# Wetted Foam Targets for IFE Applications

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Topic: Targets (manufacture)

## Executive Summary

Foam-lined capsules ("wetted foam") targets are of interest to the Inertial Confinement Fusion (ICF) community because of lower sensitivity to defects that cause hydrodynamic instabilities (Haines, 2019) and quicker layering. Additive manufacturing, while exciting because of its deterministic fabrication capabilities, will be challenging to scale-up—a key consideration for an Inertial Fusion Energy (IFE) plant expected to consume up to a million targets per day. Chemistry-based approaches are promising for near term fabrication of IFE scale quantities of targets at a few cents each. Microencapsulation, for example, is already used to fabricate tens of thousands of high-quality targets in a few hours of fabrication, and it is comparatively easy to scale up further.

Several chemistry-based processes amenable to IFE applications are discussed below, including prior state of the art, recent developments at GA, and recommendations of process development for IFE applications are discussed.

## Introduction & Previous IFE Baseline Process

General Atomics worked on IFE applications of foam targets as part of the High Average Power Laser (HAPL) program (Sethian, 2010), and General Atomics (GA) has continued to make progress in related areas since then. GA also delivered wetted foam targets for LANL shots on NIF (Haines, 2019).

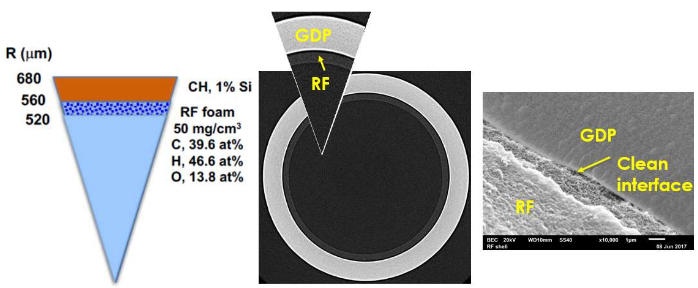


**Figure 1. Example of wetted foam target delivered for LANL shot on NIF. After coating with GDP, a clean interface between the polymer and capsule is visible in the SEM image.**

Based on this experience in target fabrication, GA believes a few chemistry-based processes are relevant for IFE applications, as summarized in Table 1.

**Table 1: Comparison of wetted foam manufacturing processes**

| Process | Ease of scaleup | Level of development | Expected Yield | Notes |
|---|---|---|---|---|
| **Microencapsulation followed by CVD coating** | Excellent, 1000s of capsules/day already possible | Depends on material, but generally high | Variable, currently material-dependent | Promising candidate route for high throughput IFE applications |
| **Injection molding of GA-CH aerogel (or similar) followed by CVD coating** | Intermediate | Low, individual steps demo'd | High | Very little work done in this area to date; it is worth exploring the unique qualities of GA-CH |
| **"Outside-In" approach fabricating foam liner inside of existing capsule** | Intermediate | Medium, significant yield issues in early tests | Currently variable, likely to improve | Hole required in capsule for solvent exchange. Flexible capsule mat'l. LLNL process (Braun, 2018) |

While further work is recommended in all areas, microencapsulation in particular merits further attention as the most established process for cheaply mass-producing targets. It was the baseline for prior IFE work and the HAPL program.

In microencapsulation, a droplet generator with nested tubes creates a shell-shaped emulsion (Figure 2). After reaction and/or solvent exchange and $CO_2$ critical point drying, cured and dry foam shells are generated. Some foam capsule materials also require an intermediate interfacial polymerization coating of polyvinylphenol to improve gas retention (Schroen, 2017). Challenges with this approach include additional process time, cost, and process yield improvements.

Dry foam shells can then be overcoated utilizing a vapor phase deposition to form the ablator. Candidates for IFE capsule materials include GDP (the previous baseline) as well as parylene, or polymers generated via initiated chemical vapor deposition (iCVD) (Baxamusa, 2017).

