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COMPARATIVE EVALUATION OF SOLAR, FISSION,
FUSION, AND FOSSIL ENERGY RESOURCES

PART III

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NUCLEAR FUSION POWER

INTRODUCTION

In the preceding section, the role of nuclear fission reactors in becoming an important power source in the world was discussed. Oil and petroleum could last another hundred years or so, breeders a few more thousand years, but fusion power is our only hope for the very long range. Unless we develop breeder reactors, the supply of fissile nuclear fuel will be severely depleted by the year 2000. With breeder reactors the world supply of uranium could last thousands of years. However, breeder reactors have problems of a large radioactive inventory and an accident potential which could present an unacceptable hazard. Although breeder reactors afford a possible solution to the energy shortage, their ultimate role will depend on demonstrated safety and acceptable risks and environmental effects. Fusion power would also be a long range, essentially permanent, solution to the world's energy problem. Fusion appears to compare favorably with breeders in safety and environmental effects. If the fast breeder program is successful, power could be produced by breeders in the mid-80's or so. A controlled fusion reactor is a competitor with the breeder reactor in solving our long range energy needs. However, the possibility of achieving controlled fusion reactors and the developmental time span is speculative.

Controlled fusion research has developed world-wide for the past twenty years. Fusion was a classified field of research in the early 1950's when very little was known about its root science, the physics of high temperature plasmas. The fusion program was declassified in 1958 and by the early 1960's

scientific problems relative to controlled thermonuclear research were identified and a systematic study was undertaken.

The motivation for achieving controlled fusion power has remained essentially the same from the beginning. Nature has made available a virtually inexhaustible source of near zero cost fuel in the deuterium contained in the world's oceans. It also appears that the generation of fusion power may have little hazard and minimal adverse environmental effects. The United States has plentiful deuterium and lithium resources and would be independent of foreign sources for power. Fusion reactors do not utilize fissionable materials which might be subjected to diversion for military purposes. A strong fusion reactor industry would strengthen the country's technological base, and the foreign sales of fusion reactors could have a favorable effect on the balance of trade.

R. F. Post,¹ head of the magnetic mirror program at Lawrence Livermore Laboratory and a long time proponent of nuclear fusion, presented an "Optimist's Fusion Power Timetable" (See Figure 1) which is useful in relative terms. Writing from a more moderate position, R. G. Mills², head of the Engineering and Development Division of Princeton University's Plasma Physics Laboratory, stated:

"Lest we forget, it has not yet been proved that a controlled thermonuclear reactor is possible. If closed geometries fail, mirrors may succeed. If mirrors fail, too, perhaps pulsed devices or the Astron will be possible. If all magnetic confinement fails, laser-ignited microbombs may carry the day, or even minibombs in underground cavities. If none of these schemes is economically feasible, then fission breeder reactors will have the full responsibility for fueling the future of mankind.

Closing on this cautionary note, however, should not mask the fact that today, in contrast to the situation a few years ago, a majority of scientists and engineers knowledgeable in the field of controlled thermonuclear research believe that fusion power will be possible and will become practical in this century."

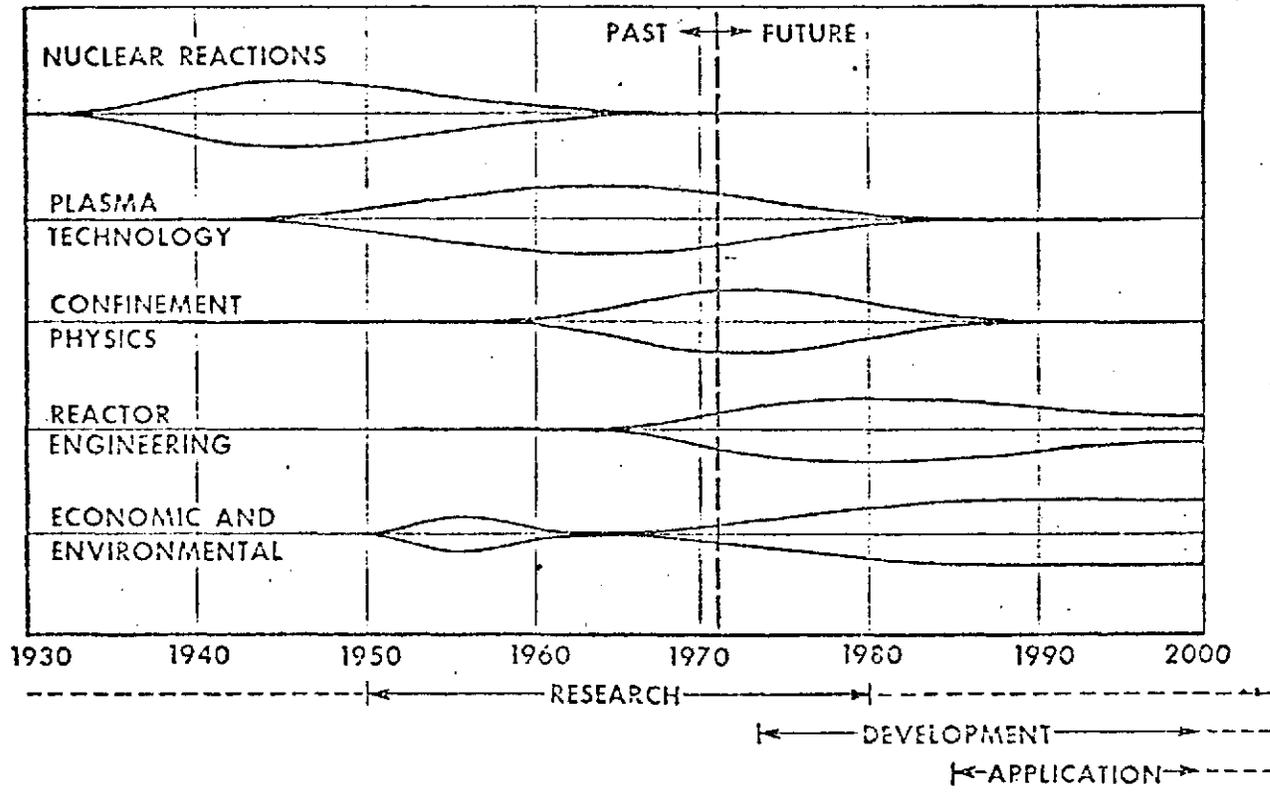


Figure 1. "Optimist's Fusion Power Timetable"

