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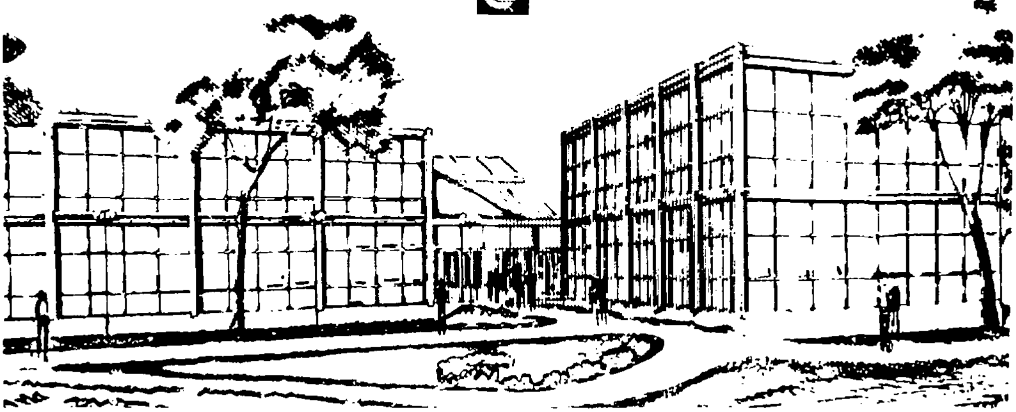

International Symposium on the
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Laser Fusion: Status, Future, and Tritium Control

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Abstract

The Laser Fusion Program today is being advanced by remarkable new developments in laser technology and new understandings of fusion physics. Steady progress in these areas has formed a solid basis for scientific feasibility demonstrations which will lead to the development of reactor scale facilities. At Livermore the 10 kJ, 20-30 TW Shiva facility is now operational and producing regular new fusion results. Design work has begun on a 200-300 TW laser designed to carry the program through the first breakeven demonstration experiments in the mid-1980's. Confidence in reaching this goal is based on the significant progress we have made in state-of-the-art, high-power Nd:glass laser technology, in experimental laser fusion and laser plasma interaction physics, and in theoretical and analytical computer codes which reliably model and predict experimental results. For all of these experiments, a variety of fusion targets are being fabricated in the laboratory, and the control and handling of tritium is now a regular and routine part of ongoing inertial fusion experiments. Target design with gains of about 1000 have been studied and the means to mass produce such pellets at low cost are also being developed.

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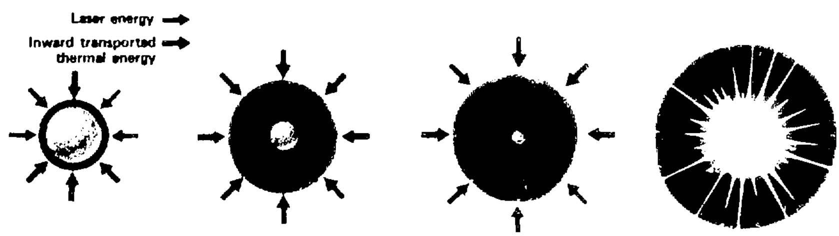
Although the reality of laser fusion power is still a long way off, we have begun to visualize laser fusion reactor systems and to design and model specific process hardware. The complete fuel cycle from the manufacture of pellets loaded with deuterium and tritium to the recovery and recycling of unburned by-products is being studied and preliminary results are available. As reactor class systems approach, we will need to demonstrate each element of the tritium life cycle. From the work done so far, we can begin to have confidence in the control and management of the tritium source term in future-day laser fusion power plants.

Laser Fusion: Status, Future and Tritium Control

The concept of laser fusion, also referred to as inertial confinement fusion, is that a sequence of tiny fuel pellets containing deuterium and tritium are projected towards the center of a reaction chamber where high power laser pulses strike each pellet, heating its fuel and releasing thermonuclear energy. The kinetic energy of neutrons from the fusion reactions is converted in an absorbing blanket to thermal energy which is coupled to make electricity through a normal thermal cycle. A schematic representation of this process is shown in Figure 1. The driver can be a laser, an electron or heavy ion beam, or other appropriate source of energy. The driver rapidly heats the surface of the target, forming a surrounding plasma, which transports energy inward, compressing and heating the fuel until the fuel at the core reaches densities dozens of times that of lead and temperatures on the order of 100,000,000^{o}C. At these temperatures the fuel ignites and thermonuclear reactions spread, multiplying by many times the input energy of the driving source.

Although the conditions required for burning deuterium-tritium fuel are similar in both magnetic fusion and inertial fusion, the means by which those conditions are obtained are quite different. In both approaches to fusion energy, ion temperatures on the order of 10 keV must be reached. In magnetic confinement fusion, the high ion temperature is maintained for relatively long times in a low-density plasma (Table 1). On the other hand, in inertial fusion the fuel is compressed to densities of a 100 grams per cc or more but only for a few trillionths of a second. The product of this very high density and short inertial confinement time leads to the same criteria or "Lawson" number as is required in magnetic fusion.