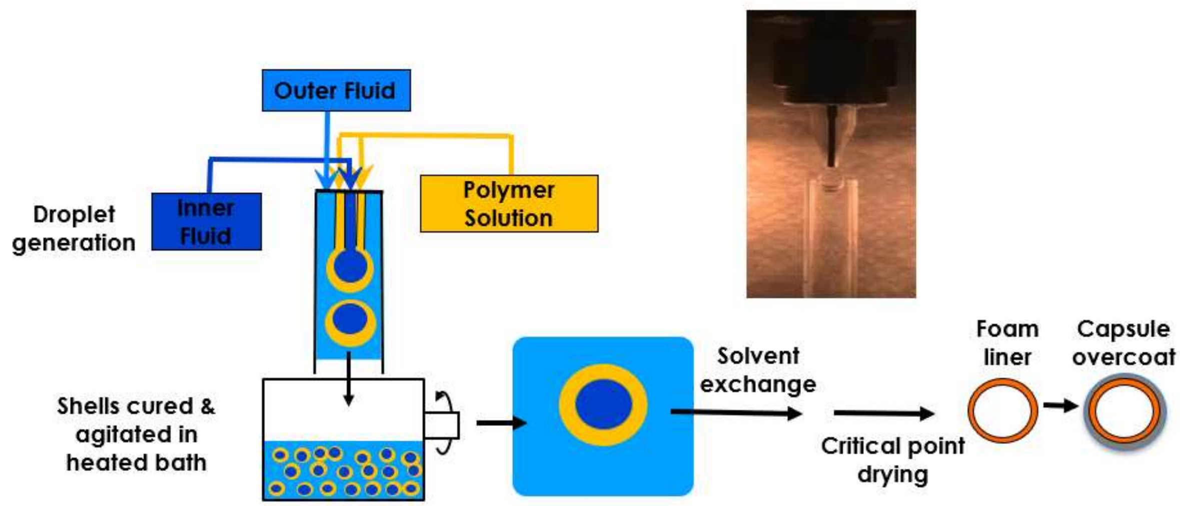


**Figure 2. Microencapsulation is a scalable mass production process for capsule fabrication**

Depending on the dimensions of the capsule (diameter, wall thickness, etc.), typical production rates are on the order of 100-1000 capsules per minute. To fabricate ~1,000,000 targets per day, approximately 10-20 droplet generators running continuously would be required (yield is unlikely to be 100%). While throughput is high, the entire process typically takes a significant amount of time—over 1 month is needed to produce finished dry ICF or IFE capsules.

Table 2 summarizes candidate materials for IFE applications. Excluding the proprietary aerogel GA-CH, these materials have all been used to fabricate foam shells in a droplet generator. GA-CH is included here as an extremely promising candidate for wetted foam experiments due to its small pore size, possibility of very low density (<10 mg/cc), semitransparency when wet, availability of fully deuterated GA-CD, and oxygen-free composition.

**Table 2: Comparison of different microencapsulated foams candidates for wetted foam**

| Foam Type | Pore Size | Yield (wall uniformity /shape) | Min. Density | Comp-osition | Level of development | Overcoat required for sealing/ |
|---|---|---|---|---|---|---|
| **Resorcinol Formaldehyde (RF)** | <1 µm | Poor | ~45 mg/cc | C/H/O | Delivered for NIF shot | No |
| **Divinyl Benzene (DVB)** | ~1 µm, opaque | Good. More stable emulsion. | ~45 mg/cc | C/H | Previous work for IFE applications | Yes, interfacial polymerization |
| **GA-CH or GA-CD (proprietary aerogel)** | <1 µm | TBD. Only proof of concept fabricated. | Promising, expect ~1-5 mg/cc lower limit | C/H or C/D | Low; needs adaptation to droplet generator | No |
| **Silica aerogel** | <1 µm | TBD | Possibly low mg/cc, but not demo'd | Si/O, High Z | Low, but previously demonstrated | Expect no, TBD |

