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The Soviet Magnetic Confinement Fusion Program: An International Future

A Research Paper

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The Soviet Magnetic Confinement Fusion Program: An International Future

A Research Paper

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July 1990

The Soviet Magnetic Confinement Fusion Program: An International Future

Summary

Information available as of 1 March 1990 was used in this report.

Since the 1950s, the leadership of the Soviet magnetic confinement fusion (MCF) program has realized that the resource demands to construct large MCF machines would require international collaboration. Soviet initiatives since the late 1970s have led to two international (involving the USSR, the United States, Japan, and the European Atomic Energy Agency) efforts to design an engineering test reactor (ETR) based on the tokamak approach to MCF. These efforts were the International Tokamak Reactor (INTOR) workshops and the present International Thermonuclear Experimental Reactor (ITER) program. The USSR has committed significant resources to these projects and to bilateral programs with the United States

Since the mid-1970s, an emphasis by the Soviets on large tokamaks probably has distorted their MCF program. As a result, small tokamak projects, and programs on alternate MCF approaches, have suffered from low priority, and large tokamak projects have been delayed and compromised because of technology shortcomings. We believe that this trend will continue. Thus we expect that ITER R&D will be the focus of the Soviet Union's domestic MCF program for as long as its participation in ITER continues

The two tokamaks that the Soviets constructed during the 1980s—TSP and T-15—will contribute little to the world fusion effort. These machines have encountered numerous difficulties and delays. We believe that neither of these machines will reach the goals established for them and that neither will become fully operational before 1992

The Soviets must join an international collaboration if they are to have access to a fusion ETR—the next step in fusion energy development—during the next 25 years. Because of economic and manufacturing constraints, they probably are unable to construct an ETR themselves. Consequently, we expect that during 1990 the Soviets will strongly pursue an agreement to continue the ITER program. Although they would prefer an agreement to build ITER, we believe they would accept an agreement to conduct a five-year engineering design phase before a construction decision is made.

The advantages to the international fusion community of including the USSR in subsequent phases of the ITER program are political and economic, rather than technical. The Soviets' fusion technology has

generally lagged that in the United States, and the gap is becoming larger. Their problems stem from poor quality control in industry, plus the general economic and political problems in their society. We expect, however, that they can contribute their fair share of resources (manpower, R&D, and equipment) if an international agreement to construct an ITER is reached.

During the last decade, the Soviets have made major conceptual and R&D contributions to INTOR and ITER. If the ITER program is extended into an engineering-design phase. we expect the Soviets to make similar significant contributions

If the ITER project is not continued, the Soviets will probably pursue an agreement to build a Pan-European ETR. The Soviets considered this approach in 1985. and recent political developments have made it even more likely

Contents

	Page
Summary	iii
Introduction	1
Soviet Tokamak Program	3
International Collaboration	3
Machines	4
Auxiliary Equipment	8
Plasma Heating	8
Plasma Fueling	8
Diagnostic and Control Equipment	8
Theory and Computations	8
Engineering and Design	8
Magnets	8
Materials	9
Manufacturing	9
Design	9
Soviet Stellarator Program	9
Soviet Open-Trap Program	10
Outlook	10
International Collaboration	10
Soviet Tokamaks	11
Plasma Heating	12
Other Support Technologies	12

Appendixes		
A.	Glossary of Terms	15
B.	Fusion Tutorial	17
C.	Tokamaks	25
D.	Stellarators	45
E.	Open Traps	47
F.	International Collaboration	51

Insets

Technical Background	2
Plasma	17
Hybrid Reactor Concept	24
Soviet Fusion Organization	30
Soviet and Soviet Bloc Institutes Contributing to Tokamak Research	32
Fusion Equipment Manufacturing	32
Soviet OTR/ITER Organization	43
1973 Agreement on Peaceful Uses of Atomic Energy	52
ITER Objectives	55
ITER Organizational Structure	56

Tables

1.	Typical Parameters of Large Soviet Tokamaks	7
2.	Initial and Small Tokamaks at IAE	28
3.	Parameters of Various T-20 Designs	34
4.	Evolution of the OTR's Design Parameters	42
5.	Engineering Test Reactor Designs	55

The Soviet Magnetic Confinement Fusion Program: An International Future

Introduction

Historically, the Soviet Union has pursued three magnetic confinement fusion (MCF) approaches (see the technical background on page 2) as potential heat sources for future electricity-generating plants. As is true in other major fusion programs throughout the world, the Soviet MCF program emphasizes research on the tokamak approach. Smaller efforts are devoted to research on open traps and stellarators,[1] as well as the alternative fusion approach known as inertial confinement fusion.

Soviet MCF research is pursued in several scientific institutes. The lead institute for the Soviet tokamak program is the Institute of Atomic Energy *imeni* I. V. Kurchatov (IAE), and research is centered in its Department of Plasma Physics in Moscow and at its branch in Troitsk. The stellarator effort is divided among the Institute of General Physics (IOF), IAE, and the Khar'kov Physical Technical Institute (KhFTI). Most Soviet research on open traps is done in the Department of Plasma Physics at the Institute of Nuclear Physics (IYaF) in Novosibirsk

For the past 15 years, the "scientific supervisor" of the Soviet MCF program has been Ye. P. Velikhov, formerly IAE deputy director (1971-88) and now IAE director. Velikhov's direct involvement in the Soviet MCF program has decreased in recent years because of increased and more varied responsibilities. However, as he became vice president (1977) of the USSR Academy of Sciences (AN), principal scientific adviser (1985) to General Secretary Mikhail Gorbachev, and a full member (1989) of the Communist Party of the Soviet Union Central Committee, his control over the general funding, priorities, and direction of the Soviet MCF program has grown.

The Soviet tokamak effort is large and widespread. The IAE employs about 1,700 people in areas related to fusion research; about 490 of them are professionals. The Department of Plasma Physics has a staff of about 900, most of whom are performing tokamak-related tasks.

The Soviet open-trap and stellarator programs are much smaller than the tokamak program. The stellarator program is fragmented and does not have a national leader. The open-trap program at the IYaF is about 30 percent of the total IYaF effort (manpower/funding/resources). The core technical staff for fusion is over 250 people; about 80 are physicists.

The Soviet MCF program is not a single integrated or coordinated program. Instead, historically, it has been several different programs funded by different agencies, with institute directors having much discretion

[1] The basic concepts of MCF, tokamaks, stellarators, and open traps are discussed in appendixes B through E, respectively.

Technical Background

***Thermonuclear fusion** is a nuclear process induced by thermal motion of the reacting particles. **Fusion** occurs in a **plasma**—a very hot gas of positive ions (nuclei) and electrons. The fusion reaction with the least strenuous requirements involves the fusing together of the nuclei of the hydrogen isotopes **deuterium** and **tritium** (DT). Tritium is radioactive and must be produced/bred*

*In the laboratory, two methods are used to contain a DT plasma long enough for large numbers of fusion reactions to occur: **magnetic confinement fusion** (MCF) and **inertial confinement fusion** (ICF). In MCF, magnetic fields are used to localize and contain the DT plasma. MCF R&D is being pursued to develop new energy sources for electrical power plants. In ICF, the DT fuel is imploded, and the mass inertia keeps the small ball of DT plasma together for short periods of time*

*Three of the design approaches to MCF being pursued are **tokamaks**, **stellarators**, and **open traps**. Tokamaks are controlled-nuclear-fusion devices with a doughnut-shaped vacuum vessel within which the plasma is contained by magnetic fields. One component of the magnetic field is provided by a **plasma current** (a flow of electrons through the center of the plasma). A stellarator is similar to a tokamak, but all components of its confining magnetic field are supplied by magnets. Unlike these circular devices, open traps are linear confinement devices that usually use "magnetic plugs" at the ends. The simplest open trap is the **magnetic mirror** machine—a magnetic solenoid with higher magnetic field coils at each end to prevent escape of the plasma. The **tandem mirror** is a magnetic solenoid with a magnetic mirror at each end. A **multiple mirror** is a series of magnetic mirrors end to end to prevent end losses. The **gas-dynamic trap** is a version of a simple magnetic mirror with a mechanism to stabilize the plasma*

*MCF devices require **auxiliary heating systems** to heat the plasmas to thermonuclear temperatures. Two types of auxiliary heating systems are **radiofrequency** (RF) and **neutral beam**. The three types of RF heating, each using a different frequency, are electron cyclotron resonance heating (ECRH), ion cyclotron resonance heating (ICRH), and lower hybrid heating (LHH). ECRH is provided by RF tubes known as **gyrotrons**; it is the Soviets' most prominent and successful technique for heating plasmas. A possible future source for ECRH is the **free electron laser**, which produces radiation by rapid movement of accelerated electrons*

*The most advanced MCF device is the **tokamak**. Present tokamaks in Western Europe and the United States are likely to use DT fuel and demonstrate **scientific breakeven** (fusion energy produced equals energy put into plasma) in the next five years. The next large tokamak to be built will be an **engineering test reactor**. This tokamak and future larger tokamaks will use **blanket** modules around the plasma. The **tritium** for future operation will be **bred** when the blanket material absorbs fusion neutrons. Material can be added to the blanket so fissionable material can be bred; this approach is known as the **hybrid reactor***

Common measures used to characterize the size of a tokamak are:

- *Major plasma radius—distance from the center of the tokamak to the center of the plasma.*
- *Minor plasma radius—distance from the center of the plasma to the edge of the plasma.*
- *Magnetic field strength.*
- *Magnitude of plasma current*
- *Amount of auxiliary heating*

Appendix A contains a glossary of technical terms and descriptions of major tokamaks. All of the above topics are discussed in more detail in appendixes B through E over the expenditure of funds. The major institutes are operated by the USSR State Committee for the Utilization of Atomic Energy (GKAE), the AN, the Ukrainian SSR Academy of Sciences, and the Siberian Division of the AN.

Soviet Tokamak Program

For clarity's sake, the Soviet tokamak program can be viewed as having five parts—international collaboration, machines, auxiliary equipment, theory and computations, and engineering and design. The present status of each is given below, and a more detailed, historical perspective on Soviet tokamaks and international collaboration is given in appendixes C and F, respectively. In reality these are neither separate parts, nor are they parts of a totally coordinated program

International Collaboration

International collaboration has played a significant role in the Soviet MCF program; we expect it to play a major role during the next 25 years. During past collaboration, the Soviets have been exposed to advanced ideas, computations, and equipment available in the West. In addition, they have conducted numerous experiments that they could not have performed on Soviet fusion devices. If the Soviets remain involved in international efforts to build a fusion engineering test reactor (ETR), we believe that the R&D for this ETR will be the major emphasis of Soviet MCF research. We expect that the Soviets will strongly pursue all possibilities to ensure their participation in a multilateral program to construct a fusion ETR

A significant US-Soviet fusion exchange was initiated in 1973 as part of an agreement on the peaceful uses of atomic energy. According to this agreement, the goal of fusion cooperation was the development of prototype and demonstration-scale fusion reactors. After some initial difficulties (mainly political and organizational), this exchange was expanded considerably during the last five years. Activities in this bilateral agreement now include joint planning of research, joint experimental efforts, and coordinated R&D related to the international tokamak program called the International Thermonuclear Experimental Reactor (ITER)

In 1978, the USSR proposed that the major world fusion programs join to design, construct, and operate a large tokamak. This proposal resulted in a series of International Tokamak Reactor (INTOR) workshops, which were held from 1979 to 1987. Although significant progress was made in these workshops, they were brainstorming sessions instead of a dedicated design effort. In addition, it became apparent after a few years that, unlike the Soviet Union, the other partners (United States, Japan, and Euratom [3]) were not interested in the joint construction of an ETR-size machine.

Discussions at the summit meetings between President Reagan and General Secretary Gorbachev during 1985 and 1986 led to the ITER project, which officially began in May 1988. At present the ITER program is a three-year effort, with the same partners as the INTOR, to develop a conceptual design for a fusion ETR based on a tokamak. Unlike the INTOR, however, the ITER is a genuine design effort with integrated R&D and a joint design team. The currently approved goal of the ITER is to provide, by the end of 1990, all the information needed for one or more participants to decide to build the ITER in the mid-1990s. Discussions are under way concerning a follow-on five-year engineering-design phase.

Soviet contributions to the INTOR and ITER conceptual design efforts have been professional and competent. We expect that future contributions to an ITER

[3] West European nuclear R&D is carried out under the umbrella of the European Atomic Energy Agency (Euratom)

engineering design phase will be of the same caliber. There would be some limitations to Soviet contributions, however. Soviet component R&D tends to be conservative because of a lack of computer power.

The Soviets began indicating their interest in becoming involved in the planned US Compact Ignition Tokamak (CIT) fusion device project in 1986. The Soviets were interested in providing electrical energy systems, electron cyclotron resonance heating (ECRH) equipment, and diagnostic equipment.

We believe that the Soviets have increased the priority of their international fusion involvements. The Soviets have been aggressive in their attempts to become part of the CIT program; V. A. Chuyanov had been the spearhead of this effort. Similarly, the Soviets initiated the campaign that led to the ITER program and continue to push for commitments to build it; Velikhov, Kadomtsev, and Chuyanov play major roles in the ITER program. In addition, the Soviets have allocated large amounts of money, manpower, and industrial priority to fulfilling their commitments to international projects. Much of these resources have been used for equipment that the Soviets had not developed for their own projects.

Machines

Since 1975, the workhorse of the Soviet tokamak program has been the T-10 tokamak (see figure 1) at IAE in Moscow. During the 1980s, the T-10 experimental program concentrated on ECRH by gyrotrons. Although the operation of T-10 ceased in May 1988, it was put back into operation during the summer of 1989.

[1] Construction of the CIT has been delayed by a lack of funding and a reexamination of the direction of the US fusion program. No US decision on Soviet participation has been made, nor is any pending.

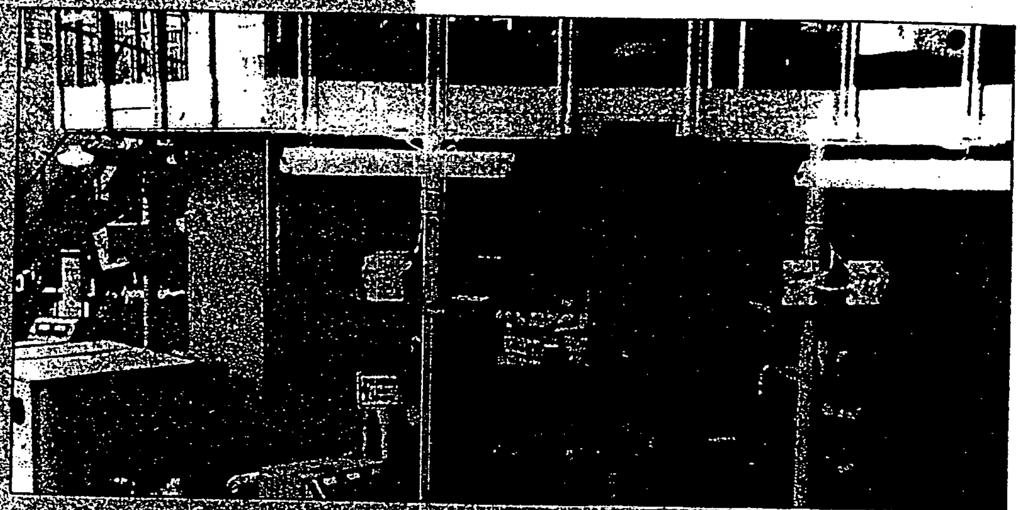
The world's first superconducting tokamak, the T-7 at IAE in Moscow (see figure 1) began operation in 1979. The superconducting magnets never operated at their design value, and the T-7 was never a major component of the plasma physics program at IAE. The superconducting magnets were not required for the physics studies carried out, and the lack of liquid helium for the superconducting magnets severely limited the available experimental time. The T-7 has been shut down since 1988.

The largest tokamak in the USSR is the T-15 (see figure 2). It is located at the IAE in Moscow and has superconducting magnets. Major delays in the completion of the T-15 occurred because of component fabrication problems, initially with the large niobium-tin superconducting magnets. Although the Soviets celebrated the startup of the T-15 in December 1988, the machine has not approached design parameters. Because of problems with the cryogenic system for the superconducting magnets, the T-15 was shut down in mid-1989. Although testing of the T-15 began in January 1990, it was scheduled to be shut down from March 1990 through the spring of 1991. Auxiliary heating systems are to be installed during this shutdown. A major component of the T-15 experimental program will be a continuation of the ECRH program started on the T-10.