INERTIAL CONFINEMENT FUSION CONCEPT



Atmosphere Formation
Laser or particle beams rapidly heat the surface of the fusion target forming a surrounding plasma envelope.

Compression
Fuel is compressed by rocket like blowoff of the surface material

Ignition
With the final driver pulse, the full core reaches 1000 – 10,000 times liquid density and ignites at 100,000,000 °C

Burn
Thermonuclear burn spreads rapidly through the compressed fuel, yielding many times the driver input energy

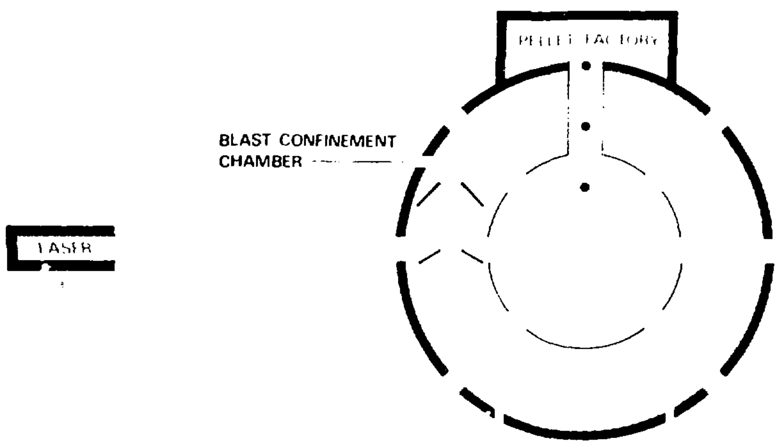


Figure 1

CONDITIONS FOR BURNING DEUTERIUM TRITIUM FUSION FUEL

	Magnetic confinement	Inertial confinement
	Lawson "breakeven"	
Temperature	10^8 K (10 keV)	10^8 K (10 keV)
$n\tau$	10^{14} s–cm^{-3}	10^{14} s–cm^{-3}
n	10^{14} cm^{-3}	10^{25} cm^{-3}
τ	1 s	10^{-11} s
	Fusion power plant	
Temperature	10^8 K	10^8 K
$n\tau$	10^{15} s–cm^{-3}	$\sim 10^{15}$ s–cm^{-3}
n	10^{14} cm^{-3}	3×10^{25} cm^{-3}
τ	10 s	$\sim 3 \times 10^{-11}$ s

Table 1

A sequence of more and more powerful lasers (Figure 2) has been constructed at Livermore to explore the physics of the interaction of lasers with matter and to achieve key fusion milestones. The sequence began with the Janus laser system in 1974 and progressed through an upgrade of Janus to the Cyclops and Argus laser systems first operational in 1975 and 1976 respectively. The first demonstration of laser driven thermonuclear burn was achieved at Livermore in 1975 with the Janus laser system. Cyclops was the laser system testbed on which components for future systems were first prototyped and tested. In particular, the technique of spatial filtering to avoid propagating and amplifying optical noise

