Fusion Reactor Design: On the Road to Commercialization

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Abstract

The worldwide effort in fusion is now approximately 2 billion dollars per year and over 12 billion dollars has been invested since 1951 in developing this energy source for the 21st century. A vital component of the past efforts in fusion research has been the conceptual design activities performed by scientists and engineers around the world. Almost 80 such designs have been published and this article discusses how recent conceptual designs have affected our perception of future fusion reactor performance.

I. Introduction

Many scientists now believe that fusion research is in the process of transition from a basic research phase into an engineering phase. Presumably, this engineering phase will transcend into a commercialization phase sometime in the early 21st century. In preparation for the commercialization phase, many laboratories around the world have conducted conceptual reactor design studies in order to obtain a preview of the important features associated with a fusion economy. Such reactor studies have been important in outlining the potential economic, environmental, and safety issues that will have to be faced as well as what new technologies have to be developed by industry.

The object of this paper is to briefly address what impact such studies have had in the past few years and, based on our knowledge today (1983), what are the issues that will shape our move from the engineering to the commercialization phase.

II. Current Status of Worldwide Fusion Effort

At the present time, fusion research programs around the world fall into three general classes. The first contains the major fusion programs from the US, USSR, Japan and Europe which employ more than 500 scientists each. The second category includes countries where 50-500 scientists are employed such as in Canada, People's Republic of China, Poland, and Australia. The third category includes programs where less than 50 scientists each are employed. Significant information on the three categories is shown in Table 1.

Table 1 Summary of Worldwide Fusion Research Effort

Category		Approx. Number of Scientists	Annual Expend. FY 82, M$	Total Expended Since Program Beginning, M$	$/Capita FY 82
I.	US	> 2,000	688	4,579	3.1
	USSR	> 1,600	~ 660	~ 4,500	~ 2.5
	Japan	~ 800	~ 300[(a)]	~ 1,300	~ 2.6
	EC	~ 1,000	287	1,960	1.1
II.	Peo.Rep.China	~ 500	~ 20[(b)]	?	~ 0.02[(b)]
	Canada	~ 50	~ 4	?	~ 0.15
	Australia	57	?	?	?
	Poland	92	?	?	?
III.	(c)	~ 250	~ 30	?	~ 0.03
		> 6,400	~ 2,000	> 12,500	~ 0.50

(a) including est. salaries
(b) 1980
(c) Austria, Czechoslovakia, Finland, Hungary, Portugal, Romania, Spain, India, Iran, Israel, Sudan, South Africa, Turkey, Korea, Malaysia, New Zealand, Argentina, and Brazil.

The current estimate of professional scientists in the world fusion program is at least 6,400. It is also of note that approximately 2 billion dollars was spent on fusion research in FY 82. Approximately 2/3 of that was spent in the United States and Soviet Union and roughly 15% each in Japan and the European Community. Since the fusion program officially began in 1951, some 12.5 billion dollars has been spent worldwide, again, mainly in the four countries of category I.

The last column in Table 1 illustrates the approximate expenditure per capita in FY 82. The investment ranges from ~ 1$ per capita in Europe to ~ 3$/capita in the US. Worldwide the investment in fusion research is ~ $0.50 per capita.

