Progress in Fusion Research, 1978-1982, Technical Summary

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FUSION TECHNOLOGY INSTITUTE

UNIVERSITY OF WISCONSIN

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Fusion Technology Institute
University of Wisconsin
1500 Engineering Drive
Madison, WI 53706

http://fti.neep.wisc.edu

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TECHNICAL SUMMARY

by

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Fusion Engineering Program
Nuclear Engineering Department
University of Wisconsin-Madison
Madison, Wisconsin 53706

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A. Introduction

Research into controlled thermonuclear fusion has been conducted since the early 1950's. It was "born" classified but in the late 1950's, scientists the world over realized that the challenge to produce useful energy from fusion was so big that it would require the efforts, and resources, of the entire scientific community. Progress in this quest has not always been as fast as desired, but as the first breakeven experiments draw near, now scheduled for the latter half of the 1980's, the pace of the quest has increased. The purpose of this summary is to examine what has happened in the last 5 years (1978-82) to illustrate the progress which has been made and also to demonstrate how far the community still has to go in this, perhaps the most difficult of all scientific endeavors. For more details on the issues presented here, please refer to the main report (Ref. 1).

The Prospects for Commercial Fusion Energy

Fusion has the potential of becoming an attractive commercial energy alternative early in the next century because:

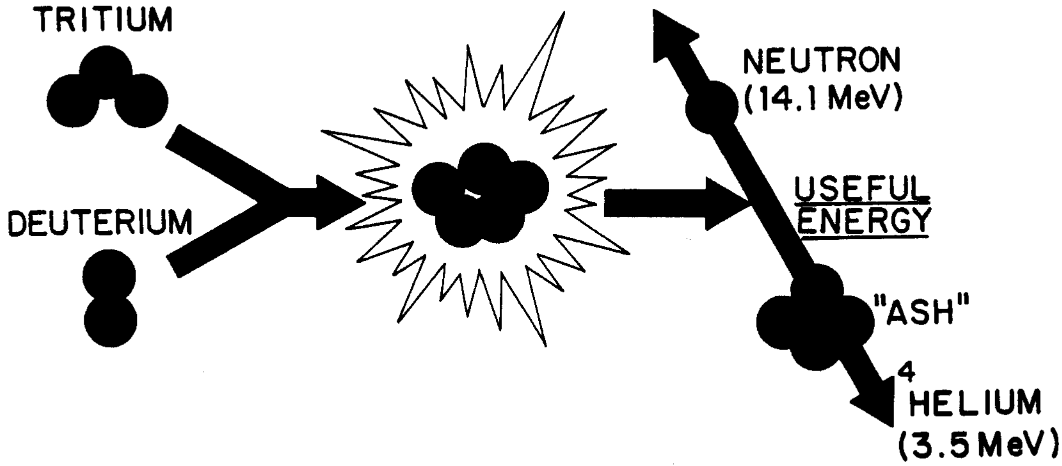
* *Enough of a scientific basis should be available to permit the development of commercial fusion plants.*
* *The fuel reserves for fusion are vast, readily available to all, and free from the threat of embargo.*
* *The environmental and safety aspects of fusion reactors appear to be reasonable and acceptable.*
* *Fusion can generate electricity as well as breed fissile material to provide fuel for conventional fission reactors, and/or generate high-grade heat for the production of synthetic fuels and for other industrial processes.*

On the other hand, successful development of commercial fusion energy could be impeded by the following:

* *Concepts which are soon to be proven scientifically will require major (billion-dollar-level) facilities to demonstrate their potential as reactors.*
* *Basic conceptual changes may be necessary to meet all the requirements for successful development with limited resources in the face of competition from other national needs.*

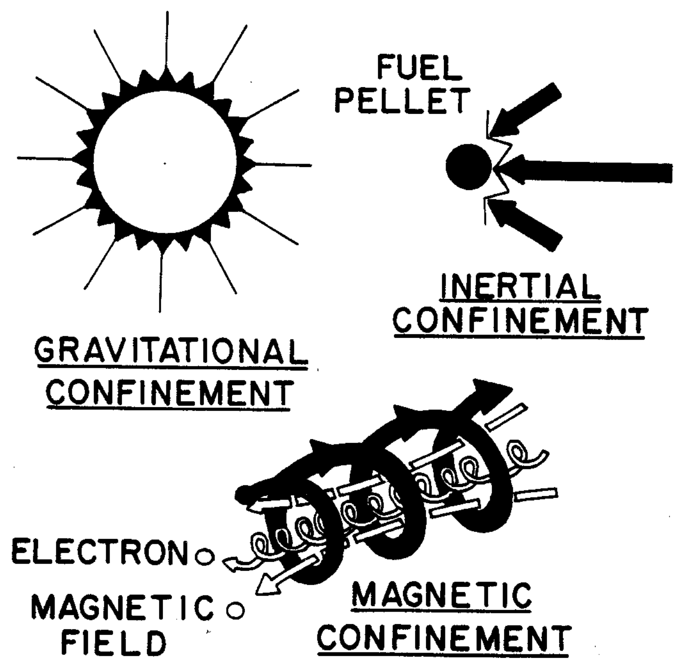
Fusion Principles

Although both fusion and fission are forms of nuclear energy, there are important fundamental differences between them. Fusion works by combining the light elements, such as hydrogen, whereas fission works by splitting heavy elements, such as uranium. In both instances, mass is converted to energy according to the Einstein equation $E = mc^2$ where m is the mass difference between the reactants and their products and c is the speed of light.



In the reaction of deuterium (D) and tritium (T) nuclei, the two nuclei fuse into ^{5}He, which immediately decays into a 3.5 MeV, ^{4}He nucleus (alpha particle) and a 14.1 MeV neutron. The total energy released is thus 17.6 MeV, corresponding to a loss of total mass in accordance with the Einstein relation $E = mc^2$.

The three means of confining a plasma: GRAVITATIONAL CONFINEMENT, as in the sun and stars, in which the total mass of the plasma is large enough that the mutual gravitational forces between the particles are sufficient to provide confinement against the enormous internal pressure of the plasma; INERTIAL CONFINEMENT, in which a pellet containing fuel material (e.g., D-T) is heated and compressed by irradiation with intense beams (light or particles). The resulting plasma by its own inertia is then contained at high pressure briefly, but long enough for a fusion reaction to occur; MAGNETIC CONFINEMENT, in which the charged particles (positive ions and electrons) of the plasma spiral along the lines of a strong magnetic field, but are otherwise constrained from moving in the direction perpendicular to the field lines.



The easiest fusion fuel to use is a mixture of the hydrogen isotopes deuterium and tritium. Deuterium (D) is abundantly available in water. Tritium (T), the other fuel component, is made from lithium which is also a plentiful element.

For two fuel nuclei to fuse, they have to collide. However, the positive charge that each nucleus carries causes the individual nucleus to repel one another and to avoid fusing. This desired fusion collision can occur only if the nuclei are traveling at very high velocities, a condition that mandates extremely high temperatures. For a mixture of D and T, the temperature required is about 100 million degrees but this temperature has already been exceeded in many experiments.

At these high temperatures, and at a sufficient density of fuel, fusion reactions become frequent enough for useful amounts of energy to be produced. For D-T reactions (see figure), the end product of fusion is a fast neutron, which carries most (~ 80%) of the energy released, and a helium nucleus (alpha particle), which carries ~ 20% of the energy but which is otherwise useless. This "ash," however, is both environmentally benign and a useful commercial product. The fast neutron escapes from the reaction zone to be captured, produce heat, and breed tritium fuel. It is not needed to keep the reaction going. Thus, this situation is distinctly different from the fission chain-reaction process in which the neutrons are used internally to keep the process going.

In fusion, the fuel atoms have lost their electrons and have become a mixture of ions (nuclei) and electrons, known as plasma. In fact, at very high temperatures, all matter exists in this plasma state. Because of the unique properties and behavior due to the electrical nature of plasma, it has been called the fourth state of matter (the others being gas, liquid, and solid).

Ninety-eight percent of all the matter in the known universe is in the plasma state, collected in the stars, and dispersed in interstellar space. It is only in special environments, such as on earth, that plasma is rare. Fusion research has given rise to the development of a new science, plasma physics, and an important spin-off from the program has been a great enhancement of our knowledge of the fundamental physical processes operating in the universe.

The very high temperatures required for fusion plasmas mean that a good thermal insulation must be found to contain plasmas and prevent cooling of the plasma. There are three ways to confine the fusion fuel long enough for the net energy release to occur (see figure). Gravity, the confinement method of stars, is not practical for use on the laboratory scale. Inertial confinement utilizes the high density of compressed fuel to keep the fusion reaction going for the required time. The principle is the same as that used in thermonuclear explosive devices. Finally, plasma can be confined by a magnetic field because the electrons and ions in the plasma are charged particles, and they tend to stick to the magnetic field lines. Such a magnetic confinement fusion system also offers an atrractive approach for commercial power development -- the primary goal of the fusion program.

Given any deterioration of these confinement schemes, the plasma will reach physical boundaries and cool, extinguishing the fusion process and stopping further release of fusion energy. Thus, fusion possesses an inherent safety against "runaway" accidents.

Magnetic Confinement Geometries

The magnetic fields confining the plasma are produced by coils that carry electrical currents. Two fundamental geometries, or configuration of magnetic fields, can be used for confining plasmas (see figure). One is the open configuration. By squeezing a straight bundle of field lines at two points to create strong magnetic field regions called "magnetic mirrors," most of the particles between the mirrors are reflected by the field and confined. This works, but not well enough: too much plasma leaks out through the mirror regions. Therefore, the basic objective of the mirror program is to "plug" the ends of the device to the point where confinement is sufficient to produce net energy. The most advanced mirror plugging concept being studied is the thermal-barrier tandem mirror.

On the other hand, magnetic field lines can be bent into a toroidal or donut shape; in principle, the plasma particles will follow the field lines around the torus without being lost. As with the open systems, however, the practical solution is more complicated. The simplest closed system has very rapid, sideways particle losses due to the curved field lines. One way to inhibit this leakage is to drive a strong current, parallel to the field lines, through the plasma. This approach, called the tokamak, was initially demonstrated in the U.S.S.R. and is now being studied at many laboratories in the United States, Europe, and Japan. It is the most advanced toroidal concept.

There are advantages and disadvantages to both types of systems. Open systems lose particles from the ends, but are geometrically simple and can hold a high plasma pressure. Toroidal systems have no end losses, but their geometry is more complicated and more limited in the attainable plasma pressure. Plasma pressure is an important quantity because the power density and hence the economics of a reactor depends strongly on it.

There are a number of other less obvious differences between the open and closed systems and among the several variants within each class. These small differences may well determine which are economically acceptable, and unacceptable, as fusion reactors. The state of understanding is sufficient at this point only to identify the critical differences and to lay out a program to evaluate them. A great deal of basic scientific and engineering work is still required to ensure the choice of the best magnetic fusion energy system.

Inertial Confinement Fusion

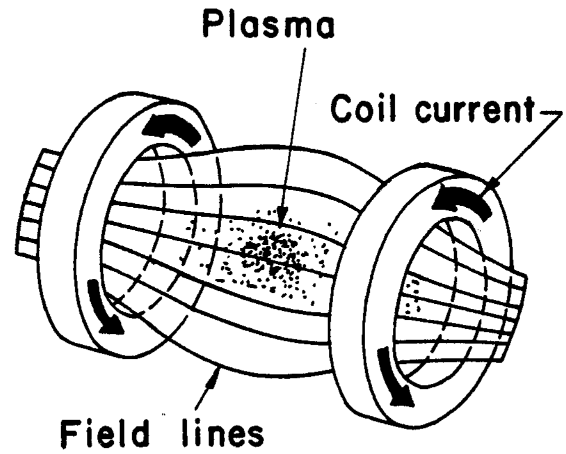
As shown (see figure), current inertial confinement fusion schemes use spherical pellets filled with deuterium and tritium. An intense beam of directed energy is focused onto the pellet, causing explosive ablation of the outer shell. This results in an equal but opposite reaction on the remaining shell material, accelerating it inward at typical velocities of 200 km/s, thus heating the fuel at the center to the required high temperature. The inertia of the imploded shell (hence the name inertial confinement fusion - ICF) holds the compressed deuterium and tritium at 100 to 1000 times liquid density. The pressure reaches several trillion atmospheres. In effect, a laboratory-scale hydrogen bomb is produced when the fuel, restrained now by its own inertia, burns in less than a nanosecond.

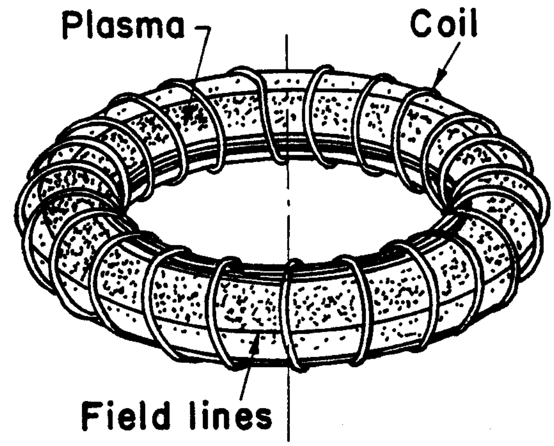
The energy sources, or drivers, that are used to bombard the pellet are lasers, or intense particle-beam accelerators. The laser drivers use photons as the bombarding medium, whereas particle-beam accelerators use light ions -- the nuclei of light-molecular-weight elements or heavy ions.

The utility of ICF for energy production will be determined by the product of the energy gain (G) times the driver efficiency (η), a quantity called the achievable gain. For energy applications, $\eta G = 20$ is required for an economically competitive electric power source. For practical driver energies of a few million joules, a gain of 100-200 may be possible. Thus η must lie in the 10-20% range. If the gain is substantially lower than 100, lasers are unlikely to achieve the efficiency needed for the required achievable gain. This issue motivated the use of light- or heavy-ion accelerators, which have the realistic possibility of operating at 20% efficiency. Thus lasers and ion-beam accelerators are both candidates for the feasibility experiment, although the potentially low values of ηG for lasers may constrain their commercial application.

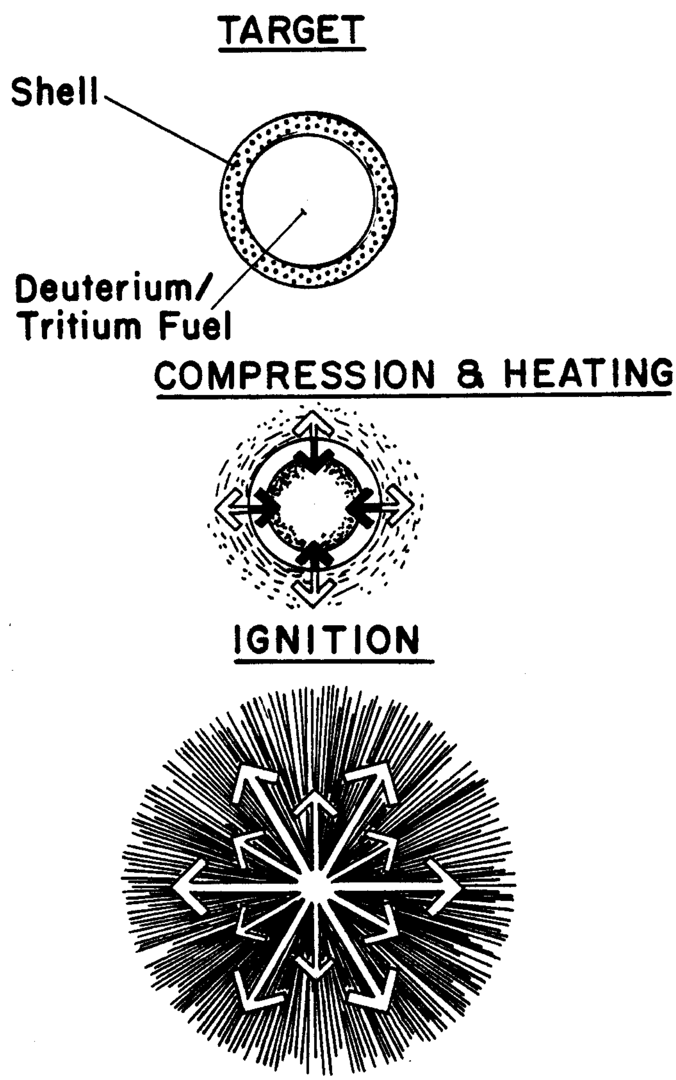
B. Assessment of Progress in Fusion Research

In order to highlight the most important events that have occurred in fusion research over the past 5 years (1978-82), 20 of the most obvious questions that are usually asked, are addressed in this report. For more details on the specific events, the reader should again refer to the main report (Ref. 1).





The two catergories of magnetic plasma confinement: the simple magnetic-mirror cell (above), and the simple torus. The simple magnetic-mirror cell forms the basic scheme for open confinement configurations, whereas the torus is the basic form of a closed system, including a more sophisticated version, the tokamak.



Inertial confinement fusion pellet, showing implosion, compression and heating, then ignition. The fusion reaction between deuterium and tritium produces helium nuclei (alpha particles) and 14 MeV neutrons. The alpha particles at 3-1/2 MeV are redeposited in the fuel and allow burning to continue. Ignition is defined as taking place when self-heating and burning of additional fuel produces a sustained reaction. In a future reactor, an absorbing blanket, located at a distance from the plasma, would capture energetic neutrons to provide heat for electrical power production.