Each candidate material has comparative advantages. Resorcinol formaldehyde (RF) microencapsulation tends to be less stable and have lower yields, but the small pore size and optical transparency are desirable (Paguio, 2011 and Nikroo, 2004). Because of this, an overcoat is not required for the capsule to hold pressure. Divinyl benzene (DVB) tends to have superior wall thickness uniformity and out-of-round, as well as being very stable during encapsulation, but it is also optically opaque and requires a cumbersome interfacial overcoat (Paguio, 2006). Silica aerogel is unlikely to be a candidate because of the high Z composition, but the low densities and small, uniform pores merit consideration.

## Recent developments at GA

As discussed above, a proprietary CH-based aerogel (GA-CH) has been developed at GA and shot at both NIF and OMEGA. Cavities have been formed in the material as a proof of concept, and it has also been machined via a special process, but additional work is needed to adapt it to fabrication with a droplet generator. Nevertheless, that effort is highly recommended since it is so promising for wetted foam applications.

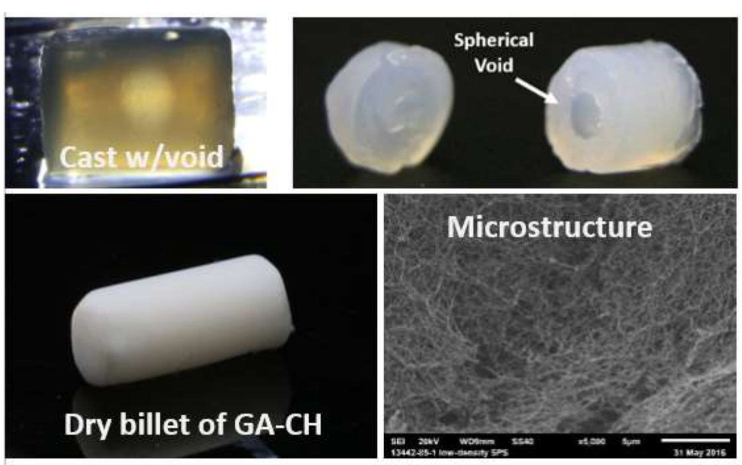


**Figure 3: GA's proprietary aerogel is very promising for IFE applications**

Key recent developments also include rapidly advancing robotic and machine learning capabilities, which facilitate efficient metrology, capsule sorting, and process automation. These new tools already automate ICF metrology and generate statistical data for process feedback. While current levels of characterization before target shipment are impractical for IFE applications, this work is expected to have large impacts on reducing target cost and improving fusion yields from higher quality capsules. Figure 4 shows an example of automated defect detection that provides process feedback. This system could be modified to screen and sort wetted foam capsules as well as generate process statistics.

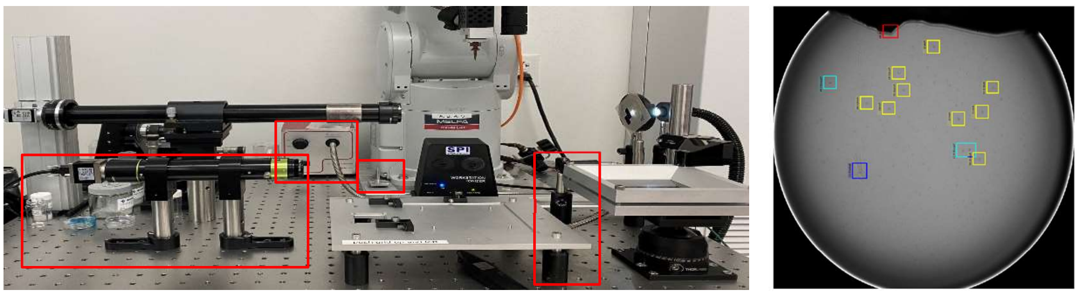

**Figure 4: GA has invested in automated capsule defect detection and sorting**

For the most recent LANL wetted foam shot, another improvement was the demonstration of a polishing process for RF-lined GDP capsules. In early testing, the polishing solution permeated through the walls and collapsed the pores of the foam. A polishing solution was identified that significantly improved the surface. Additional work might be needed in this space if domes on the capsules exceed IFE specifications.

