Starpower: the quest for fusion energy today

The Office of Technology Assessment's "Starpower" detailed the different methods of attaining fusion energy. Part 2 of a series from the OTA's report.

Fusion science and technology

Confinement concepts

Most of the fusion program's research has focused on different magnetic confinement concepts that can be used to create, confine, and understand the behavior of plasmas. In all of these concepts, magnetic fields are used to confine the plasma; the concepts differ in the shape of the fields and the manner in which they are generated. These differences have implications for the requirements, complexity, and cost of the engineering systems that surround the plasma. . . .

At this stage of the research program, it is not known which confinement concept can best form the basis of a fusion reactor. The tokamak is much more developed than the others, and tokamaks are expected to demonstrate the basic scientific requirements for fusion within a few years. However, several alternate concepts are under investigation in order to gain a better understanding of the confinement process and to explore possibilities for improving reactor performance.

The major scientific questions to be answered for each confinement approach are whether and with what confidence the conditions necessary for a sustained, power-producing fusion reaction can be simultaneously satisfied in a commercial-scale reactor. Much of the experimental and theoretical work in confinement studies involves the identification and testing of *scaling relationships* that predict the performance of future devices from the results of previous experiments. Ideally, such scaling models should be derivable from the basic laws of physics. However, the behavior of plasmas confined in magnetic fields is so complicated that a general theory has not yet been found. With some simplifying assumptions, limited theoretical models have been developed, but they are not broad enough to extrapolate the behavior of a concept to an unexplored range. Without a sound theoretical base, the risk of taking too large a step is great. A series of intermediate-scale experiments is needed to bridge the gap between concept development and a full-scale reactor. . . .