The TSP (tokamak with strong field; see figure 3), previously known as the T-14, is the first Soviet tokamak designed to use deuterium-tritium (DT) fuel. The original goal for this tokamak, which is located at IAE in Troitsk, was to use large toroidal magnetic fields and adiabatic radial plasma compression to approach break-even conditions in a DT plasma for

Figure 1
Soviet Tokamaks Built
In the 1970s

T-10



T-7

Figure 2. T-15 Tokamak

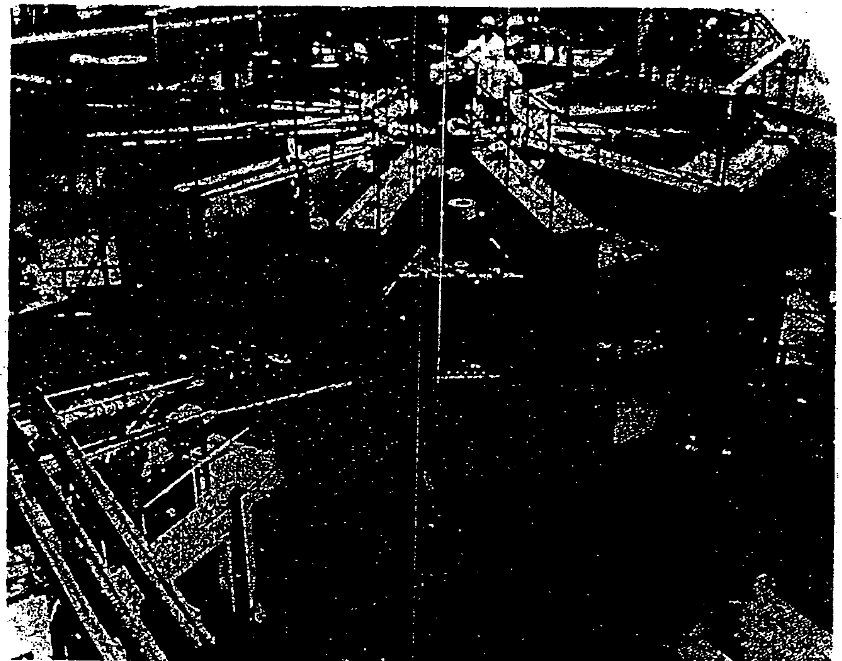


Figure 3. TSP Tokamak

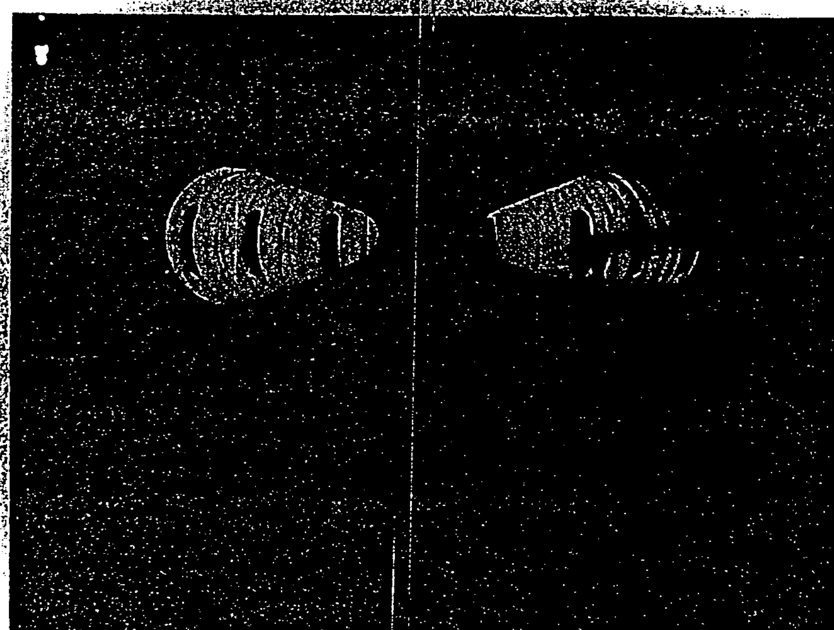


Table 1
Typical Parameters of Large Soviet Tokamaks

	T-10	T-7	T-15	TSP	OTR	T-20
Major plasma radius *(meters)*						
Minor plasma radius *(meters)*						
On-axis toroidal-magnetic field *(teslas)*						
Plasma current *(megamperes)*						
Auxiliary heating power *(megawatts)*						
Year operational	1975	1979	1988 [d]	1987 [d]	Design only	Design only

[a] Values before (and after) compression.
[b] Scheduled to be upgraded to 20 megawatts.
[c] Scheduled to be upgraded to 10 megawatts.
[d] Official Soviet startup time; not yet fully operational.

short time periods

After the first plasma was created in the TSP in late December 1987, the TSP was shut down for modifications. At present, it is operating with very reduced parameters (magnetic field, plasma current, and plasma density, for example).

The Soviets began designing a successor to the T-15, known as experimental thermonuclear reactor (OTR), in 1983. The OTR is designed to use a DT plasma and superconducting toroidal-field magnets. The goal of the OTR program is to produce a reactor-relevant plasma and to provide for testing of reactor-relevant components. Although the original designs of the OTR emphasized its fusion-fission hybrid nature, the use of hybrid components has been deemphasized in recent designs. Research for the OTR and ITER projects is now done by the same group at IAE; Velikhov is the project director, and Kadomtsev is the scientific director. During the last two years, the concentration of this research on ITER R&D has increased steadily

All large Soviet tokamaks have been conceived and built at the IAE. Some typical parameters for these large tokamaks are presented in table 1. The Soviets have indicated that they are considering the designs of small tokamaks for studying specific areas of plasma behavior in preparation for the OTR. These tokamaks apparently are in the early design stages and their future is uncertain

The operating small Soviet tokamaks are located primarily at the Ioffe Physical Technical Institute (FTI) in Leningrad. The FT series has been used to study radiofrequency methods of heating plasmas in tokamaks, and the Tuman series has been used to study magnetic compression of tokamak plasmas. The three currently operating tokamaks in the Tuman series were built between 1970 and 1981

Auxiliary Equipment

Plasma Heating. The most prominent and successful part of the Soviet effort to heat tokamak plasmas is ECRH using gyrotrons. Significant experiments were carried out on the T-10 tokamak; in early 1988, the T-10 had eleven 400-kilowatt (kW) gyrotrons. The T-15 is scheduled to have an array of twenty-four 400- to 500-kW gyrotrons. New gyrotrons are being studied and developed at the Institute of Applied Physics (IPF) in Gor'kiy.

The Soviets at present have little capability for studying ion cyclotron resonance heating, lower hybrid heating, or neutral beam heating of tokamak plasmas. In the past, they have committed only limited amounts of effort to these heating techniques, and we do not expect this to change dramatically in the future. Research on ion sources for neutral beam heating is being done at IAE and IYaF.

Plasma Fueling. The Leningrad M. I. Kalinin Polytechnical Institute (LPI) developed a light-gas-gun, hydrogen-pellet injector (based on a US design) that was used for plasma fueling experiments on the T-10 during 1984-85 the institute has developed an advanced model for use on the T-15 and is developing a centrifuge pellet injector

Diagnostic and Control Equipment. Diagnostic (including data acquisition) and control equipment on Soviet tokamaks has evolved during the 1980s as more digital electronic and computer equipment has become available. The Hungarian Central Physics Institute, which has been involved in the Soviet tokamak program for over 10 years, provided most of this electronic and computer equipment. The T-7 and T-10 have served as test beds for equipment developed for use on the T-15. The diagnostic/data-acquisition equipment now on the T-10 is a curious mixture of old (cameras and oscilloscopes) and new (computer) technologies

The development of diagnostic/data-acquisition equipment for Soviet tokamak experiments is going on at the IAE, FTI (in collaboration with LPI), the Central Institute of Electron Physics in East Germany, and the Hungarian Central Physics Institute

Little specific technical information is available on the diagnostic and control equipment for the TSP; however, has described the TSP computer control equipment as less than optimum. As part of a proposed joint collaboration on the US CIT, the Soviets had indicated that they could develop appropriate diagnostic equipment (requirements for such equipment would be similar for the CIT and TSP).

Theory and Computations

During the 1980s, Soviet tokamak theory closely paralleled, and often followed, that in the West. From the 1950s through the 1970s, the Soviets made enormous contributions to the advancement of tokamak confinement theory. At present, several prominent areas pursued in the West—such as turbulent transport (which plays a crucial role in tokamak confinement)—receive little attention in the USSR; these often are areas in which computer modeling plays an important role. The Soviets have one of the leading programs on the calculation and measurement of fusion-relevant atomic data—a basic area important to plasma modeling and diagnostics

In the area of scientific computing, Soviet fusion scientists have concentrated on problems with direct relevance to the design and interpretation of ongoing and planned experiments. Because most of this work is still done on old, BESM computers, the Soviets have developed some novel algorithms that allow them to solve multidimensional problems using very limited computational capabilities.

Engineering and Design

Magnets. The Soviets have not demonstrated the ability to fabricate large, reliable magnets. Superconducting toroidal-field magnets (coils) have been installed on the T-15, as have high-field normal magnets on the TSP. However, neither of these systems has been operated at full power or for long periods of time. The T-15 was shut down during the summer of 1989 because of problems with the cryogenic system for the superconducting magnets. The superconducting magnets included in the OTR designs seem to be based on world standards, not Soviet capabilities

Materials. The Soviets have a fledgling program to investigate the properties of materials to be used in fusion reactors, but they do not have a program to develop new materials. Most of the materials data they use in their design studies seems to come from the fission program (initial US work was based on fission experience also). The Soviets have a significant program devoted to the use of liquid metals in fusion reactors. Much of the impetus and basic data for this program also probably comes from research in the fission program. Materials and liquid-metal research are prominent parts of the US-Soviet fusion bilateral exchange program.

Manufacturing. Generally, the Soviet MCF program has suffered because of poor workmanship and lack of quality control in the manufacture of large components. Recent problems with the T-15 and TSP indicate that these conditions persist. Upheavals in Soviet society have exacerbated this condition, and it is unlikely that Soviet industry will be able to produce the highly reliable, large components required for the OTR/ITER in the next 20 years

Design. The Soviet design effort for large tokamaks is centered in the IAE Technology Group headed by V. V. Orlov, with substantial support from the Electrophysical Apparatus Scientific Research Institute *imeni* D. V. Yefremov—the Yefremov Institute. During recent years, most of this effort has been devoted to work on the INTOR and OTR programs. The present emphasis is on the ITER program. (Orlov is the assistant project director on nuclear technology aspects for the ITER/OTR project

Soviet contributions during the INTOR workshops, developed with strong input from Kadomtsev, were comprehensive and generally of good quality. Because of their inadequate computing power and lack of a program to develop new materials, however, the Soviets have a tendency to accept existing material limits and to design around them. The Soviets only recently have begun to undertake design efforts for "commercial" fusion reactors (see appendix B).

For the past decade, Soviet MCF reactor designs have emphasized hybrids. In June 1986

described the hybrid version of an OTR as a bridge between pure fission and pure fusion. the Soviets have used a hybrid reactor for a first-generation device because the design and engineering parameters are lower. The use of hybrids allowed them to introduce new technology gradually in their designs. In accordance with international emphases, the Soviets are now concentrating on pure fusion versions of the ITER/OTR.

We expect that most of the total Soviet design effort in 1990 will be devoted to the ITER program. During the first year of the ITER project, the Soviets undertook studies on liquid-metal blankets, tritium, gyrotrons, neutral beam injectors, structural materials, cryogenic systems, safety, and plasma stability. Safety analyses done by the Soviets incorporate many simplifying assumptions and do not seem to be coordinated with work done by other parts of the Soviet design team

Soviet Stellarator Program

At present the Soviet stellarator program is centered at three institutes. The major Soviet experimental stellarator program is at KhFTI. The experimental program at IOF has been in a state of flux for the last few years. The major stellarator theoretical programs are at KhFTI and the IAE; these have remained strong during the 1980

Scientists at KhFTI have developed the Uragan-series stellarators. The Uragan-2 (U-2) stellarator has been in operation since the 1960s. The U-2 is currently being used as a basic research and training tool. The U-3 has been rebuilt to eliminate errors in the alignment of its magnets. (The misalignment of the magnets was revealed and measured using a US device.) The modified U-3 (called the U-3M) uses neutral beam heating; low-level experiments were begun in 1989. The U-2M (a new version of the U-2 design) stellarator is under construction at KhFTI. Soviet scientists believe that the U-2M will be operational in early 1991

The only stellarator in operation at the IOF is the L-2, which became operational in 1975. The IOF plans to shut down the L-2 during 1990 and replace its vacuum vessel; completion of this modification is expected to take over a year. For more than five years, the IOF has been seeking approval for a follow-on to L-2 (known as L-2M or L-3). Although the GKAE earlier had approved funding for an L-2M machine, it was canceled when an industrial prime contractor for the project could not be located

Soviet Open-Trap Program

IYaF's open-trap program is pursuing several plasma confinement approaches—namely, tandem mirrors, electron-beam-heated multiple mirrors, and gas-dynamic traps. The large open-trap theory group at IYaF, headed by Ryutov, has played a significant role in the conceptual development of approaches to confinement in open-trap systems

The AMBAL tandem mirror device, constructed during 1978-84, has never operated as a tandem mirror. One of its large quadrupole magnets shorted out during testing of the whole system. Single-cell experiments were begun in the remaining quadrupole magnet in 1986. About this time, the Soviets began the design of the AMBAL-M tandem mirror device. Components of this device are under construction and are being tested individually

IYaF is operating three electron-beam-heated multiple mirrors—INAR (1973), GOL-1 (1978), and GOL-3 (1986). The GOL-1 experiments have provided information on plasma physics and technology; experiments on GOL-3 should provide information on confinement possibilities. A standardized electron beam generator (U1) has been developed (1-megaelectronvolt particle energy, 75-kiloampere beam current, and 130-kilojoule total beam energy)

The goal of IYaF's gas-dynamic-trap project is to develop a small, intense neutron source for materials testing. The researchers will heat the outflowing plasma with 20 megawatts of 240-kiloelectronvolt ion beams. Initial results on the gas-dynamic-trap experiments at IYaF were reported in 1986; results have been encouraging. This project seems to use plasma guns and neutral beams developed for AMBAL and magnet technology developed for the GOL experiments

During 1987 and 1988, American scientists spent several months at IYaF performing experiments. Ryutov is interested in expanding this activity and increasing the US commitment to research at IYaF for long periods

The IYaF open-trap program seems to be directed toward providing unique facilities for studying plasmas and a neutron source for fusion materials research. Without active support from the United States, open traps are likely to be discontinued in the Soviet Union as a confinement approach (as was done in the United States several years ago

Outlook

International Collaboration

We doubt that the Soviets will be able to independently construct and operate a fusion ETR, such as the OTR or ITER, during the next 25 years. This inability is due to technical/engineering shortcomings. The many problems with the TSP and T-15 tokamaks have demonstrated that Soviet craftsmanship and quality control are poor. Because ETRs are large high-technology machines that require very reliable components, we expect that Soviet industry will not be able to produce crucial ETR components during the next 25 years. The technical problems have been exacerbated by the recent societal unrest in the USSR

Consequently, the Soviets need to join an international collaboration if they are to have access to an ETR. We believe that the Soviet fusion leadership has realized for the last 30 years that fusion projects such as an ETR could be built only by a multinational effort. If Washington approves US participation in an ITER engineering design phase during 1990, we believe that the Soviets, as well as the Japanese and Euratom, will join this enterprise. On the other hand, we believe that, if the US Government does not reach such an agreement during 1990, the ITER enterprise probably will dissolve. We assess that, if this should occur, the Soviets will make a strong approach to Western Europe for construction of a Pan-European ETR. The Soviets considered this in 1985, and recent political events in Eastern Europe increase the likelihood of such an approach

We expect that, if the ITER program continues, the Soviets will make major contributions to the engineering design phase. They have demonstrated their capabilities in the previous INTOR and ITER conceptual design efforts. Although Soviet design capabilities generally trail those in the United States, we believe that the Soviets are capable of developing a competent OTR/ITER design. We believe, however, that the resulting machine would be larger, more conservatively designed, and more costly than a comparable one designed in the United States

The decision to include the USSR in a bilateral or multilateral program to build an ETR will be based on political and/or economical considerations. The Soviets do not possess any technological advantages over their ITER partners. However, we believe that the Soviets can, and will, contribute their fair share of resources if included in a program to build an ETR.

International collaboration has probably become a larger portion of the Soviet MCF program during the last five years. This collaboration seems to have resulted in additional funding for bilateral (CIT) and international (ITER) programs. We believe that, if the Soviets are included in follow-on phases of the ITER program, ITER will become the primary focus of the Soviet MCF program. We expect that small research programs on stellarators and open traps will be continued and that the stellarator program will be used to study areas applicable to ITER research. The most likely role for the open trap is a neutron source for testing materials of interest to the ITER program.

Soviet Tokamaks

We believe that the Soviet experimental tokamak program lags significantly behind that in the United States because of an emphasis on large tokamaks. In recent years, most of the small tokamaks at the IAE have been dismantled to make personnel and floorspace available for the T-15 project. In addition, work on the T-15 has interfered with the operations of the T-10 and T-7 tokamaks. As a result, we believe that the Soviet experimental MCF program is quite limited relative to that in the United States. To partially overcome the delays in the start of the T-15 experimental program, the T-10 was restarted in the summer of 1989 to perform ECRH experiments needed to fulfill ITER requirements

We doubt that the T-15 will make any significant contributions to the ITER/OTR program. The T-15 probably will not become fully operational before 1992, over eight years after its US counterpart (the Tokamak Fusion Test Reactor—TFTR). In addition, the T-15 will not use deuterium or tritium (the TFTR has used deuterium and is scheduled to use tritium in the next few years

We believe that the TSP tokamak will not make any significant contributions to the ITER/OTR program. We expect that the plasma parameters attained with the TSP will not exceed those already attained on the

TFTR and JET (Joint European Torus, a Euratom project) tokamaks. Because of the long delays in the TSP project, the device problems still to be corrected, and the plasma parameters likely to be attained, the Soviets probably will not use tritium in the TSP tokamak. As a result, Soviet tritium expertise will remain in the nuclear weapons program

Plasma Heating
Significant ECRH experiments on T-15 are jeopardized by the low frequency (80 to 100 gigahertz) and short pulse length (less than one second) of the available Soviet gyrotrons. Although significant near-term results on ECRH could be obtained on T-15 using advanced gyrotrons being developed in the USSR, and available in the United States, gyrotrons may not have a long-term role in ECRH. The long-pulse, high-frequency source required for ECRH in fusion power reactors may be the free electron laser (FEL). Although the United States is conducting experiments on the use of an FEL for ECRH and current drive in a tokamak, no similar experimental efforts are apparent in the Soviet MCF program. Theoretical efforts related to the use of FELs for ECRH are under way at IPF in Gor'kiy

The USSR significantly trails the United States in ICRH and lower hybrid heating technology, primarily because of neglect. Because neither of these technologies is scheduled for use on the T-15, we believe the lead of the United States will increase during the next decade. Although the Soviets have no recent experience with neutral beam heating of tokamak plasmas—unlike their American counterparts, whose extensive experience has been obtained over the last 10 years—we expect the Soviets to gain experience in neutral beam heating technology during the next decade. Significant technological developments are likely to come from IYaF, and experience will be obtained from operation of the T-15 and TSP. We believe, however, that the Soviets will continue to lag significantly behind the United States in neutral beam heating technology for the foreseeable future; a significant lag probably also will continue in plasma fueling technology. The Soviets have been exposed to state-of-the-art equipment in all these technologies during US-Soviet bilateral activities and during ITER design activities.