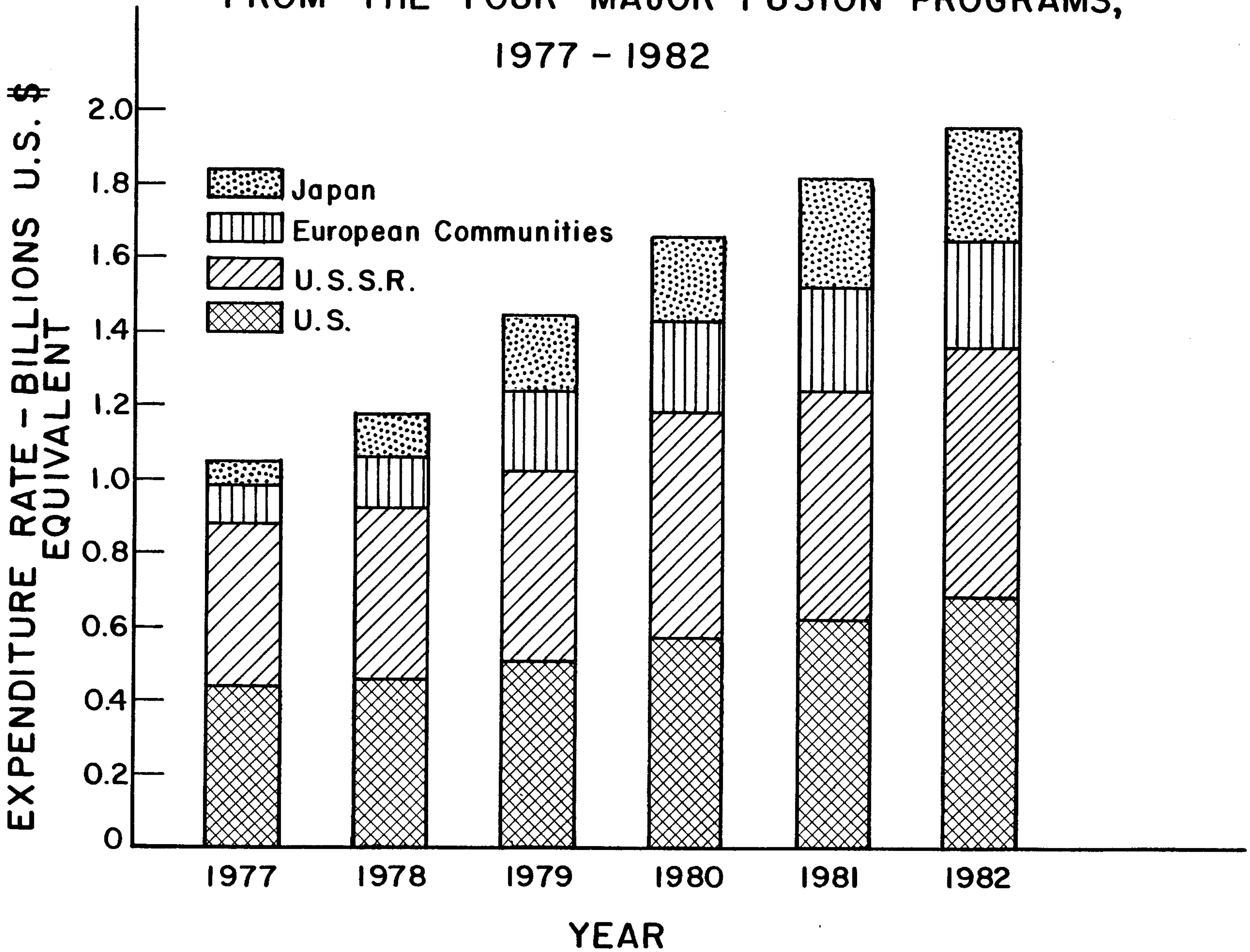
Finally, a perspective on the accelerated pace of the fusion program can be gained from Figure 1 where the estimated yearly expenditures for 1977-82 are given. It is worthwhile noting that investments in fusion research have doubled from 1 B$/year in 1977 to 2 B$/year in 1982. In fact, approximately 70% of the total expenditure on fusion to date has been made in the last five years!

III. Background for Fusion Reactor Studies

Research into the fundamental nature of the fusion process has been conducted for more than 35 years. Magnetic fusion concepts were the first to be studied but in the early 1960's, the first inertially confined fusion concepts were also investigated. Although L. Spitzer and his colleagues carried out the first "reactor" design in 1954 (NYO-6047); there were essentially no self-consistent studies ranging from plasma physics to materials, power cycles, economics and the environment until the early 1970's. From those studies, one can now

FIGURE 1

FINANCIAL SUPPORT FOR FUSION RESEARCH FROM THE FOUR MAJOR FUSION PROGRAMS, 1977 - 1982



conclude that the leading contenders for the first commercial fusion power plants in the magnetic confinement area are the tokamak and the tandem mirror concept. Similarly, the leading contenders in the ICF area are the laser and ion beam approach. Other concepts such as stellarators, compact tori, impact fusion, etc. may eventually replace these four concepts, but based on the physics knowledge of 1983, the four previously mentioned approaches are clearly far ahead. Therefore, we will only concentrate on tokamak, mirror, laser and ion beam approaches for this paper.

Tables 2 and 3 list the studies that have been published since 1967 using the major magnetic and inertial confinment concepts. Only "pure" fusion designs (i.e., not including fission-fusion hybrids, synthetic fuels production, etc.) are included here. Certainly if one were to add work on hybrids, pinch devices, compact toroids, etc., the number of studies would be somewhat larger.

These studies are broken up into two categories which are defined below. A Scoping Study is defined as:

> "A limited study with particular emphasis on a field of interest such as plasma physics, neutronics, materials, power balance, etc., performed by a few individuals and reported in short (less than 10 to 20 pages) papers or reports."

Table 2 Summary of Major DT Commercial Electricity Producing Reactor Designs

	MAGNETIC								INERTIAL							
	TOKAMAK				MIRROR				LASER				ELECTRON, LIGHT ION AND HEAVY ION BEAM			
Year Pub.	Conceptual	Ref.	Scoping	Ref.	Conceptual	Ref.	Scoping	Ref.	Conceptual	Ref.	Scoping	Ref.	Conceptual	Ref.	Scoping	Ref.
1967			Carruthers	1												
1968			Golovin	2			Rose, Fraas	3								
1969																
1970																
1971							LLL-Min. B	4			Blascon	5				
1972			MARK-I	6					LASL-Wetted Wall	7						
1973	UWMAK-I ORNL	8 9									SATURN	10				
1974	PPPL	11	JAERI BNL	12 13	LLL-Min B	14					LASL-Mag/Protec. LLL-Suppl. Abla.	15 16				
1975	UWMAK-II	17														
1976	UWMAK-III	18	MARK-II	19											SANDIA-Elec. Hearthfire-HIB	20 21
1977			Jülich	22	LLL-TMR	23			SOLASE	24	LLL-Fluid Wall	25			BAM-HIB	26
1978					LLL-Min B	27	LLL-FRM	28			LLL-Hylife	29				
1979	NUWMAK HFCTR	30 31	MARK-IIC	75			LLL-TMR/TB	32	Hylife	33						
1980	STARFIRE	34			WITAMIR-I LLL-FRM	35 36										
1981			STPR-P	74			LLL-FRM	37	Westinghouse	38			HIBALL-HIB West.-HIB	39 40		
1982									SENRI-I	67					UTLIF-I ADLIB-I	68 69
1983					MARS	66										

