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Advances in ICF Power Reactor Design

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ADVANCES IN ICF POWER REACTOR DESIGN

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ABSTRACT

Fifteen ICF power reactor design studies published since 1980 are reviewed to illuminate the design trends they represent. There is a clear, continuing trend toward making ICF reactors inherently safer and environmentally benign. Since this trend accentuates inherent advantages of ICF reactors, we expect it to be further emphasized in the future. An emphasis on economic competitiveness appears to be a somewhat newer trend. Lower cost of electricity, smaller initial size (and capital cost), and more affordable development paths are three of the issues being addressed with new studies.

INTRODUCTION

Among the many existing and potential applications for inertial confinement fusion (ICF) technology, its use as a new source of commercial power is one of the most promising and, at the same time, challenging goals. ICF shares with magnetic confinement fusion (MCF) the promise of providing a virtually unlimited energy supply that is not dependent on political boundaries. It has some inherent advantages over MCF in the design flexibility provided by the relaxed vacuum requirements and the separability of the driver, fusion pellet and reaction chamber. On the other hand, it also presents different technological challenges because of the extreme pulsed nature of its energy production and the manufacture and emplacement of its fuel pellets. Thus, while ICF shares many technological development issues with MCF, it truly represents a fundamentally different approach to commercial fusion energy.

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One important reason that the development of commercial power represents a particularly challenging goal for ICF (and MCF as well) is that the future criteria for determining desirable power plant characteristics are difficult to pin down. Among the criteria that have been used are reliability, practicality, safety, environmental impact, developability, availability of consumables, disposal of waste products, maintainability, modularity, expandability and, of course, cost (measured by several figures of merit). A further complication is that the relative weights of the various criteria appear to be fluctuating with increasing frequency. Thus, the only real "megatrend" we can foresee is an ever increasing emphasis on design flexibility, at reasonable cost, in a changing judgmental environment.

HISTORICAL PERSPECTIVE

Table 1 (compiled from Refs. 1-36) is a chronology of all published ICF power reactor concepts grouped by driver type. Table 2 gives the major operating parameters of those reactor studies that published a self-consistent set. First wall protection schemes were reviewed in 1979 by Kulcinski.[37] The paper of Monsler, et al.,[38], in 1981 provided an excellent discussion of the technical issues that must be addressed in ICF power reactors and a comprehensive review of designs proposed in the U.S. to that date (above the dashed line in Table 2). The pre-1981 concepts emphasized features like simplicity, maintainability, long structural lifetime, and low induced radioactivity. At the same time, they explored the impact of various structure protection methods, blanket and structural materials, and driver type. In the interest of showing first generation ICF reactors to be practical (given a driver and target) all of the concepts assumed use of as much existing technology as possible. In particular, two of the major assumptions were the use of DT fusion fuel and a conventional steam cycle for converting fusion energy to

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Table 1

Chronology of ICF Power Reactor Design Ideas by Driver Type: Conceptual, Scoping, and Disclosure Studies (References in Parenthesis)

Year Publ.	Laser	Heavy Ion Beam	Light Ion Beam
1971	ORNL/UR - Blascon(1)		
1972	LANL - Wetted Wall(2)		
1973	FRG - Saturn(3) LANL - Dry Wall (4)		
1974	LANL - Magnetic Protection(5) LLNL - Suppressed Ablation(6)		ANL - Li Rain(7)
1975	LANL - Gas(8)		
1976	LLNL - Dry Wall(9)	ANL - Rot. Fluid Wall(10)	SNL - Moving Wall(11)
1977	UW - Solase - Gas(12) LLNL - Fluid Walls(14) LLNL - Solid Particles (15)	BNL - Fluid Walls(13)	
1978	LLNL - HYLIFE - Fluid Walls(16) LLNL - Dry Wall Hybrid(15)		
1979	UW - Solase-H - Gas(17) LANL - Li Boiler(18) Japan - Osaka(19)		
1980	LANL - Mod. W.W.(20)		
1981		UW/FRG - HIBALL - Import Units(21) Westinghouse - Dry Wall(22)	
1982	Japan SENRI-I-Fluid Wall(23)		Japan - UTLIF-I - Gas(24) Japan - ADLIB-I - Rotating Fluid Wall(25)
1983	LLNL - Cascade - Solid granules(26) LLNL - Pulse*Star - LiPb spray(27) LLNL - Sunburst - Lithium(28)		Japan - UTLIF-II - Gas(29)
1984	Japan SENRI-II - Fluid Wall(30) UW/UR - SIRIUS(31) LANL - FIRST STEP(35) UI - LOTRIT(36)	Japan HIBLIC-I - Fluid Wall(32) UW/FRG - HIBALL-II-INPORT(33)	EAGLE(34)

electricity. Walls of the reaction chamber were protected from the effects of the fusion pulse by distance (the dry-wall concepts), magnetic fields, gas, thin liquid-metal layers (wetted wall concepts), or thick liquid-metal layers (e.g., lithium falls). The trends observed in the Monsler, et al., paper were toward higher pulse yield (reflecting the more pessimistic view of target gain vs. driver energy that emerged at that time), longer structural lifetime and lower activation (through massive wall protection from neutrons, x rays and debris).