Source: Ref. 1

In 1971 and 1972 national concern over future energy sources deepened. The House of Representatives' Subcommittee on Science, Research, and Development, chaired by John W. Davis of Georgia, convened a Task Force on Energy. The Task Force, headed by Mike McCormack, issued its report in December, 1972. With regard to controlled fusion the report stated:

"One perplexing question for planners of national energy policy is what weight to give to the prospects for a practicable controlled thermonuclear reaction, or fusion of hydrogen atoms. Scientists are confident that they know and understand the conditions in which isotopes of hydrogen will fuse together with a release of energy. The existence of the hydrogen bomb is convincing proof that an uncontrolled thermonuclear reaction is possible. But after some 20 years of expensive research and experimentation, scientists still do not know whether it will ever be possible to get useful energy from a controlled thermonuclear process. The potential fuels for such a process are deuterium and tritium. The former exists in nature where it constitutes one part of 6,500 in the hydrogen in water. The latter is made from a lithium isotope by exposing that material to neutrons. The lithium 6 isotope constitutes 7.5 percent of natural lithium. So in essence, the fuels for fusion power would be natural deuterium and transformed lithium.

The first fusion reactions likely to be achieved would use both deuterium and tritium. Later it may be possible to sustain a reaction with deuterium alone. If fusion research and development is unable to go beyond the first process, then fusion's value as a major new fuel resource will be determined by the amount of lithium in nature. Professor Manson Benedict of MIT estimates that the deuterium-tritium process would add to U.S. energy reserves 100×10^{18} Btu, or about one-tenth of the energy resource he estimates would be available from uranium and thorium assuming that breeding is perfected. If scientists and engineers are able to produce the more demanding physical conditions required to use deuterium alone as a fusion fuel, then deuterium could represent a virtually inexhaustible supply of energy. Benedict estimates successful commercial use of deuterium as fusion fuel would expand world energy resources to over 17 billion $\times 10^{18}$ Btu, a truly limitless store of energy.

THE SITUATION IN 1964

Fusion was recognized by the Interdepartmental Group in 1964 as a potentially unlimited source of energy³ But, observed the group, before a self-sustaining reaction could be achieved, an enormous amount of further research in basic plasma physics was indicated. Financial support of basic research in fusion should be continued and increased not only because of the monumental potentialities of

fusion power, but also because the fundamental knowledge secured would be invaluable to many peripheral energy fields. Of the anticipated advantages of fusion, the Group identified its limitlessness as a source of power and its inherent safety as major reasons to continue fusion research.

An immense effort would be needed with no promise of immediate returns in the immediate future. According to the Group:

....The task is immense, and there is no indication that it will be solved in the immediate future. Even if controlled fusion reactions can be achieved on a laboratory basis, it will take many years to develop an operable power generator.

THE SITUATION IN 1972

The outlook for fusion is somewhat brighter in 1972, but the scientific feasibility remains undemonstrated. Experiments in the Soviet Union with its Tokomak machine in the late 1960's revived hopes that the technical conditions for a useful controlled nuclear reaction could be achieved. This advance led to a flurry of experimental activity in the United States where some fusion research projects modified their machines to verify the reported results. More recently it has been proposed to heat the hydrogen isotopes to a temperature high enough to initiate fusion by use of a laser beam impinging upon a pellet of deuterium-tritium or deuterium to produce a burst of fusion energy.

Whether a controlled reaction can be reliably demonstrated remains speculative. Proponents of fusion expect such a demonstration within 10 or so years. However even the most optimistic of fusion advocates do not expect to see it in commercial use before the late 1990's. So barring an unexpected breakthrough, fusion will be of little importance as a useful energy source for the next few decades. If it can be achieved, then in principle, the enormous amounts of energy available would make it possible to substitute synthetic liquid and gaseous fuels for those obtained from coal, oil and gas.

For a controlled thermonuclear reaction to occur, it is necessary for engineers and scientists to find ways to raise the heat energy of heavy hydrogen molecules to from 100 million to 1 billion degrees Kelvin; to confine this hot ionized gas, or plasma for up to a second; and to maintain a certain minimum density of ions while doing so. At the same time fuel must be fed to the system and heat energy extracted from it for subsequent generation of electricity.

Many devices have been built throughout the world in attempts to achieve these critical conditions for fusion. On a world wide

basis, over \$150 million is being spent annually in fusion research. Japan, France, West Germany, Holland, Sweden, Italy, the United Kingdom, the Soviet Union and the United States each have fusion programs. Most of the research effort is carried on in the Soviet Union and in the United States which account respectively for 37 and 20 percent of the total fusion effort. Efforts in the United States have been carried out in some 40 universities, by several industrial groups, including the Texas Atomic Energy Research Foundation which is funded by electric utilities and at four major AEC funded laboratories - the Los Alamos Scientific Laboratory, the Lawrence Radiation Laboratory of the University of California, the Oak Ridge National Laboratory, and the Princeton Plasma Physics Laboratory.

Anticipatory design studies of a fusion reactor have inquired into environmental and safety factors. They suggest that fusion plants would not produce large quantities of radioactive waste, would be inherently safe against nuclear accident, and would discharge 50 to 70 percent less heat than existing steam-electric power plants. In addition, fusion theoretically offers possibility of direct conversion of heat energy into electricity through an MHD cycle."

In addition, the Task Force summarized the advice of experts in the field, including Herman Postma, then head of the Thermonuclear Division of Oak Ridge National Laboratory and presently Director of the Laboratory:

"Herman Postma of the Oak Ridge National Laboratory examined the technology, engineering, and environmental questions that will have to be faced once the scientific feasibility of fusion is demonstrated. Before fusion can be taken seriously as a possible source, he would carry the demonstration of scientific feasibility one step further to show that it is possible using real fuels -- deuterium and tritium -- to obtain more energy from a reaction than goes into producing that reaction. Though such an experiment might be small, it would show that the fusion process with real fuels occurs under actual working conditions and that a self-sustaining reaction would be possible.

