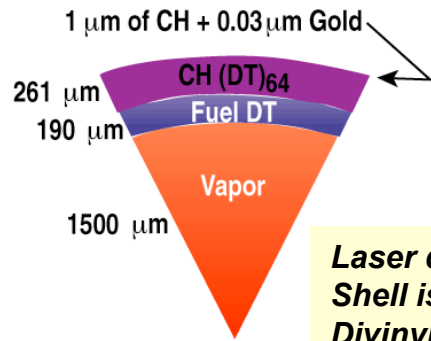




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“Reference” IFE target designs have been identified



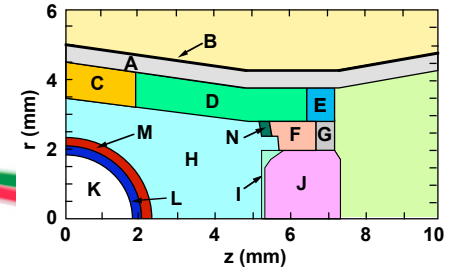
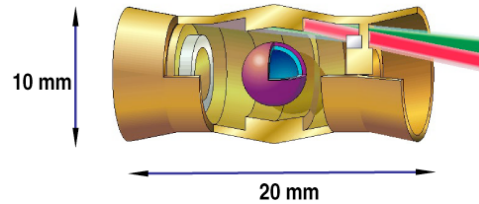
NRL High Gain Target Design

Laser driven
Shell is CH-only foam
Divinyl benzene being developed

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	~16 - 18.5K
Positioning in chamber	± 5 mm
Alignment with beams	<20 μm

LLNL Distributed Radiator Target



Two sided illumination by heavy ion beams
Energy deposited along hohlraum materials
Radiation distribution tailored by material density
Unique hohlraum materials required

Some Possible Indirect Drive Specifications

Capsule Material	CH
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	~16 - 18.5K
Positioning in chamber	less than ± 1-5 mm
Alignment with beams	<200 μm



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Overview of IFE target development status

- **Direct drive targets (laser IFE)**
 - **Most difficult issue is injection (survival during injection)**
 - **Status - models of DT response being developed and experiments underway, injection/tracking system construction underway, fabrication of NRL high-gain target being optimized, costing study and initial plant layouts**
 - **Near-term needs**
 - (a) injection/tracking accuracy demonstration
 - (b) response of DT to rapid thermal transient, strength of DT under representative conditions
 - (c) methods to protect target during injection
 - (d) mass-production cryogenic layering demonstration with hydrogen isotopes
- **Indirect drive targets (distributed radiator)**
 - **Most difficult issue is fabrication (not injection)**
 - **Status - identified fab pathways, working on materials selection, costing study**
 - **Near-term needs**
 - (a) simplification of target design
 - (b) optimization of materials in hohlraum with consideration of physics, fabrication, ES&H, removal from Flibe, and materials compatibility
 - (c) selected proof of principle fabrication of key materials
 - (d) demonstration of tracking accuracy at full length



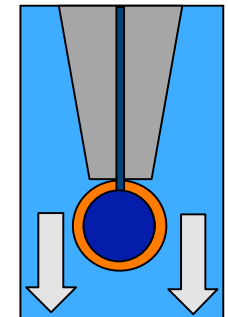
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Target Fabrication/Injection Tasks

1) Foam shell production (Schafer)

FY03 - Produce, using R&D scale equipment, target quality foam shells meeting requirements for the high gain direct drive target. Provide polymer seal coat on foam shells meeting requirements for the high gain direct drive target.



Schafer
Corp

2) Foam shell overcoat (Schafer)

FY03 - Provide polymer seal coat on foam shells meeting requirements for the high gain direct drive target.

FY04 - Adapt shell making and seal coat processes to mass production; interface with process design studies to show a feasible and economical mass-production pathway.



600 Å Pd on
PAMS shell

3) Application of high-Z layer (GA)

FY03 - Optimize high-Z over coat for high gain direct drive target target, accounting for target design, permeability, and reflectivity considerations; demonstrate techniques amenable to mass production.

 **Los Alamos**
NATIONAL LABORATORY



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Target Fabrication/Injection Tasks

4) Cryo layering #1 (LANL)

FY03 - Measure the surface finish of a DT layer formed in a torus with a foam underlay (to determine the smoothing effect of the foam).



LANL torus

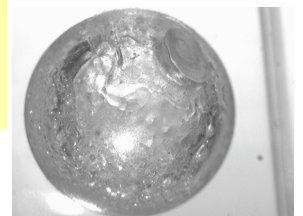
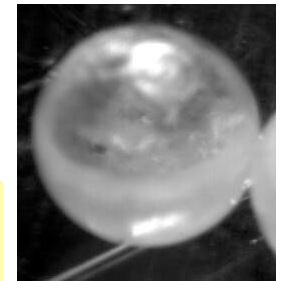
5) Cryo layering #2 (GA)

FY03 - Complete a detailed design and initiate procurement of a lab-scale system to demonstrate layering of direct drive targets by mechanical motion production (e.g., fluidized bed, bounce pan, and/or spiral tube).

FY04 - Complete procurement and install equipment to demonstrate cryogenic layering of hydrogen isotopes on lab-scale.

FY05 - Conduct shakedown and operate lab-scale system to demonstrate mass-production layering method.

Surrogate
layering demo
with
neopentyl
alcohol





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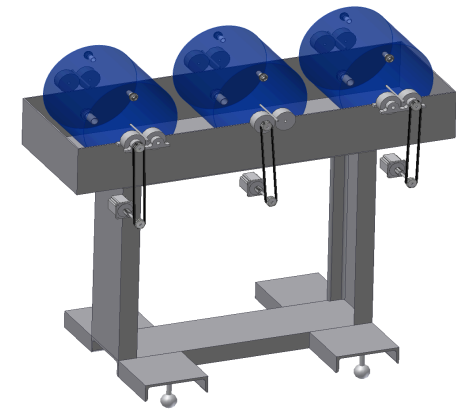
Target Fabrication/Injection Tasks

6) Process development and costing (GA)

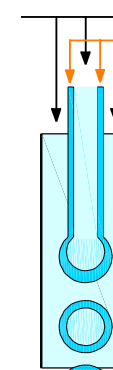
FY03 - Provide initial definition and layouts equipment for fabrication of direct drive targets. Operate microencapsulation equipment to evaluate scaleup methods and provide shells for other experiments

FY04 - Incorporate continuing target program R&D data into the Target Fabrication Facility (TFF) equipment lists and plant layouts. Operate microencapsulation equipment to parametrically evaluate methods for scale-up.

FY05 - Support the IRE decision process by providing a chemical engineering approach to the TFF and the IRE pilot-plant target factory that is integrated with results from experimental programs. Fabricate foam shells and seal coats using mass-production methods

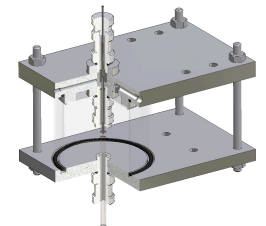
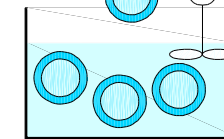


$H_2O/$
PVA



DVB with
initiator

*Example
process
equipment*





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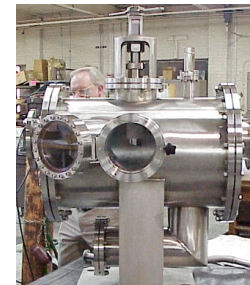
Target Fabrication/Injection Tasks

7) Target injector (GA)

FY03 - Procure components and convert system to rep-rated operation (6 Hz for 12 shots).

FY04 - Complete shakedown of injection and tracking system (gas-gun) in rep-rated mode; refine and optimize tracking system as needed.