RECENT ICF POWER REACTOR DESIGNS

Design concepts published since 1981 and treated in this section are listed in Table 2 below the dashed line. They represent either an evolution of earlier concepts or more radical approaches that go beyond first generation ICF reactors.

Liquid Metal Sprays. Several of the recent reactor concepts use liquid metal sprays to assist in protecting the structural walls. For example, the Eagle[34] design for a light ion driven reactor used sprays of lithium to augment the protection afforded by the chamber gas necessary for light ion beam propagation to the target. Similarly, the HIBLIC[32] design used sprays of liquid lithium in a heavy ion beam driven reactor. Such sprays provide wall protection from x rays and debris similar to that afforded by wetted wall concepts; but, in addition, they mitigate the transmission of ablatively generated shocks to the structure. They can also be renewed on a shorter time scale than the liquid metal falls, thus allowing a higher pulse rate. Another advantage is the uniformity of protection afforded by fine mists when compared to liquid metals flowing on metallic surfaces. An uncertainty associated with their use is the possibility that droplets may acquire trajectories that carry them into the beam lines at an inappropriate time.

Thick Liquid Metal Wall Reactors. The use of a thick (1-2 m) region of partial density liquid metal between the fusion pulse and the structural wall (not in contact with it), was thoroughly investigated for the HYLIFE reactor[16]. The concept offers advantages in stress reduction, structure lifetime, low activation, and tritium breeding. Several of the recent designs have used this feature while modifying it to improve upon some of its earlier limitations (such as low pulse rate) and applying it to other drivers.

The HIBALL studies[21, 33] used this type of reaction chamber with a heavy ion beam driver. To allow operating at higher pulse rates, the falling liquid metal (LiPb) columns are enclosed in flexible, porous "sleeves" of woven SiC. In this case, the columns do not disassemble with each pulse and the liquid metal flow rate can be reduced. Figure 1 shows a schematic of this reaction chamber. The major uncertainty introduced by the sleeve concept is the lifetime of the sleeves.

In the SENRI design series[23, 30] the use of a thick fall of liquid metal is combined with the use of a strong magnetic field. Figure 2 shows a schematic of SENRI-1A. The magnetic field is used to guide and stabilize the liquid lithium flow, control the flow velocity, suppress the disassembly of the liquid lithium and control plasma debris from the fusion pulse. The SENRI-II design also incorporated use of woven sleeves to reduce flow velocity and, thus, required pumping power. The introduction of magnetic fields, of course, adds design complexity and

Table 2

Summary of ICF Reactor Studies with a Published Self-Consistent Set of Operating Parameters