LASER FUSION ENERGY YIELD PROJECTIONS

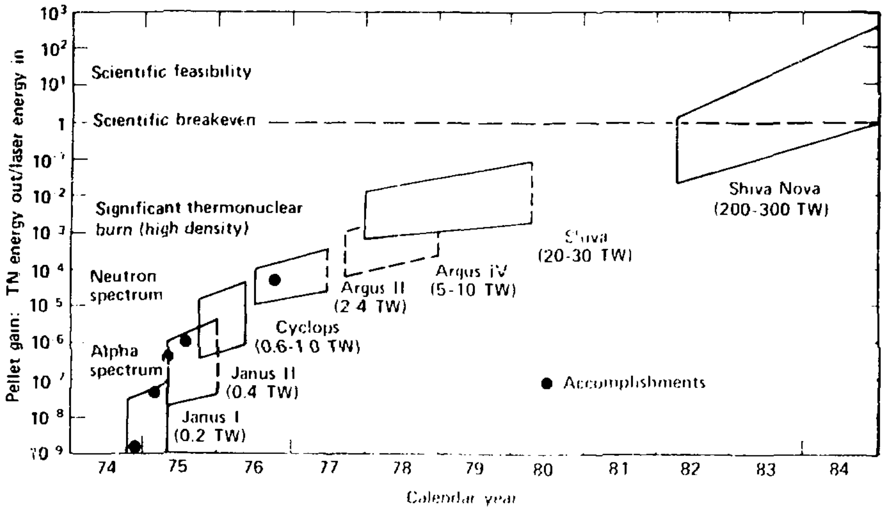


Figure 2

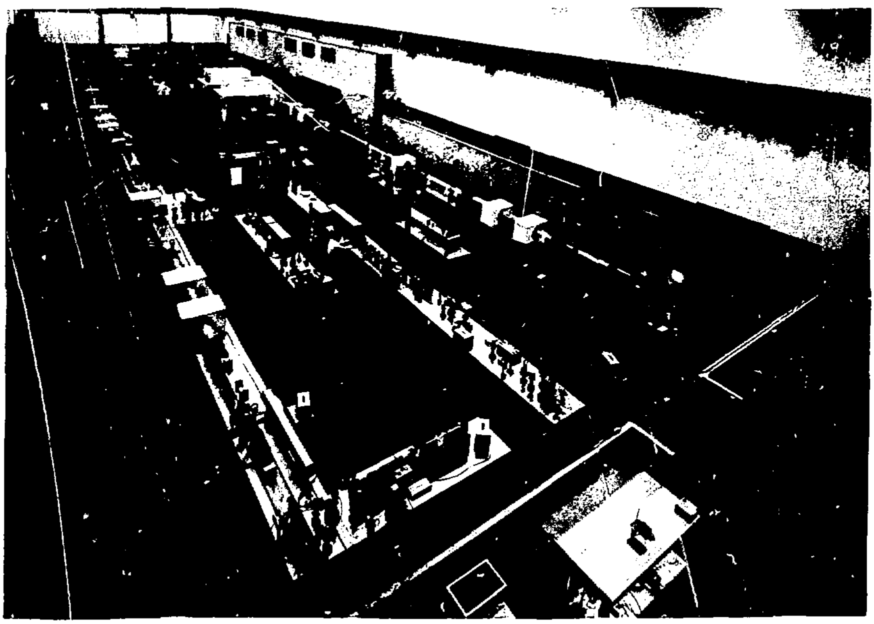
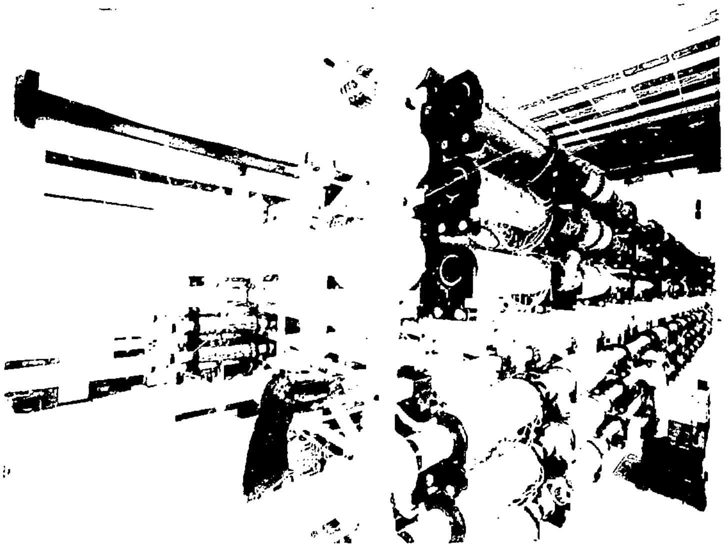


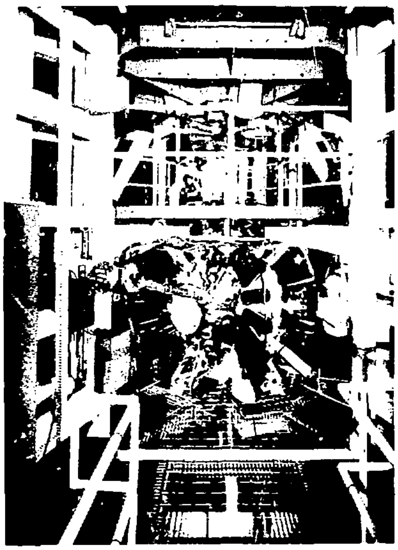
Figure 3

down each laser chain was first demonstrated on Cyclops. Success with this approach led to multiple spatial filters on Argus and Shiva. A view of the Argus laser is shown in Figure 3 with the master oscillator, beam splitter, and early preamplifier components in the foreground. As each beam is amplified, it is allowed to grow in diameter to avoid damage to optics. At the far end of the room the two beams of 20 cm aperture pass into a target chamber and are focused by lenses onto an experimental target mounted in the center of the chamber. Argus is still operational and continues to produce many important physical results. Specific target experiments on Argus have yielded up to 2×10^9 neutrons. Since high density is a requirement for inertial fusion, experiments on Argus during 1978 have been carried out with the goal of attaining densities in the range of 10 to 100 times liquid density.

The Shiva system (Figure 4) was first operational in late 1977 and has delivered over 10 kJ of energy in a one nanosecond pulse and over 26 TW in shorter pulses. The twenty beams of Shiva are focused in two f/1 clusters of ten beams each which strike the target from opposite sides. Specific targets on Shiva have produced as much as 3×10^{10} neutrons and future experiments are also planned for Shiva to achieve fuel compressions in the 10 to 100 times liquid density range. The achievement of ignition conditions in the thermonuclear fuel with target gain on the order of 10^{-3} is termed significant thermonuclear burn and is expected to be achieved first at low density, later at high density with the Shiva laser system. A further advance, termed "scientific breakeven," exists when the thermonuclear energy released from a pellet equals the light energy input to the pellet (see Figure 2). To reach scientific breakeven conditions and the first demonstrations of scientific feasibility, the full capabilities of the Nova laser system are required. Nova is an extensive upgrade of Shiva scheduled to begin construction in 1979.