FY05 - Complete injection and tracking studies of parametric conditions (velocity, acceleration, gas pressure, etc.) to demonstrate design windows for meeting tracking accuracy requirements of $\pm 20 \mu\text{m}$. Install a surrogate final optics/mirror unit on injection/tracking system and interface to tracking commands to provide an integrated demonstration of high-speed tracking and hitting the target on-the-fly with a low-power laser (with UCSD collaboration).



Injection system components



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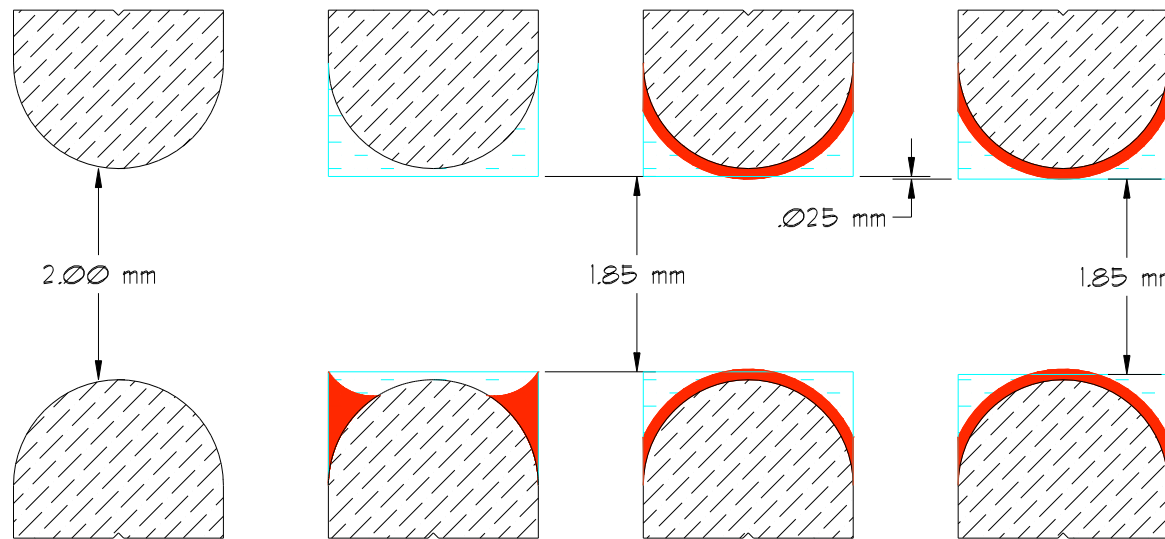
Target Fabrication/Injection Tasks

8) DT response during injection (LANL)

FY03 - Deposit a layer of DT in a torus and observe effect of rapid heat pulse

FY04 - Conduct experiments to determine the ability of DT with foam underlay to survive rapid heat pulse. Measure elastic modulus and yield strength of DT under representative strain rates, repeat with foam-reinforced DT.

FY05 - Measure DT response with rapid IR heating of filled spherical targets.



*Foam-lined torus
cutaway view, LANL*



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Target Fabrication/Injection Tasks

9) Target/chamber interface (GA/UCSD)

FY03 - Perform assessment of cryogenic materials properties necessary for target/chamber interface modeling. Develop modeling capabilities. Perform trajectory analysis in coordination with injection tasks.

FY04 - Conduct parametric analyses of target response during cryogenic handling and injection; provide feedback to guide R&D.

FY05 - Bring together materials property data, models of target response during injection, and experimental program results to show a workable solution for direct drive target injection.

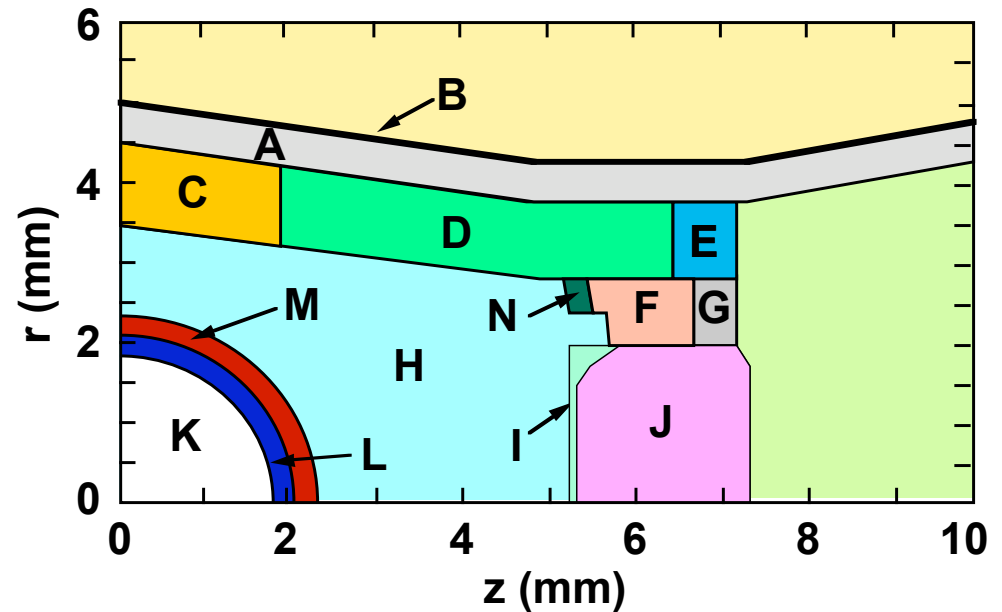


Heavy Ion Fusion Target



Process Steps

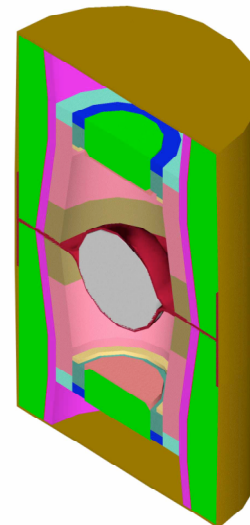
- 1) Fabricating the spherical capsule
- 2) Fabricating the hohlraum case
- 3) Fabricating the radiators
- 4) Filling the capsule with fuel
- 5) Cooling the capsule to cryo
- 6) Layering the DT into shell
- 7) Assembling the cryo components
- 8) Accelerating for injection
- 9) Tracking the target's position
- 10) Providing steering/timing info



Near Term Tasks

Develop a “credible pathway” for target supply

- 1) Simplify the target design
- 2) Optimize the target materials selection
- 3) Proof of principle fabrication of key materials
- 4) Demonstrate injection at full length



Nuclear Fusion 39,
1547



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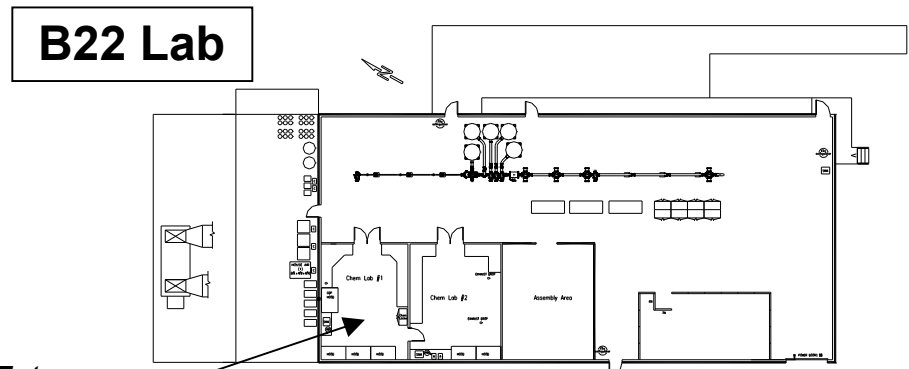