Table 3 Summary of Major DT Engineering Test or Expermental Power Reactors

Year Pub.	MAGNETIC								INERTIAL							
	TOKAMAK				MIRROR				LASER				ELECTRON, LIGHT ION AND HEAVY ION BEAM			
	Conceptual	Ref.	Scoping	Ref.	Conceptual	Ref.	Scoping	Ref.	Conceptual	Ref.	Scoping	Ref.	Conceptual	Ref.	Scoping	Ref.
1974			F/BX	41	FERF	42										
1975			T-20	43							LAFERF	44				
1976	ANL-EPR GA-EPR ORNL-EPR FINTOR-I	45 46 47 48	PETR	49												
1977	TETR ORNL-DEMO	50 51	West.-TNS JXFR-I	52 53												
1978	GA-DEMO GA-TNS ORNL-TNS	54 55 56														
1979			JXFR-II PETF	57 58												
1980	INTOR ETF	59 60					TMNS	61								
1981	FED	62	FINTOR-D	76	TASKA	63										
1982	STARFIRE-D	64			TDF	70										
1983	FER FED-R	65 72	HESTER	77	TASKA-M	73	MFTF - α + T	78							TDF-LIB	71

In contrast to a scoping study, a full Conceptual Design Study is defined for this paper as:

> "A wide ranging study performed by a large number of multi-disciplinary scientists which includes a detailed analysis in most of the following areas: plasma physics, driver (or magnet) design, heating and fuel exhaust, neutronics, blanket design and thermal hydraulics, materials, tritium, power cycles and heat rejection, environment and safety, and cost estimates."

Furthermore, full Conceptual Studies are contained in a single well documented report which covers all aspects of the design in a self-consistent manner.

The reason to separate Scoping Studies from full Conceptual Design activities is because it is difficult to obtain a complete picture of a design from a 10 to 20 page report which lists parameters but does not document their origin. It is only by extensive documentation that one can assure self-consistency between various aspects of the reactor.

Analysis of these two tables with respect to "pure" fusion and the major confinement approaches reveals the following points:

1. In the past 16 years there have been at least 78 reactor studies with 46 of them aimed at commercial electricity producing plants and 32 engineering test or experimental power facilities.

2. With respect to major concepts, the studies can be divided into the following categories.

Concept	Conceptual	Scoping	Total
Tokamak	23	18	41
Mirror	10	7	17
Laser	5	7	12
Ion	2	6	8
	40	38	78

3. In contrast to the high level of commercial tokamak design activity in the 1970's, there has not been a major commercial tokamak study performed since 1980.

4. Whereas the early design activities in the ICF design activities in the ICF area were dominated by the US, four out of last six designs studies performed since 1979 have been done by groups outside the US.

5. Over the last 10 years more than 75% of the design activity with respect to engineering test facilities has been conducted in the tokamak area. However, engineering test reactor design in the tandem mirror area has increased dramatically in the last four years as small (< 100 MW) neutron production facilities appear to be feasible.

6. Very little effort has been devoted to the design of engineering test facilities in the ICF area.

In summary, there have been at least 78 conceptual and scoping studies for commercial power plants and engineering test facilities, and over 50% of the worldwide effort has been devoted to tokamaks. In recent years, the majority of tokamak design work has been in the area of near term experimental test facilities whereas the work in the ICF area has been mainly devoted to commercial reactor studies. It is estimated that in the past 10 years alone, over 1,000 man years of effort has been applied to such design activities.

IV. Recent Examples of Commercial Reactor Studies

It is not the purpose of this report to describe the details of fusion reactor designs conducted in the past. That can be obtained from the references listed in Tables 2 and 3. However, we have included in Table 4 a general summary of the most recent, major reactor design in the area of Tokamaks (STARFIRE [34]), Tandem Mirrors (MARS [66]), Lasers (Hylife [29]) and Ion Beams (HIBALL [39]). Schematics of the reactors are shown in Figures 2-5. They all have been published since 1980 and they all are designed to produce more than 1000 MW of net electricity. The neutron wall loadings have increased from the 1-2 MW/m^2 of the early 1970's to 2-7 MW/m^2 in the most recent designs. All the reactors except MARS have utilized first wall or component protection schemes. Some of the unique features which bear on commercialization will be reviewed in the next section.