View of six of the 20 Shiva laser amplifier chains looking at the output end.

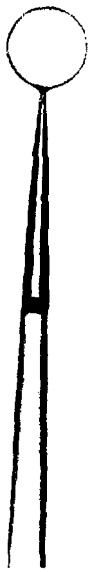


The Shiva target chamber is shown with diagnostics instrumentation being assembled for fusion experiments.

Figure 4

Many simple laser fusion experiments employ deuterium-tritium (DT) filled glass microspheres as the target. Early targets of this type were as small as 40 microns in diameter. As our laser systems have increased in power and energy, so also the targets have increased in size, and today glass microsphere targets 200-400 microns in diameter are common. Such targets are typically DT filled to a density of 2 mg/cc (approximately 150 psi), with the largest containing only 64 nanograms of DT gas. More advanced targets involving successive layers of various materials are required for high performance fusion milestones. In particular, teflon-coated glass microballoons are now being fabricated for use in target experiments designed to achieve 10 to 100 times liquid density. This target and targets which can achieve breakeven and high gain are shown in Figure 5. Surface finish is an important requirement for both the starting glass microsphere and for successive layers of other materials. We can now routinely achieve surface finishes on the order of 100 angstroms, hundreds of times better than that available through commercial sources. Coatings must not only be applied with good finish but with uniform concentricity and thickness and uniform composition throughout (Figure 6).

Results from each experiment depend on a full campaign of target design and fabrication, laser system and diagnostics readiness. Figure 7 shows a specific result from a recent target experiment, an x-ray photomicrograph of the intensity of x-rays emitted from a fusion target. The original target appears as the outermost circular contour in the photomicrograph. The hot looking central region reveals the most intense portion of the thermonuclear reaction. Within the LLL Program, we are now able to image and spectrally analyze a variety of particles from fusion reactions and are beginning to be able to time resolve those emissions.



DT-filled glass microsphere mounted on support stalk.

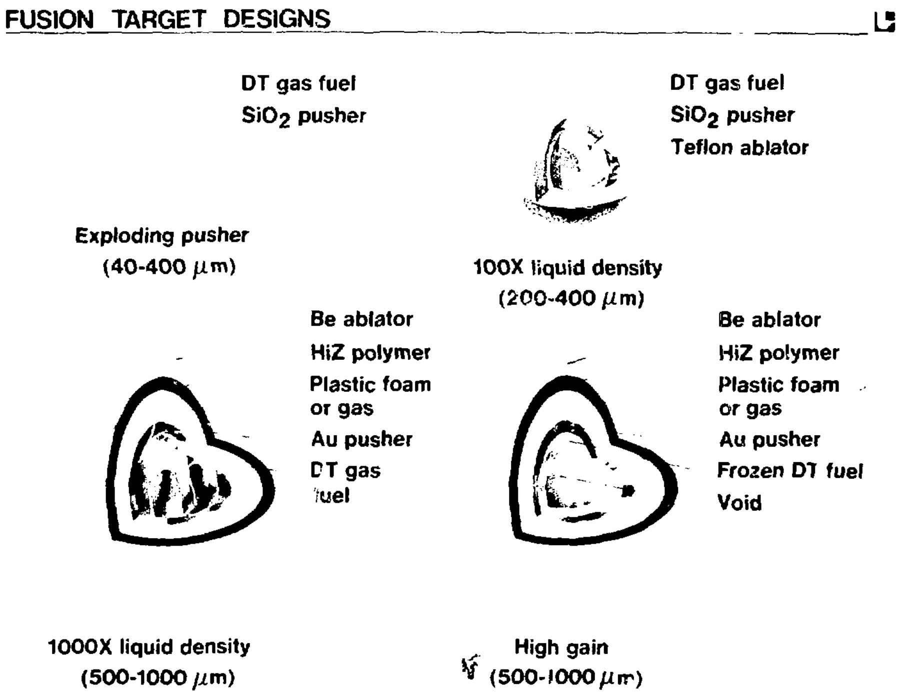
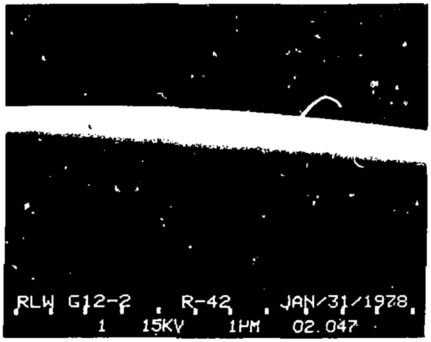