We've moved into the "Building 22" complex

Additional 7200 SF lab space

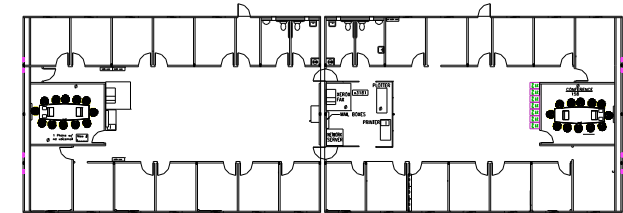
And 6900 SF of office space

GA's "IFE Development Facility"



*Future
chem labs*

**22-T
Offices**



**Gas-gun
for IFE
target
injection
demo**





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The Viability of an Economical Target Supply for Inertial Fusion Energy

D.T. Goodin, A. Nobile, D. Schroen, G. Besenbruch, L. Brown, N. Alexander, J. Maxwell, W. Meier, T. Norimatsu, R. Petzoldt, W. Rickman, W. Steckle, J. Dahlburg, and E. M. Campbell

**Second US/Japan Workshop on Target
Fabrication, Injection, and Tracking**

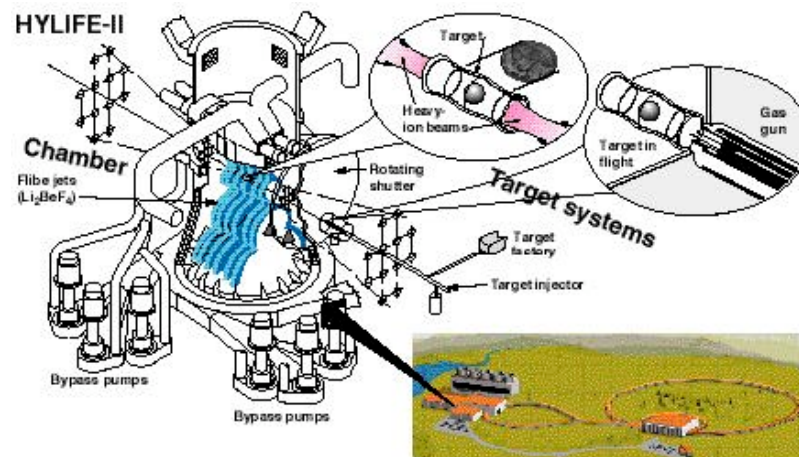
**San Diego, California USA
February 3-4, 2003**



Feasibility of economical target fabrication is a critical issue for IFE power plants

- A number of power plant conceptual designs are available
 - pulsed power systems that operate at ~6-10 Hz
- Must supply about 500,000 targets per day with:
 - precision geometry, and cryogenic, layered DT fill

Concept for “HILIFE-II”
IFE 1000 MW(e) Power
Plant (Chamber radius =
3 meters)



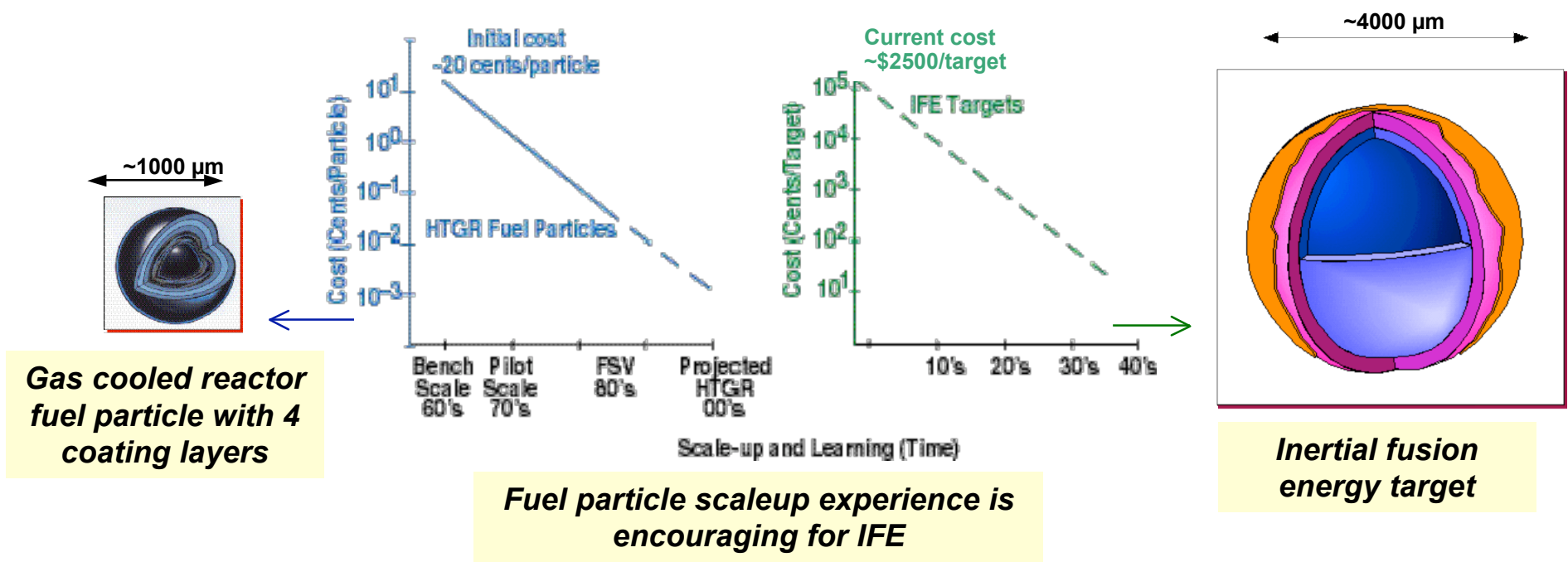
... Cost reductions from about \$2500 per target to about \$0.25 per target are needed for economical electricity production



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Cost reductions of four orders of magnitude are challenging - but feasible



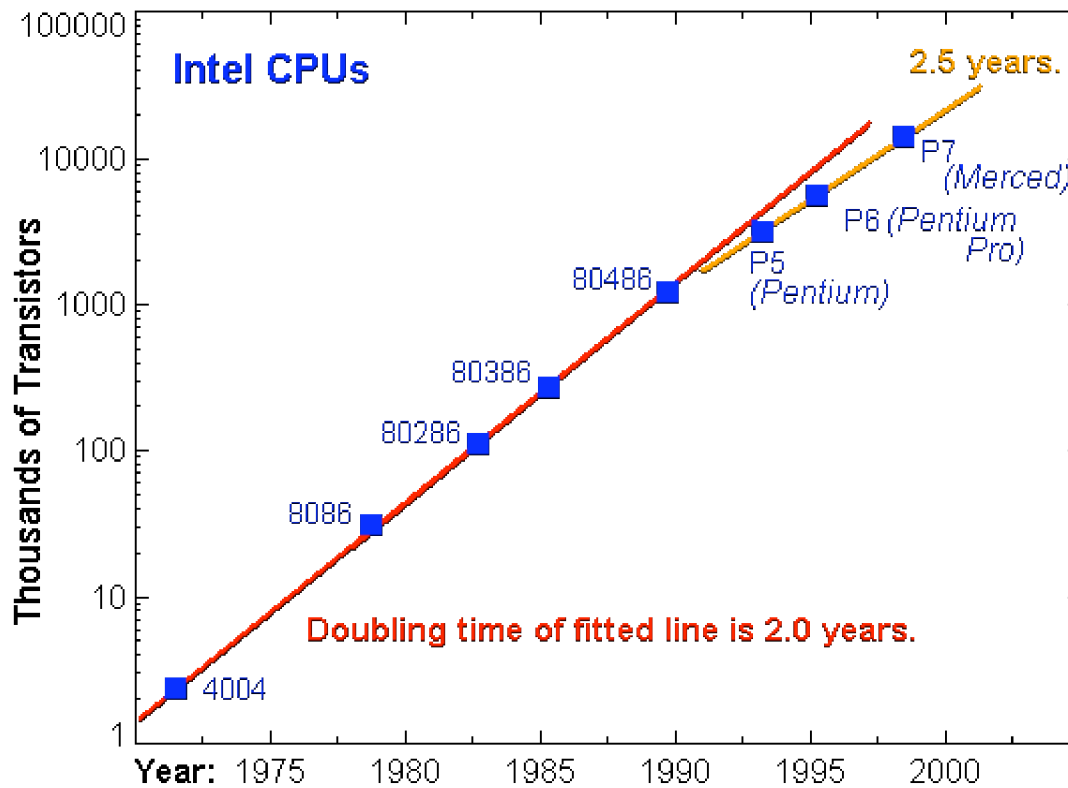
... GA has previously used fluidized bed technology to reduce costs of coated nuclear fuel particles and



