1951

GREAT EXPECTATIONS (1951-1958)
Defining basic confinement concepts

RUDE AWAKENING (1959-1963)
Solving magnetohydrodynamic instabilities

DISILLUSIONMENT (1964-1969)
Microinstabilities appear that will remain troublesome through at least 1976.

DISCOVERY (1970-1972)
Tokamaks are found to make the best "magnetic bottles"

RENEWED PROMISE (1973-1977)
New experiments, particularly with tokamaks, advance confinement prospects faster than expected.

PAY DIRT (1978-?)
First significant production of fusion energy, expected in Tokamak Fusion Test Reactor in early 1980s, could lead to inexhaustible supply of electricity.

2000

EXPLORING MAGNETIC FUSION ENERGY

Research Around the World

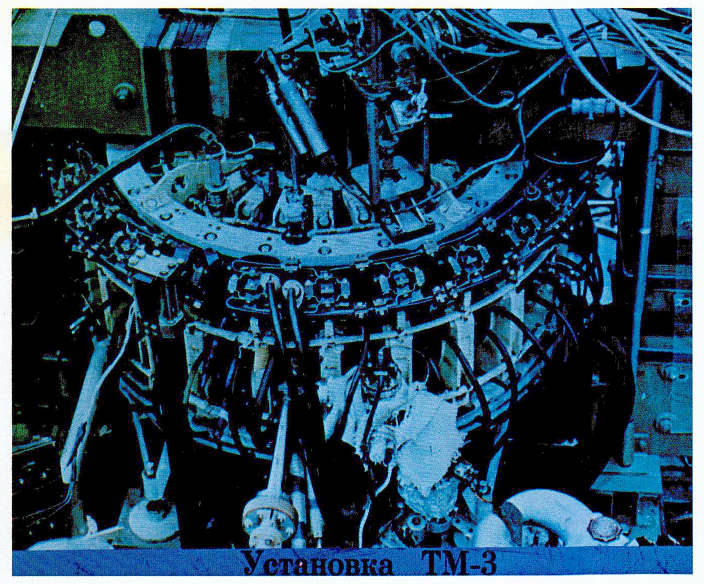
Two months after U.S. explodes first hydrogen bomb at Eniwetok, U.S. Atomic Energy Commission (AEC) considers proposal by Princeton University physicist Lyman Spitzer Jr. for controlled thermonuclear research (CTR) in **Stellarator** device (see PPPL, below) for peaceful production of power. Eniwetok test has proven man can control deuterium-tritium fusion for practical purposes. Government, which has been spending $500,000 annually on CTR since 1951, doubles amount in 1953.

AEC starts declassifying U.S. program, arranges to exchange classified fusion research data with Britain. Further declassification occurs after Soviet scientist I.V. Kurchatov presents fusion paper in Harwell, England; AEC concludes no information of military significance has been developed or is likely in foreseeable future. English physicist J.D. Lawson publishes criteria showing that the denser the plasma, the less time the fusion temperature need be sustained.

★ **If plasma is 100,000 times denser than air, proper temperature need be held for only about one-thousandth of a second.**

General Atomic Division of General Dynamics Corp. begins privately financed CTR in conjunction with Texas Atomic Energy Research Foundation.

SOVIET TM-3



AEC now is funding magnetic fusion research by LASL, LLL, LBL, PPPL, and ORNL at about $29 million per year.

Throughout mid-1960s, Soviets liberally describe their experiments with "tokamaks," Russian for "current and magnet chambers" (see PPPL, below), but U.S. scientists remain skeptical.

Soviet academician Lev Artsimovich lectures at Massachusetts Institute of Technology on Soviet tokamak experiments. U.S. scientists conclude Soviet tokamak results, if valid, represent best combination of fusion plasma density, temperature, and confinement time (possibly leading to commercial reactor) achieved anywhere in world — recommend that U.S. immediately start tokamak research.

AEC approves fabrication of tokamak at ORNL (see below) and conversion of PPPL **Stellarator** to tokamak.

U.S. spending on magnetic fusion exceeds $34 million annually. Specialists visit Soviet tokamak laboratories in line with U.S.-U.S.S.R. agreement on peaceful uses of atomic energy. Visiting British research team verifies significant progress. One of four Soviet tokamaks has reached:

★ **Four million °C,**
★ **20-millisecond confinement time,**
★ **Density of 3 x 10^{13} ions per cm^3.**

Direct Current Octopole device at General Atomic (San Diego) gives excellent confinement results; firm also begins research with **Doublet-II**, double tokamak confining plasma in chamber with kidney-shaped cross-section.

In 1969, Soviet tokamak **TM-3** maintains tens of millions degrees for 1/100th of second.

Doublet-II demonstrates stable confinement of plasma.

Russia completes **T-10** tokamak. U.S. Energy Research and Development Agency (ERDA) replaces AEC in January 1975. MIT's **Alcator** tokamak operates with:

★ **Density range from 2 x 10^{12} to 6 x 10^{14} particles per cm^3, with toroidal magnetic fields up to 75 kilogauss.**

Annual U.S. spending on fusion research now exceeds $56 million. Work begins on **Doublet-III**, slated to start up in 1978 at estimated cost of $26 million, and **Impurity Study Experiment** (ISX). Energy crisis influences increase in funding of ERDA's magnetic fusion division from $39.1 million to $304.2 million.

French achieve milestone:

★ **Fontenay-aux-Roses tokamak (TFR) operates at highest plasma current (400 kA or 400,000 amperes) known in world.**

TFR and Russia's T-10 tokamak will study plasma confinement questions similar to those put to Princeton Large Torus.