Ref.	Study or Reactor Concept	Lab.	Driver/ Type(a)	DT Fusion Power MW_{th}	Net Elec. Power MW_e	Driver Energy MJ	Driver Effic. %	Target Gain	Target Yield MJ	Rep Rate/ Cavity Hz	First Wall Protect. Scheme	First Wall Structure(c)	Breeder	Blanket Multiplication
1	Blascon	ORNL/UR	L-CO_2	3450	1035	1	10	100	100	0.1(b)	Liq. Li	SS	Li	NG
2	Wetted Wall	LANL	L-NG	100	NG	NG	NG	NG	100	1	Li WW(d)	NG	Li	1.27
3	Saturn	FRG	L-NG	5000	1540	0.6	10	83	50	100	Dry Wall	NG	Li	NG
5	Magnetic Protection	LANL	L-NG	1000	300	NG	NG	NG	100	2.5(e)	Magnetic	Nb	Li	NG
6	Suppressed Ablation	LLNL	L-SWL	700	275	0.1	10	70	7	10(f)	WW	Nb	Li	NG
9	Dry Wall	LLNL	L-SWL	200	NG	0.477	10	21	10	20	Dry Wall	C/SS	NG	NG
11	Moving Wall	SNL	I-e	3000	1000	NG	NG	NG	85	35	Moving Curtain	C	Li	1.3
12	SOLASE	Misc.	L-CO_2	3000	965	1	6.7	150	150	20	Gas	C	Li_2O	1.08
13	BAN-Fluid Wall	BNL	H	1300	500	NG	NG	NG	4000	0.33	Liq. Metal	C	Li or PbLi or Flibe	NG
14	Fluid Wall	LLNL	L-NG	1000	380	1	2	700	700	1.43	Liq. Li	SS	Li	1.24
16	HYLIFE	LLNL	L-SWL	2700	1010	4.5	5	400	1800	1.5	Liq. Li	2-1/4 Cr-1 Mo	Li	1.16
15	Hybrid	LLNL	L-SWL	200	400	0.1	2	100	10	20	Dry Wall	C	Li	Hybrid
17	SOLASE/Hybrid	Misc.	L-HF	1240	700	1.6	2.6	194	310	4	Gas	Zircaloy	Li	Hybrid
22	Dry Wall	West	H	3500	1346	2	30	175	350	10	Dry Wall-Ta	Ta/HT-9	Li	1.23
21	HIBALL Liquid	Misc./FRG		H-RF	7920(e)	3768(e)	4.8	26.7	83	400	5(e) Pb83Li17	HT-9	$Pb_{83}Li_{17}$	1.28
23	SENRI-I	Japan	L-CO_2	1000	426	5	10	200	1000	1	Liq. Li	316 SS	Li	1.24
24	UTLIF-I	Japan	I-P	2844	1100	3.5	10	135.4	474	6	Gas	V-20 Ti	Li	1.06
25	ADLIB-I	Japan	I-P	2562	900	5	10	170.8	854	3	Gas	HT-9	Li	1.08
26	Cascade	LLNL	L-SWL,H	1500	800	1.5	10	200	300	5	BeO/$LiAlO_2$ Granules	SiC	$LiAlO_2$	1.11
27	Pulse*Star	LLNL	L-SWL	2590	1115	2	10	300	600	4.3	Pb-Li-Pool	FS	$Pb_{83}Li_{17}$	1.27
28	Sunburst	LLNL	L-SWL	1800	1046	4.5	5	400	1800	1	Liq. Li	Y/Al/FG	Li	1.16
29	UTLIF-II	Japan	I-P	2844	1250	3.5	10	135.4	474	6	Gas	V-15 Cr-5 Ti	Li	1.12
32	HIBLIC-I	Japan	H-RF	4000	1500	4	25	100	400	1(f)	Li Curtain	HT-9	Li	1.08
33	HIBALL-II	Misc/FRG	H-RF	7920	3768	5	27	83	400	5(e)	Liquid	HT-9	$Pb_{83}Li_{17}$	1.28
34	EAGLE	Bechtel	I-D	900	275	5	22	60	300	3	Li Mist	HT-9	Li	NG
31	SIRIUS	Misc./UR	L-KRF	737	260	1.1	NG	100	136	5.5	Dry Wall	SiC	Li	1.32

(a) L = Laser
H = Heavy Ion
I = Light Ion or Electron
SWL = Short Wave Length

(b) 345 cavities
(c) SS = Stainless Steel
FS = Ferritic Steel
FG = Fiberglass

(d) WW = Wetted Wall
(e) 4 cavities
(f) 10 cavities NG = Not Given

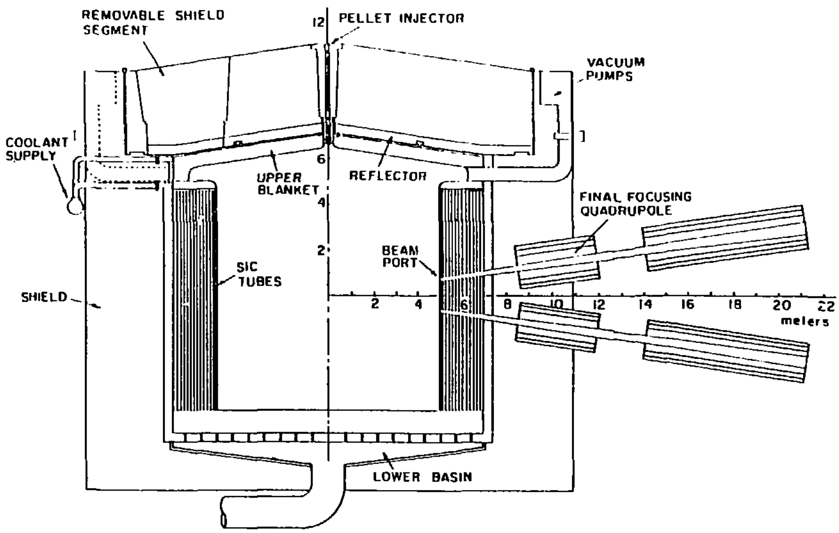

Fig. 1. HIBALL: A heavy ion beam driven, LiPb protected reactor.

