Electricity Production from Laser Fusion Reactors: *Technology Aspects of Power Conversion Chambers*

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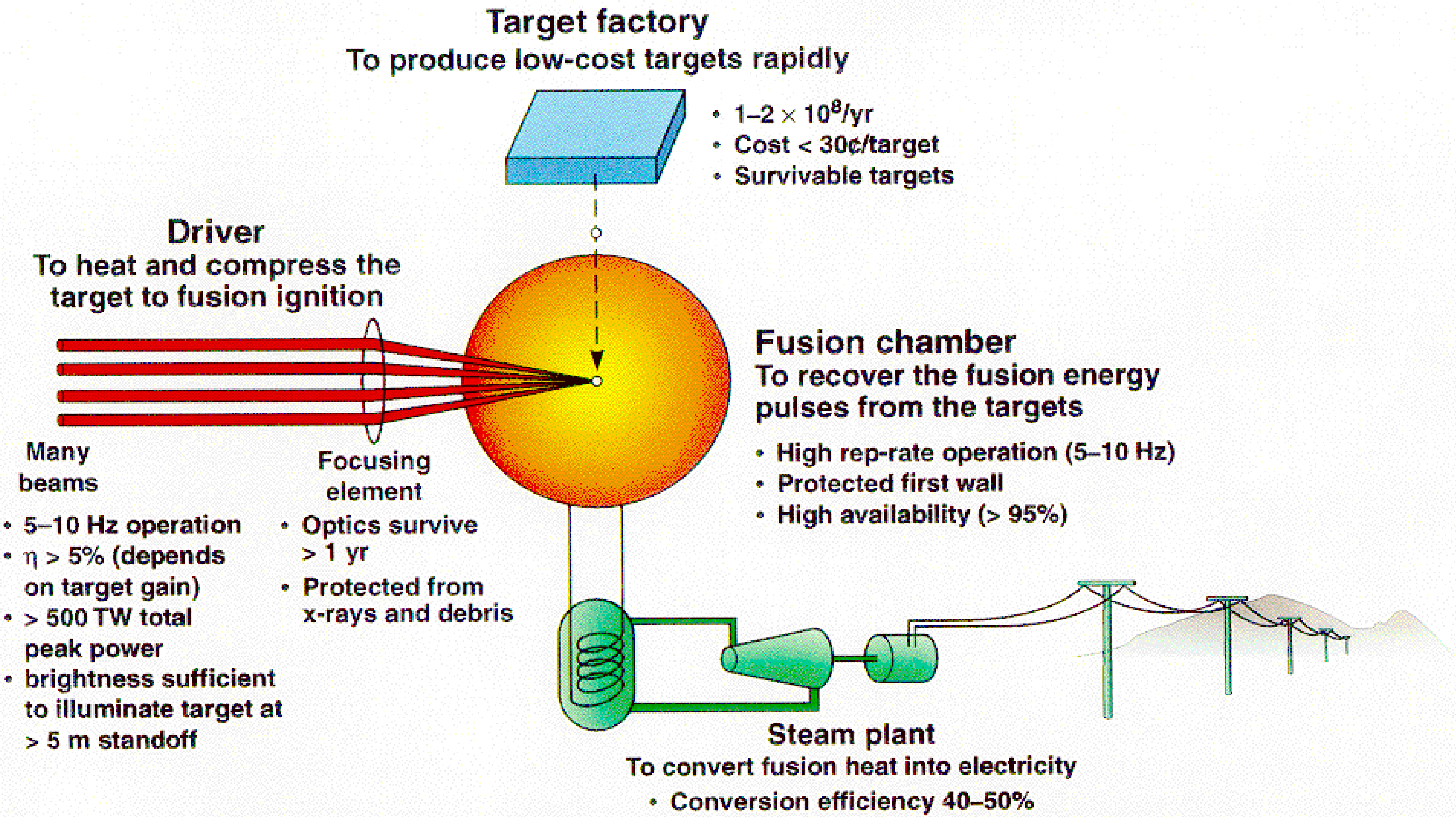
SPIE-99

November 1, 1999

Osaka, Japan

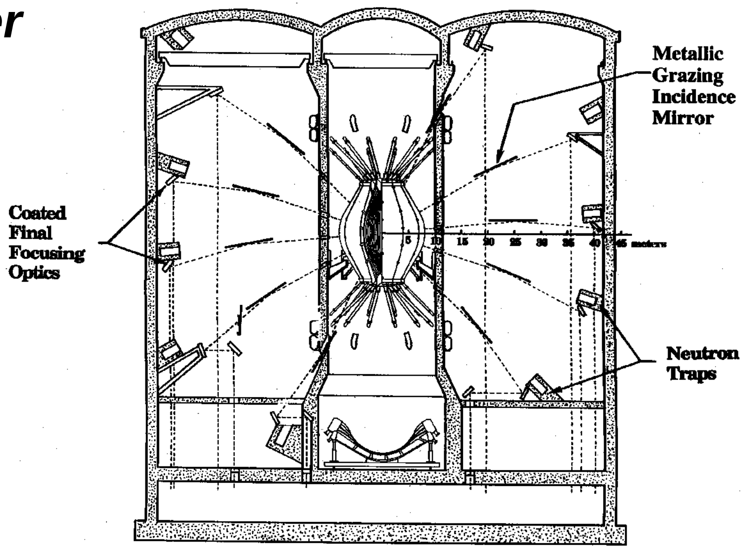
Inertial fusion energy (IFE) power plants of the future will consist of four parts



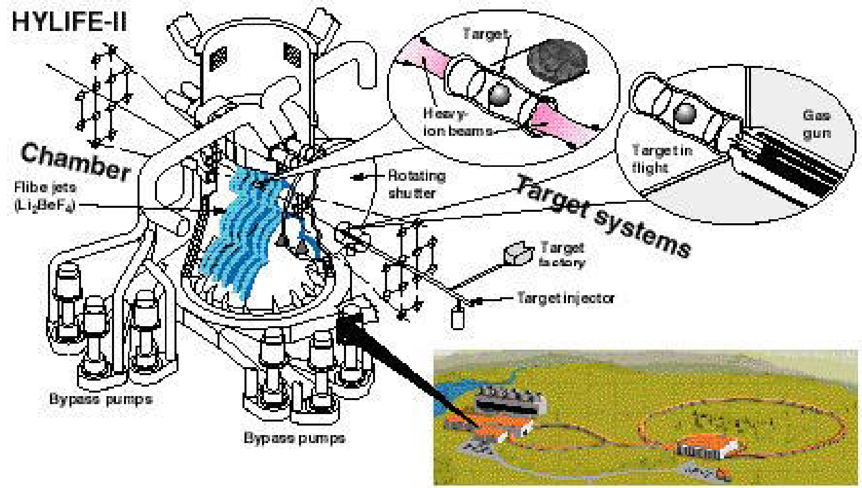
An IFE power-plant would ignite five to ten targets per second to produce as much electricity as today's one gigawatt power plant