Princeton Plasma Physics Lab gets go-ahead for design and construction of Tokamak Fusion Test Reactor (TFTR).

Experiments to divert plasma impurities are planned for **PDX** (U.S.), **DITE** (England), **DIVA** (Japan), **T-12** (U.S.S.R), and **ASDEX** (W. Germany). Dedicated plasma wall or impurity control tests also are planned for ISX (U.S.), **TEXTOR** (W. Germany), and **TFR**.

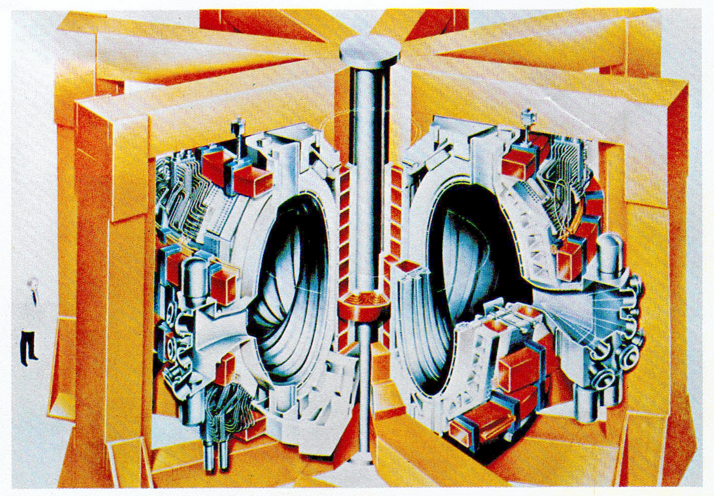
Russia begins experiments on its latest and largest **Stellarator, L-2**; its **T-7** tokamak is world's first with superconducting magnets. **Alcator** achieves world record confinement quality:

★ **Only factor of three short of breakeven (equal input and output of energy).**

By 1979, after expenditure of nearly $2 billion by ERDA's magnetic fusion division, **Alcator-C** and **Doublet-III** are expected to confirm tokamak scaling laws at reactor conditions. Japan Atomic Energy Institute is expected to complete **JT-60** tokamak, similar to PPPL's **TFTR**, which will experiment with hydrogen plasmas and may attempt neutron production with deuterium-tritium.

Japan's second tokamak, **JT-4**, probably about size of **Princeton Large Torus**, is expected to start operating in 1981. Russia's **T-12** tokamak is expected to be studying divertor action, **TM-3** electron cyclotron heating, **T-11** neutral beam heating, and **T-8** and **T-9** non-circular plasma cross-sections.

EUROPEAN JET

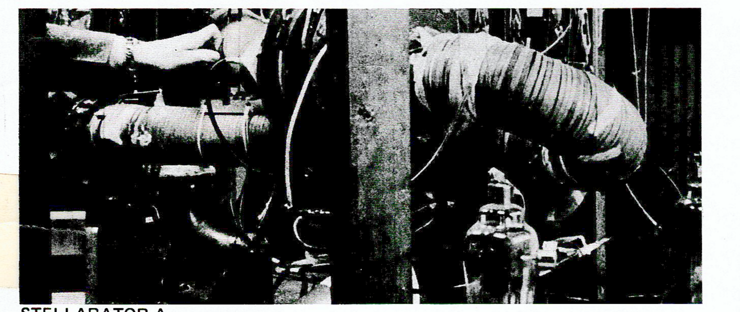


In early 1980s, production of high temperature/density plasmas is planned for **Joint European Torus** (JET), authorized by EURATOM cooperative of European countries.

Princeton Plasma Physics Laboratory (PPPL)

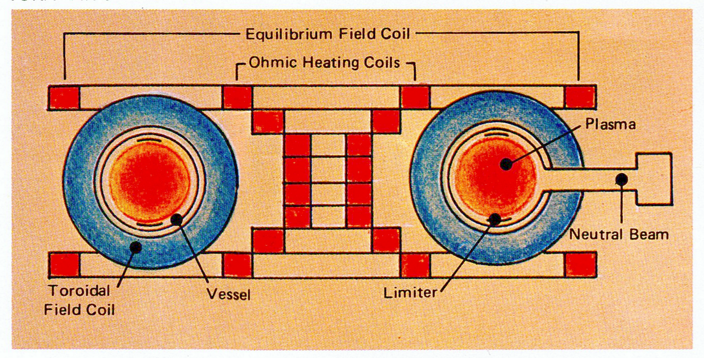
Princeton, N.J. — Tokamaks

Experimental research on fusion power begins with award of **Stellarator** study contract to Lyman Spitzer of Princeton University in 1951. (Latin word for "star" is used in expectation device will lead to same fusion reactions that heat sun and other stars.) Power will be sought from plasma created by thermonuclear reactions between deuterium and either deuterium or tritium magnetically confined in endless figure-8 tube.



STELLARATOR A

TOKAMAK OPERATION



Interchange instabilities develop and PPPL begins construction of $8.6 million **Model C Stellarator** to investigate them. Tests show confinement time increases with square of plasma's minor radius. Both spiral and transverse magnetic fields could stabilize plasma from effects of particle drifts. To limit plasma diameter and keep it from cooling by contact with container walls, metal divertor is installed; it reduces plasma impurities so much that ion-cyclotron waves or magnetic pumping can be used for ion heating.