Other Support Technologies
We believe it likely that Soviet diagnostic and control equipment is adequate for the Soviet MCF program, even though Soviet equipment lacks the sophistication found in US equipment. The absence of many types of sophisticated equipment generally means that the Soviets cannot obtain independent measurements of plasma parameters. If tritium is used in the TSP, the success of the TSP experimental program probably would depend on the availability of diagnostics for very short neutron pulses. Such equipment has not been observed in the Soviet MCF program but probably is available in the nuclear weapons program. We expect to observe increased Soviet developmental work on diagnostic equipment if the Soviets become partners in future CIT or ITER programs

Soviet tokamak confinement theory and scientific computing are competent and progressing. These technologies are unlikely to slow the progress of the Soviet domestic MCF program. The Soviets, however, trail the United States in most topics in these areas. Although the Soviets have made significant strides in utilizing algorithms and computers, these advances pale in significance when compared with the enormous computing power added to the US MCF program during the last decade

We believe it unlikely that Soviet industry could produce the large, reliable superconducting magnets required for the construction of an ETR in the next 20 years. Soviet magnet technology significantly lags that in the United States. Although the completion of the niobium-tin superconducting magnets for T-15 represents a significant achievement, we believe that the Soviets have not yet addressed all the major problems of these magnets. In addition, the design, fabrication, and conductor technologies used are not nearly as sophisticated as those available in the

United States. The superconducting magnets on the French Tore Supra tokamak, which was completed in April 1988, have parameters superior to those of the T-15 magnets, but are made from the less demanding niobium-titanium superconductor

We believe that the Soviets' fusion materials research program significantly trails that in the United States. The Soviets, through their fission program, continue to contribute to the radiation damage data base for fusion materials. We assess, however, that the Soviet program for the development of new materials lags significantly behind that of the United States. We expect this situation to continue in the near term. The Soviets have a significant program on the use of liquid metals in fusion reactors

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Appendix A

Glossary of Terms

Auxiliary heating system: system used to heat plasma in a magnetic confinement fusion device to thermonuclear (roughly 100 million kelvins) temperatures.

Blanket: modules placed around a plasma-containing chamber; used to breed tritium, to breed fissile fuel (see hybrid reactor), and/or to remove heat.

Breeding: creation of tritium or fissile material by neutron absorption in an appropriate material.

Compact Ignition Tokamak (CIT): a proposed US tokamak.

Current drive: use of heating techniques to create and maintain the plasma current in a tokamak.

Deuterium: heavy hydrogen isotope; will be used to fuel fusion power reactors.

Electron cyclotron resonance heating (ECRH): type of radiofrequency (RF) heating that energizes (accelerates) electrons.

Engineering test reactor (ETR): generic term for the next generation of large tokamak; will be used for engineering testing of proposed power reactor components.

Experimental thermonuclear reactor (OTR): Soviet national version of an ETR.

Free electron laser: accelerator-based source of coherent, intense electromagnetic radiation.

Fusion: the combination of light nuclear particles to create new particles and energy.

Gas dynamic trap: a new Soviet version of a magnetic mirror; possible candidate for a large neutron source.

Gyrotron: RF tube used for ECRH.

Hybrid reactor: a fusion reactor with blanket modules for breeding fissile fuel.

International Thermonuclear Experimental Reactor (ITER): object of present international program to design an ETR.

International Tokamak Reactor (INTOR): subject of previous international workshops to discuss ETR design.

Ion cyclotron resonance heating (ICRH): type of RF heating that energizes ions.

Joint European Torus (JET): largest tokamak in Western Europe.

JT-60: largest tokamak in Japan.

Lower hybrid heating (LHH): type of RF heating; energizes electrons and ions.

Magnetic confinement fusion (MCF): containment of thermonuclear plasma using magnetic fields.

Magnetic mirror: open trap with "magnetic plugs" at each end.

Magnetic trap: MCF device in which external magnets provide the entire confining magnetic field configuration.

Major plasma radius: distance from the geometric center of the tokamak to the center of a contained plasma.

Minor plasma radius: distance from the geometric center of the plasma to the plasma edge.

Megaelectronvolt (MeV): an energy of 1 million electron volts; 1 electron volt corresponds to a kinetic temperature of 11,605 kelvins.

Multiple mirror: a series of magnetic mirrors.

Neutral beam injection: the injection of neutral hydrogen atoms for heating of plasma ions by collision.

Open trap: linear magnetic trap for which external magnetic coils provide the entire confining magnetic field.

Plasma: a hot ionized gas.

Plasma current: flow of electrons along the central axis of the plasma.

Poloidal coil/magnet: magnet that encircles a plasma-containing chamber and creates a toroidal (axial) magnetic field.

Radiofrequency (RF) heating: type of auxiliary heating using electromagnetic waves; particular kinds are ECRH, ICRH, and LHH.

Scientific breakeven: point when the plasma produces fusion energy equal to energy needed to heat plasma.

Stellarator: a toroidal (closed) magnetic trap.

T-7: Soviet tokamak with superconducting poloidal coils.

T-10: major Soviet tokamak since 1975.

T-14: tokamak now known as TSP.

T-15: largest Soviet tokamak; not yet fully operational.

T-20: very large tokamak designed by Soviets in late 1970s; not built.

Thermonuclear fusion: fusion caused by thermal motion of ions.

Tokamak: most developed MCF device; has a strong toroidal magnetic field created by external magnets; part of the total magnetic field is created by plasma current.

Tokamak Fusion Test Reactor (TFTR): largest US tokamak.

Toroidal magnetic field: magnetic field parallel to plasma axis.

Tritium: radioactive hydrogen isotope; will be used with deuterium in initial fusion power reactors.

TSP: new Soviet tokamak; will use compression of plasma; not yet fully operational.

Appendix B

Fusion Tutorial

Two nuclear reactions can be used to provide nuclear energy for producing electricity—fission and fusion (thermonuclear). These energy-producing nuclear reactions are possible because the mean binding energy per nucleon (that is, neutron or proton) is less in both the lightest (for example, hydrogen) and the heaviest (for example, uranium) nuclei than it is for nuclei in the intermediate mass range (for example, iron). This is shown schematically in figure 4. The nuclei produced by either of these reactions are less massive than those that entered into the reaction. In accordance with Einstein's equation, $E=mc^2$, the loss of mass shows up as energy. This paper deals only with thermonuclear fusion.

Thermonuclear fusion is a nuclear process in which two light nuclei fuse together, react, and release energy. Because nuclei have positive electrical charges, they naturally repel each other. For a large number of fusion reactions to occur in a quasi-continuous manner, the nuclei must be given large velocities. The increased motion of the nuclei improves the probability that they will collide and fuse together. These conditions apply in a plasma (see inset).

For energy production, the most useful fusion reactions are those involving the heavy isotopes of hydrogen—deuterium and tritium (the nuclei are referred to as deuterons and tritons, respectively). The fusion reaction with the largest cross section (that is, probability of occurrence) at the lowest temperature is the deuterium-tritium (DT) reaction. This reaction (see figure 5) will be used in the first fusion reactor (that is, initial fusion power-producing device). Because tritium is radioactive (a half-life of 12.2 years) and the DT reaction produces copious quantities of high-energy neutrons, it is desirable that fusion reactors eventually use deuterium-deuterium reactions. Deuterium is a naturally occurring hydrogen isotope that can be extracted from seawater.

From the viewpoint of electricity production, fusion is just another type of combustion. Although it is nuclear combustion (involves nucleons) rather than chemical

Plasma

A state of matter known as a plasma is produced by adding thermal (heat) energy to a gas. When heat is added to a gas (that is, when the temperature of the gas is raised), its constituent molecules gain energy of motion (that is, kinetic energy), which is proportional to the square of their velocity. Collisions between molecules with thermal kinetic energies exceeding their molecular binding energies result in the dissociation of the molecular gas into an atomic gas. As the temperature of the gas is increased further, the atoms acquire enough thermal energy to dislodge electrons during collisions. This transition from an atomic gas to a macroscopically neutral, but highly ionized, gas (plasma) occurs gradually with increasing temperature.

On the surface of the Earth, plasma is a manmade state of matter. Outside these narrow confines, however, plasma is the normal state of matter in the universe. Lightning and auroral discharges in the atmosphere produce plasma. The ionosphere and the Van Allen belt surrounding the Earth are plasmas. More important, the stars and most of interstellar space are plasmas.

The particle kinetic energies (about 10 kiloelectronvolts) required for fusion greatly exceed the energy needed to create a plasma. The energy required to dissociate most molecules and ionize most atoms is less than 10 electron volts (eV). (A thermal kinetic energy of 1 eV corresponds to a kinetic temperature of 11,605 kelvins [K].) Thus, at the temperatures of interest to fusion (100 million K), the hydrogen fuel is in the form of a plasma. Thermonuclear fusion, therefore, means that the fusion reactions are nuclear and are instigated by raising the kinetic temperature of the nuclei.

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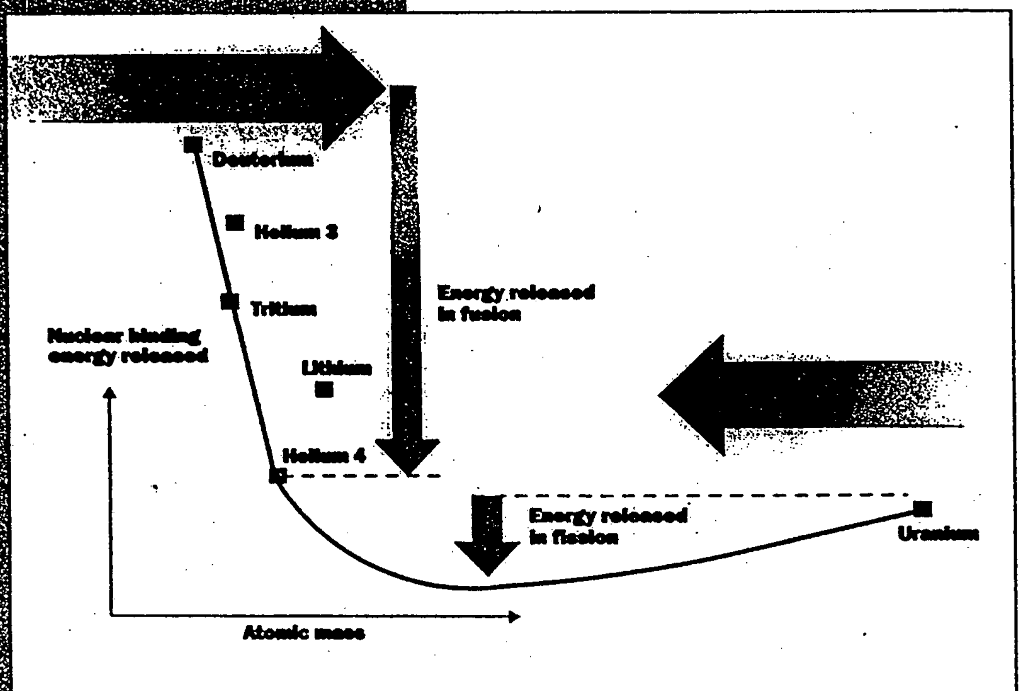

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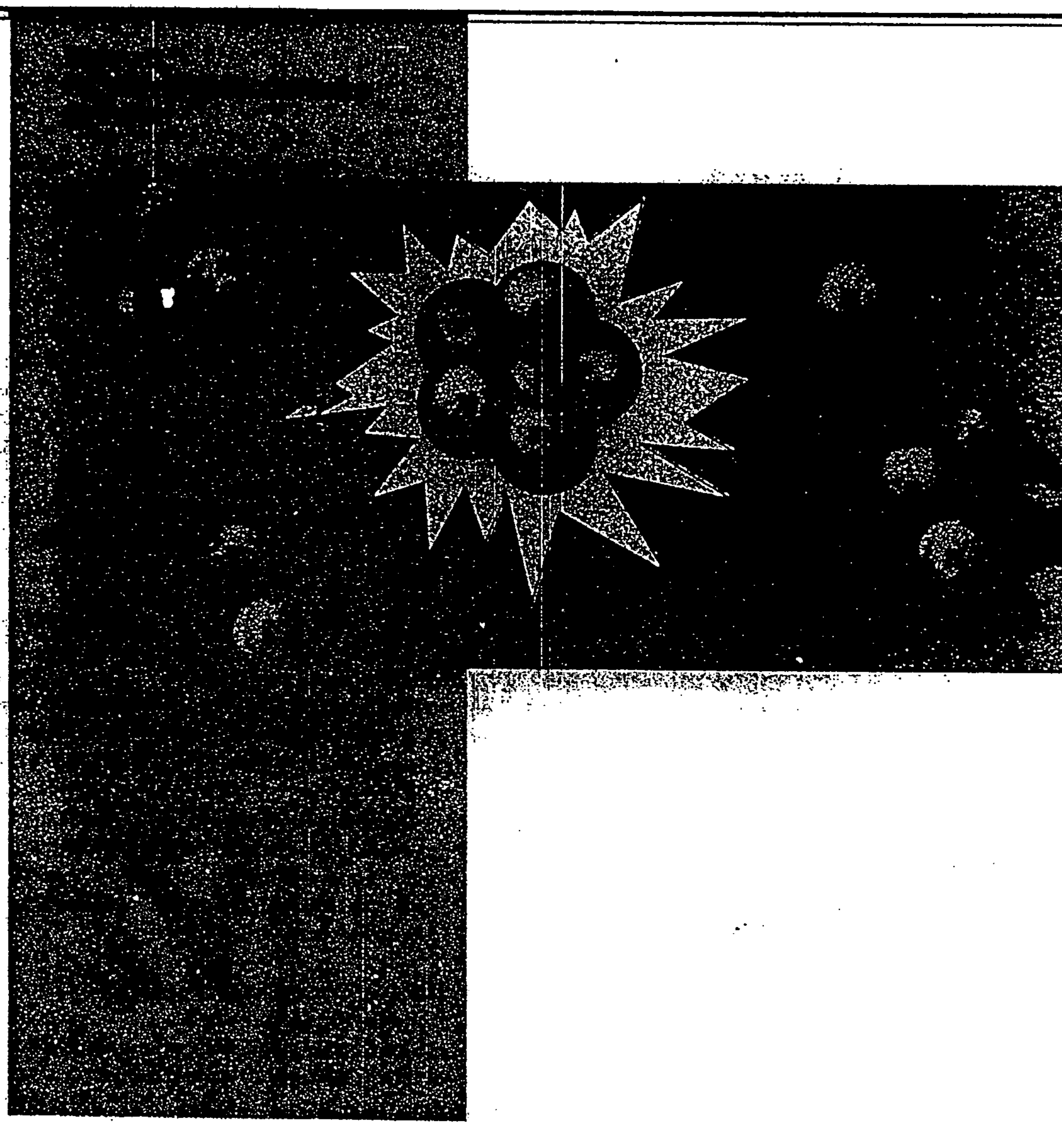


combustion (involves electrons), it follows the same types of processes. Fusion involves localizing the fuel and heating it to its ignition temperature (point at which the fuel releases more useful energy than it loses to its surroundings), maintaining the fuel at (or above) its ignition temperature, and replenishing with fresh fuel. A significant difference is the hot temperature involved in fusion.

The fusion process is a practical energy source because the temperature involved is that corresponding to the kinetic energy (energy of motion) of the particles. Fortunately, very little radiant energy (which increases as the fourth power of the radiation temperature) is emitted during the fusion process. If this were not the case, the hot fusion fuel could not be located in the vicinity of man or material. (The heat energy encountered when approaching the mouth of a coal-burning furnace or the sun is radiant energy.

The three basic methods of containing a hot fusion plasma are magnetic fields, mass inertia, and gravity (see figure 6). The latter occurs in the stars but is not relevant to terrestrial research. Inertial confinement fusion uses laser or particle beams to implode a small pellet (radius of micrometers) of DT fuel. The inertia (inward moving mass) produced keeps the resultant hot, dense DT plasma together for short time periods (nanoseconds) while a large number of DT reactions occur.

The third type of containment, magnetic confinement fusion (MCF), is the topic of this paper. MCF is based on the fact (see figure 6) that charged particles (nuclei, ions, and electrons) spiral around and, therefore, are confined by magnetic field lines. Unlike inertial confinement fusion, which is a short-pulsed, high-density approach to plasma confinement, MCF is a low-density (plasma density about 10^{-4} of the density of room air), long-lived (order of seconds) phenomenon. The goal of MCF is to develop a practical device with a magnetic field configuration that can stably contain a fusion plasma in a quasi-steady manner.

The basic components of an MCF research device, and components that will also be necessary parts of a fusion reactor, are a vacuum vessel and an external magnetic field system. MCF devices can be divided into two categories—those in which the external magnetic field systems provide the entire confining magnetic field configuration and those in which they do not. The most prominent of the latter is the tokamak. An important component of the tokamak's magnetic field is provided by an axial electrical current that flows through the plasma in the vacuum vessel (see figure 7). The former type of device is referred to as a magnetic trap.

The two types of magnetic traps that have been prominently investigated as candidates for a fusion reactor are the stellarator and the open trap. The stellarator, and related torsatron, are toroidal devices (see figure 7) that may use an axial current for plasma heating (method known as ohmic heating). Open traps are linear devices that generally have "magnetic plugs" at both ends. The simplest types of open traps are magnetic mirrors (see figure 8).

At present, MCF is in the R&D phase. Because MCF machines are physics devices, they require large amounts of diagnostic equipment to collect data on plasma behavior and confinement. They also require auxiliary heating systems to bring the plasmas to fusion temperatures and to keep them there. The next generation of large tokamaks—an engineering test reactor—will be used to perform physics experiments, but its primary function will be to address many reactor-relevant engineering issues. As these issues become further defined, extensive R&D will be required to solve them.