There are 4 Current ICF Drivers

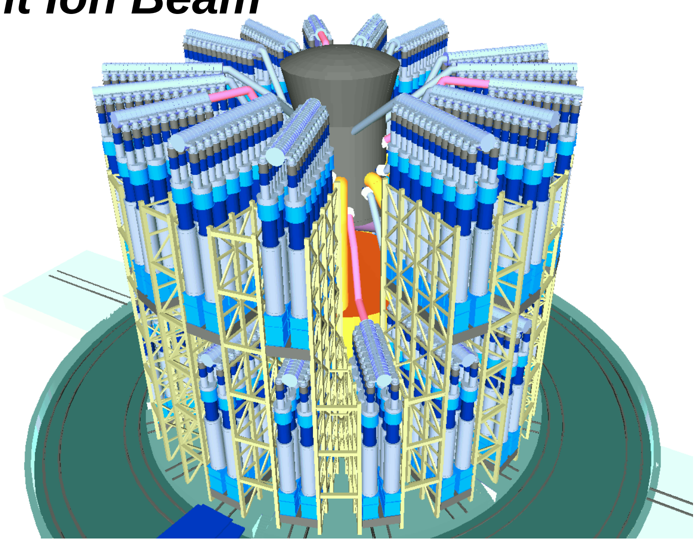
Laser



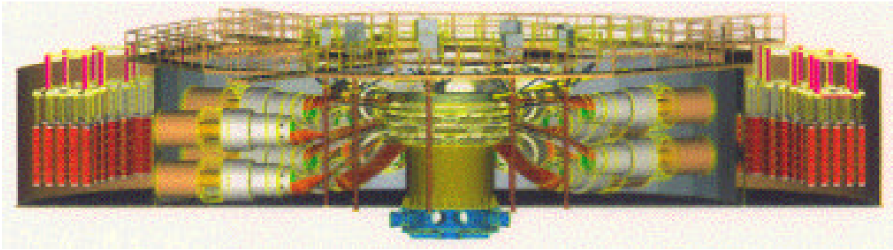
Heavy Ion Beam



Light Ion Beam



Z-Pinch – Energy application depends on finding a credible rep-rate concept

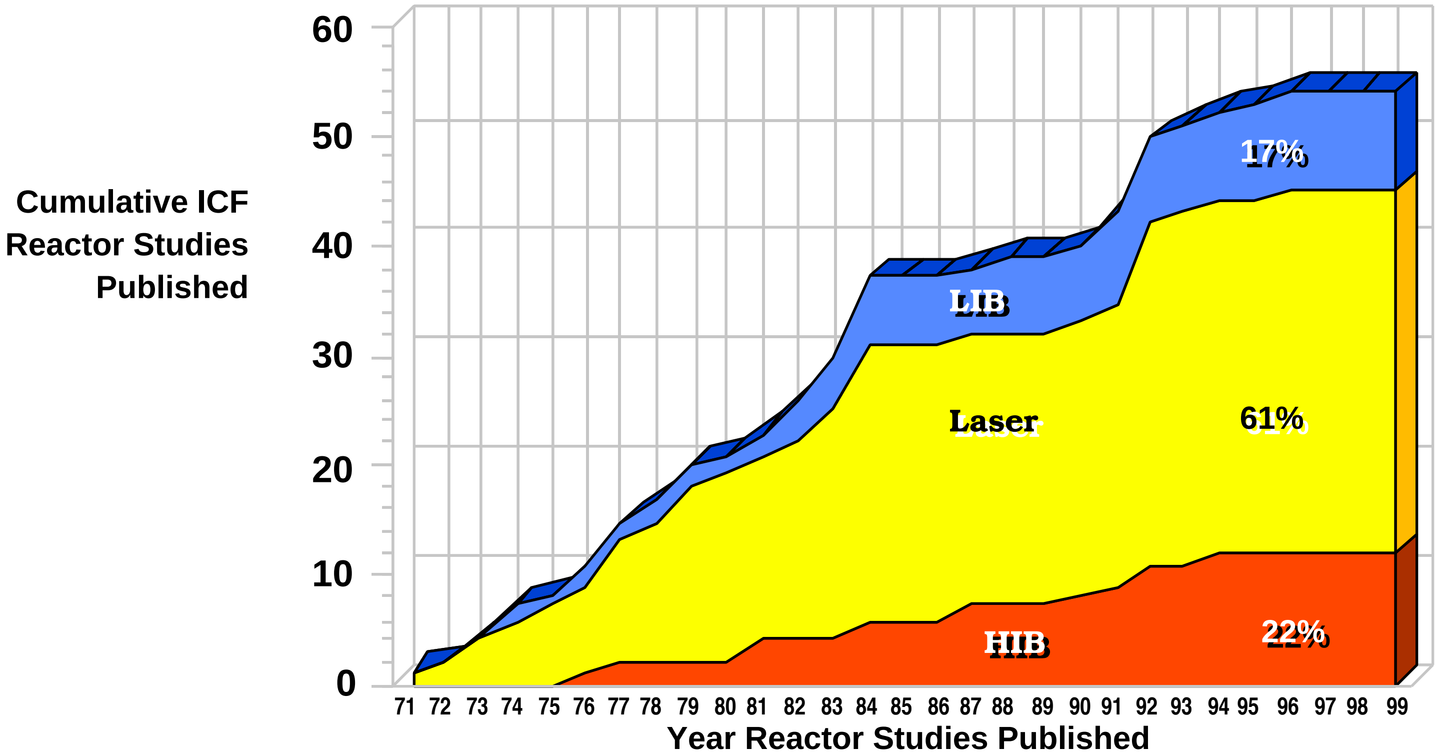


Light ion development currently on hold due to inability to focus adequately

Approximately 80% of the IFE Reactor Designs are 15 Years Old and Need to Incorporate Recent Target, Driver, and Chamber Improvements

- The level of research on IFE power plants has historically been much lower (by a factor of ≈ 10) than for MFE power plants

- In spite of the lower level of investment, there have been over 50 individual IFE power plants analyzed since 1972



Current Status of IFE Power Plant Design

Promise

- Decoupling of Driver and Chamber Reduces Development Costs and Increases Reliability
- Capability to Greatly Reduce Structural Materials Development Program
- Capability to Greatly Reduce Long Lived Radioactive Waste (volume and level)
- Indications of Lower Direct Capital Cost

Problems

- Target Design Still Uncertain
- High Efficiency (>10%), High Rep Rate Lasers Still Needed
- Cost of Laser and Ion Driver Pushes Economic Power Plants to ~ 1 GWe

Key Considerations for IFE Power Plant Designs

	Driver
Lasers	• NIF Will Give Reactor Level Energies (1.8 MJ, 500 TW) • SWL KrF/DPSSL Lasers Needed for Rep Rate
Heavy Ions	• RF or Induction Linacs Favored • Must Scale up to Higher Energy (both MJ and GeV)
Light Ions	• "Inexpensive' Hermes Technology Demonstrated at Reactor Level Energies • Have Not Demonstrated Sufficient Beam Focusing and Purity
Z Pinch	• "Inexpensive" Pulsed Power Demonstrated • Rep Rated Coupling to Target Design Not Shown

Characteristics of Drivers for Recent IFE Power Plant Designs

	Laser	HIB	LIB	Z-Pinch (estimated)
Energy - MJ/pulse @ ~300-500 TW	1-5	2-5	5-10	5-20
Driver Efficiency-%	>5	25-40	20-25	15-20
Efficiency to Capsule-%	>5	2-3	2-3	1-2
Total # Pulses	$>10^{10}$	$>10^{10}$	$>10^{10}$	$>10^{9}$
Current Status	•Glass ~ 40 kJ, 40 TW x-rays •KrF ~ 5 kJ •DPSSL ~ 0.1 kJ •NIF-1.8 MJ, 500 TW	•SLAC~10^{11} pulses, 180 Hz •I_{inj}~1 A	•Hermes ~ 300 kJ, 13 TW, 10^{-4} Hz •RHEPP-II~3 kJ, 120 Hz	•Z ~ 1.8 MJ, 280 TW x-rays, 2×10^{-5} Hz

Differences Between KrF and DPPSL Laser Power Plants

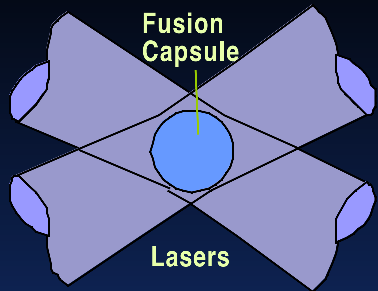
- DPSSL drivers may require up to 5% of the target chamber solid angle for beams, while the SOMBRERO KrF design called for 0.25%.

- The larger solid angle leads to more or larger ports that will have some effects on blanket design (the SOMBRERO granular flow will be perturbed).