1. **HOW HAS THE MAGNITUDE OF THE WORLDWIDE EFFORT IN FUSION RESEARCH CHANGED OVER THE PAST 5 YEARS?**

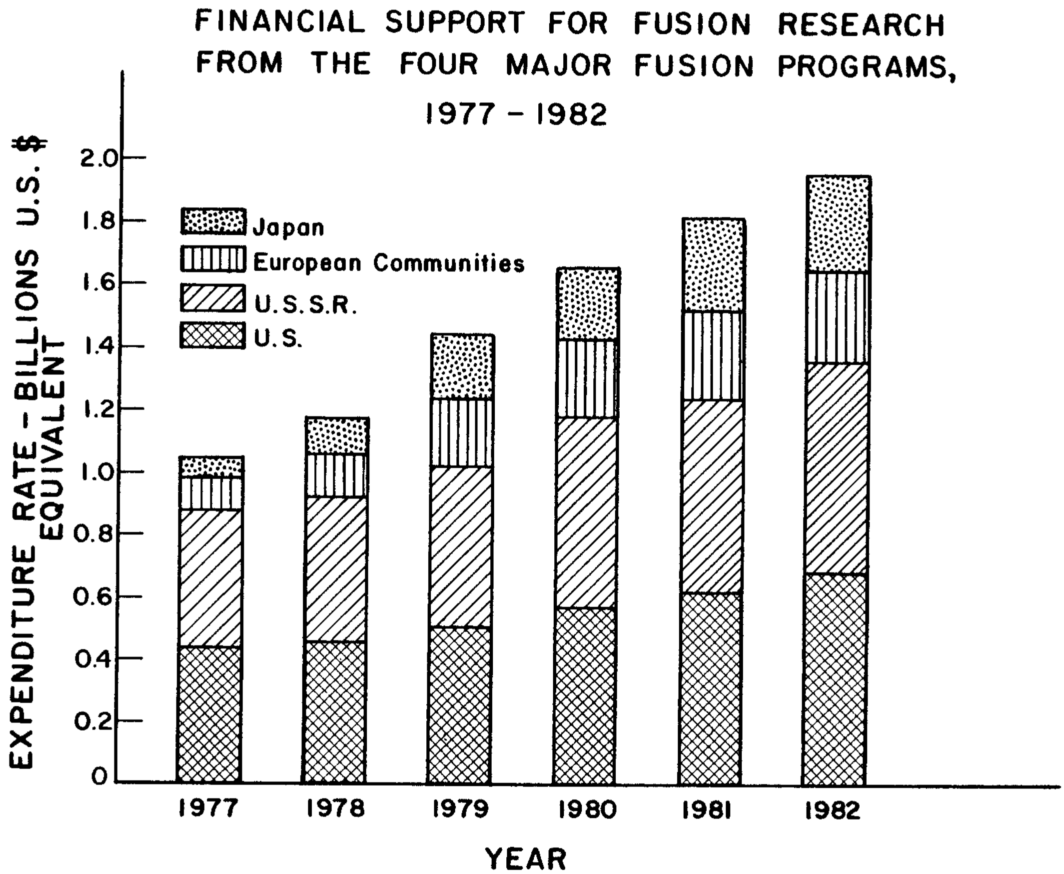
If the worldwide effort in fusion research can be measured by money expended on it, then the magnitude of the effort has doubled in the past five years. The figure shows that the estimated expenditures by the four major fusion programs in the world [U.S., USSR, Japan, and the European Community (EC)] rose from 1.1 billion dollars in 1977 (the year before this five year assessment) to ~ 2 billion dollars in 1982. While detailed information is available for three of the research programs (U.S., Japan and the EC), one is forced to speculate on the USSR program. The best estimate is that it is equivalent to the U.S. program and has been over the past 30 years.

One of the most striking features of the three major programs for which information is available, is the rate of increase. While the U.S. has increased its total program by ~ 60% over five years (essentially the increase due to inflation), the European program has increased by ~ 280% and the Japanese program by ~ 460%.

The predominant worldwide research effort in fusion still appears to be in the magnetic fusion area with the inertial confinement program only accounting for about 1/3 of the U.S. program, less than 10% of the Japanese program and a negligible amount of the EC program.

It is estimated that there are now some 6,000 professionals engaged in fusion research in the four major programs while there are another 500 to 1,000 professionals in 22 additional programs around the world.

Over the past 31 years (1951-1982), between 12 and 13 billion dollars have been spent on worldwide fusion research program (see table). Obviously the bulk of this has been spent in the four major programs and it is worthwhile to note that on a per capita basis, the U.S. leads Japan and EC in its investment for fusion research.



Summary of World Fusion Research Expenditures

Million Dollars (Equiv.)

Country	1982	1978-82	1951-82	\$/Capita in 1982
USA	688	2,851	4,579	3.1
EC	287	1,204	1,960	1.1
Japan[a)]	300	1,085	1,300	2.6
USSR (est)	~ 660	~ 2,800	~ 4,500	~ 2.5
Other (est)	~ 70	~ 150	~ 200	
Total	~ 2,000	~ 8,100	~ 12,500	

a) adjusted to include salaries

2. WHAT MAJOR TOKAMAK FACILITIES HAVE BEEN COMPLETED AROUND THE WORLD IN THE PAST 5 YEARS?

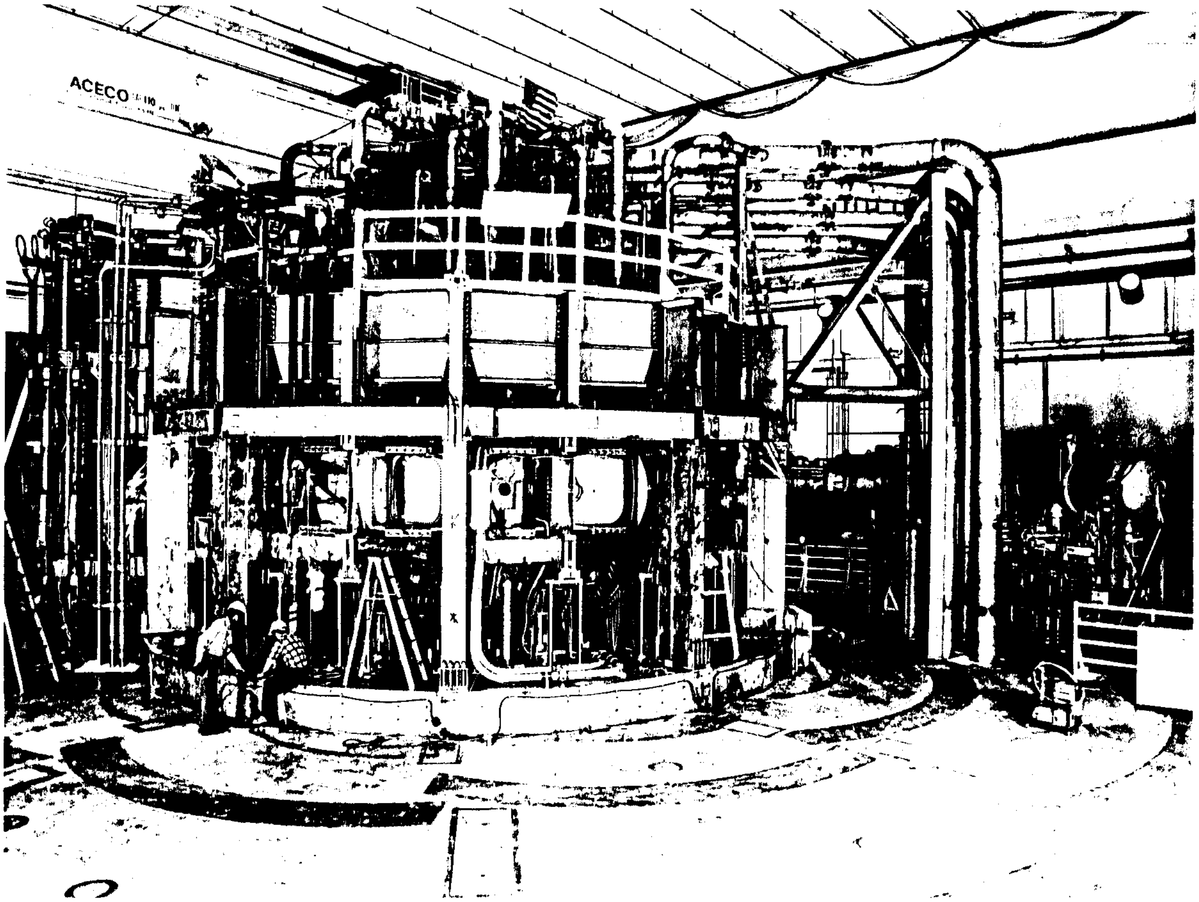
A number of substantial tokamak facilities have been put into operation since 1978. These devices and their parameters are given in the table below. This generation of facilities has extended the physics data base for tokamaks and provided a foundation for the next generation of facilities, which are currently under construction. Particularly noteworthy is TFTR, which has just begun operation. This is the largest tokamak to date and has the objective of reaching energy breakeven in 1985-86; this can be considered the establishment of the scientific feasibility of controlled fusion. The figures show a recent view of TFTR and also of Doublet-III.

Of the devices under construction, JET is the nearest to completion with JT-60 in Japan scheduled for 1984 operation. The Soviet T-15 device is now scheduled for 1985 operation while the Tore-Supra device in France will be completed in 1985 or 1986.

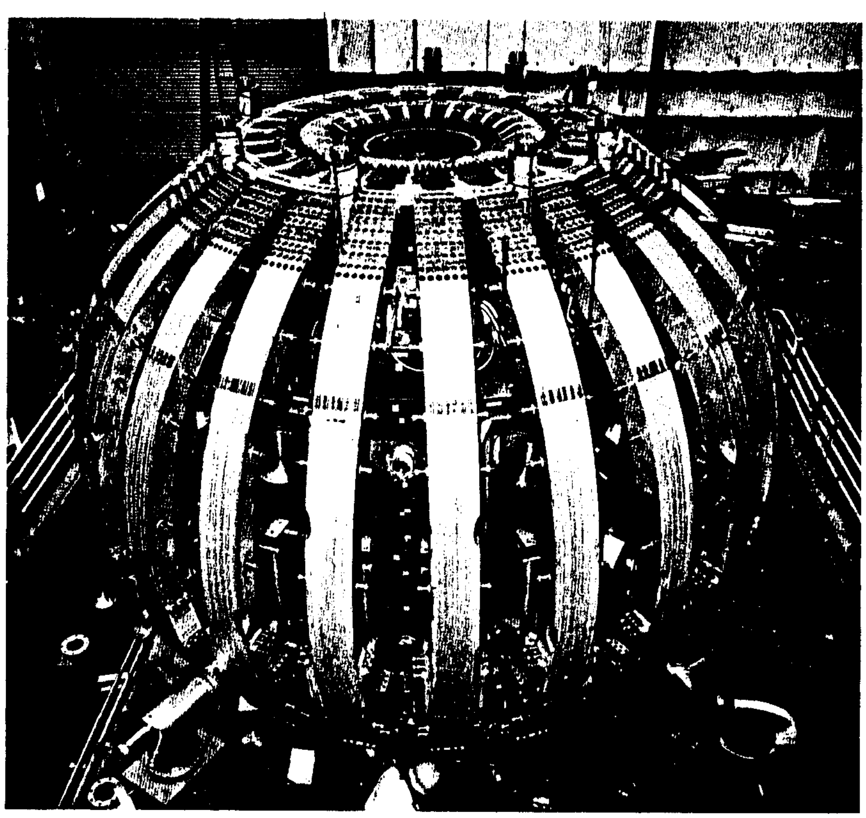
Major New Tokamaks in the Last 5 Years

Device	Country	Date of Initial Operation	Major Radius (m)	Magnetic Field (T)*
Alcator-C	USA	1978	0.64	14
Doublet-III	USA	1978	1.43	2.5
PDX	USA	1978	1.45	2.4
T-7	USSR	1980		2.5
ASDEX	W. Germany	1980	1.65	2.8
Textor	W. Germany	1981	1.75	2.6
TFTR	USA	1982	2.5	5.2
Under Construction				
JET	Euratom	1983	3	3.5
JT-60	Japan	1984	3	4.5
T-15	USSR	1984/85	2.4	5
Tore-Supra	France	1985	2.15	4.5

*1 T is a unit of magnetic field equal to 10,000 times the earth's magnetic field.



TFTR (Tokamak Fusion Test Reactor) facility at Princeton University, USA.



Doublet III

Doublet III Facility at GA Technologies, Inc., San Diego, California, USA.

3. WHAT ARE THE MAJOR MIRROR FACILITIES COMPLETED OR UNDER CONSTRUCTION DURING THE PAST 5 YEARS?

The tandem mirror, invented in 1976, has emerged in the last few years as the leading mirror confinement concept. A number of tandem mirrors (TMX, GAMMA-6, Phaedrus) have been built and the basic concept has been verified. The thermal barrier concept, proposed in 1979, has greatly improved the reactor prospects of the tandem mirror and led to a second generation of tandem mirrors with thermal barriers. Both TMX-Upgrade and Gamma-10 are in their early phases of operation. Both should demonstrate thermal barriers in the 1983-84 period. The TARA device at MIT in Cambridge, Massachusetts, USA, is also designed to demonstrate the thermal barrier concept, but with a symmetrical end plug configuration. The MFTF-B device, the largest and most significant tandem mirror facility, is scheduled to begin operation in 1986 or 1987 with tritium burning experiments slated for 1988. The table gives some design parameters for these devices; the figure shows the TMX-U facility at Lawrence Livermore National Laboratory.

New Tandem Mirror Devices Operating or Under Construction in the Last Five Years

	TMX	TMX-U	GAMMA-10	TARA	MFTF-B
Country	USA	USA	Japan	USA	USA
Date of Operation	1978	1982	1983	1984	1986/87
Thermal Barrier Design	No	Yes	Yes	Yes	Yes
Central Cell					
Ion temp., keV*	0.25	0.9	1.	0.4	15.
Beta	0.14	0.25	0.1	0.03	0.5
Length, m	5.3	8	6.6	10	16.5
Magnetic Fields, T					
Central cell	.2	.3	.4	.2	1.0
Barrier	---	---	3.0	3.0	12.0
Yin-yang peak	2.0	2.0	2.1	1.0	6.0

*1 keV = 10 million degrees Celsius

TMX-U at Lawrence Livermore National Laboratory.

4. WHAT ARE THE MAJOR PHYSICS ADVANCES THAT HAVE OCCURRED IN THE MAGNETIC FUSION PROGRAM OVER THE PAST 5 YEARS?

There has been significant progress on a number of physics issues:

- Higher beta operation in tokamaks. Beta values (the ratio of the plasma pressure to the magnetic field pressure) of 4.6% have been reported in Doublet-III; a number of other facilities have beta values of 2-3%. Reactors normally require beta about 6-8%, which is not far from the present record.

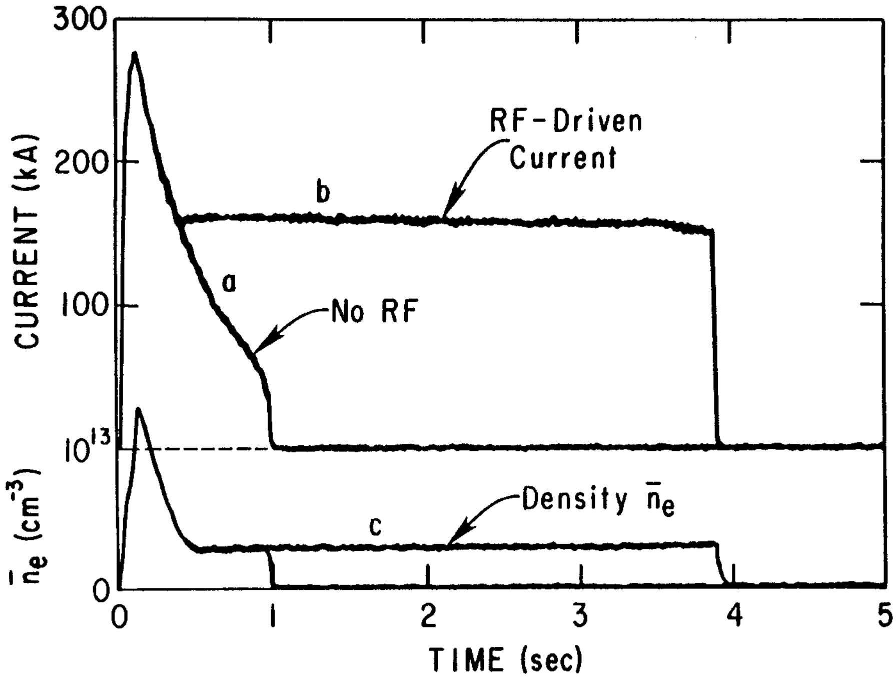
- Ion heating by means of radiofrequency (RF) waves has developed to the point of being a credible heating method with significant technological advantages over neutral beam heating. The next generation of tokamaks is based primarily on this heating method and it is a vital part of all tandem mirrors currently in operation.

- Plasma current drive in tokamaks has been demonstrated in low density plasmas using RF (see figure). The goal is to achieve steady-state or very long pulse operation of the tokamak and thereby avoid the engineering problems associated with pulsed operation. Considerable development is required, however, before the viability of truly steady-state operation is established.

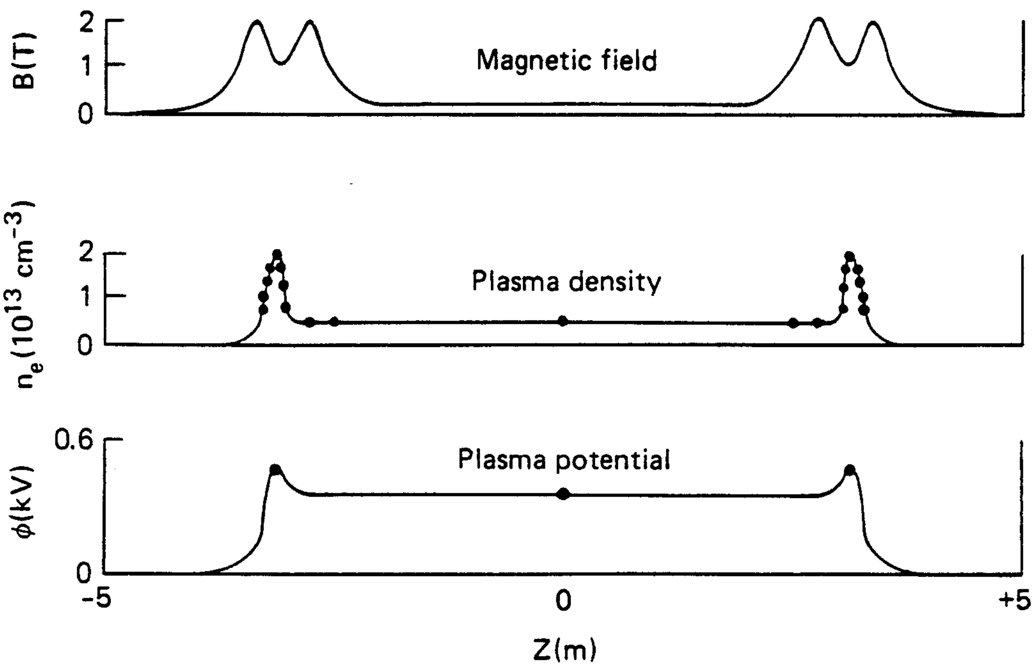
- Experimental confirmation of the tandem mirror concept has been obtained in several facilities (see figure). This mode of operation has opened the way for more simple linear reactor geometries.