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Technological improvements lead to dramatic changes in products (i.e. Moore's Law)



*Technology
Review, C. Mann,
May/June 2000*

... The number of transistors on a chip increased 4 orders of magnitude from 1971 to 1999.



One can estimate IFE target production costs beginning with current experimental-target costs

- One can find the approximate cost per current-day target by *Total Project Cost/ Number of Delivered Targets = ~\$2500 (capsule only)*
- However, there are tremendous differences in the program requirements - and in the consequent approaches to manufacture

<u>Item</u>	<u>Experimental Program</u>	<u>IFE Program</u>
Production Rate	Relatively Small (few thousand targets.year by GA)	500,000 per day
FOAK Costs	Very high - targets always vary	Essentially none
Characterization	Extensive - individual details needed	Statistical sampling
Product Yield	Low - product varies, small amounts needed	High - development
Batch sizes	Small - small amounts needed	Large



... but to truly define the cost we must define the fabrication pathway



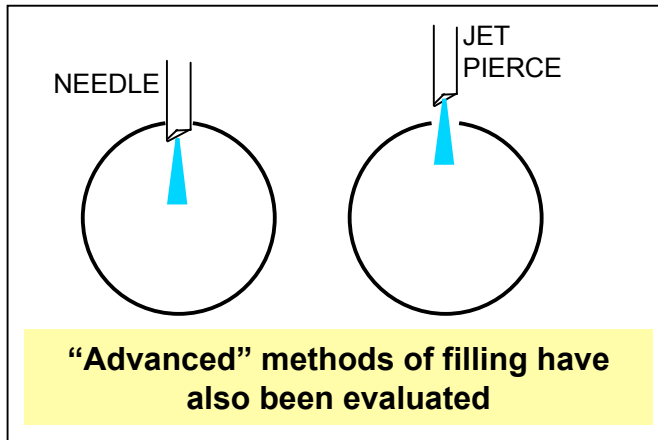
There are many decisions to be made when selecting a target supply pathway

<u>Step</u>	<u>Methods</u>	<u>Comments/Issues</u>
Capsule Fabrication	Microencapsulation	Simple, suitable for hi-volume Issues: sphericity, non-concentricity
	GDP coating onto mandrels	Could solve NC problem; demo'd in small coaters; Issues: multi-step adds cost
	Solution spray drying	Produce stronger, higher density PI; Issues: surface smoothness, cost
Filling	Permeation	Demonstrated; Issues: T inventory
	Liquid filling	Developmental, capsule damage
Layering	Fluidized bed	Demo'd in principle, req's fast assembly
	In-hohlraum	Extreme precision/uniformity
Hohlraum Comp. Fab	Casting	For Flibe sleeve, remote handling
	LCVD	For hi-Z matl's, developmental, cost
	Metal foams	Pore sizes, density
	Wire arrays	Uniformity, structural integrity
	Doping of CH foams	For radiator matl's, mass-prod methods, handling, precision
Target Injection/Tracking	Gas-gun, electromagnetic	Building demo system

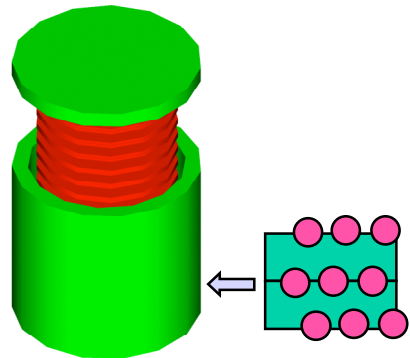
.... For indirect drive targets, recycling of metal components is a key process decision



Filling of the capsules with DT can be done by permeation through the capsule wall



- Issue = Minimum T inventory “at-risk”
- Targets typically contain ~3-4 mg of tritium
- 1.5 to 2 kg of tritium/day injected into reactor



Pressure cell with trays

Six shots per second
 Void fraction - 5%
 Fill Temperature - 27C
 Cool time - 0.5 h
 Evacuation time - 1 h
 □-Layering time - 8 h
 IR-Layering time - 2 h
 Fill overpressure - 75% of buckle

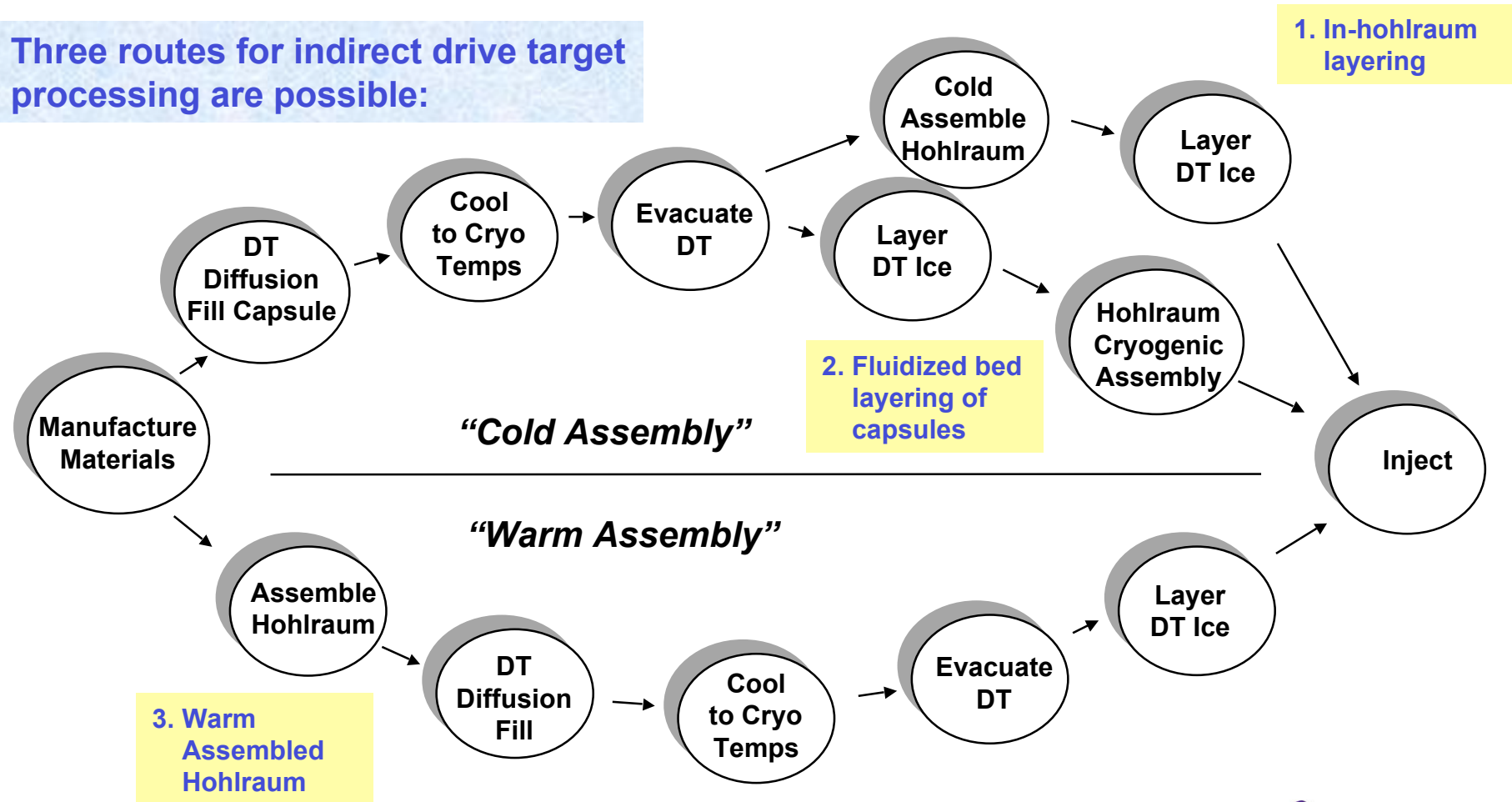
Hohlraum cryo-assembly	HIF Target
Buckle Pressure	449 atm
Fill Time	2.8 hours
Tritium Inventory with beta-layering	0.57 kg
Tritium Inventory with beta-layering + IR	0.27 kg