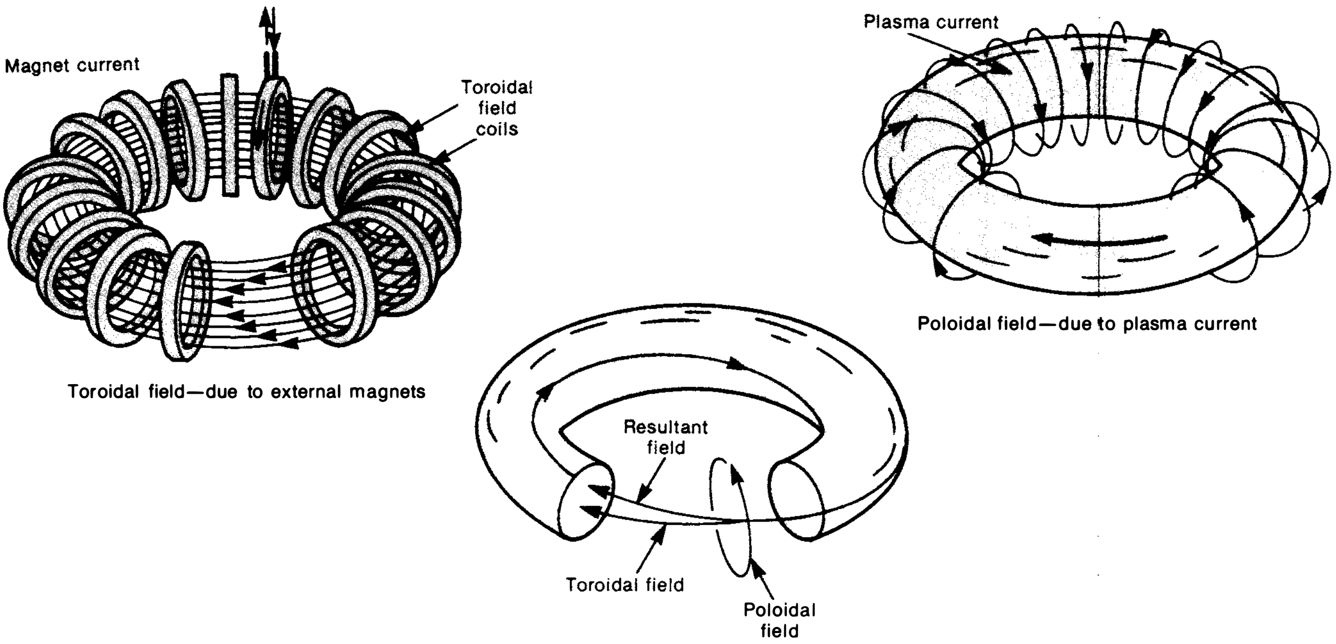
'Closed' concepts

In "closed" magnetic confinement configurations, the plasma is contained by magnetic lines of force that do not lead out the device. Closed configurations all have the basic shape of a doughnut or inner tube, which is called a *"torus."* A magnetic field can encircle a torus in two different directions (**Figure 3**). A field running the long way around the torus, in the direction that the tread runs around a tire, is called a "toroidal" field. This field is generally created by external magnet coils, called toroidal field coils, through which the plasma torus passes. A magnetic field perpendicular to the toroidal field, encircling the torus the short way, is called a "poloidal" field. This field is generated by electrical currents induced to flow within the plasma itself. Together, toroidal and poloidal magnetic fields form the total magnetic field that confines the plasma.

Conventional tokamak. In a tokamak, the principal confining magnetic field is toroidal, and it is generated by large external magnets encircling the plasma. This field alone,

FIGURE 3

Tokamak magnetic fields



Source: Princeton Plasma Physics Laboratory, Information Bulletin NT-1: Fusion Power, 1984, p. 4.

however, is not sufficient to confine the plasma. A secondary poloidal field, generated by plasma currents, is also required. The combination of poloidal and toroidal field produces a total field that twists around the torus and is able to confine the plasma (Figure 3).

The tokamak concept was developed in the Soviet Union, and, since the late 1960s, it has been the primary confinement concept in all four of the world's major fusion research programs. It has also served as the principal workhorse for developing plasma technology. The scientific progress of the

TABLE 1

Major world tokamaks (a)

Device	Location	Status
JET	European Community (UK)	Operating
DIII-D	United States (GA)	Operating
Alcator C-Mod	United States (MIT)	Under construction
T-14	USSR (Kurchatov)	Under construction
TFTR	United States (PPPL)	Operating
JT-6	Japan (Naka-machi)	Operating
T-15	USSR (Kurchatov)	Under construction
ASDEX-Upgrade	West Germany (Garching)	Under construction
Tore Supra	France (Cadarache)	Under construction
Frascati Tokamak Upgrade	Italy (Frascati)	Under construction
PBX-M	United States (PPPL)	Under construction
TEXTOR	West Germany (Julich)	Operating

(a) Listed in decreasing order of plasma current, one of the many parameters that determines tokamak capability.

TABLE 2

Major world stellarators (a)

Device	Location	Status
ATF	United States (ORNL)	Under construction
Wendelstein VII-AS	West Germany (Garching)	Under construction
URAGAN-2M	USSR (Kharkov)	Under construction
Heliotron-E	Japan (Kyoto Univ.)	Operating
URAGAN-3	USSR (Kharkov)	Operating
CHS	Japan (Nagoya Univ.)	Under construction
L-2	USSR (Lebedev)	Operating
H-1	Australia (Canberra)	Under construction

(a) Listed in order of decreasing stored magnetic energy, a parameter which in turn depends both on magnetic field and plasma volume.

TABLE 3

Major world reversed-field pinches (a)

Device	Location	Status
CPRF	United States (LANL)	Under construction
RFX	Italy (Padua)	Under construction
OHTE	United States (GA)	Operating
HBTX 1-B	United Kindom (Culham)	Operating
ZT-40M	United States (LANL)	Operating
MST	United States (U of Wis)	Under construction
ETA BETA II	Italy (Padua)	Operating
Repute 1	Japan (Tokyo Univ)	Operating
TPE-1RM(15)	Japan (Tsukuba Univ)	Operating
STP-3M	Japan (Nagoya Univ)	Operating

(a) Listed in order of decreasing plasma current, a rough measure of reversed-field pinch performance.

tokamak is far ahead of any other concept. Major world tokamaks are listed in **Table 1**.

Advanced tokamak. Various features now under investigation may substantially improve tokamak performance. Modifying the shape of the plasma cross-section can increase the maximum plasma pressure that can be confined with a given magnetic field. The Doublet III-D (D III-D) tokamak at GA Technologies and the Princeton Beta Experiment Modification (PBX-M) tokamak at Princeton Plasma Physics Laboratory are being used to investigate shaped plasmas according to this principle. Other variants on tokamak design would permit more compact cores to be constructed, which could lead to less expensive reactors; these improvements are under study.