Assuming that the scientific feasibility of fusion is demonstrated in the later 1970's or early 1980's, Postma outlines a series of intermediate steps toward the goal of economically useful fusion power. These are essentially the same as specified by Benedict. The first step is to design, construct, and operate an experimental power reactor to provide detailed engineering tests as well as understanding of dynamics of a plasma in a reactor. This reactor would not produce useful power. It might be built within 5 to 7 years after demonstration of scientific feasibility, depending upon the complexity and the results of the feasibility experiments.

The second stage would be to design, construct and operate prototype reactors. These would operate at higher power outputs, from 200 to 400 megawatts of thermal energy, and with power cycles designed to give reliable and continuous output. It may be necessary to operate such reactors for several years. From the time of conceptual design to the time of working demonstration could take as long as 10 years. At the end of that time, a substantial interest by industry would be expected. Successful operation of prototype fusion reactors would lead to the third stage: construction of demonstration fusion reactors of a size large enough to be commercially acceptable. These demonstration reactors would produce about 1000 megawatts of heat energy and would be operated to demonstrate reliability over long periods of time and to indicate the economics of commercial fusion power. The operation would allow vendors, utilities and the public to decide the usefulness of fusion power in terms of economic, physical, social and environmental conditions.

In summary, Postma postulates a sequential evolution of fusion research and development from the demonstration of scientific feasibility to that of commercial acceptability as taking at least 30 years beginning in the mid 1980's. The cost of this development and demonstration would likely be several billion dollars."

The question, "When fusion?" has been previously discussed by Rose⁴ and Post⁵ and by Gough and Eastlund.⁶ The latter state:

"If fusion power is pursued as a 'national objective,' expanded programs could be carried out across the entire density range accompanied by parallel strong programs of research on the remaining engineering and materials problems to determine as quickly as possible the best routes to practical fusion power systems. Therefore, depending on one's underlying assumptions on the level of effort and the difficulties ahead, the time it would take to produce a large prototype reactor could range from as much as 50 years to as little as 10 years.

A recent budget proposal of the U.S. Atomic Energy Commission for fiscal years 1974, 1975, and 1979 is on an increasing scale: \$145M, \$250M, and \$400M, respectively. On such a budget it is proposed to construct a scientific feasibility or physics test reactor in the early 1980's, a prototype power reactor in the late 1980's and a demonstration power reactor in the mid-1990's. Thus the A.E.C. forecasts availability of

small amounts of fusion power in some twenty years. The subsequent rate of increase of fusion power availability would be determined by technological, economic, and social considerations. One technological consideration is the rate at which new tritium would become available for the startup of new reactors. Current estimates of tritium doubling time vary from a month to a year. Economic and social considerations will be conditioned by progress in the fast breeder program and by world energy demand some years hence.

BASIC PRINCIPLES

Nuclear Fusion Reactions

This section will serve only as a brief survey of basic principles. Most fusion reactors employ one or a combination of the following nuclear reactions:

<u>Reaction Equation</u>	<u>Approximate Threshold Plasma Temperature</u>
$D+T \rightarrow {}^4\text{He} (3.5 \text{ MeV}) + n (14.1 \text{ MeV})$	10 keV
$D+D \begin{cases} \rightarrow {}^3\text{He} (0.82 \text{ MeV}) + n (2.45 \text{ MeV}) \\ \rightarrow T (1.01 \text{ MeV}) + p (3.02 \text{ MeV}) \end{cases}$	50 keV
$D+{}^3\text{He} \rightarrow {}^4\text{He} (3.6 \text{ MeV}) + p (14.7 \text{ MeV})$	100 keV

Each cycle requires an energy investment to initiate fusion, and each utilizes deuterium which occurs abundantly in nature and is available at low cost.

The first reaction requires tritium which does not occur naturally and which therefore must be bred. The third reaction utilizes ${}^3\text{He}$ which can be obtained from DD reactions. All cycles involve emission of neutrons from the primary or secondary reactions (e.g., DD reactions in the $D{}^3\text{He}$ cycle).

The DT Reaction

The DT reaction is considered most attractive for first generation fusion reactors because of its high energy gain and its low threshold temperature. The features of the reaction determine many of the basic characteristics of a DT fusion reactor.

1. Because about 80% of the energy output is carried by the neutrons, a special blanket of low atomic number materials will be required to convert neutron kinetic energy to thermal energy, as well as to provide a biological shield.
2. The blanket region of a DT reactor will become radioactive because nearly all materials become activated to some degree by energetic neutron bombardment. This activity will be minimized by appropriate materials choices.
3. DT reactors will work primarily on a thermal conversion cycle because neutron moderation gives rise to thermal energy.
4. Tritium must be bred. Neutron absorption in natural lithium appears attractive. Breeding ratios to 1.5 may be possible, giving doubling times of about a month. (A ratio of 1.3 appears typical.)
5. The elemental reaction product is inert helium.
6. There is some flexibility to deal with system losses and inefficiencies because the energy gain is high.
7. The DT cycle has the potential of being self-sustaining since the energetic charged fusion products (helium) can feed energy directly into the plasma.

The DD Reaction

Although the other cycles have lower energy gains, they have a number of attractive features. DD reactions utilize naturally occurring deuterium and hence do not require external tritium breeding, removing an important constraint from the blanket requirements. The reaction products (T and ^3He) are themselves fuel and will partially react with the deuterium before escape from the plasma. Unburned T and ^3He could be reinjected to improve the fractional burnup.

The D^3He Cycle

By increasing the operating temperature and reinjecting only the ^3He , the DD cycle can operate so that D^3He reactions contribute most of the output power, as little as 10% of the output being from DD neutrons (and its tritium by product). With efficient direct conversion of the energy from the charged D^3He reaction products, increased overall system efficiencies appear possible.

PHYSICAL CONDITIONS FOR FUSION

Temperature

Because the fuel nuclei are positively charged, high kinetic temperatures are required. Relative kinetic energies of the order 10 keV or larger are needed in order to overcome the mutual electrostatic repulsion of the fuel nuclei; these energies correspond to 100 million degree kinetic temperatures. The necessity of these high ignition temperatures is unavoidable. A large proportion of the effort to date has been directed at the attainment of these high temperatures. The highest temperature, to date, has been achieved in the magnetic mirror at the Lawrence Radiation Laboratory in the United States where ion temperatures of 6-10 keV are reported.