Figure 5

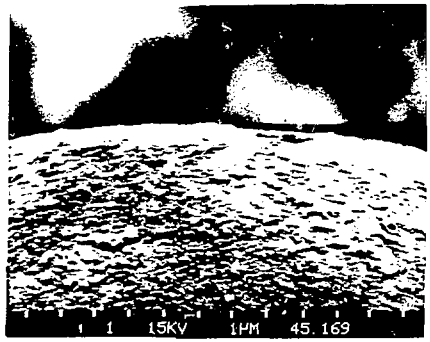
LASER FUSION GLASS MICROSPHERES

LLL microspheres



Surface finish, 100–200 Å

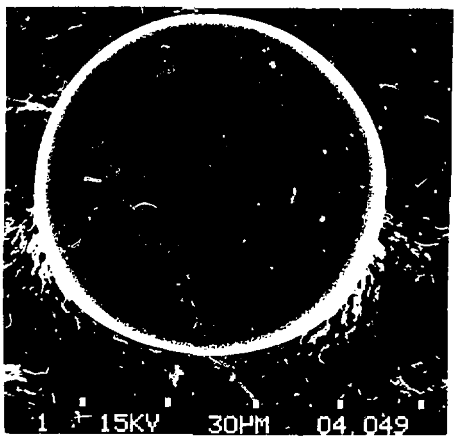
3M microspheres

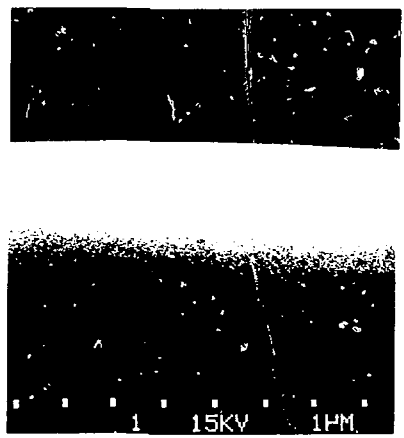


Surface finish, 0.5–2μ

TARGET QUALITY CF_2 COATED GLASS SHELL

2 μ Glass 22 μ CF_2

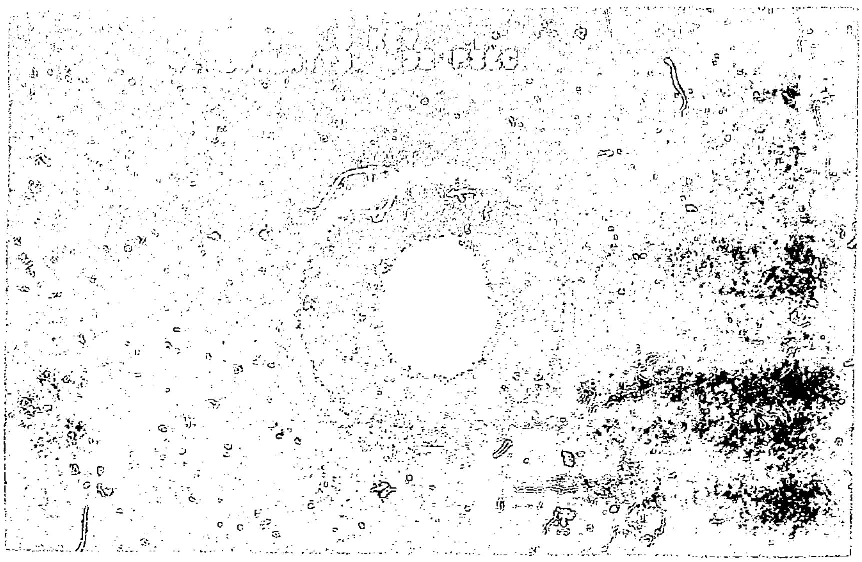




On a production basis glass shells are coated with the following specifications

Coating	• $CF_{1.3}$	Total surface variation	• 0.1 – 0.2 μ
Mandrel	• 140 μ glass shell DT filled	Concentricity	• 3 – 5%
Ambient surface	• 100 – 200 Å	Thickness	• 1 – 30 μ

