Target Fabrication and Injection Challenges in Developing an IFE Reactor
GA has a long history with both ICF and IFE targets
- HAPL, HIF, ZFE, now LIFE

• Extensive experience in ICF target fabrication:
  • Role: to develop ICF target fabrication and characterization techniques and provide targets
  • Collaboration with all labs as a central hub for targets since 1991
    - Several 1000’s targets/year
    - Staff ~100, ~1/4 PhD’s
    - Specialized equipment
    - ISO 9001:2008

• Leveraged expertise from ICF to IFE
  • Target fab
  • Injection and tracking
  • Continued tradition of close interactions with national labs

We have a good team to tackle challenges
We believe that targets can be mass-produced for IFE and meet the requirements for fusion energy

• Challenges and critical issues for the IFE target supply chain have been identified

• Much work has been done on the target supply process for a number of IFE approaches – much work remains …

• Mass production of an IFE target is a difficult but manageable task
  – Will require a sustained development effort that should occur in parallel with other reactor technologies
  – Iteration with design is critical - as in the case of ignition targets
  – “Nth-of-a-kind” cost studies have shown that cost-effective target manufacture is possible

• This talk will summarize four different target designs and the work that has been done to define manufacturing methods and to show acceptable cost
  – Show examples with different levels of maturity - many are conceptual

Despite different IFE approaches there are commonalities in much of the basic required target fabrication capabilities
“Critical issues” were identified in program plans more than a decade ago.

“Chamber and Target Technology Development for Inertial Fusion Energy”, W. Meier et al, April, 1999, LLNL, UCRL-ID-133629

1- Target fabrication
   critical issues:
   a) Ability to fabricate target capsules & hohlraums
   b) Ability to fabricate them economically
   c) Ability to fabricate, assemble, fill and layer at required rates

Power plant studies have concluded that $0.25 targets are needed – reduced 3-4 orders of magnitude from current targets

2- Target injection, tracking
   critical issues:
   a) Withstand acceleration during injection
   b) Survive thermal environment
   c) Accuracy and repeatability, tracking

A detailed experimental plan for target injection was prepared - Nuclear Fusion, 41. May 2001
Studies have shown the feasibility of a cost-effective IFE target supply for energy.

<table>
<thead>
<tr>
<th>IFE Concept</th>
<th>Target Design</th>
<th>Target Yield (MJ)</th>
<th>Est'd Cost/target for 1000 MW(e)</th>
<th>% of E-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser Fusion</td>
<td>Direct drive foam capsule</td>
<td>~400</td>
<td>$0.17</td>
<td>~6</td>
</tr>
<tr>
<td>HIF</td>
<td>Indirect drive distributed radiator</td>
<td>~400</td>
<td>$0.41</td>
<td>~14</td>
</tr>
<tr>
<td>ZFE</td>
<td>Dynamic hohlraum</td>
<td>~3000</td>
<td>$2.90</td>
<td>~13</td>
</tr>
<tr>
<td>LIFE</td>
<td>Indirect drive Pb rugby hohlraum</td>
<td>~132</td>
<td>~$0.30</td>
<td>~30</td>
</tr>
</tbody>
</table>


Current target designs have evolved - discuss these here for the process.

Collaboration with LANL, LLNL, LBNL

Foam layer: Divinyl Benzene (DVB) or Resorcinol-Formaldehyde (RF)

DT Vapor Foam + DT DT ~ 2.3 mm rad

1-10 µm CH Overcoat

Direct Drive Laser Fusion

HIF

Heavy Ion Fusion

ZFE Z-Pinch IFE (ZFE)

LIFE Laser Inertial Fusion Engine (LIFE)

Collaboration with LLNL

~20 mm HAPL ~1 cm

DT overcoat - “old” (magLIF)

“new” (magLIF) ~1 cm

Collaboration NRL
Close interaction and trade-off between target designers and fabricators is essential...

Such interactions have been central to identifying and solving target challenges for the various approaches.