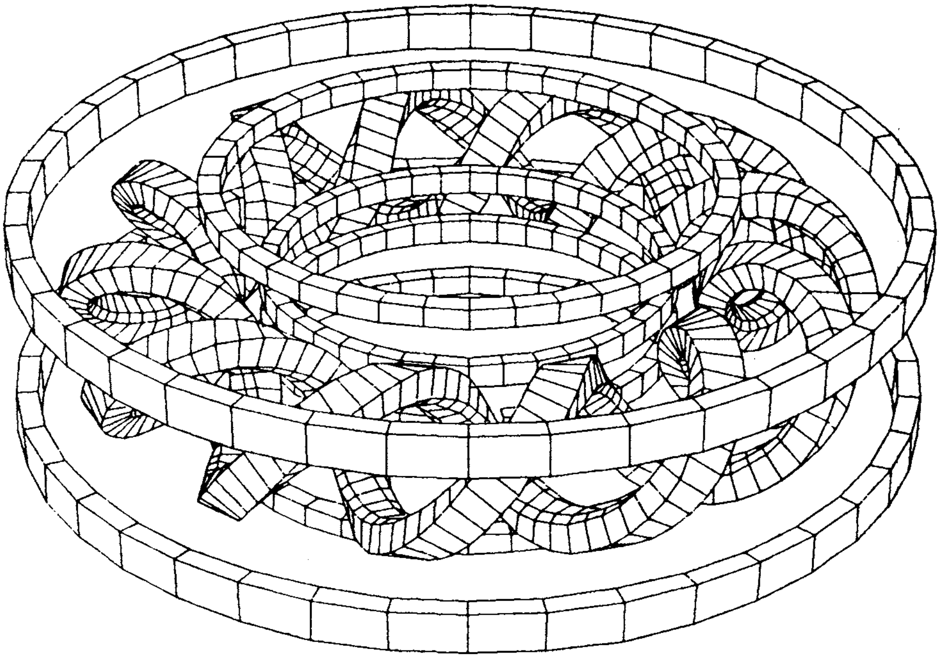
Still other improvements would permit tokamaks to run continuously. The technique typically used today to drive the plasma current in a tokamak can be run only in pulses. Technologies for driving continuous, or steady-state, plasma currents are being investigated at a number of different experimental facilities.

Stellarator. The stellarator is a toroidal device in which both the toroidal and poloidal confining fields are generated by external magnets and do not depend on electric currents within the plasma. The external magnets are consequently more complicated than those of a tokamak (**Figure 4**). However, the absence of plasma current in a stellarator enables steady-state operation to be achieved more directly without the need for current drive.

The stellarator concept was invented in the United States. After the discovery of the tokamak in the late 1960s, however, the United States converted its stellarators into tokamaks. The stellarator concept was kept alive primarily by research in the Soviet Union, Europe, and Japan, and, due to good results, the United States has recently revived its stellarator effort. Stellarators today perform as well as comparably sized tokamaks.

FIGURE 4

Magnet coils for the advanced toroidal facility, a stellarator



Source: Oak Ridge National Laboratory.

Major world stellarator facilities that are operating or under construction are listed in **Table 2.** Not shown on the table is the Large Helical System proposed to be built in Japan at a cost several times that of the largest stellarator machine now under construction; if built and operated, the new Japanese device would be the largest operational non-tokamak fusion experiment.

Reversed-field pinch. In a reversed-field pinch, the toroidal magnetic field is generated primarily by external magnets and the poloidal field primarily by plasma currents. The toroidal and poloidal fields are comparable in strength, and the toroidal field reverses direction near the outside of the plasma, giving the concept its name (see **Figure 5**). In a tokamak, the toroidal field dominates and points in the same direction throughout the plasma.