Table 4 Summary of Most Recent Major Commercial Fusion Reactor Designs

	Tokamak STARFIRE	Mirror MARS	Laser Hylife	Ion Beam HIBALL
Year Pub. (Ref.)	1980 [34]	1983 [66]	1978-83[33]	1981 [39]
Net Elec. Output - MWe	1200	1200	1004	942x4 (a)
DT Fusion Power - MW	3500	2570	2700	2000x4 (a)
Volume of Reaction Chamber - m^3	950	237 (b)	634	793x4 (a)
Pulse Length	Cont.	Cont.	1.5 Hz	5 Hz (a)
n Wall Loading - MW/m^2	3.6	4.3	6.9 (c)	2.3 (c)
Coolant/Breeder	H_2O/Solid	$Pb_{83}Li_{17}$	Li	$Pb_{83}Li_{17}$
Structure	St. Steel	HT-9	2 1/4 Cr-1 Mo	HT-9/ SiC
Maximum Coolant Temp. °C	320	500	500	500
Key Confinement Technologies	•S/C Mag. (11.1 T) •Lower Hyb. RF (90 MW)	•Hybrid Mag.(24 T) •ECRF (84 MW)	•KrF (4.5 MJ)	•10 Gev Bi (4.8 MJ)
Unique Design Features	•Current Drive •Pumped Limiter	•Drift Orbit Pumping •Gridless Direct Convertor	•Li Jets	•SiC tubes filled with liquid Pb-Li alloy •Multiple cavities

(a) 4 chambers per driver
(b) including end plugs but not direct convertor
(c) at first wall without liquid metal protection

FIGURE 2

STARFIRE REFERENCE DESIGN

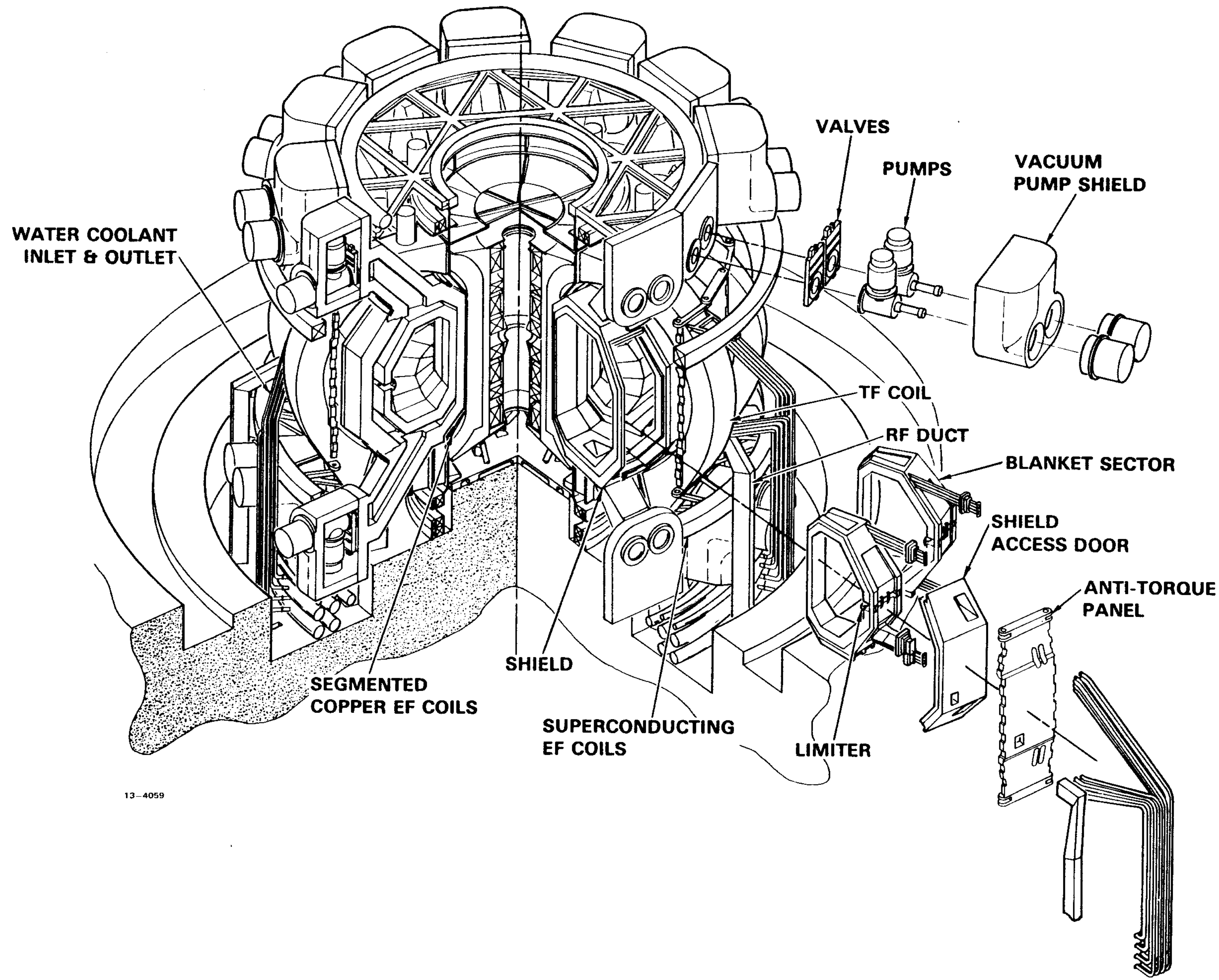
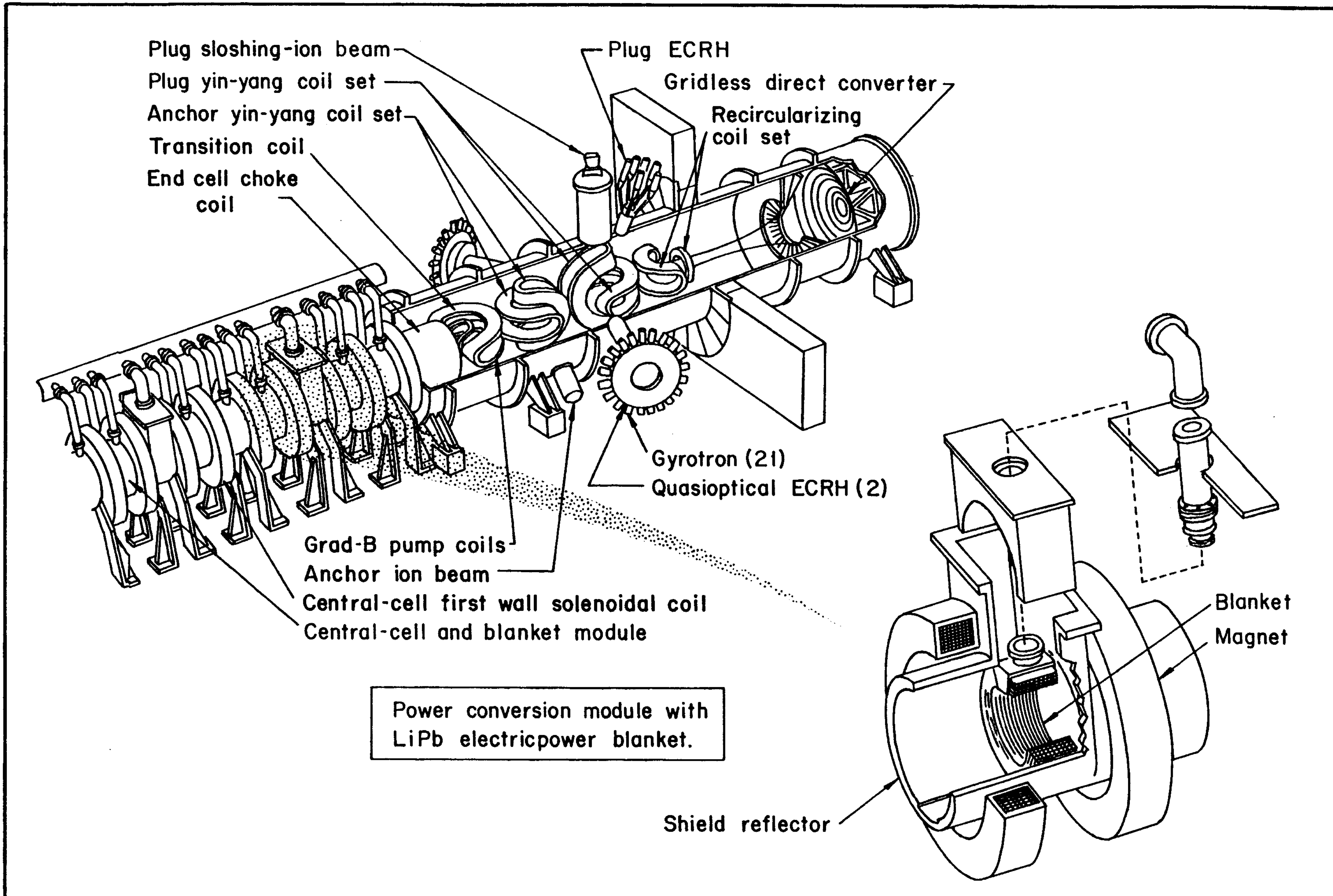