**Example:**

The heavy-ion driven target had a number of unique and challenging materials*

The materials range of 11 - 13,500 mg/cc:

- A: AuGd 0.1 g/cc
- B: AuGd 13.5 g/cc
- C: Fe 0.015 g/cc
- D: (CH)_{2,0}Au_{6.03} 0.011 g/cc
- E: AuGd 0.11 g/cc
- F: Al 0.07 g/cc
- G: AuGd 0.26 g/cc
- H: CD_{2} 0.001 g/cc
- I: Al 0.055 g/cc
- J: AuGd “sandwich” 0.1/1.0/0.5 g/cc
- K: DT 0.0003 g/cc
- L: DT 0.25 g/cc
- M: Be_{6.03}Br_{0.003} 1.845 g/cc
- N: (CD_{2})_{0.31}Au_{0.003} 0.032 g/cc

Alternatives and example changes:
- AuGd replaced with Pb/Hf
- Doped foam replaced low-density Fe
- Al foam replaced with silica aerogel
- Tamping gas replaced with He

*Nuclear Fusion 39, 1547 (1999)

LCVD to “grow” hohlraums and foam initiated, a plant was conceptualized...

Iteration with target design - tradeoffs on materials, fabrication, and energy

... allows making the impossible possible
The process to build each component depends upon the material selection.

**Example for current LIFE target design:**

<table>
<thead>
<tr>
<th>Component</th>
<th>Material</th>
<th>Processes</th>
<th>Alternate materials</th>
<th>Alternate Processes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hohlraum</td>
<td>Pb; 5% Sn or Sb</td>
<td>Die-cast</td>
<td>Hg, High-Z, plated CH</td>
<td>Stamping, swaging, molding, injection-molding</td>
</tr>
<tr>
<td>Capsule</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ablator</td>
<td>C</td>
<td>CVD</td>
<td>CH;Be,B</td>
<td>micro-encapsulation, stamping, injection molding</td>
</tr>
<tr>
<td>Dopant</td>
<td>Ta</td>
<td>CVD</td>
<td>Ge</td>
<td>CVD</td>
</tr>
<tr>
<td>Foam</td>
<td>DCPD (&lt; 20 mg/cc)</td>
<td>Sol-gel</td>
<td>SiO2 (5 mg/cc)</td>
<td>Sol-gel</td>
</tr>
<tr>
<td>DT</td>
<td>DT</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Support</td>
<td>C</td>
<td>CVD</td>
<td>polyimide</td>
<td>Spin-coat</td>
</tr>
<tr>
<td>IR window</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Substrate</td>
<td>C</td>
<td>CVD</td>
<td>polyimide</td>
<td>Spin-coat</td>
</tr>
<tr>
<td>Metalization</td>
<td>Al</td>
<td>Sputter</td>
<td>Ag,Au</td>
<td>Evaporation</td>
</tr>
<tr>
<td>P2 shield</td>
<td>Pb; 5% Sn or Sb</td>
<td>Stamp</td>
<td>High-Z</td>
<td>Die-cast</td>
</tr>
<tr>
<td>LEH window</td>
<td>C-O</td>
<td></td>
<td>C</td>
<td>CVD</td>
</tr>
</tbody>
</table>

For each component there are favored and alternate materials selected.
Requirements and “considerations” in designing a target and in selecting fabrication methods all have much in common

- Meet target physics requirements for fusion gain - ALL
- Survive acceleration forces and thermal environment of injection - ALL
- Have position determined relative to laser pointing to within ~20-100 µm (ALL)
- Have materials with low hydrogen content to reduce load to the tritium recovery system - ALL
- …
- Have materials compatible with low cost, high throughput manufacturing techniques - ALL

How do you reduce costs by 3-4 order of magnitude - major “paradigm shift” from current day targets

Fabrication of IFE capsules for various approaches has many common features.
Much work was done for the “direct approach” of making a HAPL foam capsule