- The invention of the thermal barrier as a means to greatly improve the reactor prospects of the tandem mirror was a major event in the mirror community. Experimental tests of thermal barriers are underway now and the TMX-U device at LLNL has already demonstrated the "sloshing ion" aspect of thermal barrier operation.

- Improved plasma confinement in stellarators. This was demonstrated on the Wendelstein VII-A stellarator in W. Germany. Such experiments along with the prospects for modular stellarators have caused renewed interest in this class of toroidal confinement schemes for reactors.



Experimental data from a plasma discharge illustrating the use of RF waves to maintain the plasma current in the PLT (Princeton Large Torus).



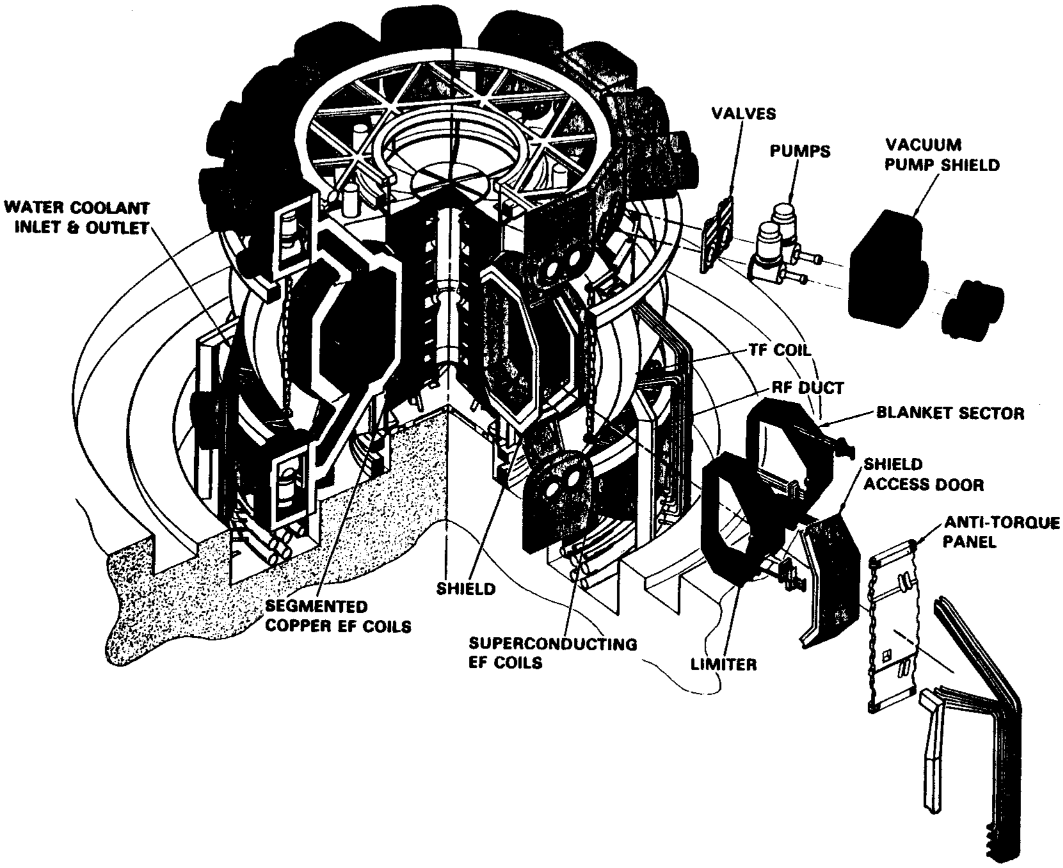
Experimental results verifying tandem mirror concept on TMX at the LLNL in the USA.

5. HOW HAVE THE PROSPECTS FOR A COMMERCIAL TOKAMAK FUSION REACTOR CHANGED OVER THE PAST 5 YEARS?

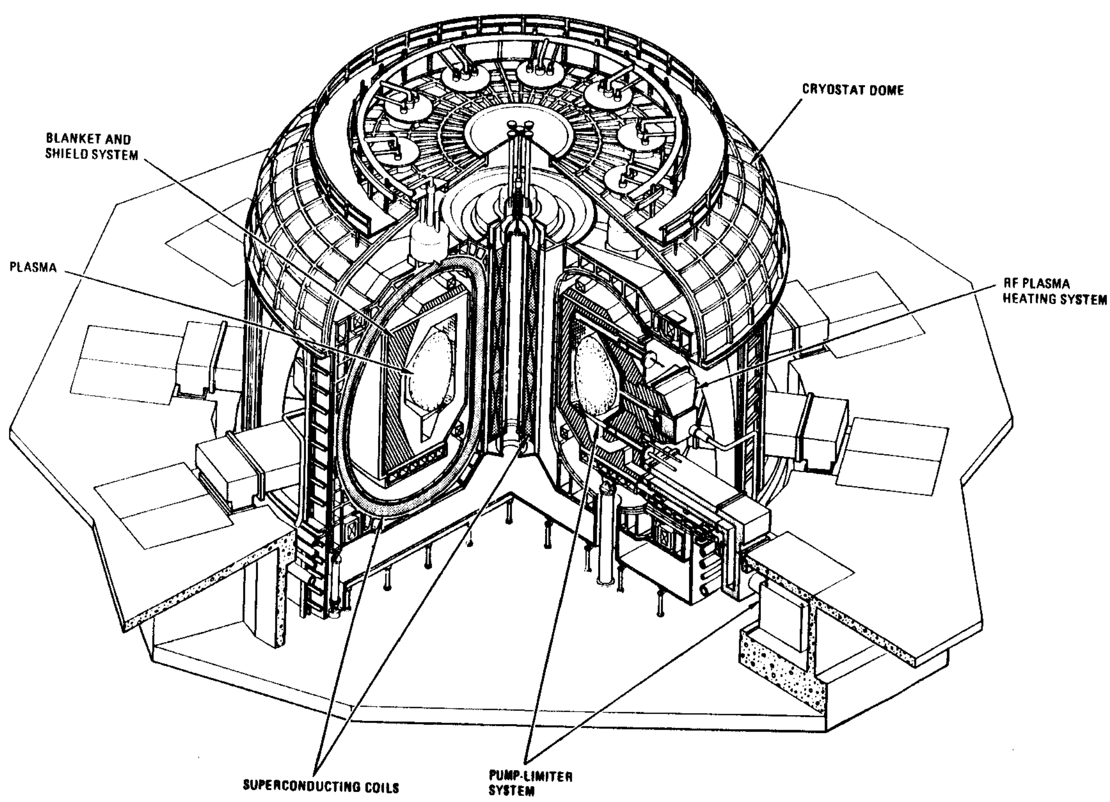
Tokamak reactor conceptual designs have evolved in a number of ways over the past 5 years which improve their suitability for a power reactor. The new ideas presented in these designs include:

- Steady-state or long pulse operation using RF or other means to maintain the plasma current. This reduces the engineering problems associated with pulsed operation, but requires confirmation in present facilities.
- Radiofrequency (RF) heating of the plasma to ignition. Encouraging results from present experiments indicate that RF may be a good alternative to neutral beam heating; RF heating also has technological advantages over neutral beam heating with respect to neutron streaming.
- The development of the pumped limiter and cool plasma blanket concepts for impurity control. These simplify the design of the reactor and reduce the amount of tritium tied up in the vacuum pumping and plasma refueling systems.
- The use of tritium breeding materials other than liquid lithium. The focus has been on lithium-lead in the liquid form and solid breeders in the lithium-aluminate, silicate and oxide forms. These offer improved safety through the decrease in the fire potential although the solid breeder materials may produce unacceptably large tritium inventories.

The figures show schematics of the STARFIRE conceptual tokamak power reactor completed in 1980 and the Fusion Engineering Device, a near term conceptual tokamak test reactor completed in 1982.



The STARFIRE commercial reactor design completed in 1980 by a large community wide effort coordinated by Argonne National Laboratory.



FED (Fusion Engineering Device) reactor configuration completed in 1982 by the Fusion Engineering Design Center with participation from a large number of industrial, university and government laboratories.

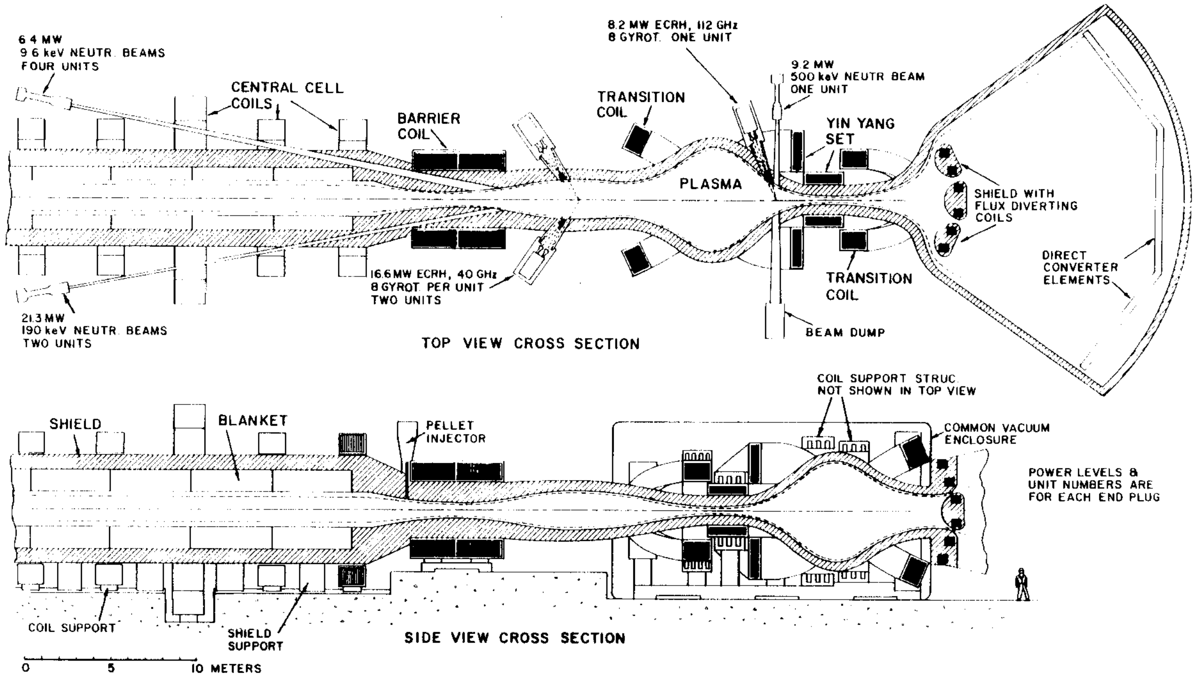
6. HOW HAVE THE PROSPECTS FOR A COMMERCIAL MIRROR FUSION REACTOR CHANGED IN THE PAST 5 YEARS?

The tandem mirror approach has emerged as the leading mirror concept for a fusion reactor since 1977. This is because of encouraging experimental results from present tandem mirror facilities and theoretical innovations, such as the thermal barrier, which have improved the reactor prospects for the tandem mirror. This progress can be measured by the improvement in Q, which is the fusion power produced per unit of injected power required to sustain the plasma. Early values of Q for standard "minimum $\overline{B}$" configuration designs were about 5, which is marginal for a power reactor. More recent values for tandem mirrors with thermal barriers are about 20-30, and the technology demands for magnetic fields and intense high energy neutral beams have eased immensely. The Q-values for some major tandem mirror reactor studies are shown in the table. The latest reactor studies, WITAMIR-I and MARS, are shown in the figures.

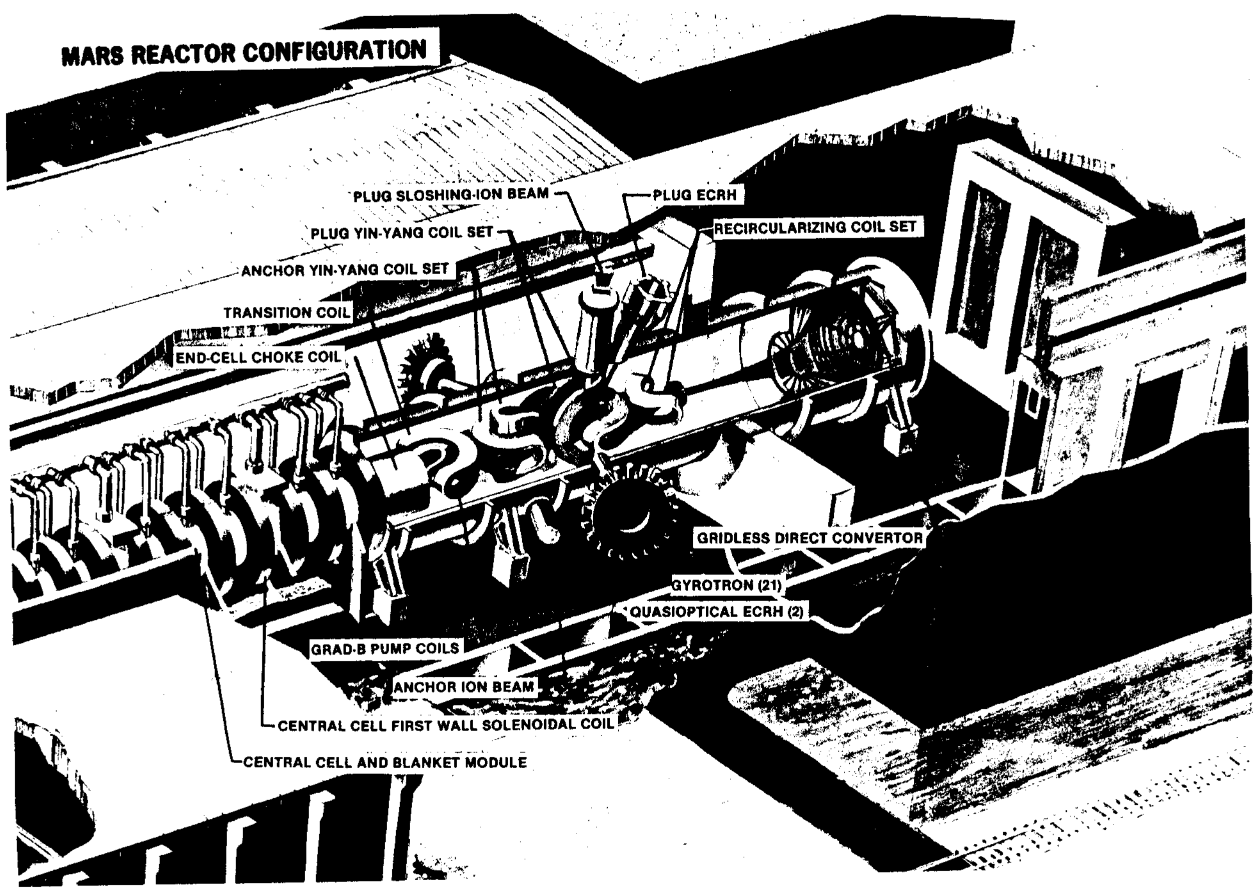
Progress in Q for Tandem Mirror Reactors

Reactor Study	Standard TMR (LLNL)	Thermal Barrier TMR (LLNL)	WITAMIR-I (Wisconsin)	MARS (Joint)*
Year of Study	1977	1979	1980	1982/1983
Energy Multiplication, Q	4.3	14	24	13 (1982) 26 (1983)

*Joint collaboration with LLNL, TRW, Univ. of Wisconsin along with General Dynamics, Grumman Aircraft, EBASCO and SAI.



Conceptual design of WITAMIR-I, a Wisconsin tandem mirror fusion reactor design.



MARS Power Plant

7. WHAT HAS HAPPENED IN THE AREA OF ALTERNATE CONCEPTS OVER THE PAST 5 YEARS?

The main thrust of alternate concepts research has been in five areas:

1. EBT
2. Stellarators
3. Compact tori, for which no magnetic field coils intersect the central region of the torus.
4. Very high field toroidal devices.
5. Advanced fuels.

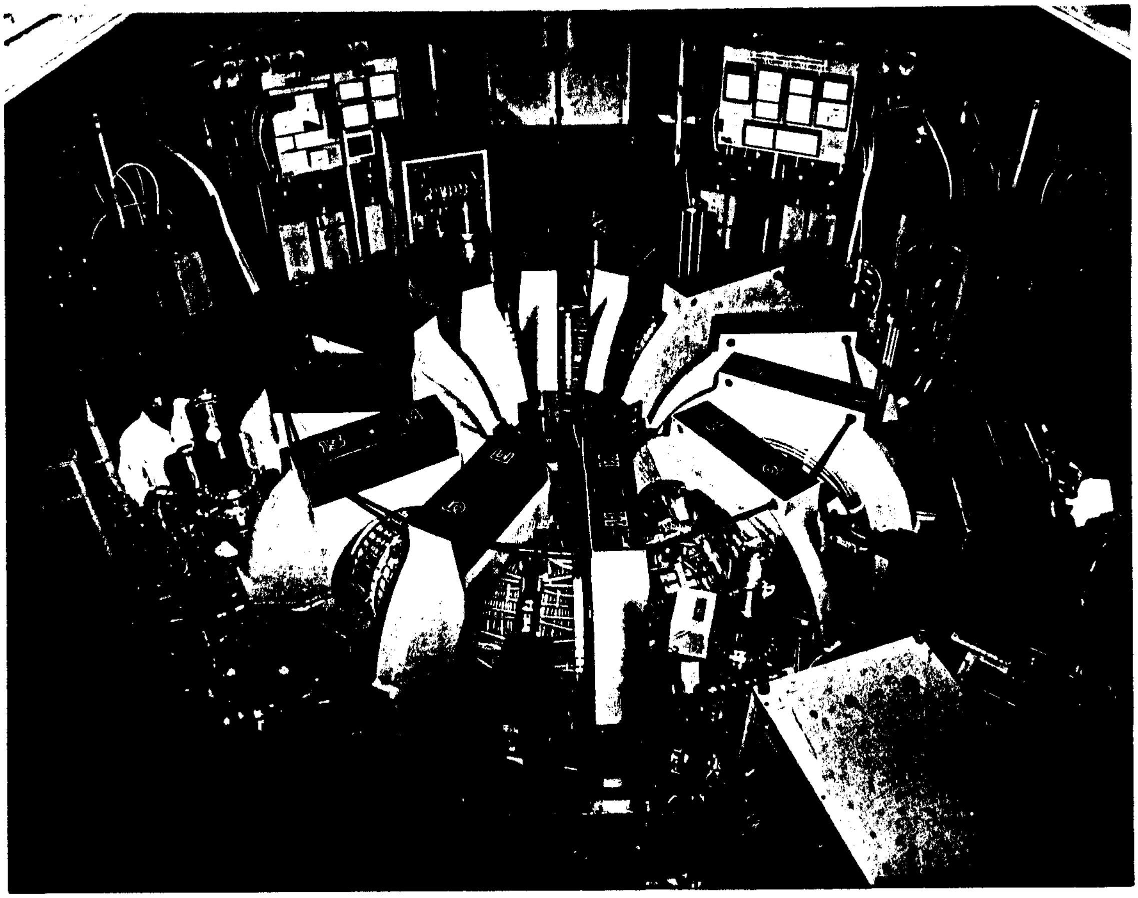
EBT is a toroidal configuration where microwave power sustains a set of relativistic electron rings which stabilize the plasma. A major experiment, EBT-P, was designed, but indefinitely postponed because of concern about the results in EBT-S, the present experiment. Newer measurements indicate that plasma confinement may not be as good as thought earlier.