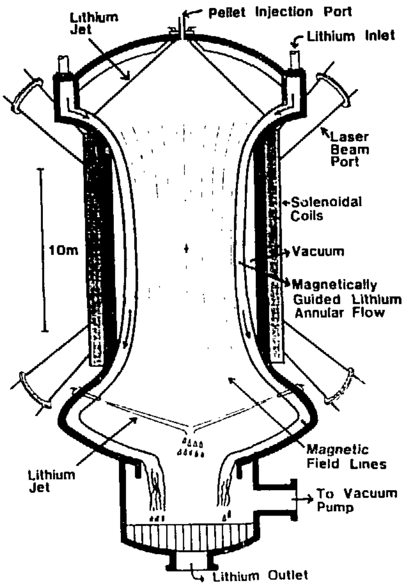

Fig. 2. An ICF reactor concept with magnetically guided Li flow, SENRI-IA.

could be difficult to use with particle beam drivers.

The Pulse*Star design[27] (Figure 3) has two features that make it different from other ICF reactor concepts. First, it is a pool-type reactor in which the reaction chamber, pumps and heat exchangers are submerged in a pool of liquid metal coolant (LiPb or Li). This simplifies the design and increases the power density inside the containment structure. Second, in Pulse*Star the thick liquid metal region is created by very dense sprays that are controlled by impacting upon a screen about 2 m inside the structural wall. This dense spray region absorbs neutrons as well as providing a large surface area for recondensation of vaporized material and, therefore, allowing a higher pulse rate. The design and lifetime of the screen is still quite uncertain. It must stop the liquid metal droplets from falling into the beam lines, withstand the fusion pulses, be easy to replace, and allow the vaporized coolant to flow through to the droplets.

Self-Renewing Dry Wall. The Cascade reactor[26], shown in Figure 4, combines features from two previous ICF reactor designs.[10, 15] Li-ceramic granules are fed by gravity into the ends of a double-conical,

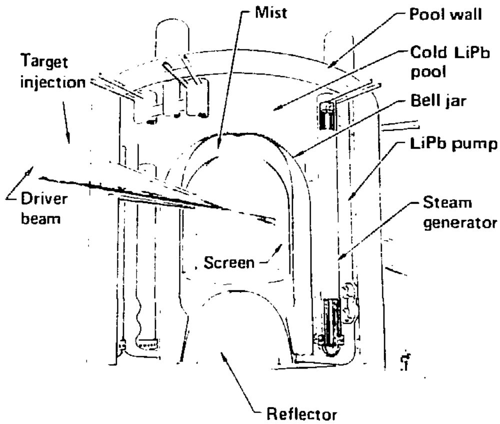

Fig. 3. Pulse*Star: A Pool-Type, LiPb Cooled Reactor.

rotating reaction chamber. Held against the wall by centrifugal action, the meter-thick blanket flows toward the equator where the granules are literally thrown into a vacuum heat exchanger. The rate of flow is controlled by the size of the equatorial openings and the rate of rotation. Using a combination of a fast moving surface layer of BeO and a slower moving thick layer of $LiAlO_2$, a mean exit temperature of ~ 1700 K can be achieved. Coupled with a high temperature helium turbine cycle, it is anticipated that thermal to electric conversion efficiencies of over 55% are achievable. Using a SiC ceramic chamber wall allows high temperature operation and results in minimal activation. The pulse rate of this reactor is limited by the recondensation of granule material vaporized with each pulse. A recent study[39] has indicated that the gas-flow rate into the granular bed will be large enough that many layers of granules will be available for recondensation. Therefore, a pulse rate of at least 5 Hz is estimated. The major technological uncertainty associated with the Cascade concept is the possible comminution (breaking apart) and/or aggregation of the granules.

Symmetric Illumination Reactor. Almost all the previous reactor studies assumed asymmetric illumination of the fusion pellet by the driver beams (even though some had allowed many beams). The SIRIUS design[31] allows spherically symmetric target illumination by 20 or 32 beams. A dry wall design was selected as the most appropriate (see Figure 5). The chamber wall consists of a 20-sided icosahedron of SiC tiles that act

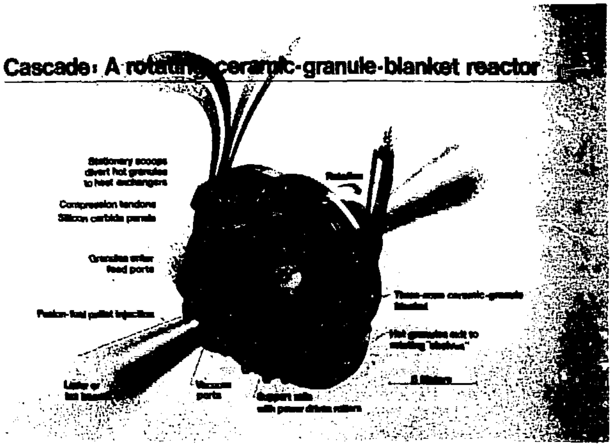

Fig. 4. Cascade: A rotating, granular ceramic wall reactor.