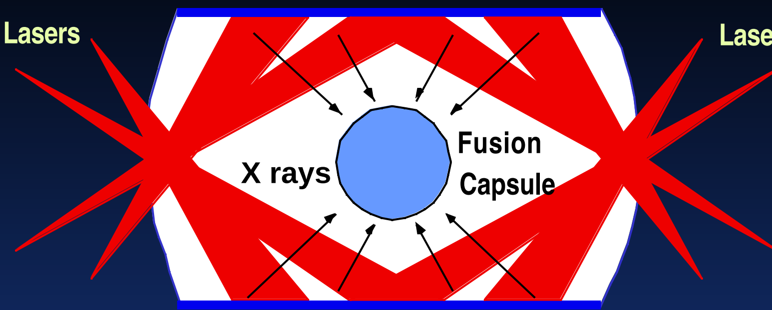
- DPSSLs will also require more or larger final optics.

- DPSSL lasers have a wavelength of 0.35 μm compared with 0.25 μm for KrF. This affects laser-target coupling, laser transport through chamber gases, and the choice of final optics (KrF light is absorbed in silica, so transmissive final optics are hard to imagine).

There Are Four Different ICF Target Designs

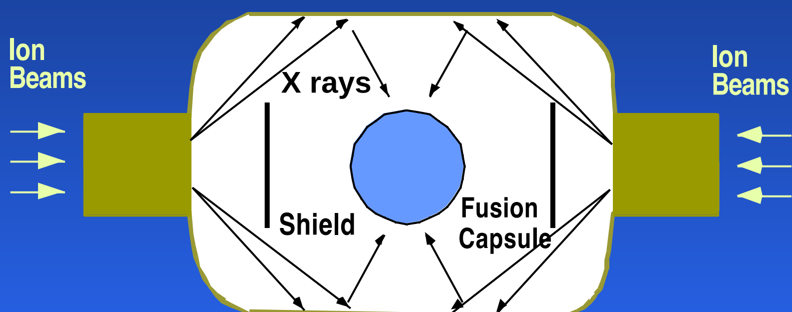


Direct Drive Lasers

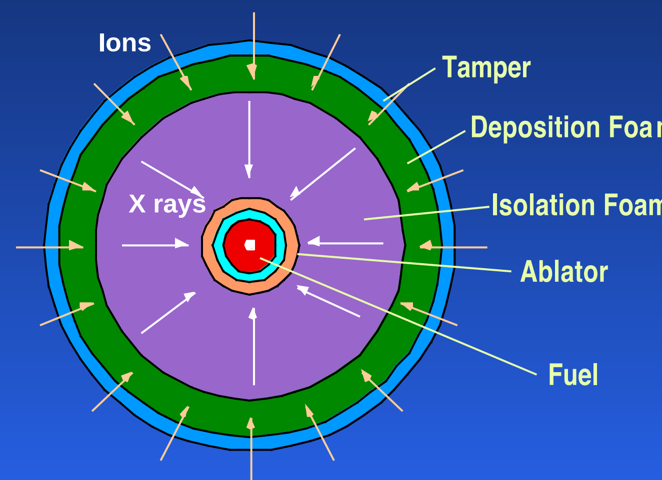


Indirect Drive Lasers

(Fast Ignitor Variation)

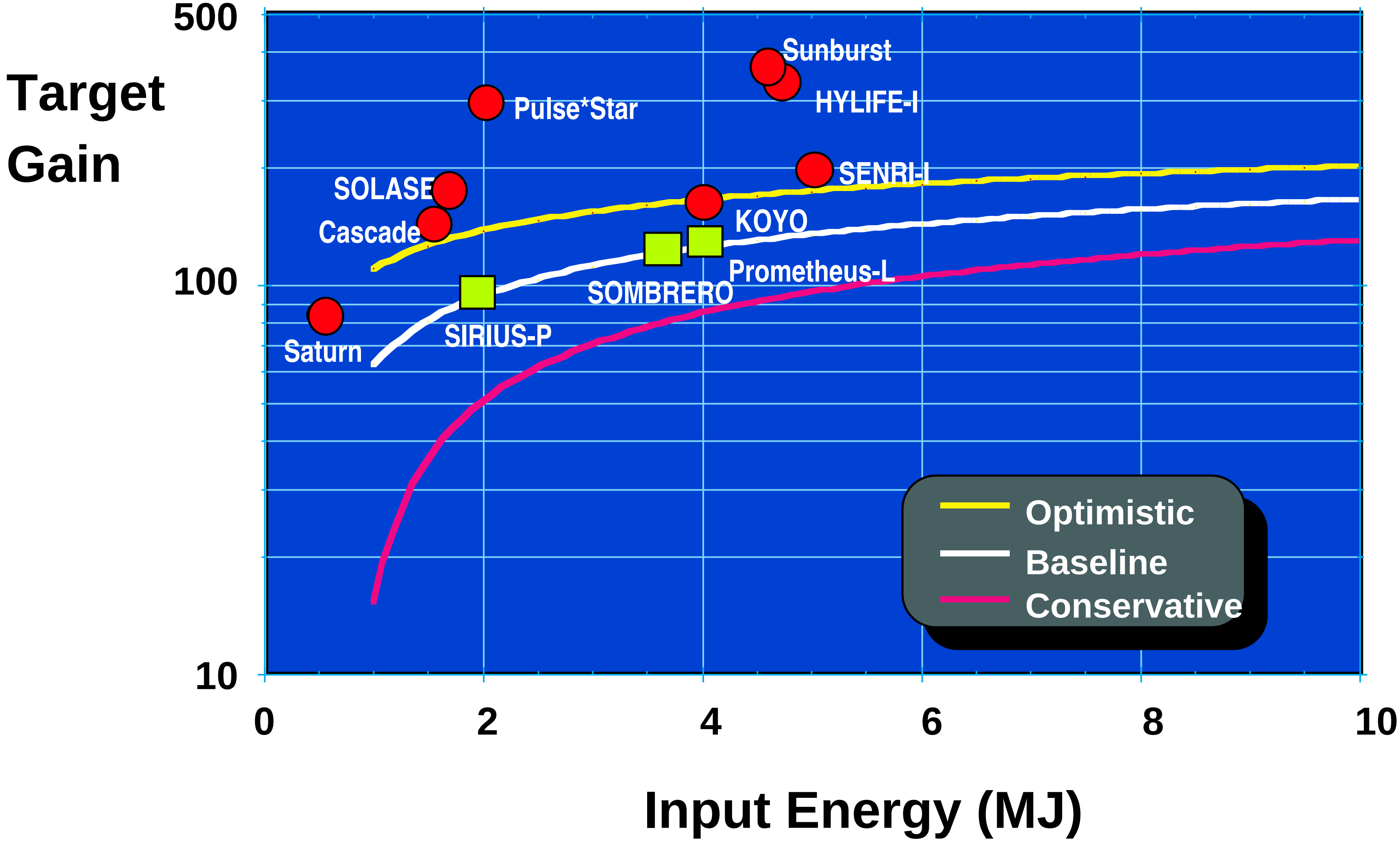


Indirect Drive Heavy Ions



Indirect Drive Light Ions

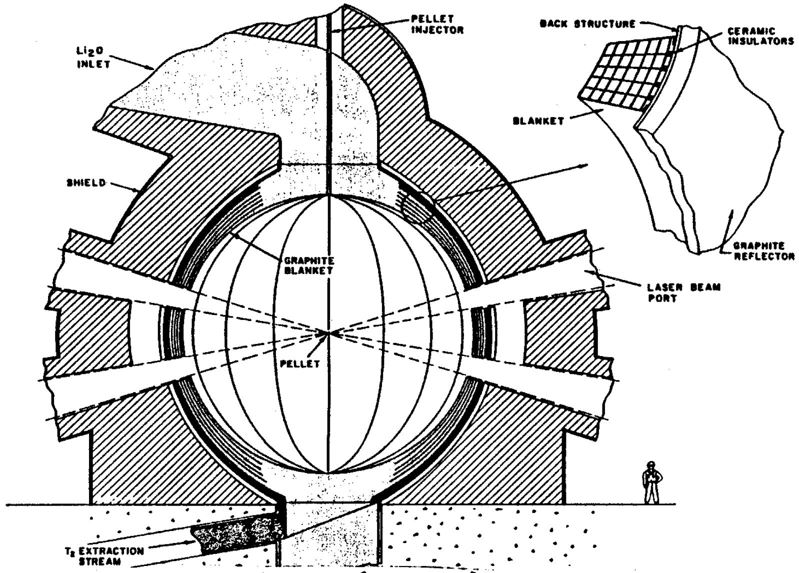
Baseline Target Gain Curves Were Used for the Last Laser Fusion Power Plant Designs