The stellarator is a toroidal configuration in which external helical coils provide the necessary magnetic field shape for plasma confinement. The primary stellarator facilities are in Europe and Japan; the U.S. has not had a substantial program since 1969. Because of good results elsewhere, the U.S. has just recently authorized the construction of a major stellarator type experiment, ATF, at Oak Ridge National Laboratory.

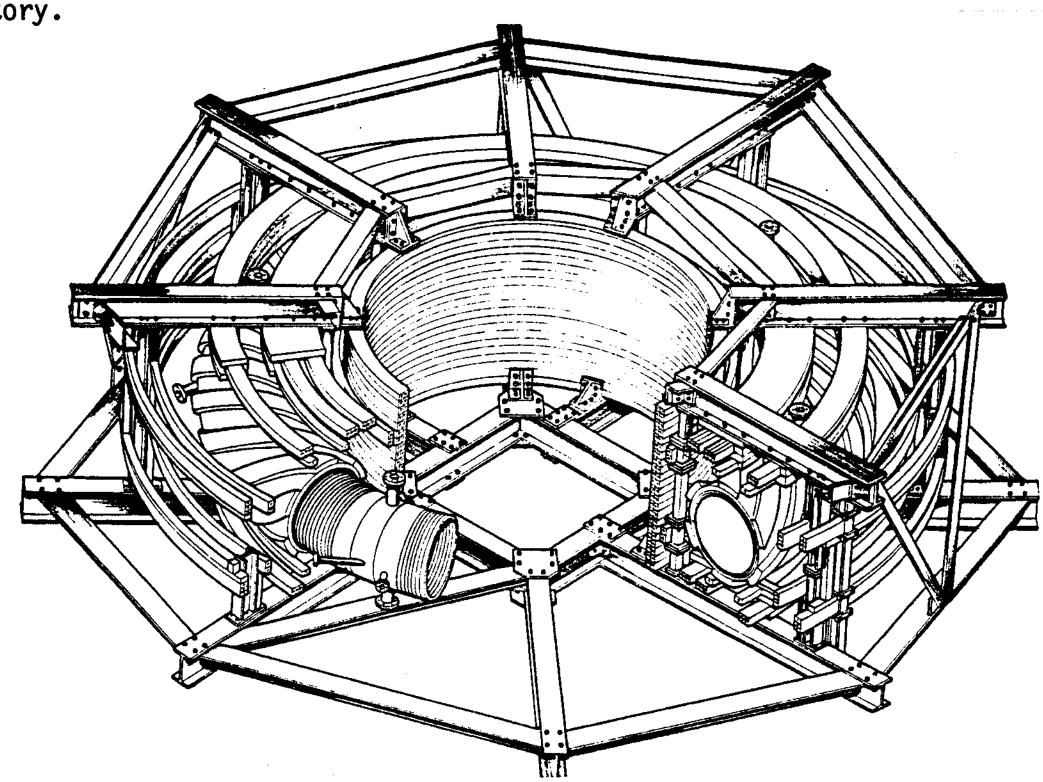
The compact tori class encompasses field reversed configurations, such as the field-reversed mirror and spheromaks. A related concept is the reversed field pinch (see figure). Considerable physics progress has been made with reversed field pinches, but the field-reversed mirror program at Lawrence Livermore National Laboratory has been canceled because of poor physics results. A recent entry is OHTE (see figure), a reversed-field pinch surrounded by helical coils. This experiment is funded by GA Technologies and Phillips Petroleum.

An example of a very high toroidal field device is the Riggatron, which is a high density, high field tokamak under design at INESCO. The high magnetic field is generated by copper coils next to the neutron producing plasma. This results in a high neutron flux to the coils and blanket; its chief difficulty may be an unacceptable operating lifetime in that hostile environment.

The topic of advanced fuels includes all fusion reactions other than D-T. These reactions require higher plasma temperatures than D-T, but offer the prospect of reduced neutron production and, therefore, radiation damage and related problems. Unfortunately, side reactions often produce neutrons, and the main reaction rates are generally too small to allow economic reactors. Presently, research is at a lull, awaiting new innovative approaches.



The ZT-40 facility, a reversed field pinch device at Los Alamos National Laboratory.



The OHTE (Ohmically Heated Toroidal Experiment), a project funded by GA Technologies and Phillips Petroleum.

8. WHAT ARE THE MAJOR TECHNOLOGICAL ADVANCES IN PLASMA HEATING OVER THE PAST 5 YEARS?

The best understood technique of heating magnetically confined plasma, namely the positive-ion-based neutral beam, has been greatly enhanced in the 1970's. Neutral beam sources are now in operation in quasi-steady-state (~ seconds) capable of delivering tens of amperes of current at energies in the range 50 to 160 keV.

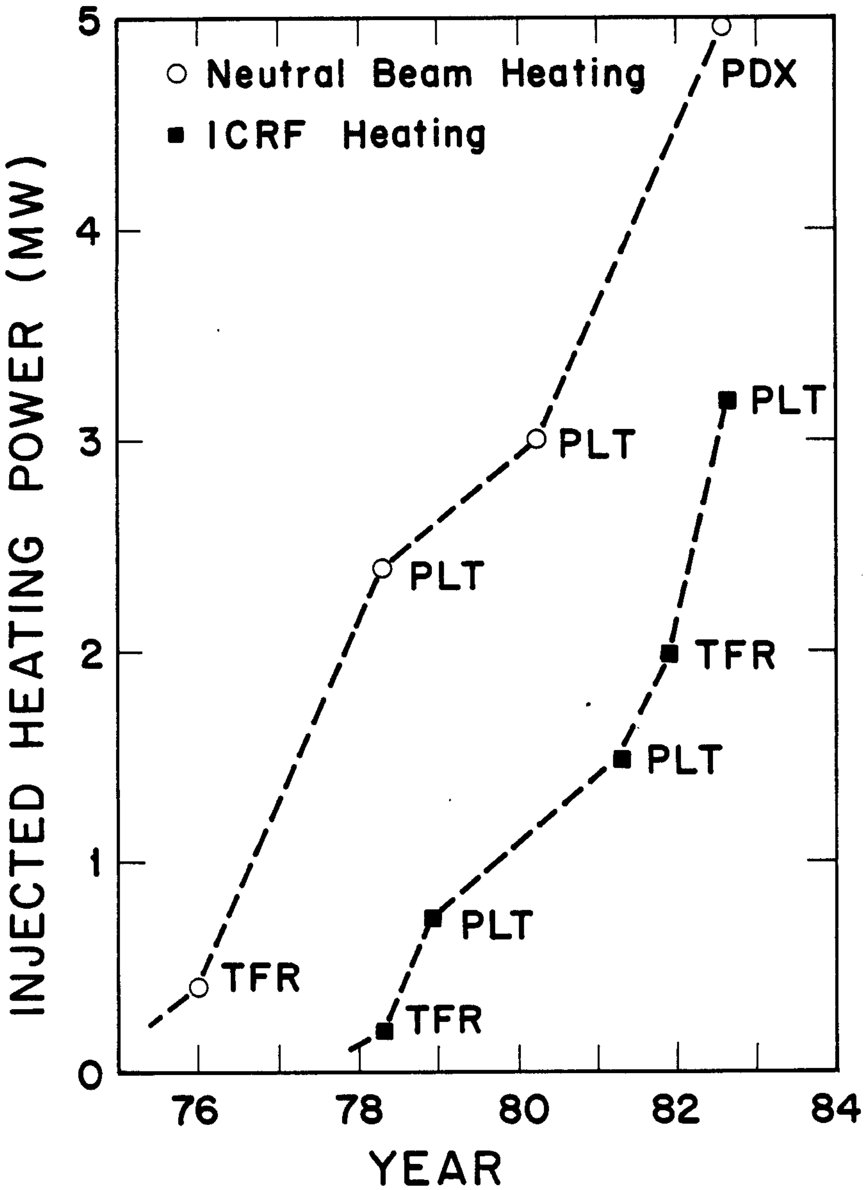
If the 1970s can be considered the era of neutral beams, then the 1980s may prove to be the age of radiofrequency (RF) technology. In fact, one of the most interesting features of magnetic fusion in the last five years has been the rapidly growing interest in the utilization of RF. Its major use for plasma heating has been expanded by its capacity to sustain current drive in tokamaks and for potential enhancement and thermal barrier maintenance in tandem mirror machines.

Electron cyclotron resonance heating (ECRH) in the RF regime of tens of GHz is now achievable with acceptable efficiency with the recently available high power gyrotron tube. Current state of the art for developed gyrotrons is the 28 GHz, 200 kW CW tube completed in the U.S. in 1980.

RF heating in the ion-cyclotron range of frequencies (ICRF) lies in the tens of MHz regime where efficient generation of large amounts of RF power is relatively simple. With the exception of the launching antennas, ICRF hardware is already commercially available. Its principal engineering advantage has proved to be the ability to locate the bulk of the equipment remotely from the reactor core, thus promoting reliability and simplified maintenance. In 1980, ICRH was selected as the main heating system for JET. In the final DT phase of operation, JET will operate with 25 MW of auxiliary heating, 15 MW of which will be supplied by ICRF.

As a pertinent example of the growing emphasis on RF heating, consider the recent policy statement by the FED/INTOR committee:
"The decision between ICRF and neutral beam injection (NBI) rests on a trade-off between the engineering and technological advantages of ICRF and the greater confidence in the physics basis for NBI. The recent advances in ICRF physics indicate that the balance has shifted in favor of ICRF. Therefore, ICRF should be adopted as the prime heating option for long range tokamak applications. The principal backup for near term and long term device commitments should be positive and negative ion beams, respectively."

The accompanying figure highlights recent progress in plasma heating by illustrating the best results obtained by both neutral beams and ICRF in terms of the year of achievement.



Recent progress in plasma heating technology. The best results obtained by neutral beams and ICRF are shown in terms of both the year of achievement and the experimental device concerned [TFR - Tokamak Fusion Reactor (France), PLT - Princeton Large Torus (US), PDX - Poloidal Divertor Experiment (US)].

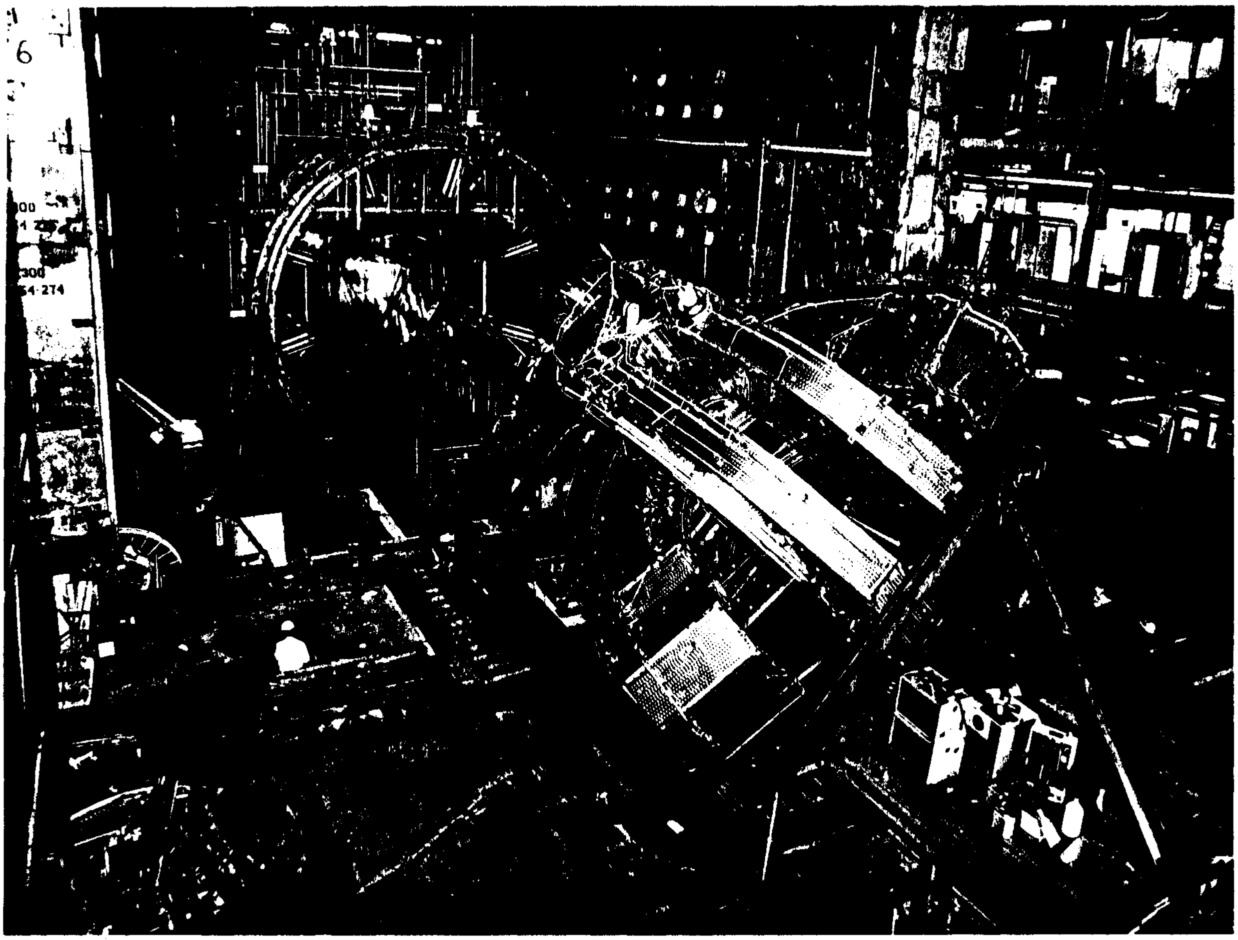
9. HOW MUCH PROGRESS HAS BEEN MADE IN SUPERCONDUCTING MAGNETS IN THE PAST 5 YEARS?

Major progress has been made in superconducting magnets for fusion in the past five years. Several large near reactor size magnets for tokamaks and mirrors have been or are being constructed and progress has been made in material development, conductor design, structural considerations and cooling schemes.

In the area of toroidal fields for tokamaks, there are three major worldwide efforts. The Large Coil Task, based at ORNL, involves six D-shaped magnets which produce a magnetic field of 8 T. Three magnets are being built by U.S. industry and the other three by Japan, Switzerland and Euratom, respectively. The set will be tested in a toroidal configuration with a simulated plasma current in mid-late 1983. In the USSR, a 24 coil superconducting tokamak, T-15, is being constructed. Scheduled operation is early 1985. The third effort is the French Tore-Supra tokamak. It will have 18 circular bore coils reaching a maximum field of 9 T with completion expected in 1985 or 1986.

Whereas the mirror concept utilizes steady state coils, some of them are of complex geometry. The most ambitious tandem mirror project, MFTF-B at Livermore, requires two yin-yang coils for the end plugs with $B = 7.7$ T and a stored energy of ~ 410 MJ. The first coil has been constructed (see figure) and successfully tested at full current by Livermore, while the second coil is well underway. Central cell solenoids of 5 m bore and 3 T on axis are also in progress at General Dynamics Corporation. The complete set will have a stored energy of 1.6 GJ.

Materials development has progressed to the point where reliable high field niobium-tin conductors are now available. Other alloys such as niobium-titanium-tantalum which display higher critical fields at temperatures less than 4.2°K are also being developed. To complement them, the technology of superfluid HeII cooling is proceeding well.



Insertion of the 750,000 lb. yin-yang magnet coils into the Mirror Fusion Test Facility (MFTF) vacuum vessel. The magnet coils are encased in liquid nitrogen jackets and maintained at 4.5 K by internal circulation of liquid helium from a cryogenic refrigerator; the stainless steel vessel measures 10.6 m in diameter.

10. WHAT ADVANCES IN MATERIAL RESEARCH HAVE BEEN MADE OVER THE PAST 5 YEARS?

There are three areas in which major advances have been made between 1978 - 1982:

1) More detailed stress and lifetime analyses of first wall materials.
2) Increases in swelling resistances of austenitic alloys.
3) Discovery of favorable radiation damage resistance of ferritic alloys.