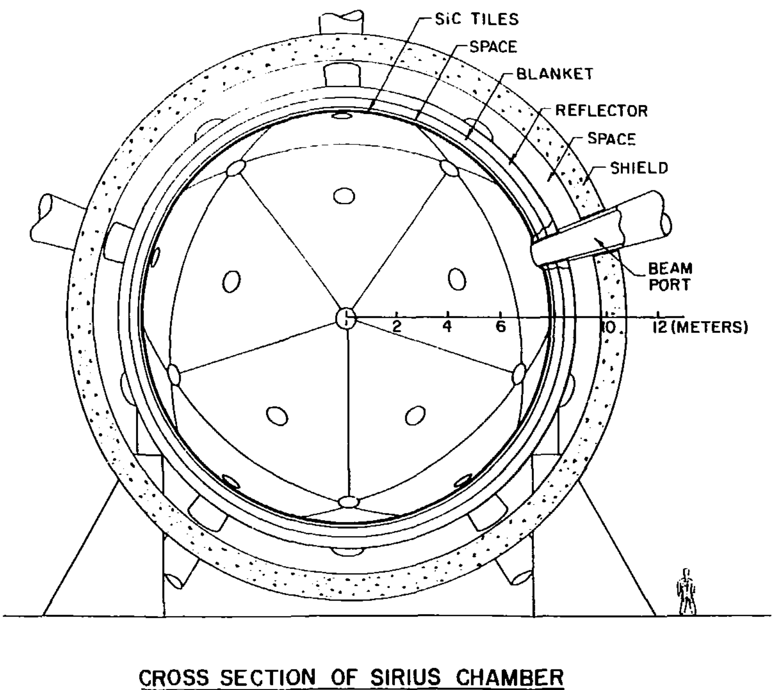

Fig. 5. SIRIUS: A dry wall, symmetrical illumination reactor.

as a thermal damper for the liquid lithium cooled HT-9 structure beyond. The low yield fusion pulse (134 Mj) and power (737 MW) allows placement of the dry first wall at a radius of 8 m. The final mirrors for the 32 beams are placed at a radius of 21 meters to produce as compact a design as possible for uniform illumination. Some of the critical technical issues identified in this study include the lifetime of the large SiC tiles, survivability and dimensional stability of the final optics, induced radioactivity, and extrapolation to an economically viable power.

Advanced Fuels. The LOTRIT reactor[36] was conceived to reduce the tritium inventory in an ICF reactor to a minimum. A tritium catalyzed DD fuel is used in the fusion pellet. The small amount of tritium needed for catalysis is bred in the fuel pellet itself so that no external breeding blanket is required. In LOTRIT a liquid lead fall is used for wall protection and heat transfer. The major new technological risk involved in this reactor is the use of the DD fuel itself. The achievement of high gain in a catalyzed DD burner is more difficult than in a DT burner and not likely to be achieved until much later.

Direct Conversion. The economic attractiveness of ICF reactors can be enhanced by improving the efficiency of converting fusion energy into electricity, if that can be done without increasing the cost too much. Many studies are pursuing this goal for coal and fission plants. For ICF to make a relative gain we must take advantage of some unique quality of fusion energy.

In the Sunburst design[28] the fusion energy is trapped in a 3-m radius ball of lithium that is injected with the fusion pellet. The lithium ball is designed to maximize the conversion of fusion energy into kinetic energy of the lithium. This kinetic energy could then potentially be extracted at rather high efficiency by having the moving lithium compress a magnetic field. In another recent proposal[40], a fusion pellet with a large fraction of debris energy is surrounded by a massive solid lithium shield that deflects the debris through an MHD device. In both cases, further energy must be extracted through a thermal cycle. For Sunburst, such an approach could produce a total efficiency approaching 60%. Both these designs, of course, have associated technological challenges. It is not clear whether the high conversion efficiencies can be realized in practice and the necessity to inject large masses of Li with the fusion pellet may limit the pulse rate.

Development Facilities. The potentially high cost of fusion technology development facilities may be a major obstacle even if an attractive reactor is foreseen. Increasing the number of customers for such facilities may increase the benefit/cost ratio. In the FIRST STEP[35] study it is suggested that a low-power ICF facility might address the needs of ICF physics and engineering research, produce some nuclear materials for other customers, and ultimately produce some power for sale. Recently the SIRIUS-M[41], an ICF materials test facility, has been designed to address the issue of lower cost development facilities. Such a multipurpose facility approach may be more palatable than one dedicated to a single purpose.