Methodology by A. Schwendt, A. Nobile (LANL), Fusion Science and Technology (to be published)



Indirect drive - layering in-hohlraum or not?

Three routes for indirect drive target processing are possible:



...Tritium inventory will likely require cryogenic assembly 

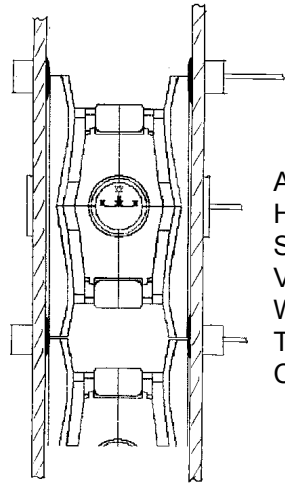


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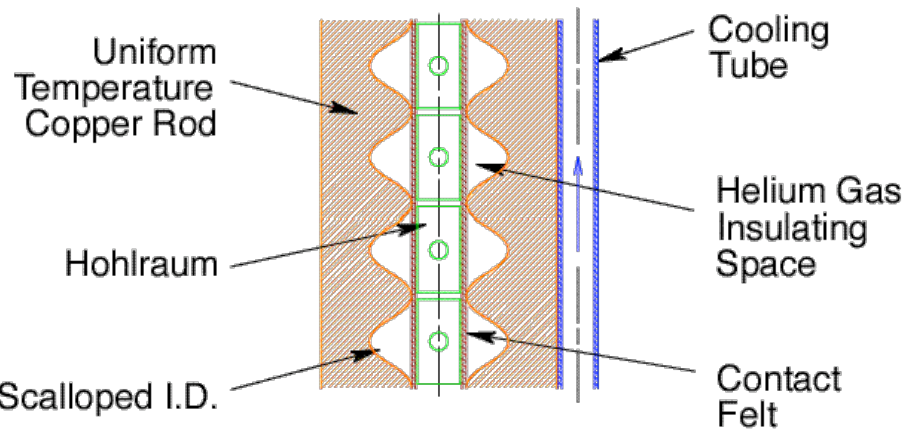
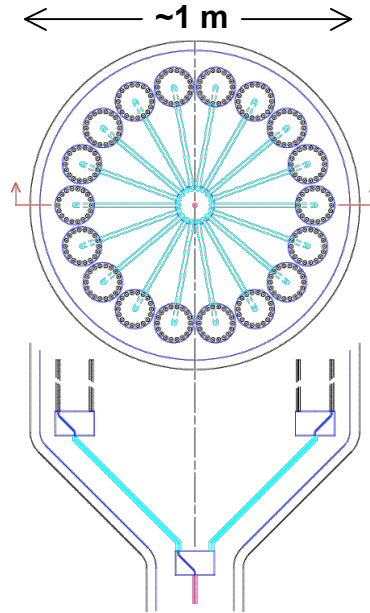
Two potential layering methods identified



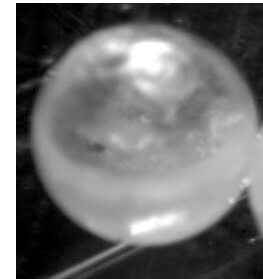
In-hohlraum "tube" layering



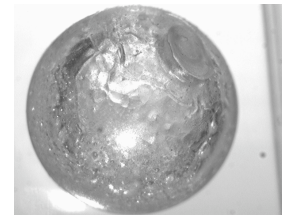
ASSEMBLED HOHLRAUMS ARE STAGED IN VERTICAL TUBES WITH PRECISE TEMPERATURE CONTROL