Figure 6



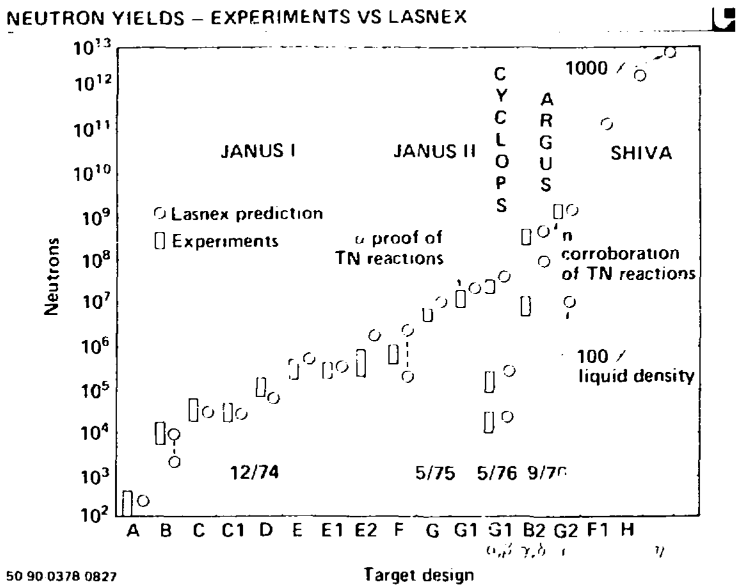


Figure 8

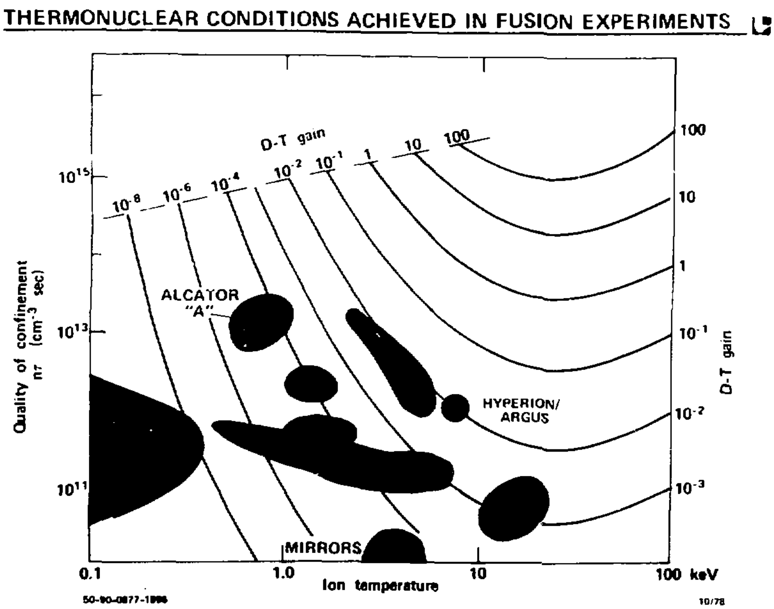


Figure 9

NOVA LABORATORY FACILITY

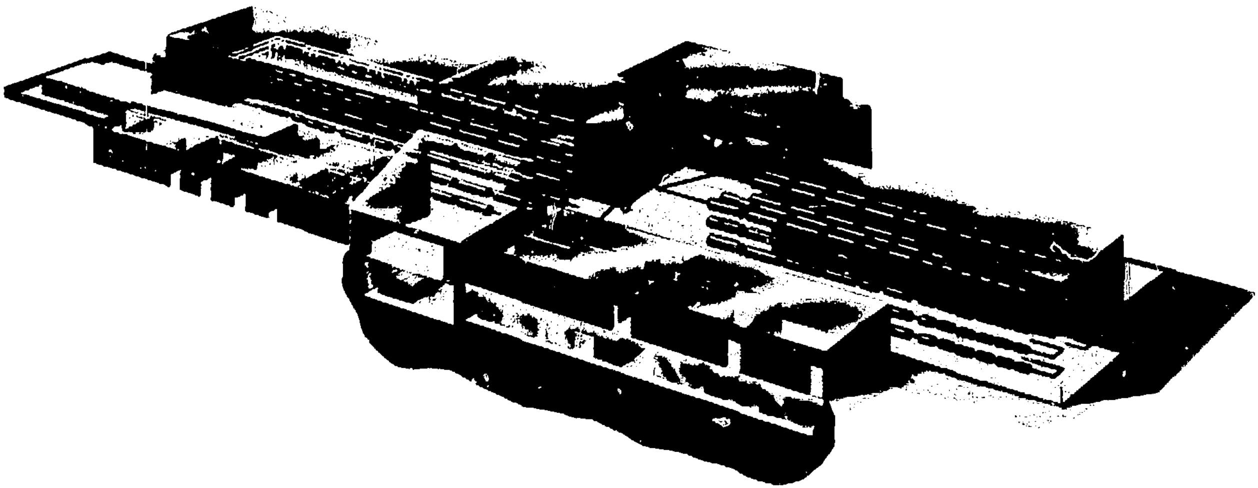


Figure 10

From the success with inertial fusion experiments and calculations so far, we can begin to visualize the laser fusion power plant of the future. Current designs show the source laser located in a separate building and independent from containment systems associated with the reactor chamber (Figure 11). In one concept in particular, the reactor chamber uses a thick liquid lithium "wall" operating at 500°C (Figure 12). An array of 548 liquid lithium jets, each 20 centimeters in diameter, creates an effective thickness of 1 meter of lithium, reducing the neutron fluence at the first structural steel wall to roughly 1/20th of that without the lithium. The lithium in the High Yield Lithium Injection Fusion Energy (HYLIFE) design reduces long lived radioactive waste by a factor of ten or more and eliminates the need for replacement of the first wall and reactor structure within the thirty-year lifetime of the power plant. The lithium fall also provides an environment for tritium breeding, and breeding ratios (atoms produced per fusion event) as high as 1.7 are calculated for this design. That is, for every three atoms of deuterium and tritium, one is burned, two are unburned and recovered, and 1.7 atoms are bred, processed and recycled. An important feature of the liquid lithium injection design is that the breeding ratio can be adjusted, providing flexibility for the use of tritium either at the source reactor or at other potential user sites.