AEC plans to complete ion-cyclotron heating tests in **Stellarator C** and then modify it to provide "minimum average B" property (plasma stabilization by improved distribution of magnetic forces). High shear investigations in **Stellarator** devices prove encouraging. PPPL builds superconducting toroidal multipole **Spherator**:

★ **First internal-ring device to achieve steady-state (nonpulsed) operation.**

Model C Stellarator is converted after only four months "down time" to tokamak, Russian-invented "current and magnetic chamber." First U.S. device is termed **"Symmetric Tokamak"** (ST), uses **Stellarator** parts, and studies radio-frequency heating of plasma. It produces doughnut-shaped plasma with temperature of 20 million °C, a small fraction of theoretical ignition (self-sustaining) temperature.

To scale up experimental designs of pioneering ST, construction is begun on **Princeton Large Torus** (PLT), $14 million tokamak with triple the toroidal diameter.

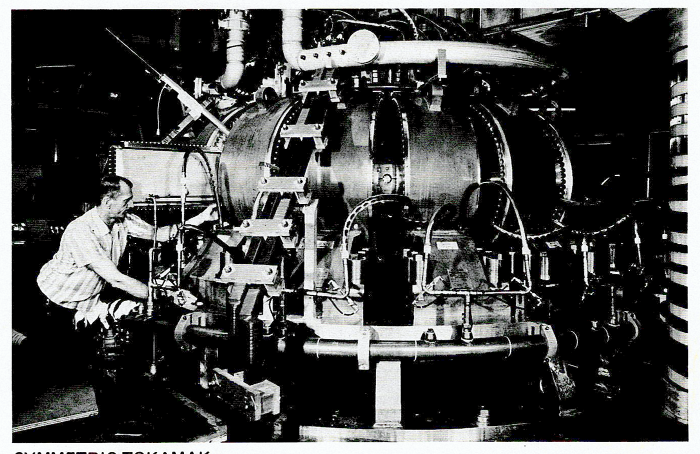
Planned PLT tests with neutral beam heating in 1978 are expected to yield results of major importance to future of tokamak fusion power reactors.

Considerable gains are made with $1.3-million **Adiabatic Toroidal Compressor** (ATC):

★ **Plasma compression increases temperature three-fold;**

★ **Density increases six-fold.**

Experiments demonstrate tokamak-like systems can operate effectively without heavy copper shells used by earlier devices to stabilize hot plasma, leading then AEC Chairman James R. Schlesinger (now President Carter's chief energy administrator) to state:



SYMMETRIC TOKAMAK

★ **"The new results further brighten the prospect of realizing commercial fusion power in a tokamak confinement system."**

ATC demonstrates tokamak plasma heating by injection of neutral particle beams:

★ **Achieves 50% increase in ion temperatures and demonstrates densities needed for practical tokamak reactor.**

ST is dismantled to make room for PLT. In 1978, $14 million PLT, with ohmic and neutral beam heating, is planned to demonstrate scaling with temperature. In 1979, it will test limits of plasma toroidal beta (ratio of plasma pressure to magnetic pressure) hopefully as high as 10%. In 1979, PLT with 2.5-MW neutral beam injection heating is expected to achieve central electron temperature of about 50 million °C. So far, 30 million° has been reached without neutral beam injection.

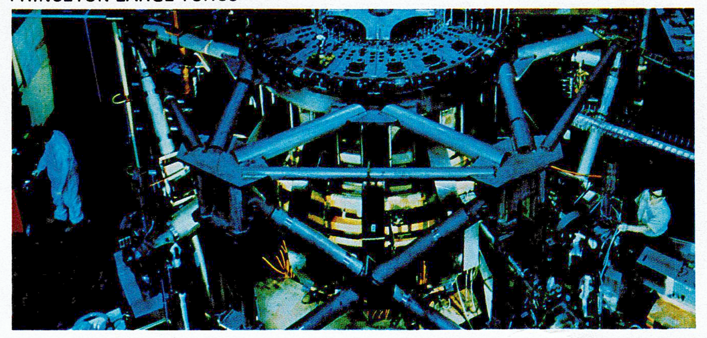
In 1975, PPPL designs largest U.S. tokamak, **Tokamak Fusion Test Reactor** (TFTR), and selects Ebasco/Grumman to do TFTR system design and installation.

Using 250-kw neutral injection power, ATC shows that plasma ion temperature continues to rise with increasing injector power.

★ **PLT achieves 600 kA, surpassing French tokamak and equaling Russian T-10 tokamak's high plasma current.**

ATC is dismantled to make room for **Poloidal Divertor Experiment** (PDX), scheduled to start up in 1978 to study effectiveness of magnetic divertors.

PRINCETON LARGE TORUS

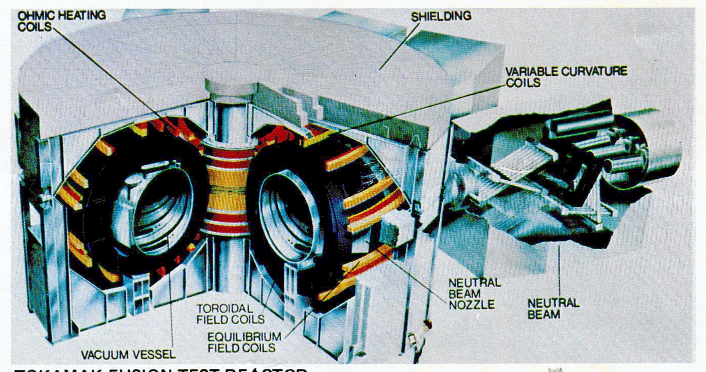


Site construction begins for the $228-million **Tokamak Fusion Test Reactor**, largest U.S. fusion project, with completion scheduled for 1981. The huge tokamak will have five-meter major and two-meter minor plasma diameters. TFTR will operate initially with hydrogen plasma.