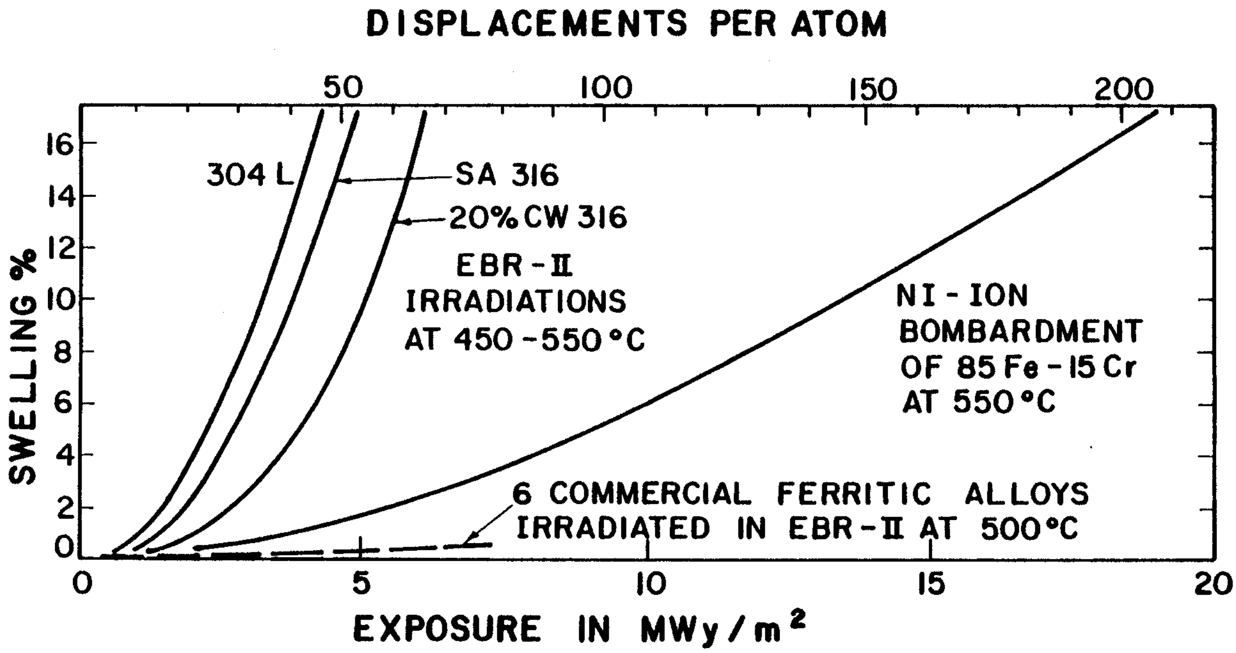
The ability to account for cyclical, thermal and swelling induced stresses along with steady state creep has allowed the design community to more confidently predict first wall lifetimes of almost 5 MW-y/m^2 before the walls need to be replaced.

A new understanding about the characteristics of swelling in austenitic materials has revealed that the major effect of cold working, thermo-mechanical treatments, alloying or induced helium atoms is to alter the incubation dose to start swelling. Once swelling begins, it has been shown by scientists at Hanford Engineering Development Laboratory (HEDL) that the rate of swelling is ~ 1% per dpa, regardless of prior treatment of the austenitic alloys (see figure). Such considerations limit the useful lifetime of austenitic alloys to ~ 5-10 MW-y/m^2.

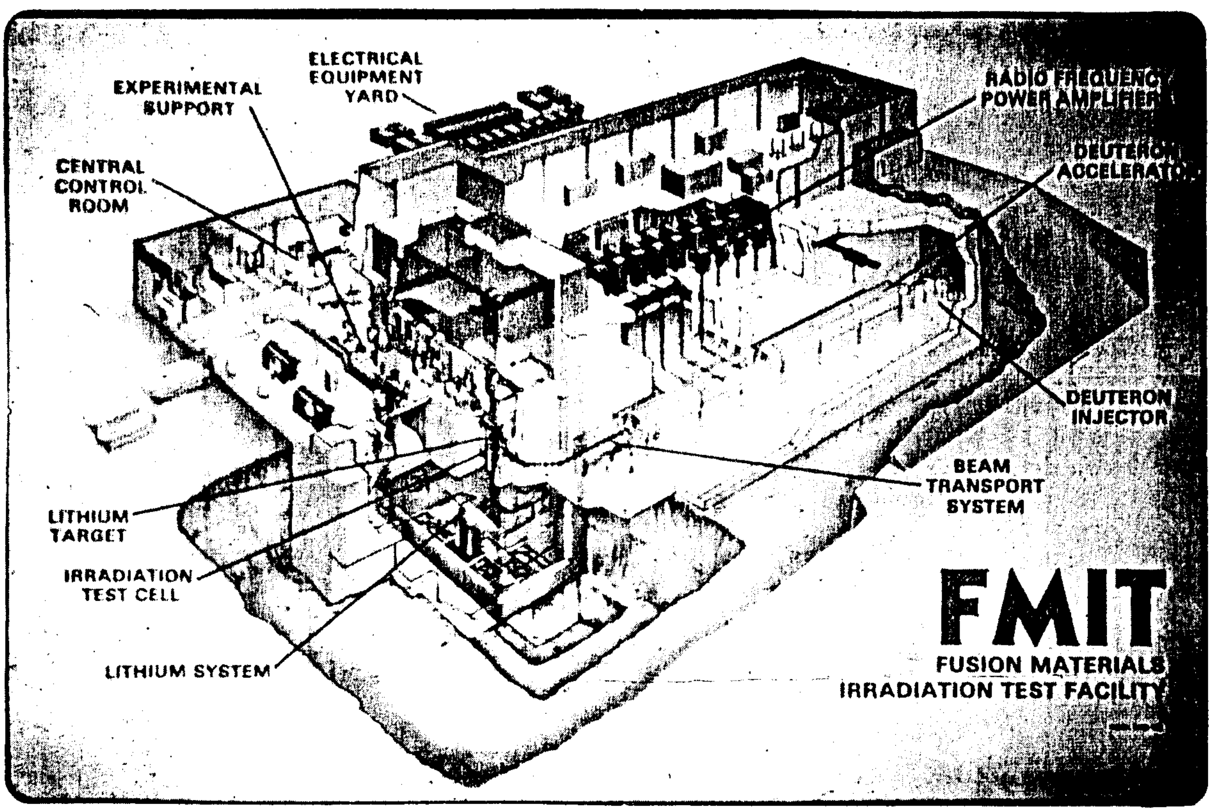
Fortunately, it was found that the ferritic steels are much more resistant to swelling with an incubation dose to begin swelling about the same as for austenitic alloys. The important feature of the ferritic alloys is that they swell at only ~ 0.1% per dpa (see figure) which should extend their useful lifetime to 150 to 200 dpa. At the conversion of 10 dpa ≅ 1 MW-y/m^2, there is considerable optimism that we may be able to reach useful lifetimes of 15-20 MW-y/m^2.

Finally, some progress has been made toward the construction of a high flux, high energy neutron production facility to test materials. The Fusion Materials Irradiation Test (FMIT) facility at HEDL (see figure) was first proposed in 1976 and scheduled for completion in 1982. Several delays in funding for the facility have now occurred and the FMIT facility is scheduled for operation in 1987 if money from the Japanese and Euratom laboratories can be obtained to finish the project. At the time of this report (1983), it is not clear whether or not the project will be completed.

As of the end of 1982, the highest 14 MeV fluence to a sample at room or elevated temperatures is ~ 0.006 dpa (equivalent to less than one day in a typical power plant). Obviously, there is a long way to go before one can confidently predict high fluence behavior of irradiated material.



Summary of recent swelling results for stainless steels irradiated with neutrons. Both austenitic and ferritic alloys show an incubation period before swelling starts but the steady-state swelling rate is ~ 1% per year for austenitic alloys and 0.1% per dpa for ferritic alloys.



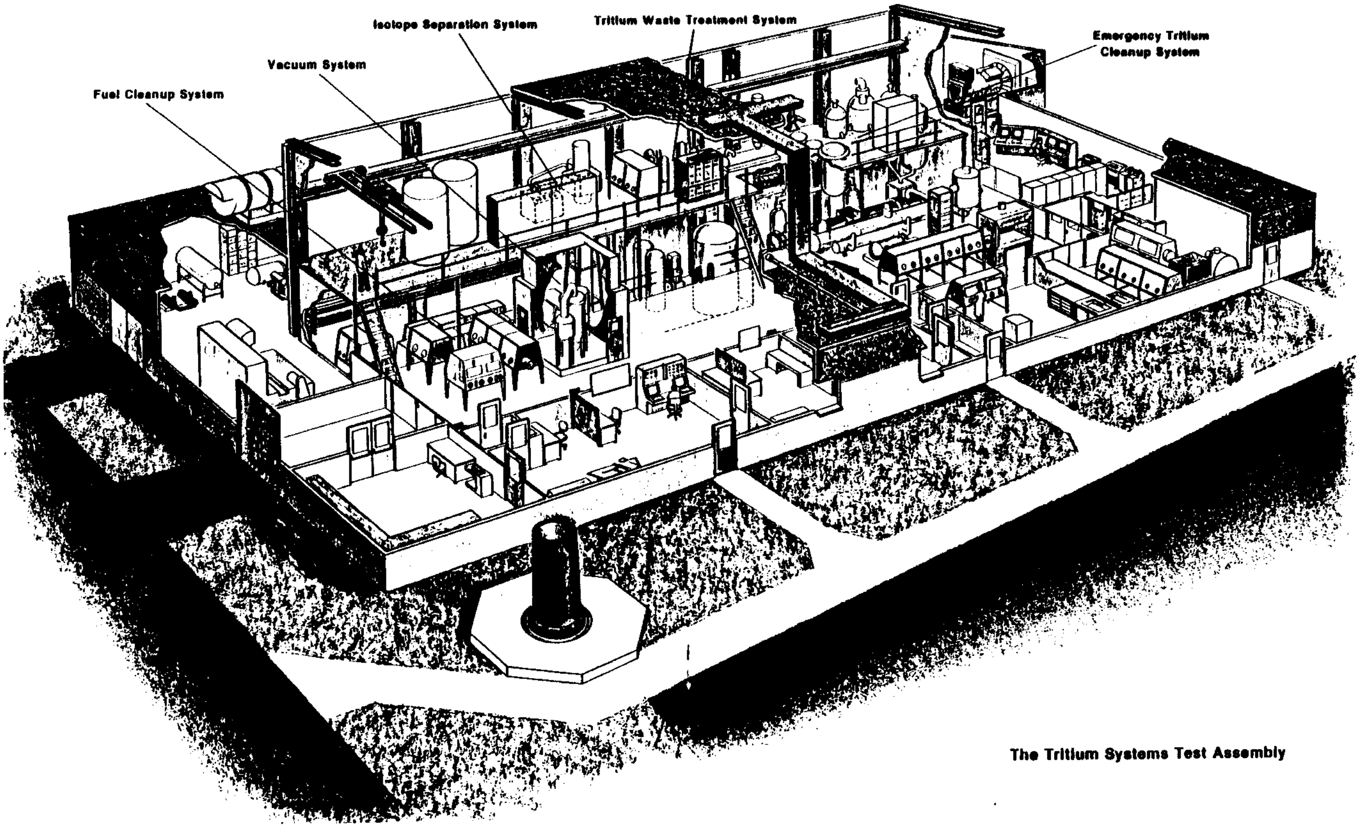
FMIT -- Proposed fusion materials irradiation test facility at Richland, Washington.

11. WHAT ADVANCES HAVE BEEN MADE IN GENERIC FUSION TECHNOLOGY OVER THE LAST 5 YEARS?

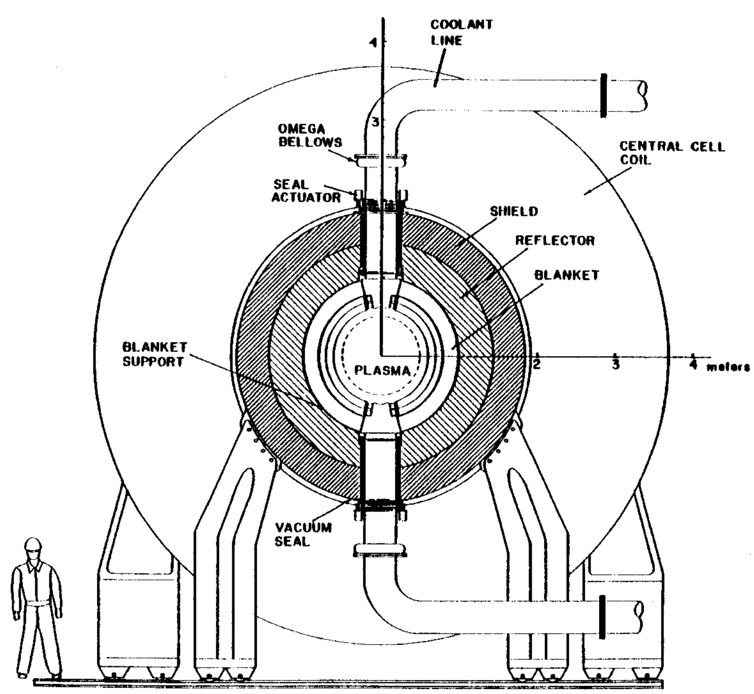
TRITIUM SYSTEMS The successful operation of DT fusion reactors will require safe and reliable tritium handling and containment systems. The recently completed Tritium Systems Test Assembly (TSTA) at LANL (see figure) will test the various technologies required for fuel processing. The facility will also demonstrate tritium containment systems, emergency cleanup, data acquisition and control and tritiated waste treatment. The DT circulating gas loop is designed to handle 1.8 kg of tritium per day which is the approximate flow rate anticipated in a near term reactor. Considerable practical experience also exists in the handling of tritiated water from the Canadian CANDU reactors where a heavy water detritiation unit is now under construction for operation in 1985.

BLANKET MATERIALS There have been many recent studies on the choice of breeder/coolant/structure options for DT-fusion reactor blankets. Primary breeding material candidates in current reactor designs include the liquid metals (lithium and lithium-lead alloys), and solid breeders. The recent STARFIRE tokamak reactor design, for example, employed a water-cooled blanket comprising lithium aluminate contained in the advanced austenitic stainless steel PCA. By contrast, the MARS tandem mirror design has selected a liquid lithium-lead as the combination breeder/coolant contained in the ferritic stainless steel HT-9 (see figure). The lead-lithium alloy combination has been shown to provide the best combination of breeding, heating and safety of the liquid metal approaches.

HIGH HEAT FLUX TECHNOLOGY There are a variety of requirements for high heat flux (HHF) surfaces in fusion reactor devices including neutral beam dumps, direct convertor end-plates, first wall surfaces in the vicinity of high charge-exchange heat fluxes and surfaces for divertors and pumped limiters. In addition to the design of optimum heat transfer methods, attention has been directed to the surface material itself in the search for high mechanical strength, low sputtering properties and low tritium diffusion rates. Examples of state of the art HHF surfaces include the swirl-water-cooled tubular beam dumps composed of the molybdenum alloy TZM for MFTF-B and the vapor-cooled copper alloy "Hypervapotron" beam dumps employed for the JET neutral beams. Maximum steady-state heat loads for these surfaces have been experimentally verified to 1-2 $kWcm^{-2}$, respectively. Experimental facilities to test components to heat fluxes of more than 10 kW/cm^2 have been constructed at Westinghouse-Pittsburgh and Sandia National Laboratory in Albuquerque. The latter facility has recently been testing the stability of coatings for high heat flux surfaces.



Schematic drawing of the Tritium Systems Test Assembly (TSTA) at the Los Alamos National Laboratory. The facility was placed into operation in 1982.



Schematic drawing of MARS tandem mirror central cell blanket design which utilizes a $Li_{17}Pb_{83}$ alloy for breeding and cooling a ferritic steel blanket.

12. WHAT NEW LASER FACILITIES HAVE BEEN BUILT OVER THE PAST 5 YEARS?

The two major types of lasers used in ICF research in the past five years are solid state Nd:glass and gaseous CO_2. The parameters for some of the major ICF laser facilities are given in the table. In addition to these large systems, there are somewhat smaller lasers at KMS, NRL, Osaka, NRC Canada and other labs where many of the experiments studying basic physics of the interaction of lasers and plasmas have been completed.

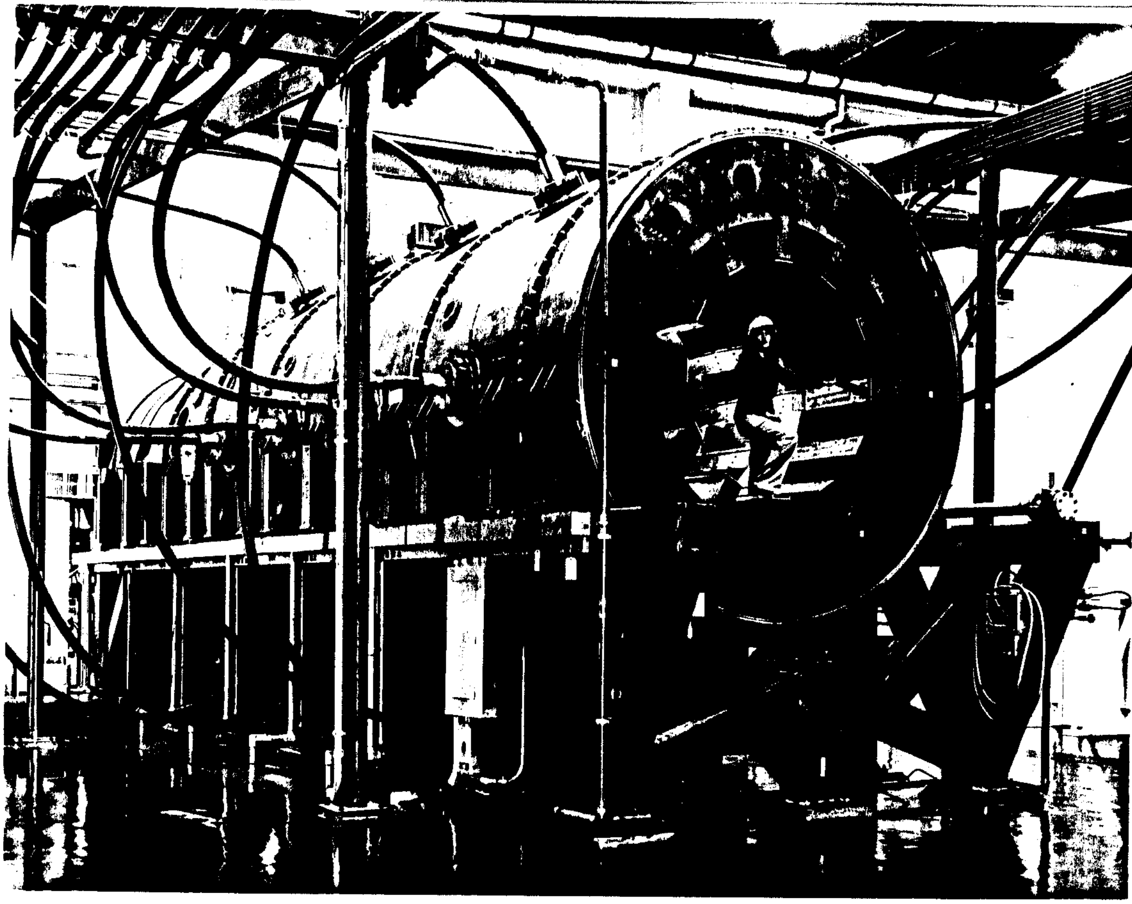
Major technological advances in the design and construction of large CO_2 laser systems have been made in the past 5 years. Much of the development of CO_2 lasers has been done at LANL (see figure). Major advances have been made in optics, power amplifiers, energy storage and control systems for these lasers. Understanding has been gained into the physics of parasitic oscillations, energy transfer kinetics in gas lasers and the use of plasma shutters as a means of protecting the laser from reflected light.