The two major techniques for auxiliary heating of MCF devices are radiofrequency (RF) and neutral beam. The three primary RF techniques (with frequency range and source device) are electron cyclotron resonance heating (ECRH; above 10 gigahertz [GHz], the gyrotron), lower hybrid heating (1 to 8 GHz, the klystron), and ion cyclotron resonance heating (50 to 100 MHz, the tetrode tube). As their names imply, electron and ion cyclotron resonance heating energize electrons and ions using an electromagnetic

Types of Plasma Confinement

Magnetic | Inertial | Gravitational

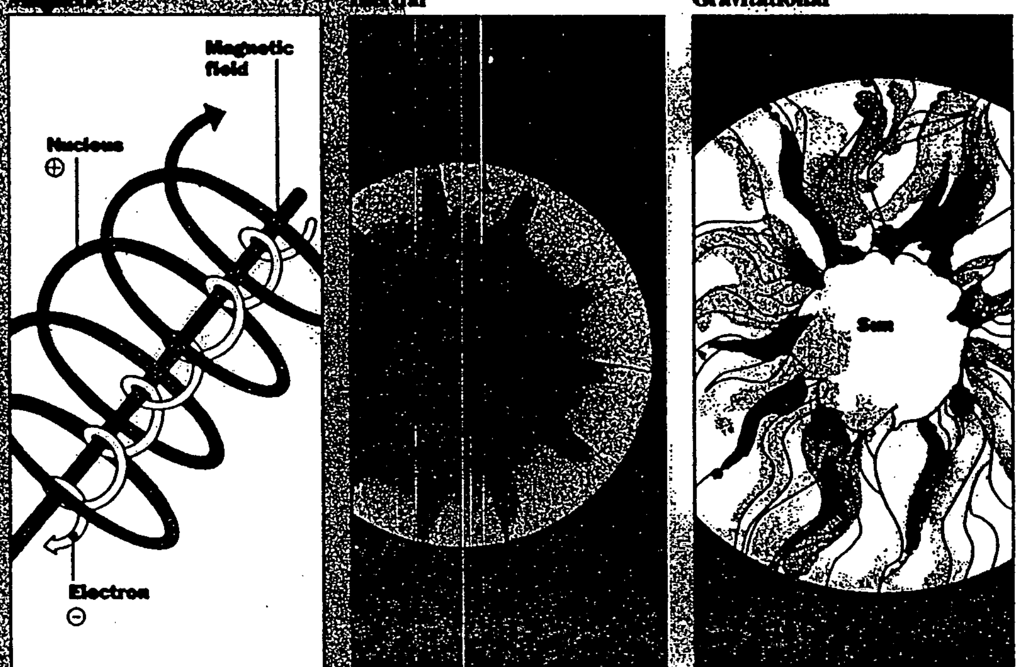
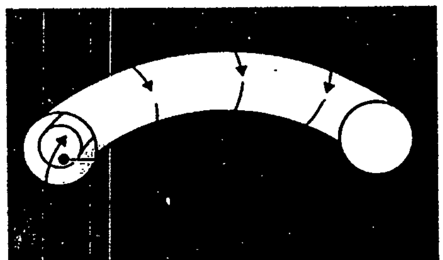
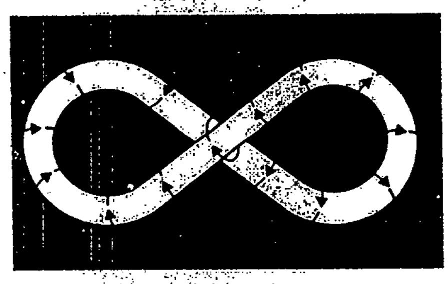


Figure
Types of Toroidal Magnetic Confinement Fusion Devices

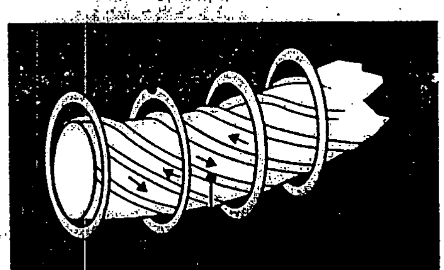
In the tokamak, the main toroidal magnetic field is [illegible]



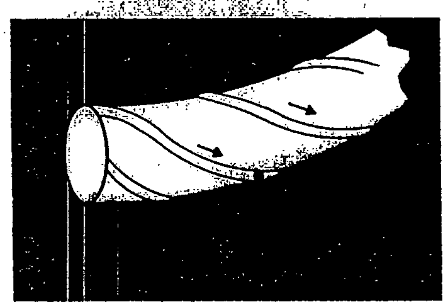
The [illegible]



In the classical stellarator, the total magnetic field is created by a set of poloidal coils plus a set of helical coils with the current flowing in the opposite direction.



The torsatron has a single set of helical windings to provide the toroidal and poloidal magnetic fields. Generally, an additional set of poloidal coils (not shown) is required as necessary to provide an additional vertical field.



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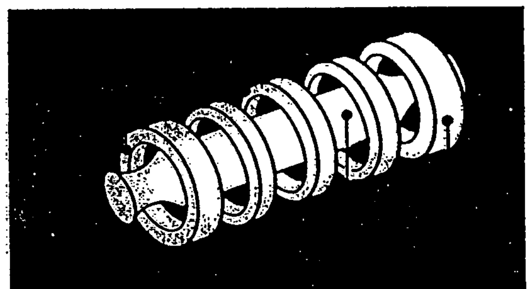

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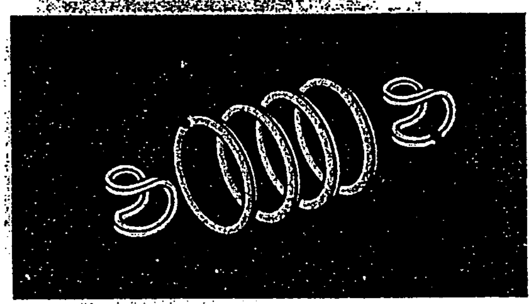


wave tuned to the particle's cyclotron frequency. Because this frequency depends on the magnetic field, effective heating depends on varying the source frequency with the magnetic field of the device (for ECRH, a frequency near 80 GHz is appropriate for a field of 3 teslas [T] and 140 GHz for 5 T

For effective neutral beam heating, the energy of the injected beam must be matched to the size and density of the plasma. Neutral beam injectors on present MCF devices accelerate positive deuterium ions to energies on the order of 100 kiloelectronvolts (keV). Future MCF reactors, however, will require beam energies on the order of 200 to 500 keV in order to deposit heat in the core of the plasma. For efficiency reasons, negative ion beams will be used to obtain these energies

For the past 20 years, the United States has been developing reference designs for "commercial" fusion reactors. These are not blueprints for the future but are problem finders. They help delineate what types of systems and materials will be required and what kinds of research are needed to acquire them. These designs have played a large role in the definition of the content and direction of the US fusion program.

Hybrid Reactor Concept

In concept, the complementary neutronic nature of the fission and fusion reactions can be combined in the fusion-fission hybrid reactor. The fission reaction is neutron poor, and the fusion reaction is neutron rich (they produce 1.3 and 5.7 neutrons, respectively, per 100 megaelectronvolts of nuclear energy). In addition, the fission neutrons are required to maintain a fission chain reaction, but fusion neutrons play no role in future fusion reactions other than breeding tritium

In a hybrid reactor, the vacuum vessel of the fusion device would be surrounded by blanket modules containing fertile material (that is, material such as natural uranium that can be converted into fissile material such as plutonium by the absorption of neutrons). Such a device could be used to continuously supply the fuel for a number of nuclear fission reactors. This was one of the driving forces for the consideration of hybrids in the past, especially in the USSR. A major drawback of hybrids, however, is that fissions in their blankets create the same highly radioactive fission product wastes as in fission reactors. Because of the radioactivity problems caused by the USSR's Chernobyl' reactor accident, the attraction of hybrids has diminished

The advantage of the hybrid reactor is that it could use a fusion system with less demanding plasma parameters than a pure fusion power reactor. Theoretically, this should make a hybrid a more near-term possibility than a pure fusion power reactor. The addition of a fertile blanket, however, may seriously complicate the engineering of the reactor and the politics of its acceptability. Studies on the design and safety of hybrid reactors are in an early stage

Important features of a fusion reactor will be size, economics, and safety. MCF reactors tend to be large because they have low plasma densities. The density is limited because the inward pressure of the magnetic field must be larger than the outward pressure of the hot plasma (the available magnetic field is limited by the magnetic forces or pressures between toroidal magnets that can be handled practically). There is a further limit because the fusion power increases as the square of the plasma density. If the power density of the plasma becomes too high, the high-energy-neutron and thermal loads on the material walls of the reactor become so great that the lifetimes of the materials become impractically short

Fusion reactors will need to use superconducting magnets. Normal copper magnets are not practical for the continuously operating, high-field magnets required in reactors. The size and operating costs of copper magnets would make the reactor uneconomical.

To operate quasi-continuously, an MCF reactor will require a plasma refueling system. This system is likely to be a pellet (deuterium or tritium ice) injector (pneumatic, centrifugal, or railgun). Auxiliary heating systems will be used to bring the plasma to fusion temperatures and possibly to maintain it there

Although the DT fusion neutrons are not useful in maintaining fusion reactions, they play two crucial roles in a fusion reactor. They are absorbed in blanket modules containing lithium and breed the tritium necessary to fuel the reactor. The heat energy released as the neutrons slow down by collisions is removed by a coolant and used to create steam for the production of electricity. A third, possible use entails absorption of the neutrons in blanket modules containing uranium. Such hybrid reactors (see inset) would be used to breed plutonium for the fission reactors in the nuclear power industry

Appendix C

Tokamaks

Tokamak Tutorial

The tokamak (Russian acronym for *toroidal kamera magnetik* or toroidal magnetic chamber) is a Soviet concept. (The tokamak configuration was described theoretically in the USSR and the United States in the early 1950s, but US scientists did not pursue this approach until the 1970s.) A tokamak is an axially symmetric toroidal system (see figures 7 and 9) in which the plasma is confined by a strong toroidal magnetic field (produced by an external toroidal solenoid of independent magnets), together with a weaker poloidal magnetic field (produced primarily by a toroidal/axial electric current flowing in the plasma itself—the plasma current). The combination of the two fields produces nested toroidal magnetic surfaces composed of helical field lines. The poloidal magnetic field is responsible for the equilibrium of the plasma, and the toroidal magnetic field suppresses the main magnetohydrodynamic plasma instabilities.

All tokamaks, both built and designed, use a transformer, with or without an iron core, to induce and maintain the toroidal current (see figure 10). The ring of plasma acts as a one-turn secondary winding for the transformer. Use of a transformer causes the tokamak to be an inherently pulsed machine. Research is under way on radiofrequency (RF) techniques to create and maintain the toroidal current (these techniques are known as RF current drive) in lieu of using a transformer. If this technique is successful, the tokamak could operate as a quasi-continuous reactor.

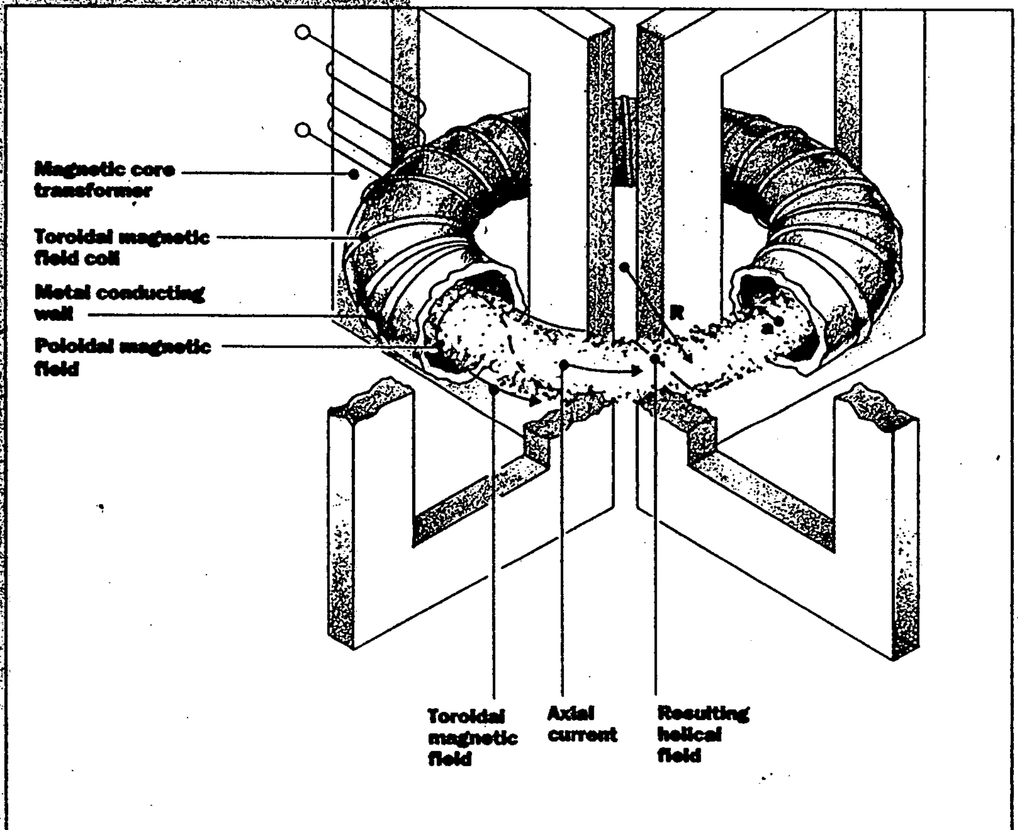
Tokamak plasmas are created and heated toward fusion temperatures by the toroidal current (electrons) flowing through them and colliding with the constituent particles; this is known as ohmic heating. However, it is characteristic of plasma resistance that it decreases as the temperature increases. As a result, ohmic heating alone cannot be used to reach fusion temperatures. Therefore, even for a tokamak, auxiliary heating systems are required

The first wall of a tokamak is the material wall closest to the plasma. Protection of the first wall is paramount for reactors because first-wall failure can lead to long downtimes and complicated maintenance problems. First-wall failures can be caused by stresses (such as thermal, magnetic, and pressure), radiation damage, surface bombardment, and chemical reactions

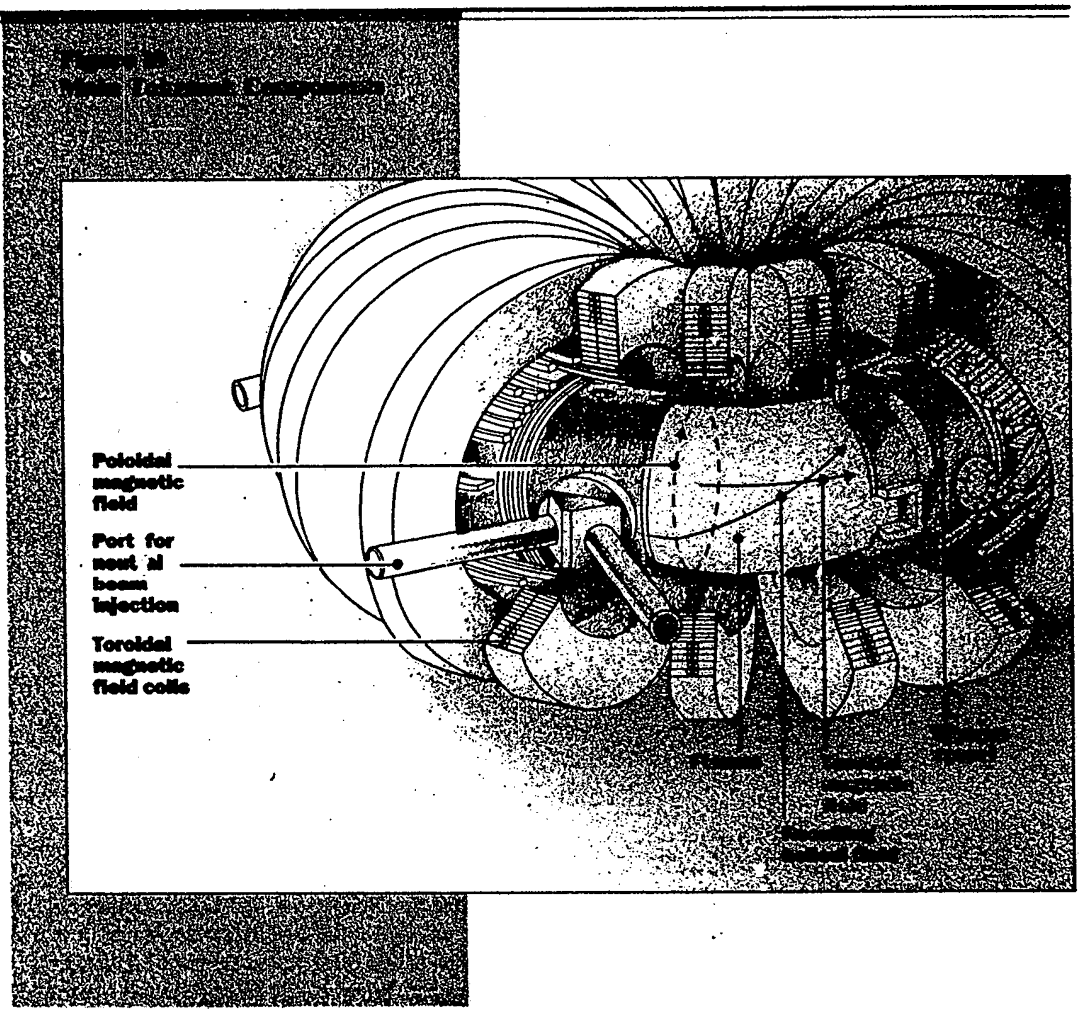
A tokamak plasma must be kept free of impurities (nuclei heavier than hydrogen) that can cool the hydrogen nuclei. Because most impurities (generally nuclei sputtered off the first wall or other structural materials) are located in the outer layers of the plasma, they can be removed using a limiter or a divertor. A metal limiter extends around the circumference of the torus (vacuum vessel) in the toroidal direction. When nuclei strike the plasma side of the limiter, they are neutralized and pumped away. A divertor is a device that bends the outer magnetic field lines away from the plasma and into an external chamber. The outer layers of the plasma are continuously removed, cooled, neutralized, and pumped away from the divertor. This process not only removes impurities but also decreases first-wall bombardment that leads to sputtering of impurities

The aspect ratio of the torus of a tokamak, defined as the ratio of the major plasma radius (R) to the minor plasma radius (a) (see figure 9), seems to play a major role in stability and confinement conditions for the tokamak. Because the theoretical understanding of these conditions/relationships is limited, the form of these relationships has generally been determined experimentally. These experiments have been accomplished by continually building larger tokamaks and varying parameters such as the aspect ratio, toroidal magnetic field, toroidal current, and the amount and type of auxiliary heating. An understanding of these relationships is required for developing an optimal reactor design

Figure 9
Tokamak Showing
Plasma Radii



For a tokamak, the major plasma radius (R) is the distance from the center of the device to the center of the plasma. The minor plasma radius (a) is the distance from the center of the plasma to the edge of the plasma.