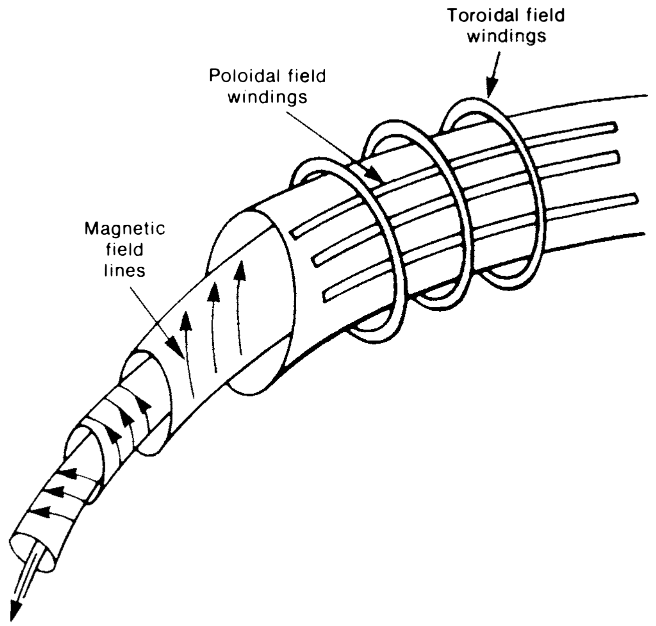
The reversed-field pinch generates more of its magnetic field from plasma currents and less from external magnets, permitting its external magnets to be smaller than those of a comparably performing tokamak. The nature of the magnetic fields in a reversed-field pinch may also permit steady-state plasma currents to be driven in a much simpler manner than is applicable in a tokamak. Moreover, a reversed-field pinch plasma may be able to heat itself to reactor temperatures without the complex and costly external heating systems required by tokamaks.

Los Alamos National Laboratory in New Mexico is the center of U.S. reversed-field pinch research. The Confinement Physics Research Facility (CPRF) to be built there will hold the largest reversed-field pinch device in the United States. A variant of the reversed-field pinch, the Ohmically Heated Toroidal Experiment, or OHTE, was built at GA Technologies in San Diego, California. Reversed-field pinch research is also conducted in both Europe and Japan. **Table 3** lists the major world reversed-field pinches.

Spheromak. The spheromak is one of a class of less developed confinement concepts called "compact toroids," which do not have toroidal field coils linking the plasma loop and therefore avoid the engineering problem of constructing rings locked within rings. Conceptually, if the torodial field coils and inner walls of a reversed-field pinch were removed and the central hole were shrunk to nothing, the resultant plasma would be that of the spheromak. Its overall shape is spherical; although the internal magnetic field has both toroidal and poloidal components, the device has no central hole or external field coil linking the plasma (**Figure 6**). The plasma chamber lies entirely within the external magnets. If the spheromak can progress to reactor scale, its small size and simplicity may lead to considerable engineering advantages. However, the present state of knowledge of spheromak physics is rudimentary.

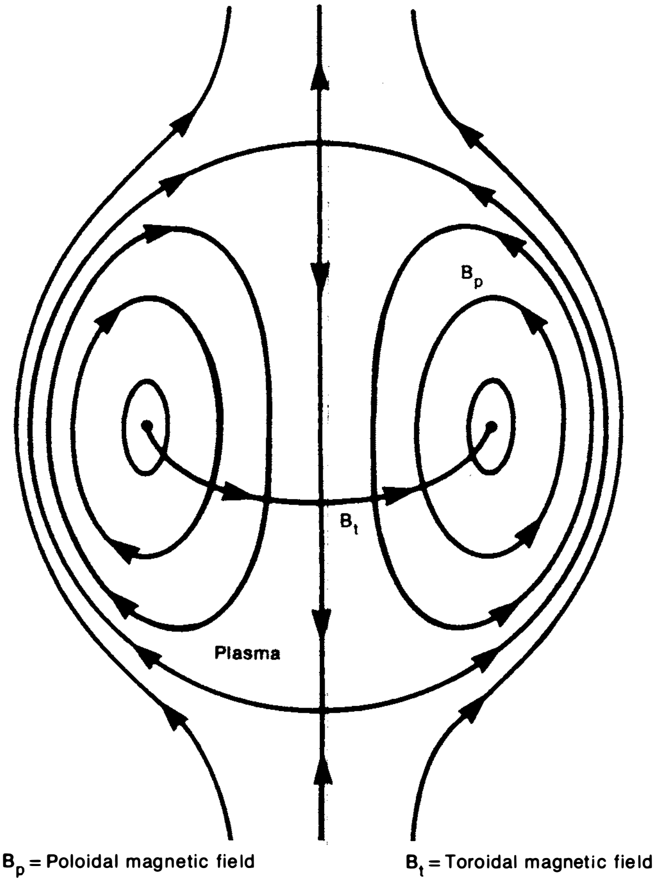
Spheromak research at Los Alamos National Laboratory was terminated in 1987 due to fiscal constraints, and another

FIGURE 5
Reversed-field pinch



Sources: Adapted from National Research Council, *Physics Through the 1990s: Plasmas and Fluids* (Washington, D.C.: National Academy Press, 1966).