**Approach** = apply laboratory demo for everything…

- **HAPL** program dealt with throughput and dimensionality issues
- Wall uniformity, surface finish, and reliable gas retention remained

**Fabricate foam capsules**

**Micro-encapsulation**

**Addn’l Overcoats**

A) Interfacial reaction

B) GDP coating

C) Sputter coating of metal (Au/Pd)

**FTF-sized (2.4 mm OD) foam capsules**

**IFE (~4.6 mm OD) foam capsules**
The mandrel method is the primary technique being considered for LIFE capsules

- Starts with silicon mandrel
- Strong-walled capsule allows handling to create foam on inside
- Holds DT fill pressure at room temperature

**Chemical Vapor Deposition (CVD) diamond coating**

<table>
<thead>
<tr>
<th>Throughput per batch</th>
<th>45,000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost/target</td>
<td>~5 cents</td>
</tr>
<tr>
<td>Process tolerance</td>
<td>± 5 μm OD; ± 2 μm thk; ~5 nm RMS surface roughness</td>
</tr>
</tbody>
</table>
Current CVD diamond capsules satisfy NIC specifications

- **H₂ + CH₄**
- Mircowave plasma
- 700–900°C
- CVD process uses cheap materials
- 4 kHz Nd:YAG laser
- Laser-drill hole for DT fill
- 2 mm diameter polished diamond capsule
- Uniform walls
- 5 micron hole laser drilled for DT fill

LIFE
Foams in capsule are created by polymerizing solgel in capsule and extracting solvent.

- The interior foam could be a pathway to avoid the difficult process of DT “beta-layering”
- Challenges include dealing with picoliter volumes, and successful wetting of the foam
- Could this approach be used for direct drive as well?

The chemistry of this process is currently being studied at LLNL.
Lead hohlraum parts can be die-cast

Hohlraum quarters can be die-cast

Die-cast parts are used in many consumer products

Die cast process: molten lead in the chamber (1) can be pumped into the die (2) where it is cooled and removed (3). Post machining on the parts (4) may be required to remove parting lines and sprue defects.

Design simplifications from learning at NIF should make these processes more realizable
How do you assemble full targets?

Prepared capsule with:
- high-density carbon coating
- Low-density foam inner layer
- Filled with DT, plug to seal
- If direct drive, cool and inject...
- For indirect, use **robotic assembly**

**Hohlraum**

- Die-cast Pb hohlraum parts
- Attach CVD-diamond membranes
  - Pre-formed capsule support
  - IR shield
  - LEH window (graphene-oxide)
- Assemble hohlraum parts
- Place capsule into hohlraum
- Assemble hohlraum halves
  - Cool to ~18K, filling foam
Example of GA-robot assembling 1.5 micron polymer film to surrogate hohlraum

• Mitsubishi RV series 6-axis industrial robots with 20 µm repeatability
• Piezo stage assembly base gives 10 nm resolution
• Vision system for guidance

IFE process

High-speed robots to assemble parts:
• Array processing to speed throughput
• Fixtures to provide alignment
• Features in parts for self-alignment

Components will be designed-for-assembly
Example of the details in the LIFE cost analysis

