Indirect Drive Target Costing Studies and Materials Selection

Bill Rickman, Dan Goodin, Art Nobile, Jennifer Young, and Lloyd Brown

Presented by Ron Petzoldt

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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 glove box or hot cell handling)
5) Pb/Hf (70:30) is high Z material
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¢

Steps for target fabrication are challenging

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**

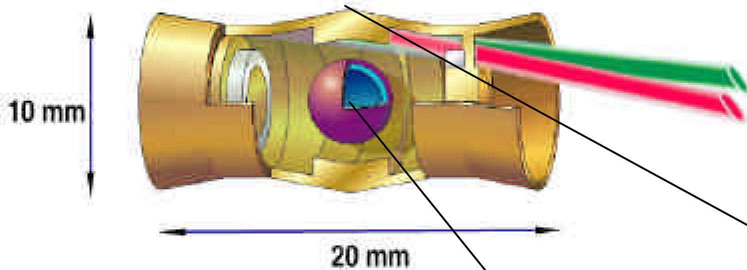
Some Possible Indirect Drive Specifications

Capsule Material	CH
Capsule Diameter	~4.6 mm
Capsule Wall Thickness	250 µm
Out of Round	<0.1% of radius
Non-Concentricity	<1% of wall thickness
Shell Surface Finish	10-200 nm RMS
Ice Surface Finish	1-10 µm RMS
Temperature at shot	~18.5K
Positioning in chamber	less than ± 1-5 mm
Alignment with beams	<200 µm

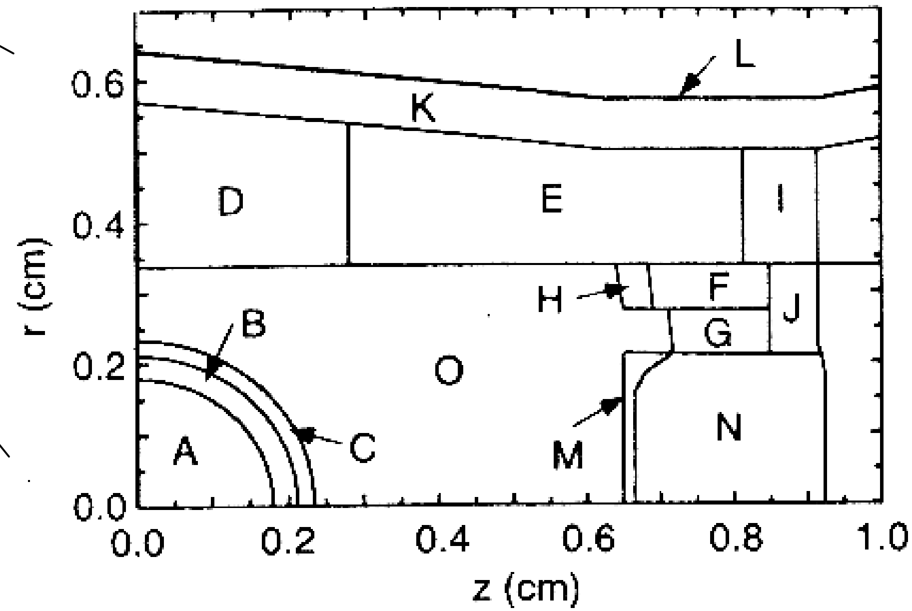
.... Process development programs for target fabrication and target injection are underway

The standard distributed radiator target of Tabak and Callahan is the reference HIF design

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



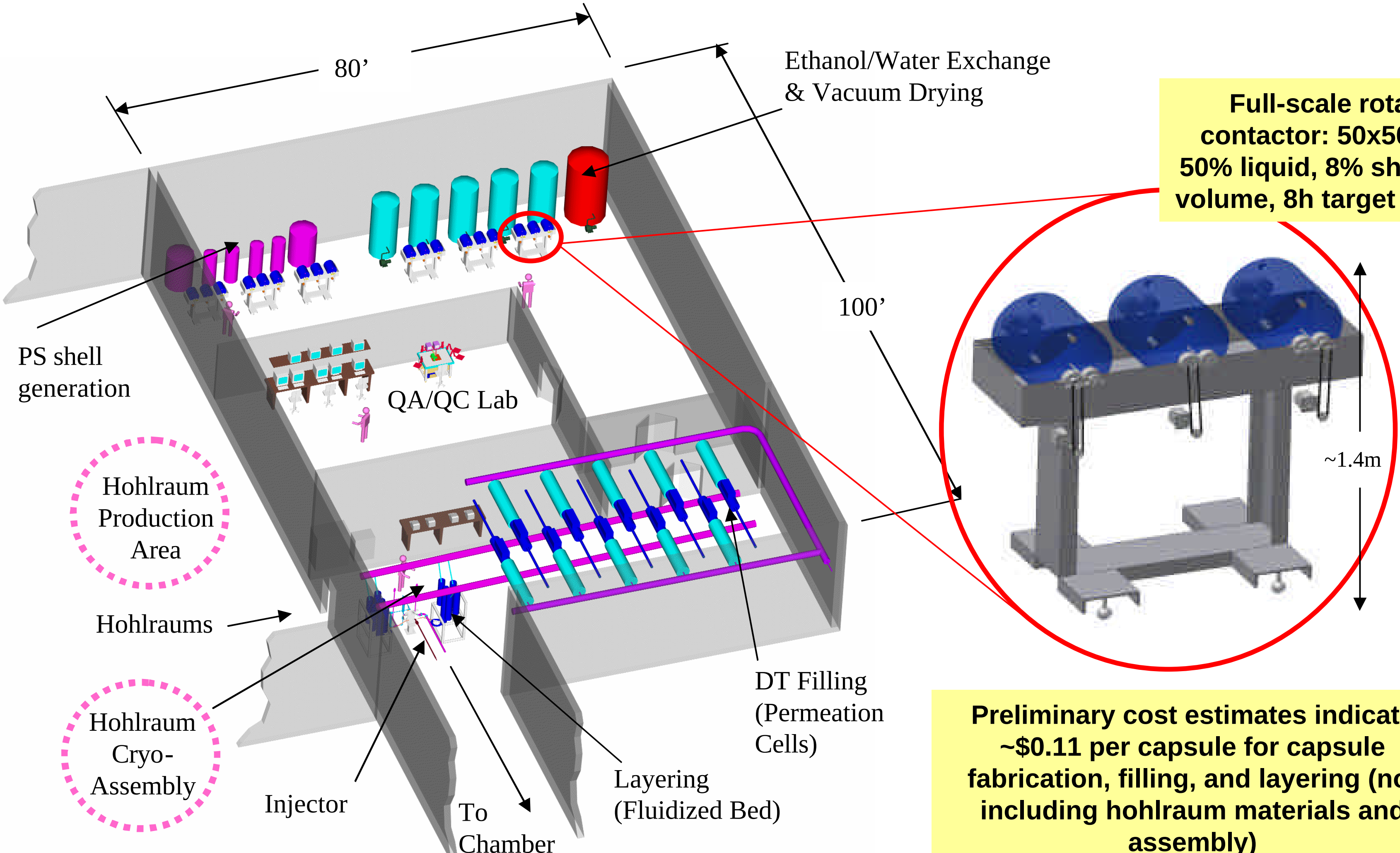
LLNL Close-Coupled Heavy Ion Driven Target



Standard (not close coupled) design used for calculations

Ref: Nuclear Fusion, Vol. 39, No. 7 (1999)

Preliminary "Target Fabrication Facility" (TFF) layout

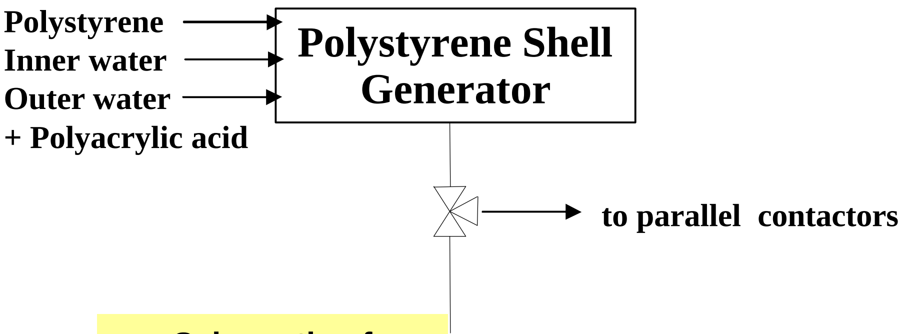


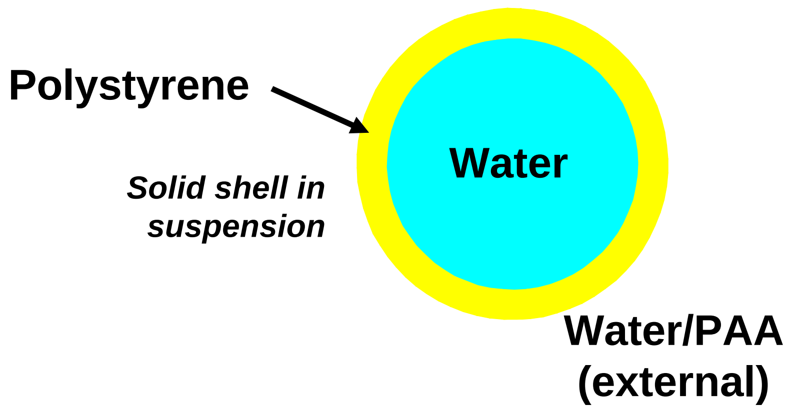
Full-scale rotary contactor: 50x50 cm, 50% liquid, 8% shells by volume, 8h target supply

Preliminary cost estimates indicate ~$0.11 per capsule for capsule fabrication, filling, and layering (not including hohlraum materials and assembly)

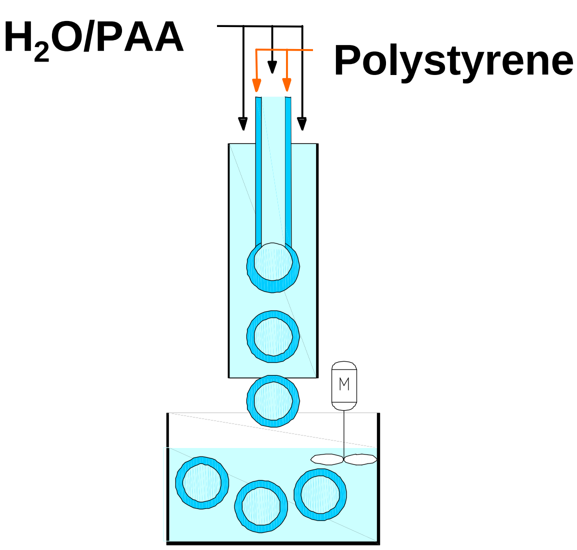
…Polystyrene capsule manufacture is similar to - and uses similar equipment - as the direct drive capsule

Generation of Polystyrene Shells



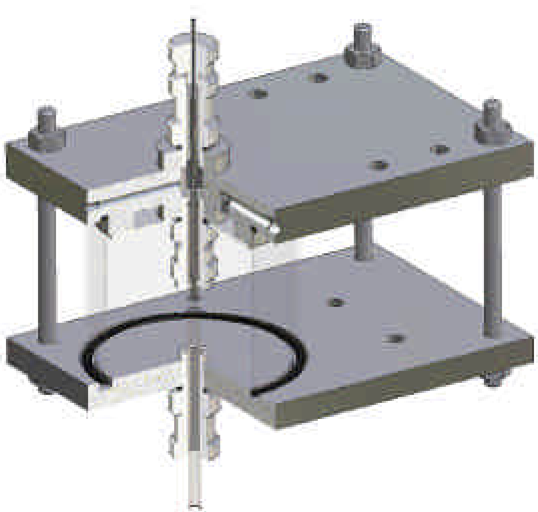


Schematic of microencapsulation process



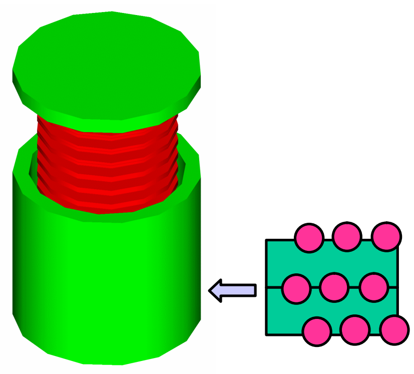
Polystyrene hollow shells, flow with the outer water into rotary contactors where the targets comprise ~8% of the contactor volume

CAD model of lab unit for microencapsulation



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

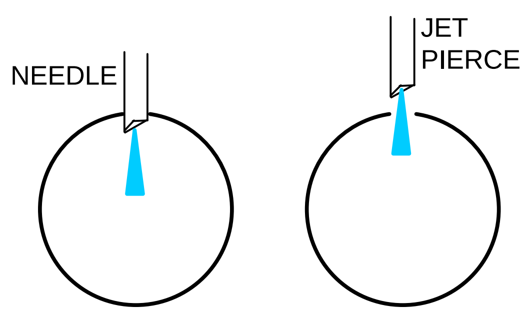


Pressure cell with trays

Six shots per second
Void fraction - 5%
Fill Temperature - 27C
Cool time - 0.5 h
Evacuation time - 1 h
β-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