★ **First deuterium-tritium experiments in U.S. magnetic fusion program are planned for 1982.**

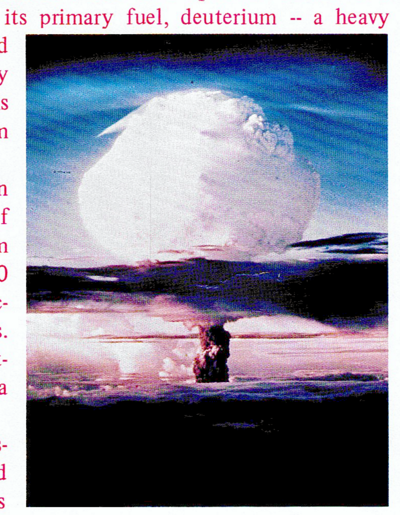
TFTR could be first machine to demonstrate proper combination of plasma confinement time, density, and temperature — conditions approximately those needed for an experimental power reactor. Another key objective is scientific **break-even**, operation at which neutral beam power input equals fusion power output.

TFTR should provide essential link between current and planned scientific machines and first experimental fusion power reactor, which might start up in early **1990s**.



TOKAMAK FUSION TEST REACTOR

Controlled thermonuclear fusion has been under study as a major energy source since the first hydrogen bomb was imploded more than 25 years ago. A fusion electric power reactor would draw upon the oceans for a cheap, almost limitless supply of its primary fuel, deuterium -- a heavy isotope of hydrogen easily separated from seawater. The most readily attainable fusion process on earth is the combination of a deuterium nucleus with one of tritium.



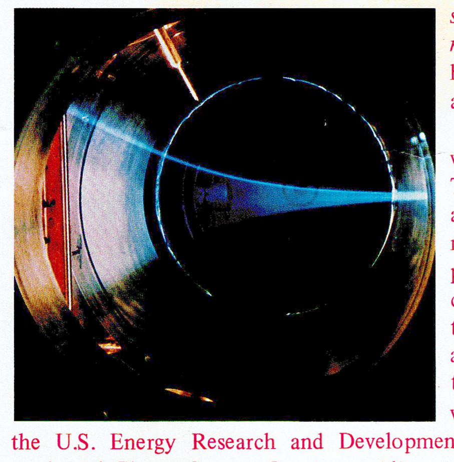
The potential for useful fusion energy is staggering. Each gallon of seawater contains enough deuterium to produce energy equivalent to 300 gallons of gasoline at an extraction cost of less than four cents. The oceans contain enough deuterium to fuel fusion reactors for a billion years.

Fused under tremendous pressure and temperature, deuterium and tritium nuclei release enormous amounts of energy -- heat for driving a turboelectric generator. The process requires sustained temperatures of 100 million degrees Celsius (180,000,000°F), about six times hotter than the center of the sun.

The problem on earth of constraining a plasma in one place long enough for fusion to occur is much different than on the sun, whose enormous mass provides the gravity for such constraint. Lacking sufficient g-force on earth, U.S. scientists have been exploring two other methods of confinement, inertial and magnetic. The inertial method uses powerful laser beams to implode tiny spheres of deuterium-tritium fuel -- "mini-H-bombs" -- each with a force of about five pounds of TNT.

The magnetic approach uses doughnut-shaped containers with strong magnetic fields to control and stabilize the volatile plasma, as well as straight tubes plugged at each end with magnetic "mirrors" to reflect the charged particles back and forth for fusion reactions. In both approaches, the challenge is to heat the fuel so rapidly that the nuclei will interact before escaping to the container walls, where cooling inhibits fusion.

Magnetic means of "bottling a star" have long received our government's strongest emphasis. Depicted in this chart are representatives of the enormous and expensive magnetic fusion research machines -- from the early *stellarators* to the latest *tokamaks* -- whose quest is for ever hotter, denser, longer-lived, and more stable plasmas.



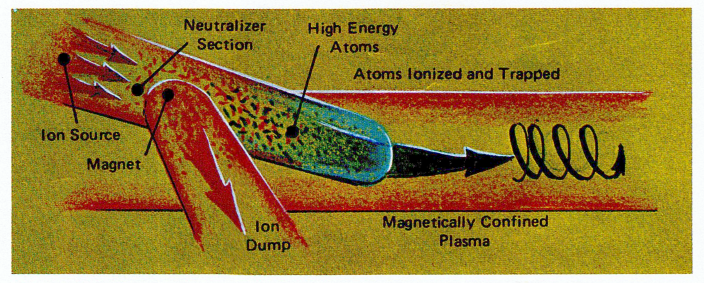
Grumman Aerospace is at work on the Tokamak Fusion Test Reactor (TFTR), largest and quite likely the first machine to demonstrate the proper combination of plasma confinement time, density, and temperature. One of the few aerospace firms in this relatively new field, Grumman won a competitive award from the U.S. Energy Research and Development Administration (ERDA) to work with Ebasco Services Inc. in providing system management, engineering, procurement, assembly, and installation services. The $228-million TFTR is scheduled for completion in mid-1981 at Princeton University's Plasma Physics Laboratory.

The huge TFTR's design goals include achieving at one time conditions required for break-even (i.e., that point at which the energy produced will equal the amount used to start the process). Scientists believe that once this milestone has been reached we will be ready to begin design of the first commercial fusion power reactor.