ICF REACTOR DESIGN TRENDS

Much of the recent ICF reactor design work continues to explore the possible design and operating space for ICF technology. The separability of effects in ICF reactors permits a large number of combinations and we, therefore, expect to see further exploration of this type in the future. Beyond this, however, there do seem to be some discernable trends. Our remarks on these will address two issues: 1) safety and environmental impact, and 2) economic competitiveness.

Safety and Environmental Issues. Since radioactive materials will exist in any fusion reactor, attention must be paid to the amounts of such materials that might be released in an accident, that will be released routinely during steady state operations, and that must be safely disposed of during the lifetime of the plant. One factor that is important to the perceived safety in accidental release senarios is the quantity of stored energy that is present in a plant at any one time. For a 1000 MW_e plant of nominal 40% thermal/electric conversion efficiency, there will be about 10^{12} J of stored thermal energy at any given time (about the same as the chemical energy in a railcar of propane). All such reactors will have to deal with this and, thus, the perceived safety of other stored energy is often judged relative to this value (even though the potential rate of energy release is far more important). The HYLIFE reactor has about 10^{13} J of stored chemical energy in its liquid lithium (about the same as an LMFBR). Even though a lithium fire releases energy more slowly than a gasoline fire, the large potential energy often gives rise to the perception of significant hazard. Several of the recent reactor studies have explored the use of non-flammable materials like LiPb or Li ceramics to reduce this concern. The only identifiable stored energy capable of rapid release in these reactors is the 10^7 J of electrical energy for the driver.

A great deal of attention is also being paid to the routine release of radioactivity in steady state operations. For ICF reactors, the principal concern is tritium. Here studies[42] have indicated that control of steady state tritium release in reactors using LiPb may be more difficult than in those that use lithium. The lithium ceramics, on the other hand, may address both the fire and tritium leakage issues. One of the new designs, LOTRII, addresses this tritium control issue by using an advanced fuel pellet that eliminates the need for external (to the pellet) tritium breeding.

Concerning the induced activity and its impact, Tables 3, 4 and 5 show three indicators of recent design trends: the total induced activity, the decay heat and the inhalation biological hazard potential. All figures are given for a nominal 1000 MW_e power plant after 30 years of operation. In the tables, results are compared for a typical pressurized water reactor (PWR), the Starfire tokamak fusion design, and two ICF designs, HYLIFE and Cascade. For these calculations, an older version of Cascade using Li_2O granules was used. It is seen in Table 3 that the Cascade not only has the smallest amount of activity at shutdown, but its activity is short lived. In fact, at 50 years the activated material from Cascade would satisfy current U.S. government standards for shallow land disposal without dilution (10 CFR 61).

Decay afterheat shown in Table 4 is an indicator of the need for emergency cooling to prevent meltdown. If values are smaller than a few MW, it is likely that radiative cooling would be sufficient and no active emergency cooling system would be required. Both ICF designs satisfy this criterion.

Finally, the inhalation biological hazard potential (BHP), an indicator of the potential risk due to release of debris to the biosphere, is shown in Table 5. It is the volume of air that must be mixed with the induced radioactive material in order to make it safe for humans to breathe. Of course, only a small fraction of the material would be released in any given accident but, again, the total amount is used as a relative indicator of the magnitude of the problem. Cascade again appears to have the lowest potential risk by a large margin.

It is clear that there is a strong trend to produce inherently safer reactors that have minimal environmental impact. We expect these design trends to continue indefinitely since they enhance inherent advantages of fusion power over fission. Furthermore, ICF studies will clearly continue to take advantage of their ability to put massive amounts of radiation absorbers inside the reaction chamber.

Economic Competitiveness. When costs were estimated for the first self-consistent ICF power plant concepts, the impression was created that such plants will be large and expensive. Work on the recent designs has, therefore, tended to emphasize ways to improve economic competitiveness.

Closer looks at the economics of ICF power plants[43] have concluded that optimal yields are somewhat smaller and pulse rates higher than suggested earlier. However, it was also found that the dependence is very weak above about 5 Hz. Thus, many of the new designs have tended to operate in this regime.

A great amount of effort has, and will continue to be, spent on the most important element of an ICF plant with respect to improving economic competitiveness, the driver. Studies and experiments on all drivers are directed toward lowering the cost and increasing the efficiency. Progress has been made on short wavelength lasers (gas, FEL and solid state) and on ion beams (light and heavy). Each system still has its advocates and no clear cut winner is yet discernable.