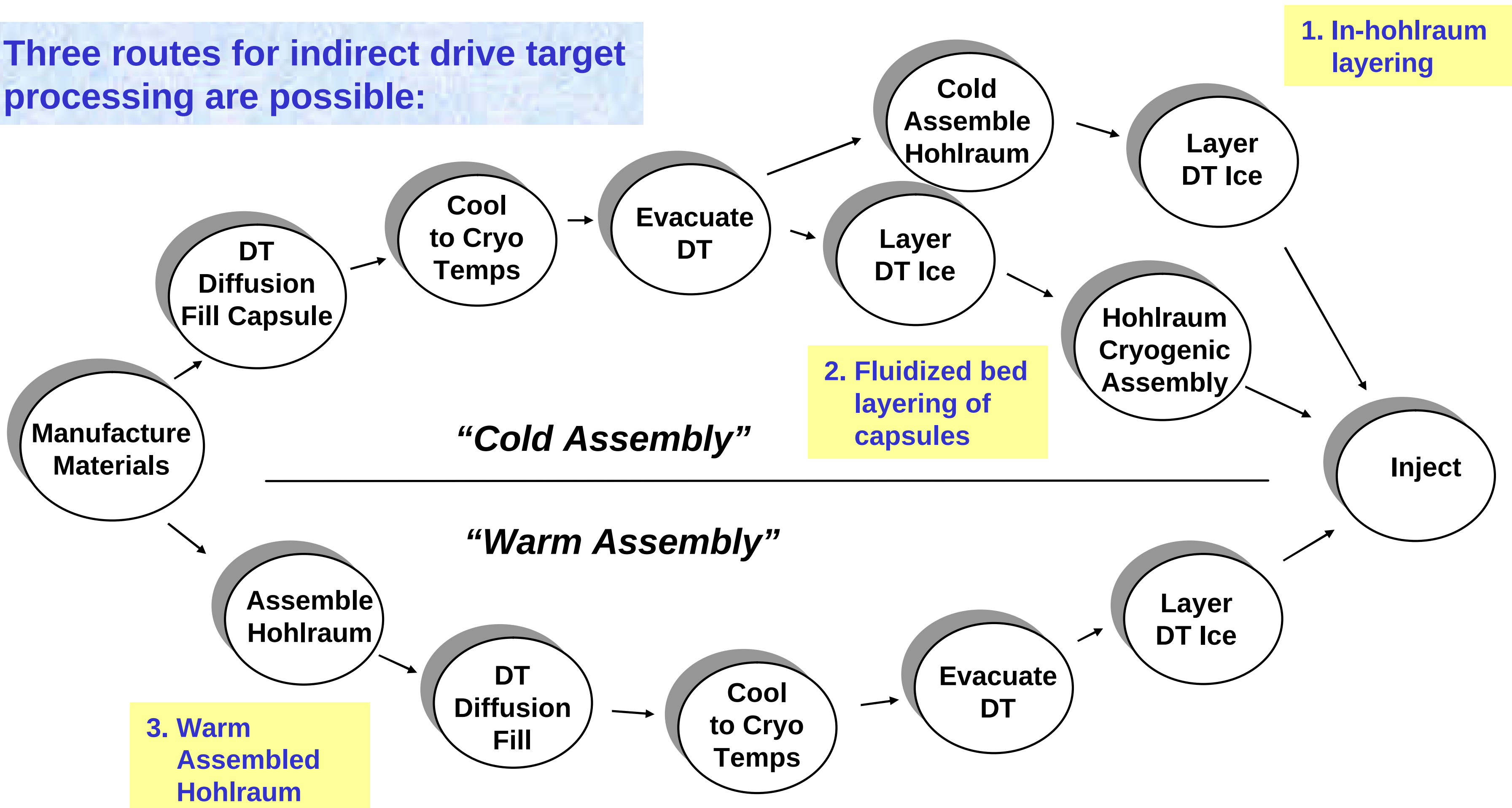
Methodology by A. Schwendt, A. Nobile (LANL)*, Fusion Science and Technology *(to be published)



“Advanced” methods of filling have also been evaluated

Layering in-hohlraum or not?

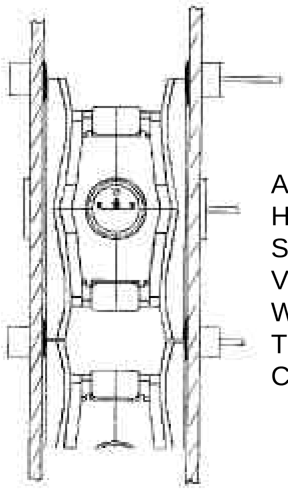
Three routes for indirect drive target processing are possible:



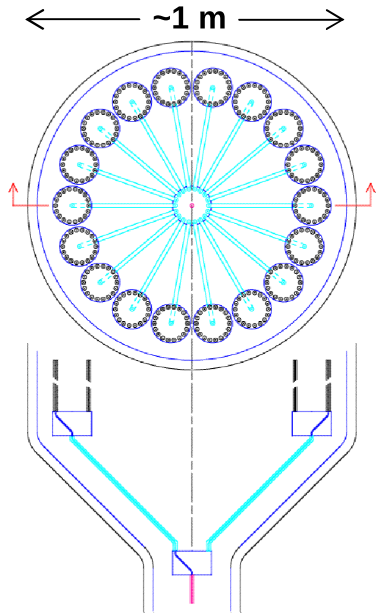
…Tritium inventory will likely require cryogenic assembly

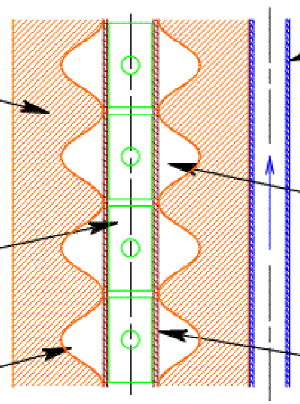
Two potential HIF layering methods identified

In-hohlraum "tube" layering

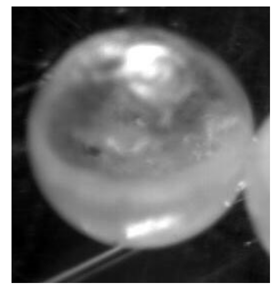


ASSEMBLED HOHLRAUMS ARE STAGED IN VERTICAL TUBES WITH PRECISE TEMPERATURE CONTROL

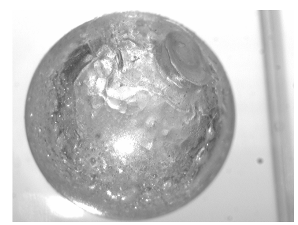




Cryogenic fluidized bed layering (Requires "last second" cryogenic assembly)

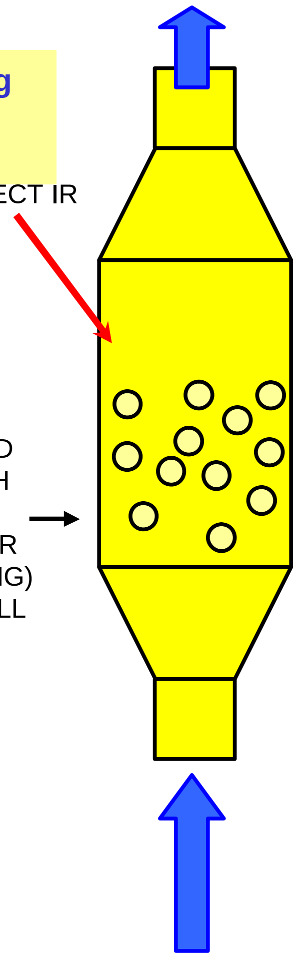


Before



After

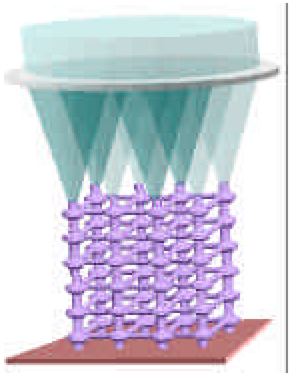
Neopentyl alcohol as surrogate for hydrogen - proof of principle demo



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

Laser chemical vapor deposition allows very low-density high-Z materials to be fabricated in-situ

Laser-assisted Chemical Vapor Deposition is being evaluated at LANL *(J. Maxwell, IAEA-TM June 17-19, 2002)*



Each of 112 unit processors have

• 16 basic Optical Assemblies	$14k each
• 16 XYZ-Motion Systems	$35k each
• 16 solid-state laser systems	$130k each
• 8 Gas Flow Systems, and	$12k each
• 2 load-lock transfer systems	$23k each

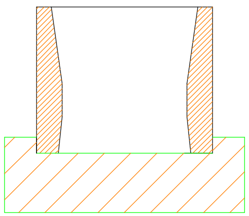
The estimated cost of each unit Processor is then $3 Million.

Hence the *current* cost for all 112 Unit Processors is $336 Million but should drop for the following reasons.

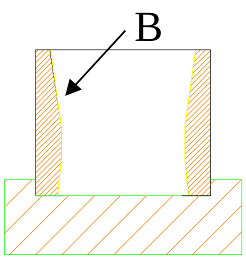
- **The cost of diode laser systems is falling**
- **The majority of the cost is the laser system**
- **Very large numbers of components will be ordered,**

We estimate the system cost as $200 Million in 5-10 years.

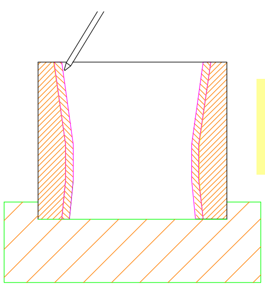
The majority of fabrication is done by LCVD



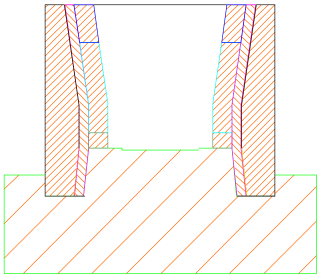
Begin with a plastic sleeve to provide a non-radioactive structural support (or Flibe for radioactive assembly)



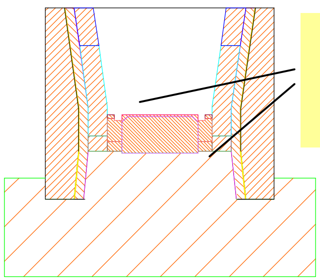
Add 20 mm high-Z layer by CVD or "exploding wire"



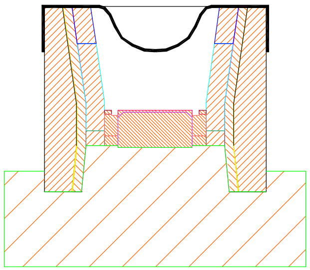
Add high-Z by LCVD



Add foams by LCVD

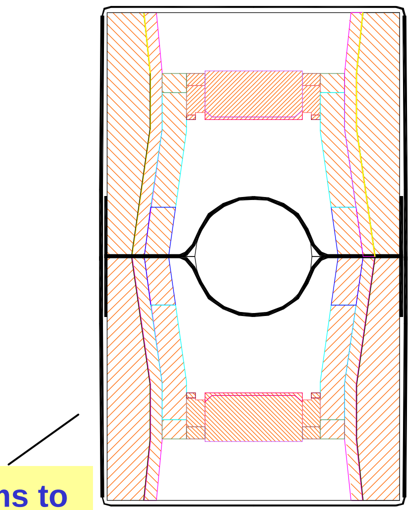


Add final components by LCVD



Kapton film to hold capsule

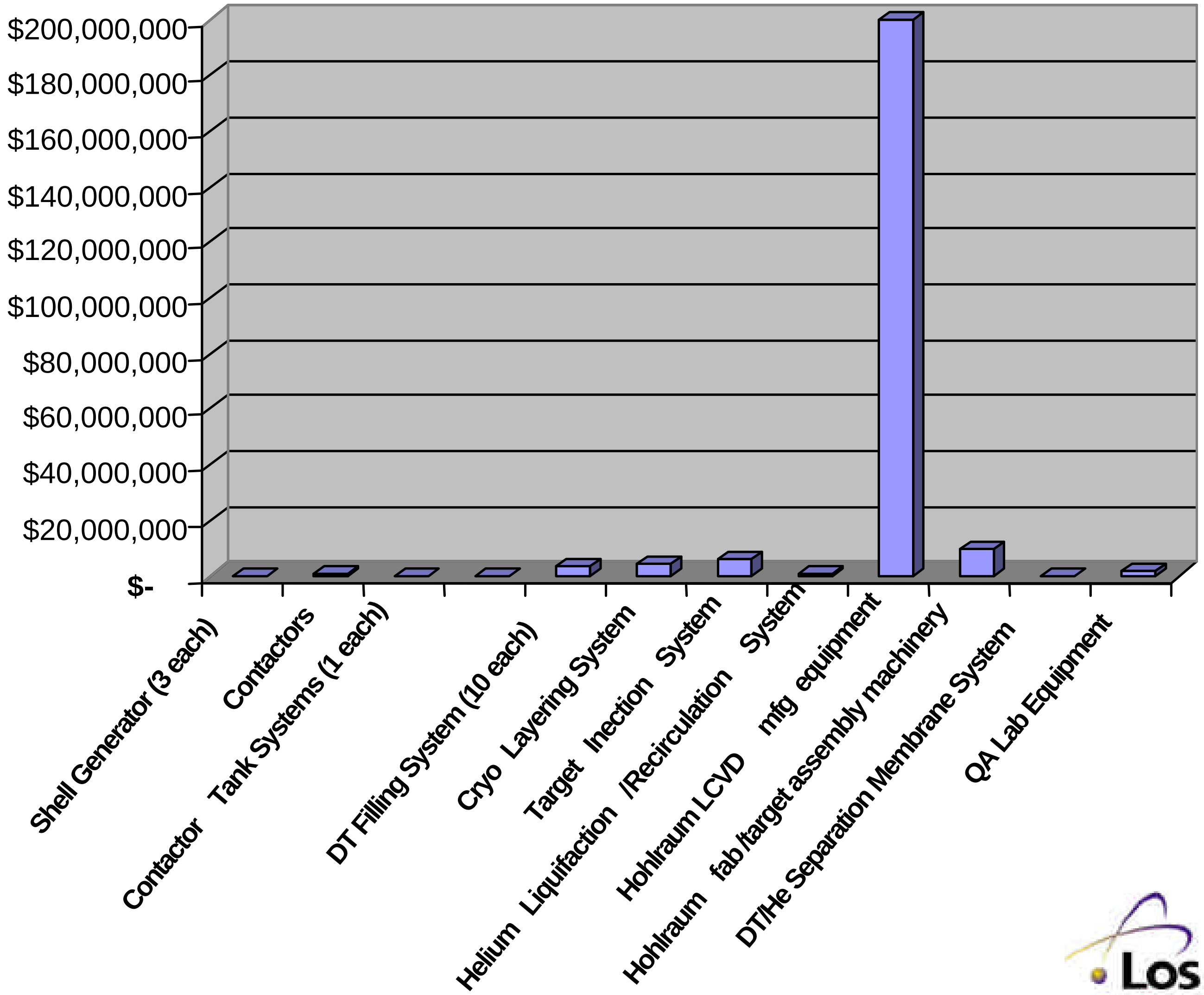
"Last second" cryogenic assembly is required to prevent damage to the cryogenic DT layer



