritium inventories (we discuss this in more detail below). A drawback of this approach is that the capsule must be assembled into the hohlraum while the capsule is cold (the capsule cannot hold its DT fill gas at room temperature). Assembly at cold temperatures involves more complex manipulation of target components at cryogenic temperatures.

Figure 1: HIF Target showing the target materials. A-DT gas; B-DT Solid; C-CH or Be; D-Au foam; E-Metal-doped CH foam; F-Fe foam; G-Fe foam; H-Metal-doped CH foam; I-AuGd foam; J-AuGd foam; K-AuGd foam; L-AuGd; M-Al foam; N-AuGd foam; O-D₂.

Figure 2: Direct drive target design

A second approach for filling and assembly of target components is the "Cryogenically Assembled Hohlraum" (CAH) approach. This approach also fills the capsule before assembly, but the uniform DT ice layer is formed before assembly into the hohlraum. The advantage of this approach is that the capsule can be layered by placement in a spherically uniform environment (such as an isothermal spherical cavity), and this eliminates the complexity associated with thermal shimming of the hohlraum. In this approach, the assembly and injection of the target must occur in a few minutes time in order that the spherically nonuniform hohlraum does not have time to cause the DT ice layer to redistribute.

The third and final approach shown in Figure 3 is the Warm Assembled Hohlraum (WAH). In this approach, the entire target is assembled warm. The capsule is filled with DT while it is in the hohlraum. Higher DT inventories are needed, but cryogenic manipulation and assembly of parts is avoided. This approach also requires temperature shimming of the hohlraum to form the uniform DT ice layer.

In the direct drive approach there is no hohlraum. However, it is possible that the capsule will be placed in a sabot before target chamber injection. Placement in the sabot is assumed to be similar to placement in a hohlraum. Little thought has been placed into the design of the sabot, so we have not evaluated this.

IV. Modeling of Minimum Tritium Inventories Required for Target Filling

Both the HIF and direct drive targets considered in this paper have polymeric capsules. Filling of these capsules can be accomplished by diffusion filling under DT pressure. This is the filling technique that will be used to fill polymeric ignition capsules for NIF. While other filling methods are being considered, such as injection filling of the target with cryogenic liquid, we do not discuss these methods in this paper because they are in the very early stages of development.

Figure 3. Options for filling and assembly of HIF targets.

In the diffusion fill process, the capsule is placed in DT gas under pressure. Because the capsule wall is relatively permeable to DT, the capsule fills relatively rapidly. Capsule filling rates increase as the capsule external pressure increases. However, capsules have a characteristic buckling pressure above which the capsule will buckle from the external pressure forces.

Typically, capsules are filled by increasing the DT pressure during diffusion filling such that a relatively constant ΔP across the capsule walls is maintained. This approach minimizes the fill time by keeping the ΔP as high as possible without crushing the target.

In this study we evaluate the minimum tritium inventory that is necessary to fill targets at the rates needed for injection into the reactor chamber. Our approach assumes that targets are filled in a “just-in-time” manner. This means that each target is subjected to a filling cycle that prepares targets at the exact rate needed for injection into the chamber. In this manner, we evaluate the minimum inventory that is required to produce targets at the required rate. This approach eliminates from consideration any engineering assumptions as to the number, size, and frequency of fill batches. At a later stage in the development of the model, we will introduce these engineering assumptions. With the minimum inventory approach, we must then develop an engineering approach that uses tritium inventories that are as close as possible to the minimum inventories.

In the model, we evaluate the tritium inventories for the following target filling scenarios:

- Fill of HIF targets in the hohlraum (WAH approach)
- Fill of HIF targets before assembly (TSH or CAH approach)
- Fill of direct drive targets

In the model, we attempt to evaluate the minimum tritium inventory associated with each step of the fill process. The process steps that involve tritium inventories are as follows:

- Permeation filling of the capsule
- Cooldown of capsules in the fill system
- Evacuation of DT from the fill system
- Beta-layering or enhanced layering of the capsules to form the internal DT ice layer.

We then sum the inventories for each fill process step. To evaluate the minimum inventory, we assume that targets are filled in a “just-in-time” manner. With this approach, rather than consider targets as being filled in batches, we assume that each target is filled in its own fill cell, and that there are enough fill cells such that targets are being produced at a rate that is equal to the rate at which they are being injected into the target chamber. By taking this approach, we evaluate a theoretical minimum required tritium inventory. For the development of the model, the system is defined as each step of the fill process and is examined at an instant in time. Therefore, the total inventory is the sum of the inventories over all the fill cells in the process. Once minimum theoretical inventory has been evaluated, we then can perform the task of engineering the fill systems that most closely approach this theoretical minimum inventory.

Figure 4: Pressures in the fill cell (P_{ext}) and in the target (P) during filling.