<table>
<thead>
<tr>
<th>Process</th>
<th>Number of machines</th>
<th>Total floorspace (sqrft)</th>
<th>WIP (parts)</th>
<th>Total capital cost ($)</th>
<th>Annulized capital cost ($/yr)</th>
<th>Consumables + electricity + maintenance + equip replace + utility($/yr)</th>
<th>Personnel costs ($/yr)</th>
<th>Cost/target</th>
<th>Off-site fabrication</th>
<th>On-site fabrication</th>
</tr>
</thead>
<tbody>
<tr>
<td>CVD diamond ablator</td>
<td>140</td>
<td>21,323</td>
<td>9,288,015</td>
<td>48,107,750</td>
<td>3,704,297</td>
<td>20,285,676</td>
<td>3,500,000</td>
<td>0.051</td>
<td>0.051</td>
<td></td>
</tr>
<tr>
<td>Capsule foam</td>
<td>8</td>
<td>344</td>
<td>189,000</td>
<td>12,911,000</td>
<td>994,147</td>
<td>7,610,191</td>
<td>200,000</td>
<td>0.018</td>
<td>0.018</td>
<td></td>
</tr>
<tr>
<td>DT Fill</td>
<td>33</td>
<td>1,850</td>
<td>15,315</td>
<td>103,535,000</td>
<td>7,972,195</td>
<td>4,997,969</td>
<td>825,000</td>
<td>0.027</td>
<td></td>
<td>0.027</td>
</tr>
<tr>
<td>Hohraum injection-molded/plated quarters</td>
<td>7</td>
<td>1,190</td>
<td>150</td>
<td>5,783,470</td>
<td>5,783,470</td>
<td>3,558,235</td>
<td>175,000</td>
<td>0.020</td>
<td>0.020</td>
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<tr>
<td>Capsule-support assy</td>
<td>119</td>
<td>4,199</td>
<td>27,990</td>
<td>9,529,366</td>
<td>9,529,366</td>
<td>5,540,891</td>
<td>2,975,000</td>
<td>0.032</td>
<td>0.032</td>
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<tr>
<td>IR-window/LEH assy</td>
<td>310</td>
<td>11,338</td>
<td>236,435</td>
<td>323,230,000</td>
<td>24,888,710</td>
<td>13,221,249</td>
<td>7,750,000</td>
<td>0.081</td>
<td>0.081</td>
<td></td>
</tr>
<tr>
<td>Hohraum-half assembly</td>
<td>128</td>
<td>3,072</td>
<td>990</td>
<td>2,858,856</td>
<td>2,858,856</td>
<td>3,798,729</td>
<td>3,200,000</td>
<td>0.014</td>
<td>0.014</td>
<td></td>
</tr>
<tr>
<td>Hohraum-capsule assy</td>
<td>80</td>
<td>2,256</td>
<td>510</td>
<td>3,653,188</td>
<td>3,653,188</td>
<td>2,631,750</td>
<td>2,000,000</td>
<td>0.013</td>
<td></td>
<td>0.013</td>
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<tr>
<td>DT cool</td>
<td>1</td>
<td>41</td>
<td>108,000</td>
<td>5,756,334</td>
<td>443,238</td>
<td>975,448</td>
<td>25,000</td>
<td>0.003</td>
<td></td>
<td>0.003</td>
</tr>
<tr>
<td>Recover and recycle</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.000</td>
<td></td>
</tr>
<tr>
<td>Facility management costs</td>
<td>2,000</td>
<td></td>
<td></td>
<td>500,000</td>
<td>38,500</td>
<td>70,420</td>
<td>6,250,000</td>
<td>0.013</td>
<td>0.011</td>
<td>0.002</td>
</tr>
<tr>
<td>Total process</td>
<td>826</td>
<td>47,613</td>
<td>9,866,405</td>
<td>515,864,964</td>
<td>59,865,966</td>
<td>62,690,559</td>
<td>26,900,000</td>
<td>0.272</td>
<td>0.226</td>
<td>0.046</td>
</tr>
<tr>
<td>Add material</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.303</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Total estimated target costs are ~30 cents at 15 Hz
Layering” is the process of re-distributing the DT into a precise, uniform thickness

- **Single crystal beta-layering - slow (10 hours on NIC)**
  - ![Diagram of single crystal beta-layering](image)
  - Belt grows from seed
  - Fully formed belt
  - Belt widens along c-axis

- **Alternative: liquid DT wicked into nanofoam**
  - Liquid? (best, smooth!)
  - Liquid survives acceleration?
  - Is vapor pressure low enough?
  - OR - possibly “quick freeze” before grooves can form

- **DT-filled nanofoam**: pore size ~100 nm, < 30 mg/cc density to permit ignition