Technological advances in Nd:glass lasers have been made at LLNL and other labs. Efficient conversion of the light from a wavelength of 1.06 μm to 0.53 μm and 0.35 μm has been a major achievement and has allowed the measurement of the wavelength dependence of laser-plasma interactions. Work is also proceeding on improving the efficiency of the lasers and on the basic physics of solid Nd:glass amplifiers with the Novette facility at LLNL representing the most advanced facility to date (see figure).

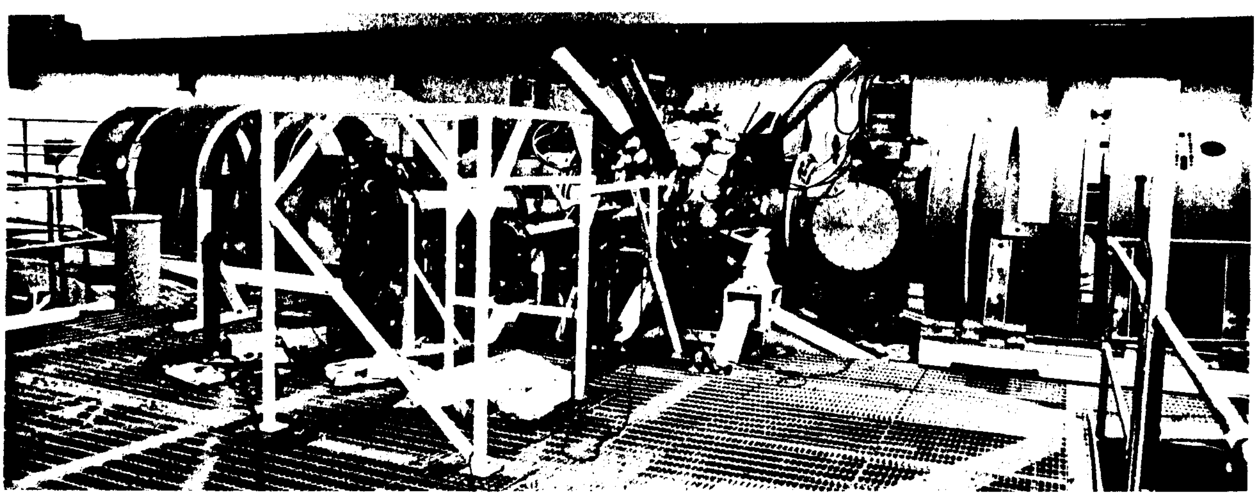
Neither CO_2 nor Nd:glass are very promising at this time as drivers for ICF power plants. Basic research is underway on Free Electron Lasers and Rare-Gas-Halide Lasers which may have the higher efficiencies and repetition rates needed for power generation.

Major ICF Laser Facilities in Operation or Nearly Completed

	Argus	Shiva	Novette	Omega	Helios	Antares	Lekko VIII
Laboratory	LLNL	LLNL	LLNL	Rochester	LANL	LANL	Osaka Univ.
Type	Nd:glass	Nd:glass	Nd:glass	Nd:glass	CO_2	CO_2	CO_2
Date of Operation	1976	1977	1982	1978	1981	1984	1980
Pulse Width (ps)	30-1000	100-2000	100-5000	30-100	1000	1000	1000
No. of Arms	2	20	2	24	8	24	8
Total Power (TW)	5	30	20	12	10	40	10
Max. Energy in Pulse (kJ)	2	15	30	4	10	40	10



Twenty kilojoule Antares CO_2 power amplifier under construction at Los Alamos National Laboratory in the USA.



Novette laser facility under construction at the Lawrence Livermore National Laboratory in the USA. The facility was operational in 1982.

13. WHAT UNCLASSIFIED PROGRESS HAS BEEN MADE IN TARGET PHYSICS OVER THE PAST 5 YEARS?

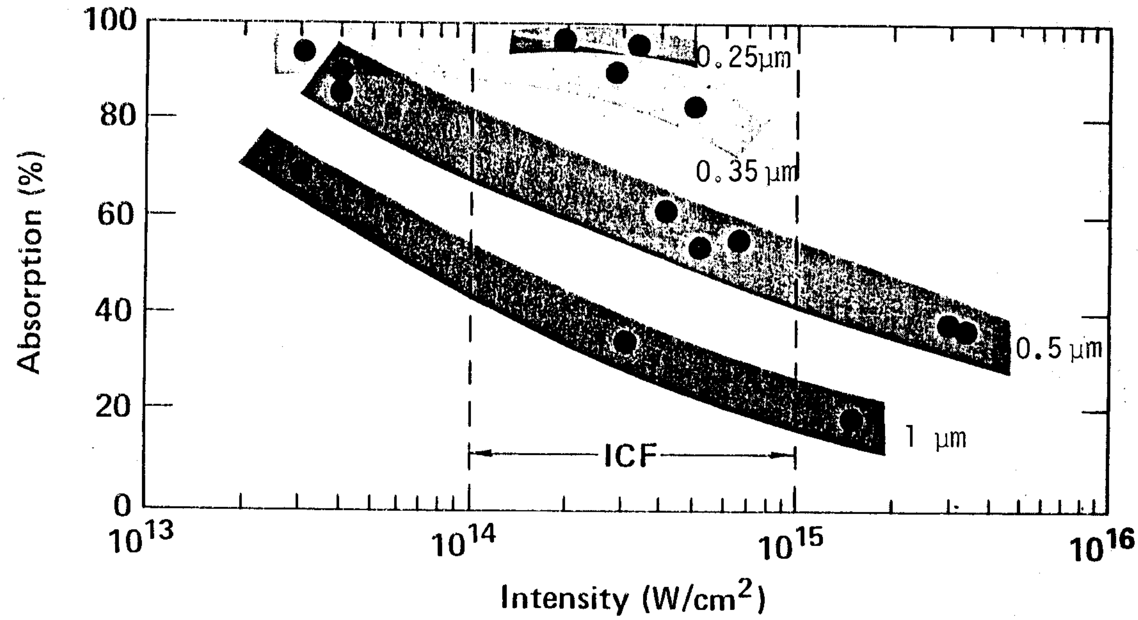
In the past 5 years, progress in target physics has been made in the areas of target simulation computer codes, experimental diagnostics, laser-target interactions, target manufacturing and fluid instabilities. In these areas of research some of the results are unclassified and may be discussed openly while others are classified and may not be commented on in this report. One should be aware that advances in unclassified work are only a small part of the complete picture.

Since only the large laser facilities are currently able to focus their energy onto a small target, most of the experimental target results have been for laser drivers of various wavelengths. A tremendous amount of work has been done both experimentally and theoretically on laser target interactions. One of the most significant results is the greatly improved absorption of light by the target at high powers at short wavelengths (see figure). The physical understanding gained in this area has led to improvements in computer codes used to design targets, and has led to an increase in fuel compression and temperature (see figure).

Important studies have been done at NRL on the behavior of thin layers of matter accelerated by lasers which has led to an understanding of the increased importance of illumination symmetry at short wavelengths. Fluid instabilities in accelerated thin layers have been studied theoretically and experimentally at several labs.

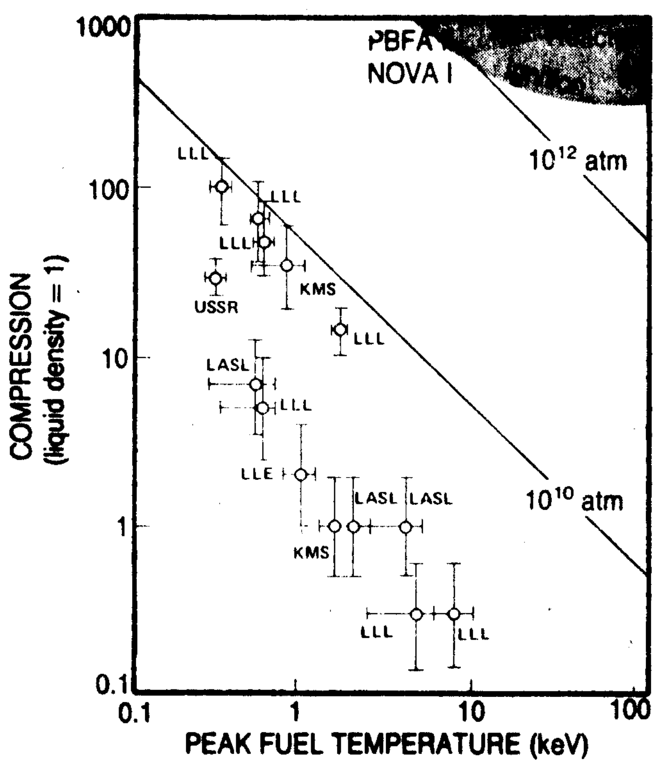
The declassification of the radiation driven target approach to ICF has occurred within the past five years. The details of these target designs remain classified, but they hold the potential of greatly reducing the symmetry requirements of the driver beams focused onto the target. This is particularly significant in the area of reactor design because complete symmetry and some first wall protection schemes are incompatible.

LASER LIGHT ABSORPTION INCREASES DRAMATICALLY WITH SHORTER WAVELENGTH



Data compiled from Ecole Polytechnique, Univ. of Rochester, and LLNL.

Experimental data showing that laser light absorption increases dramatically with shorter wavelength.



ICF High Density Experiments - Achieved and Projected

14. **WHAT PULSED POWER FACILITIES HAVE BEEN USED TO STUDY LIGHT ION BEAM FUSION OVER THE PAST 5 YEARS?**

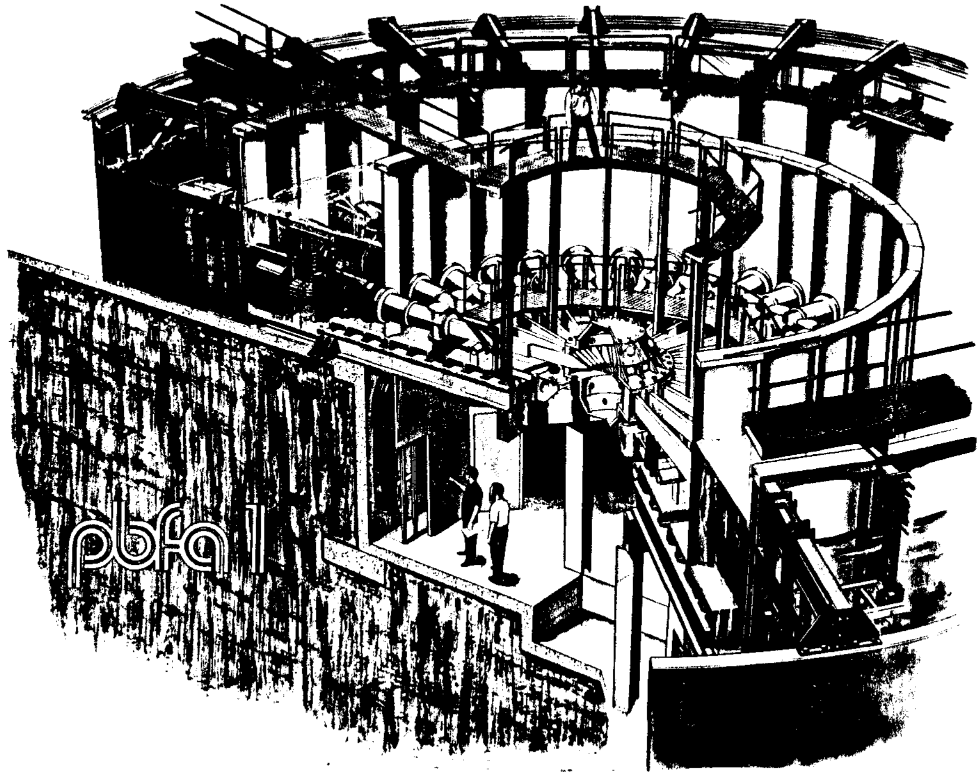
There are two basic types of ion beam drivers: heavy ion beam accelerators and pulsed power light ion beam accelerators. There are presently no heavy ion beam facilities dedicated to fusion research so the only present facilities are the light ion beam machines listed in the table below. One should notice that the total energy available from these machines is much larger from present day lasers but that the pulse width is much longer leading to powers that are roughly the same. The efficiency of ion drivers (~ 20%) is generally much higher than those for lasers (< 5%) but there are much greater difficulties in focusing an ion beam to a small spot than accomplishing the same thing with a laser beam.

There are two basic types of heavy ion accelerators: rf and induction linacs. A conceptual design of an rf linac for a fusion power plant (HIBALL) has been designed at GSI in Germany. The major advances in rf linacs have occurred in the building of accelerators for particle physics experiments. Basic work on induction linacs has been done in the USA at LBL.

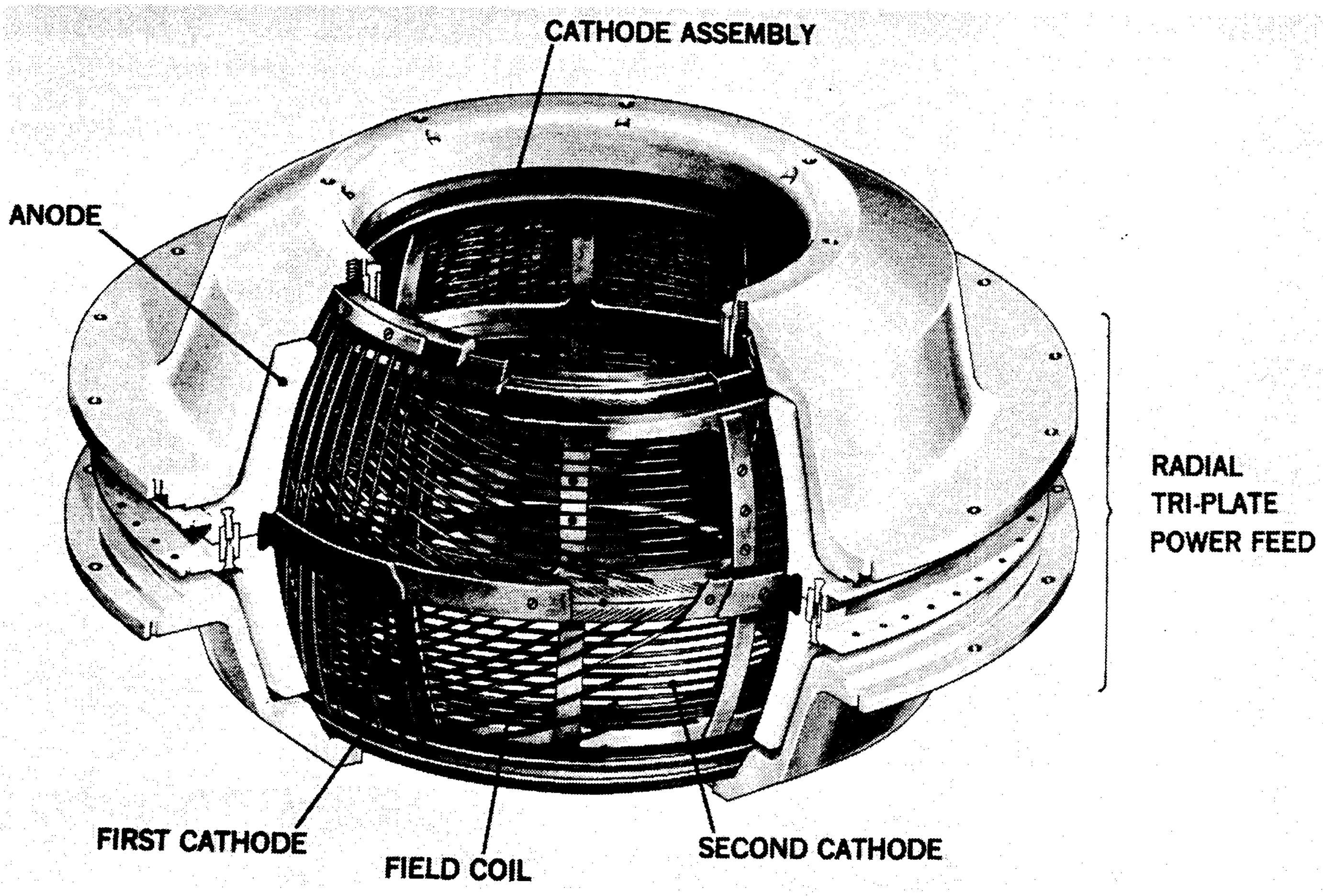
Technological advances in pulsed power machinery, ion diodes and ion beam propagation have been made at SNL, NRL and other labs around the world. The largest and most recent pulsed power machine is PBFA-I at Sandia (see figure) and PBFA-II is scheduled for operation in 1985. Among the greatest improvements in pulsed power are new switches which are more reliable, have shorter pulse widths and may be used repetitively. Since the change in emphasis from electron beams to ion beams less than five years ago, ion diode work at SNL has produced a new type, the Ampfion (see figure). Work on ion sources is continuing as is work on basic diode physics. Ion beam propagation in preformed plasma channels has been demonstrated at ion currents up to 50 kA.

Major Pulsed Power Drivers in the U.S.

	Proto-I	Proto-II	PBFA-I	PBFA-II	Gamble-II	Aurora
Laboratory	SNL	SNL	SNL	SNL	NRL	Harry Diamond
Diode Voltage (MV)	1-2	1-3	2-4	2-16	0.8-1.4	5
Current (MA)	0.5	10-3.3	15-7.5	50-6.3	0.3-0.7	0.07
Power (TW)	0.5-1	10	30	100	0.24-1.0	0.4
Pulse Width (ns)	25	50	30	40	50	140
Total Energy (MJ)	0.12-0.25	0.5	0.9	4.0	0.05	0.05



Schematic of the PBFA-I (Particle Beam Fusion Accelerator) facility at Sandia National Laboratory in the USA. The facility went into operation in 1981.