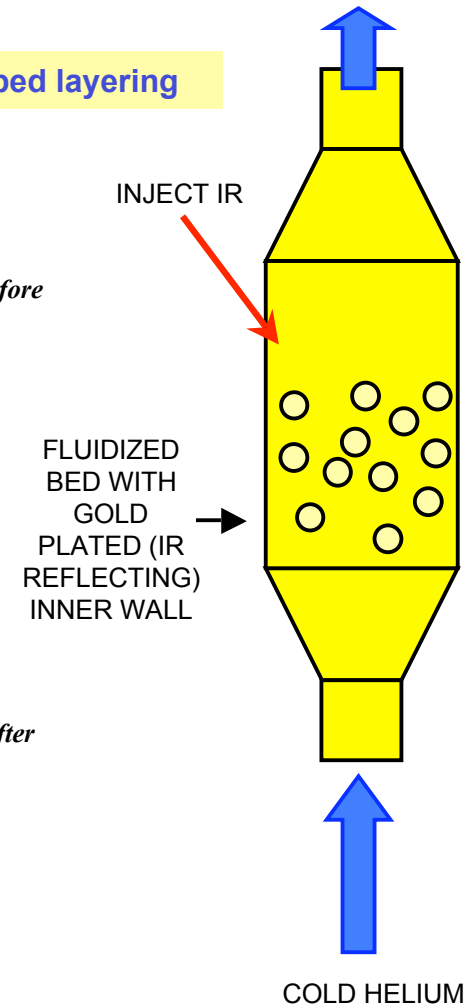
Cryogenic fluidized bed layering



Before



After

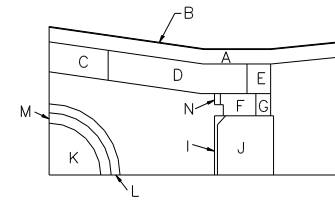


Neopentyl alcohol as surrogate for hydrogen - proof of principle demo

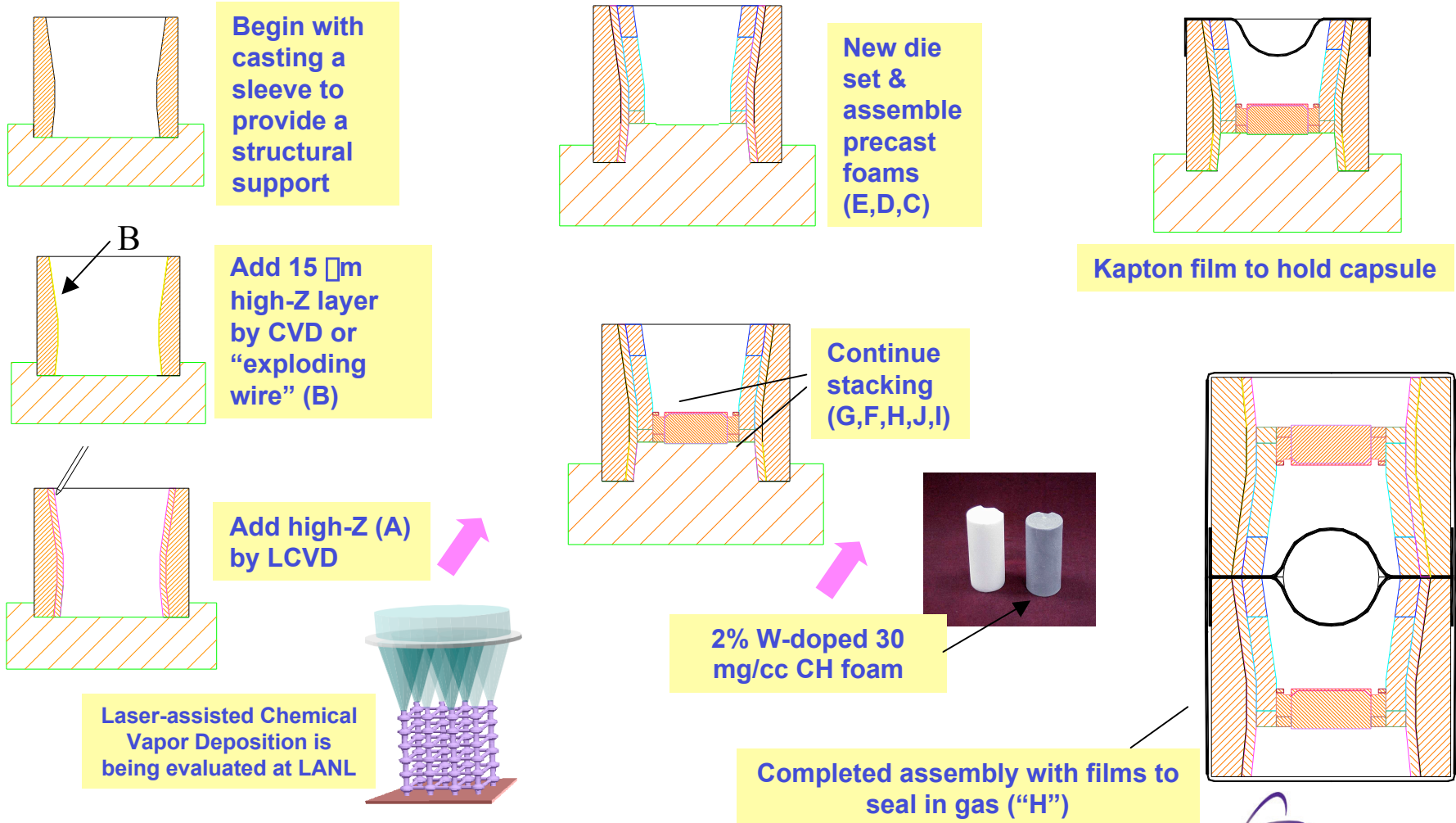
...Fluidized bed layering is can be used for either direct or indirect drive targets



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Manufacture of the hohlraum components and assembly



...Remote processing is required if we recycle metals



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Approach to cost estimating of the TFF

- **What this is not:**
 - a final cost estimate, or final design and layout of the TFF plant
 - doesn't mean that R&D is done and process decisions are made
- **It does:**
 - assume that development will be accomplished to allow scaling of current laboratory methods to larger sizes
 - provide a generous allowance for equipment, labor, and process time for currently known processes
 - uses chemical engineering scale-up principles and practices
 - use established industrial and power plant cost-estimating methods and factors for an *nth of a kind* plant
- **Model provides:**
 - a first cut at the facility design concepts and cost
 - a framework to compare and contrast future design decisions
 - a tool to help guide future research directions

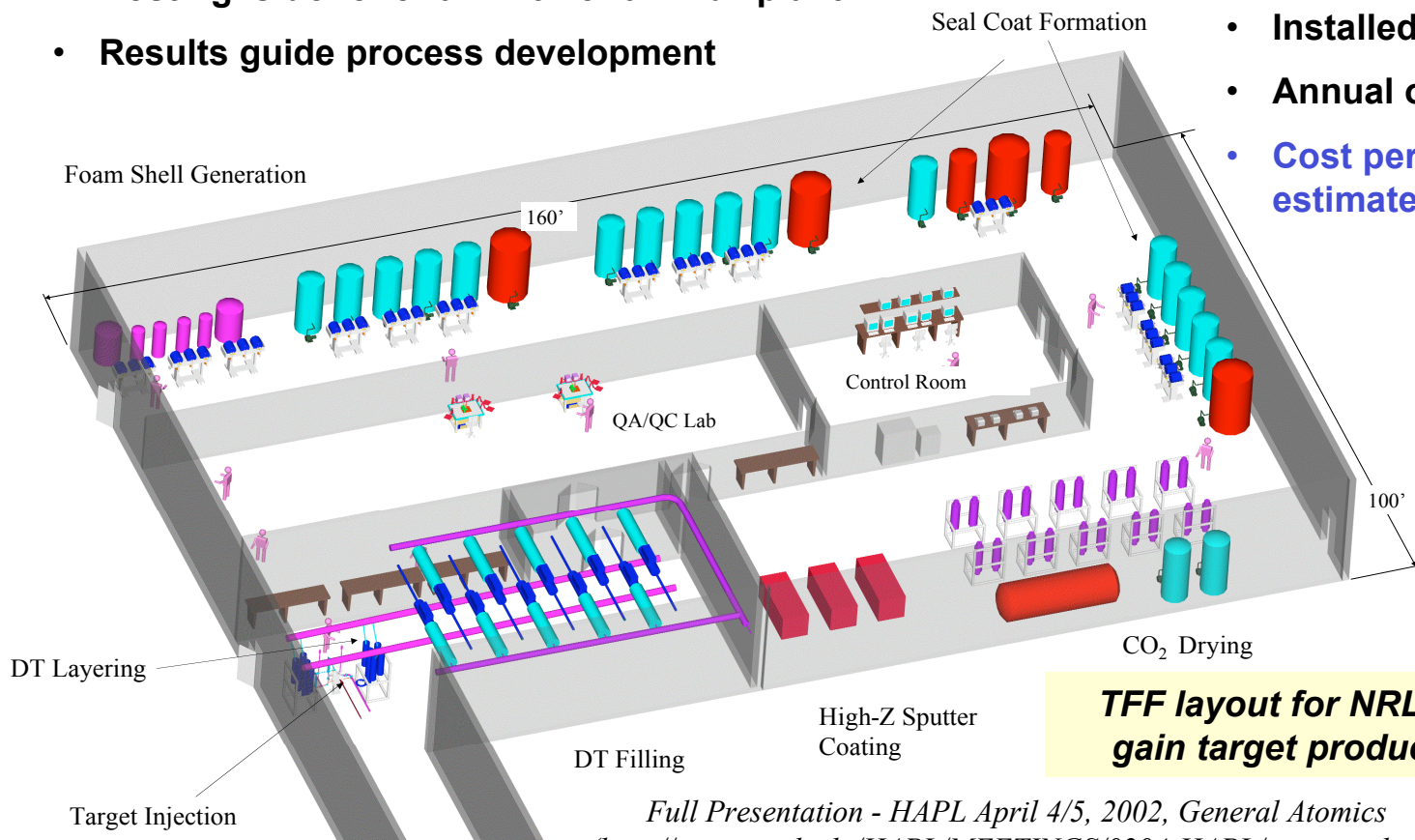


Our estimates for direct drive target production costs are encouraging

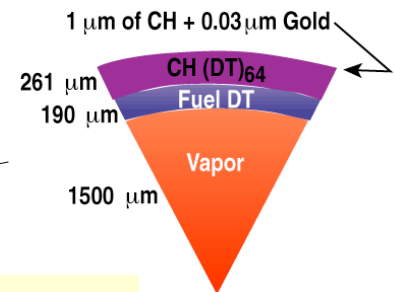
- Chemical engineering approach to Target Fabrication Facility (TFF)
- Costing is done for an “nth-of-a-kind” plant
- Results guide process development