- **Fluidized bed layering cryostat**
- **HAPL - roughness over foam less severe...?**
- **Temperature oscillation helpful...**
A cryogenic fluidized bed was constructed to demo mass-production layering

- Static controlled
- Scoping tests show good randomization
- Initial cryostat cooldowns to ~11K
- Method to “grab” one shell for characterization has been done at cryogenic conditions

Fluidized bed

Cryocoolers
Cryogenic circulator
Helium Compressors

Shells (empty) at 11 Kelvin

Includes filling with HD (via permeation thru overcoats)
DT fill process can be performed in large batches in a pressurized, room temperature chamber.

DT fill in 300 K, pressurized chamber

1) Place capsules in pressure chamber at ~264 atm
2) Capsules are filled with DT gas
3) Apply plug
4) UV cure epoxy-coated plug
5) Reduce temperature to 77 K; evacuate chamber

Possible plug configurations feature UV glue-coated carbon plugs.

<table>
<thead>
<tr>
<th>Step</th>
<th>External pressure (atm)</th>
<th>Temperature (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capsules in chamber</td>
<td>0</td>
<td>300</td>
</tr>
<tr>
<td>DT fill</td>
<td>264</td>
<td>300</td>
</tr>
<tr>
<td>Plug fill hole</td>
<td>264</td>
<td>300</td>
</tr>
<tr>
<td>Lower chamber temperature</td>
<td>68</td>
<td>77</td>
</tr>
<tr>
<td>Evacuate DT from chamber</td>
<td>0</td>
<td>77</td>
</tr>
<tr>
<td>Transport</td>
<td>1</td>
<td>77</td>
</tr>
<tr>
<td>Assemble capsule into hohlraum</td>
<td>6</td>
<td>300</td>
</tr>
<tr>
<td>Transport to injector</td>
<td>1.6</td>
<td>77</td>
</tr>
<tr>
<td>Prepare for injection</td>
<td>0.4</td>
<td>18</td>
</tr>
<tr>
<td>Inject into chamber</td>
<td>0.4</td>
<td>17</td>
</tr>
</tbody>
</table>

Higher temperatures enable bonding; lower temperature during transport reduces diffusion through the ablator parts.

Room temperature processes enable polymer bonds.
The HAPL program demonstrated several acceleration options ...

The HAPL program demonstrated (gas-gun):
- Velocity ≥400 m/s, time jitter 0.5 ms, 2-piece sabot separation in vacuum
- Target placement accuracy of 10 mm at 17 meters standoff (1σ) ~590 μrad

Range of options, including:
1. Gas-gun for >400 m/s
2. Induction accelerator

With slower injection, accuracy demo’d at 50 m/s (w.o. 2-piece sabot) → 4 mm at 17 m (1σ), with ~1 mg projectiles (direct drive capsules, 235 μrad)
“Sabot separation” was a feature of direct drive injection demo with a gas gun

The HAPL program demonstrated sabot separation in-flight:
- Sabot with support-film to avoid point-loading
- Velocity $\geq 400$ m/s

Repeated sabot-separation and deflection was demonstrated
Electrostatic steering has been shown to improve placement accuracy (direct drive).

Without target steering:
\[ \sigma_x \approx \sigma_y \approx 500 \, \mu m \, (\sim 1000 \, \mu rad) \]

With target steering (0.5 m standoff):
\[ \sigma_x = 9 \, \mu m \, \sigma_y = 7 \, \mu m \]
- X offset = -1 \, \mu m; Y offset = 4 \, \mu m
- 27 of 30 in 20 \, \mu m radius from aim point

In-flight target steering could be used to improve accuracy of a target injection system.
Target heating on injection has been modeled - indicates low heating of DT ice

The capsule heats from the circulating He in the second compartment DT= ~85 mK

The front IR shield confines the warming helium to the front quarter of the target

Circulating Helium removes heat from the LEH window and gives it up to the cool Pb side walls