Several of the recent design studies were directed toward reducing the cost of electricity. In particular, the use of multiple reactors with a single driver (HIBALL), a pool-type reactor (Pulse*Star), high operating temperature (Cascade), and non-steam power production cycles (Sunburst) were all aimed at that goal. It is likely that this design trend will continue. In particular, Nuckolls[44] recently suggested that the community look beyond first generation ICF reactors to catch a glimpse of the ultimate economic potential of ICF power. He concludes that economic competitiveness is likely with reasonable physics progress and with more innovative designs that make better use of the high quality of fusion neutrons and ions.

In the last several years it has also been recognized that economy of scale may not save fusion power because of the great forecasting and financial risks such large power plants represent. There has emerged a "think small" mentality, although it is difficult to project what small will mean in the far future. The fission community is considering the concept of the modular plant. Another paper at this conference[45] considers such an approach for ICF reactors. A small plant (e.g., 500 MW_e) is built first and then more reactor modules (including reaction chambers, heat exchangers, containment

Table 3

Total neutron induced activity (kCi) for a 1000 MW_e reactor operating 30 years.

Reactor Type	Time after shutdown 0	1 d	1 m	30 y	100 y
PWR	1.7 (10^7)	(a)	(a)	(a)	(a)
Starfire	6 (10^6)	(a)	(a)	2400	292
HYLIFE	300,000	200,000	150,300	90	33
Cascade	200,000	7,000	6,000	11	8

(a) Not available

Table 4

Decay heat of induced activity (kW) for a 1000 MW_e reactor operating 30 years.

Reactor type	Time after shutdown 0	1 d
PWR	180,000	(a)
Starfire	70,000	(a)
HYLIFE	2,000	200
Cascade	8,000	11

(a) Not available

Table 5

Inhalation bhp (km^3) for a 1000 MW_e reactor operating 30 years

Reactor type	Time after shutdown 0	1 d
PWR	1.2 (10^{10})	---
Starfire	1.7 (10^{10})	---
HYLIFE	5 (10^7)	3 (10^7)
Cascade	8 (10^6)	1.3 (10^6)

buildup, and turbines) are added to the same driver later as needed. The cost of electricity is high at first, but as modules are added, it rapidly falls almost as far as if the larger plant had been built in the first place. The advantage of this approach is that the capital costs are smaller for the initial module, and operating revenues gained from the first module can be used to help finance later modules. Since the ICF driver can service more than one chamber, it is particularly adaptable to this process. We expect that more work will be done on specific ICF designs to explore this possibility.

The final economic issue we expect to see given more attention in the future is the development costs. It is clear that several large facilities are going to be needed to move ICF technology out of the laboratory and into commercial reality. It has been suggested that for ICF (and MCF as well), one of the major difficulties may be in finding an affordable development path. We expect a new round of studies of development facilities that are more affordable.

REFERENCES

1. A. P. FRAAS, ORNLK-TM-3231, July 1971.

2. L. A. BOOTH, (Ed.) LA-4858-MS, Feb. 1972.

3. F. H. BOHN, et al., In Proc. 5th Symp. Engr. Probl. of Fusion Research, Princeton, NJ, CONF-73119, Nov. 1973, p. 107.

4. J. M. WILLIAMS and T. G. FRANK, Los Alamos Report, LA-UR-73-1625 (1973)

5. T. FRANK, et al., In Proc. 1st Top, Mtg. on Tech. Controlled Nucl. Fusion, San Diego, 1974, CONF-740402, p. 83.

6. J. HOVINGH, et al., In Proc. 1st Top. Mtg. Tech. Controlled Nucl. Fusion, San Diego, 1974, CONG-74042, p. 96.

7. R. J. BURKE, Argonne Report, ENG/CTR/TM-31, (1974).

8. L. A. BOOTH, D. A. FREIWALD, T. G. FRANK and F. T. FINCH, Los Alamos Report, LA UR-75-1808 (1975).

9. J. HOVINGH, p. 765 in Proc. Second Topical Meeting on Tech. of Controlled Thermonuclear Fusion, Ed., Kulcinski, G. L., CONF-760935-P2 (1976).