Major Parameters

- 500,000 targets per day
- 2-3 weeks on “assembly line”
- Installed capital of \$97M
- Annual operating cost of \$19M
- **Cost per injected target estimated at 16.6 cents**



NRL high gain target



TFF layout for NRL high gain target production

Full Presentation - HAPL April 4/5, 2002, General Atomics
(<http://aries.ucsd.edu/HAPL/MEETINGS/0204-HAPL/program.html>)



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Direct Drive TFF – major parameters & summary

- 1) **Production rate - 500,000 usable radiation preheat targets/day**
- 2) **Assumed reject rate of 25% (at end of process)**
- 3) **Use of ~42 moveable "contactors" of ~100 liters with an ~8h target supply**
- 4) **Twenty seven supply and interim processing tanks**
- 5) **Targets spend ~2-3 weeks on the "assembly line"**
- 6) **Approximately 100' by 160' single-story facility**
- 7) **Total employees estimated at 152 (24/7 shifts) \$8.9M per year**
- 8) **Installed Capital cost estimated at \$97M**
- 9) **Annual materials and utilities ~\$4.3M**
- 10) **Annual maintenance costs (labor and materials) ~\$5.8M**
- 11) **Cost per injected target is estimated at ~16.6¢**

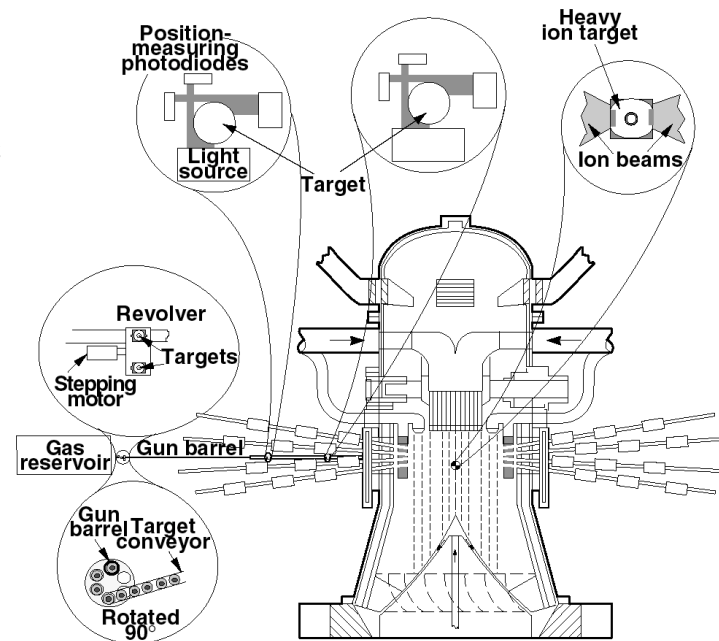
.... We think this is a very important conclusion for the feasibility of direct drive IFE!



Target injection costs are estimated at less than 2 ¢ each

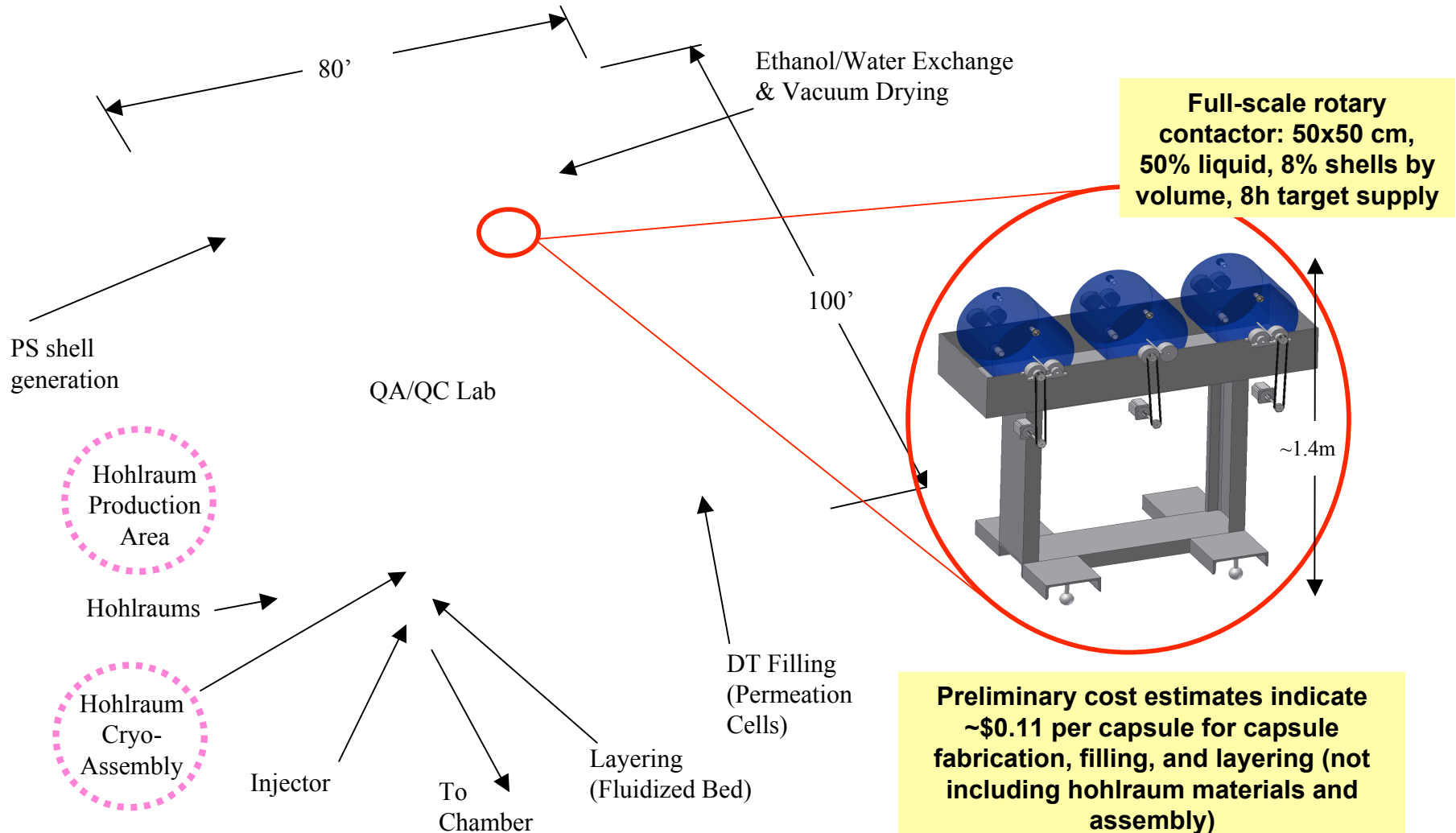
- Less detail than fabrication study
- Estimate 6 full-time staff and an installed capital cost of \$20 million (negligible utility costs assumed for now)
- Using factors developed in the fabrication study produces these results:
 - Annualized capital cost of 12.5% x \$20M = \$2.5M
 - Operating costs = ~0.5M
 - Total annual costs = ~\$3M
 - Cost per usable target = ~1.6 ¢

**HYLIFE-II power plant
concept
showing basic injector
components**





Preliminary indirect drive target TFF layout (without hohlraum)