Completed assembly with films to seal in gas

…Final assembly is similar to direct drive target in sabot

The LCVD equipment dominates all equipment costs



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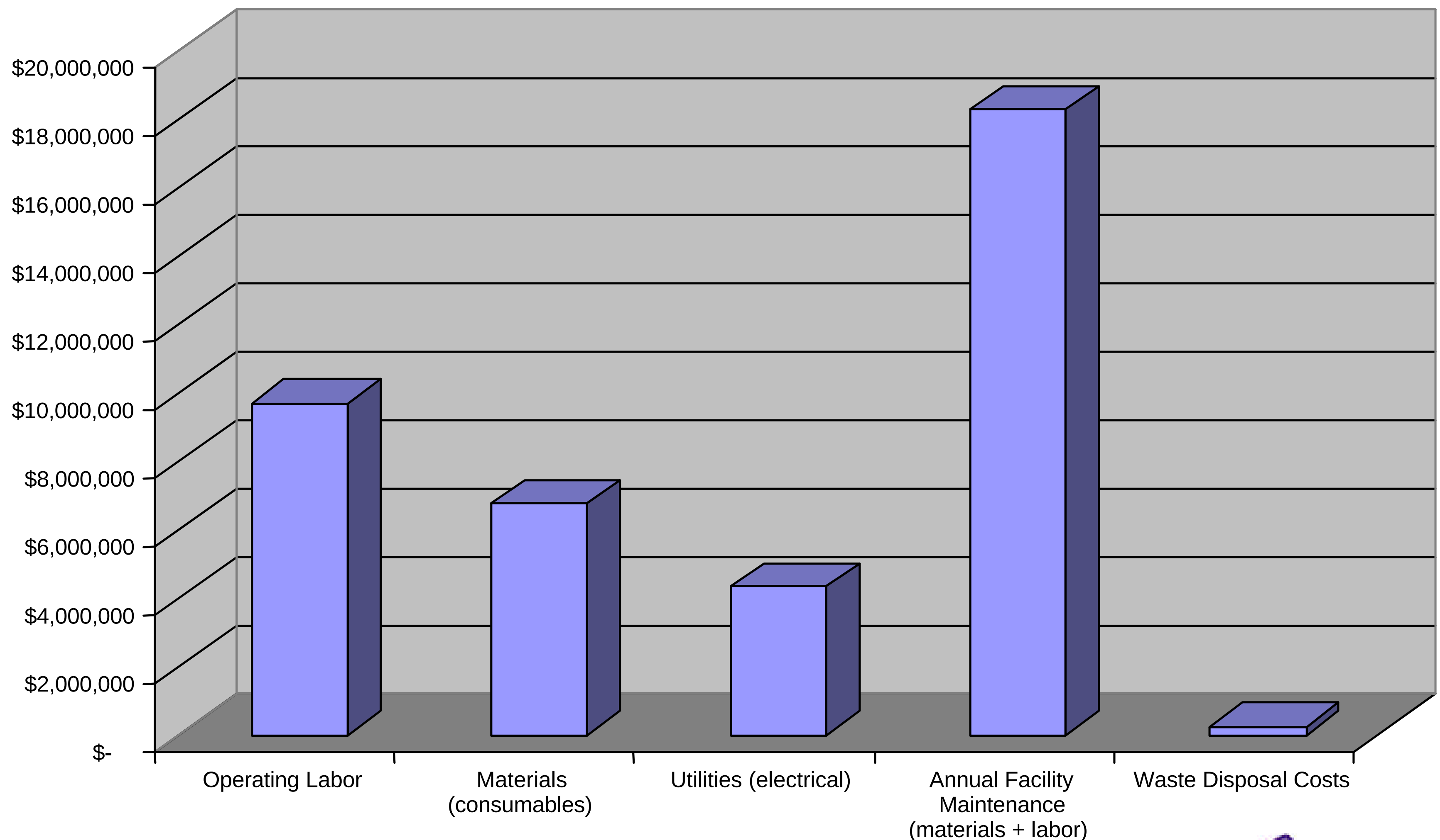
Operating costs account for half of the annual target costs



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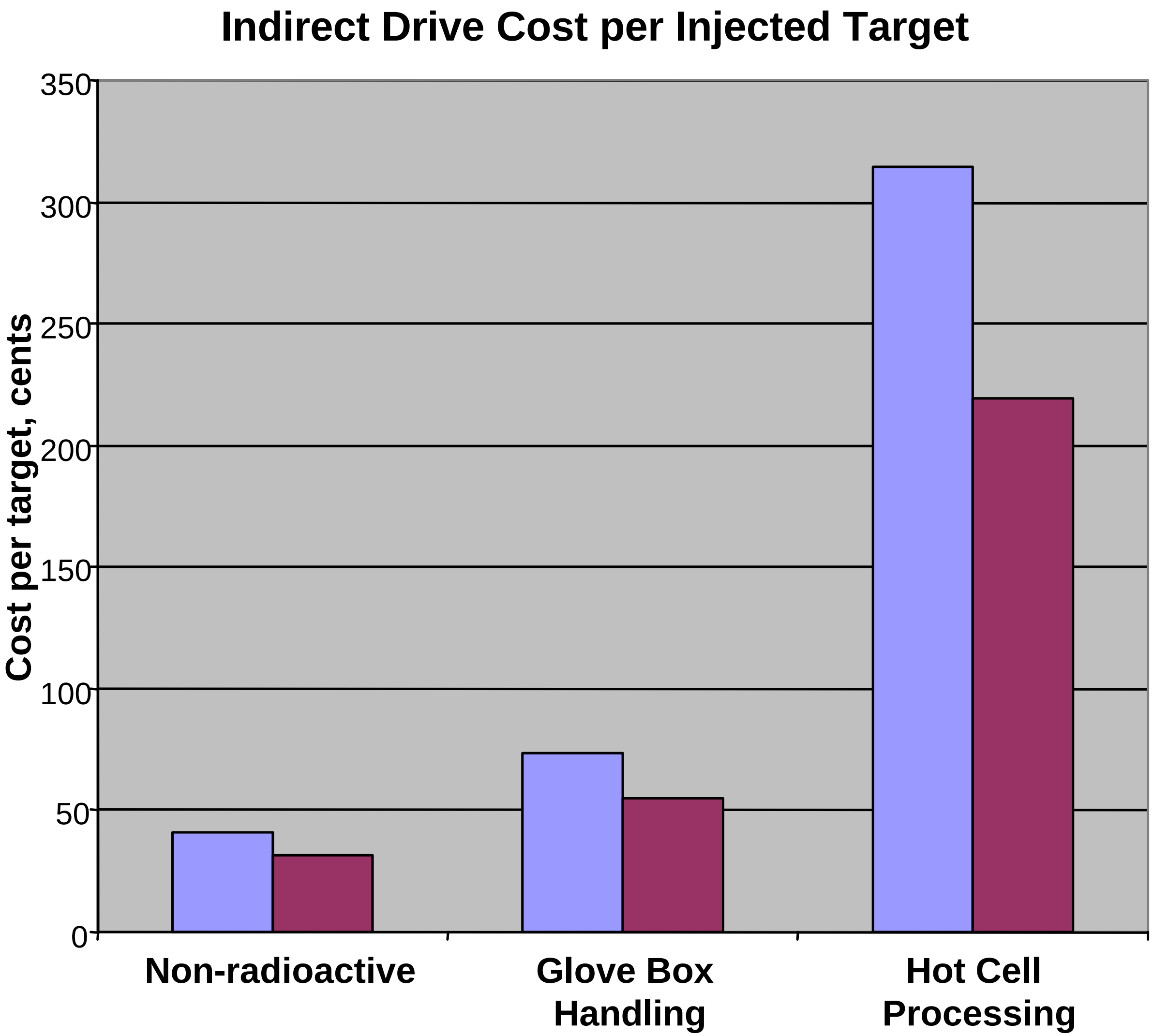
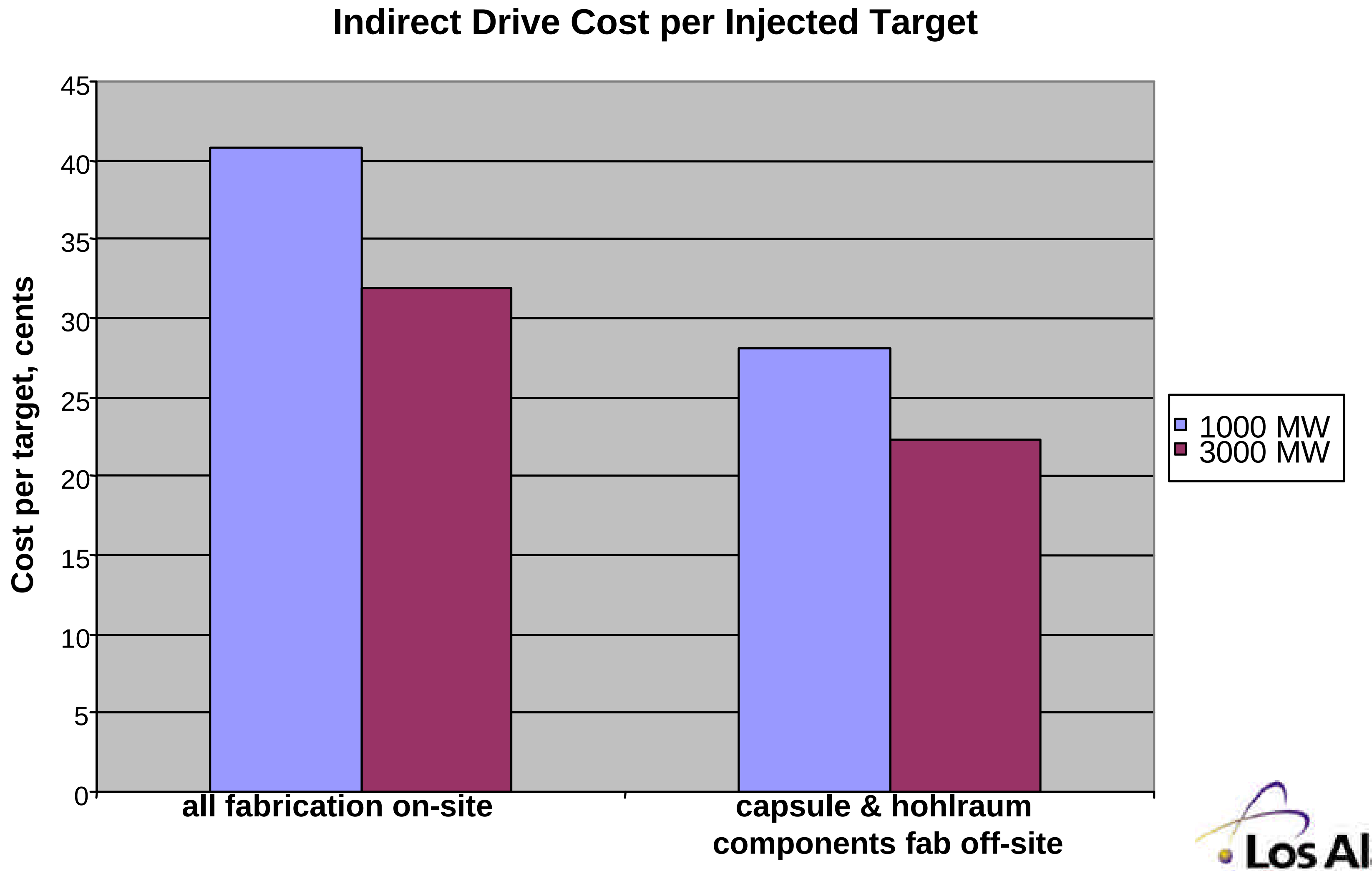
Costs would be higher with radioactive hohlraum fabrication



Preliminary estimates assume nominal cost factors of

Glovebox		
	Capital	**2X**
	Operating	**1.5X**
Hot Cell		
	Capital	**10X**
	Operating	**3X**