Plasma Confinement

It is necessary to isolate the fusion plasma from the surroundings. From the very beginning almost the entire effort in fusion research was devoted to the study of one particular approach to confinement, namely magnetic confinement. A magnetic field can confine a plasma by controlling the motion of its individual charge particles acting as a non-material means for insulating the plasma from the material walls of the chamber that shields it from the atmosphere. Magnetic confinement takes advantage of the fact that the fusion plasma is an almost ideal collisionless gas. A simple magnetic field seems an almost ideal container for fusion plasmas. Of course there is a problem in that a straight uniform field in a tube cannot prevent the confined plasma from dumping out of the ends. There are two basic forms

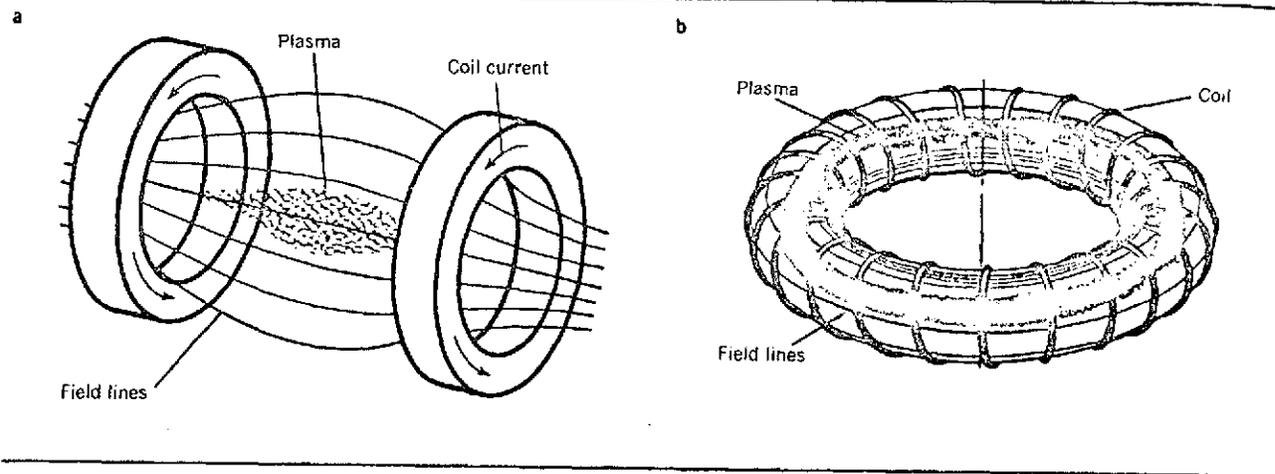


FIGURE 2.

Open and closed configurations for magnetic confinement of a plasma. Open (mirror) systems (a) use the repelling force that gyrating charged particles experience as they move into regions of increasing fields. Particles are trapped between the end "mirrors." In closed (toroidal) systems (b) particles course freely along the magnetic field lines, which are contained within a doughnut-shaped region. Diagram from R. F. Post, "Prospects for Fusion Power," Physics Today, April 1973.

of magnetic bottles: the "open" and "closed" geometries are utilized in a search for stable configuration. In the open system, as shown in Figure 2, the well-known magnetic mirror effect -- that is, the repelling force experienced by gyrating charged particles as they move into regions of increasing magnetic field -- is used to inhibit end losses. In the closed toroidal systems the particles course freely along the magnetic lines which are all contained within a doughnut shaped region. Various approaches involving particular reactor configurations will be discussed later.

More recently another approach to fusion has been proposed. It is the laser reactor idea, the newest one on the fusion scene. It is really the simplest one conceptually. In this concept tiny pellets of fusion fuel are irradiated by pulsed focused laser beams of nanosecond duration. These beams heat and densify the pellet interior, resulting in a burst of fusion energy. For densities which are envisioned, confinement is by means of inertia forces which confine the hot core in place for a sufficiently long time that no other confinement means is required.

Plasma Density

Two operating modes or regimes of fusion reactors are possible: 1) steady and 2) pulsed. In steady-state reactors which are limited to low power density by heat transfer and other considerations, a relatively narrow range of fuel density - about 10^{14} - 10^{15} fuel ions per cubic centimeter - obtains. Higher densities involve a pulsed operation mode, up to and including micro-explosion modes such as those contemplated for laser irradiated pellets. The operating fuel density is dictated only by practical requirements. Fusion power densities

vary as the square of the fuel density since each fusion reaction involves a collision of two reacting nuclei. At densities of approximately 10^{-5} of atmospheric density (corresponding to 3 times 10^{14} particles per cubic centimeter), power densities are as large as tens of megawatts per cubic meter and at atmospheric densities they would be 10^{10} times larger.

Confinement Times

Given an operating temperature, the fuel density would determine the power density. The requirements that the reaction be self-sustaining in turn defines a minimum average lifetime for the fuel ion. This is the time for the nuclear reactions to regenerate the energy invested in heating the fuel. The relevant quantity is $n\tau$, the product of density and confinement time. First criterion was published by J. D. Lawson in 1957⁷:

"For a successful thermonuclear reactor not only does the temperature need to be sufficiently high, but also the reaction has to be sustained for a sufficient time. The reason for this is that the energy used to heat the gas is ultimately degraded to the temperature of the walls of the apparatus, and, consequently, sufficient thermonuclear energy must be released during each heating cycle to compensate for this degradation."

Lawson was the first to evaluate this important confinement parameter $n\tau$, the product of the plasma density and the confinement time. Mills⁸ treated the situation further. Some of Mills' results are shown in Figure 3. Roughly, $n\tau$ must be greater than 10^{14} seconds per cubic centimeter, implying confinement times of between 0.1 and 1.0 seconds for a steady state reactor. For high density (pulsed systems) the time would be considerably shorter. Demonstration of the scientific feasibility of controlled thermonuclear fusion would require not only the achievement of the minimum fuel temperature but also a demonstration of the Lawson criterion.