FIGURE 3a

SCHEMATIC OF PART OF MARS CENTRAL CELL AND ONE END PLUG REGION



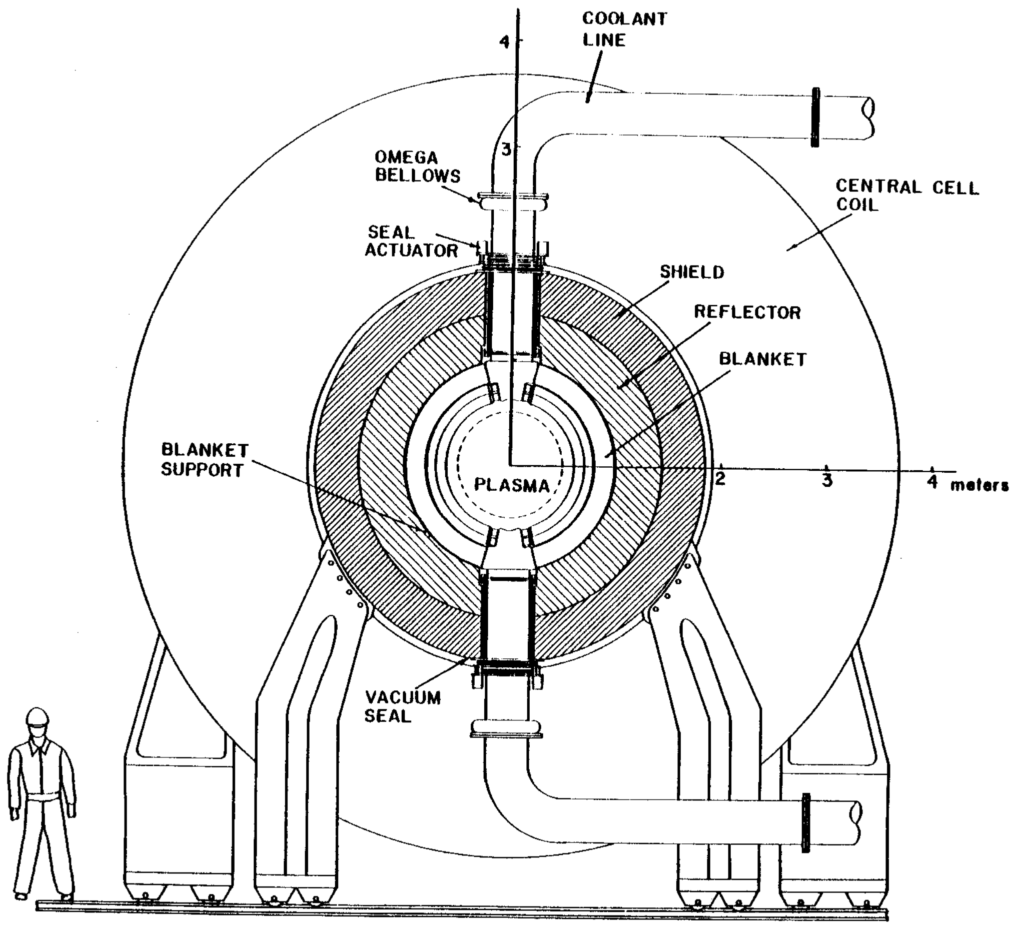


Figure 3b. Schematic of MARS Central Cell. Lead-lithium alloy enters from the bottom of the blanket and flows out the top to a double wall steam generator.

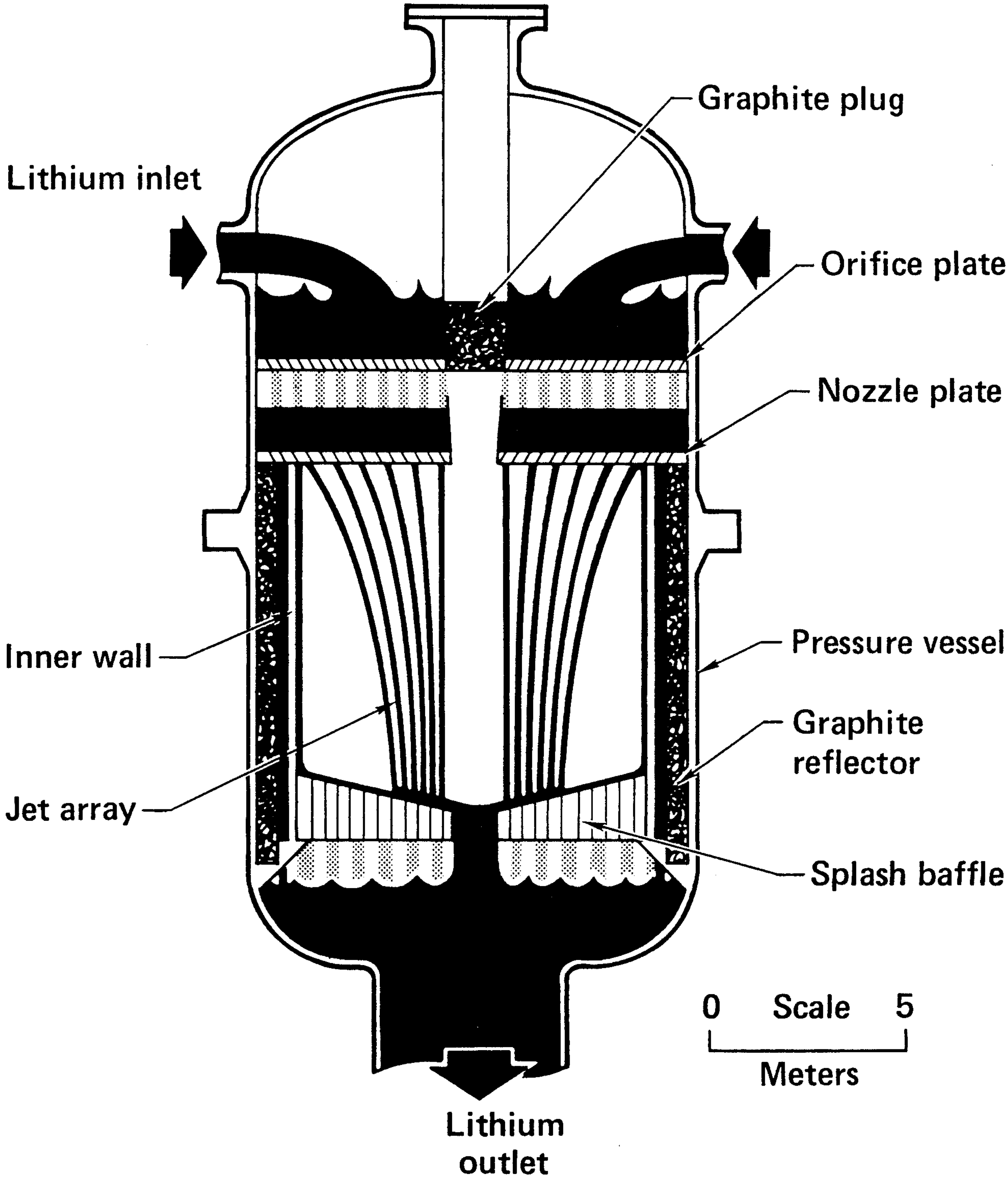


Figure 4. Schematic of Hylife Reaction Chamber. Two beams of laser light converge on a target in the center of the chamber. The target debris and energetic neutrons are captured by the jets of liquid Li injected into the chamber.