Costs would be lower with offsite hohlraum manufacture and with higher plant power



Single use for hohlraum materials appears preferabl

Laila El-Guebaly recommended single use of low cost materials for the following reasons:
-Hohlraum walls represent less than 1% of total waste stream
-Recycling produces high level waste
-Recycling requires remote handling in target fabrication
-Au/Gd materials cost $80 M/year
-Other materials are much cheaper and still effective

Ref: El-Guebaly ARIES presentation, October 2002

Single use results in lower cost of electricity

Summary - Target costing study

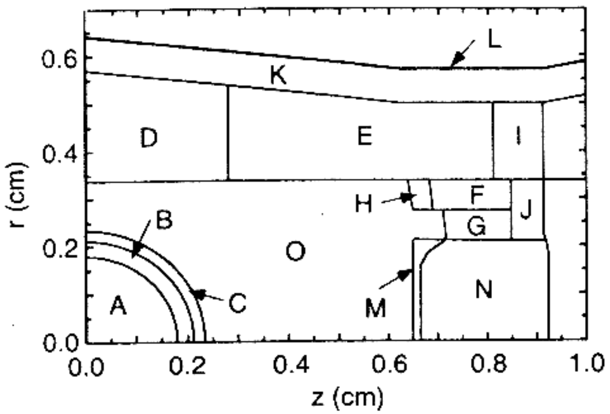
- A first cut at cost of target fab including hohlraum
- Cost is evenly split between capital and operating
- Major capital equipment is LCVD to fab hohlraum components
- Reference cost is 41¢ (For 1000 MWe plant and on site fab)
- Lowest cost estimate is 22¢ (For 3000 MWe plant and central fab)
- Radioactive handling (recycling) would increase costs substantially
- We have a modeling structure that is easily updated as new process information becomes available

Final selection of materials requires and overall systems view

- -Fabricability
- -Target energetics
- -Materials separation
- -Radioactive inventory and handling
- -Materials compatibility
- -Injectability

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

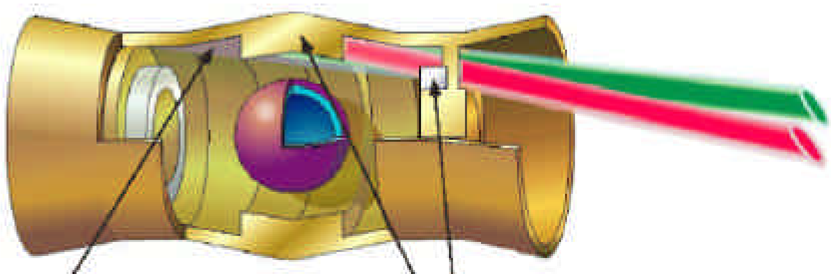
A:	DT	0.0003 g/cc
B:	DT	0.25 g/cc
C:	$Be_{0.995}Br$	1.845 g/cc
D:	Au	0.032 g/cc
E:	$CD_2Au_{0.03}$	0.011 g/cc
F:	Fe	0.064 g/cc
G:	Fe	0.083 g/cc
H:	$CD_2Au_{0.03}$	0.032 g/cc
I:	AuGd	0.1 g/cc
J:	AuGd	0.26 g/cc
K:	AuGd	0.099 g/cc
L:	AuGd	13.5 g/cc
M:	Al	0.055 g/cc
N:	AuGd "sandwich"	0.1/1.0/0.5
O:	D_2	0.001 g/cc



***Nuclear Fusion* 39, 883**

… Simplification and material substitutions are needed to reduce complexity of the target

Final selection of materials requires an overall systems view



- -Fabricability
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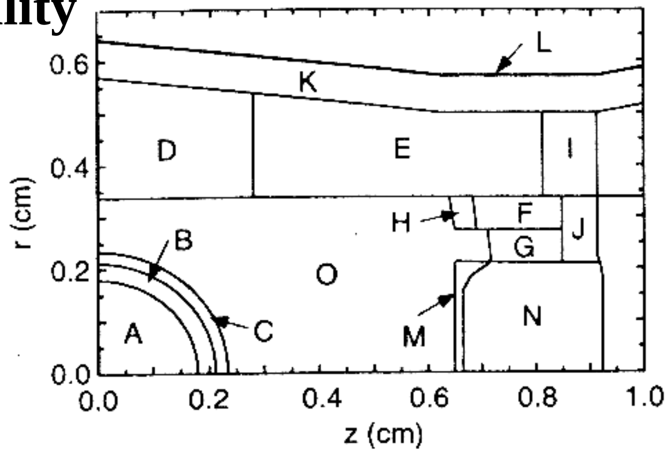

(Nuclear Fusion 39, 883)

Part	Material	Alternate Materials
A	DT	--
B	DT	--
C	$Be_{0.995}Br_{0.005}$	Polystyrene (CH)
D	Au	--
E	$(CD_2)_{0.97}Au_{0.03}$	--
F	Fe	Au-doped CH foam
G	Fe	Au-doped CH foam
H	$(CD_2)_{0.97}Au_{0.03}$	--
I	AuGd [high-Z only]	*Various* - Au, Pb/Ta, Pb/Ta/Cs, Hf/Hg/Xe/Kr, Pb/Hf
J	AuGd sandwich (high-Z only)	*Various* - Au, Pb/Ta, Pb/Ta/Cs, Hf/Hg/Xe/Kr, Pb/Hf
K	AuGd [high-Z only]	*Various* - Au, Pb/Ta, Pb/Ta/Cs, Hf/Hg/Xe/Kr, Pb/Hf
L	AuGd [high-Z only]	*Various* - Au, Pb/Ta, Pb/Ta/Cs, Hf/Hg/Xe/Kr, Pb/Hf
M	Al	CH or Doped CH
N	AuGD	*Various* - Au, Pb/Ta, Pb/Ta/Cs, Hf/Hg/Xe/Kr, Pb/Hf
O	D_2	He gas

Hohlraum wall materials selection affects the target energetics

Material	$E_{wall} / E_{wall\ AuGd}$
Au/ Gd (50 :50)	1.00
Au	1.25
Pb	1.28
Hg	1.26
Ta	1.25
W	1.25
Pb/ Ta (50:50)	1.08
Pb/ Ta (70:30)	1.06
Hg/ Xe (50:50)	1.18
Pb/ Ta/ Cs (50:20:30)	1.01
Pb/ Ta/ Cs (45:20:35)	1.01
Hg/ Ta/ Cs (45 :20:35)	1.03
Hg/ W/C s (45:20 :35)	1.04
Pb/ Hf (70:30)	1.04
Pb/ Hf/ Xe (45:20:35)	1.00
Th/ Bi/ Ta/ Sm/ Cs	0.82
U/P b/ Ta/ Dy/ Nd	0.76

Uranium and thorium may be undesirable due to fission radioactivity

Pb/Hf has good performance, simplicity and low cost

Ref: D. A. Callahan-Miller and M. Tabak, "Progress in target physics and design for heavy ion fusion," Physics of Plasmas 7 (2000) 2083-2091

Moir's screening of high Z materials leaves many candidates

Z	Element	Comments	separation methods
~~96~~	~~**Cm**~~	**makes fission products, unstable, alpha emitter**	**React with beryllium**
~~95~~	~~**Am**~~	**"**	**"**
~~94~~	~~**Pu**~~	**"**	**"**
~~93~~	~~**Np**~~	**"**	**"**
~~92~~	~~**U**~~	**"**	**"**
~~91~~	~~**Pa**~~	**"**	**"**
~~90~~	~~**Th**~~	**"**	**"**
~~89~~	~~**Ac**~~	**unstable, alpha emitter**	**"**
~~88~~	~~**Ra**~~	**alpha emitter**	**"**
~~87~~	~~**Fr**~~	**unstable**	**"**
~~86~~	~~**Rn**~~	**alpha emitter; short half-life too costly ~$300/target**	**volatility**
~~85~~	~~**At**~~	**"**	
~~84~~	~~**Po**~~	**unstable, alpha emitter**	
83	**Bi**		**centrifuge**
82	**Pb**		**"**
81	**Tl**		**"**
80	**Hg**		**volatility, centrifuge**
~~79~~	~~**Au**~~	**too costly ?**	**centrifuge**
~~78~~	~~**Pt**~~	**too costly ?**	**"**
~~77~~	~~**Ir**~~	**too costly ?**	**"**
~~76~~	~~**Os**~~	**too costly ?**	**"**
75	**Re**		**"**
74	**W**		**"**

Continued next page

*Ralph Moir, Flibe coolant cleanup and processing in the HYLIFE-II inertial fusion energy power plant, UCRL-ID-143228 (2001)

GENERAL ATOMICS
AND AFFILIATED COMPANIES

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Additional candidate high Z material

73	**Ta**		**TaF_5, volatility, electrochemical**
72	**Hf**		**HfF_4, electrochemical**
71	**Lu**		**reductive extraction/metal transfer = Bi extraction**
70	**Yb**		**YbF_3, Bi extraction**
69	**Tm**		**TmF_3, Bi extraction**
68	**Er**		**ErF_3, Bi extraction**
67	**Ho**		**HoF_3 Bi extraction**
66	**Dy**		**DyF_3, Bi extraction**
65	**Tb**		**TbF_3, Bi extraction**
64	**Gd**		**GdF_3, Bi extraction**
~~63~~	~~**Eu**~~	**too costly**	**EuF_3, Bi extraction**
62	**Sm**		**SmF_3, Bi extraction**
~~61~~	~~**Pm**~~	**unstable**	**PmF_3, Bi extraction**
60	**Nd**		**NdF_3, Bi extraction**
59	**Pr**		**PrF_3 PrF_4, Bi extraction**
58	**Ce**		**CeF, Bi extraction**
57	**La**		**LaF_3, Bi extraction**
~~56~~	~~**Ba**~~		**not volatility, not centrifuge, BaF_2, chemically similar to LiF_2**
55	**Cs**		**CsF, volatility,**
54	**Xe**		**volatility**

*Ralph Moir, **Flibe coolant cleanup and processing in the HYLIFE-II inertial fusion energy power plant, UCRL-ID-143228 (2001)**

