GA–A24816

DEMONSTRATING A TARGET SUPPLY FOR INERTIAL FUSION ENERGY

by

D.T. GOODIN, N.B. ALEXANDER, L.C. BROWN, D.A. CALLAHAN, P. EBEY,
D.T. FREY, R. GALLIX, D. GELLER, C.R. GIBSON, J. HOFFER,
J.L. MAXWELL, B.W. MCQUILLAN, A. NIKROO, A. NOBILE, C. OLSON,
R.W. PETZOLDT, R. RAFFRAY, W.S. RICKMAN, G. ROCHAU,
D.G. SCHROEN, J. SETHIAN, J. SHELIAK, J.E. STREIT, M. TILLACK,
B.A. VERMILLION, and E.I. VALMIANSKI

DECEMBER 2004

DISCLAIMER

GA–A24816

DEMONSTRATING A TARGET SUPPLY FOR INERTIAL FUSION ENERGY

by

D.T. GOODIN, N.B. ALEXANDER, L.C. BROWN, D.A. CALLAHAN,*
P. EBEY,† D.T. FREY, R. GALLIX, D. GELLER,† C.R. GIBSON, J. HOFFER,†
J.L. MAXWELL,† B.W. MCQUILLAN, A. NIKROO, A. NOBILE,† C. OLSON,‡
R.W. PETZOLDT, R. RAFFRAY,£ W.S. RICKMAN,+ G. ROCHAU,‡
D.G. SCHROEN,# J. SETHIAN,¶ J. SHELIAK, J.E. STREIT, # M. TILLACK,£
B.A. VERMILLION, and E.I. VALMIANSKI§

*Lawrence Livermore National Laboratory
†Los Alamos National Laboratory
‡Sandia National Laboratories
£University of California, San Diego
+TSD Management Associates
#Schafer Corporation
¶Naval Research Laboratory
§Consultant to General Atomics

This is a preprint of a paper presented at the 16th ANS Topical Meeting on the Technology of Fusion Energy, Madison, Wisconsin, September 14–16, 2004 and to be published in *Fusion Science and Technology.*

Work supported by
the U.S. Department of Energy
under Contract No. DE-AC03-98ER54411,
and Subcontract N00173-02-C-6010

GENERAL ATOMICS PROJECT 30183
DECEMBER 2004

DEMONSTRATING A TARGET SUPPLY FOR INERTIAL FUSION ENERGY

D.T. Goodin,[1] N.B. Alexander,[1] L.C. Brown,[1] D.A. Callahan,[2] P.S. Ebey,[3] D.T. Frey,[1] R. Gallix,[1] D.A. Geller,[3] C.R. Gibson,[1] J.K. Hoffer,[3] J.L. Maxwell,[3] B.W. McQuillan,[1] A. Nikroo,[1] A. Nobile,[3] C. Olson,[4] R.W. Petzoldt,[1] R. Raffray,[5] W.S. Rickman,[6] G. Rochau,[4] D.G. Schroen,[7] J. Sethian,[8] J.D. Sheliak,[1] J.E. Streit,[7] M. Tillack,[5] B.A. Vermillion,[1] and E.I. Valmianski[9]

[1]General Atomics, P.O. Box 85608, San Diego, California 92186-5608, email: dan.goodin@gat.com
[2]Lawrence Livermore National Laboratory, P.O. Box 808, Livermore, California 94551
[3]Los Alamos National Laboratory, P.O. Box 1663, Los Alamos, New Mexico 87545
[4]Sandia National Laboratory, P.O. Box 5800, Albuquerque, New Mexico 87185
[5]University of California, San Diego, 9500 Gilman Drive, La Jolla, California 92093
[6]TSD Management Associates, 873 Eugenie Avenue, Encinitas, California 92024
[7]Schafer Corporation, SNL, P.O. Box 5800, Albuquerque, New Mexico 87185
[8]Naval Research Laboratory, 4555 Overlook Avenue, SW, Washington, DC 20375-5000
[9]Consultant to General Atomics, P.O. Box 85608, San Diego, California 92186-5608

A central feature of an Inertial Fusion Energy (IFE) power plant is a target that has been compressed and heated to fusion conditions by the energy input of the driver. The technology to economically manufacture and then position cryogenic targets at chamber center is at the heart of future IFE power plants. For direct drive IFE (laser fusion), energy is applied directly to the surface of a spherical CH polymer capsule containing the deuterium-tritium (DT) fusion fuel at approximately 18 K. For indirect drive (heavy ion fusion, HIF), the target consists of a similar fuel capsule within a cylindrical metal container or "hohlraum" which converts the incident driver energy into x-rays to implode the capsule. For either target, it must be accurately delivered to the target chamber center at a rate of about 5–10 Hz, with a precisely predicted target location. Future successful fabrication and injection systems must operate at the low cost required for energy production (about \$0.25/target, about 10^4 less than current costs).