After British verification in 1969 of Soviet claims about the good confinement properties of tokamaks, worldwide attention turned to them. Since that time, the major world magnetic confinement fusion (MCF) programs have devoted a large portion of their personnel and funding to tokamak research. As a result, the tokamak is the most developed MCF approach and is likely to be the basis for the first MCF reactor.

Soviet Tokamak Program

History

The basic idea of the tokamak was described in the early 1950s by I. E. Tamm and A. D. Sakharov. During the mid-1950s, the first experimental tokamak

Table 2
Initial and Small Tokamaks at IAE

Tokamak	Major Plasma Radius *(meter)*	Minor Plasma Radius *(meter)*	Initial Operation	Comment
TMP	0.8	0.13	1955	
T-1			Pre-1960	
T-2			Pre-1960	
T-3	1.0	0.18	1960	
T-4	0.9	0.2	1970	Modified T-3
T-5	0.62	0.25	Pre-1970	Modified T-1
T-6	0.7	0.25	Pre-1970	Modified T-5, became FT-1
T-8	0.28	0.11	1975	
T-9	0.36	0.07	1972	
T-11	0.7	0.25	1975	
T-12	0.3	0.08	1975	Possibly modified T-9
T-13			1980	
T-3M	1.0	0.28	1980	Modified T-3
TO-1	0.6	0.18	1970	
TO-2	0.6	0.12	1981	
TM-1	0.4	0.1	1960	
TM-2	0.4	0.1	1961	
TM-3	0.4	0.1	Pre-1973	Modified TM-2
TM-4	0.4	0.1	1978	
TM-G	0.4	0.08	1980	Modified TM-3

device was built in an Institute of Atomic Energy (IAE) division (now called the Department of Plasma Physics) under the leadership of L. A. Artsimovich. Tokamak research at the IAE was under the direction of first I. N. Golovin and then N. A. Yavlinsky; by the early 1960s, Artsimovich had assumed direct control.

The tokamaks at the IAE were developed to investigate specific plasma physics issues. Table 2 is a list of the initial and small tokamaks built and operated at the IAE; photographs of several of these tokamaks are displayed in figure 11. Areas in which research has been conducted include most topics of interest to the world tokamak community. During recent years, the small tokamak program at the IAE has been discontinued, and personnel and floorspace have been transferred to the T-15 effort.

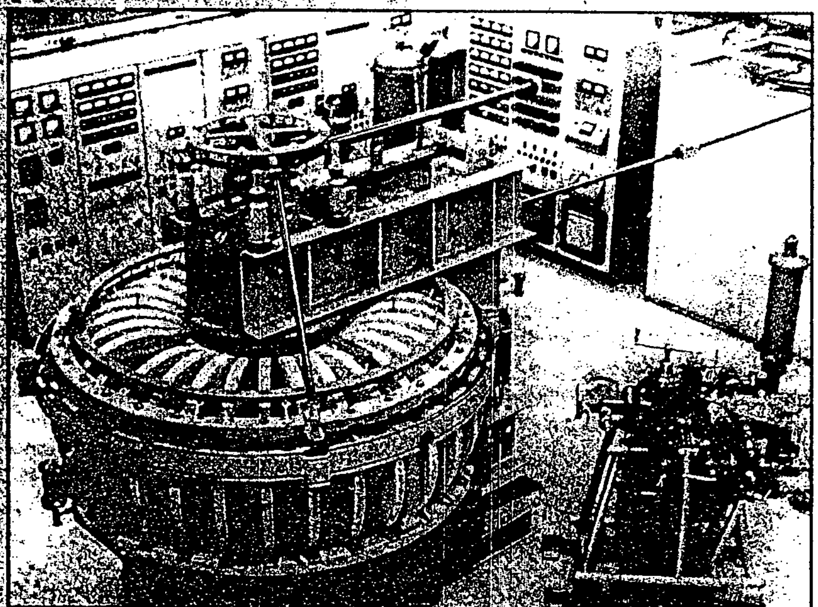
The Ioffe Physical Technical Institute began experiments on small tokamaks in about 1971. Work on developing diagnostic methods for high-temperature plasmas has been going on since the late 1950s. RF heating, particularly lower hybrid heating (LHH), experiments have been conducted on the FT series of tokamaks. The Tuman series has been used to investigate adiabatic compression with ohmic heating (these experiments provided the physics data base for TSP) and, more recently, ion cyclotron resonance heating (ICRH)

The tokamak program at the IAE, and thus of the USSR, has been disturbed by an overemphasis on very large tokamaks. Once the T-10 was brought into operation in 1975, the Soviets turned their attention to the T-20, with a major plasma radius of 5 meters. By about 1977, the Soviets realized that a tokamak the size of T-20 was too large, too complex, and too costly a project for the USSR, and very likely for any other country. In 1978, they proposed to the International Atomic Energy Agency (IAEA) that a tokamak like the T-20 be built as an international project. Meanwhile, domestically they decided to build the T-15 and TSP. During recent years, the effort to complete the T-15 has led to the elimination of IAE research on small tokamaks, decreased research on the T-7, and interrupted research on the T-10. Separate discussions of the large tokamaks planned and built at the IAE (see table 1) are given below

Organization
The Soviet tokamak community is large and varied. Pages 30 and 31 and the insets on page 32 show institutional contributors to Soviet tokamak research, Soviet descriptions of the organization of their fusion program, and the procedures followed to get fusion equipment manufactured

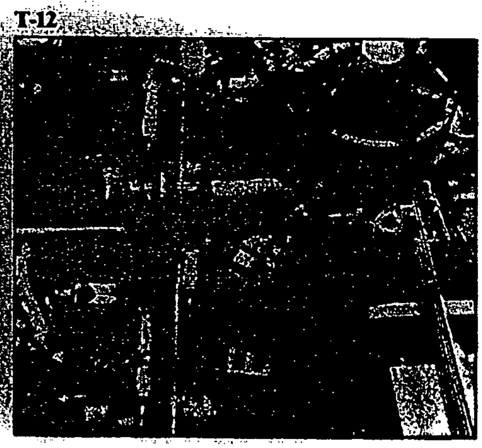
Figure 11
Several Small
Soviet Tokamaks

T-6



TM-3

T-12



Secret

Soviet Fusion Organization

Who? Fusion research in the USSR is carried out mainly under the auspices of USSR State Committee for the Utilization of Atomic Energy (GKAE) and the USSR Academy of Sciences (AN). Because a large number of the scientific and engineering personnel doing fusion research are concentrated in institutes subordinate to the GKAE, the GKAE has the primary role in organizing fusion research. The responsible organization within the GKAE is the Main Administration of Accelerator and Thermonuclear Research (ATR), headed by A. A. Vasil'yev. The deputy head of the ATR in charge of fusion research is N. S. Cheverev. Under Cheverev is a department of plasma physics and fusion headed by L. G. Golubchikov and consisting of eight specialists. The areas for which the specialists, most of whom worked previously at the IAE, are responsible include tokamaks, demonstration fusion reactors, stellarators, materials, diagnostic equipment, and inertial confinement fusion.

In the AN, fusion research is supervised by the vice president in charge of the Department of General Physics and Astronomy, as well as the Department of Nuclear Physics. During the previous decade, this vice president has been Ye. P. Velikhov, who is also "scientific supervisor" of Soviet fusion research. Velikhov's predecessor in the latter position was L. A. Artsimovich.

The main fusion work of the GKAE is done at:
- *IAE, Moscow.*
- *IAE branch at Troitsk.*
- *Electrophysical Apparatus Scientific Research Institute* imeni *D. V. Yefremov—the Yefremov Institute.*
- *Siberian Physicotechnical Institute.*
- *Inorganic Materials Scientific Research Institute.*

And the work of the AN is done at:
- *Lebedev Physics Institute.*
- *Institute of General Physics.*
- *Ioffe Physical Technical Institute.*
- *Institute of Nuclear Physics.*
- *Khar'kov Physical Technical Institute.*

What? The main role of the GKAE is to prepare recommendations for decisions on fusion work programs that must be confirmed at the governmental level; these recommendations include the content and purpose of the programs. The ATR is responsible for developing fusion work programs, plans for construction, financial support, and communications with construction organizations and industry.

The initial stage in organizing fusion work is adoption of long-term target programs for research and construction. The development of target programs may be linked to the beginning of the next five-year plan or to the next major research stage. When finalized, these programs contain detailed information on the research to be undertaken, construction and equipment required, finances, and involvement of GKAE and non-GKAE organizations

How? The first formal step in developing a target work program is taken by a commission of prominent fusion scientists. This commission, which generally is headed by the national fusion "scientific supervisor," develops suggestions for long-term programs for research and construction. Recent results from Soviet and worldwide fusion programs are a primary input to the commission's deliberations. After scientific discussions at all levels, these suggestions are sent to the ATR, where they are formalized. Once these formalized programs are agreed on by all involved departments and ministries, a draft resolution is sent to the USSR Council of Ministers for approval.

When? The long-term target programs are the basis for developing five-year and annual plans. Even though long-term target programs approved by the Council of Ministers contain decisions on total expenditures, the amount to be spent during a financial year (which begins on 1 January) must be approved each year. The GKAE fusion laboratories must submit detailed annual thematic plans (including required financing) to the ATR by May. Within a month, the ATR sends the plans to the GKAE Planning Agency for presentation to the USSR Council of Ministers. By October, the ATR receives a decision on total funding. From this the ATR develops an annual program for each institute. About 80 percent of the financial allocation for fusion passes through the GKAE.

Comments. We do not know to what extent the procedures described represent past or present practices. Available information, however, indicates that the procedures related to the management and financing of fusion research, and research in general, have been changing since 1987. In January 1989, we noted that under new regulations institutional funding from the national government was allocated for specific budget items, such as personnel salaries and equipment. This has decreased the flexibility and autonomy project managers have to move monies around in a particular project. The new regulations also require project managers to provide detailed justifications for their budget requests and to demonstrate the benefits of the program to Soviet society. We believe that in the past the goals of the planning and budgeting procedures were the allocation and prioritizing of resources, not the development of an integrated fusion program

1989 Information

During a fusion bilateral meeting in Moscow during December 1989, the Soviets provided information on their fusion budgets and budgeting procedures. This information is summarized below.

Fusion financing is approved by the USSR Council of Ministers and delivered to the Ministry for Atomic Power and Industry (the Ministry of Medium Machine Building, to which the GKAE reported, is now part of this new Ministry) and the AN. The two different types of expenditures relate to R&D and to direct and indirect capital costs (that is, manufacture of equipment and construction of buildings and installation

Almost 80 percent of the fusion R&D expenditures were for magnetic confinement fusion (MCF) facilities; 90 percent of the MCF expenditures were distributed by the Ministry for Atomic Power and Industry. In 1989, the IAE (Moscow and Troitsk) received 70 percent of the fusion R&D expenditures; and the Yefremov Institute received 13 percent. About 70 percent of the financing given to the IAE was spent internally.

The manager and customer of R&D in the GKAE is the Main Department for Fundamental Issues of Nuclear Physics and Controlled Thermonuclear Fusion. Funding is transferred from the Main Department to the fusion institutes by means of contracts. Contracts include a timetable for completion of key elements, work cost, performance specifications, and schedule of funding. During 1989, the Main Department awarded 35 contracts. The fusion institute is the executor of the contracts. In 1989, the IAE had a 26-million-ruble contract to use the T-10 and T-15 tokamaks to study physics relevant to the OTR/ITER (experimental thermonuclear reactor/International Thermonuclear Experimental Reactor) project. About 30 percent of the total amounts of these R&D contracts are for wages. Quarterly and annual reports must be submitted to obtain the funds due.

Design documents for construction projects must be approved by the Ministry for Atomic Power and Industry or the AN. In recent years, all construction of fusion devices has been funded by the Ministry. As of 1 January 1989, 80 percent of the capital expenditures for the T-15 and TSP tokamaks (total capital budgets of 187 and 216 million rubles, respectively) had been spent. The other 20 percent of the funding is to be spent for auxiliary structures.

Soviet and Soviet Bloc Institutes Contributing to Tokamak Research

- *Institute of Atomic Energy* imeni *I. V. Kurchatov (IAE), Moscow and Troitsk*
- *Ioffe Physical Technical Institute (FTI), Leningrad*
- *Electrophysical Apparatus Scientific Research Institute* imeni *D. V. Yefremov, Leningrad*
- *Kirov "Electrosila" Electrical Machines Production Association, Leningrad*
- *Khar'kov Physical Technical Institute (KhFTI)*
- *Institute of Applied Physics (IPF), Gor'kiy*
- *Moscow State University (MGU), Moscow*
- *Applied Mathematics Institute* imeni *M. V. Keldysh (IPM), Moscow*
- *Mathematics Institute* imeni *V. A. Steklov (MIAN), Leningrad*
- *Institute for Nuclear Research (IYaI), Kiev*
- *Leningrad M. I. Kalinin Polytechnical Institute (LPI), Leningrad*
- *Institute of General Physics (IOF), Moscow*
- *Physical Technical Institute (FTI), Sukhumi*
- *Institute of High Temperatures (IVTAN), Moscow*
- *Inorganic Materials Scientific Research Institute (All-Union) (VNIINM), Moscow*
- *Baikov Institute of Metallurgy*
- *Atomic Reactors Scientific Research Institute* imeni *V. I. Lenin (NIIAR), Dmitrovgrad*
- *Research Design Institute of Power Engineering, Moscow and Leningrad*
- *Shatura facility of Soviet Ministry of Energy*
- *Central Institute for Electron Physics, Berlin*
- *Hungarian Central Physics Institute, Budapest*
- *Czechoslovak Institute of Physics, Prague*

Fusion Equipment Manufacturing

The following is a synopsis of Soviet procurement procedures as of October 1987

Fusion equipment is manufactured both in fusion laboratories and in industry. Laboratories manufacture small units for which their production facilities are sufficient. The Yefremov Institute has developed and fabricated most of the tokamaks of T-3 size (see table 2) or smaller. As fusion units became larger, large industrial plants became involved in the manufacture of fusion equipment. Broad industrial involvement began in 1970 when work started on the T-10. Kirov "Electrosila" Electrical Machines Production Association, in cooperation with the Yefremov Institute, has manufactured major pieces of equipment for the TSP and T-15

Equipment to be manufactured is designed by the Yefremov Institute and the involved industrial facility. A contract, which indicates the type of equipment to be manufactured, its cost, and the period of execution, is concluded between the institutional user and the industrial facility. Design documents generally are transferred to the industrial facility a year before production is to be started. In case of difficulties, it is the responsibility of the USSR State Committee for the Utilization of Atomic Energy or the USSR Academy of Sciences to eliminate them.

Large Tokamaks

The USSR has constructed or planned six large tokamaks. The following outlines the history and details of these machines

T-10

The T-10 (see table 1 and figures 1 and 12) has been the workhorse of the Soviet tokamak program since 1975. The experimental program originally emphasized ohmic heating; later the emphasis was changed to RF heating, primarily electron cyclotron resonance heating (ECRH) with gyrotrons. At the time the T-10 was designed, the Soviets apparently believed that ohmic heating alone could be used to reach fusion plasma temperatures. As a result, the T-10 had only small observational/experimental ports and relatively poor access to the vacuum vessel. This precluded the use of neutral beam heating and severely limited ICRH

Figure 12. T-10 Tokamak Under Contructio

The availability of 80- to 90-gigahertz (GHz) gyrotrons with power levels of 100 to 200 kilowatts per tube in the late 1970s allowed the Soviets to use the small experimental ports on the T-10 to undertake ECRH experiments. Soviet theoreticians believe that ECRH can be as effective as ohmic heating if the spatial distribution of the power deposition can be made similar. Recent experiments have concentrated on studying the power balance and transport when ECRH is deposited noncentrally in the plasma. The Soviets have demonstrated substantial heating of electrons, having obtained electron temperatures in the center of the plasma near 10 kiloelectronvolts (keV).