Oak Ridge National Laboratory (ORNL)

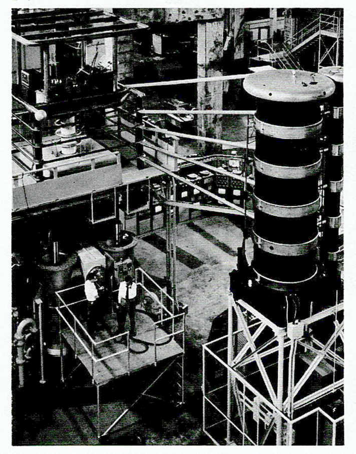
Oak Ridge, Tenn. — Tokamaks

In 1953, ORNL applies World War II experience in electromagnetic separation of uranium isotopes to design and construction of ion injector for use at Lawrence Livermore Laboratory (LLL). Studies of arc discharge in injector source lead to initial measurements of diffusion of ions across magnetic field. In addition to other Project Sherwood research, ORNL studies different heating and injection techniques for **Stellarator** and magnetic mirror types of plasma confinement.

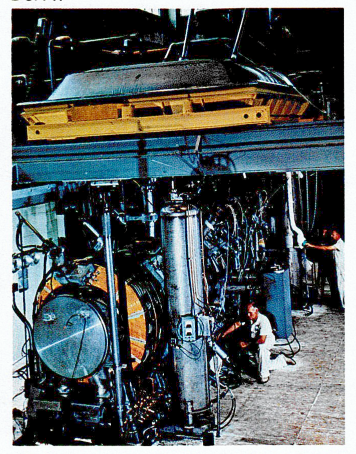


ION INJECTION

DCX



DCX-II



In **Direct Current Experiment** (DCX), molecular ions from high-voltage accelerator are injected into discharge chamber where they are dissociated and trapped in mirror field (see LLL/LBL, below). It is eventually recognized confinement properties are not adequate to support self-sustained thermonuclear reaction in DCX.

DCX-1 gives quantitative knowledge of losses of fast, trapped ions by charge exchange and instability processes and improved DCX-2 goes into operation. It demonstrates that instability of plasma must be controlled for possible mirror magnetic thermonuclear reactor.

AEC recommends ORNL emphasize development of intense ion sources and energetic plasma production, stressing neutral beam injection.

David J. Rose of Massachusetts Institute of Technology (MIT) reports "On the Feasibility of Power by Nuclear Fusion." First comprehensive treatment since Spitzer's 1954 publication, report covers fusion reactor parameters, plasma thermal balance, magnetic system scaling and efficiency, system engineering, and costs. It concludes:

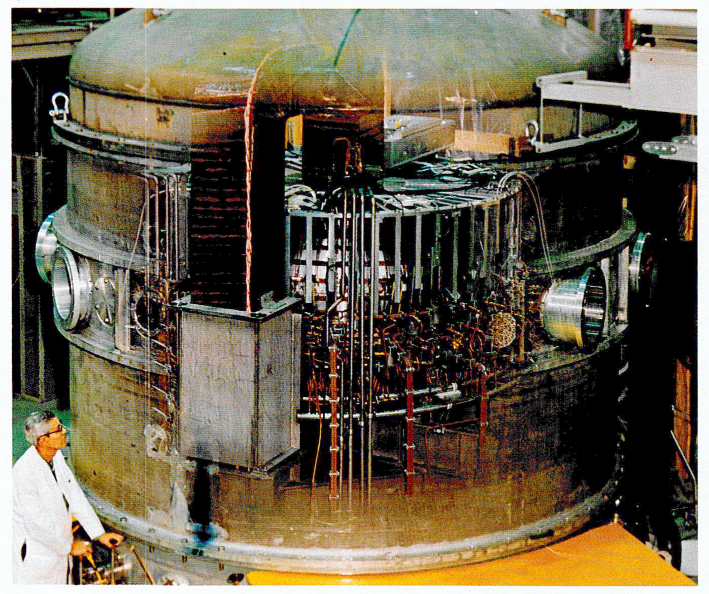
★ **Tokamak systems hold great promise as reactors.**

Levitated Toroidal Quadrupole (LTQ) uses quadrupole windings to generate special field which eliminates interchange instability. LTQ is converted to small tokamak as prototype for larger **Ormak**.

Injection Microwave Plasma (IMP) device uses advanced microwave technology in experiments that show:

★ **Plasma grossly stable but limited by steep magnetic field gradients;**
★ **Superconducting coils promise future larger devices.**

ORMAK



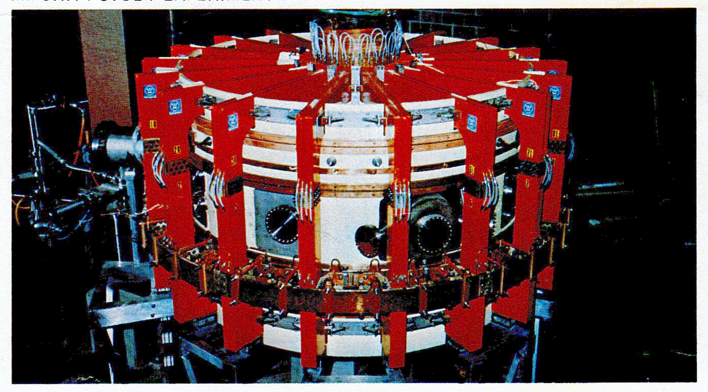
Ormak results confirm theoretically predicted confinement for tokamak scaled up in size, demonstrate neutral beam injection into plasma confined by increased magnetic fields.

The 500-kw **Ormak** shows plasma ion temperature continues to rise with increasing injector power. After achieving hotter plasma and higher plasma beta than ever before produced in U.S., **Ormak** experiment is terminated near end of its program because of overheating damage to toroidal magnets. Facilities of neutral beam test stands continues in effort to produce high ion temperature in **Princeton Large Torus** and **Impurity Study Experiment**.