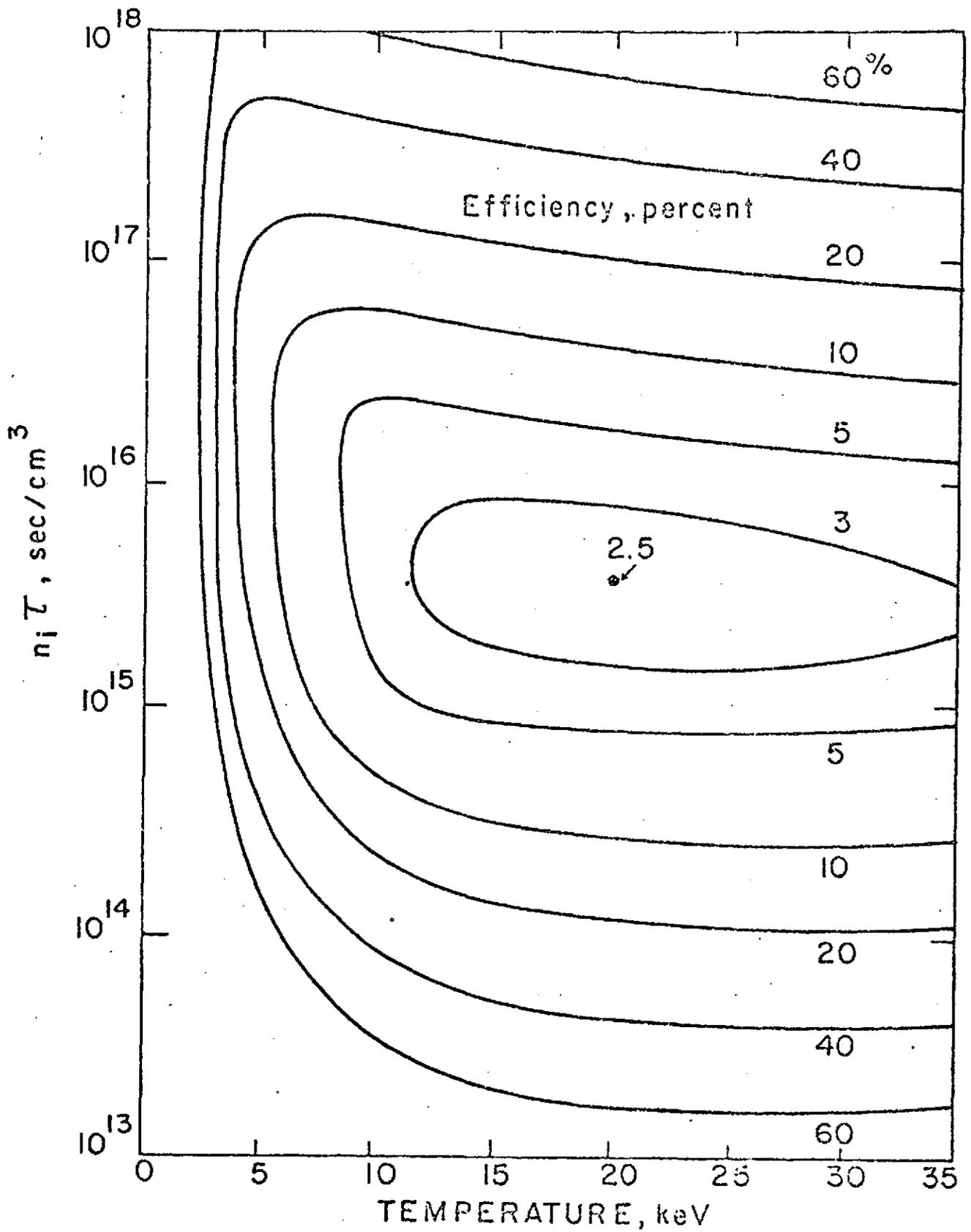


FIGURE 3. The Lawson Criterion and the Equilibrium Condition as a Function of Ion Temperature. Figure taken from R. G. Mills, Lecture Notes, Princeton University (1972).

THE WORLD FUSION EFFORT

In evaluating timetables for fusion development, it is useful to understand the balance of world effort in fusion research. The United States effort competes with extensive foreign programs in regard to international prestige. Moreover, owing to international recognition of the potential benefit of achieving fusion power, research results are shared through regular conferences such as those sponsored by the International Atomic Energy Agency. An estimate of the 1971 balance of research expenditures in controlled fusion research is shown in Figure 4, where it is noted that the U.S. contribution was only 16%. International developments have modified, and will continue to modify, the prospects for timely development of controlled fusion.

A recent development expected to bear on the question "When fusion?" is the decision by Euratom countries to begin design studies for a Joint European Tokamak (JET) device.⁹ The present design team, headed by P. Rebut of Fontenay-aux-Roses, projects that JET will produce a plasma current of 3 megamperes, comparing with the present 230 kiloamperes record of the Soviet T-4 and French TFR devices, with 0.8 - 1.0 megamperes for the Soviet T-10 device scheduled for completion in 1975, and 1.6 megamperes for the Princeton Large Torus scheduled for completion also in 1975. Reactor conditions are expected to lie in the 10-20 megampere range.

The Japanese program presently holds the world record for plasma confinement in toroidal devices. The Japan Fusion Torus 2 (JFT-2) in March 1973 claimed an electron temperature of 700 eV and confinement time of 0.02 second¹⁰. An increase of magnetic field from 10 to 18 kilogauss by summer

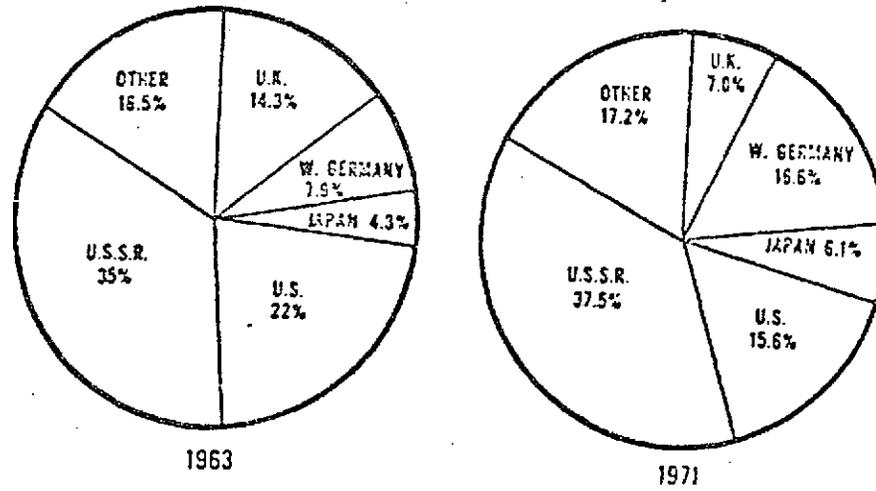


Figure 4. International Distribution of Fusion Effort.
Source: Joint Committee on Atomic Energy Hearings,
10-11 November 1971

of 1974 is expected to yield a confinement time of 0.05 to 0.07 second, and to raise the electron temperature to 1 keV.