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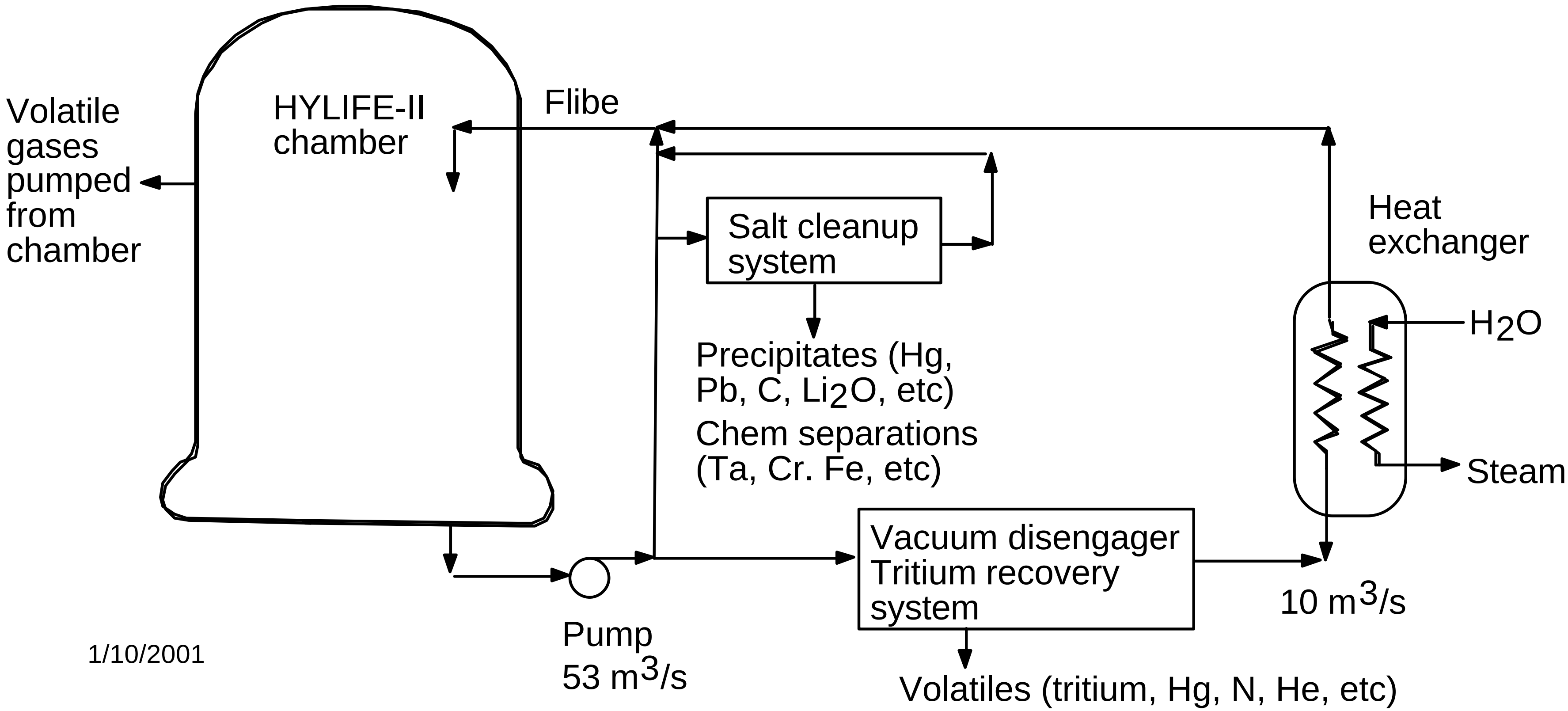
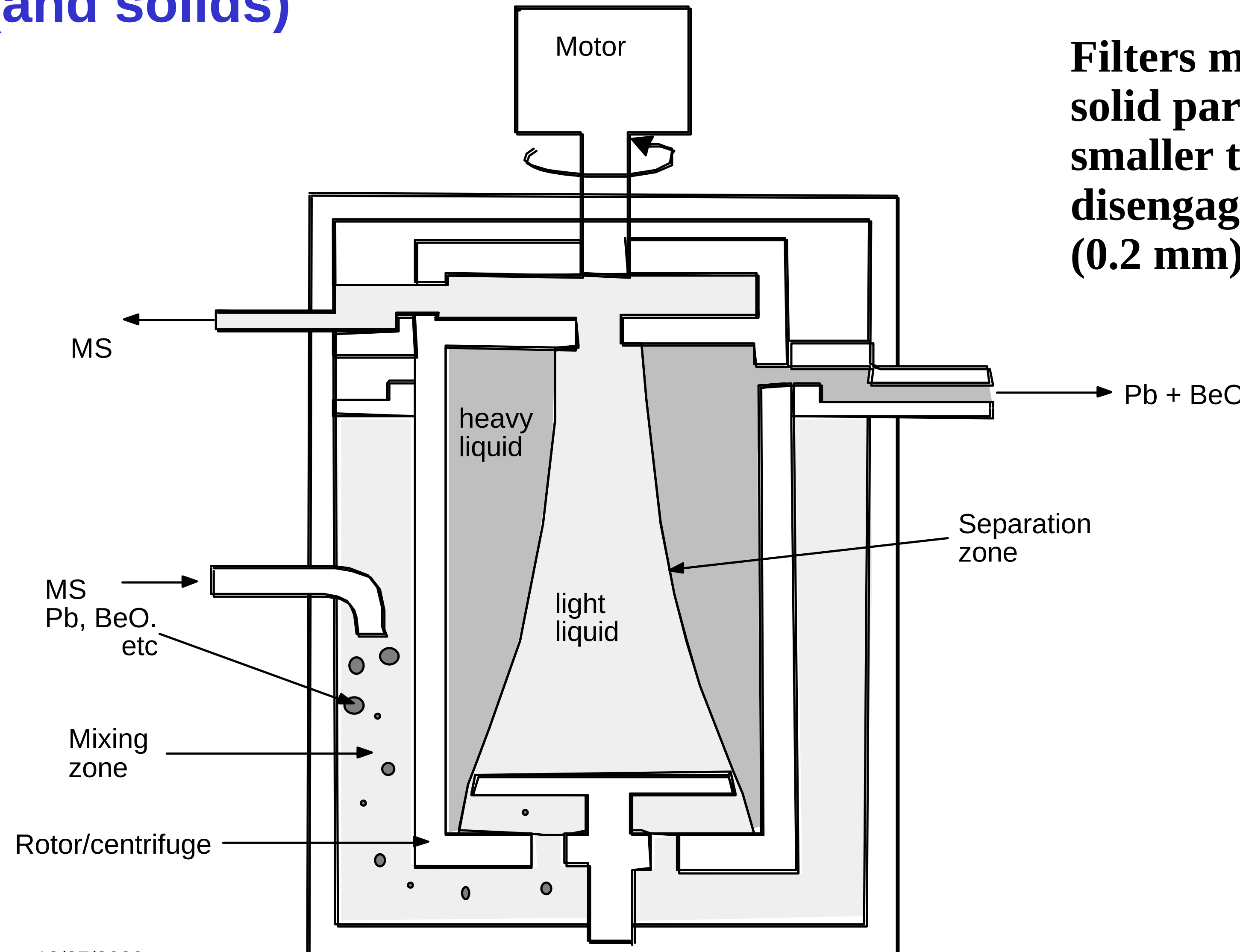
Volatile, centrifugal and chemical processes are used for impurity separation*



1/10/2001

*Ralph Moir, **Flibe coolant cleanup and processing in the HYLIFE-II inertial fusion energy power plant, UCRL-ID-143228 (2001)**

A centrifuge will effectively remove insoluble liquids (and solids)



Filters may remove solid particulates smaller than vacuum disengager openings (0.2 mm)

Flow rate ~ 1 l/s

Target materials selection summar

Pb/Hf appears to be acceptable but not necessarily optimum

-Room temperature fabrication

-Good energetics

-Low cost materials

-Some others are better energetically (e.g. U and Th cocktails)

-Some are more easily separated from Flibe (e.g. Hg and Kr)

-Pb may be separated by centrifuge

-Hf requires electrochemical separation by first contacting with Be

Specific suggested testing

-Carbon separation experiments using hydrogen purge

-Strength tests of low density LCVD materials

We propose a qualitative materials ranking by elemen

The following factors will be considered
-Target fabrication
-Target injection
-Flibe purification
-Target energetics
-Material costs
-Others

Element pairs will be suggested for further analysis

Ultimately, target materials selection must be based on a cost analysis.
A thermomechanical process flow simulation can provide input to the cost model.

Backup slides

GENERAL ATOMICS
AND AFFILIATED COMPANIES

Schafer

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

Step	Methods	Comments/Issues
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 high-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

.... Many of the steps above have issues associated with remote handling, dose rate, CTE mismatches on assembly

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Approach to cost estimating of the TFF

- **What this is <u>not</u>:**
  - **a 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 is 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 <u>*nth of a kind*</u> 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**

Target Mass Production

Classic "chemical engineering approach" to Target Fabrication Facility (TFF) design

The TFF is a chemical process plant

PFD's

Mass-Bal. FS's

E-Bal. FS's

Prel. Equip. Types/Sizes

Preliminary TFF Layout
-Floor Space
-Height Reqs.

"Baseline Process"

Capsule Manufacture

Microencapsulation
Int. Polycondensation
Sputter Coating

Filling

Permeation
Cooldown
DT Removal
Transfer

Layering

Fluidization
E by IR/RF
Removal

Injection

Target Assembly
Removal & Recycle
Prop. Gas R&R
Tracking

"Alternate Process"

Microencapsulation For Mandrels

Fluidized Bed Ctg.
-GDP
-Solution

IRE Support

Demonstrate a credible pathway to producing 500,000 per day

Status

- **Completed preliminary layout and equip. sizing**
- **Costing model for indirect drive target**
- **Cost results encouraging!**
- **Planning review & more details**

.... Important step in showing feasibility of target fabrication

Use of plastic vs FLIBE outer shells

Using plastic rather than flibe for the target shell is a trade-off between recovery of much larger amounts of hydrocarbon material from the chamber, and the potentially lower cost of the targets. Dr Peterson points out that since we must have at least some plastic due to capsules and support membranes, this appears to be more of an optimization question than a viability question.

some of the advantages to plastic outer hohlraum shells would be:

(1) elimination of radioactive handling in the hohlraum production process, and,
(2) ability to produce the hohlraums at a central large-scale facility (instead of at each reactor site) - thus improving the economies of scale and reducing costs significantly

the poly-CH2 plastic shell would char to produce solid carbon particulates suspended in the FLIBE - these char particulates could potentially be controlled in 2 ways:

(a) filtration (they may be fairly fine and it may be tough to develop a sufficiently durable filtration media), or,
(b) gasification - the hydrogen-bearing reducing conditions in the reactor loop should favor (thermodynamically) the formation of light hydrocarbons such as CH4, etc, which would separate easily as gases from the molten FLIBE
- the question is whether mass-transfer (getting the hydrogen to the carbon surface) or kinetics (is it hot enough?) will overly limit the gasification reaction rate - but the process is favored by both the high diffusivity of hydrogen and the high surface area of the carbon char - it may be that these factors coupled with long residence times can maintain reasonably low equilibrium concentrations of solid char in the FLIBE

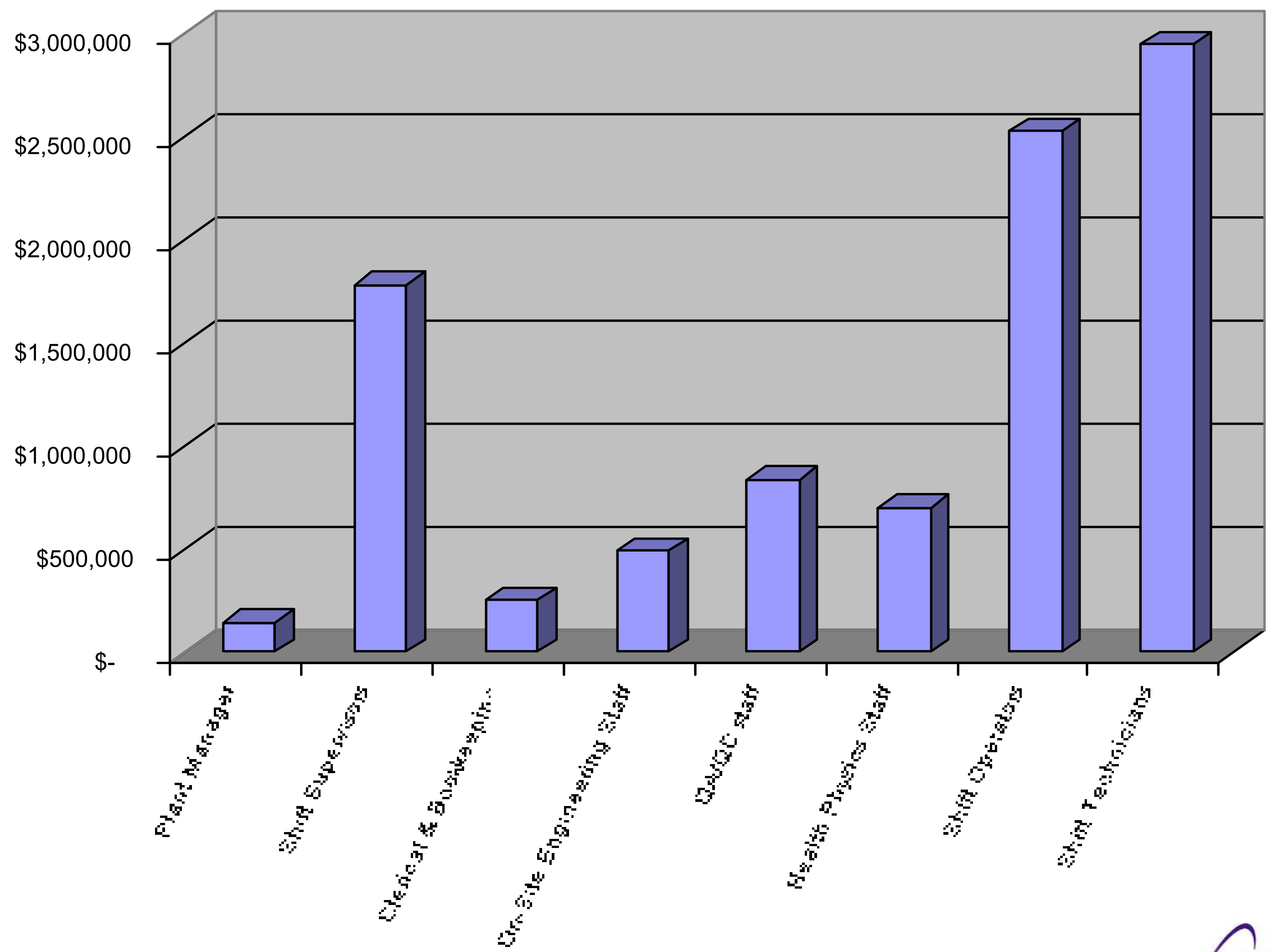
what we would need therefore is some initial data from a simple lab-scale test - wherein some plastic shards (such as poly-propylene) are immersed in FLIBE at typical loop temperatures and varying hydrogen partial pressures to determine the evolution of C (presumably as gaseous hydrocarbons) from the FLIBE as a function of time - this could be done in a standard thermogravimetric analysis (TGA) set-up with a GC outlet gas analyzer