Elmo Bumpy Torus device starts operating in 1973 to increase understanding of magnetohydrodynamically stable toroidal plasmas and to determine scaling of plasma parameters with frequency and power of microwave sources. Two dozen magnetic coils of hollow, water-cooled copper are equally spaced around torus.

Impurity Study Experiment (ISX) is begun in 1977 to study sputtering, particle and energy fluxes, confinement wall chemistry, and impurity control (such as gas blankets) in tokamaks. The $2.5 million device features flexibility, access, and relative ease of assembly and disassembly. New toroidal field coils are demountable and vacuum chamber can be removed vertically, permitting wall exposed to plasma to be replaced or modified conveniently.

IMPURITY STUDY EXPERIMENT



ISX-B modification will be used to study high-beta plasmas in non-circular confinement, stepping up neutral beam units operating at 40-50 keV at one megawatt to steady-state. Goals are:

★ **At least 15 keV;**
★ **Power up to 10 megawatts.**

Industrial programs are underway on superconductor wire development for **Large Coil Project** (LCP) test scheduled for 1981.

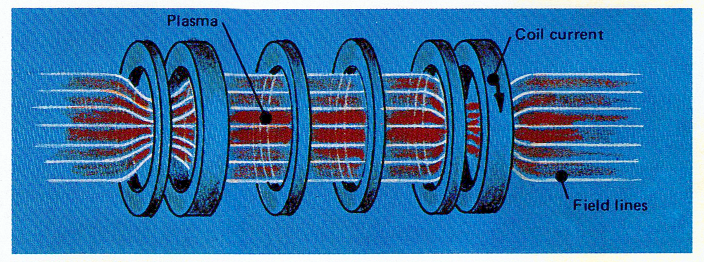
Lawrence Livermore Laboratory (LLL) and Lawrence Berkeley Laboratory (LBL)

Livermore and Berkely, Calif. — Magnetic Mirrors

AEC establishes branch of University of California Radiation Laboratory (Berkeley) at Livermore in June 1952 to work on end-stoppering of chambers with intense magnetic fields called "mirrors."

Toy Top, Table-Top, and other mirror devices demonstrate:

★ **Plasma confined by solenoid coils for many milliseconds, several hundred times longer than expected if plasma instabilities were present.**



MIRROR OPERATION

Ratio of outward plasma pressure to inward magnetic pressure (beta) is low but much higher than in such low-beta toroidal machines as **Stellarators.**

Work is begun on **Astron** machine to demonstrate whether circulating beam of relativistic electrons can establish stable electron layer that will effectively reverse magnetic field in central region. By project termination in 1973,

★ **Astron circulating currents represent 75% of field reversal requirement.**

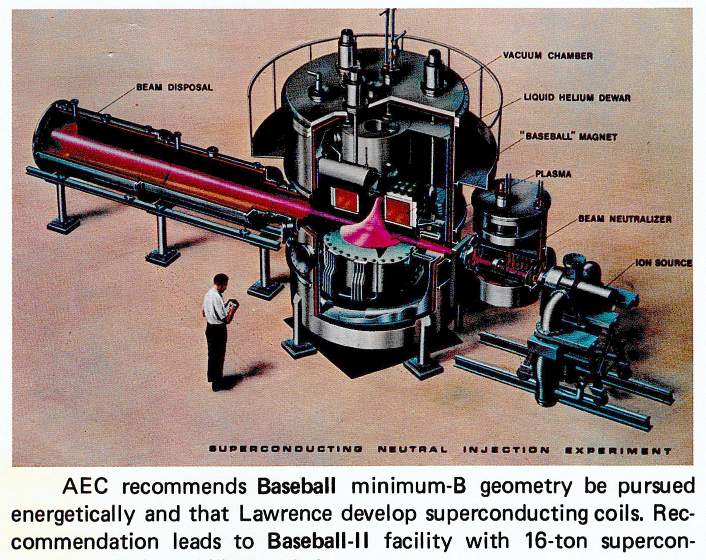
Adiabatic Low-energy Injection and Capture (Alice) device tests injection of 20 keV neutral atom beam into mirror confinement chamber.

After 12-pole positive-gradient field is added to **Alice**, gross magnetohydrodynamic (MHD) instabilities are stabilized, leading to:

★ **Ten-fold increase of peak plasma density.**

Minimum-B magnetic field technique (improved distribution of magnetic forces) demonstrates theoretical and experimental resolution of MHD instabilities in magnetic mirror confinement. Other plasma escape routes from magnetic bottles are more subtle. They result from "microinstabilities," wave motions difficult to calculate and observe, or "wave-particle" instabilities.

BASEBALL II



AEC recommends **Baseball** minimum-B geometry be pursued energetically and that Lawrence develop superconducting coils. Recommendation leads to **Baseball-II** facility with 16-ton superconducting coil shaped like baseball seam.

Levitron tests stabilizing effects of shearing magnetic field in closed tube. **Toy-Top** is extensively modified into **2X** device using magnetic-well-shaped field to try to suppress hydromagnetic instabilities, verify their existence and type, and investigate means of reducing associated losses.

After special field generated by quadrupole windings is added, **2X** operates without interchange instability. Now confinement is apparently limited only by microinstabilities.

The **2X** magnetic mirror experiment demonstrates:

★ **Plasma temperatures from 40-70 million °C;**
★ **Growing conviction that large-scale direct conversion is possible for future fusion power plants.**

Construction begins in 1973 on **2X-IIB** device, primary magnetic mirror containment experiment in open systems program, with up to 12 megawatts of neutral beam power injected into plasma:

★ **This produces 13 keV ion temperature with density-confinement time product of about 10^{11} per second per cm^3.**

In July, 1975, ERDA Administrator Robert Seamans announces 2X-IIB advances:

★ **Deuterium plasma has been confined at 120 million °C;**
★ **At same time, density has approached power reactor requirement of a few times 10^{13} ions per cm^3.**

But confinement time is only about five-thousandths of a second. Significant fusion energy may be released in follow-on mirrors, but so far they prove too "leaky" to achieve net power at reasonable cost from fusion alone.