Z-pinch driven IFE (ZFE) utilizes high current pulses to compress plasma to produce x-rays that indirectly heat a fusion capsule. ZFE target technologies utilize a repetition rate of about 0.1 Hz with a higher yield.

This paper provides an overview of the proposed target methodologies for laser fusion, HIF, and ZFE, and summarizes advances in the unique materials science and technology development programs.

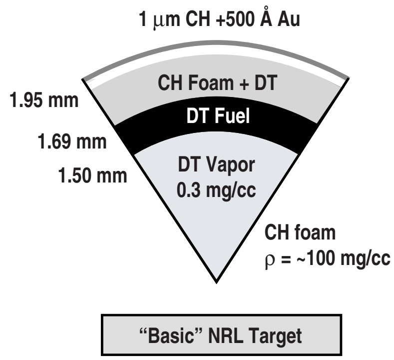
I. INTRODUCTION

A central feature of an Inertial Fusion Energy (IFE) power plant is a target (Fig. 1, for example, shows a laser fusion target) that has been compressed and heated to fusion conditions by the energy input of the driver beams. A target development program is underway to demonstrate successful target technologies for IFE applications.[1]

For direct drive IFE,[2] energy is applied directly to the surface of a spherical CH polymer capsule[3] containing the deuterium-tritium (DT) fusion fuel at approximately 18 K. For indirect drive[4] (heavy ion fusion, HIF), the target consists of a similar fuel capsule within a cylindrical metal container or "hohlraum" which converts the incident driver energy into x-rays to implode the capsule. Either target must be accurately delivered to the target chamber center at a rate of about 5–10 Hz, with a precisely predicted target location.[5,6] The relatively fragile cryogenic targets must survive injection into the target chamber without damage.[7]

The Target Fabrication Facility (TFF) of a laser or heavy ion IFE power plant must supply about 500,000 targets per day. The feasibility of developing successful fabrication and injection methodologies at the low cost required for energy production (about \$0.25/target, about 10^4 less than current costs) is a critical issue for inertial fusion.[8,9]

Z-pinch driven IFE (ZFE)[10] utilizes high current pulses to compress plasma to produce x-rays which indirectly heat a fusion capsule. ZFE target technologies differ somewhat from the other IFE concepts in that the repetition rate is only about 0.1 Hz and the target yield is significantly higher (about 3000 MJ per target compared



Some Expected Direct Drive Specifications

Capsule Material	CH (DVB) foam
Capsule Diameter	~4 mm
Capsule Wall Thickness	290 µm
Foam shell density	20-120 mg/cc
Out of Round	<1% of radius
Non-Concentricity	<1% of wall thickness
Shell Surface Finish	~20 nm RMS
Ice Surface Finish	<1 µm RMS
Temperature at shot	~15 - 18.5K
Positioning in chamber	± 5 mm
Alignment with beams	<20 µm

Fig. 1. Laser fusion baseline high-gain target and expected target specifications.

to about 400 MJ for laser and HIF).[a] In addition to these features, the (baseline) ZFE capsule is made of Be, which leads to some different requirements for Z-pinch driven systems.

II. LASER FUSION

The target supply process for laser fusion, heavy ion fusion, and even ZFE have significant elements in common. The various development programs take advantage of this commonality. The basic requirement for the TFF of a laser fusion power plant is to provide about 500,000 targets per day (at ~6 Hz) with precision geometry, and with precision cryogenic layered DT fuel. The targets include a divinylbenzene foam shell[11] to contain the DT fusion fuel. Density matched microencapsulation has been used in the laboratory to produce these shells. This fabrication step is relatively well-understood and demonstrated, although work remains to scale the process to larger batches and to increase product yields for IFE capsules. The principal technical issues are meeting non-concentricity and out-of-round requirements when fabricating the CH capsules at large diameter and with thick walls. Filling of polymer capsules with hydrogen isotopes by permeation through the wall, removal of the excess DT after cooling to cryogenic temperatures (to reduce the capsule internal pressure and prevent rupture), and transport under cryogenic conditions has been demonstrated in the laboratory.[12,13] Demonstration of capsule filling with DT and subsequent cryogenic removal of the excess DT has been demonstrated at LANL.[14] Estimates of the DT filling (and layering) time and models to predict its effect on tritium inventory in the Target Fabrication Facility have been prepared.[15] The principal issue regarding permeation filling with DT is minimizing the tritium inventory "at risk", and thus maximizing the attractiveness of the power plant. Layering,[16,17] is the process of redistributing the cryogenic DT fuel into a smooth uniform layer inside the ablator. Layering requires establishing an extremely precise (~250 µK), uniformly spherical temperature distribution at the surface of the capsule. A cryogenic fluidized bed experiment has been designed to demonstrate this process with hydrogen isotopes in a batch-mode. This concept is for the fluidized bed to rapidly randomize the targets yielding a very uniform time-averaged surface temperature. Layering in a fluidized bed is followed by a very rapid (a few seconds or less) removal of the layered capsule from the bed, and assembly into a sabot for injection. The sabot protects the cryogenic target during injection, and springs apart and is deflected from the capsule trajectory prior to its entering the target chamber. The target in the back half of the sabot is supported by a thin membrane which distributes the load and prevents point-contact loading of the fragile capsule during the ~1000 g acceleration.