SOVIET FUSION EFFORT

Soviet work on the concept of magnetic confinement for controlled thermonuclear reactions began at the Kurchatov Institute of Atomic Energy in Moscow in 1951. The first results of this work were reported at the Second International Conference on the Peaceful Uses of Atomic Energy in Geneva in 1958. Subsequently the basic Soviet toroidal magnetic confinement concept has come to be known as the "Tokamak" concept. By 1964 four Tokamak installations had been completed. In 1968 a joint Soviet-British effort using the T-3 Tokamak demonstrated that plasma diffusion times in the Tokamak devices were considerably longer and thus better than the pessimistic results obtained previously with stellarator concepts. The latter gave the so-called Bohm diffusion time:

$$\tau_{\text{Bohm}} \sim \frac{10^{-2} r^2 B}{T}$$

whereas the Tokamak results were between the Bohm diffusion time and the classical diffusion time

$$\tau_{\text{DIF}} \sim \frac{100 r^2 T^{3/2}}{\beta}$$

Subsequent developments have led to the so-called neoclassical theory of diffusion on which the scaling of Tokamak devices and reactor concepts is presently based. Record confinement parameters achieved with the T-3 were: $n = 3 \times 10^{13}$ to $5 \times 10^{13} \text{ cm}^{-3}$, $\tau = 10$ to 15 msec , $T_e = 1.5 \times 10^3 \text{ eV}$, and $T_i = 700 \text{ eV}$. Since the 1969 international conference in Dubna, large and small Tokamaks have been installed throughout the world¹¹. A complete review of this work is available.¹²

* In these formulas T is in keV, B is in webers/ M^2 and r is in meters.

Recently available in English translation are the forty-three Soviet papers presented at the Fourth International Conference on Plasma Physics and Controlled Fusion Research held in Madison, Wisconsin.¹³ Fully described is theoretical and experimental work in pinch stabilization, Tokamaks (T0-1, T-4, T-6), plasma focus, laser, and electron-beam methods, plasma turbulence, open confinement systems (PR-6), closed confinements systems (TOR-1, L-1, Saturn-I, Uragan Stellarator) and high-frequency heating.

In addition to the Tokamak work at the Kurchatov Institute, stellarator work is being continued at the Physics and Engineering Institute of the Academy of Sciences of the Ukrainian SSR and the P. N. Lebedev Physics Institute of the USSR Academy of Sciences (FIAN). The comparative lack of success in previous U.S. and Soviet stellarator programs is now believed to result from a small poloidal magnetic field. In newly designed stellarator systems such as the Uragan-IM machine¹⁴ confinement time is comparable to that of Tokamaks. Experiments at Culham and FIAN show near classical diffusion times.

The status of nuclear data for fusion reactor neutronics design has recently been addressed by Soviet workers at Kurchatov^{15,16}. The Chernilin paper addressed the overall plan of a Soviet reactor concept based on the Tokamak, and discussed the nuclear materials requirements for the vacuum wall, tritium breeding blanket, coolant, supplementary neutron multipliers, moderator, and coil shielding. The nuclear data for lithium and niobium are reviewed in detail and graphs for the measured partial cross-sections of neutronics interest are presented against the British AWRE evaluation. It is concluded that while fission reactor requirements result in a firm data base from thermal to 5 MeV, much less data is available in the range of interest to fusion reactor design, particularly in the range 8-13 MeV.

At the P.N. Lebedev Physics Institute early results in the Soviet laser fusion program provided a yield of some 10^4 neutrons from a CD_2 target heated by a focused nanosecond beam at 50 J energy. A larger, nine-beam laser system was developed and delivered 214 J in 6 nsec with an average plasma temperature of 840 eV . Subsequently, a 27 beam spherical geometry system was constructed. At the Sixth European Conference on Controlled Fusion and Plasma Physics at the University of Moscow (August 1973) Soviet workers reported the generation of 600 joules of which 360 joules are transmitted to the target. From measurements of the plasma density in a spherical target pellet it was concluded that central compressions of a factor of thirty at a pressure of 2×10^8 atmospheres were attained. The 600 joule energy of the Soviet laser compares with 840 joules measured at KMS Fusion and up to 1400 joules available at KMS with higher flashing voltage. The Battelle twelve beam laser is claimed to be the world's most powerful, delivering 900 to 1500 joules in 1.5 to 5.0 nanoseconds. Energy breakeven for laser systems is generally believed to lie near a threshold of 10 kilojoules. Such laser systems are presently being planned at the Lawrence Livermore Laboratory and the Lebedev Physics Institute. An economic reactor may require 100 to 1000 kilojoules.

THE U.S. FUSION EFFORT

At present, fusion research within the United States is supported primarily, but not entirely, by the Atomic Energy Commission, within the Division of Controlled Thermonuclear Research (DCTR). The most recent statement of the prospects for fusion power issued by the AEC is contained in a DCTR memorandum of February, 1973, entitled "Fusion Power: An Assessment of Ultimate Potential."¹⁷ We shall refer extensively to this memorandum. At the outset it is stated that

"Although it is exceedingly difficult to predict when fusion power will become available, it is clear that there are many technical and socio-economic variables which could speed or slow its development. Present estimates indicate that an orderly aggressive program might provide commercial fusion power about the year 2000, so that fusion power could then have a significant impact on electrical power production by the year 2020.