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Indirect Drive TFF – major parameters & summary

- 1) Production rate ~500,000 usable targets/day (with hohlraum)
- 2) Assumes “nth-of-a-kind” plant
- 3) Capsules are solid polystyrene
- 4) Plastic outer hohlraum case to eliminate radioactive processing lines
(Flibe also considered but requires expensive hot cell handling)
- 5) Pb/Hf (70:30) is high Z material (single use)
- 6) Internal hohlraum components are made by LCVD only
- 7) Total employees estimated at 167 (24/7 shifts)
- 8) Installed capital cost estimated at \$304M (\$38 M annualized cost)
- 9) Annual materials and utilities ~\$11M
- 10) Annual maintenance costs (labor and materials) ~\$18M
- 11) Annual operating labor costs ~\$10 M
- 12) Cost per injected target is estimated at ~40.8¢



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Single use for hohlraum materials appears preferable

- It has been long assumed that the hohlraum materials would be recycled, which would require fully remote processing for all hohlraum steps
- Laila El-Guebaly (UW) has recommended single use of low cost materials for the following reasons:
 - Hohlraum walls make up <1% of total-plant waste stream
 - Will be low-level waste if used “once through”
 - Recycling produces high level waste
 - Recycling requires remote handling in target fabrication (\$\$\$)
 - Au/Gd materials cost \$80 M/year, so must recycle
 - Other materials are much cheaper and still effective
- Replacing Au/Gd with Pb/Hf mixture allows potential single use and discard
 - Pb cost per hohlraum = 0.02 cents (~\$100 per day)
 - Hf cost per hohlraum = 1.6 cents (~\$8000 per day)
- Removing metals from Flibe coolant and taking back to elemental purity for target use will also be much more expensive than simply providing “Flibe cleanup”

Ref: El-Guebaly ARIES presentation, October 2002

.... single use results in lower cost of electricity

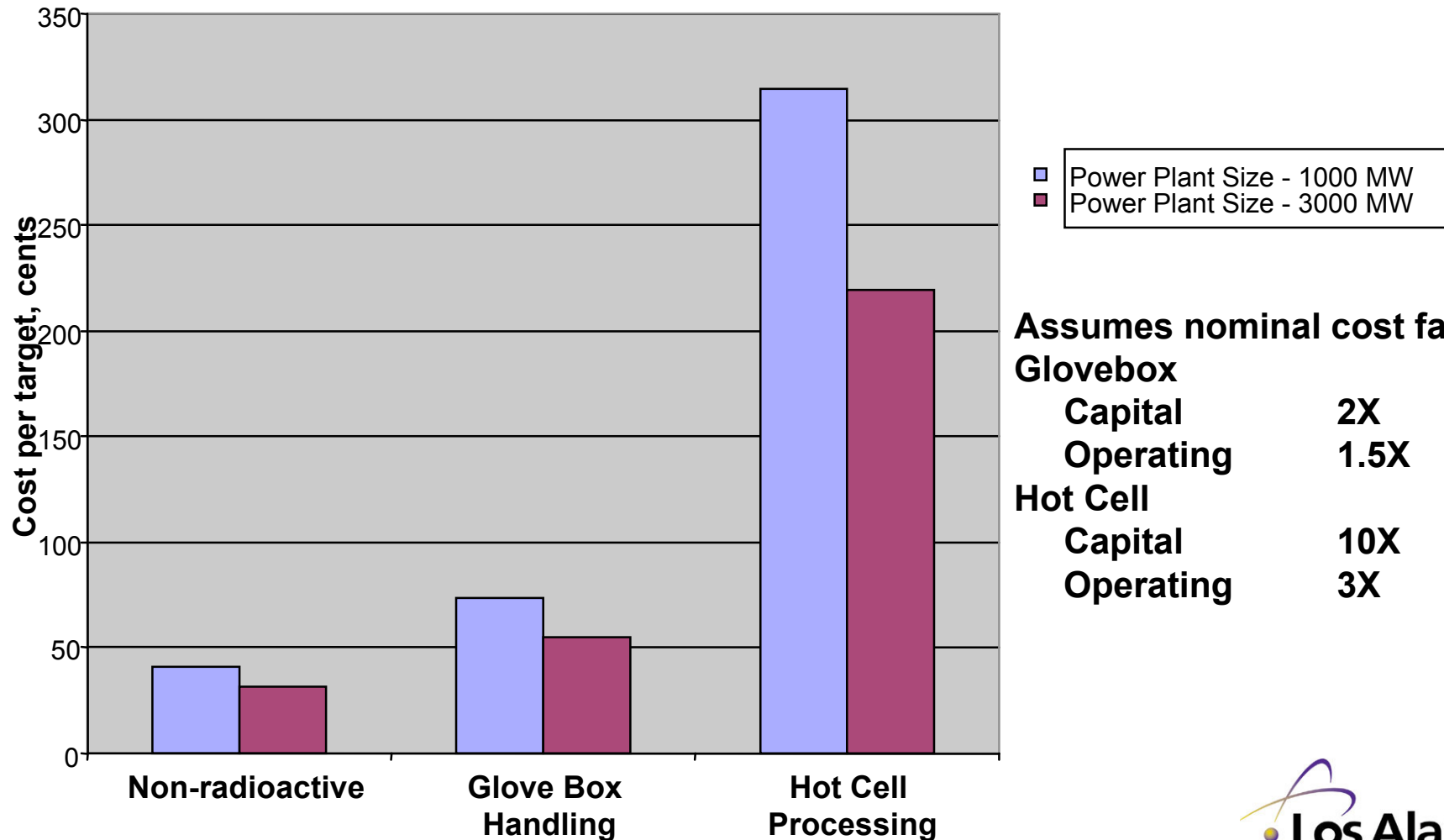


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Costs would be higher with radioactive hohlraum fabrication

Indirect Drive Cost per Injected Target



Assumes nominal cost factors

Glovebox

Capital 2X

Operating 1.5X

Hot Cell

Capital 10X

Operating 3X



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What's included in the target costing study?

CAPITAL-RELATED COSTS

- Purchased Equipment
- Engineering/Contingency
- Buildings/Auxiliaries
- Piping/Electrical/Instrumentation
- Financing Expenses

OPERATING COSTS

- Operating Staff (including sampling/inspection)
 - a) 12 mgmt/admin staff on day shift only (supervisors, engineers and clerks)
 - b) 28 operating staff on each shift for 24/7 coverage (operators, technicians, health physicists, QA/QC specialists)
- Chemicals, maintenance, utilities, waste disposal

COSTS NOT INCLUDED IN THIS MODEL

- Tritium (assumed to be provided on-site)
- Security/safety staff, insurance, janitorial staff, cafeteria staff, medical staff, patent royalties (if any), federal, state and local taxes
- Cost of Flibe cleanup systems



GENERAL ATOMICS
AND AFFILIATED COMPANIES



Summary - target costing study

- **Direct Drive Targets (Laser IFE)**
 - We have a well-defined target to make
 - We have a relatively well-known fabrication process (prior experience)
 - Research plans for developing the target processes are specific
 - Experimental R&D programs are well underway
 - Production cost estimate for reference case is ~16.6¢ per target!
- **Indirect Drive Targets (Heavy Ion Fusion)**
 - Good recent progress in developing potential fabrication pathways
 - Iterations are underway to simplify the target design
 - We have a method (LCVD) that we believe can fabricate the difficult foams in the hohlraum
 - We have a first cut at fabrication cost including hohlraum
 - Production cost estimate for reference case is ~40.8¢
 - We expect this cost estimate to decrease with further study and simplifications

.... we have a modeling structure that can be easily updated, and will guide the R&D for development of a “credible pathway” for IFE targets