A potential option for the laser fusion target that helps protect it from thermal radiation during its injection is a "foam-insulated" target which uses a relatively thin layer of foam to reduce the heat load to the cryogenic DT.[18] The degree of heating of the target during injection is determined by the radiation heating from the first wall and by heating from the gas in the chamber. The pressure of the gas in the chamber for first wall protection is the subject of current trade studies for laser fusion. Modeling of cooling mechanisms for gas within the chamber, the temperature of the gas during target injection, recombination of the plasma after the shot, and the heat flux the target will experience has been initiated.[19] Preliminary results show that heat fluxes of 0.6 to 0.7 W/cm^2 can be obtained only with extremely low gas densities (< 10^{20} m^{-3}), whereas thermally insulated targets could withstand modest gas densities (~10^{20} –10^{21} m^{-3}). A large-scale convective motion induced within the chamber was found to be an effective way to speed up the

[a]A proposed, large ZFE power plant has 12 chambers, with 10 chambers operating at any one time, each chamber at 0.1Hz to produce a total of about 1000 MW(e).

plasma cooling and recombination, by effectively bringing hot particles closer to the wall.

The cost of the target is also a key issue in the IFE target supply. Laser fusion targets have been the subject of the most extensive and well-documented analyses for future target manufacture of all the IFE concepts considered. We have prepared preliminary equipment layouts,[20] and determined floor space and facility requirements for nth-of-a-kind production of high-gain laser-driven IFE targets. The results for a 1000 MW(e) baseline plant indicate that the installed capital cost is about $100M and the annual operating costs will be about $19M (labor $9M; materials/utilities $4M; maintenance $6M), for a cost per target of slightly less than $0.17 each.

To arrive at this cost, a number of process assumptions have been made, based on 1) preliminary requirements for the NRL high gain direct drive targets, 2) discussions with researchers in each of the enumerated process steps to reflect their latest findings, and 3) interactions with vendors of process equipment that is adaptable to this service ~such as critical point driers. The plant conceptual design includes a process flow diagram, mass and energy balances, equipment sizing and sketches, storage tanks, and facility views (plan, elevation, and perspective). The cost estimating process uses established cost-estimating methods and factors for the chemical process industry. Recycle and beneficial reuse of process effluents is designed into the facility. A detailed material and energy balance was prepared to provide information on flow rates and quantities of raw materials, finished products, and byproducts for the entire plant. All of the cost calculations for chemical, utilities, and waste disposal use mass quantities calculated in the material and energy balances. Statistical sampling of target batches will be performed at each process step to avoid unnecessary further processing of out-of-spec targets. Finished dry shells will be sampled at 100% quality assurance in a final flow-thru step and stockpiled, potentially at a central facility serving multiple power plants. The target would be DT-filled and layered onsite prior to injection. For these cost estimates we make an arbitrary assumption that the final product reject rate is 25%[b]. Plant capital costs are treated as an annual expense. Standard financial treatments result in a levelized charge rate corresponding to an annual expense. Here we assume a 12.5% fixed charge rate for a 30 year facility.

A generous operating staff has been allocated to the laser fusion target production plant. Maintenance expenses are calculated using a factored percentage, 6% per year of installed capital costs. Utilities, waste disposal and chemical costs are calculated based on current day vendor prices coupled with mass and energy balance data. In these analyses, it is assumed that the power plant produces its own tritium which is extracted from the breeding material and purified — the cost of the tritium production, extraction, and purification steps are not included in the target production cost and must be considered separately. The per-target cost basis is for current-year dollars; one can assume an escalation factor of 3% to 5% per year depending on inflation rate until plant construction takes place. Further details of the laser fusion cost estimating process can be found in Ref. [21].