Target Fabrication Facility capital costs are treated as an annualized expense

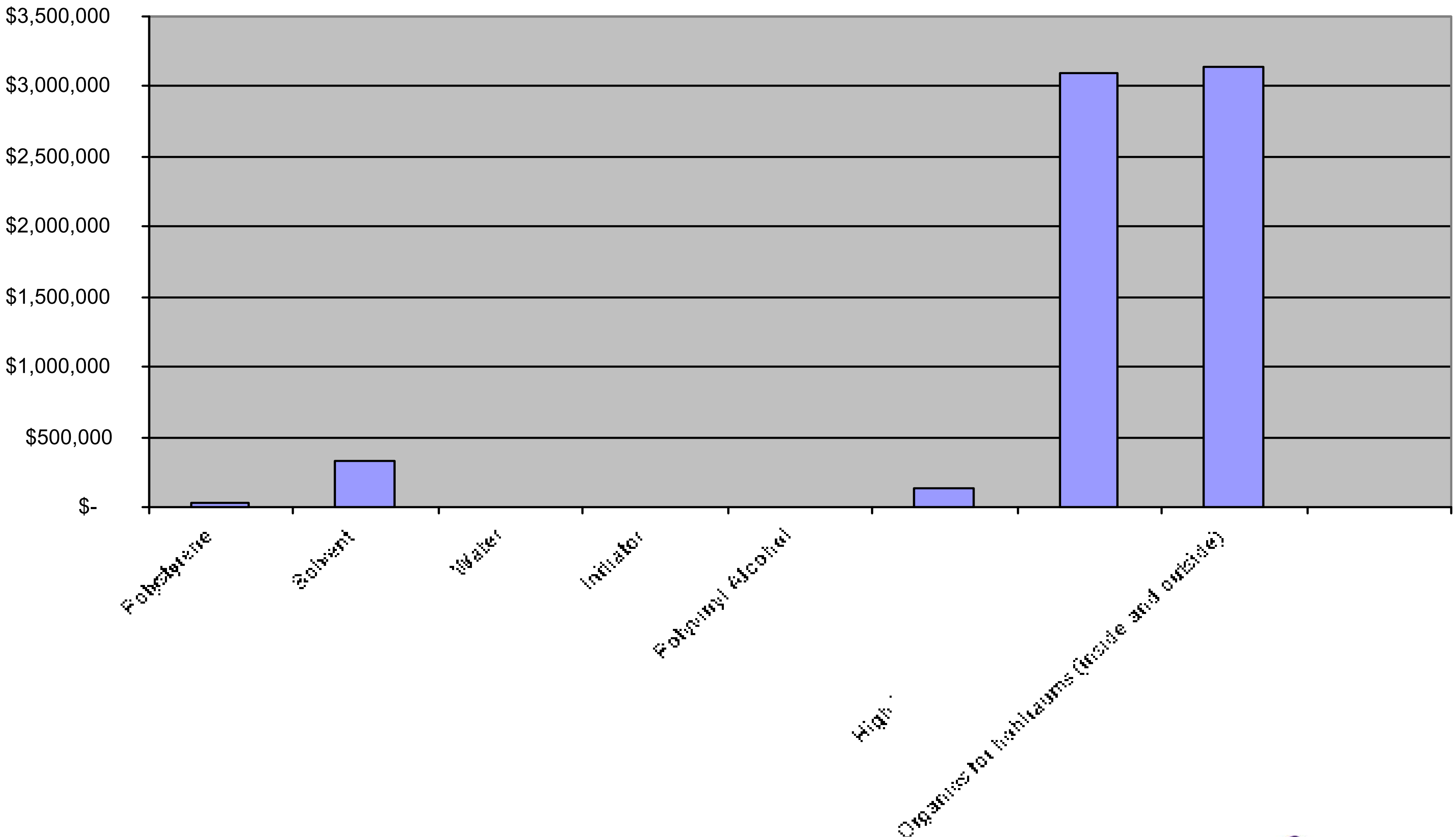
- Design and construction costs are typically paid for by a combination of
  - Debt (bonds)
  - Preferred dividend stock
  - Common equity stock
- Standard financial treatments (Ref. 1) result in a levelized "fixed charge rate" of expressing the annualized expense or repaying the design and construction costs to these three sources.
- The fixed charge rate is calculated using inputs ranging from interest rates, stock returns, tax rates, depreciation schedules, etc.
- For a 30-year facility with typical financial assumptions, the fixed charge rate is estimated to be 12.5% per year.

Ref. 1: A Reference Data Base for Nuclear and Coal-fired Powerplant Power Generation Cost Analysis, DOE/NE-0095, 1988.

Operating Labor Costs for Polystyrene Target Production

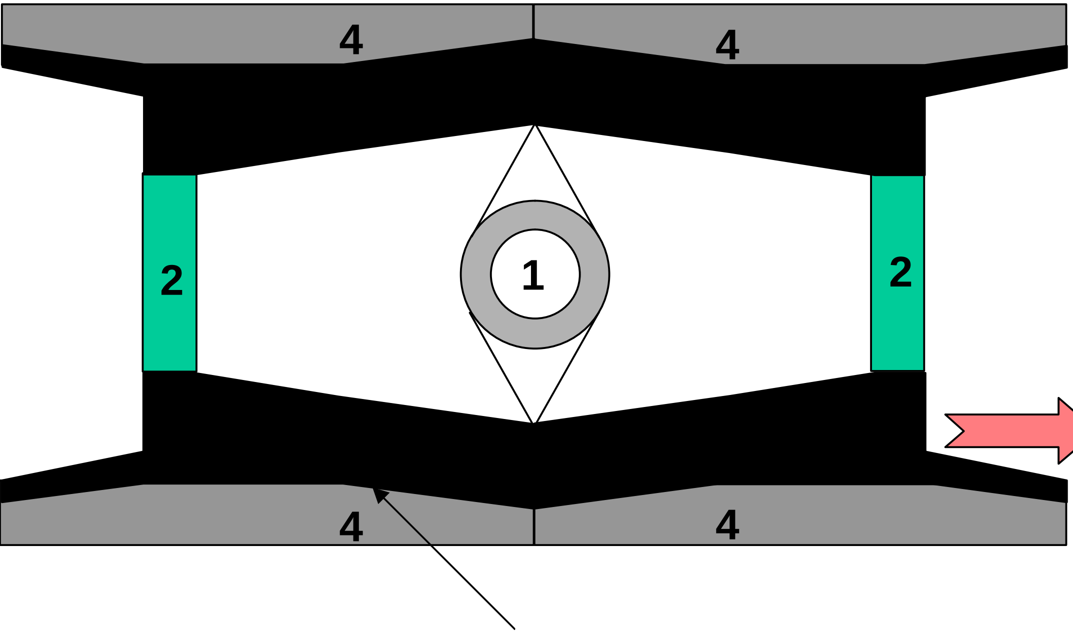


Materials Costs (consumables) for Polystyrene Target Production



Target fabricator's vision of an "ideal" distributed radiator target

Functionally - 4 Components
1. Capsule
2. Beam Block
3. Absorber/Radiator
4. Structure & Radiation Case

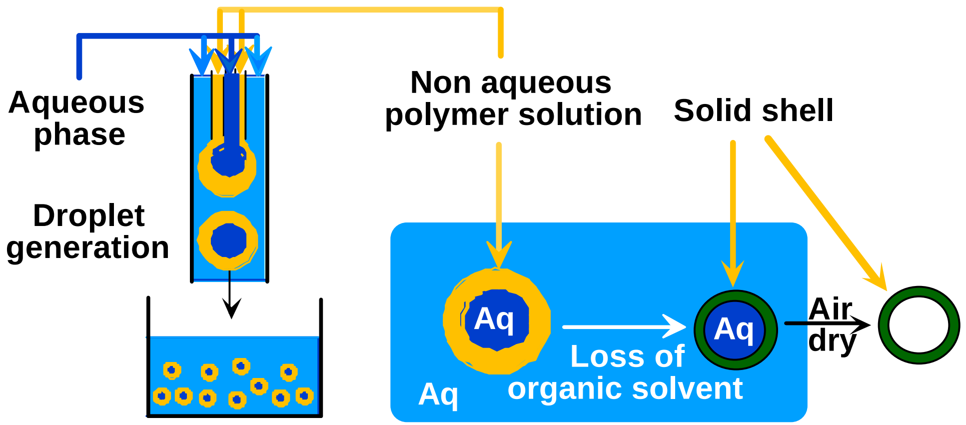


High Z surface
supplied by physical vapor deposition

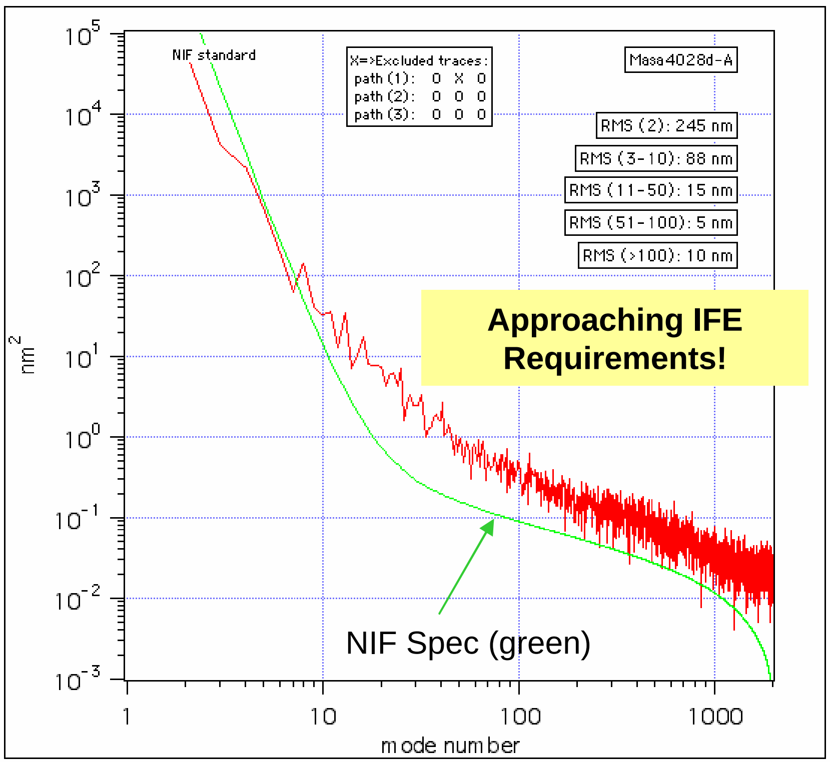
Graded density
& composition

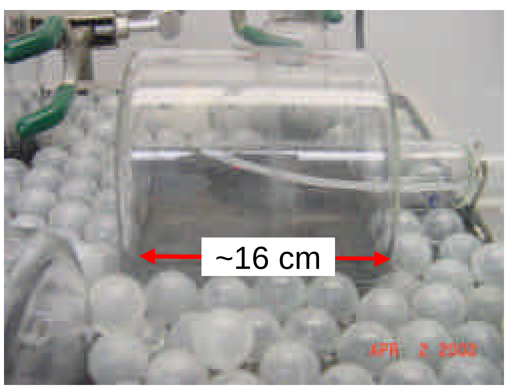
Direct capsule fabrication by microencapsulation

Schematic of microencapsulation



Power spectrum of 4.6mm CH capsule, 45 µm wall, OOR <1% of radius, NC <3% of wall, rate 36/minute (M. Takagi)