FIGURE 6
Spheromak



Source: M.N. Rosenbluth and M.N. Bussac, "MHD Stability of Spheromac," *Nuclear Fusion,* 19(4):489-498 (Vienna, Austria: International Atomic Energy Agency, 1979).

major U.S. device at Princeton Plasma Physics Laboratory is to be terminated in fiscal year 1988. The remaining U.S. spheromak research effort takes place at the University of Maryland. Spheromaks also are being studied in Japan and the United Kingdom. Major world spheromak devices are listed in **Table 4.**

Field-reversed configuration. The field-reversed configuration (FRC) is another form of compact toroid. Despite the similar name, it does not resemble the reversed-field pinch. It is unusual among closed magnetic confinement concepts in providing confinement with only poloidal fields; the FRC has no toroidal field. The plasma is greatly elongated in the poloidal direction and from the outside has a cylindrical shape (**Figure 7**).

Like the spheromak, the FRC does not have external magnets penetrating a hole in its center; all the magnets are located outside the cylindrical plasma. The FRC also has the particular virtue of providing extremely high plasma pressure for a given amount of magnetic field strength. If its confining field is increased in strength, the FRC plasma will be compressed and heated. Such heating may be sufficient to reach reactor conditions, eliminating the need for external heating. Existing FRC plasmas are stable, but whether stability can be achieved in reactor-sized FRC plasmas is uncertain. A new facility, LSX, is under construction at Spectra Technologies in Bellevue, Washington, to investigate the stability of larger plasmas.

U.S. FRC research started at the Naval Research Laboratory in Washington, D.C., in the late 1960s. Increased effort in the United States in the late 1970s, centered at Los Alamos, was undertaken largely in response to experimental results obtained earlier in the decade from the Soviet Union and the Federal Republic of Germany. Soviet research has continued, but German and British research programs have stopped. Meanwhile, a program in Japan has begun. Major field-reversed configuration experiments around are listed in **Table 5.**

'Open' concepts

Plasmas in open magnetic confinement devices are confined by magnetic fields that do not close back on themselves within the device but rather extend well outside the device. Since plasma particles can easily travel along magnetic field

TABLE 4

Major world spheromaks (a)

Device	Location	Status
S-1	United States (PPPL)	To be terminated
CTX	United States (LANL)	Terminated
MS	United States (U of Md)	Under Construction
CTCC	Japan	Operating
Manchester	United Kingdom (U of M)	Operating
TS-3	Japan	Operating

(a) Listed approximately by decreasing order of the size of the spheromak research effort at each site; it is difficult to specify any single physical parameter as a rough measure of spheromak capability.

TABLE 5

Major world field-reversed configurations (a)

Device	Location	Status
LSX	United States (Spectra T)	Under Construction
FRX-C	United States (LANL)	Operating
BN, TOR	USSR (Kurchatov)	Operating
TRX-2	United States (Spectra T)	Operating
OCT, PIACE	Japan (Osaka Univ.)	Operating
NUCTE	Japan (Nihon Univ.)	Operating

(a) Listed approximately by decreasing order of size; similarly sized devices at the same institution are listed together.

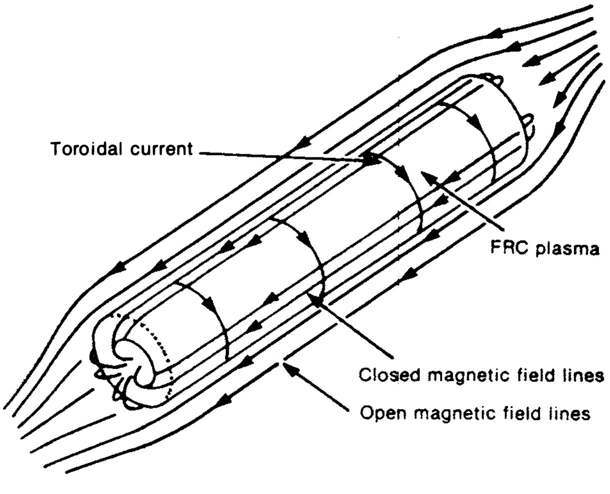
lines, some additional mechanism is required to reduce the rate at which plasma escapes out the ends of an open confinement device.