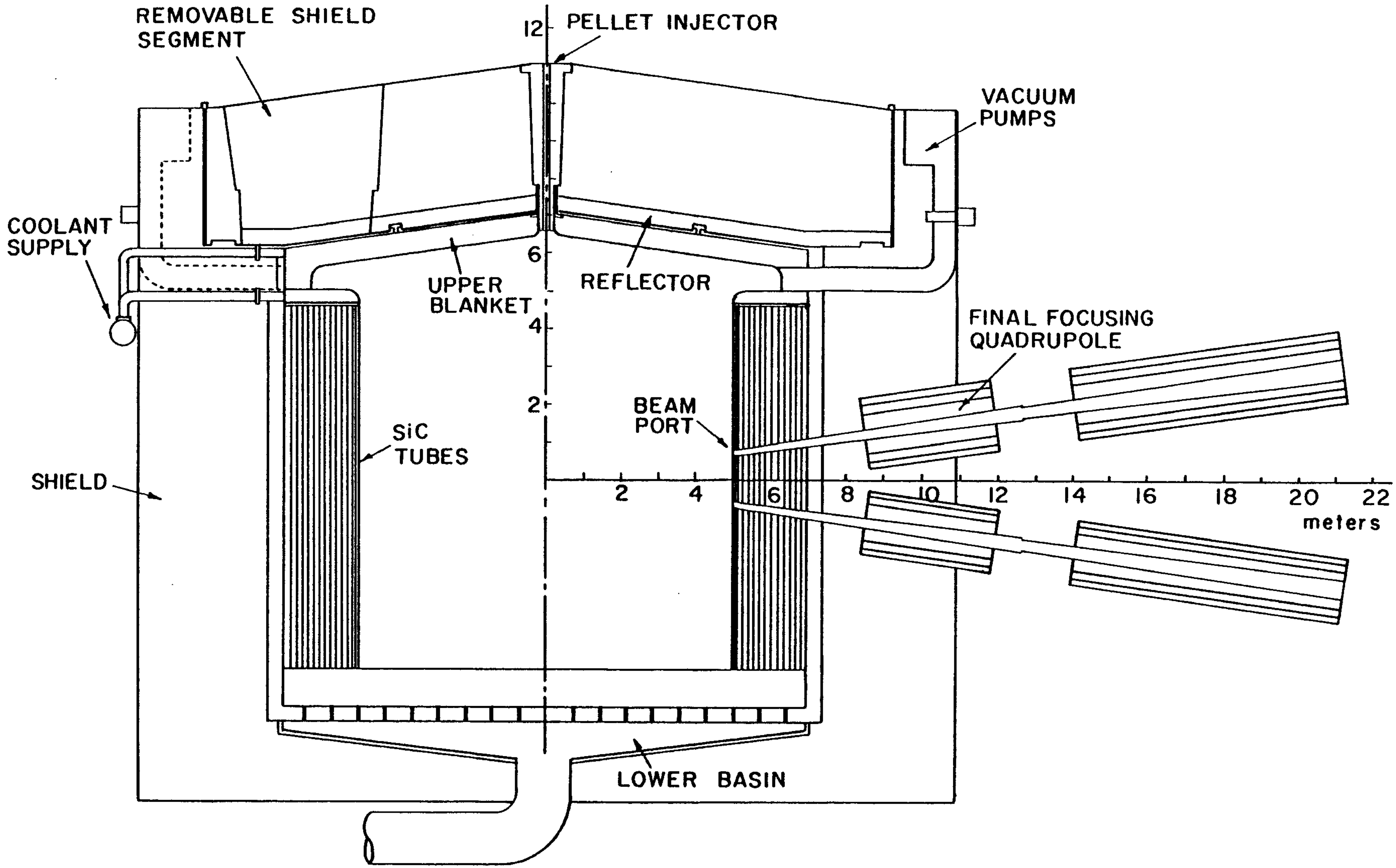


Figure 5. Cross Section of HIBALL Reaction Chamber. Twenty beams of 10 GeV bismuth ions converge on a target in the center of the chamber. Target debris and the energetic neutrons are captured by SiC tubes filled with Pb-Li alloy which cover the outside surface of the chamber.

V. Implications of Recent Designs to Commercialization of Fusion

A brief examination of the four designs in Table 4 (as well as those studies leading up to the most recent designs) reveals dozens of features which will have a major impact on the safety, economic, and environmental aspects of fusion. However, for this paper the list will be narrowed to four items which will be briefly discussed here. This list includes:

- A major trend towards using RF power for both heating and confinement of fusion fuel.
- The possibility of very long (if not continuous) burn times in tokamaks.
- The use of Pb-Li breeder/coolant materials.
- Use of liquid metal protection schemes for ICF cavities.