Fusion power has been recognized as having the potential of minimum environmental insult. This expectation is very general and deserves detailed backup. Because some second generation fusion reactor system designs have recently been developed, it is now possible to analyze the ultimate potential of fusion power to a meaningful extent and that is the subject of this report. The approach taken was to evaluate the projected characteristics of fusion power plants in an absolute sense but not to compare fusion systems with current or other projected energy sources."

Thus it is apparent that a systematic comparison of fusion power with its alternatives would comprise a needed addition to the growing literature on energy resources.

In its study the AEC has compared four leading reactor concepts: the tokamak, the theta pinch, the magnetic mirror, and the laser-fusion system. The most developed of the reactor studies, namely the Oak Ridge study¹⁸, was selected tentatively for the Reference Controlled Thermonuclear Reactor, or

Reference CTR. The reference designs will be treated in subsequent sections.

Owing to the authoritative nature of the WASH-1239 study we quote the summary conclusions in their entirety:

"For the purposes of this study the ultimate potential of fusion power has been appraised by considering a set of reference designs for full scale fusion reactors based upon the deuterium-tritium (DT) fuel cycle. One design -- referred to as the Reference Controlled Thermonuclear Reactor or Reference CTR -- was analyzed specifically.

Deuterium for the Reference CTR is obtained directly from sea water at low cost. Tritium is bred in a blanket surrounding the plasma region by neutron absorption in lithium. Typical breeding ratios are about 1.3, giving a doubling time of about a month. With neutron absorbers this ratio can be easily reduced when excess tritium is no longer needed.

During routine power plant operation, tritium is anticipated to be the only radioactive effluent, and it appears to be readily controllable. A tritium leakage rate to the atmosphere from the Reference CTR of 0.0001%/day (based on a system inventory of 6 kG of tritium) appears reasonable from a design standpoint. Assuming that this leakage is to be discharged from the reactor building through a 200 foot stack, the maximum concentration at ground level would be reduced to the point where it would give a maximum dose rate downwind of 1 mrem/yr, i.e., less than 1% of the average dose to the population from natural radioactivity.

The primary source of radioactive waste from a fusion reactor will be the activated structural material of the blanket, which will have a finite useful lifetime within the reactor owing to radiation damage. Approximately 9000 Ci/MW yr. of long-lived radioactivity would be produced in the niobium structure of the Reference CTR. If vanadium were substituted for niobium, this activity would be reduced by a factor of 1000-10,000, depending upon the type and concentration of alloying material.

The DT fuel cycle requires use of a thermal power conversion system. The Reference CTR utilizes a niobium structure which appears capable of operation at 1000°C, which is sufficiently high to provide cycle efficiencies greater than 50%. Using stainless steel for the structure, temperatures are limited to about 500°C, which would give cycle efficiencies near 40%.

Urban siting of fusion power plants would allow rejected heat to be used for heating and cooling and industrial processing. The land despoilment associated with fusion plants appears to be similar to that for fission plants with the exception that urban siting would decrease the land requirements for power transmission.

To start up a fusion power plant, an initial fuel charge of deuterium and tritium will be needed. Thereafter, a continuous supply of deuterium and lithium will be required at the rate of about a kilogram per day. Further tritium shipment will be necessary only to supply the initial charges to start up new power plants. The blanket structure of a fusion plant will become radioactive and will have a finite lifetime of the order of 10-20 years. It will then have to be shipped for reprocessing or storage.

A projected worldwide production of 10^7 MWe from fusion and/or many other types of power will give rise to some resource use conflicts which will have to be resolved. Fusion requirements for niobium for magnets and structure could just be met by known reserves. However, additional reserves may be found or other superconducting magnet materials developed.

To estimate fusion power capital costs, reactor designs developed for the various concepts were analyzed to determine the approximate amounts of the various materials used in their construction. Current prices for the required quantities of these materials in finished form were then used to estimate component costs. These estimates yielded capital costs for the nuclear "island" of roughly the same order as projected for other types of plants in the year 2000. Because of major uncertainties, it is believed that these projections serve only to suggest that fusion power capital costs could be competitive with other energy sources.

Fusion power fuel costs are determined by the costs of deuterium and lithium, and they are essentially negligible -- of the order of 0.007 mils/KWh. The safety and environmental characteristics of fusion reactors should make them potentially acceptable for urban siting, which would further reduce total fusion power costs by savings in transmission costs as well as possible savings associated with the sale of waste heat for building heating and cooling and/or industrial processing.

Fusion reactors appear very attractive when considered from the point of view of accident potential. A runaway reaction will not be possible in a fusion reactor both because of the inherent nature of plasmas and because of the low fuel inventory -- about one gram -- that would be resident in the core during operation.

Studies of the afterheat produced in the Reference CTR indicate that it is possible to evolve a design that is virtually unaffected by a loss-of-coolant accident. An analysis of the consequences of a complete loss of coolant in both the niobium blanket and the shield region of the Reference CTR indicates that all of the afterheat could be removed by thermal radiation and conduction with a temperature rise of no more than about 100°C in the high temperature zone during the first week after the outage, assuming no action whatsoever by automatic controls or the plant operating personnel. If stainless steel were employed for the blanket structure, the afterheat would be reduced by a factor of about

two relative to that of niobium, or, if vanadium were employed, the afterheat immediately following shutdown would be reduced by a factor of about four.

The inventory of volatile radioactive material is probably the most important factor to be considered in appraising the requirements for engineered safeguards to protect against accident hazard. For a fusion reactor this means that the tritium inventory, particularly the active inventory in the liquid metal system, is the most vital consideration because it will be the only volatile activity present.

By holding the tritium concentration in the lithium to 1-10 ppm and isolating the lithium and tritium handling equipment in a single, well sealed and monitored compartment, this potential accident hazard can be kept very low.

The national security aspects of fusion power would be many-fold. The U.S. has plentiful deuterium and lithium resources and would therefore be independent of foreign sources. Fusion reactors do not utilize fissionable materials which may be subject to diversion for clandestine purposes. A mature fusion reactor industry would strengthen the country's technological base and foreign sales of fusion reactors would have a favorable effect on the balance of payments. Some reliance on foreign sources of materials such as nickel and chromium will be inherent to fusion as well as many other power sources."