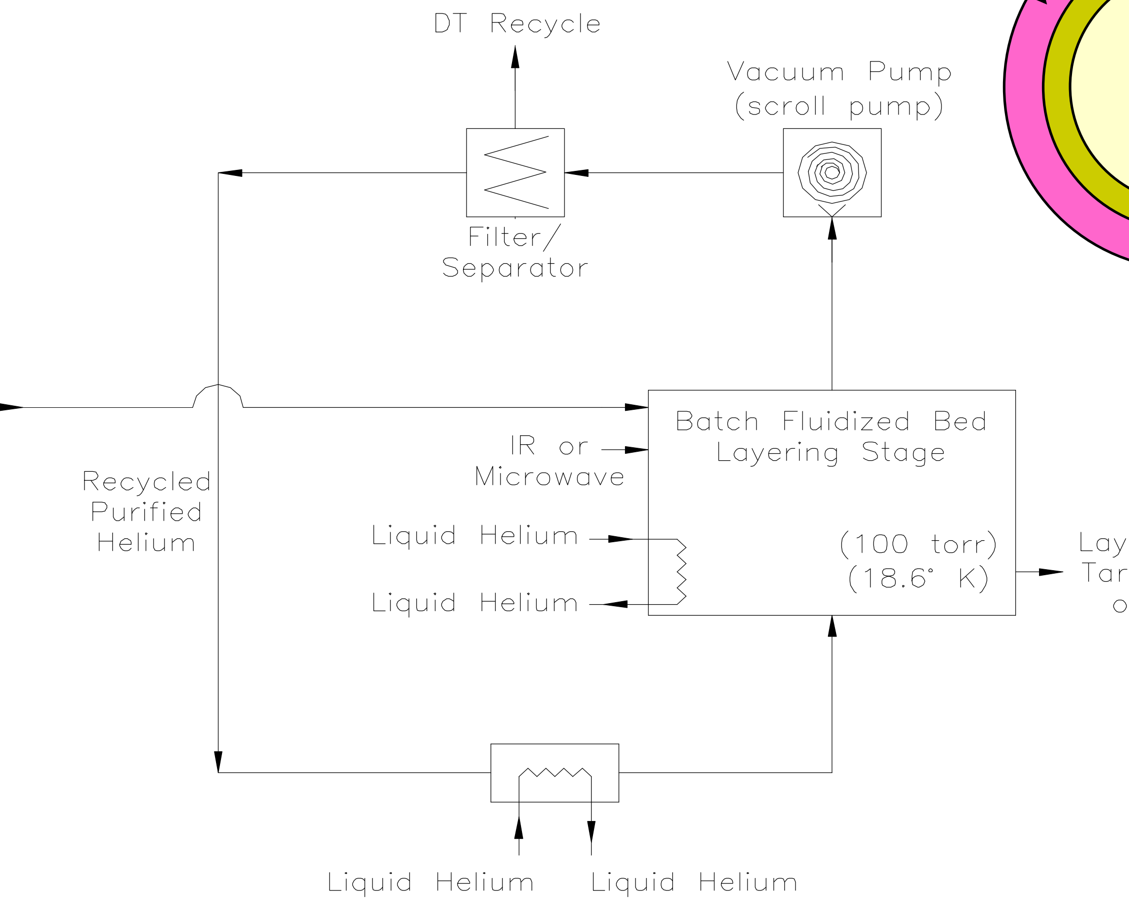


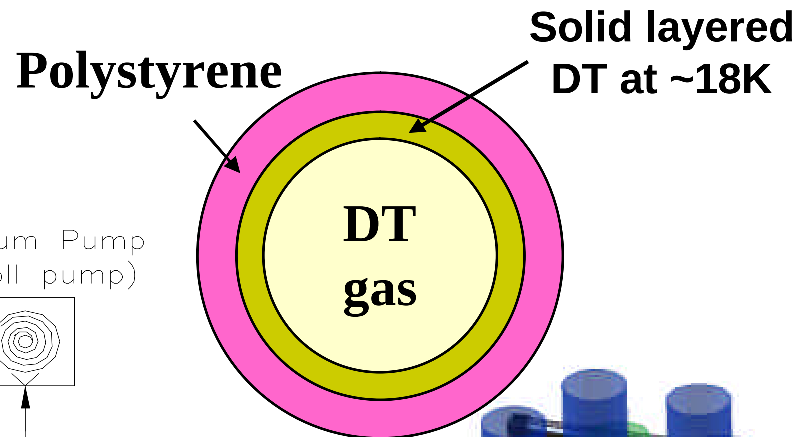


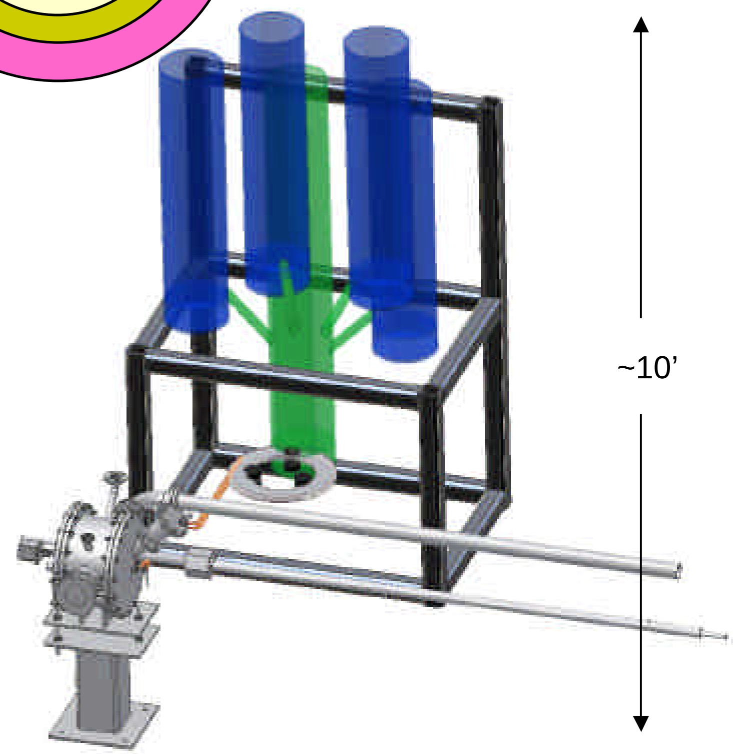
Laboratory scale rotary contactor

Microencapsulation may be most cost-effective pathway...

Cryogenic fluidized bed layering & transfer to assembly station





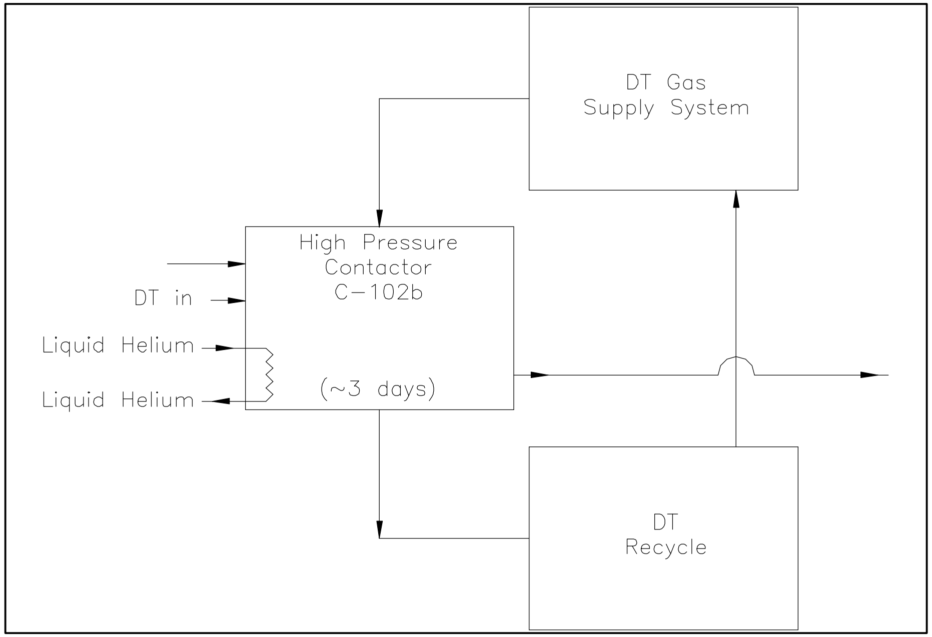


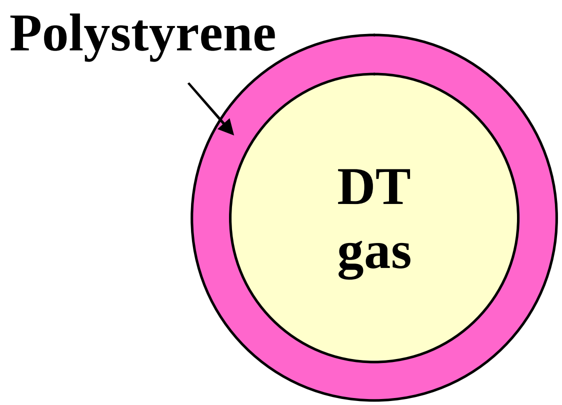
Ethanol exchange and vacuum drying occur in contactor

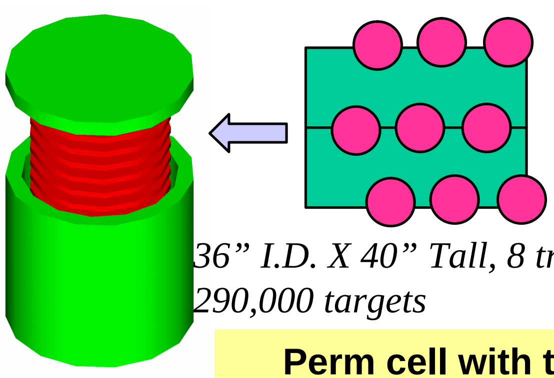
- Sequenced ethanol solution begins drying process
- Ultrasound nucleates vapor in shell
- Vacuum completes the drying process
- Ethanol rinse and vacuum drying occur in same contactor

Production scale contactor

DT filling in a permeation cell

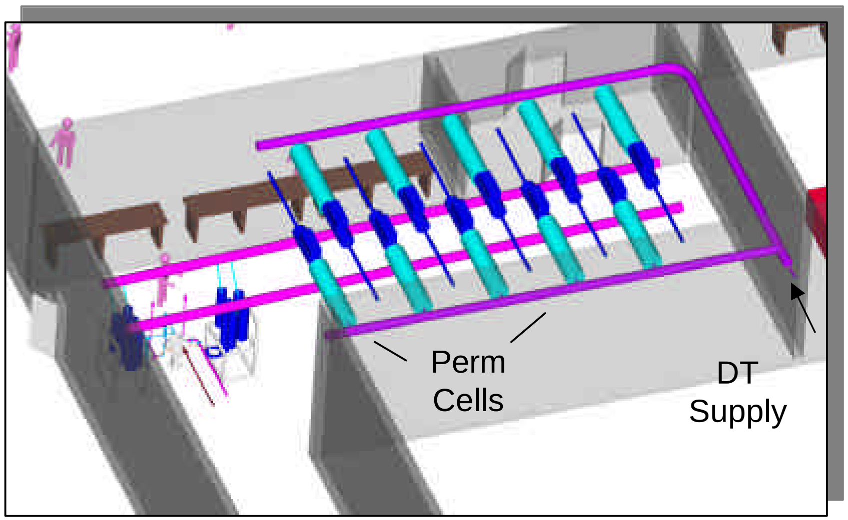






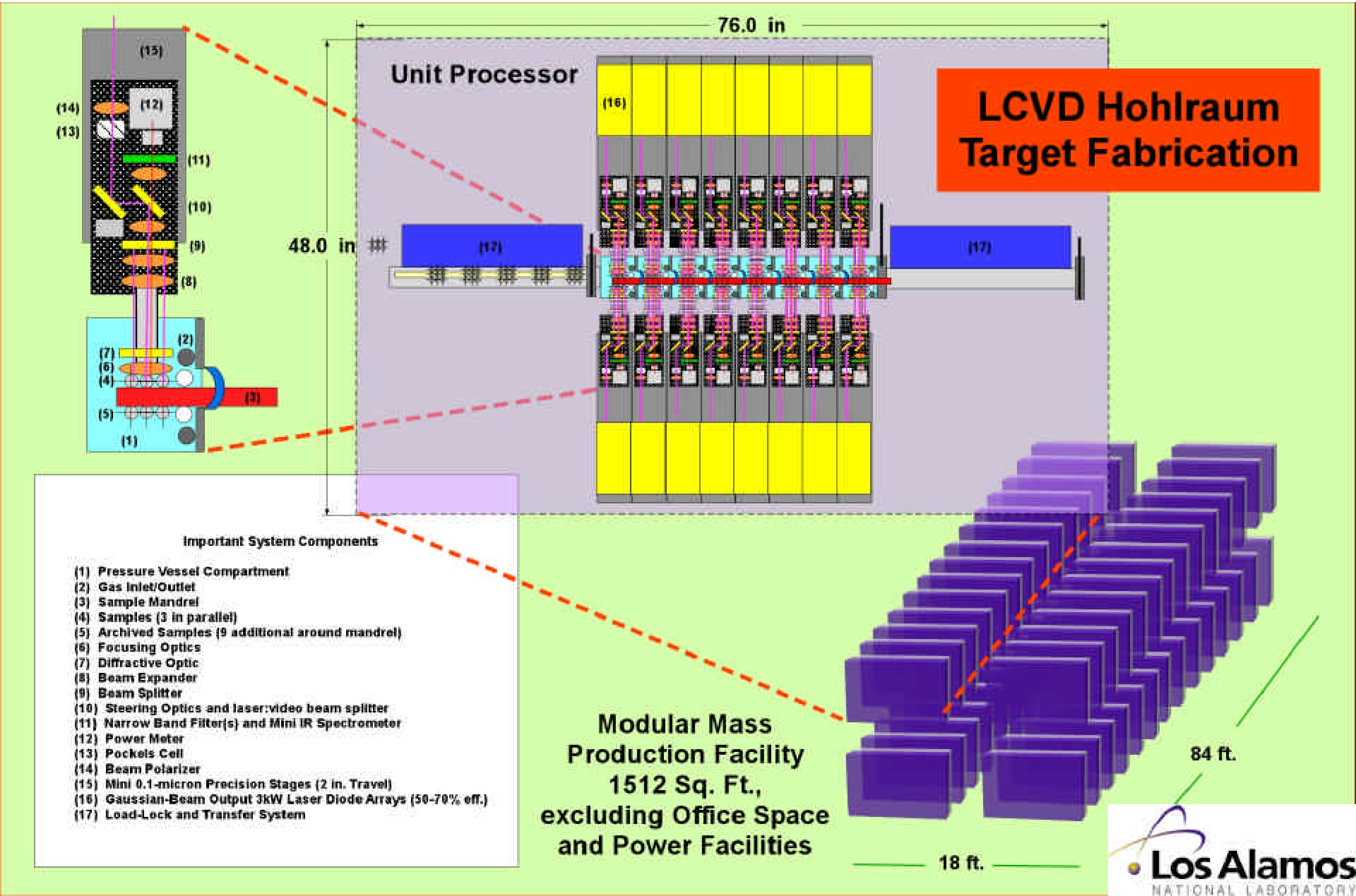
36” I.D. X 40” Tall, 8 trays,
290,000 targets