LEH window heats quickly

Hot 8000 K Xe gas heats leading LEH window to 2200 K

STARCCM simulation 8000K Xe flowing over hohlraum at 250 m/s
Stress during injection has been modeled - DT stress depends on membrane wrap angle

**DT stress for 1000 g acceleration at 18 K**

- Membrane support for direct drive target is part of sabot
- Also used to support capsule in hohlraum
Tracking and engagement—hitting a target “on the fly”

- Direct drive requirement = alignment of lasers and target to 20 µm
- First step - demo “ex-chamber” sensors, prediction to ~500 µm

**Ex-chamber tracking schematic**

- This evolved into “continuous” tracking (in-chamber)
- System using lasers, optics and fast steering mirror
- Also - “glint” from target ~1 ms before the shot aligns optical train (target itself is the reference point)...

Tracking - optical table demo of “hit-on-fly” engagement

Lane Carlson, GA/UCSD collaboration

- Scaled experiment, velocity ~ 5 m/s
- Standard deviation accuracy ~28 microns

Tracking beams determine the target’s location, timing, transverse position, and tilt

- Tracking beam array mounted on mechanically isolated structures
- Defines the shot coordinate system

A target passing through an orthogonal pair of beams alters the transmitted signals.
Extracting the timing, the velocity, and the target tilt from the tracking beams

A fast diode records the received signal through a slit.

Linear CCD (10 frames)

A linear CCD array detects transverse position versus time.

Timing values are extracted from the plot

Position and tilt values are extracted from the plots
Each beam’s pointing offset relative to the target is determined immediately before the shot.

A short pulse illuminates the target at a specific distance from the shot point (6-7mm).

The final optic of each beam collects light scattered from the target and sends it back along the main beam path.

An engagement sensor compares the direction of light from the target with the laser alignment beam.

A predetermined engagement angle corresponds to correct alignment at shot time.

Beam deflectors in the laser box implement pointing corrections.
Working together with SNL and others, target systems for Z-pinch driven IFE were conceptualized. Design concepts indicate sufficient time available for cryogenic target assembly and handling.

- Be capsule
- Liquid H\textsubscript{2} “buffers”
- >30 s at 298K
- + ~4s at 900K

**Plant Design Data**
- Rep-rate = 0.1 Hz
- Yield = 3 to 20 GJ
- Power = ~1100 MW(e)

“ZP-3, A Power Plant Utilizing Z-Pinch Fusion Technology”, Rochau et al. IFSA2001
The ICF community has a common viewpoint

- Demonstration of laboratory ignition will establish that the physics underpinning IFE exploitation is fundamentally sound.
- IFE is a field in which the US is a clear world leader – academically, technologically and industrially.
- We have an opportunity to capitalize on this leadership position over the next few years, and leverage prior substantial defense program investment.
- Recent action by the DOE to propose a new IFE development program and secure a stable home for IFE is timely and very welcome.
- Moving forward, the IFE program needs to focus on the requirements of an operating power plant, with design choices managed at a systems-level.
- The inherent modularity and separability of IFE provides significant benefits when considering power plant development, operations, and evolution.
- Taking advantage of significant prior research, future development activities in this program need to include IFE scale science and technology development and demonstration.
- IFE is a national scale program requiring a coordinated effort by academic, Laboratory, and industrial partners.
- A phased program with competition and unambiguous selection criteria is needed
Summary and conclusions - target technology

• Targets are a major component of any IFE approach
• Critical issues for the IFE target supply identified
• Much work has been done on the target supply process for a number of IFE approaches
• Mass production of an IFE target is a difficult but manageable task
  • Will require a sustained and properly supported development effort that should occur in parallel with other reactor technologies
  • “Nth-of-a-kind” cost studies have shown that cost-effective target manufacture is possible
• We have summarized here four different target designs and the work that has been done to define manufacturing methods and to show acceptable cost

We believe that targets can be mass-produced for IFE and meet the requirements for fusion energy