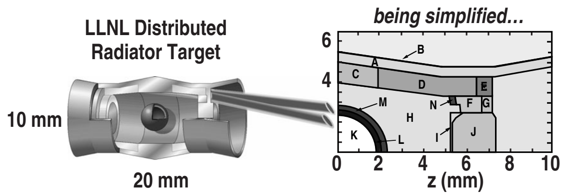
III. HEAVY ION FUSION

IFE power plant conceptual designs for heavy ion fusion (HIF) have been published over the past few decades.[22,23] A variety of target designs have been analyzed for heavy ion fusion, including the “distributed radiator” design illustrated in Fig. 2,[24] which is the current focus of development interest (along with closely related “hybrid” designs). This target utilizes illumination by a number of beams from two sides, focused in an annular ring on the ends of the target. The ion beams deposit their energy all along the nearly cylindrical hohlraum materials, thus the term distributed radiator. The distribution of radiation is accomplished by tailoring the density of radiator materials in the target; which means that fabrication of a number of special high-Z doped CH foams and high-Z (metal) foams are required. These hohlraum materials are the subject of materials development tasks unique to the HIF target. Other manufacturing aspects of the HIF target are similar to laser-driven direct-drive IFE targets and to current experimental inertial confinement fusion targets (e.g., spherical shells, permeation filling). The selection of materials (element and composition) for the hohlraum areas indicated in Fig. 2 remains the subject of evaluations and studies.[25]

In a previous paper,[26] we described an outline for the entire pathway, from beginning to end, for fabrication of a high-gain, distributed radiator target for energy production. This pathway has been further detailed in Ref. [27]. The capsule[c] supply process is very similar to laser fusion, up to the point where the filled and layered capsule is placed within the sabot for injection – instead the HIF capsule is placed within the prepared, cryogenic hohlraum. A room temperature assembly of the capsule and hohlraum (followed by layering within the hohlraum)

[b]Actual final product reject rates are of course expected to be much less than 25%, and the rejects will take place at various stages throughout the process.

[c]A full density CH capsule is used for HIF.



Two sided illumination by heavy ion beams
Radiation distribution tailored by material density
Unique hohlraum materials - newer designs may eliminate "high-Z only" materials

Some Possible Indirect Drive Specifications

Capsule Material	CH or Be
Capsule Diameter	~4.6 mm
Capsule Wall Thickness	250 μm
Out of Round	<1% of Radius
Non-Concentricity	<1% of Wall Thickness
Shell Surface Finish	20–200 nm RMS
Ice Surface Finish	1–10 μm RMS
Temperature at Shot	~15–18.5 K
Positioning in Chamber	±1–5 mm
Alignment with Beams	<200 μm

Fig. 2. LLNL distributed radiator target is driven by heavy ion beams.[4]

is not favored for IFE since void space within the hohlraum would result in up to 30 times more tritium inventory during filling as compared to filling of capsules alone. Using cryogenic assembly, the HIF inventory should be the same as predicted for direct drive targets,[15] or less than ~ 1 kg tritium in the TFF.

The challenge of the HIF target that is unique for fabrication is its distributed radiators. To fabricate these materials, a new process, high-pressure laser chemical vapor deposition (LCVD), is being experimentally demonstrated.[28] LCVD utilizes a laser to catalyze a chemical vapor deposition in a controlled manner. A precursor molecule containing the high Z element of interest is laser-decomposed to form lattices of high Z low density material. Diffractive optics are used to generate an array of hot-foci on an initial substrate, and the fibers are grown normal to the substrate by thermal decomposition of the precursor mixture. As the entire array is grown under computer control, the overall shape of the material can be varied at will, and (axial and radial) material gradients can be built into the lattice – simplifying the design and assembly of target hohlraums. Thus, LCVD can "grow" fibers and interlink fibers on the scale of a few microns to produce a "microengineered" foam structure to meet the needs of material density, pore size, strength, rigidity, and geometric shape. This process is rapid and thus amenable to production scaleup. LCVD opens the door for more flexible hohlraum designs, as it is capable of creating functionally-graded materials that vary in both density and elemental composition. In addition, to some degree, the physical, mechanical, and thermal properties of the metal foams can be controlled to meet the target functional requirements (by controlling the microstructure of the matrix created).