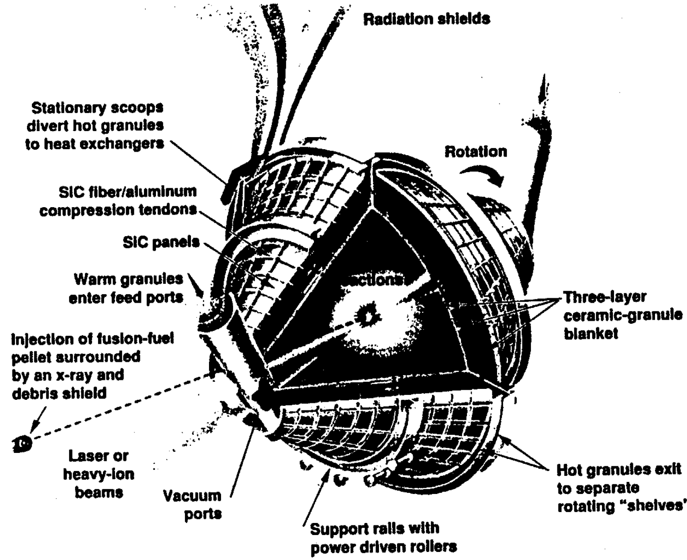
Key Considerations for IFE Power Plant Designs

	Chamber
Lasers	• Symmetric Illumination Favors Dry/Wetted Wall Approach With Gas Protection
Heavy Ions	• 2 Sided Indirect Drive Allows for Thick Free or Inhibited Flow Liquid Metallic/Molten Salt Protective Walls
Light Ions	• Could Use Dry/Wetted/Liquid Walls With Gas Protection
Z Pinch	• Chamber Design Uncertain Until Rep Rated System Identified • Shrapnel from Target Will be a Problem

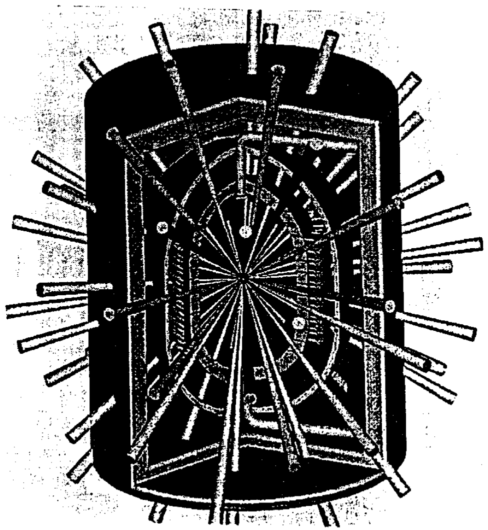
Laser Driven Reactor Designs



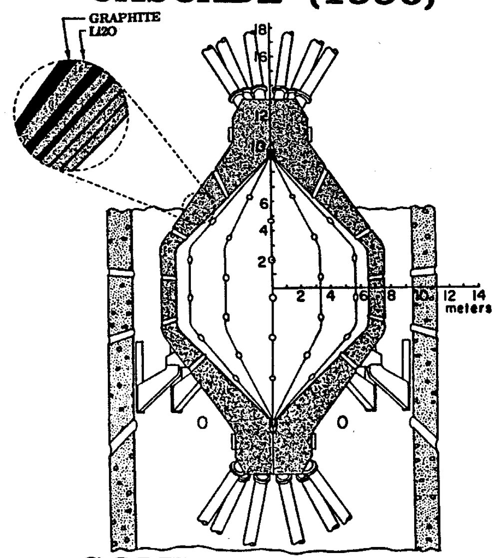
SOLASE (1977)



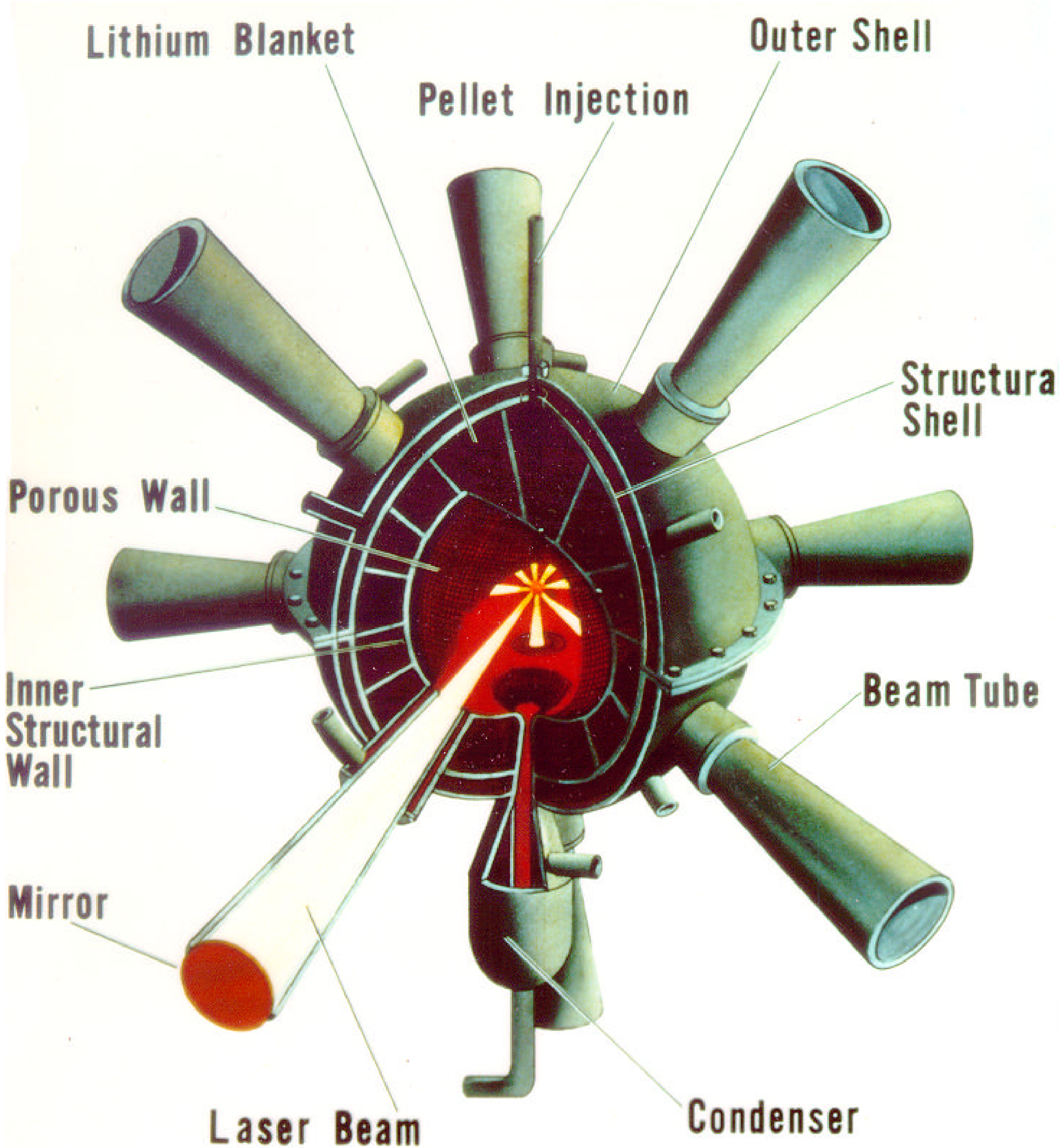
CASCADE (1990)