In the early 1970's essentially all magentic confinement designs used neutral beams to heat, and sometimes fuel the plasmas. As more and more detailed designs were developed, it was discovered that the neutral beam injection (NBI) schemes were 1) very large and hence used up valuable real estate outside the reactor; 2) very costly at the energies required (> 150 keV), and 3) major leakage paths for neutrons which reduced the tritium breeding ratio and caused very high radiation environments outside the reactor. About the same time as the difficulties with NBI technologies appeared, experimental success was being achieved with ICRF and ECRF heating of plasmas. These systems represented small and compact units which could be powered by power sources placed well away from the reactor itself. The leads for the RF antenna or the waveguides themselves occupied relatively small sections of the blankets and could be bent so as to reduce neutron leakage. Later success in the use of RF to aid confinement through the establishment of thermal barriers in tandem mirrors [79] and for current drive in tokamaks [34] made the move toward RF even more desirable. The situation today is that RF heating and confinement schemes should make fusion devices smaller, more compact, easier to shield and maintain. Unfortunately, the cost of RF power coupled into the plasma is still about the same as for NBI schemes and progress in that area is required.

For at least 10 years after the tokamak was studied as a reactor, it was thought that it would be an inherently pulsed device. Pulse lengths were as short as 30 seconds or as long as 1-2 hours and were determined by the amount of stored magnetic energy that could be economically achieved. The idea of current drive, i.e., induction of a plasma current by electromagnetic waves opened up the possibility of very long or even continuous burn pulses in tokamaks. The achievement of this goal would greatly alleviate the fatigue problems identified in the tokamak studies of the 1970's and would allow much more confidence in safe, economical blanket and first wall designs. The implications of long burn times are now being investigated at the same time as experimental measurements of current drive are being made.

The first breeder coolant proposed for fusion was lithium metal. It appeared to be an efficient way to produce the necessary tritium while at the same time removing the heat generated in the blankets. Unfortunatley, Li suffers from two major disadvantages: it is very reactive and readily burns in contact with water, concrete, etc. It also tends to retain tritium at a relatively high concentration.

Solid breeders such as Li_2O or $LiAlO_2$ were proposed to alleviate the reactivity problem but the T_2 inventory in realistic solid breeder blanket designs at times exceeded 10's of kgs. In 1979, the use of the alloy $Pb_{83}Li_{17}$ was proposed [80]. This alloy is liquid above 235°C and is relatively inactive even when dropped into water when the metal is at 500°C. This Pb-Li eutectic also has a very low solubility for hydrogen and tritium blanket inventories of 0.01 to 0.1 kg per 1000 MWe plant may be achievable [35]. It is also an efficient heat transfer medium. The use of $Pb_{83}Li_{17}$ in commercial reactor designs has become quite common since the late 1970's with the result that the safety and environmental aspects of fusion now appear much more favorable than they did before.

When inertial confinement fusion (ICF) devices were first designed, a major problem was the protection of the first wall from the intense heat flux and blast wave. The first approaches to alleviate this problem were to cover the walls with a thin coating of liquid metal but there was a difficulty in insuring 100% coverage between shots. The resultant shock wave generated by the inverse rocket action of the expanding vapor also presented severe fatigue problems for first wall designs. In addition, the thin coatings of metal did not do anything to moderate the effects of neutrons.

This problem was solved by using jets [29] or tubes [39] of liquid metals inside the reaction chamber to intercept the X-ray and target debris while at the same time moderating the effects of neutrons [81]. The first designs used jets of lithium but later work (taking advantage of the Pb-Li alloy properties just described) reduced the vapor pressure in the cavity and increased the allowable shot rate by enclosing the liquid metal inside of flexible, porous tubes of SiC [82]. Not only did this scheme enhance the safety of the reactor but it allowed the tritium to be extracted inside the cavity. The allowable shot rate could be raised from 1 Hz for free flowing jets to approximately 5 Hz for the tubes. Solid metallic components could also be protected from the neutron damage by moderating and absorbing the neutrons. This should allow most of the metallic components to last the lifetime of the reactor.

The commercial implications of these liquid metal protection schemes include a considerable development effort on circulating and extracting heat from large volumes of liquid metal. The collection of radioactive pellet debris is accomplished naturally by the flowing metal schemes and methods for extracting and disposing of the radioactive debris need to be developed. When the advantages and disadvantages of the liquid metal schemes are considered, it is concluded that they should reduce the total amount of radioactive components that will have to be replaced and therefore have significant environmental and economic impacts.

VI. Conclusion

The use of reactor designs to understand and enhance the potential of fusion has been very successful over the past 10-15 years. As we pass from the fundamental research phase into the engineering phase where the financial commitment of nations to fusion exceeds 2 billion dollars a year, the effort in fusion reactor design will definitely have to accelerate. From the nearly 80 reactor designs that have already been conducted, the community has a reasonably good picture of how a fusion economy might impact the environment and quality of life around the world. As each new generation of fusion reactor is designed, scientists and engineers are finding ways to make the energy source of the 21st century even more attractive.

Acknowledgment

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