The performance of the T-10 has been hampered by conservative design and accidents resulting from shortcuts taken to bring the tokamak into operation quickly and to keep it operational. These accidents resulted in damage to toroidal magnets and power supplies, as well as an electrical fire. In addition, the T-10 research schedule has been convoluted during recent years by the T-15 effort; this has been exaggerated by the long delays experienced in the T-15 project. During the last half of 1986, for example, the T-10 was shut down while its power supplies were modified for use on the T-15

The Soviets used the time made available by shutdowns in 1986 to replace the vacuum vessel and to double the available ECRH power by increasing the number and quality of the gyrotrons. In April 1986, six gyrotrons providing 1.5 megawatts (MW) were available, and, by early 1987, 11 gyrotrons were producing 4 MW of power. The gyrotrons were used in two groups, each operating at a different frequency (because of the curvature of a tokamak, the magnetic field varies across the plasma). The pulse lengths of the gyrotrons were limited to 30 milliseconds by fringe magnetic fields produced in the gyrotrons. The Institute of Applied Physics in Gor'kiy developed these gyrotrons

The T-10 was scheduled to be shut down on 2 May 1988, and many of its components were to be transferred to the T-15. This shutdown was put off until 27 May 1988, and additional ECRH experiments were done. Because of delays on the T-15, approval was given in the summer of 1989 for additional operating time on the T-10. As a result of the shutdown of the T-15 in the summer of 1989 and of requirements to do ECRH experiments for the International Thermonuclear Experimental Reactor (ITER) program, the operating time for T-10 was extended to June 1990. The Soviets have talked about initial conceptual design work on the T-10S—a modification of the T-10 with an entirely new magnetic system

T-7

The T-7 (see table 1 and figures 1 and 13) was the world's first, and until April 1988 the world's only, operating tokamak with superconducting magnets. The toroidal superconducting magnet system was tested in 1978, and physics experiments were begun in 1979. Although the structural and magnetic designs of the T-7 permit operation at about 3 teslas on axis, the T-7 generally has been operated with less than 2 teslas on axis. The operating time of the T-7 has been severely limited by the availability of liquid helium, IAE politics, and T-15 priorities

Figure 13. T-7 Tokamak Under Contructio

[ ] the T-10 and the T-7 have served as test beds for equipment to be used on the T-15; the physicist who runs the T-7 will be responsible for the T-15 experimental program

The T-7 has been used to study ECRH, LHH, ICRH, and current drive. Although no clear data on electron cyclotron resonance (ECR) current drive have been obtained, successful lower hybrid (LH) current-drive experiments have been performed. In 1987, current-drive experiments with LH and ECR in combination were undertaken in collaboration with the Czechoslovak Institute of Physics and the East German Central Institute of Electron Physics

T-20

Although the T-20 tokamak was never built, it demonstrates the dominant role of large tokamaks in the Soviet program. During three years in the 1970s, most of the Soviet tokamak design efforts were devoted to the T-20. The results of the T-20 design efforts are still visible in the Soviet tokamak program

The Soviets envisioned the T-20 to be a demonstration fusion reactor that would use deuterium-tritium (DT) reactions to generate as much energy as was used. An

Table 3
Parameters of Various T-20 Designs

	I	II	III	Hybrid
Major plasma radius *(meters)*	5	5	4-5	6.4
Minor plasma radius *(meters)*	2	1.75	1-1.5	1.5
Plasma current *(megamperes)*	6	5	3-4	4
Toroidal magnetic field on axis *(teslas)*	3.5	3.7	6	6

initial design was presented at an IAEA conference in Dubna, USSR, during July 1975. During the next three years, the T-20 design went through several iterations as the Soviets considered the possibility of rebuilding the T-20 after the completion of its experimental program and of modifying the T-10 as an intermediate step before the construction of the T-20 (see table 3). In the latter two designs, particular attention was paid to the inclusion of hybrid blanket modules

The research program of the T-20, as envisioned in 1975, was to advance in three stages. The overall program was to take four to seven years and to involve 100,000 pulses with DT plasmas. The Soviets calculated that each DT pulse would produce 10^{20} neutrons. The original T-20 design required ohmic heating plus 50 MW of auxiliary heating to reach the maximum plasma temperature of 10 keV. An equal amount of auxiliary heating was required to maintain that temperature. Initially, the T-20 was to have five neutral beam injectors providing a total of 60 MW of 80-keV deuterium to the plasma (total consumed power of the injectors was 190 MW)

The T-20 was designed to use normal copper magnets—a total of 2,100 metric tons (hereafter referred to simply as tons) of copper. T-20 was also to have 24 toroidal-field magnets requiring a peak power of 1,200 MW and weighing 3,500 tons. The Soviets calculated that the T-20 would require a peak power of about 1,500 MW and would use five times 10^{10} joules per pulse. The Soviets considered the use of five flywheels (total of 11,000 tons) to store over 10^{11} joules [redacted]

During 1977-78, when the Soviets were developing designs for the T-20 and a modified T-10m, they had also begun to consider, at IAE and the Yefremov Institute, the development of an "experimental-industrial hybrid thermonuclear electric power plant." Some of the initial parameters of this hybrid are compared with those of the T-20 designs in table 3. This hybrid was to be a DT-burning tokamak that would produce 2,000 MW (electrical) and 4,000 kg of fissile fuel per year. It was to use superconducting magnets and neutral beam injectors [redacted]

T-15

Soviet design activities that developed into the T-15 began in 1976, when the Soviets considered a new, superconducting version of the T-10 known as T-10M. By 1980, the T-10M had become the T-15, and subsequently the T-15 became the center of attention for the Soviet tokamak program. The Soviets projected in 1980 that the T-15 would begin operation in 1984 [redacted]

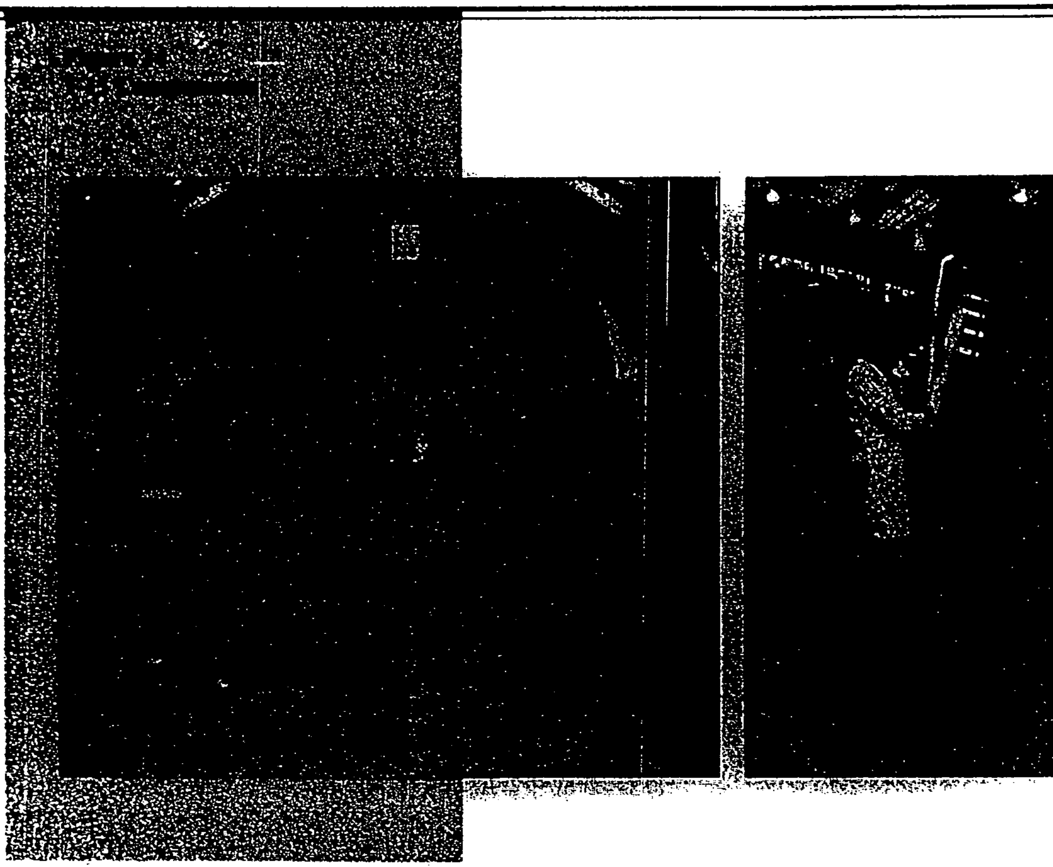
In early 198[redacted] it was extremely important that the T-15 be completed by December 1988. [redacted] other tokamak experiments were being delayed or discontinued to allow maximum effort on the T-15. During the morning of 23 December 1988, the Soviets brought the T-15 into what they called "operational status." [redacted]

The Soviets probably will not be able to conduct any meaningful experiments on T-15 before 1991, and the device may not be fully operational before 1993. When the T-15 was "started up" in December 1988, the superconducting magnets were energized (toroidal field was 0.1 tesla), and a very low plasma current was created. After being optimistic about the future operations of T-15 in early 1989, the Soviets shut it down in the summer of 1989 because of problems with the cryogenic system for the superconducting magnets. In December 1989, startup experiments were begun. [redacted] the T-15 was to be shut down for a year in March 1990 to install auxiliary heating systems (9 MW of 80-keV neutral beams and 10 MW of ECRH at 83 GHz). Few pieces of diagnostic equipment were operational in late May 1989, even though [redacted] that the main diagnostics had been delivered by mid-1987.

The T-15 superconducting toroidal-field magnets were fabricated at the Yefremov Institute. Testing in early 1986 revealed problems that led to some redesign of the magnets. There are indications that the brittleness of the niobium-tin superconductor continues to cause the Soviets problems. These magnets apparently were too complicated for Soviet construction capabilities when they were ordered, and reportedly the Soviets spent two years looking for a manufacturer. Only limited worldwide experience in using the niobium-tin superconductor in large magnets exist [redacted]

Although major delays in the construction of the T-15 were caused by magnet problems, the project was also slowed by other problems. Poor quality control led to interfacing problems during construction; often retrofitting was required [redacted].

The T-15 (see table 1 and figures 2 and 14) is 11 meters in diameter, 6 meters high, and weighs 1,500 tons. The T-15's torus has 12 sectors, each consisting of two superconducting magnets and a vacuum vessel module. The toroidal-field magnets weigh 300 tons and store up to 370 megajoules of energy. In July 1988, the cost of the T-15 facility was given as 320 million rubles; in December 1989, the Soviets gave the capital construction costs as 187 million rubles. [redacted]



The T-15 will operate with a hydrogen plasma; no provisions have been made for the use of deuterium or tritium. After an initial period of ohmic heating experiments, ECRH and neutral beams will be used to heat the plasma to higher temperature [redacted]

In October 1988, the Soviets planned to conduct the T-15 experimental program in two phases. The machine parameters for the first phase are those given in table 1. During the second phase, should it occur, the toroidal magnetic field, plasma current, and auxiliary heating would be increased by 30 to 50 percent [redacted]

The T-15 control room was built and equipped by the Hungarians. [redacted] the control room contains a US PDP-11/70 computer, a Hungarian copy of the same computer, and about 13 Hungarian copies of the US PDP-11/34. These computers will be used to monitor and control the superconducting magnets, neutral beam injectors, ECRH gyrotrons, diagnostics, and the plasma. The computers also will be used to collect and analyze data. Most of this electronic equipment has been in place and collecting dust for several years. [redacted]

TSP

In June 1981, the Soviets presented a conference paper on the design of a tokamak incorporating two-stage plasma compression. An article, coauthored by E. A. Azizov, Ye. P. Velikhov, B. B. Kadomtsev, V. D. Pismennyy, V. A. Chuyanov, and others, was published in February 1982. This tokamak (see figures 3 and 15) became known as the T-14, and in 1987 the Soviets started calling it the TSP (tokamak with strong field). Chuyanov, the head of the TSP project during construction, was replaced by Azizov in February 1989

[redacted], the TSP concept arose in about 1978 as an idea by Velikhov and Pismennyy for combining fusion and pulsed power. Pismennyy, director of the IAE branch in Troitsk, indicated in late 1988 that he had obtained a large funding for the TSP project in order to provide for future large-scale pulsed power work. He has expressed interest in using the pulsed power system of the TSP complex to drive a large laser fusion facility [redacted] the TSP complex, including housing and schools, cost the equivalent of $300 million and the tokamak cost the equivalent of $16 million. In September 1988, [redacted] there was a total TSP staff of 350, including 150 researchers [redacted]

The first solid pieces of information on the TSP were obtained when a Soviet delegation, headed by Chuyanov, visited the United States in December 1986 to discuss compact ignition tokamaks [redacted]

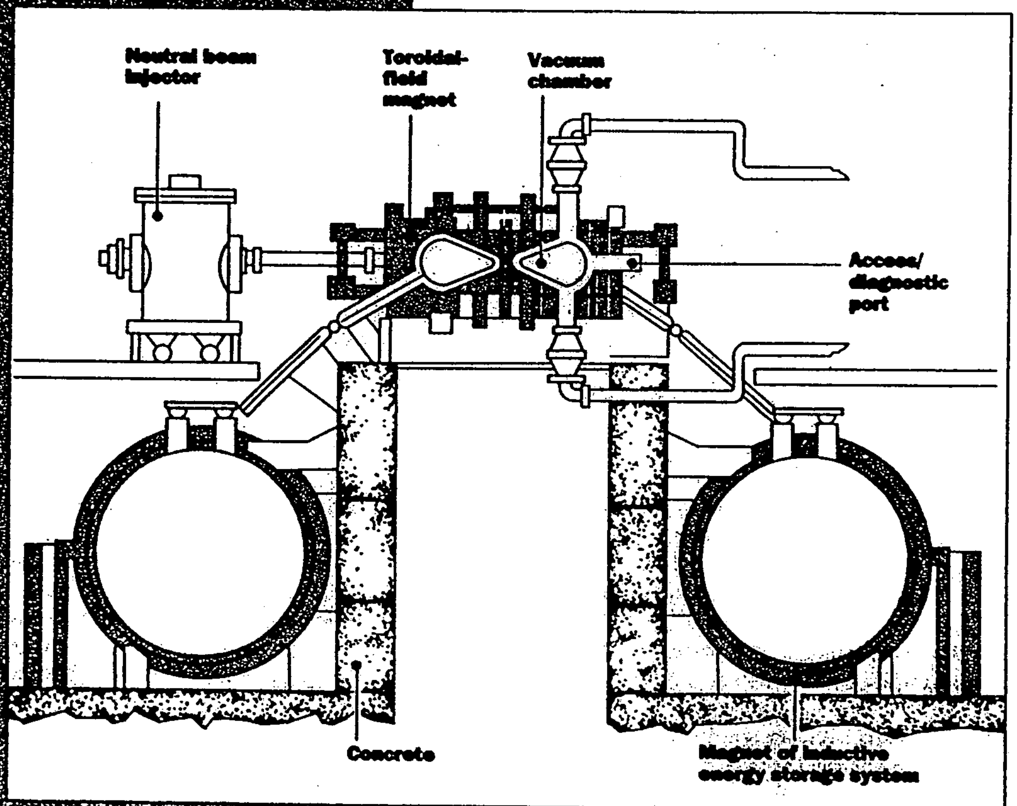
[redacted] In October 1987, Velikhov and Kadomtsev escorted a tour of these facilities; numerous visits have occurred since that time.

[redacted]

The Soviets are modifying four standard industrial TKD-200 generators for use in the TSP flywheel motor-generator sets. The steel cylindrical flywheels for the sets, which are about 10 meters long and weigh over 80 tons, each store over 1 gigajoule (GJ) of energy. Only two sets have been installed thus far, and the motors on these apparently began causing vibration problems in 1987. During the latter half of 1988, the Soviets replaced the motors. In December 1989, only one generator was operational. It is no longer clear when, or if, the last two flywheel motor-generator sets will be installed [redacted]

The TSP tokamak (see table 1) sits atop the support column for a 1-GJ inductive energy store consisting of 32 separate magnets (see figures 15, 18, and 19). The store has a radius of about 4 meters, and the magnets are designed to operate at about 5 teslas. The inductive energy store has been completed but not yet tested at full capacity. The local electrical utility cannot yet provide enough electrical power to the TSP complex. The bare tokamak was manufactured by the Yefremov Institute and the Kirov "Electrosila" Electrical Machines Production Association and was transported to Troitsk in two pieces. The vacuum vessel consists of 16 sectors, each including two toroidal-field magnets and a large port. The large ports will be used for auxiliary heating equipment, and the more numerous small ports will be used for diagnostic equipment. The toroidal-field magnets consist of a single-turn, copper-zirconium-bronze alloy encased in an external stainless steel structure. [redacted]

The first plasma in TSP was created [redacted] 1987, but the machine operated under very limited parameters (plasma current of 30 kiloamperes [kA], magnetic field of 1.5 teslas, and duration of 30 milliseconds). A capacitor bank was used to energize the magnets during this test. Following this initial operation, the tokamak was removed from atop the inductive energy store and dismantled. The gasket seals between the vacuum vessel sectors were replaced by welds, and diagnostics were added. The plasma current had been raised to 140 kA by November 1989, and there were plans to go to 300 and 500 kA. In


Neutral beam injector
Toroidal-field magnet
Vacuum chamber
Access/diagnostic port
Concrete
Magnet of inductive energy storage system

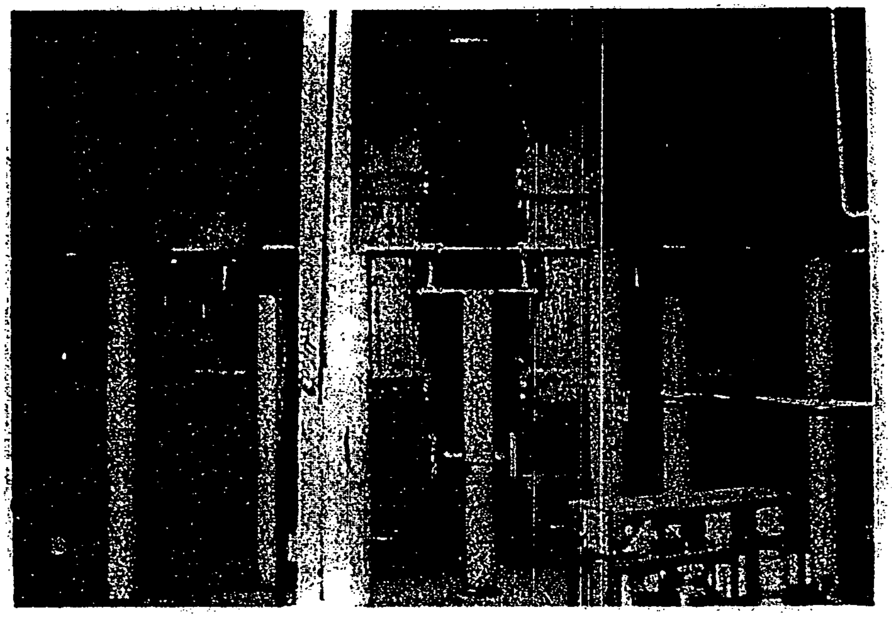


Figure 18. TSP Inductive Stor

December 1989, the Soviets admitted to still having difficulty controlling the vertical stability of the plasma. They envisioned only short operating periods with limited machine parameters for the period 1990-91.