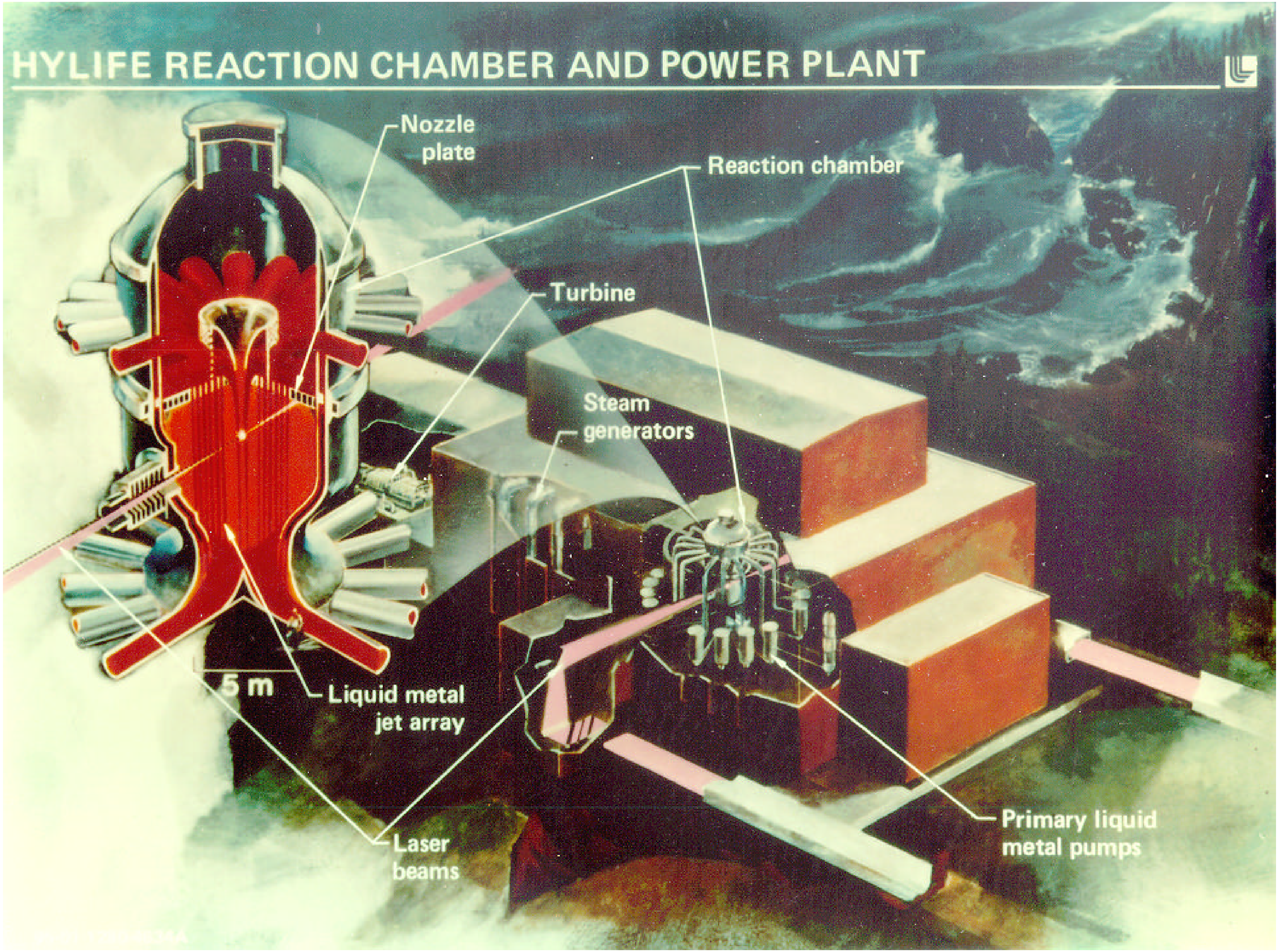


PROMETHEUS-L (1992)