Figure 13 shows a schematic of a possible tritium fuel cycle from the initial fabrication of individual pellets to the breeding, separation and recycling of deuterium-tritium fuel.

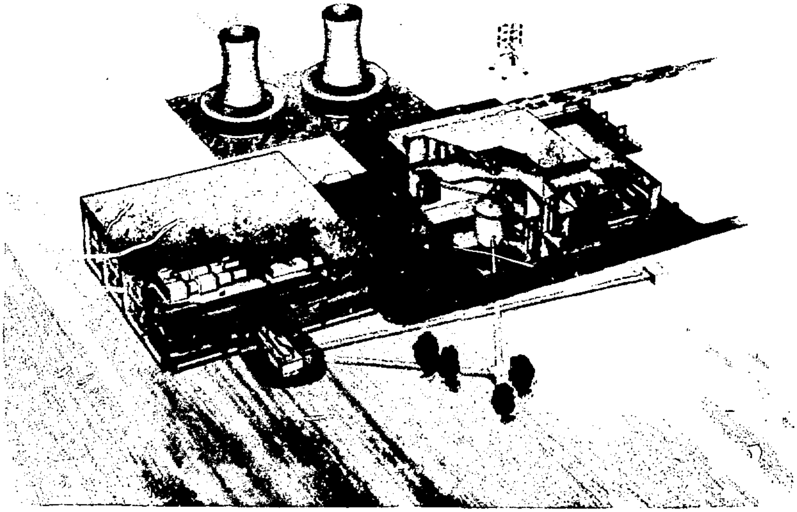


Figure 11

HYLIFE CONVERTER CONCEPT

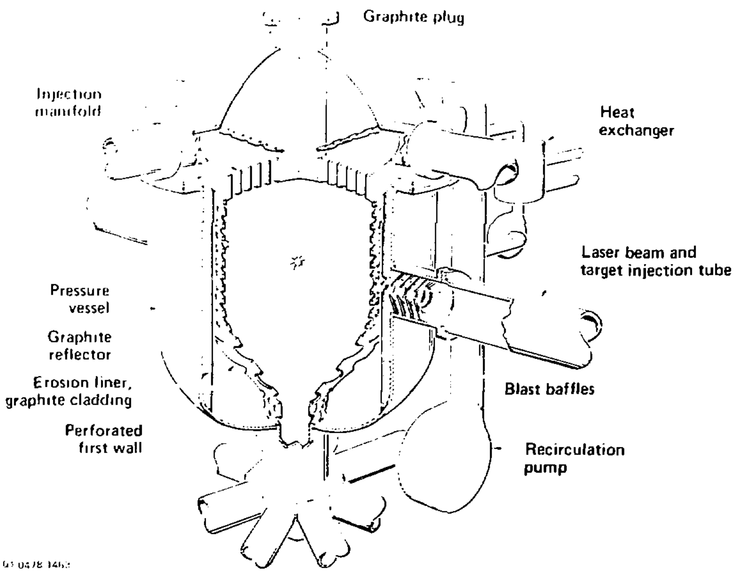


Figure 12

LIQUID LITHIUM "WATERFALL" FUEL CYCLE

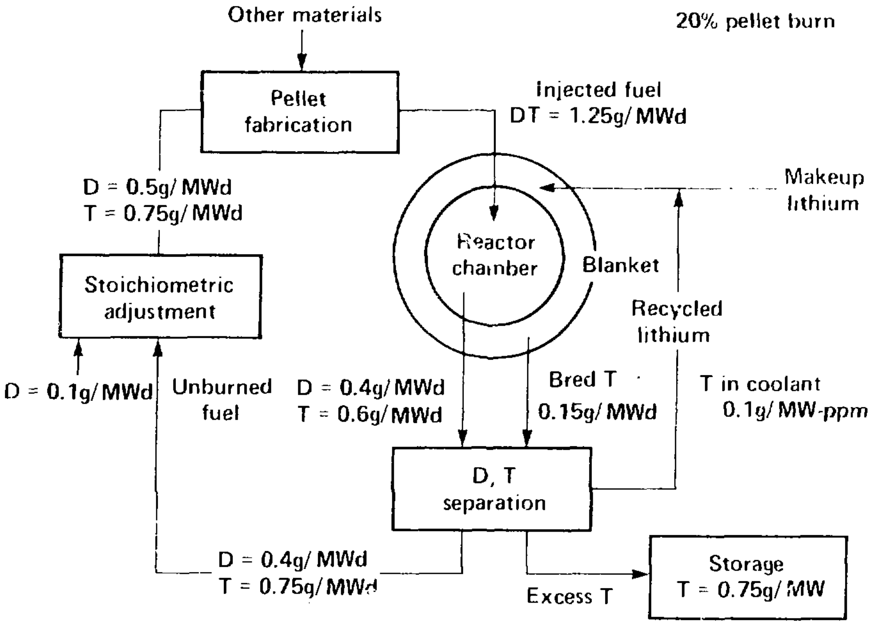


Figure 13

To extract tritium from the liquid lithium, two methods are being studied: diffusion through a refractory material and molten salt extraction cells. In addition, tritium must also be extracted from gases circulating in the reactor chamber including helium that is being produced at the same rate as tritium in the breeding process. Also, inert cover gas and double-wall containment gas will need to be processed to remove tritium. Once again, several methods exist for tritium extraction: circulation through an aluminum-zirconium getter, preferential diffusion of the carrier gas through a ceramic, and molecular sieving of the tritium after conversion to tritiated water. In a nominal 1000 MW_e laser fusion power plant of the "HYLIFE" type, approximately 64 grams of tritium are processed each hour (1.5 kg/day). A review of the inventory of tritium in the HYLIFE power plant shows that approximately 5 kilograms are held and continuously recycled in the liquid lithium loops. Approximately 1.25 kilograms of tritium are required each day to fuel a day's supply of reactor pellets. This figure also determines the daily throughput of tritium found within the tritium reprocessing system itself, say 1.5 kilograms, since the amount of tritium dissolved in the extraction system is negligible. Finally, assuming a 1.7 breeding ratio and a ten-day supply of tritium bottled for feed to pellet fabrication, roughly 12.5 kilograms of tritium would also be stored in inventory to allow for reasonable down times. Thus, of a total inventory of 19 kilograms of tritium, only a relatively small quantity, 1.5 kilograms, is found in the "active" portion of the fuel cycle. The major portion of the total tritium is either bottled for future targets or captured in the lithium flow within the primary reactor cooling system.

Tritium handling, control, and storage are perhaps best considered in light of reducing the overall social cost burden presented to society by large-scale electric power production. Table 2 lists estimates of social costs for various present day and future energy options. The coal and LWR columns give data derived from actual operation of these systems, while the remaining four columns present estimates for advanced sources of power. Fission breeders, solar electricity plants, and the two types of fusion are commonly referred to as "inexhaustible sources" because their supply of fuel is either somewhat regenerative or so abundant as to last for the foreseeable future of man on earth.