Recent work has identified a process flow for hohlraum manufacture that minimizes handling and assembly steps and basically "grows" the hohlraum "from the inside out" in a single chamber. This method avoids precision machining steps, and eliminates issues of handling and assembly of the low density materials by maximizing use of the LCVD. A multiplexed laser array produces fibers of the desired material. Precursor gas flows are controlled to allow changing materials, even allowing a gradual change of density and material content within the sample. Junctions without distinct boundaries can be created within the lattice, so that the individual "pull-out strength" of each fiber approaches the yield strength of the fiber material itself. After the foam components are produced, suitable processes (such as flame spray or plasma spray) are used to overcoat the foam wall and build a thick overlayer for support and containment. The hohlraum is then inserted into a casing with a cap to facilitate reactive injection molding of a polymer case (for handling and injection purposes). A filled, layered capsule freshly taken from a cryogenic fluidized bed is then placed within the bottom hohlraum part, and the top part is placed over the capsule to provide an assembled HIF target for subsequent injection.

It is our near-term goal to show the viability of manufacturing targets at a cost that will allow economical generation of electricity. The electricity value in one HIF target is approximately $3.00. While there is no fixed requirement for the "fueling" cost of a future IFE power plant, one can consider that spending about 10% of the electricity value on fuel would be a reasonable solution. This rough approximation results in the cost goal for IFE targets of about $0.30, which has been mentioned often. To evaluate whether such cost goals can be met, we have prepared preliminary layouts and cost estimates for future HIF target fabrication.

A key factor in the cost of the HIF target is the choice of hohlraum materials. A systematic review of available information for all high atomic number elements has been conducted to evaluate candidate hohlraum materials.[25] Effect of materials on target fabrication, energy cost, target gain, radioactivity, chemical toxicity, and potential for recycle were considered. Lead and tungsten are estimated to be the lowest cost acceptable materials. The combination of Pb and W provide better target gain than either material alone. However, precipitation of the W in the primary coolant is a concern (W growth can plug small openings in power plant components such as vacuum tritium disengagers; seeding the primary coolant with sub-micron sized W particles can minimize this but further experiments are needed to assure acceptable use of W). Thus we have prepared a preliminary cost analysis using a 70/30 mixture of lead and hafnium. Pb and Hf are the next materials of choice with regard to target gain. Lead is easily removed from the Flibe by centrifugation. Hf removal will require an electrochemical process that requires further development, but Hf does not suffer from the precipitation/plugging concerns of W. We have also assumed a process of single use and discarding of the hohlraum materials. This is a key decision of course. Recycling would reduce the volume of radioactive waste streams from the facility, but requires a high level of material purification (for re-use in a hohlraum) and also requires remote (and/or contaminated) manufacturing process steps due to the high activation of the materials.[29] Our preliminary estimate of the cost to provide fully remote handling of the recycled hohlraum materials in this case (as well as fully remote maintenance of related target handling equipment) was more than the electricity value of the target.[d] The estimated cost for mass-production of HIF targets with Pb/Hf hohlraums and CH capsules is about $0.41 each.[e] The installed capital cost is estimated at $304 million (38 million annualized cost). Annual operating costs include materials and utilities ($11 million), maintenance ($18 million for labor & materials), and operating labor ($10 million). The single most significant factor in the cost per target is the capital cost associated with the LCVD system. While optimizing of the target design and fabrication processes will certainly continue, this is a very encouraging result with respect to meeting target supply cost goals.

IV. Z-PINCH DRIVEN IFE

In contrast to "injecting" laser and HIF targets into a chamber, ZFE targets are "placed" in the chamber about once every 10 s.[10] Z-Pinch targets represent a variant of the "indirect drive" design. The target assembly (Fig. 3) is surrounded by a concentric wire array. The wire array consists of approximately 300 fine tungsten wires arranged vertically in a cylindrical shape. During the shot, a large current flows axially down the wires. The current

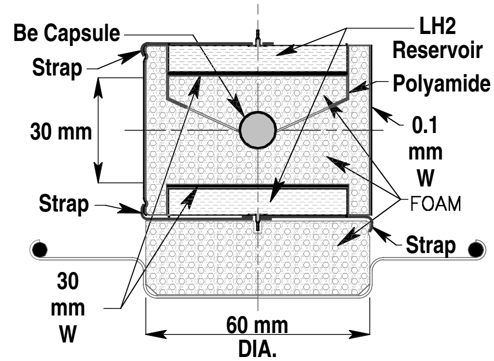


Fig. 3. Z-pinch target assembly from SNL is placed within a "dynamic hohlraum".

creates a large circumferential magnetic field which implodes the wire array towards its center. The wires vaporize from the heating into a plasma, which continues to carry the current. The plasma is accelerated inward until it strikes the outer wall of the target assembly. The baseline target configuration for ZFE (Fig. 3, designed by Sandia National Laboratory) is based on a "dynamic hohlraum".