The TSP was designed as a two-stage compression device. The idea was to create a plasma, heat it, compress it in the direction of the minor radius, and then compress it in the direction of the major radius. During these operations, the toroidal magnetic field would increase from 2 to 13 teslas on axis (23 teslas at the magnet), and the plasma volume would decrease by a factor of almost 20. Preheating would be accomplished using ohmic heating, neutral beam injection, ECRH, and ICRH. The plasma is expected to remain in the compressed state for about 25 milliseconds. We believe that the experimental program will start with ohmic heating of a hydrogen plasma and then use auxiliary heating to raise the plasma temperature. If these phases are successful, the Soviets will attempt compression experiments. It appears unlikely that tritium will be introduced into the TSP; it is unclear whether deuterium will be used. Controversy continues, both inside and outside the USSR, over whether the complexities of TSP operation are fully understood. (As late as November 1989, the Soviets were discussing ways to get the Compact Ignition Torus built in either the United States or the USSR. This interest probably is an indication of the poor performance many expect from the TSP.

We assess that the Soviets have not adequately addressed the problems associated with using tritium. [redacted] extensive shielding had been built into the TSP building to shield against radiation produced when tritium is introduced. The walls are borated concrete, nearly 3 meters thick, and the door is almost 2 meters thick. [redacted] building is designed so that, when tritium is in use, the building can be heated to 200 degrees Celsius in order to reduce the air pressure by 50 to 100 millitorr [redacted] building is maintained as a contained system, with the option of

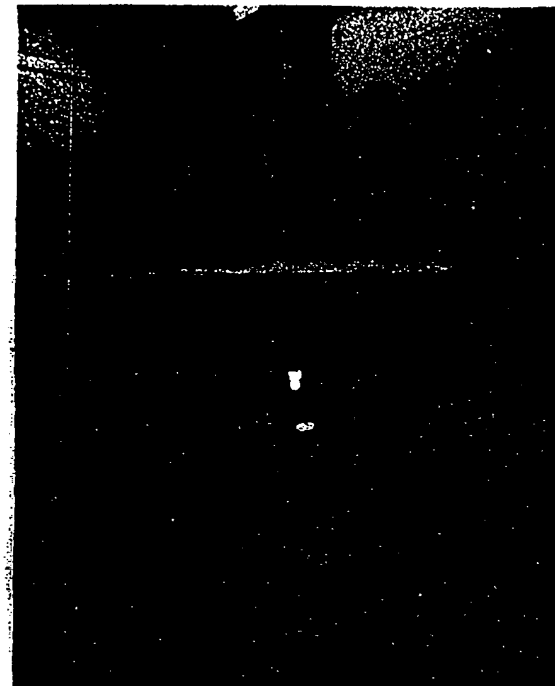


Figure 19. Base for the TSP Tokamak

Table 4
Evolution of the OTR's Design Parameters

	1984	1987
Major plasma radius *(meters)*	5.5	6.3
Minor plasma radius *(meters)*	1.1	1.5
Plasma current *(megamperes)*	5.1	8
Toroidal magnetic field on axis *(teslas)*	6.0	5.8
Fusion power *(megawatts)*	490	500
Burn time *(seconds)*	600	600
Auxiliary heating power *(megawatts)*	50-60	
ICRH		80
ECRH		10
Lower hybrid current drive *(megawatts)*		10
Tritium breeding ratio	1.05	1.05-1.2
Tritium consumption *(kg/yr)*	19	15
Plutonium breeding ratio *(atoms per fusion neutron)*		0.67
Plutonium production *(kg/yr)*	150	

venting the building to the outside. Azizov said that his group had a contract with the Yefremov Institute to design handling systems consistent with tritium use. Past Soviet schedules have called for three years of conditioning and experimentation before tritium is introduced into the TSP. In 1987, Chuyanov expected to produce 10^{17} to 10^{18} neutrons per shot with tritium and to conduct 100 to 1,000 tritium shots. As of late 1988, Soviet plans called for an inventory of 30,000 curies (that is, 3 grams) of tritium and the presence of 3,000 curies of tritium in the vacuum chamber during a shot. In December 1989, the Soviets had unrealistic plans to limit the tritium inventory to 1,000 curies (this value is very low).

Little is known about the diagnostics the Soviets intend to use during TSP experiments. Equipment that has been mentioned includes magnetic probes, infrared cameras, a Thomson scattering apparatus, neutron detectors, bolometers, X-ray spectrometers, particle spectrometers, and an electron-cyclotron-emission apparatus. (In July 1989, most of the diagnostic equipment was still in boxes.) As part of the US-USSR exchange agreements, a US optical-fiber-coupled Doppler spectrometer is scheduled to be installed on the TSP. The small T-11 tokamak has been moved to Troitsk to serve as a diagnostic test bed for the TSI

Reportedly, the diagnostic instruments on the TSP are electrically isolated from the control room by fiber-optic breaks. Many of the diagnostic packages are connected to dedicated IBM-AT clones made in the Soviet Bloc. When their data acquisition system is fully developed, the Soviets expect it to total 20 megabytes per shot

Soviet OTR/ITER Organization

At a US-Soviet exchange meeting in May 1989, the Soviets presented a paper on their organization for work on the ITER. The following is a summary of that paper.

The USSR State Committee for the Utilization of Atomic Energy (GKAE) exercises overall control of ITER work. Also involved in this work are the USSR Academy of Sciences, ministries of industry, and the State Committee for Science and Technology. Work on ITER is accomplished primarily through existing cooperation agreements established to implement the national OTR project

Within the GKAE, a Directorate of Projects OTR/ITER has been created to support Soviet participation in the ITER project. Ye. P. Velikhov is director of the OTR/ITER directorate, B. B. Kadomtsev is scientific director, and V. A. Chuyanov is first assistant project director. The other Soviet member of the ITER Scientific and Technology Advisory Council (Kadomtsev and Chuyanov are also members), A. I. Krylov, is assistant project director for design. Y. A. Sokolov, Soviet member of the ITER Management Committee, is an assistant project directo

More than 30 specialists devote all their time to ITER work. The total number of specialists involved in project work is greater than 100, with an equal number of specialists conducting R&D. Five research institutes carry out the basic work on the ITER project. They receive assistance from over 30 research and industrial organization

The five lead organizations and their areas of research are:

- *Institute of Atomic Energy* imeni *I. V. Kurchatov (IAE), Moscow—overall coordination of work on ITER, fundamental studies of plasma physics, experimental and theoretical studies of plasma physics in tokamaks, and R&D on heating and current drive systems.*
- *The Yefremov Institute, Leningrad—design and development of basic engineering systems, design and research of superconducting magnet systems, and solid-fuel pellets for fusion.*
- *Research Design Institute of Power Engineering, Moscow—design and development of nuclear technology systems, design and research of tritium-producing blankets, and development of structural materials for the first wall and for divertor plates.*
- *Inorganic Materials Scientific Research Institute, Moscow—tritium systems and materials.*
- *Research Design Institute of Power Engineering, Leningrad—general engineering systems, layout of overall reactor facilities (construction, site selection, and construction approva*

OTR

The Soviet OTR (experimental thermonuclear reactor), whose design was undertaken in 1983, is a modernized and revised version of the T-20. In 1984, Kadomtsev listed the objectives of the OTR program as:

- Demonstrate feasibility of reliably and safely producing electricity and fissile fuel in a fusion (that is, hybrid) reactor.
- Gain experience with a tokamak reactor having parameters typical of a power reactor.
- Provide an experimental station for scientific and engineering studies.
- Test materials for use in a fusion power plant.

Some of the design parameters for OTR presented by Kadomtsev in 1984, as well as those discussed by the Soviets during July 1987, are presented in table 4.

Design parameters discussed by the Soviets in October 1988 were essentially the same as those discussed in 1987.

The OTR has been the long-range focus of the Soviet MCF program. In mid-1986, funding for the design effort had been approved through 1990 and the equivalent of 60 full-time people was devoted to the effort. At the end of 1986, about 90 researchers from IAE and the Yefremov Institute, as well as 40 from other institutes, were working on OTR and INTOR. A larger contingent is now working on the OTR and the ITER, with the major effort being devoted to the ITER program (see inset on page 43). As long as the Soviets remain participants in ITER, we believe they will devote practically all their efforts to ITER R&D.

The OTR originally was designed as a fusion-fission hybrid reactor; the OTR was a bridge between pure fission and pure fusion. In mid-1987, the Soviets began to stress the flexibility and diversity of the OTR vis-a-vis its hybrid nature. As of April 1988, the Soviets were considering two blanket modules (of a total of 12) for the demonstration of fissile fuel breeding

The present OTR design calls for a 70,000-ton device with niobium-tin superconducting toroidal-field magnets. The total magnetic system would weigh 12,000 tons and store 54 GJ. It would have a tritium inventory of 5 to 7 kg and use pellet injection for refueling. The design calls for tritium self-sufficiency (15 kg of tritium would be consumed each year) and specifies lithium-lead eutectic (a solid alloy) as the primary candidate for the breeding materia'

As of April 1988, construction of OTR was planned for the years 2000 to 2005. The Soviets envisioned a 13-year, three-phase experimental program:

- Three years of hydrogen operation and a few DT tests.
- Three years of DT operation.
- Seven years of DT operation to demonstrate the production of electricity and fissile fuel

Appendix D

Stellarators

A stellarator is a toroidal magnetic confinement device (see figure 7) in which plasma confinement is achieved by generating closed toroidal magnetic surfaces, much like those appearing in a tokamak. Unlike the tokamak, however, stellarators generate their confining surfaces entirely by means of currents flowing in external magnets

To compensate for outward drifts and to provide equilibrium in a torus, it is necessary to generate closed magnetic surfaces (that is, to keep the magnetic field lines from closing on themselves after one pass around the torus). This can be accomplished by introducing a twist in the direction of the poloidal magnetic field. Tokamaks provide the necessary twisting of the magnetic field lines by passing a current in the toroidal direction through the plasma. In stellarators, the twist is provided by deforming the torus itself or utilizing a set of twisted helical magnets.

A stellarator, especially when it uses ohmic heating, can be made to look much like a tokamak. Much of the plasma physics derived from stellarator experiments can be applied to tokamak studies. However, the stellarator also has properties that make it quite different from a tokamak. One of the most obvious is that the stellarator does not depend on a large plasma current for its confining magnetic fields. This feature eliminates some large electrical equipment and plasma instabilities, as well as making the stellarator an inherently steady-state device

During the late 1960s, when tokamaks were achieving prominence, experimental and theoretical research on stellarators was painting a gloomy picture for the future. For the next decade, stellarator research, especially in the United States, went into decline as tokamak research underwent a significant increase. By the early 1980s, stellarator research had turned the corner, and the stellarator was recognized to have confinement properties that rivaled or surpassed those of tokamaks with a similar size. By this time, however, tokamaks were much larger and received the lion's share of the fusion budget worldwide

Soviet stellarator research began in the early 1960s. A continual program of machine construction and physics experiments has been conducted at the Khar'kov Physical Technical Institute. The stellarator program at the Institute of General Physics has been in a state of decline since the death of its leader, M. S. Rabinovich, in 1982

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Appendix E

Open Traps

Background

Magnetic confinement fusion approaches can be divided into two types. One is the toroidal or "closed" type (tokamak and stellarator), in which magnetic lines remain within the plasma volume. The other is the linear or "open" type, in which field lines escape out of the ends. In the open type of device, the plasma also escapes unless the ends are "plugged" by some means. The most successful means of end-plugging has been the magnetic mirror. (The magnetic mirror concept was suggested in the early 1950s independently by the Soviet G. I. Budker and the American R. F. Post.)

The magnetic mirror effect occurs because charged particles spiraling along magnetic field lines tend to be reflected by a region of stronger field. This mirror effect can be used to plug the ends of a linear magnetic fusion device (see figure 8). The simplest device using the mirror effect is the "simple" mirror—a linear device with high-magnetic-field circular choke coils at both ends. Curvature of the magnetic field lines in the simple mirror causes this device to be unstable, even at low plasma densities

The magnetic-well (minimum-B field) mirror geometry was developed to overcome the instability of the simple mirror. M. S. Ioffe (IAE) achieved this configuration in 1961 by adding current-carrying bars between the end coils. Over the years, this setup evolved into the baseball magnet (which has the shape of the seams of a baseball) and then into the Yin-Yang magnet (1969), which essentially is a combination of two baseball magnets.

By the late 1960s, mirror fusion research had arrived at a standard configuration consisting of the magnetic-well magnet design and neutral beams to create and maintain the plasma. However, the leakage of the plasma through the end plugs made this mirror system an unattractive candidate for a power-producing reactor. The concept of the tandem mirror machine was developed to overcome this limitation.

Although a paper on the tandem mirror geometry was published in 1967, the advantages were not appreciated until they were demonstrated by the work of G. I. Dimov (the USSR's Institute of Nuclear Physics—IYaF) and T. K. Fowler (United States) in the mid-1970s. The basic idea behind the tandem concept is that small mirror machines can serve as end plugs for a simple solenoidal central section (see figure 8)

An attraction of magnetic mirror devices has been their technical simplicity and experimental flexibility. They have been used to study turbulent heating, the interaction of electromagnetic radiation with plasma, electron beam injection, plasma stability and confinement, and other plasma physics

Soviet Program

The largest Soviet effort in open traps is carried out at the IYaF in Novosibirsk. Two experimental groups and one theoretical group are working on open traps at IYaF, for a total of about 130 people. The IYaF makes use of the large central machine shops, computer services, and other support functions of the USSR Academy of Sciences' Akademgorodok complex near Novosibirsk

Planning for the AMBAL tandem mirror device began in 1978, soon after the concept was developed at IYaF by Dimov and colleagues. Although the design and fabrication of prototypes advanced rapidly, the fabrication of the large magnets, the vacuum chamber, and power supplies took considerable time. During tests of the AMBAL device in 1984, a short occurred in one of the large quadrupole (end) magnets. In addition, power supply problems were encountered. Subsequently, tandem mirror experiments on AMBAL were abandoned, and single-cell experiments (often called AMBAL-U) were begun in 1986 using the remaining good quadrupole magnet.

The AMBAL group has continued on with the design of a follow-on experiment, the AMBAL-M. This new device will incorporate the new ideas for stability developed in the United States and the USSR. Some components for this device have been built and tested and are operational. The Soviets apparently intend to test the stability of all components before the AMBAL-M is put together. (The United States constructed a large tandem mirror, but it was never used, and support of open-trap research was discontinued.)

The Soviets have also pursued several alternative approaches to open-trap research. At the IYaF, these include rotating plasmas, multiple mirrors, and gas-dynamic traps (GDT; GDL in Russian). The rotating plasma concept uses crossed electric and magnetic fields to create a confining barrier for the rotating plasma. The multiple mirror concept, proposed by Budker and others of IYaF in 1971, is based on the idea of a slow outward flow of plasma through a system of consecutive magnetic mirrors. The idea of the GDT was developed by D. D. Ryutov and others during the early 1980s. The GDT relies on the gas-dynamic outflow of plasma at the ends of a mirror machine (long magnetic solenoid and high-field mirror end cells) to stabilize the plasma; neutral beam injectors are used to compensate for these losses

The concept for reducing end loss by multiple magnetic mirrors, spaced on the order of the particle mean free path, was developed in the United States and the USSR. The effort at the IYaF, conducted on GOL devices, couples this approach with high-current, electron-beam heating. (Both multiple mirrors and electron-beam heating have been dropped by the United States.) Testing of the GOL-3 (1-megaelectronvolt, 75-kiloampere electron beam injected into a 7-meter-long plasma) device began in 1988; apparently this device will also be used for weapons-related experiments. The Soviet effort has concentrated on electron beam heating, studying both physics and technology issues. Over the past 10 years, the level of effort on multiple mirror research has varied from six to 20 scientists.