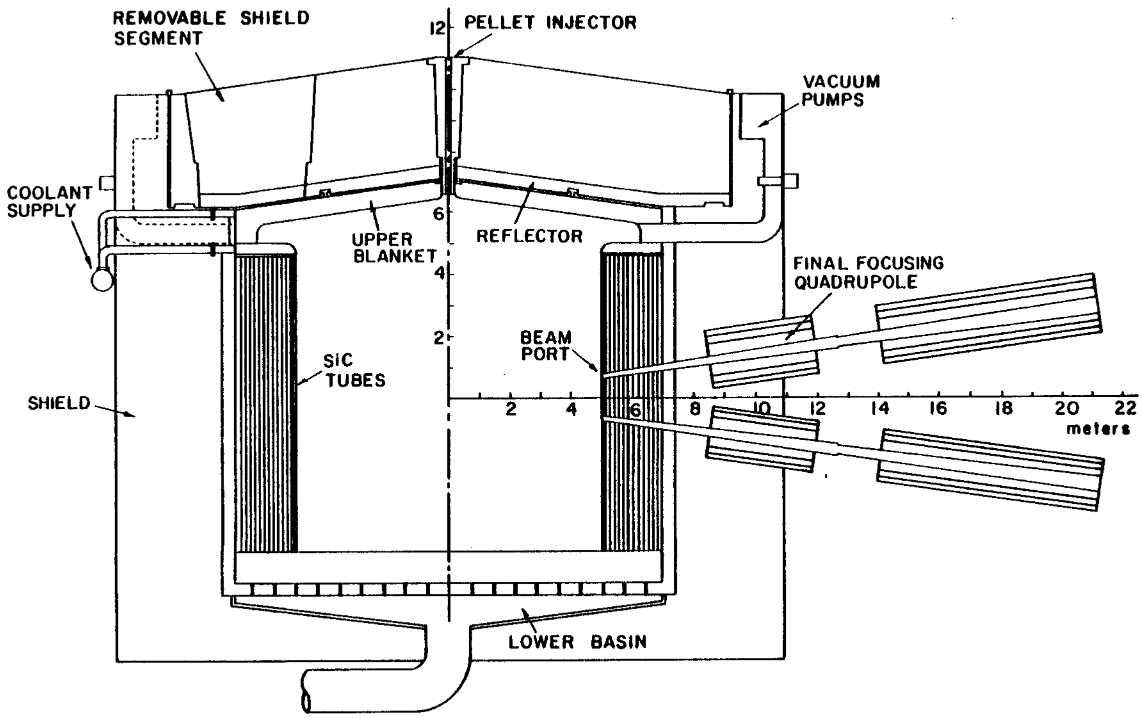


AMPFION - Hybrid diode mode for Sandia National Laboratory to produce protons in PBFA-I.

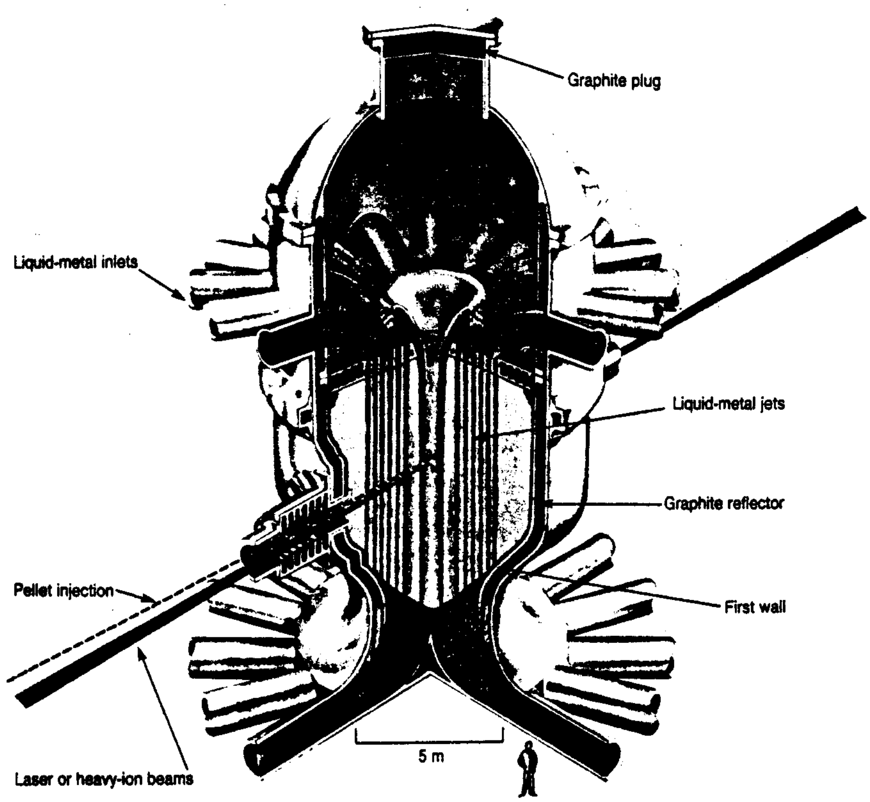
15. HOW HAVE THE PROSPECTS FOR AN ICF POWER REACTOR CHANGED OVER THE PAST 5 YEARS?

The basic figure of merit for ICF power plant economy is the product of driver efficiency η and target gain G. This product, ηG, must equal about 20 for the ICF power plant to be economically competitive with comparable magnetic fusion based plants. In the past five years, the predictions of feasible target gain at realistic driver energies (i.e., less than 10 MJ) have been drastically reduced from 1000 to about a maximum of 200. These new low estimates of target gain nearly rule out low efficiency (3-7%) short wavelength lasers as ICF power plant drivers. In place of low efficiency lasers, interest has turned to potentially higher efficiency (~ 15-30%) light or heavy ion beam driven reactors. One such heavy ion beam reactor, HIBALL, is shown in the accompanying figure, and another, HYLIFE, is shown in the other figure.

On the technology side, the past five years have seen an ever expanding interest in the use of liquid metals (e.g. Li or $Li_{17}Pb_{83}$) as the coolant and first wall protection mechanism in ICF reactors. In the HIBALL reactor, this liquid metal flows through easily replaceable porous SiC tubes. The thin film of liquid metal on the surface of the tube protects it from the x-rays and debris from the exploding target. At the same time, the liquid metal inside the forest of tubes protects the first structural wall from neutron damage so that it can remain in place for the lifetime of the plant. This permanent first wall is a significant advantage of the ICF concept over the magnetic fusion approach to reactor design.



Schematic of HIBALL heavy ion beam reactor design performed by GSI-Darmstadt and KfK-Karlsruhe in Germany and the University of Wisconsin/Fusion Power Associates group in the USA.



Schematic of the most recent HYLIFE reactor design conducted at the Lawrence Livermore Laboratory in the USA.

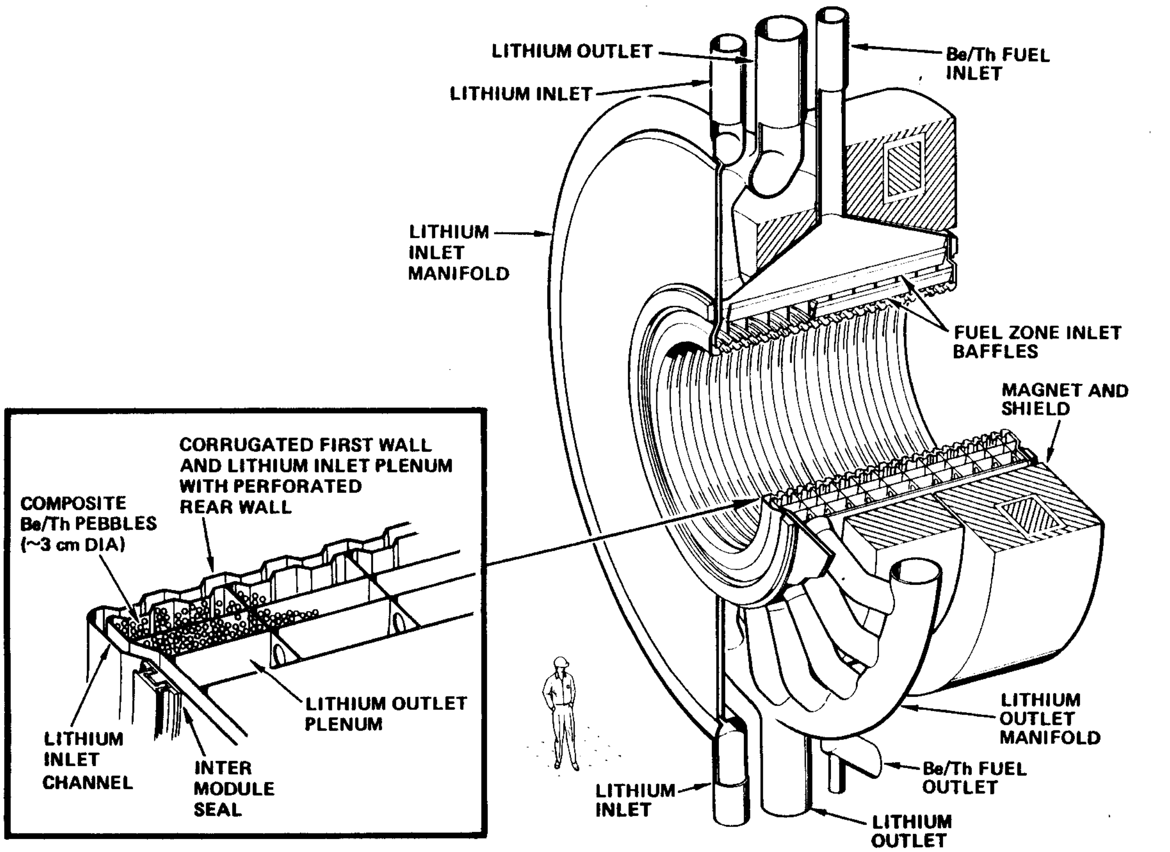
16. WHAT ADVANCES HAVE BEEN MADE IN FISSION-FUSION HYBRIDS IN THE PAST 5 YEARS?

The work in fission-fusion hybrids in the past five years has produced no revolutionary breakthrough but rather has seen a consistent refinement and definition of the role of the hybrid and further developments in hybrid concepts and designs. The latter is due in part to the more complete understanding of the requirements for the various fusion drivers and in part due to a better understanding of the design trade-offs in the blanket of the hybrid device.

Three rather different approaches to hybrid design are illustrated by the Westinghouse Commercial Tokamak Hybrid Reactor (CTHR), the Wisconsin SOLASE-H reactor, both sponsored by EPRI, and the Fission Suppressed Tandem Mirror Hybrid Reactor designed by Lawrence Livermore, TRW, General Atomic, Westinghouse and Oak Ridge and sponsored by the Department of Energy.

The Westinghouse CTHR is based on a tokamak and two blanket concepts were considered: UC fueled with stainless steel cladding and structure, He cooled or UO_2 fueled zircalloy cladding, stainless steel structure, and boiling water cooled. Both were tritium self-sufficient. The SOLASE-H design was based on laser driven inertial confinement and used PWR fuel bundles fabricated with fertile material for enrichment in place. This material could then be directly inserted into a LWR with no intermediate reprocessing. The fission suppressed tandem mirror design (see figure) investigates a hybrid operating mode in which fission of the fertile and fissile fuel was suppressed through the use of neutron multipliers and on-line reprocessing. Again, two blanket designs were considered; the first utilized liquid lithium for tritium breeding and a molten salt as the carrier for the fertile material. The second used beryllium as a neutron multiplier, thorium oxide as the fertile material, and lithium as a tritium breeding and heat transfer material. The basic characteristics of each design are shown in the table.

At the present time, the research support for hybrid studies is at a low level in the USA, almost non-existent in Europe and Japan, and a major component of the USSR program. Prospects for future support in the West look rather dim.



Schematic of fission suppressed tandem mirror hybrid breeder blanket design coordinated by LLNL.

<u>Summary of Recent Hybrid Reactor Designs</u>

	CTHR Tokamak		SOLASE-H Laser ICF	Fission Suppressed Tandem Mirror (Dec. 1982)
	UC-SS	UO_2-Zr		
Fusion Power (MW)	1200		1240	3000
Neutron Wall Loading (MW/m^2)	2		1.9	1.3
Tritium Breeding Ratio	1.20	1.13	1.08	1.06
Fissile Atoms/ Fusion Neutron	0.97	0.54	.43	0.69
Fissile Production kg/y	2730	1524	2030	5646

17. WHAT ARE THE MAJOR FINDINGS IN OUR ASSESSMENT OF THE SAFETY AND ENVIRONMENTAL ASPECTS OF FUSION REACTORS OVER THE PAST 5 YEARS?

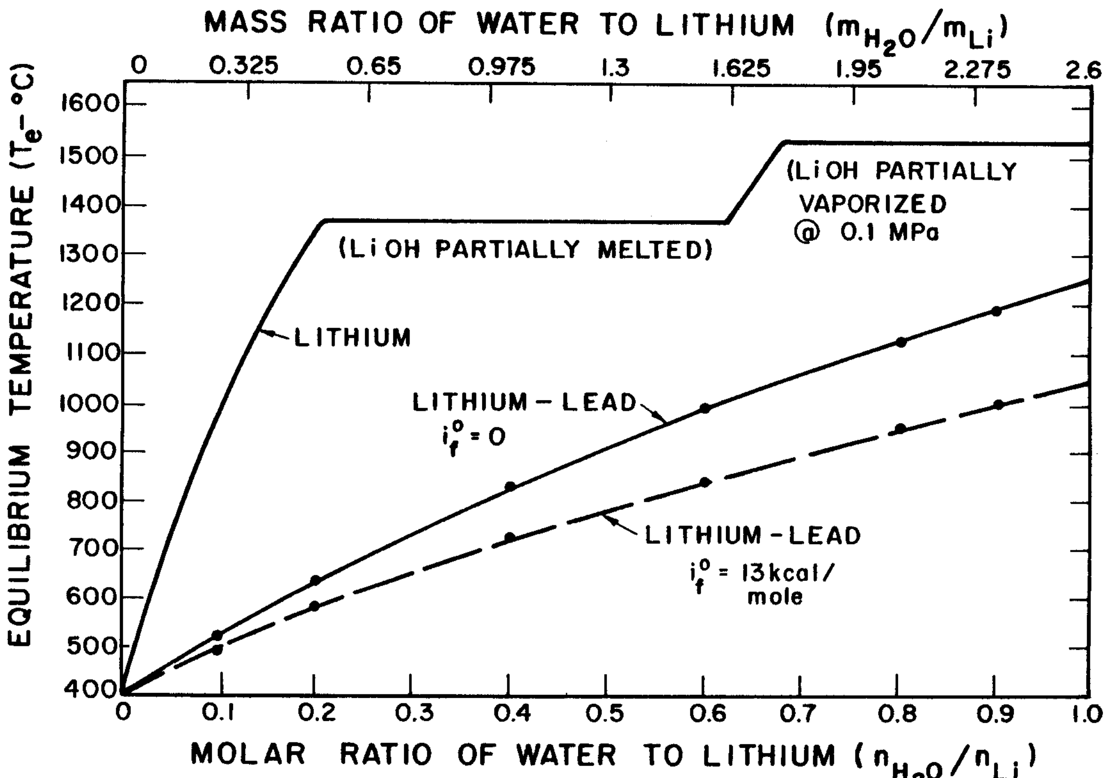
It has only been within the past 5 years that attempts have been made to systematically address fusion reactor safety issues. Unfortunately, far too little effort has gone into such work in the past and because the design of fusion reactors is still in a "premature" stage, only the most obvious problems have probably been addressed. Nevertheless, some general points have emerged.

1. The quantity of volatile radioactivity in the tritium fuel is ~ 1000 times smaller than for the "fuel" in a fission reactor.
2. Depending on the structural material chosen, there is almost as much radioactivity in the structure of a fusion plant as that tied up in the fuel of a fission plant. However, the radioactivity in a fusion plant structural material is relatively immobile and most of it decays away with half lives of less than 100 years.
3. The potentially high flame temperture of Li - water reactions can be avoided by using the eutectic mixture of Pb and Li (see figure). The neutronic performance of the Pb-Li alloy is in fact better than Li and the tritium inventory in the Pb-Li alloy can be less by a factor of 1000 or more.
4. The use of double wall heat exchangers can greatly reduce the tritium loss to the steam cycle and reduce the total cost of the heat transport system at the same time.