At its center is a 330 µm-thick, 10 mm-diameter, DT-filled, beryllium capsule with an inner layer of frozen D-T. 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.

One process for manufacturing the Be capsules has been identified and used for cost estimating purposes for Z-pinch driven IFE. In this process, poly-alpha methyl styrene (PAMS) spherical capsules are formed by a droplet generator in a micro-encapsulation column. The PAMS capsules are cured and vacuum dried to yield empty capsules with an outside diameter specified at ~9.2 mm and a wall thickness of ~150 mm. The PAMS capsules are moved to a 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 (the GDP polymer is needed to withstand the higher temperature exposure in the subsequent physical vapor deposition [PVD] step). A ~330 mm thick layer of beryllium is subsequently sputtered by PVD onto the outer surface of the GDP/PAMS mandrels, producing ~10 mm diameter Be/GDP/PAMS capsules. These capsules are laser drilled to provide a 5 µm-diameter hole through the wall, then

[d]The original published target design [22] utilized gold and gadolinium at various densities. The cost would require that these materials be recycled. We therefore evaluated lower cost hohlraum materials that could be used in a "once-through" cycle and then discarded as low level waste.

[e]The Pb/Hf mixture results in about a 2% plant energy loss (as compared to the original Au/Gd), and results in about $8000 per day worth of source material being discarded, which is small compared to the additional cost of utilizing highly radioactive material in the target production plant.

placed in an oven to remove the PAMS and GDP coatings. They are then transferred to a cryocondensation chamber where a thermal gradient is placed upon the shell (about 16 K at its bottom and 40 K at the top) and the capsules are filled with their DT allocation. To rapidly seal the capsules, a laser beam, shining through a top window, quickly melts a spot and seals the hole at the top of each shell, thus trapping the desired mass of DT in each Be shell. These beryllium shell supply processes are currently being developed and experimentally demonstrated in inertial confinement fusion programs (albeit for very small quantity production).

The beryllium capsule is placed within the target assembly as further detailed in Fig. 4; 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 containing the capsule. The reservoirs are filled with a total of ~80 cm^3 of liquid hydrogen at atmospheric pressure, initially at 18 K. An unsealed pedestal of low-density foam thermally insulates the above subassembly from the Replaceable Transmission Line (RTL) sealing plate. Three 0.1 mm-thick carbon-steel straps clinch together all of the above described components into the finished target assembly. The target assembly is located and mechanically supported on a removable RTL sealing plate. 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, by the "beta-layering" process.

The above-described design of the target assembly is driven by the need to control the capsule temperature in the vicinity of 18 K 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 liquid hydrogen 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. A thermal analysis of this designs shows that the total time available to insert a target assembly into the RTL, transport the 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. Finally, to minimize cost

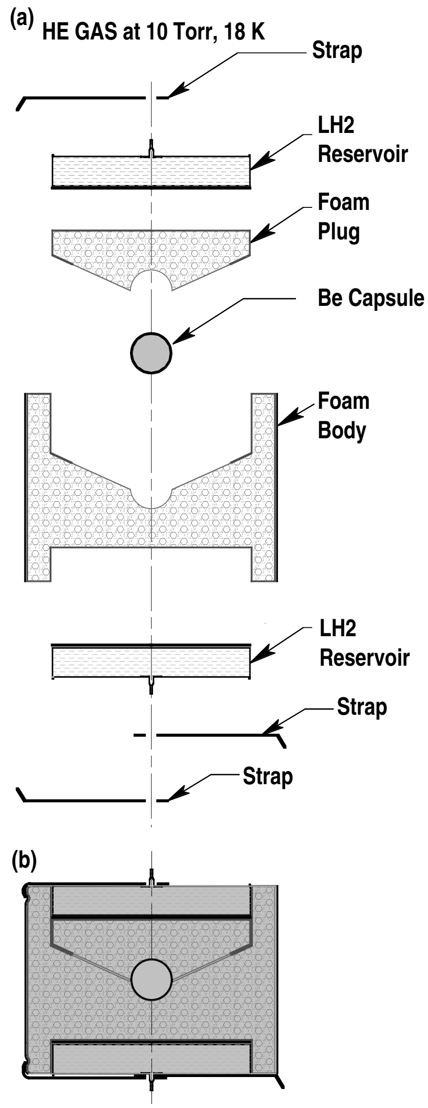


Fig. 4. (a) Componentsof Z-pinch target subassembly, (b) completed target subassembly.