The GDT is not a good confinement device, but it is well suited for a neutron source. The parameters of a GDT in use at the IYaF are given below:

Parameter	Design Value
Mirror-to-mirror length	7 meters
Maximum magnetic field	
Mirror section	16 teslas
Solenoid	0.2 tesla
Injection energy	20 kiloelectronvolts
Injection current	350 amperes

Rapid rotation of a plasma in a simple mirror can lead to stabilization of certain plasma disruptions. Although this concept was conceived in the early 1970s by European physicists, it was never explored as a serious fusion concept in the West. The PSP-1M rotating-plasma device was operated at the IYaF with stable rotating plasmas during 1976-79. The SVIPP-1 experiment had a smaller rotating plasma that derived its rotation from neutral beam injectors. By 1982, this experiment had demonstrated that the concept could be scaled using modest technology. The PSP-2 experiment, which began operation in 1981, is a large facility with a complicated power system for heating and rotating the plasma. Although this device failed as a plasma confinement experiment, IYaF continued to run the device for technology tests In 1988, the PSP-2 was replaced by the PSP-2M

The Institute of Atomic Energy (IAE) had an extensive magnetic mirror research program during the 1960s and 1970s. However, this effort has decreased drastically in recent years. Research on the Ogra-IV (which has a baseball-type magnet) device began in 1985. Soviet experiments emphasized the use of gyrotrons for electron cyclotron resonance heating; however, priority for this device was low and few experiments have been done. Operation of the PR-8 (4-meter central cell with a mirror field of 2 teslas) began in 1987; it will use ion cyclotron resonance heating. Activity at the IAE appears to have increased during the last two years. Open-trap research has been going on at the Khar'kov Physical Technical Institute since the 1960s; however, this work has been of low quality and has not influenced other open-trap research

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Appendix F

International Collaboration

Background

Although magnetic confinement fusion (MCF) research is now unclassified worldwide, it began as classified programs in the USSR, the United States, and the United Kingdom. The concern about MCF research revolved around the belief that, by 1960, fusion could provide a very intense source of high-energy (14-megaelectronvolt) neutrons. In April 1956, I. V. Kurchatov, director of the Institute of Atomic Energy, accompanied General Secretary Nikita Khrushchev to the United Kingdom. At his own request, Kurchatov delivered an extensive talk on the Soviet fusion program to an audience of British scientists

Extensive presentations on fusion research were presented at the 1958 Atoms for Peace conference held in Geneva. The Soviets provided a four-volume compendium of the research they had conducted during the years when fusion work was classified. In a paper prepared by L. A. Artsimovich, it was stated that "we must not underestimate the difficulties which will have to be overcome before we learn to master thermonuclear fusion" and "the problem of controlled thermonuclear fusion seems to have been created especially for the purpose of developing close cooperation between the scientists and engineers of various countries working at this problem according to a common plan." By the end of the conference, it was clear to most delegates, including those from the USSR, that the mastery of fusion was an immense task and much work was being wastefully duplicated in the programs of the United States, the United Kingdom, and the USSR. Thus began the first re[illegible] discussions of international collaboration in fusion

By the early 1960s, Artsimovich had become the "scientific supervisor" and major spokesman for the Soviet MCF program. Artsimovich was convinced of the need for international collaboration in fusion and other areas and worked toward the achievement of such collaboration. This dedication is exemplified by his involvement in the Pugwash conferences on disarmament in the 1960s.

After Artsimovich's death in the early 1970s, Ye. P. Velikhov became "scientific supervisor" and chief spokesman for the Soviet MCF program. Velikhov has been responsible for maintaining, strengthening, and expanding the bilateral cooperation agreement with the United States. In 1978 and 1985, he pushed international programs to build a large tokamak that would function as an engineering test reactor (ETR). International efforts to design such a tokamak resulted from both of Velikhov's initiatives. During the last five years, Velikhov has attained unprecedented power in the Soviet scientific, political, and military communities. Velikhov's positions have allowed him to pursue international collaboration in disarmament, education, and numerous other areas. The increased responsibilities of Velikhov during 1989 have greatly decreased the amount of effort he can devote to MCF. We believe that someone else will have to pick up the torch, especially in the international arena

Bilateral Agreements

The Soviet's most productive bilateral exchanges for fusion have been with Soviet Bloc countries and the United States. The other fusion bilaterals have not been much more than information and visit exchanges. The bilateral arrangements with the Soviet Bloc countries have been working arrangements in which the Bloc scientists were fully integrated into Soviet research programs. These arrangements have been crucial components of the Soviet fusion program. It is not clear how recent political events in Eastern Europe will affect these bilateral exchanges

US-Soviet MCF cooperation started modestly in the late 1950s but has developed into a large collaboration. Formal agreements providing for the exchange

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1973 Agreement on Peaceful Uses of Atomic Energy

In this agreement, it was stated that the aim of cooperation in the area of fusion was the development of prototype and demonstration-scale fusion reactors. Such cooperation could include theoretical, experimental, and design/construction studies at all stages up to industrial-scale operations. Possible forms that the cooperation might take were listed as:

- *Working groups for design and execution of joint projects.*
- *Joint development and construction of experiments.*
- *Joint work in national research centers.*
- *Joint seminars.*
- *Exchanges of equipment and instrumentation.*
- *Exchanges of information and specialists*

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of fusion information and scientific visits were instituted between the USSR and the United States in 1958 and 1959. A 10-year exchange program (part of the Agreement on Atomic Energy: Scientific and Technical Cooperation for Peaceful Uses, signed by President Nixon and General Secretary Brezhnev) including scientific meetings, laboratory visits, and joint projects (see inset) was agreed to in 1973. The overall agreement was renewed for five more years in 1983. In December 1989, the wording of the fusion bilateral agreement was approved by the participants at a meeting in Moscow. The new atomic energy agreement was signed at the summit meeting in June 1990

During meetings in 1986 and 1987, four thematic areas for joint planning (fusion materials research, stellarator confinement concepts, ignited plasmas, and fusion blanket development and safety) were identified. During 1987 meetings under the US-Soviet bilateral exchange, experts met to start the process of joint planning in these four areas. These initial meetings served to provide an understanding of the scope and content of the programs in both countries, to examine the key technologies of mutual interest, to list the problems to be addressed, and to prepare recommendations for the solution of these problems.

It was decided that principal attention should be paid to the analysis of stellarator reactor configurations, development of radiofrequency heating of stellarator plasmas, consideration of problems associated with fusion reactor blankets, the investigation of radiation damage to steels, and the investigation of strong thermal effects in first walls

The major scientific areas of cooperation, however, are included in a fifth thematic area—experimental and theoretical work in confinement systems. Joint R&D on topics important to the International Thermonuclear Experimental Reactor (ITER) design effort are carried out under this rubric. The size of this collaboration in the future will depend on US and Soviet participation in the next phases of ITER. If the Compact Ignition Torus (CIT) should be built, Soviet participation in the CIT project would also come under this thematic area.

Of the 14 exchange visits in the 1988 program, nine were in the first four thematic areas for joint planning and the other five were in the fifth thematic area. There were seven long-term exchanges (visits of at least three weeks). The three long-term visits to the USSR involved the use of US diagnostic equipment on the Soviet T-10 tokamak, Uragan-3 stellarator, and the gas-dynamic trap (GDT) mirror experiment. These experiments were each preceded by a one-week advance visit to plan the joint experiments. During their extended visits to the United States, the Soviets worked on the TFTR tokamak (Princeton Plasma Physics Laboratory), DIII-D tokamak (GA Technologies), and ATF stellarator (Oak Ridge National Laboratory,

Sixteen exchange visits occurred in the 1989 program; nine of these were long-term exchanges. The United States supplied support and diagnostic equipment for experiments on the GDT mirror device and the L-2 stellarator. The installation of US diagnostic equipment, such as a Doppler spectrometer, on the TSP was deferred to 1990. The Soviets conducted experiments on the TFTR, PBX (Princeton Plasma Physics

Laboratory), DIII-D, and TEXT (University of Texas, Austin) tokamaks, as well as the ATF stellarator. They provided an X-ray pulse height analysis system for experiments on the DIII-D. A workshop in the USSR evaluated the use of present-day diagnostics and the development of new diagnostic tools for the study of ignited plasmas.

At the request of the US delegation, only follow-on projects were considered for the 1990 bilateral exchange program. The program for cooperation during 1990 includes the following projects:

- Workshops on stellarator topics.
- Experiments on the ATF and installation of Soviet diagnostic equipment.
- Experiments on the TSP and installation of US diagnostic equipment.
- Experiments on the TFTR and DIII-D.
- Commissioning of the T-15.
- Experiments on the T-10.
- Workshops on environmental, safety, and economic issues; and fusion materials R&D.
- Joint R&D on topics required for the ITER international program.

Because of the joint planning implemented in recent years, many of the present exchange visits are for long periods of time and are part of long-term cooperations.

The Soviets have been satisfied with the lengthy visits of exchange scientists and have expressed interest in expanding the visits. A team of US scientists participated in a series of experiments on the AMBAL-U at the Institute of Nuclear Physics (IYaF) from June through August 1987. The United States provided the time-of-flight neutral particle analyzer used for these experiments. A series of joint experiments on the GDT and GOL-3 at IYaF were completed in 1988. These visits involved only a few US scientists. The Soviets have proposed that a group of about 15 US scientists be associated with the IYaF for work on open traps for a five-year period

As early as December 1986, V. A. Chuyanov expressed interest in Soviet participation in the CIT program. Chuyanov stated in October 1987 that after internal discussions most Soviet fusion scientists were in favor of a CIT collaboration vis-a-vis building a duplicate Soviet tokamak. At the same meeting, Velikhov stated that he supported the project because the United States and the USSR needed more experience working together

In January 1988 that the Soviets would like to play an active role in the research, design, and construction of CIT. He indicated that, even if the collaboration cost the Soviets up to $50 million, it would be better than building a duplicate tokamak that the Soviets would consider supplying motor-generators, neutron/gamma diagnostics, magnets, and studies of magnet options and divertors. In May 1988, the Soviets released a paper on an alternate concept for the CIT toroidal magnet system

At a meeting in June 1988, a proposal was drawn up to outline the possible extent of Soviet participation in a US-Soviet CIT collaboration. The Soviets would concentrate on electrical energy systems, electron cyclotron resonance heating (ECRH), and diagnostics, with work on other areas to a lesser extent. The Soviets will consider supplying generator/flywheel units with a stored energy capacity of about 7 gigajoules. They agreed to undertake the development of high-frequency (280 gigahertz), steady-state ECRH sources; they hope to demonstrate this capability by the end of 1990 and to undertake commercial manufacturing of 10- to 20-megawatt ECRH equipment within a few years. The Soviets would research divertor designs and investigate possible divertor materials. The Soviets also agreed to develop neutron, alpha particle, and gamma ray diagnostic equipment; they will propose the type of detectors to be supplied after completing their evaluation of similar diagnostics being developed for the TSP. Over 30 Soviet scientists from 13 institutes attended this June meeting.

In January 1989, Chuyanov stated that he had $200,000 to $300,000 to spend on developments for the CIT project. He noted that he also had $600,000 to spend on the development of a flywheel for the CIT power system. According to Chuyanov, the Soviets were willing to contribute up to $30 million to the CIT experimental program. Most of this contribution would be in the form of diagnostic equipment and instrumentation, with the rest being in the form of technical personnel for the program

At a US-Soviet exchange meeting in December 1989, the Soviets demonstrated some concern about the cost and value of bilateral projects. Cheverev's superior at the USSR State Committee for the Utilization of Atomic Energy, A. A. Vasil'yev, attended for the first time. Although there had been indications that the Soviets intended to suggest various new initiatives, none were proposed. During the meeting, Velikhov revealed that the Soviet Government now encouraged institutes, with their own funding, to make direct connections, without governmental control, with foreign institutions for purposes of collaboration

International Projects

INTOR

At Velikhov's initiative in 1978, the USSR proposed to the International Atomic Energy Agency (IAEA) that the major fusion programs (those of the United States, the USSR, Japan, and Euratom) join together to design, construct, and operate a large tokamak. A series of International Tokamak Reactor (INTOR) workshops under the auspices of IAEA was begun in 1979. These workshops, which were terminated in 1987, proceeded in phases, with each phase being approved by the participating governments. The delegations met in Vienna for about 10 weeks each year, but the bulk of the work was completed in home institutes. Each participant committed a total of at least 150 man-years of effort

The Soviet contributions to INTOR were the most comprehensive documentation of Soviet capabilities in fusion reactor design activities available before 1988. These contributions were of good quality and contained several examples of incisive physical insight; they also reflected a limited capability for detailed computations. The Soviets were very serious about this effort from the beginning. The chief of the delegation, B. B. Kadomtsev, was a prominent fusion scientist dedicated to developing a truly cooperative effort. When INTOR was launched, the Soviets assigned their T-20 design team to it. They maintained a delegation of competent and prominent scientists and engineers throughout the project

ITER

Before the US-Soviet summit in Geneva in November 1985, Moscow proposed that the two governments jointly sponsor a multilateral project to design, build, and operate a fusion ETR. At the conclusion of the summit, a joint statement was issued emphasizing the importance of fusion and calling for extensive international cooperation. Subsequent discussions bogged down because of Soviet insistence on a commitment to construct the ETR and the concerns of the United States and its allies (Euratom and Japan) about technology transfer

After the meeting between President Reagan and General Secretary Gorbachev in Iceland in October 1986, the United States presented a proposal for an ETR design effort. In March 1987, a quadripartite committee met under the auspices of the IAEA for the initiation of the ITER project. The committee appointed a technical working group to develop the detailed objectives for ITER. The working group's report was approved by the quadripartite committee in October 1987 and was submitted to the participants (Euratom and the governments of the United States, the USSR, and Japan) for approval. By mid-March 1988 all four had agreed to join the ITER project

The document approved is known as the Terms of Reference (TRs) concerning Conceptual Design Activities (CDAs) for an ITER. The TRs specify the activities to be conducted, the schedule, the organizational structure, and the objectives. The CDAs, which are to be completed by the end of August 1990 and put into a final design report by mid-November 1990, are:

- To define a set of technical characteristics of the ITER.
- To carry out the design work necessary to establish its conceptual design.

Table 5
Engineering Test Reactor Designs

	INTOR	ITER	OTR
Major plasma radius *(meters)*	5	5.8	6.3
Minor plasma radius *(meters)*	1.2	2.2	1.5
Plasma current *(megamperes)*	8	22	8
Fusion power *(megawatts)*	585	1,000	500
ICRH *(megawatts)*	50	100	80

- To define future R&D needs.
- To draw up cost, manpower, and schedule estimates for the realization of such a device.
- To define the site requirements for the ITER.
- To perform a safety and environmental analysis.
- To carry out in a coordinated manner specific validating R&D work.

In table 5, some parameters developed for ITER (1988) are compared with those for INTOR (1987) and the experimental thermonuclear reactor (OTR, 1987). The ITER's organizational structure and ob-iectives are discussed in the insets on pages 55 and 56.

ITER work is done by a 40-person design team that meets in Garching, West Germany, and by research teams in the home c·untries. During 1988 and 1989 the design team worked in Garching for a total of about 12 months. A number of specialist meetings and workshops were held during the past two summer sessions and are being held during the 1990 summer session. About six months of joint work will occur during 1990. In the TRs, it was estimated that each participant would contribute R&D activities worth approximately $10 million per year, as well as 80 to 100 man-years over the period of the CDAs. These amounts have been demonstrated to be too low and have been increased voluntarily

ITER Objectives

The overall objective of the ITER program is to demonstrate the scientific and technological feasibility of fusion power. The ITER is to accomplish this by demonstrating controlled ignition and extended burn of a deuterium-tritium plasma, with steady-state operation being the ultimate objective. In accomplishing its objectives, the ITER will provide the data base in physics and technology necessary for the design and construction of a demonstration fusion power plant. In addition, the operation of ITER must demonstrate the potential for safe and environmentally acceptable operation of a power-producing fusion reactor

The ITER design is to be based on the scientific and technological data base expected to be available at the end of 1990. This design should provide the information needed to make a decision by the end of 1990 to proceed to the engineering design phase and then to the construction phase in 1995. To the extent possible, however, the design should be flexible enough to allow the introduction of advanced features and new capabilities. The ITER is to be designed to meet its programmatic, plasma physics, and technical objectives with reasonable cost

After a period of commissioning and optimization using hydrogen and deuterium plasmas, ITER operation is to be carried out in two phases: a physics phase devoted mainly to the achievement of the plasma physics objectives and a technology phase devoted to engineering objectives and the testing program. These goals result in the following machine parameters:

- *A plasma current greater than 10 megamperes, possibly over 20 MA.*
- *An average neutron wall loading of about 1 megawatt per square meter.*
- *A useful lifetime neutron fluence of about 1 megawatt year per square meter*

ITER Organizational Structure

The CDAs are directed and managed by the ITER Council (IC) and the ITER Management Committee (IMC); the IC is advised by the ITER Scientific and Technical Advisory Council (ISTAC). The IC, which consists of two members from each party, has the responsibility for the overall direction of the CDAs and exercises overall supervision of their execution. The IMC has four members and is responsible for the execution of the CDAs within the overall directions established by the IC. The members of the IMC manage and coordinate work done in the participating countries in order to achieve a coherent and workable conceptual design; any joint R&D is done under the auspices of existing bilateral and multilateral agreements. The ISTAC, which consists of three members from each party, advises the IC on scientific and technical issues

The Soviet members of the IC are Ye. P. Velikhov and N. S. Cheverev. B. B. Kadomtsev is the ISTAC chairman; the other Soviet members are V. A. Chuyanov and A. I. Krylov. The Soviet IMC member, Y. A. Sokolov, is the overall manager for Soviet ITER R&D.

The CDA organizational structure for design activities has two basic functions:
- *A coordinating function carried out by project units.*
- *A detailed design function carried out by design units.* (U)

The project units and design units report to the IMC. Four project units were created:
- *Physics.*
- *Basic device engineering.*
- *Nuclear engineering.*
- *System analysis.*

Eight design units were created:
- *Magnet.*
- *Poloidal field system.*
- *Containment structures.*
- *Plasma facing component.*
- *Blanket.*
- *Heating and current drive systems.*
- *Fueling and exhaust systems.*
- *Assembly and maintenance system.*

G. Shatalov is chairman of the project unit on nuclear engineering, V. Muratov is the leader of the design unit on containment structures, and V. Vdovin is the leader of the design unit on heating and current drive system:

The CDAs will be completed in a definition phase and a design phase. During the first phase, a preliminary reactor configuration was developed and the needed R&D was identified and assigned. This phase was completed during the 1988 summer session, and its report was approved by the ITER Council (IC) in November 1988. During the second phase, the design team is developing a conceptual machine design; performing a safety and environmental analysis; defining future R&D needs; developing site requirements; and estimating cost, manpower, and time schedules. The final conceptual design report is due at the end of 1990. An interim conceptual design report has been completed and was published in January 1990

Following its meeting in late November 1989, the IC issued a letter to the governments of the participants. Realizing that progress has been excellent and that any work beyond 1990 must await formal governmental decisions, the IC suggested that the parties should each decide before April 1990 if they want to enter into nonbinding discussions about a five-year, follow-on engineering design phase. The Soviets preferred to proceed directly to negotiations, while the other parties wished to begin with discussions

The ITER Management Committee has made preliminary estimates of the costs of continuing ITER through the construction phase:

- Engineering design phase, five years.
- Professional man-years, 1,000.
- R&D costs, $500 million.
- Construction, $4.9 billion

(REVERSE BLANK)