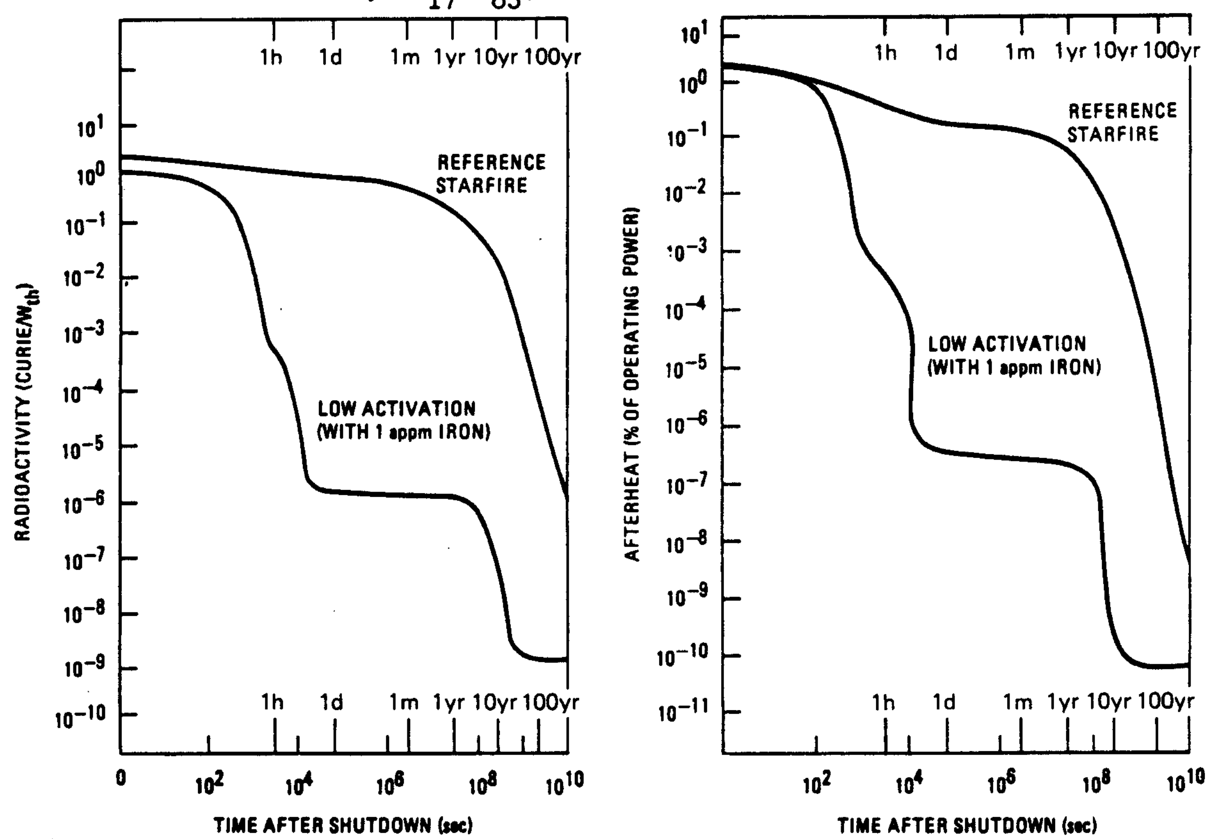
The establishment of the Safety Center at EG&G in Idaho Falls, Idaho has provided a focal point for safety research in the USA.

The environmental issues associated with fusion reactors have been recognized at least in a qualitative way almost since the first proposals for fusion power plants were made and the perceptions of them were often cited as part of the rationale for the development of fusion power. However, no complete assessment of the environmental impact of fusion systems or of any particular design concept has ever been published. At the present time, the U.S. Department of Energy has contracted with the Oak Ridge National Laboratory for a generic environmental impact statement on magnetic confinement fusion. This study will be published in 1983 and deals with one particular design concept, STARFIRE. Enough alternatives will be considered to make it applicable to most magnetic fusion systems.

One of the issues that has been considered in the past 5 years is the disposal of radioactive waste from fusion power plants. A wide variety of structural materials has been considered and comparisons are made between a standard 316 stainless steel and aluminum alloy with low impurity levels (see figure). The conclusion drawn thus far is that the total radioactivity levels can be reduced by a factor of 1,000 to 1,000,000 depending on the choice of materials. However, other considerations such as temperature of operation, corrosion resistance, and radiation damage resistance make the choice of the optimum material very difficult.



The maximum equilibrium temperature from a lithium-water interaction as a function of the ratio of water to lithium (note: i_f^o denotes the heat of formation for lithium-lead, $Li_{17}Pb_{83}$).



Post shutdown radioactivity and decay heat levels for the STARFIRE reference and low activity designs.

18. **WHAT MAJOR REVIEWS OF THE FUSION RESEARCH PROGRAM HAVE TAKEN PLACE OVER THE PAST 5 YEARS AND WHAT EFFECT HAVE THEY HAD?**

In the past five years, there have been five major reviews of the United States fusion program, one of the European program and one conducted on the International Tokamak program. The United States reviews were mainly in the area of magnetic confinement and after reviewing the essence of what was concluded by these panels, one could make the following observations:

Ad Hoc Experts Group on Fusion (Foster Panel) 1978	Diversify the fusion program away from such heavy emphasis on tokamaks and lasers. Revise governmental administrative structure to lay the ground work to commercialization.
Atomic Industrial Forum Committee on Fusion-1979	Called for accelerated, focused program in which industry could effectively compete.
Advisory Panel on Fusion Energy (Hirsch Panel) 1979-80	Concluded *"...pace of the development of fusion power is now primarily in the hands of Congress and the President, not in the hands of the technologists."*
INTOR Fusion Experts Committee-1979	*"...it is concluded that it is scientifically and technologically feasible to undertake the construction of an INTOR-like device to operate in the early 1990's..."*
Fusion Review Panel of Energy - Research Advisory Board (Buchsbaum Panel) 1980	The panel felt the fusion community had gone too far in the design of the Engineering Test Facility and asked that a more modest step be taken.
European Fusion Review Panel (Beckurts Panel) 1981	Concluded that the European program concentrate on the tokamak and that alternate approaches should play a minor role.
Magnetic Fusion Advisory Committee - 1982 (MFAC continued in 1983)	Concluded that 1.) *"The tokamak and mirror concepts can be embodied in viable reactor designs of roughly similar characteristics."* and 2.) the Reversed Field Pinch concept be pursued with a higher priority than the EBT or stellarator concepts and 3.) a long pulse ignited tokamak should be the next step beyond TFTR.

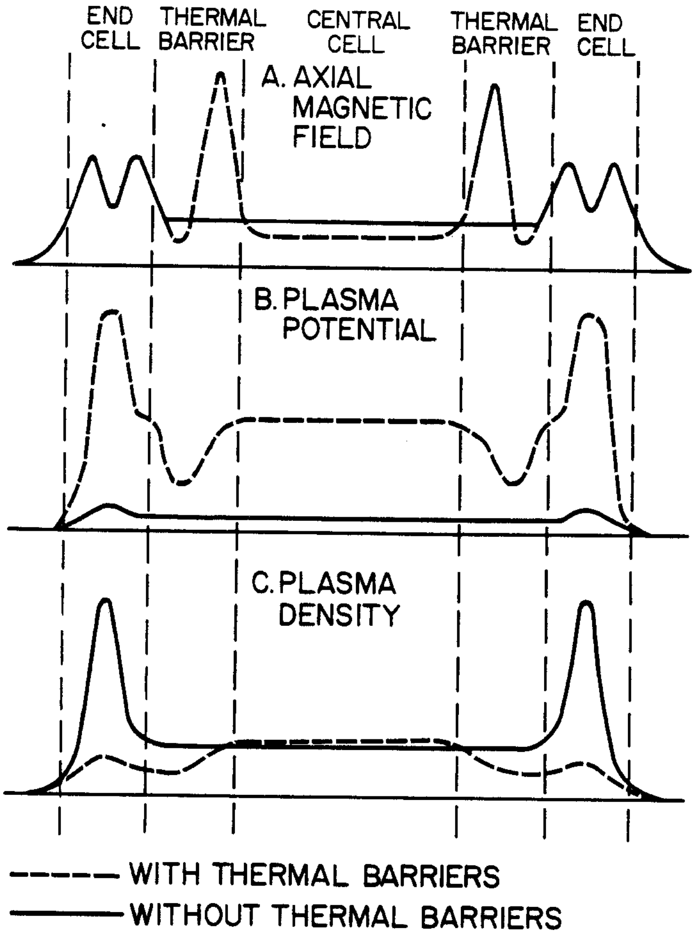
As a result of the review activity in the United States, especially by the Hirsch panel and by Representative Mike McCormack (see figure), the passage of the MFEA-1980 was indeed an important milestone. The important features of the Act are 1.) the acceleration of the funding for the current fusion program by a factor of two in uninflated dollars by 1987 and 2.) creation of a national magnetic fusion engineering center. Unfortunately, the recommendations of the act have not been followed by Congress and the current (FY-1983) budget of 447 million dollars is actually <u>lower</u> than the FY-81 budget when inflation is considered.

Congressman Mike McCormack (WA) and Senator Paul Tsongas (MA), principal proponents of, and largely responsible for passage of the Magnetic Fusion Energy Engineering Act of 1980.

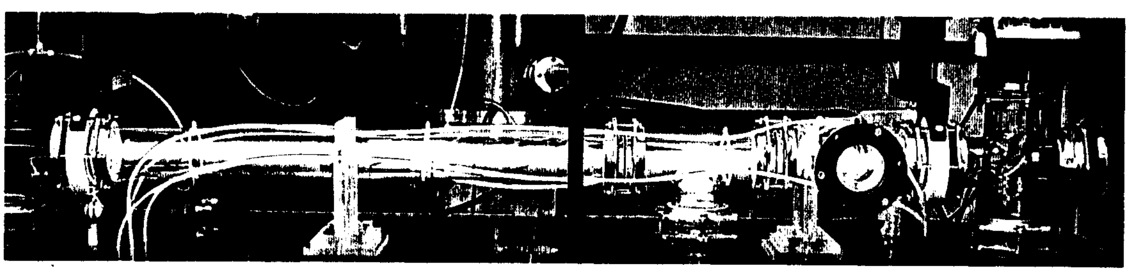
19. OVERALL, WHAT MAJOR EVENTS HAVE OCCURRED AND WHAT TRENDS HAVE BECOME EVIDENT IN THE U.S. FUSION PROGRAM?

There have been four major developments in the U.S. magentic fusion program which have had dramatic effects on the commercial potential for fusion. The first is the proposal and partial verification of current driven tokamaks. If future research in this area is successful, the lack of pulsing should insure longer lived, less complex reactor components. The second advance is the invention of the thermal barrier concept in tandem mirrors (see figure). This exciting concept is responsible for the revival of the mirror program in the U.S. and will help to insure the high Q-values so necessary for economical operation. The third major trend is the increased use of RF heating in both experimental and commercial fusion devices. Whereas before 1978 most tokamaks were heated with beams, in 1982 practically all future experiments and reactors are RF heated. Finally, the fourth major trend is the de-emphasis of the long term commercial reactor studies. There are presently no commercial tokamak studies taking place in the U.S. and current plans do not call for any studies (mirrors or tokamaks) after September, 1983. Continuation of this policy will be very detrimental to the public understanding of the commercial potential of fusion and of its engineering credibility.

In the inertial confinement area, there are also four major events to consider. The first is the declassification of the radiation driven target concept and the associated relaxation of symmetry requirements for target illumination. The second event is that the potential for CO_2 lasers has diminished because of the unfavorable coupling to plasmas. On the other hand, interest in short wavelength lasers has increased because of more efficient coupling. On the ion beam side, the period from 1978 to 1982 saw the switch from electron beams to light ion beams as the proposed driver. Finally, perhaps the most discouraging trend in the last five years is the separation of the ICF program from commercial applications. At the present time (early 1983) this is <u>no</u> civilian ICF program supported by DOE and hence consideration for future commercial applications must be made by private initiative.



Profiles of a tandem mirror system with and without thermal barriers. The invention of this concept by scientists at LLNL has had perhaps the most far reaching effect on the mirror program since its inception in the early 1950's.



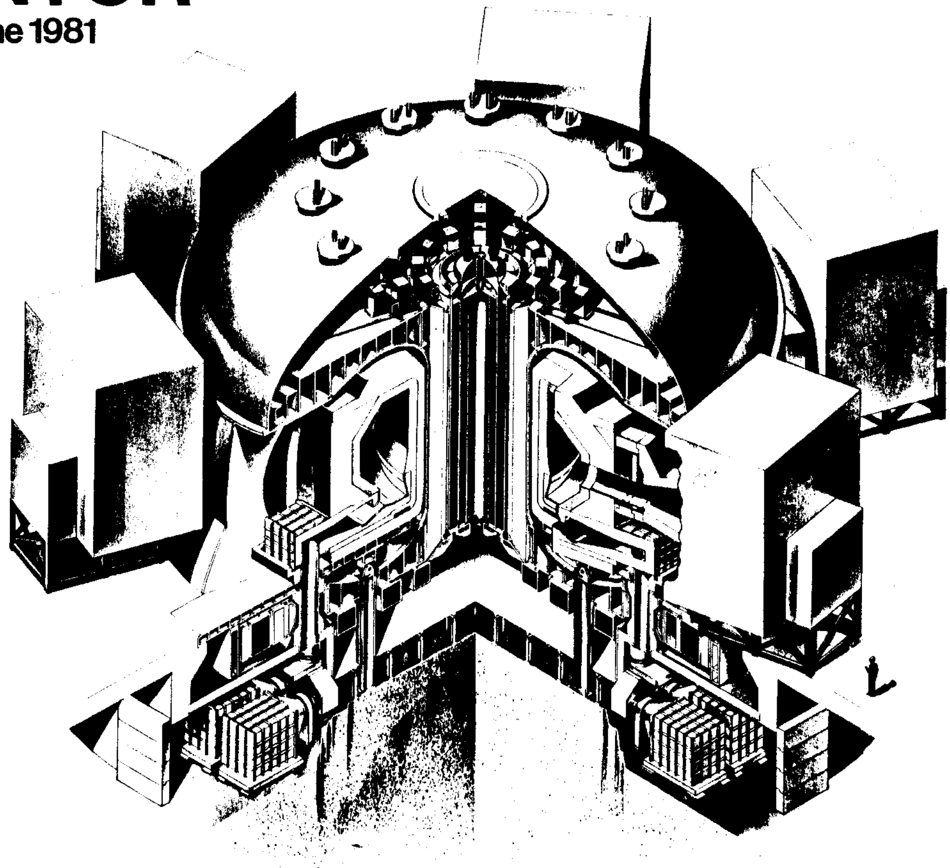
A laser-triggered discharge for propagation of ions in a channel.

20. **OVERALL, WHAT MAJOR EVENTS HAVE OCCURRED AND WHAT TRENDS HAVE BECOME EVIDENT IN THE WORLD FUSION PROGRAM?**

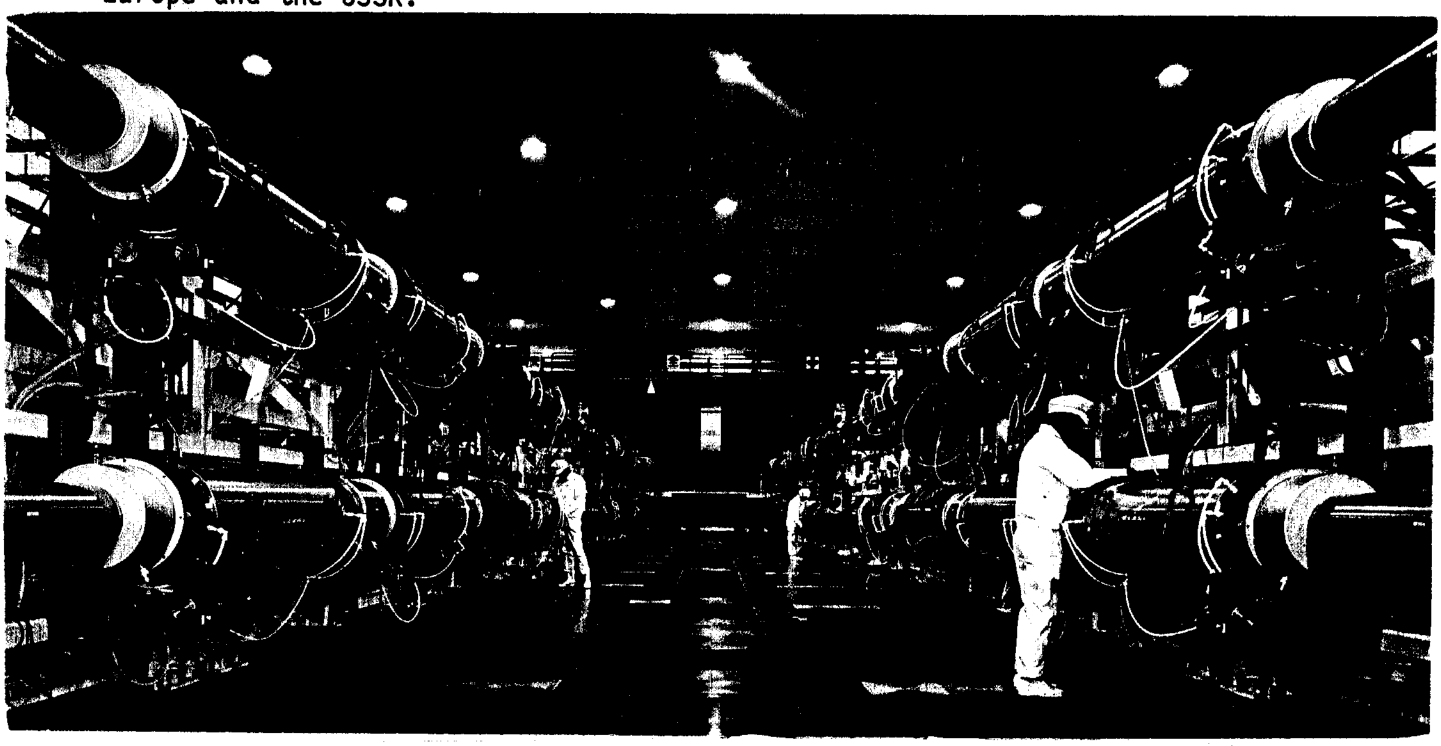
In the international area, there are two major events which have occurred in the magnetic fusion area. Perhaps the most dramatic is the collaboration of the U.S., USSR, Japan and European Community on the INTOR project (see figure) from 1979-1982. The success of this collaboration bodes well for future work and the project will perhaps even extend beyond 1983. The second event of note is the rapid rise in the level and quality of the Japanese program. Aside from a 460% increase in budget, the current Japanese program in tokamaks may be the most aggressive in the world.

The major events in the ICF field are in four areas. First, a consensus has developed to use ions instead of electrons as drivers in ICF research. The second event is the rapid increase in the Japanese ICF program both in the laser (see figure) and ion beam area. Similarly, a third major event occurred with the establishment of a West German program in the ion beam area with work on heavy ions at Darmstadt and light ions at Karlsruhe. Finally, the international visibility of the USSR program has dropped in both the laser and ion beam programs. It is not known whether this is a real de-emphasis or a lack of communication.

INTOR
June 1981



Schematic of the International Tokamak Reactor (INTOR) design. This conceptual design is the result of over 400 scientists in the USA, Japan, Europe and the USSR.



Main amplifier chains of GEKKO XII glass laser at the Institute of Laser Engineering, Osaka University.

References for Section A

The authors appreciate the help of the Lawrence Livermore National Laboratory and Sandia National Laboratory in the graphics and some of the technical summaries in Section A.

1. B. Badger et al., "Progress in Fusion Research, 1978-1982," University of Wisconsin Fusion Engineering Progress Report, UWFDM-496, September 1983.