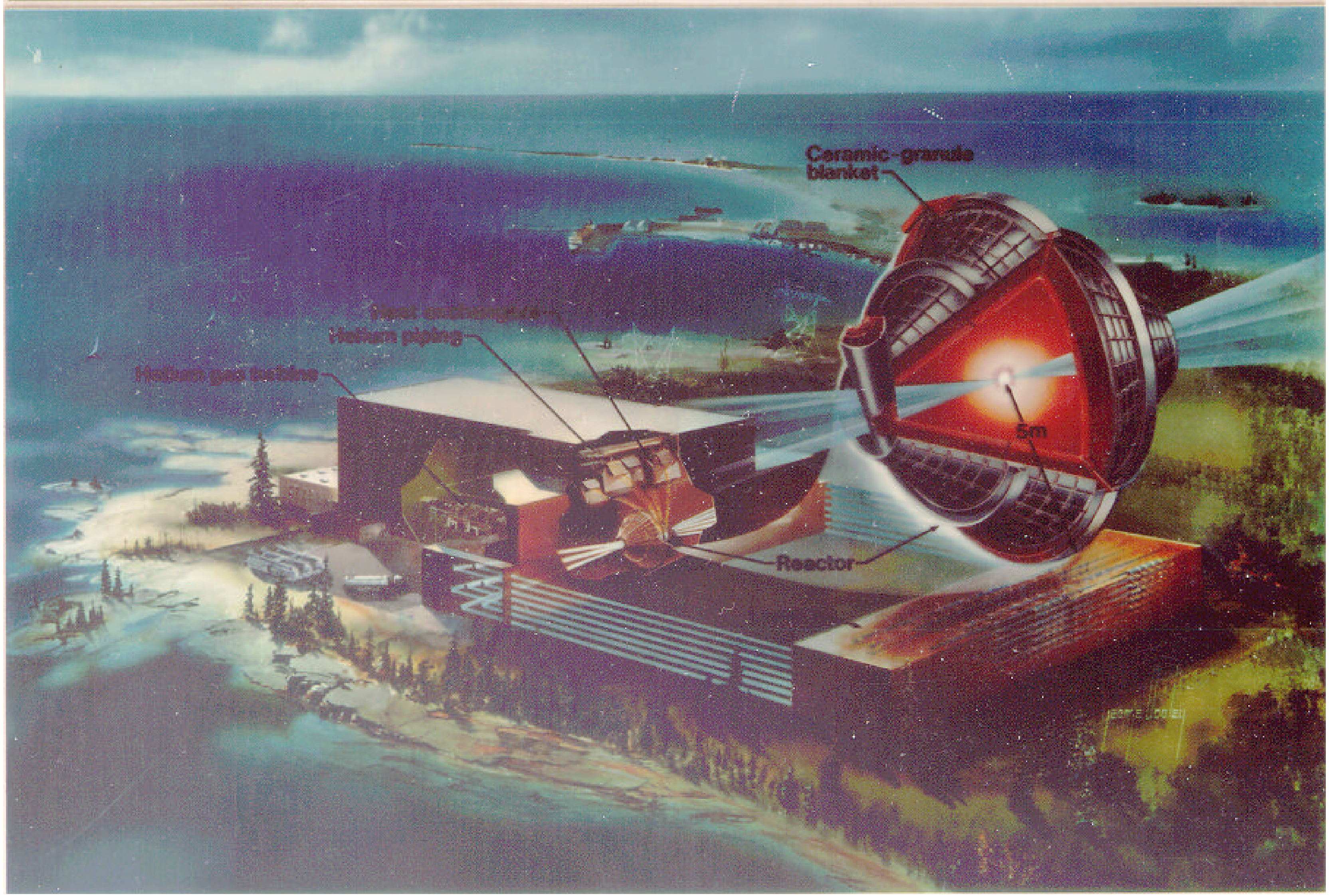


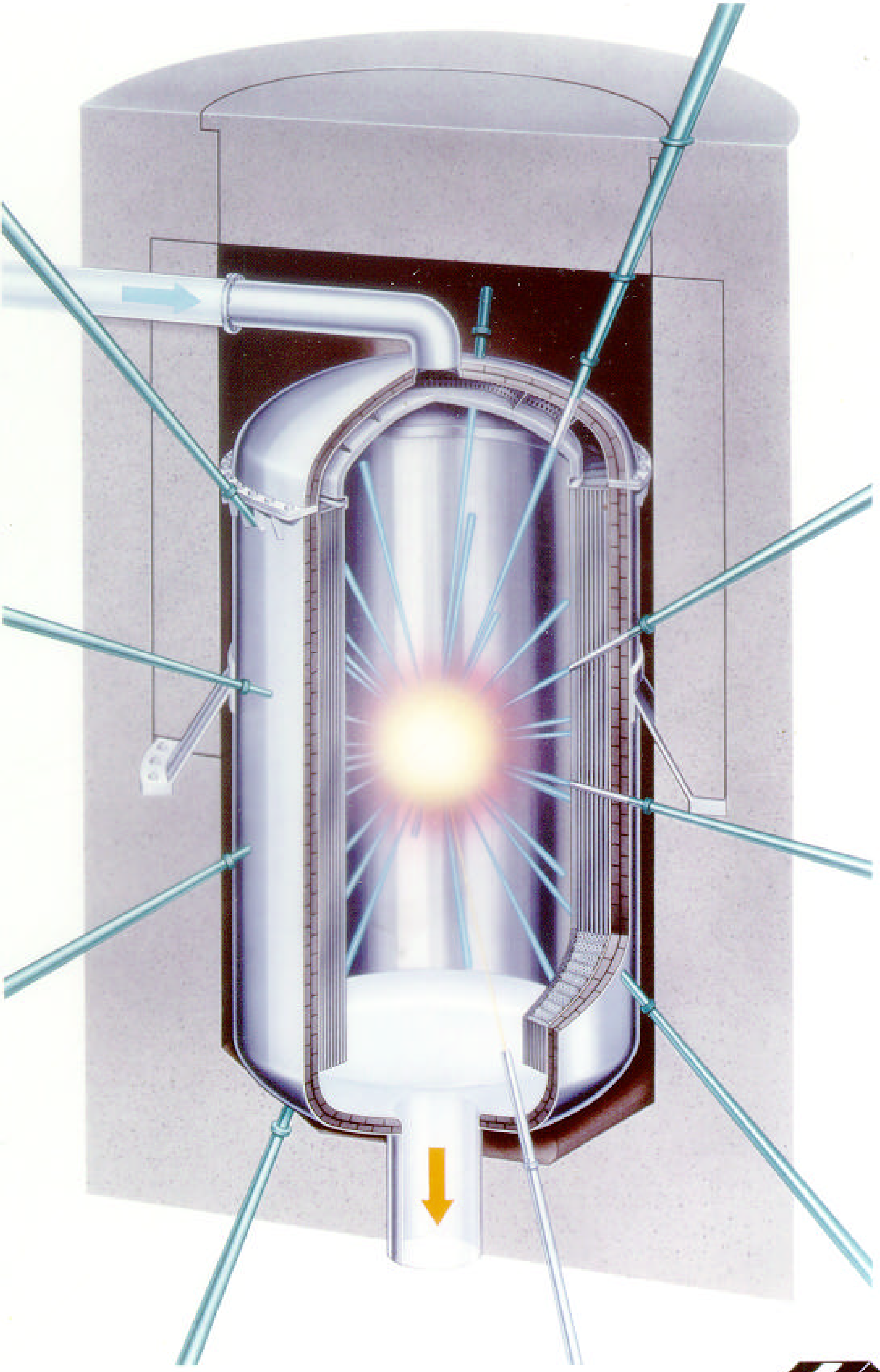
SOMBRERO (1992)


Lithium Blanket
Pellet Injection
Outer Shell
Structural Shell
Porous Wall
Inner Structural Wall
Beam Tube
Mirror
Laser Beam
Condenser


HYLIFE REACTION CHAMBER AND POWER PLANT
Nozzle plate
Reaction chamber
Turbine
Steam generators
5 m
Liquid metal jet array
Laser beams
Primary liquid metal pumps

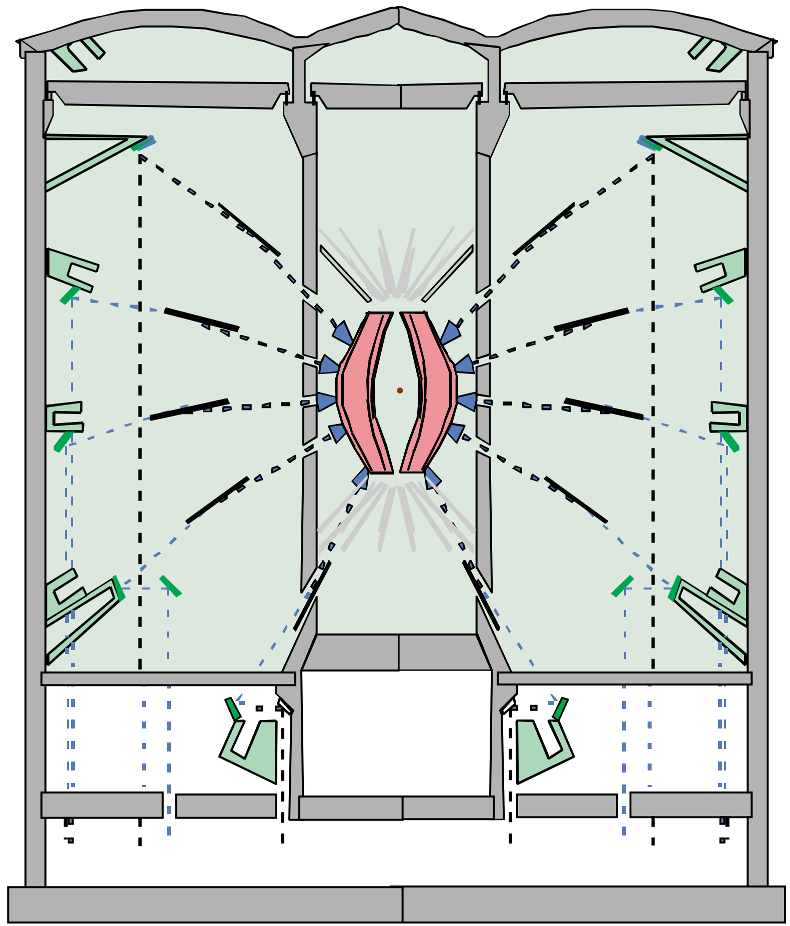
A stream of ''stars'' could fuel an electric power plant