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.

The Be capsule for ZFE offers significant advantages. The relatively high thermal conductivity of the Be capsule wall greatly simplifies the requirement for uniform isothermal temperature control during the layering process (i.e., one can cool an entire assembly and uniform temperature around the capsule will occur). The proposed process requires significant development for for mass- production. Another option is to utilize a C H polymer capsule similar to HIF. In this case, the capsule must be cooled to cryogenic temperatures prior to removal from a pressure (permeation filling) cell, it must be transported cryogenically, and the layering process must provide a highly isothermal environment. One sequence to allow use of CH capsules takes advantage of the synergism between ZFE and laser fusion development programs. The CH capsule is permeation filled and is then layered in a cyrogenic fluidized bed system. The filled, layered capsule is then "quickly" assembled into the dynamic hohlraum target assembly with the liquid hydrogen thermal buffer cans at each end for cooling. The foam is pre-formed to allow for positioning of the capsule within the target assembly. While each of the two approaches, Be or CH capsules, have uncertainties and require significant development, they represent promising design concepts that indicate the feasibility of utilizing a Z-Pinch system for producing energy.

On the same basis for costing as described above for laser fusion and HIF, we performed preliminary analyses of methods for the mass production of target assemblies (foam plus capsule) to be used in a Z-Pinch driven power plant. Using chemical engineering analysis techniques, we have devised detailed sequences of necessary manufacturing operations. We have analyzed a commercial-scale 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. 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 estimated the production cost for a base case of a 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. 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. Additional optimization of the mass-production process could be expected to further reduce this estimated cost. Of course, the additional components of the RTL must be considered in a total fueling cost estimate.

V. SUMMARY AND CONCLUSIONS

At present, individual targets used in inertial confinement fusion experiments are produced with considerable time and expense. In contrast, the "Target Fabrication Facility" of a laser fusion or heavy ion driven IFE power plant must supply more than 500,000 targets per day, including manufacturing the spherical target capsule and other materials, filling the capsules with the DT fusion fuel, redistributing the frozen DT uniformly around the inside of the capsule, and assembling the hohlraum (for indirect drive). Demonstrating a credible pathway to a reliable, consistent, and economical target supply is a major part of establishing that IFE is a viable energy source. We have presented here an overview of the proposed baseline target manufacturing methodologies that have been derived from the development programs associated with fueling of an IFE power system. These development programs focus on the unique materials science and chemistry for each target design. We have prepared preliminary estimates of the costs associated with producing large quantities of targets, and we found that these costs are within the range of commercial feasibility. This is a significant conclusion for the viability of future inertial fusion power plant concepts.

Over the next several years, we can expect to see target concepts further defined with detailed process scenarios, and we can expect to see targets meeting specifications that are produced using equipment and processes that are scalable to mass production. For target injection, a new and versatile facility for studying injection and tracking has been constructed and room-temperature target injection experiments have begun, both single shot and rep-rated. The system has successfully demonstrated the sabot separation needed for handling of direct drive targets. We have defined the characteristics and requirements of a next-phase project to validate the technology of full-scale components for direct drive[30] Elements of the facility include mass production (in batch mode) of cryogenic targets, injection into the chamber (under simulated background gas and wall temperature conditions), and steering of a low-energy pulsed laser onto the target in flight.

Overall, reference target designs, issues and R&D needs have been identified and a program of concept demonstration is well underway. Much progress has been made in defining mass production scenarios for laser, heavy ion, and Z-Pinch driven IFE and addressing the science and technology issues for target fabrication and injection. Although much work remains to be done, our initial results are promising and suggest that a credible pathway to a reliable, consistent and economical target supply is within reach.

ACKNOWLEDGMENT

Work supported by US Department of Energy through NRL Contract N00173-03-C-6010 and Contract DE-AC03-98ER54411.

REFERENCES

[1] D.T. GOODIN, *et al.*, *Fusion Eng. Des.* **69**, 803 (2003).

[2] J.D. SETHIAN, *et al.*, *Nucl. Fusion* **43**, 1693 (2003).

[3] D.T. GOODIN, *et al.*, "Progress Towards Demonstrating IFE Target Fabrication and Injection," *Proc. of the 2nd International Conference on Inertial Fusion Sciences and Applications*, Kyoto, Japan, Tanaka, Meyerhofer, Meyer-ter-Vehn, editors, ElSevier, (2001), 746.

[4] D.A. CALLAHAN-MILLER, and M. TABAK, *Nucl. Fusion* **39** 1547 (1999).