In the first step of the process, capsules are diffusion filled by ramp up of DT pressures in a fill system. We assume that the pressure in the fill system is ramped up so that the differential pressure across the capsule wall is 75% of the capsule buckle pressure. Assuming that each capsule is filled in its own individual fill cell and that filled capsules are produced at the rate required for injection into the chamber, the number of fill cells needed is:

$$N_{fill} = (\text{shot rate}) \times (\text{fill time})$$

Figure 4 illustrates schematically the fill cell and target pressures during filling. Each fill cell pressure is different, so the tritium inventory in each fill cell is different. The inventory necessary to fill capsules is determined by summing the inventory over all of the fill cells. Each fill cell has three significant volumes to consider: the volume of the gas outside the capsule but within the fill cell (V_{outer}), the volume of the gas inside

the capsule (V_{inner}), and the volume of the spherical capsule shell (V_{shell}). The total volume of the fill cell is then:

$$V = V_{outer} + V_{inner} + V_{shell}$$

Therefore, in each fill cell, there is tritium inventory associated with DT gas outside of the capsule and DT gas inside the capsule. The number of grams of tritium outside of the capsules in the fill cells is determined by summing the DT quantity of all of the fill cells, as follows:

$$g_{fill_outside} := \frac{MW \cdot V_{outer}}{R \cdot T_{fill}} \cdot N_{fill} \cdot \sum_{n=1}^{N_{fill}} P_{ext}(n)$$

where MW is the molecular weight of tritium, R is the gas constant, and T_{fill} is the fill temperature. $P_{ext}(n)$ is the externally applied overpressure to capsule n and is defined as:

$$P_{ext}(n) := P_0 + \frac{n-1}{N_{fill}-1} \cdot P_{fill}$$

where P_0 is the overpressure (75% of the buckle pressure) and P_{fill} is the desired final pressure inside the capsule.

The number of grams of tritium inside the capsules in all of the fill cells is as follows:

$$g_{fill_inside} := \frac{MW \cdot V_{inner}}{R \cdot T_{fill}} \cdot N_{fill} \cdot \sum_{n=1}^{N_{fill}} P(n)$$

where $P(n)$ is the pressure inside of the capsule and is defined as:

$$P(n) := \frac{n-1}{N_{fill}-1} \cdot P_{fill}$$

The total number of grams of tritium in the permeation fill step is the sum of tritium inside and outside of the capsule in the fill cells:

$$g_{fill_TOTAL} := g_{fill_outside} + g_{fill_inside}$$

Once the targets are permeation filled, the next step in the process is cooldown of targets. During this step, the DT inventory in each fill cell remains constant during

the cooldown cycle. Thus, the inventory in the cooling process is:

$$g_{cool} := \frac{MW \cdot P_{fill} \cdot (V_{outer} + V_{inner})}{R \cdot T_{fill}} \cdot N_{cool}$$

where N_{cool} is the number of targets in the cooling step of the process:

$$N_{cool} = (\text{shot rate}) \times (\text{cool time})$$

For our calculations, we assume a cooling time of 2 hours. Scaling arguments suggest this to be an attainable goal. However, forthcoming future work will provide a more rigorous calculation of the cool time.

Once the fill cells are cooled to cryogenic temperature, the DT outside of the target is evacuated from the fill cell. After this evacuation, only the DT inventory in the capsule remains in the fill cell. For our calculations, we assume an evacuation time of 1 hour. The inventory during this step is as follows:

$$g_{evacuate} := \frac{N_{pump} \cdot MW \cdot P_{fill}}{R \cdot T_{fill}} \cdot \left(\frac{V_{outer}}{2} + V_{inner} \right)$$

where

$$N_{evacuate} = (\text{shot rate}) \times (\text{evacuation time})$$

The final step in the fill process is layering of DT to form a smooth DT ice layer inside of the capsule. Experience with DT layering experiments in support of the development of NIF ignition capsules (6,7) has shown that beta-layering requires approximately 8 hours to produce smooth ice surfaces. However, experiments have shown that if heat in addition to tritium decay heat is added to the DT ice, such as by infrared light, the layering time can be substantially shortened to approximately 2 hours. The tritium inventory during this layering process is the inventory associated with the capsules that are undergoing the layering process. This inventory is given by:

$$g_{layering} := \frac{N_{layering} \cdot P_{fill} \cdot V_{inner}}{R \cdot T_{fill}}$$

where

$$N_{layering} = (\text{shot rate}) \times (\text{layering time})$$

Having established the above equations, the total inventories for several scenarios can be evaluated. Table 1 shows the tritium inventory for filling of HIF capsules in the hohlraum, filling of capsules before assembly into the hohlraum, and filling of direct drive capsules. Also shown are tritium inventories where layers are formed by beta-layering and IR layering. Table 2 shows the values of the parameters assumed for the calculations.

Table 1: Buckle pressures, fill times, and tritium inventories associated with filling HIF and direct drive IFE targets at room temperature (300K).

	HIF-fill in hohlraum	HIF-fill before assembly	Direct Drive
Buckle Pressure (atm)	545	545	0.062
Fill Time (hours)	7.3	7.3	222
Tritium Inventory (kg) (beta-layering)	27.1	1.3	14.8
Tritium Inventory (kg) (beta-layering + IR)	26.8	0.9	14.4

Table 2: Values of the parameters necessary for the calculations.