Further **2X-IIB** advances:

★ **Confinement of nearly 10^{11} (100 billion) particles per cm^3 per second at 150 million °C (270 million °F), a record plasma temperature.**

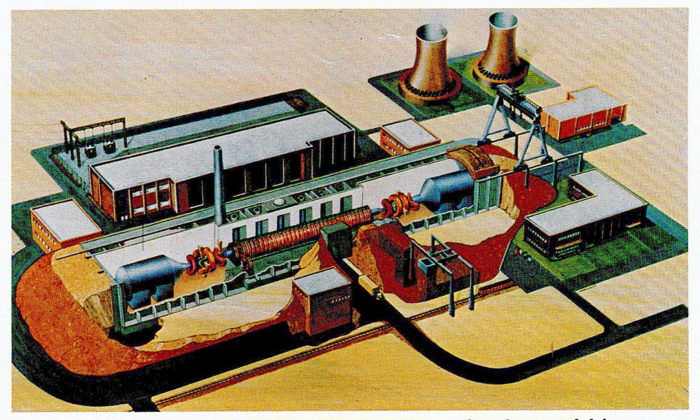
Mirror design goals are 10^{12} particles per cm^3 and 500 million °C (900 million °F). Breakeven (power-out equals power-in) is estimated to require at least 10^{14} particles/cm^3/second.

Baseball II is terminated after tests of means of starting mirror machines by neutral beam injection in steady-state magnetic field.

LBL begins fabricating prototype of neutral beams required to achieve high plasma temperatures in Princeton's **Tokamak Fusion Test Reactor** (TFTR).

Rotating Target Neutron Source (RTNS-II), slated for completion at LLL in 1978, will be first high-energy, high-intensity neutron irradiation facility dedicated to fusion reactor materials program. Five-million-dollar facility will provide neutron sources and support facilities for "pure" 14 MeV neutron energy component. Source is based on deuterium-tritium reaction produced by impinging accelerated deuterium beam on solid, rotating, titanium tritide target.

MIRROR FUSION TEST FACILITY



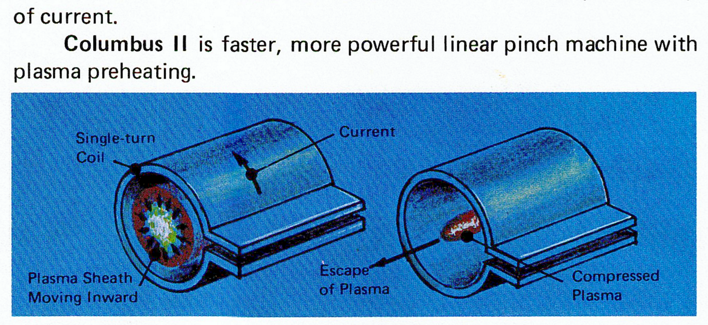
ERDA approves $94.2-million **Mirror Fusion Test Facility** (MFTF), to operate by 1981. It will use yin-yang magnet of superconducting type (like 2X-IIB's) to verify energy-scaling laws at 500 million °C. MFTF and TFTR operations are expected to provide basis for comparing mirrors with tokamaks as potential reactors.

Los Alamos Scientific Laboratory (LASL)

Los Alamos, N.M. — Pinch experiments

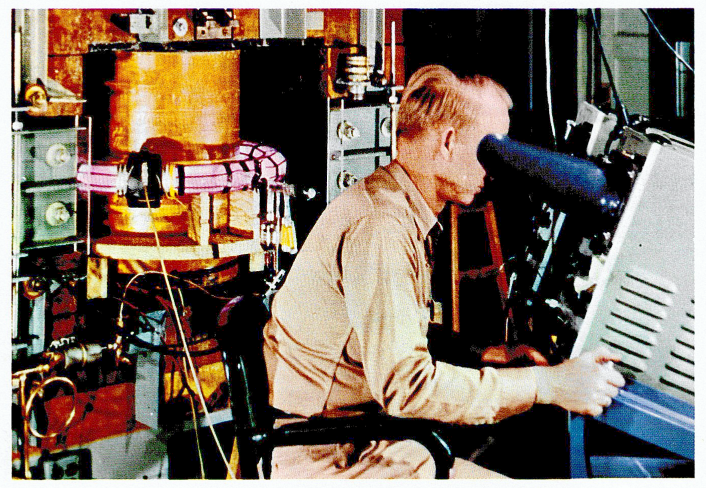
In January 1952, LASL sets up small group under James L. Tuck to develop ideas for fusion research device he terms **"Perhapsatron"** in response to skeptic who has jokingly labeled concept "Impossibilitron." In this **Z-pinch** machine, stream of rapidly-moving charged particles produces its own magnetic field, "pinching" itself into dense, hot filament of current. **Columbus I** tests rapid buildup of current.

Columbus II is faster, more powerful linear pinch machine with plasma preheating.