[5] D.T. GOODIN, *et al.*, *Fusion Eng. Des.* **60**, 26 (2002).

[6] D.T. GOODIN, *et al.*, *Nucl. Fusion* **41**, No. 5, 527 (2001).

[7] R.W. PETZOLDT, *et al.*, *Nucl. Fusion* **42**, 1351 (2002).

[8] J. WOODWORTH and W. MEIER, *Fusion Technology*, **31** (1997) 280.

[9] W.S. RICKMAN, and D.T. GOODIN, *Fusion Sci. Technol.* **43** 353 (2003).

[10] G.E. ROCHAU, "ZP-3, A Power Plant Utilizing Z-Pinch Fusion Technology," *Proc. of the 2nd International Conference on Inertial Fusion Sciences and Applications*, Kyoto, Japan, Tanaka, Meyerhofer, Meyer-ter-Vehn, editors, ElSevier, (2001), 706.

[11] J. STREIT and D. SCHROEN, "Development of Divinylbenzene Foam Shells for Use as Inertial Fusion Energy Reactor Targets," *Fusion Sci. Technol.* **43**, 321, (2003).

[12] C. STOECKL, *et al.*, *Phys. of Plasmas*, **9**(5), 2195 (2002).

[13] D.T. GOODIN, *et al.*, *Proc. of 19th Symp. on Fusion Technology*, Lisbon, Portugal, C. Varandas and F. Serra, editors, ElSevier, (1996), 1289.

[14] Private Communication, Peter S. Ebey, Los Alamos National Laboratory, September 7, 2004.

[15] A.M. SCHWENDT, *et al.*, *Fusion Sci. Technol.*, **43**, 217 (2002).

[16] A.J. MARTIN, *et al.*, *J. Vac. Sci. Technol. A*, **6**(3), 1885 (1988).

[17] J.K. HOFFER, and L.R. FOREMAN, *Phys. Rev. Lett.* **60**, 13 (1988).

[18] T. NORIMATSU, *et al.*, "Foam Insulated Direct-Drive Cryogenic Target," *Proc. of the 2nd International Conference on Inertial Fusion Sciences and Applications*, Kyoto, Japan, Tanaka, Meyerhofer, Meyer-ter-Vehn, editors, ElSevier, (2001), 752.

[19] B.K. FROLOV, *et al.*, "Simulation of Afterglow Plasma Evolution in an Inertial Fusion energy Chamber, *accepted for publication in Physics of Plasmas*, (2004).

[20] D.T. GOODIN, *et al.*, "A Cost-Effective Target Supply For Inertial Fusion Energy," to be published in a special issue of *Nucl. Fusion*, (2004).

[21] W.S. RICKMAN and D.T. GOODIN, "Cost Modeling for Fabrication of Direct Drive IFE Targets," *Fusion Science and Technology,* **43**, 353 (2003).

[22] W.R. MEIER, *Fusion Engineering and Design* **25**, 145, (1994)

[23] R.W. MOIR, *et al.*, *Fusion Technology* **25**, 5, (1994).

[24] M. TABAK, D. CALLAHAN-MILLER, D.D.-M. HO, G.B. ZIMMERMAN, *Nuclear Fusion,* **38**, 509 (1998).

[25] R.W. PETZOLDT, "Materials Selection for Heavy Ion Fusion Hohlraums," to be submitted for publication in *Fusion Science and Technology*.

[26] D.T. GOODIN, "A Credible Pathway for Heavy Ion Driven Target Fabrication and Injection," *Laser and Particle Beams*, **20**, 515 (2002).

[27] D.T. GOODIN, *et al.*, "Progress in Heavy Ion Driven Target Fabrication and Injection," Proc. of the 15th International Symposium on Heavy Ion Inertial Fusion, Princeton, New Jersey, to be published in *Nucl. Instr. and Methods in Physics Research Section A.*

[28] J.L. MAXWELL, *et al.*, "A Process-Structure Map for Diamond-like Carbon Fibers from 1-Ethene at Hyperbaric Pressures," accepted for publication in *Advanced Functional Materials.*

[29] L. EL-GUEBALY, *et al.*, "*Recycling Issues Facing Target and RTL Materials of Inertial Fusion Designs,*" these proceedings.

[30] M.S. TILLACK, *et al.*, "A Target Fabrication and Injection Facility for Laser-IFE," *Proc. 20th IEEE/NPSS Symposium on Fusion Engineering (SOFE)*, October 2003, San Diego, California, to be published in *Fusion Sci. Technol.*