	<u>HIF</u>	<u>Direct Drive</u>
Target Yield	350 MJ	400 MJ
Fusion Power	2100 MW	2677 MW
Capsule Outer Radius	0.230 cm	0.1951 cm
Solid Polymer Thickness	.025 cm	0.8 μ m
Foam thickness	NA	0.025 cm
Tritium Inventory in target	0.00387 g	0.00423 g
Final Fill Pressure (300K)	792 atm	1156 atm
Shot rate	6.0 Hz	6.7 Hz
Cool Time	2 hrs	2 hrs
Evacuation Time	1 hr	1 hr
Beta Layering Time	8 hrs	8 hrs
Beta + IR Layering Time	2 hrs	2 hrs

In comparing HIF and direct drive targets, it is noted that because of the thick wall of the HIF target, its buckle pressure is 3 orders of magnitude higher than the direct drive target. As a result, it takes significantly longer to fill the direct drive target. Because of the large hohlraum, tritium inventories associated with filling of the capsule in its hohlraum are much higher than filling the capsule before placement in the hohlraum. This result suggests that there is a large reduction in tritium inventory that can be realized by filling the capsule and then assembling the components at cryogenic temperatures. Beta-layering vs. IR-layering reduces the tritium inventory by 0.3 kg.

An important goal in any fusion facility is to reduce as much as possible the tritium inventory. With our model, we can now examine the effects of some of the fill parameters and attempt to minimize the tritium inventory. One way to reduce tritium inventory is to increase the fill temperature. At higher temperature, the fill time is shortened due to increased permeability. Figure 5 shows the effect of temperature on fill time.

Figure 5: Effect of temperature on diffusion fill time of a HIF capsule.

Increasing the temperature by 40 K decreases the fill time by more than a factor of 4. Figure 6 shows the effect of temperature on the tritium inventory for an HIF target filled before assembly into the hohlraum. Use of IR layering and higher temperatures also significantly reduces tritium inventories. A similar benefit from operating at higher temperature is realized in the case of direct drive targets. Figure 7 shows the tritium inventory vs. temperature for direct drive targets. Significant reductions in inventory are realized by filling at higher temperature, but because the amount of tritium in the fill system is much higher than the amount of tritium in the

capsules being layered, use of IR layering has little effect on the overall tritium inventory.

Another parameter that influences tritium inventory is the void volume in the fill system. The calculations shown above for the HIF target filled before assembly into the hohlraum and the direct drive target assumed that the void fraction during filling is equivalent to void volumes in close packed spheres (0.33). However, if capsules are placed in trays with spherical "holes" to contain the capsules, then the void fraction can be reduced to below the close packed sphere value. Figure 8 shows the tritium inventory for HIF target before assembly vs. the system void fraction.

Figure 6: Effect of temperature and layering method on tritium inventory for an HIF target.

Figure 7: Tritium inventory vs. temperature and fill method for direct drive targets.

Figure 8: Effect of void fraction on tritium inventory for HIF targets at 340 K.

Above we show a few examples of the fill parameters that can be optimized to reduce tritium inventory. Future work will focus on further optimization of the fill parameters, as well as incorporating into the model real engineering considerations, such as the effect of fill batch size on tritium inventories.

V. Target Material Manufacturing Processes

In an IFE TFF, target materials will need to be fabricated on a much larger scale than is currently done for ICF targets. For both the HIF and direct drive IFE approaches, poly(α -methylstyrene) (PAMS) mandrels will be needed to produce capsules. A triple orifice droplet generator produces current mandrels for ICF capsules (8). Water containing about 1% polyvinyl alcohol (PVA) passes through the center orifice of the droplet generator. A solution of PAMS in fluorobenzene is passed through the annular orifice of the droplet generator. Water containing 1% PVA is passed through the outer orifice. With this technique, approximately 36,000 shells are made in a period of about 20 minutes. Once produced, these shells are cured to remove fluorobenzene from the shell, the shells are washed with water, the water inside the shell is then extracted with ethanol, and the shells are vacuum dried. Approximately 3 days are required to produce a batch of shells. Once the mandrels are produced, they would be overcoated with GDP or other ablator material.

An IFE plant would require 500,000 shells per day. Scaleup of the current droplet generator process would require a stirred tank reactor with volume of approximately 100 liters. Approximately 14 droplet

generators producing shells into the 100 liter reactor would produce enough shells for a single day of operation. After the shells are produced, they would be cured, washed, ethanol-extracted and dried.

Curing of the shells could be done in the reactor in which the shells were produced. Washing and ethanol extraction can occur in stirred tank reactors. Drying of the shells can be accomplished in a fluidized bed by heating the shells in a stream of dry nitrogen.

Overcoating of the shells with glow discharge polymer or other ablator could also be performed in a fluidized bed reactor. We are currently evaluating the sizes of these various reaction vessels in an attempt to define the process equipment

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