While not specifically involving wetted foam, work on polystyrene capsules for LLE's 100GBar Initiative has resulted in significant improvement to the capsules: improved wall uniformity that meets the 0.2 μm specification, significant reductions to vacuole defects, and superb AFM data. Similar optimization efforts could be applied to microencapsulation of wetted foam capsules.

Table 3 includes recommended development projects to scale up, improve yield, increase efficiency, improve target quality, and adapt chemistry-based processes to IFE applications. As these different processes and shell/capsule materials have comparative advantages that are not yet fully explored, further work is recommended before down-selection.

Key metrics for wetted foam development work include cost per target (estimated at a few cents) and capsule yield for expected IFE specifications.

**Table 3: Key recommendations for IFE wetted foam capsule development effort**

| Recommended R&D | Effort | Impact | Notes |
|---|---|---|---|
| ***Economics*** | | | |
| Develop cost models for different processes and capsule materials | Medium | High | Wetted foam-specific cost models are needed to evaluate impact of different process options. |
| ***Foam development*** | | | |
| Improve wall uniformity and out-of-round for microencapsulated shells | High | High | Especially important for RF and GA-CH capsules. Chemistry-based optimization recommended. |
| Fabricate GA-CH foam shells in droplet generator | High | High | GA-CH is most promising for IFE applications due to small pore size, very low densities, and CH or CD composition. Droplet generator mods required. |
| Improve microencapsulation process stability and/or use microfluidics to facilitate scale-up | High | High | Currently shell fabrication with droplet generators requires strict monitoring since encapsulation can be unstable (especially RF). Machine learning is one approach to automatically identify and fix encapsulation issues. |
| Improve interfacial polymerization process for certain foam types (especially DVB) | High | Medium | Current PVP interfacial condensation process to seal targets is lengthy and introduces defects; improvement is needed (investigate ALD, etc.). |
| Develop polishing process to reduce defects on outer surface | Medium | Low | Preliminary polishing data is promising, but more work is needed. Might not be needed for IFE applications, especially with optimization of polymer overcoat. |
| Investigate injection molding process for fabricating GA-CH capsules | High | High | GA-CH has unique capabilities that could minimize defects at the parting line typically formed in injection molding. Several approaches are possible for the formation of the central void. |
| Improve yield, process stability, and scale-up for “outside-in” approach | High | High | Current process requires x-ray imaging and pressure cycling and has a high failure rate via delamination. Further process development is recommended. This process is agnostic to capsule material, so other options can be used (including microencapsulated capsules). |
| ***Metrology and efficiency*** | | | |
| Automate sorting/screening of foam capsules before coating | Medium | High | Screening is needed even with microencapsulation process improvements. Recommended at multiple steps—while foam is still wet (more transparent, reduces downstream burdens) and after coating. |
| Improve efficiency of capsule drying | Medium | Medium | Current process requires critical point drying, which is currently lengthy and requires pressure vessels. |
| Scale up CVD-based capsule fabrication (GDP, etc.) for higher throughput/lowest cost | High | High | Current throughput for CVD-based capsule fabrication process is significantly lower and might dominate the overall cost. |
| Evaluate alternative capsule materials (iCVD, parylene, etc.) | High | High | New capsule materials are available that have not been evaluated for IFE applications. |
| Image wetted foam filling process to check for collapsed pores and liquid distribution | Medium | Medium | A process for validating the effectiveness of new foam materials is needed. |
| Build IFE prototype to improve cost model and transition to continuous operation | High | Medium | Other research is needed first, but after process and material down-selection, fabrication at an intermediate scale is recommended. |
| Evaluate approaches to reduce raw material costs | High | High | Evaluate alternative solvents, recycling, cheaper process materials, etc. |

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