PINCH OPERATION

PERHAPSATRON

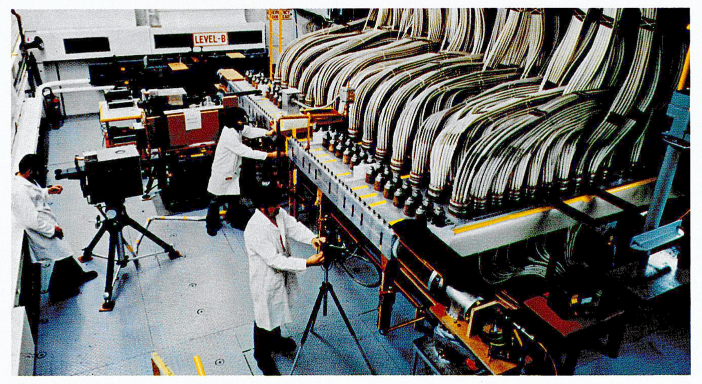


Scylla I scores early successes in 1957. Using only part of its designed power supply:

★ **Theta-pinch device produces first thermonuclear neutrons.**

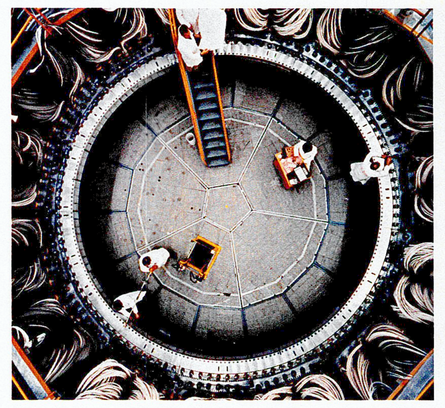
Work begins on **Scylla IV** in 1962 to study means of lengthening plasma confinement time.

Scylla IV theta-pinch compression experiments with ion temperatures to 50 million° reveal no plasma instabilities. But rapid plasma leakage from ends of one-meter-long straight container foreshortens desired containment period. AEC authorizes construction of larger, full-torus **Scyllac** theta-pinch device.

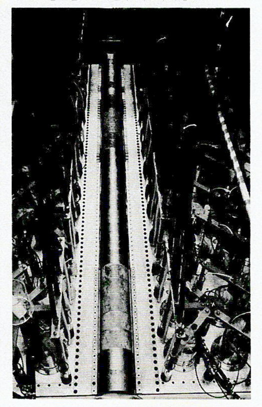


SCYLLA IV-P

SCYLLAC



STAGED THETA PINCH



Scyllac confinement studies show toroidal, helical plasma equilibrium can be achieved. Toroidal **Scyllac** eliminates end-loss, but instabilities limit confinement of high-beta plasma at temperatures in 1 keV range.

Staged Theta-Pinch (STP) begins tests in 1975 of separate staged shock heating followed by slow-rising field for better containment of "fat" plasma. Full-torus **Scyllac** then is converted to derated eight-meter sector to study feedback stabilization of plasma.

Scylla and **Scyllac** experiments indicate:

★ **Classical diffusion of plasma across magnetic fields more than enough for reactor confinement.**

On-line digital computers are applied to data-taking on fast time scales of **Scyllac**, now devoted to theta-pinch confinement work. Laser holography is used to study shock structure and basic heating of theta-pinches.

Continued plasma instabilities force termination of **Scyllac** and preparations are started for long linear theta-pinch device.

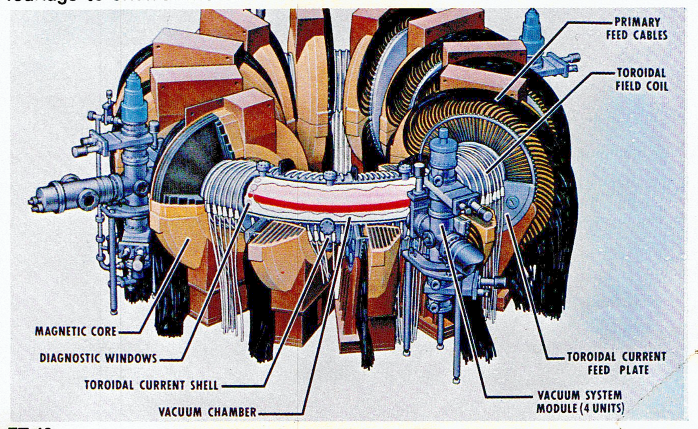
End stoppering of **Scylla-IVP** shows:

★ **30% increase in confinement time.**

Work begins on **Intense Neutron Source** (INS) device for radiation studies of reactor materials.

A **Z-Pinch Toroidal** device (ZT-1) starts testing fast rise-time toroidal current to shock-heat and confine plasma. Commercial Z-pinch reactor would be in theta-pinch class of high-sensitivity pulse reactors. A **Z-Pinch Scaling** (ZT-S) toroidal reversed-field device with 81-cm major diameter and 15-cm minor diameter begins operation. ZT-40, with 2.3-meter major and 40-cm minor diameters, is scheduled for completion in 1979.

Prototype fusion fuel cycle system, **Tritium Systems Test Assembly** (TSTA), is to be built and operated at LASL in 1980. Relying on tritium handling experience in ERDA weapons programs, LASL plans to demonstrate self-contained fuel cycle operating at high tritium throughput and low tritium inventory with negligible leakage to environment.



ZT-40

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UNITS AND TERMS:

A	ampere
kA	Kilo-ampere (1,000 amperes)
MA	mega-ampere (1,000,000 amperes)
eV	electron volt
keV	kilo-electron volt = 1,000 electron volts; plasma at 1 eV is roughly equivalent to 11,600 °Celsius, 1 keV to more than 11,000,000°C.
MW	megawatt (1,000,000 watts)
Millisecond	thousandth of a second
Microsecond	millionth of a second
Plasma Density	Number of particles per cubic centimeter (typical fusion plasma density is 100 trillion particles)