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[1]By way of contrast, the total DT inventory required for today's ongoing LLL laser fusion experiments is less than 0.5 gram (4800 ci).

THE SOCIAL COSTS (HEALTH, ENVIRONMENT AND SAFETY) OF GENERATING 1 GWe OF ELECTRICITY

	Coal	LWR	Breeder reactor	Solar	Magnetic fusion	Laser fusion
Land use (acres)						
Power plant	300	100 200	100 200	6,000 19,000	100 200	100 200
Fuel cycle (30 years life)	3,000 12 000	600 12 000	15	0	0	0
Transportation (tonne/yr) requirements	3×10^6	200	23	Unknown	100 400	10
Gaseous effluents						
Non radioactive (tonne/yr)	40,000	21	5	Unknown	0	0
Radioactive (ci/yr)						
Tritium	0	15,700	2000	0	1000	1000
Other	?	350,000	150,000	0	0	0
Solid waste						
Non radioactive (tonne/yr)	1×10^6	91 000	9 100	Unknown	Negligible	Negligible
Radioactive (m^3/yr)	0	340 1100	450 1200	0	450	30
Safety						
Accident consequences	Low	Very high	Very high	Very low	Low	Low
Accident probability	High	Very low	Very low	Very low	Very low	Very low
Premature deaths/yr						
Occupational	0 8	0.1 0 9				0 004
Public	2 111	0.01 0 2	?	?	?	0 003
Total	2 120	0 1 1				0 007
Proliferation hazard	No	Yes	Yes	No	No	No

Table 2

It is clear that any source of relatively inexhaustible energy is likely to be more expensive than present-day electrical generation sources: for example, the cost of a laser fusion power plant or a large breeder reactor of the 1000 MW_e class is projected to be roughly 2 billion 1978 dollars. However, the ultimate selection of one or more of these alternatives may well depend on the social cost factors inherent in the design as much as in the capital investment required.

The typical 1000 MW_e light-water fission reactor operating in the world today discharges over 15 kilocuries of tritium as a gaseous effluent each year. In contrast, conceptual designs for fusion power plants show that their effluent can be limited to 1 kilocurie per year by applying present-day tritium technology. In perspective, since the present (October 1978) installed capacity of nuclear power plants in the United States is 51.421 MW_e, a total of 807 fusion reactors of 1 GW_e each could be operated with the same total curies of tritium effluent. This generating capacity is 1.5 times as great as the entire U.S. installed power today. It appears that tritium control, although an important factor to be considered in the design of future laser fusion systems, is a manageable characteristic. When coupled with the other social cost advantages indicated, including the low discharge of radioactive and inert wastes of all kinds, laser fusion has great potential as a safe and environmentally acceptable source of long-range energy.