Perm cell with trays



Tritium Systems

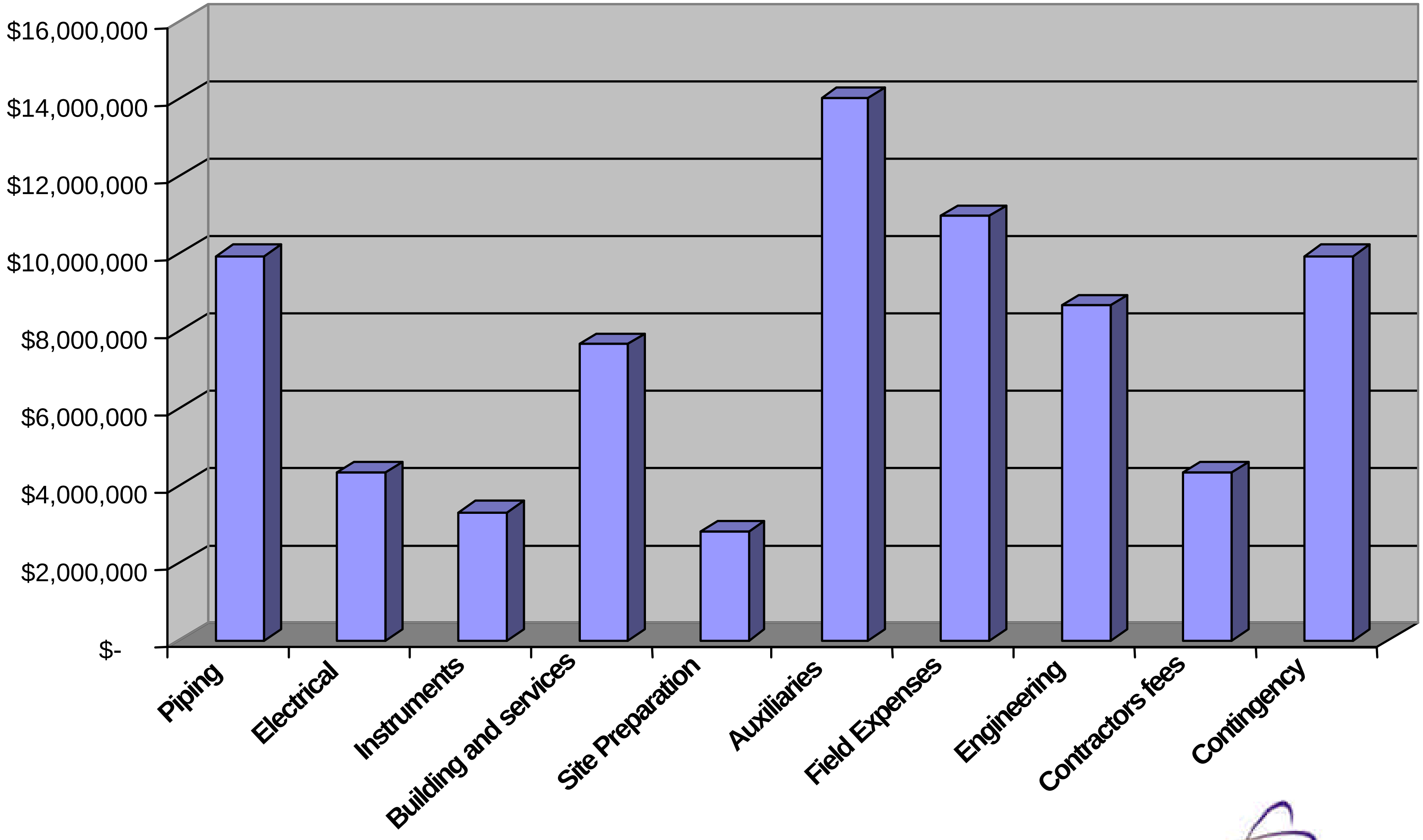
Laser chemical vapor deposition allows very low density high-Z materials to be fabricated in-situ



The number of LCVD unit processors are estimated based on axial growth rates

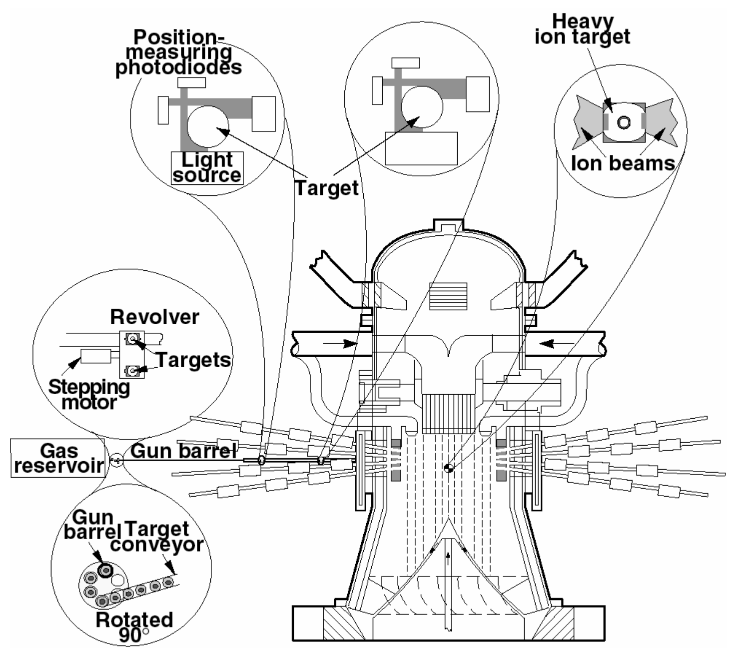
- The total volume of all low-density hohlraum material is approximately 2100 mm^3/target, based on current designs.
- Assume 100x100 spot arrays for each beam, with 12 micron spacing between fibers→1.4 mm^2 cross-sectional area of each "pixel."
- Axial growth rates on the order of 2mm/s→ 2.8 mm^3/s volumetric growth rate for each Hohlraum.
  - This growth rate is typical, and potentially underestimates the actual growth rate by an order of magnitude.
- Each Hohlraum takes 750s to grow→12.5 minutes. Load-lock and Transfer times are assumed to be negligible in comparison.
- However, each Unit Processor grows 48 samples simultaneously, with 192 samples per load-lock cycle; 112 Unit Processors are operating in parallel, so 5376 hohlraums are being made simultaneously.
- The production rate of the Facility is 7 Hohlraums/s→~17% overcapacity

Balance of plant costs for target fab are also significant



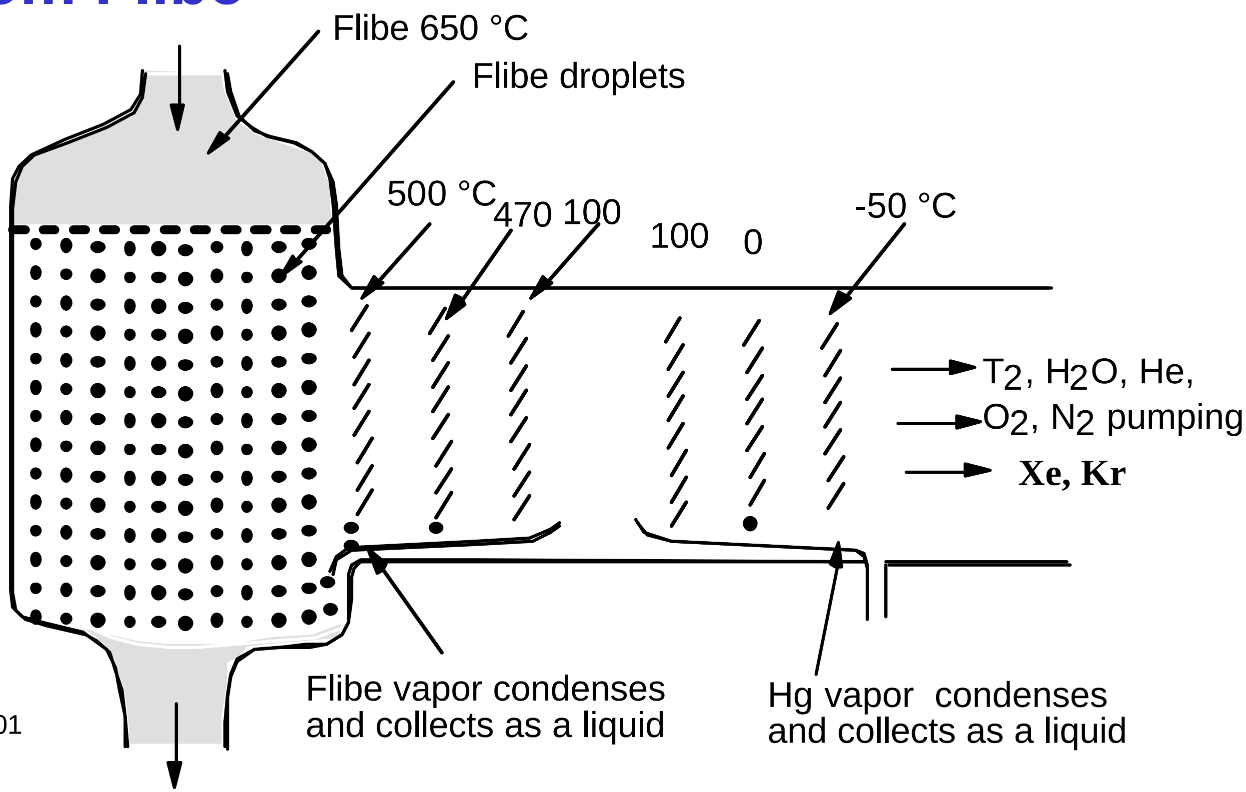
Target injection costs are estimated at less than 2 ¢ each

- 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

Mercury, xenon, and krypton are volatile and easily removed from Flibe*



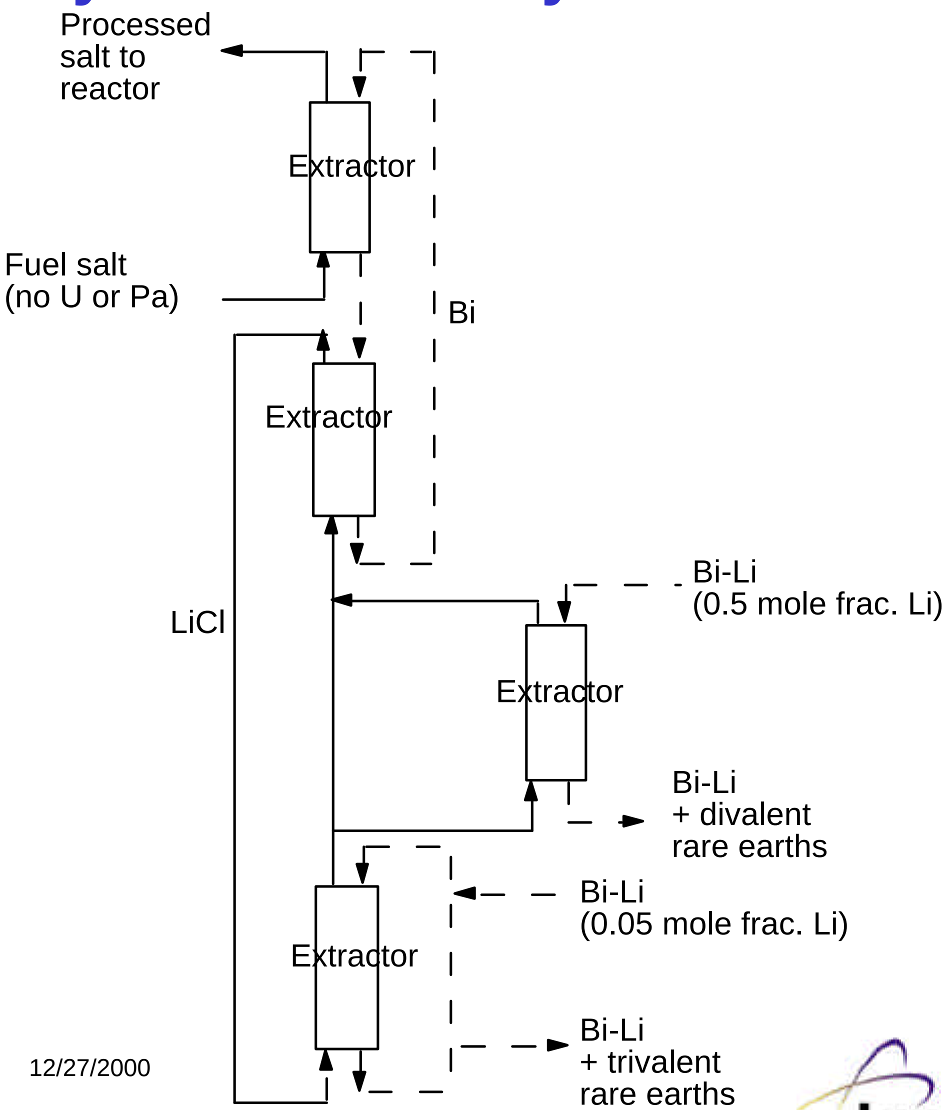
1/19/2001

Flow rate up to 10,000 l/s

This allows much lower impurity concentrations and lower separation costs

***Ralph Moir, Flibe coolant cleanup and processing in the HYLIFE-II inertial fusion energy power plant, UCRL-ID-143228 (2001)**

Lanthanid -Fluorides may be removed by a bismuth extraction process



Flow rate

~ 0.1 l/s

***Ralph Moir, Flibe coolant cleanup and processing in the HYLIFE-II inertial fusion energy power plant, UCRL-ID-143228 (2001)**

GENERAL ATOMICS
AND AFFILIATED COMPANIES

Schafer

Oxygen may be removed with HF or $_2$ purge*

Oxygen in Flibe produces BeO
Solubility is 125 wppm
For 1000 g/day oxygen, 75 days accumulation is allowed
Small slipstream may be processed with H2 or HF purge

Flow rate ~ 0.1 l/s

It may be possible to remove carbon particulates with an H2 purge producing hydrocarbon gases (experiments needed)

*Dai Kai Sze - e-mail to Per Peterson, September 2002

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Order of magnitude cost estimates for cleanup processes

Process	Cost est.	Process rate, PR	Cost scaling	Inventory/ concentration /holdup time
Volatility, Hg	$\$10^7$	100 *l*/s	$(PR)^{0.6}$	0.17 kg/7 wppm/3.3 hr
Centrifugation, Pb	$\$10^7$	1 *l*/s	$(PR)^{0.6}$	1740 kg/700 wppm/13.9 d
Reductive extraction, Gd	$\$2\times10^7$	0.1 *l*/s	$(PR)^{0.6}$	17,400 kg/7000 wppm/139 d
Volatility, Xe	$\$5\times10^6$	1000 *l*/s	$(PR)^{0.6}$	0.017 kg/0.7 wppm/20 min.

*Ralph Moir, Flibe coolant cleanup and processing in the HYLIFE-II inertial fusion energy power plant, UCRL-ID-143228 (2001)