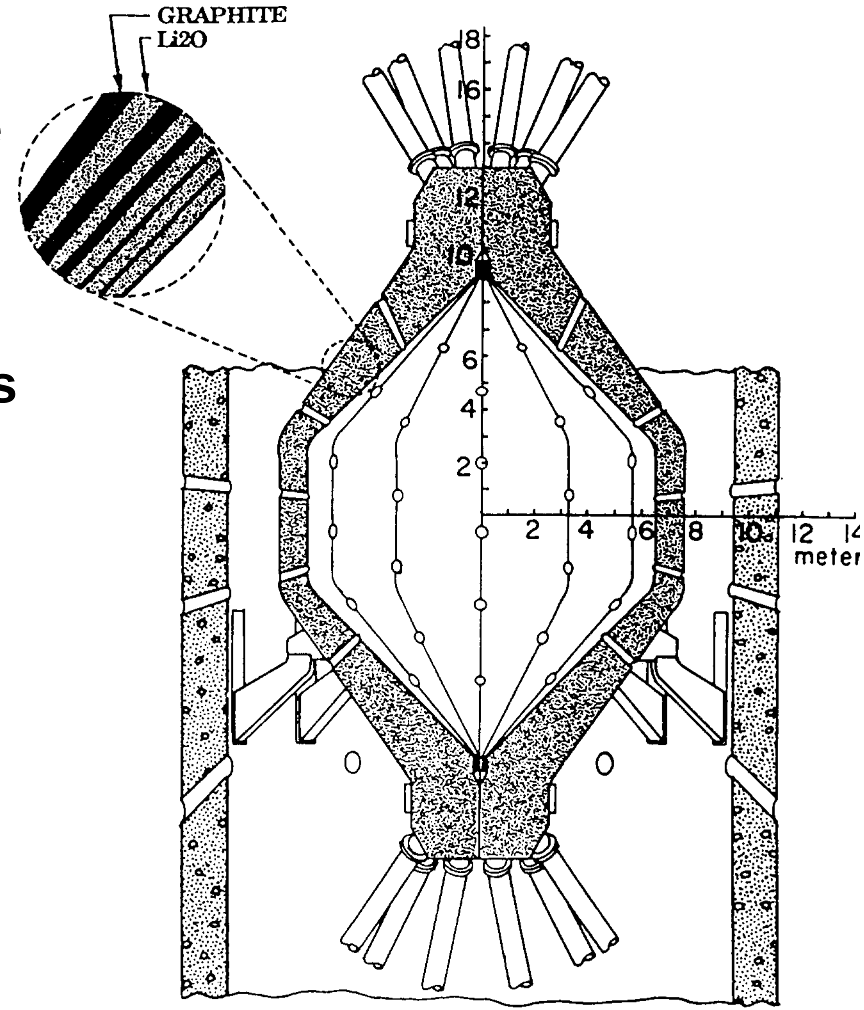
Laser Fusion Reactor Chamber「光陽」

ILE OSAKA



Xenon Gas in SOMBRERO Protects First Wall

- **In SOMBRERO, 0.5 torr of Xe stops 1.6 MeV carbon ions (containing most of the non-neutronic target output) before they reach the target chamber wall.**
- **The fireball radiation emission is slow enough that the graphite first wall stays below the sublimation limit. BUCKY predicts a peak surface temperature of 2155 C.**
- **The shock applied to the wall applies an impulse of 2.21 Pa-s and a peak pressure of 0.013 MPa.**
- **BUCKY simulations show that wall survival is sensitive to Xe opacity.**



Laser Fusion Reactors Have Evolved Over the Past 20 Years

	SOLASE	HYLIFE	Cascade	SOMBRERO	KOYO
Year Published	1977	1978	1983	1992	1993
Laser	CO_2	SWL	SWL	KrF	DPSSL
Laser Energy, MJ	1	4.5	1.5	4	4
Net Power, MWe	965	1010	800	1000	2840 (4 units)
Driver Eff., %	6.7	5	10	7.5	12
Illumination	quasi-sym.	2-sided	2-sided	symmetric	symmetric
Target Gain	150	400	200	118	150
Rep Rate, Hz	20	1.5	5	6.7	3
n, MW/m^2	5	0.3	0.2	3.5	0.07
Th. Eff., %	43	39	55	47	43
Breeding Matl.	Li_2O	Li	$LiAlO_2$	Li_2O	PbLi
Structural Matl.	C	Steel	SiC	C	SiC

Historical Trends in Laser Fusion Power Plant Designs

Time Period	*Driver/Target Related*	*Reactor Chamber Related*
70's	• Long Wavelength Lasers • Low Driver Energy ≈ 1 MJ • High Gain Curves • Direct Drive	• Liquid Li Emphasis • Wetted FW Protection • High Rep Rate (10-100 Hz) • Internal Liquid Protection Introduced
80's	• Short Wavelength Lasers • Higher Driver Energy ≈ 1-5 MJ • Lower Gain Curves • Indirect Drive Considered	• Solid Li Compounds for T_2 • Granular Solids FW Protection • Lower Rep Rate (1-10 Hz)
90's	• KrF/DPSSL Lasers • Driver Energy ≈ 5 M • Fast Ignitor Concept Explored • Grazing Incidence Angle Mirrors • Direct Drive More Prominent	• Fluidized LiO_2 Coolant • Dry FW Reanalyzed for Direct Drive • Emphasis on SiC/C FW • Liquid Metal “Curtains” for Indirect Drive

The Driver and Conventional Power Conversion Equipment Dominate the Capital Cost of IFE Power Plants

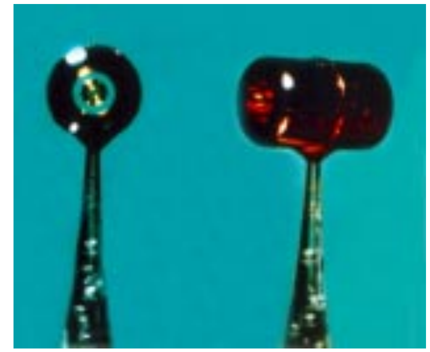
Example

	% of Total Capital Cost in Category				
	Driver	Chamber	Bldgs.	Heat Transfer/ Turbine/Electric	Other
SOMBRERO	31	9	15	34	11
OSIRIS	37	8	9	34	12

Conclusion: Highest leverage is gained through the driver. The cost of the chamber is only of secondary importance with respect to the capital cost.

IFE WILL REQUIRE TARGET DEVELOPMENT

- **CURRENT ICF TARGETS COST ~$500-$2500 EACH DUE TO:**
  - Few-of-a-kind designs — constantly changing
  - Small scale production — batches of ~5-25 targets
  - Extensive characterization — each individual target has a "pedigree"

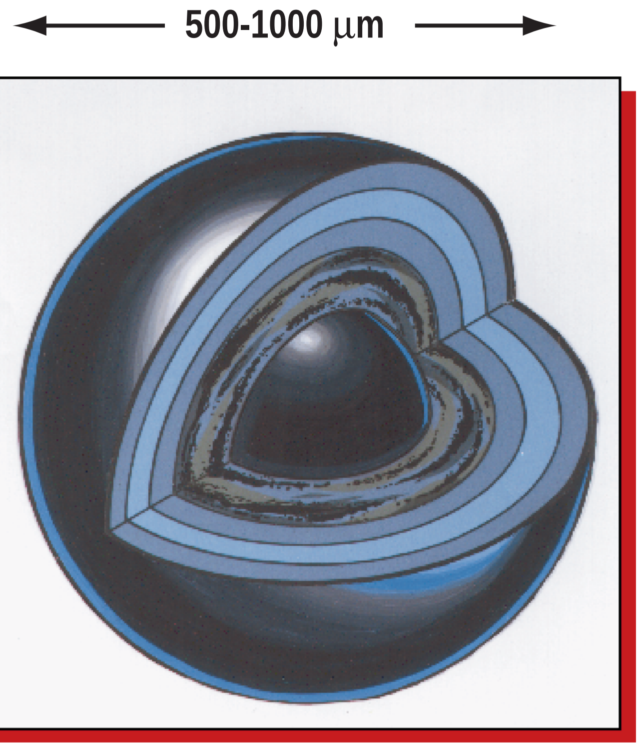


- **IFE TARGETS MUST COST ≤ 25¢ EACH**

- **WHAT DEVELOPMENT IS NEEDED?**
  - IFE target designs — including fabrication considerations and tolerances
  - IFE-specific target fabrication development — capsules, hohlraums, assembly, fill and layering, characterization