Magnetic mirrors. . . . The tandem mirror concept was developed simultaneously in the United States and the Soviet Union in the late 1970s. The Mirror Fusion Test Facility B (MFTF-B), located at Lawrence Livermore National Laboratory in California, is the largest mirror device in the world and the largest non-tokamak magnetic confinement fusion experiment. Budget cuts, however, forced MFTF-B to be mothballed before it could be used experimentally. The Tandem Mirror Experiment Upgrade (TMX-U) at Livermore, a smaller version of the MFTF-B, was terminated as well, and the TARA device at the Massachusetts Institute of Technology will be shut down in 1988. At that point, Phaedrus at the University of Wisconsin will be the only operational U.S. mirror machine. Mirror research is still conducted in the Soviet Union and Japan. **Table 6** presents a list of major world tandem mirror facilities.

Dense z-pinch. In this concept, a fiber of frozen deuterium-tritium fuel is suddenly vaporized and turned into plasma by passing a strong electric current through it. This current heats the plasma while simultaneously generating a strong

FIGURE 7

Field-reversed configuration



Source: National Research Council, *Physics Through the 1990s: Plasmas and Fluids* (Washington, D.C.: National Academy Press, 1966).

TABLE 6

Major world tandem mirrors*

Device	Location	Status
MFTF-B	United States (LLNL)	Mothballed
TMX-U	United States (LLNL)	Mothballed
Gamma-10	Japan (Tsukuba Univ)	Operating
TARA	United States (MIT)	To be terminated
Phaedrus	United States (U of Wis)	Operating
Ambal M	U.S.S.R. (Novosibirsk)	Under construction

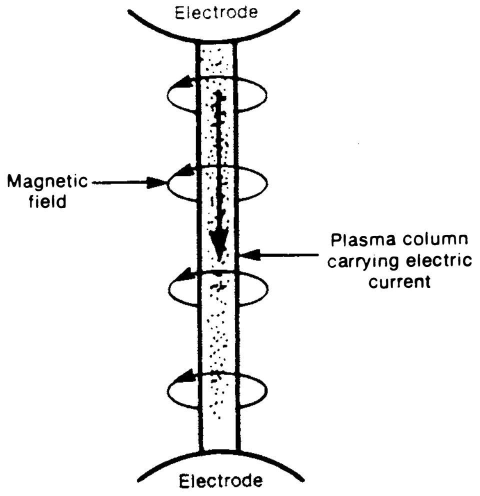
*Listed in decreasing order of size

magnetic field encircling the plasma column (**Figure 8**), "pinching" it long enough for fusion reactions to occur. Many devices investigated in the earliest days of fusion research in the 1950s operated in a similar manner, but they were abandoned because their plasmas had severe instabilities and were unable to approach the confinement times needed to generate fusion power.

The dense z-pinch differs from the 1950s pinches in several important aspects that, as calculations and experiments have shown, improve stability. Crucial to the modern experiments are precisely controlled, highly capable power supplies that would have been impossible to build with 1950s technology, and the use of solid, rather than gaseous, fuel to initiate the discharge. However, it is much too early to tell whether this concept can be developed successfully. If the concept can be developed, the device has the potential to be far smaller and far less expensive than devices based on other concepts. External magnets are not needed since the plasma current supplies the entire confining field. Dense z-pinch research is taking place in the United States at two facilities: the Naval Research Laboratory and Los Alamos National Laboratory.

FIGURE 8

Dense Z-pinch



Source: Office of Technology Assessment, 1987

Conclusions concerning confinement approaches

A number of general conclusions can be drawn from studies of the confinement concepts that have evolved of the past 10 to 15 years:

- Many fusion concepts are under study because the frontrunner tokamak, while likely to be scientifically feasible, may yet be found weak in some critical area or less economically attractive than alternatives. . . .
- Different confinement studies complement each other: . . .
- A great deal of progress in understanding fusion plasmas and confinement concepts has been made to date. Many concepts studied earlier, such as the simple magnetic mirror, are no longer studied today because they cannot compare attractively to improved or alternate concepts. At the same time, as in the case of the dense z-pinch, problems once considered intractable may be solved with additional scientific understanding and more advanced technology.
- Research on all confinement concepts has benefited from international cooperation.
- Not all confinement concepts can be developed to reactor scale. . . .
- Progress in fusion science depends on progress in fusion technology. Time after time, the exploration of new ranges of plasma behavior has been made possible by the development of new heating, fueling, and plasma shaping technologies.