10. R. J. BURKE, to be published.

11. S. G. VARNADO and G. A. CARLSON, Nucl. Tech., 29, 415 (1976).

12. B. BADGER, et al., "SOLASE - A Laser Fusion Reactor Study", UWFDM-220, 1977.

13. J. POWELL, et al., "A Liquid Wall Boiler and Moderator (BAM) for Heavy Ion Pellet Fusion Reactors", BNL-50744, 1977.

14. J. A. MANISCALSO, W. R. MEIER, and M. J. MONSLER, UCRL-79652, 1977.

15. J. MANISCALSO, et al., Lawrence Livermore Laboratory Report, UCRL-52349 (Nov. 1977).

16. Laser Program Annual Report - 1978, Vol. 3 Chapter 9, UCRL-50021-78, published March 1979.

17. B. BADGER, et al., UWFDM-270, 1979.

18. J. H. PENDERGRASS, et al., LA-UR-79-1316, 1979.

19. C. YAMANAKA, ILE-7913P, 1979.

20. J. H. PENDERGRASS, T. G. FRANK, and Bohachevsky, I. O., LA-UR-80-2891, 1980.

21. B. BADGER, et al., "HIBALL - A Conceptual Heavy Ion Beam Fusion Reactor", UWFDM-450/KfK-3202, June 1981.

22. G. SUCOV, to be published.

23. C. YAMANAKA, et al., "Concept and Design of ICF Reactor - SENRI-I", Inst. of Laser Engineering Report, ILE-8127 P, Oct. 5, 1981. See also ILE Reports 8128 P, 8207 P, 8215 P, 8216 P.

24. H. MADARAME, et al., Univ. of Tokyo Report 0142, Sept. 1982.

25. H. MADARAME, et al., Univ. of Tokyo Report 0144, Sept. 1982.

26. J. H. PITTS, "Cascade: A Centrifugal-Action Solid-Breeder Reaction Chamber," Nucl. Tech./Fusion, Vol 4, No. 2, Part 3, pp. 967-972 (1983), also Lawrence Livermore National Laboratory, Livermore, Calif., UCRL-88208 (1983).

27. M. J. MONSLER, "Pulse*Star: Ideas for a Commercial Inertial Fusion Power Plant", 1982 Laser Program Annual Report, Lawrence Livermore National Laboratory, Livermore, Calif., UCRL-50021-82, Chap. 8, 1983.

28. C. P. LASCHE, "Inertial Confinement Fusion with Direct Electric Generation by Magnetic Flux Compression," Lawrence Livermore National Laboratory, Livermore, Calif., UCRL-53434 and Nuclear Technology/Fusion, Vol. 4, No. 2, Part 3, pp. 866-871, 1983.

29. H. MADARAME, et al., UTNL-R-156, Univ. of Tokyo, December 1983.

30. S. EDD, et al., to be published in Laser Interaction and Related Phenomena - Vol. 6, Ed. by H. Hora and G. Miley, Plenum Pubs., 1986.

31. "SIRIUS - A symmetric Illuminated Low Poer Fusion Reactor, Progress Report", UWFDM-568, by Univ. of Wisconsin, 1984.

32. "Heavy Ion Fusion Reactor - HIBLIC-1", Nagoya Univ., IPPJ-663, Jan. 1984.

33. B. BADGER, et al., "HIBALL-II", FPA-84-4-KfK-3840/UWFDM-625, Univ. of Wisconsin, December 1984.

34. To be published - Bechtel.

35. W. W. SAYLOR, et al., "A 'FIRST STEP' Toward ICF Commercialization", ANS Transactions, Vol. 46, pp. 241-244, June 1984.

36. G. MILEY, et al., "An ICF Reactor Concept using ^{3}He-AFLINT Targets," Nucl. Tech./Fusion, Vol 4, No. 2, Part 3, pp. 889-894 (1983).

37. G. L. Kulcinski, J. Nucl. Materials, Vol. 85 and 86, 87 (1979).

38. M. J. MONSLER, et al., "An Overview of Inertial Fusion Reactor Design", Nucl. Tech./Fusion, 1, pp. 302-358, July 1981.

39. W. J. HOGAN, et al., "Chamber Clearing Time", Lawrence Livermore National Laboratory Laser Program Annual Report 1984, (to be published).

40. R. TSUJI, and S. IDO, "Inner Frozen Metal Blanket Concept from ICF Reactor", Japanese Journal of Applied Physics, 22, No. 6, pp. 987-991, June 1983.

41. To be published - University of Wisconsin.

42. J. A. BLINK, and N. J. HOFFMAN, "Tritium Control and Activation in the Pulse*Star Reactor", Lawrence Livermore National Laboratory, UCRL 89291 and 10th Symposium on Fusion Engineering, Philadelphia, Penna., December 1983.

43. W. R. MEIER, "Cost Goals for ICF Reactors", Lawrence Livermore National Laboratory, Laser Program Annual Report '83, UCRL 50021-83, Livermore, 1984, pp. 7-46 to 7-50.

44. J. H. NUCKOLLS, "Economic Potential of Inertial Fusion", Proc. of "A Symposium on Fusion Power Development - The Next Decade", Fusion Power Associates, April 1984 (to be published).

45. W. R. MEIER and W. J. HOGAN, "HIB Fusion Economics", 6th Topical ANS Conference on Fusion Technology, March 1985.