10^4 REDUCTION IN HTGR FUEL PRODUCTION COST

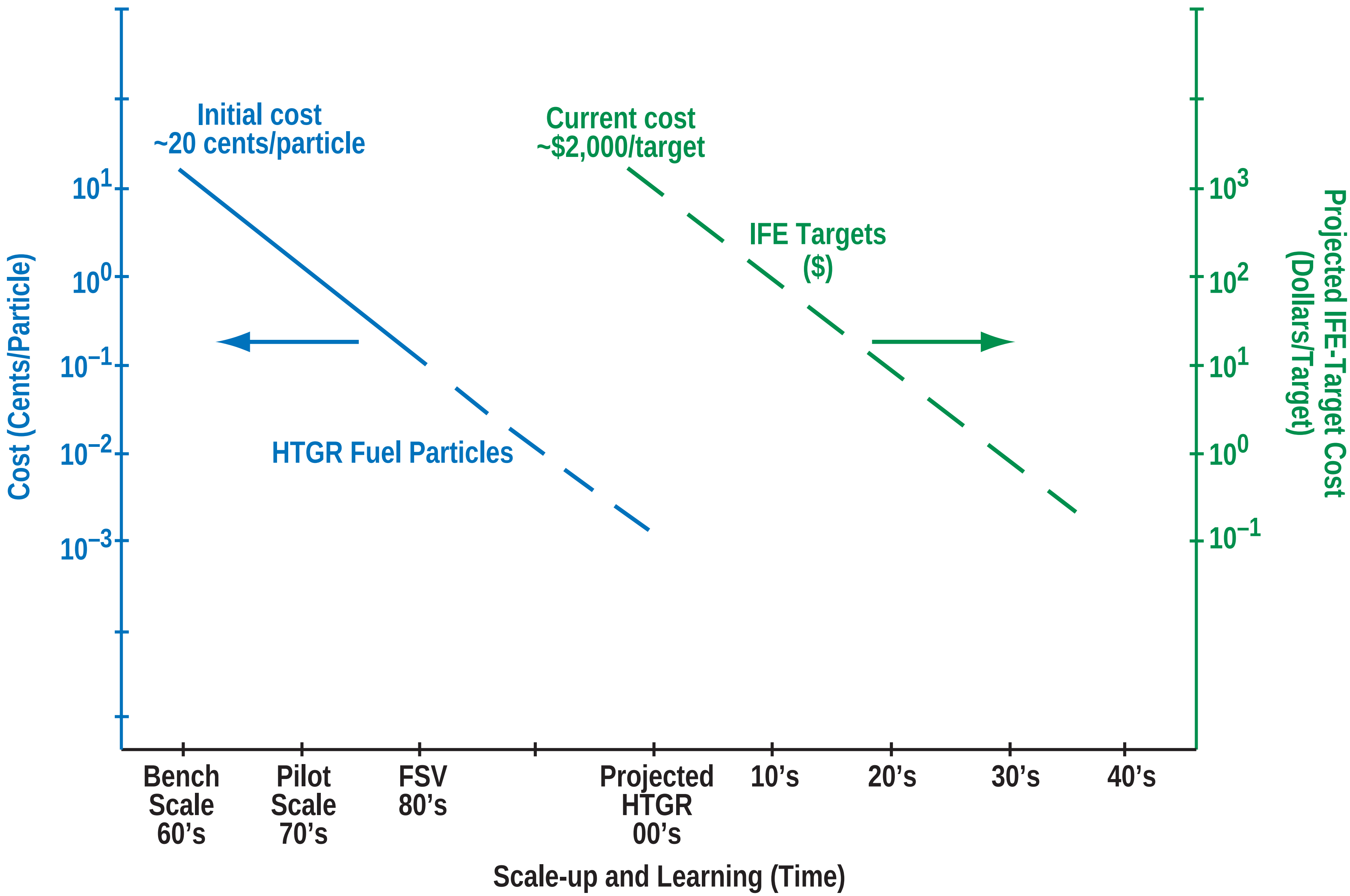
- High-temperature gas-cooled reactor (HTGR) fuel has similarity to IFE capsules
  - — Multiple layers of high and low density coatings
  - — Stringent quality requirements
- Over 10^{11} fuel particles have been produced in a small commercial production facility for Fort St. Vrain reactor
- Quality control was carried out by statistical means
  - — Production yield was ~90%
- Cost reduction was ~10^4 due to scale-up
  - — Bench scale 20¢ per particle
  - — FSV was less than 0.2¢ per particle
  - — Projected commercial 0.002¢ per particle



HTGR fuel particle with
4 different coating layers

. . . Indicates that low cost IFE targets are not out of reach, but greater precision will be required

COST REDUCTION OF HTGR FUEL PARTICLES WAS SIGNIFICANT



GENERAL ATOMICS

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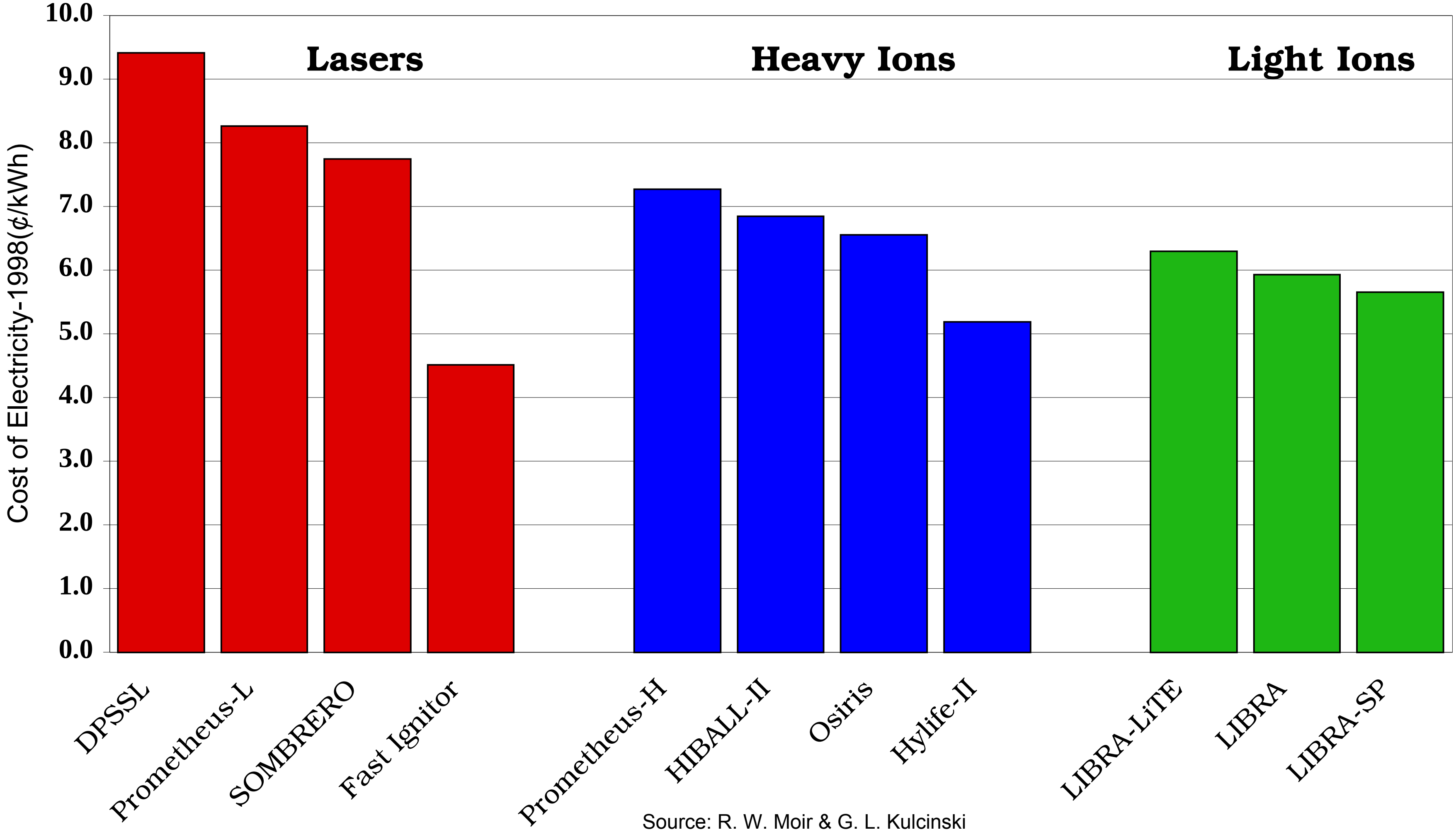
There Are Many Ways That The Predicted Cost of Electricity from IFE Power Plants Can Be Reduced



Source: R. W. Moir & G. L. Kulcinski

Conclusions

- Target gain and driver efficiency high enough for <30% of power recirculated to driver ($\eta G>7$) [CoE increases 20% at $\eta G = 5$].
- Low cost driver: <$1 B total capital cost [CoE increases 20% at $2 B].
- Low cost targets: <30 cents/target [CoE increases 20% at $1.1/target].

Conclusions (contd.)

- **Lifetimes** for driver, chamber, final optics allowing >80% plant availability.
- **Radioactivity low** enough to avoid need for public evacuation plans (<1 REM site boundary dose in worst-case accidents), to avoid active safety systems, and to avoid high-level waste disposal (achieve Class C or better).
- **Affordable development:** driver test prototype <$150 M hardware and ability to test fusion chambers at reduced scale (<1 m radius).