In support of research efforts directed at the achievement of such fusion power reactors by 2000, the AEC currently (FY 1974) spends annually \$44.5 million in the Division of Controlled Thermonuclear Research, of which \$16.3 million is spent on Research and Development, and \$28.2 million on Confinement Systems. This compares to \$350-400 million allocated annually to the LMFBR program. R & D expenditures comprise the development of larger superconducting magnets and larger neutral beam sources for plasma heating. Within Confinement Systems, funding for open-systems such as the magnetic mirror is currently \$5.5 million, down slightly from FY 1973. Closed-systems, such as the Princeton Large Torus, the Los Alamos Scyllac, and the Oak Ridge Ormak devices, are currently funded at \$17.7 million, up \$2.8 million from FY 1973. This budget reflects a commitment to the construction

of the Princeton Large Torus, scheduled for completion by the middle of 1975 at a cost of \$13 million. On balance, about 60% of the budget is allocated to low-beta toroidal experiments, 20% to the magnetic mirror, and 20% to the theta pinch systems. In addition, the AEC Division of military applications has a \$30 million program in laser fusion for the current fiscal year.

The present plan of attack calls for the leapfrogging of a scientific feasibility experiment, employing inert hydrogen plasma, formerly scheduled for the early 1980's, and proceeding directly to the construction of a device with facilities for burning deuterium-tritium. The target date for hydrogen operation is advanced to 1979-1980. Owing to recent progress in tokamak type experiments, it is presently believed that the deuterium-tritium device would be of similar design, but deuterium-tritium burning magnetic mirrors and theta pinch systems are continuing through the design phase pending the outcome of crucial plasma confinement experiments in these devices over the next few years. Estimated cost of the deuterium-tritium burning experiments is about \$100 million per device.

National Laboratory Efforts

The research and development efforts in the national laboratories are concentrated in the AEC experimental facilities at Oak Ridge, Los Alamos, and Livermore, with a smaller program at Argonne National Laboratory. Smaller programs exist at the National Aeronautics and Space Administration Lewis Research Center, the Air Force Special Weapons Center, and the Naval Research Laboratory. Historically the controlled fusion programs evolved from military applications of thermonuclear reactions developed at Los Alamos and Livermore.

Los Alamos Scientific Laboratory

The present efforts at Los Alamos are concentrated in theta-pinch systems (F. Ribe) and laser systems (K. Boyer). In addition to the plasma confinement and plasma compression work associated with the scientific feasibility demonstrations, both groups have conducted preliminary reactor analyses.

The theta-pinch in toroidal geometry (Scyllac) has received the most detailed engineering considerations in collaboration with the Argonne Controlled Fusion Interdisciplinary Group. Following Ribe¹⁹, current construction plans call for a plasma test torus with a 45-60 kilogauss magnetic field scheduled for completion in February 1974. The operating goals include a plasma temperature of approximately 1 keV and a particle density of approximately $2-3 \times 10^{16}$. Current interest in such theta pinch concepts has stemmed from attainment of plasma parameters in previous linear theta pinch devices which are closer to thermonuclear conditions than other experiments. In particular the linear Scylla theta pinch device, five meters in length, leads to plasma parameters of $T = 2.7$ keV, $N = 2 \times 10^{16}/\text{cm}^3$, and t (confinement time) = 11.5×10^{-6} s. Addition of magnetic mirrors increases the confinement time to 18.9×10^{-6} s, thus yielding an Nt product of 10^{11} sec/cm³, and associated plasma temperature of 2-3 keV. This comprises the best set of plasma parameters obtained in all candidate thermonuclear geometries to date. The scientific feasibility device which is contemplated would be of 30 meter radius and employ superconducting energy storage for 1 ms cycling of the compression/confinement field. In support of the theta pinch experimental program, Los Alamos supports a plasma diagnostics effort including the use of coupled-cavity interferometry, field probes with differencing circuits,

and bremsstrahlung luminosity apparatus with on-line Abel inversion for derivation of the plasma beta parameter. The power reactor concept for theta-pinch²⁰ is summarized in WASH-1239

"A theta-pinch fusion reactor would utilize a shock-heating phase and an adiabatic compression phase. The shock-heating phase would have a risetime of a few hundred nsec and a magnitude of a few tens of kG to drive an implosion of a fully ionized plasma whose density is of the order of 10^{15}cm^{-3} . After the ion energy associated with the radially directed motion of the plasma implosion has been thermalized, the plasma would assume a temperature characteristic of equilibration of ions and electrons. After a few msec the adiabatic compression field (risetime ~ 10 msec and final value $B \approx 100$ to 200 kG) would be applied by energizing a compression coil.

A schematic diagram of a theta pinch reactor system is shown in Figure 5. The inner shock-heating coil with (for example) 8 radial transmission-line feeds is surrounded by a Li-Be-C blanket which has three functions: (a) it absorbs all but a few percent of the 14 MeV neutron energy from the plasma, which its flowing lithium carried out to heat exchangers in the electrical generating plant. (b) It breeds tritium by means of the Li^7 (n, n' α) T and Li^6 (n, α) T reactions. (c) The high Reynolds-number flow of liquid lithium cools the first wall (shock-heating coil).

Outside the inner blanket region is the multiturn compression coil which is energized by the slowly rising current (~ 10 kA per cm of its length) from the secondary of the superconducting magnetic energy store. The compression coil consists of the coiled up parallel-sheet transmission lines which bring in the high voltage to the feed slots of the shock-heating coil. Each side of the horizontal feed of the secondary coil also serves as a ground plane for the high-voltage shock-heating field. Each transmission line delivers of the order of 100 kV to one slot of the shock-heating coil.

Outside the compression coil and its titanium coil backing is the remainder of the neutron blanket for "mopping-up" the last few percent of neutron energy and breeding the last few percent of tritium. Unlike the inner blanket, which would run at ~ 800°C to provide high thermal efficiency of the generating plant, this portion of blanket could run much cooler. Surrounding the outer blanket is a neutron shield, and beyond the shield the radially emerging transmission lines are brought around to make contact with the secondary coil current feeds and the high-voltage shock-heating circuits. To the right is shown the cryogenic energy storage coil in its dewar. At the bottom of the storage coil is the variable-inductance transfer element which reversibly transfers energy from the storage coil to the compression coil and back again.

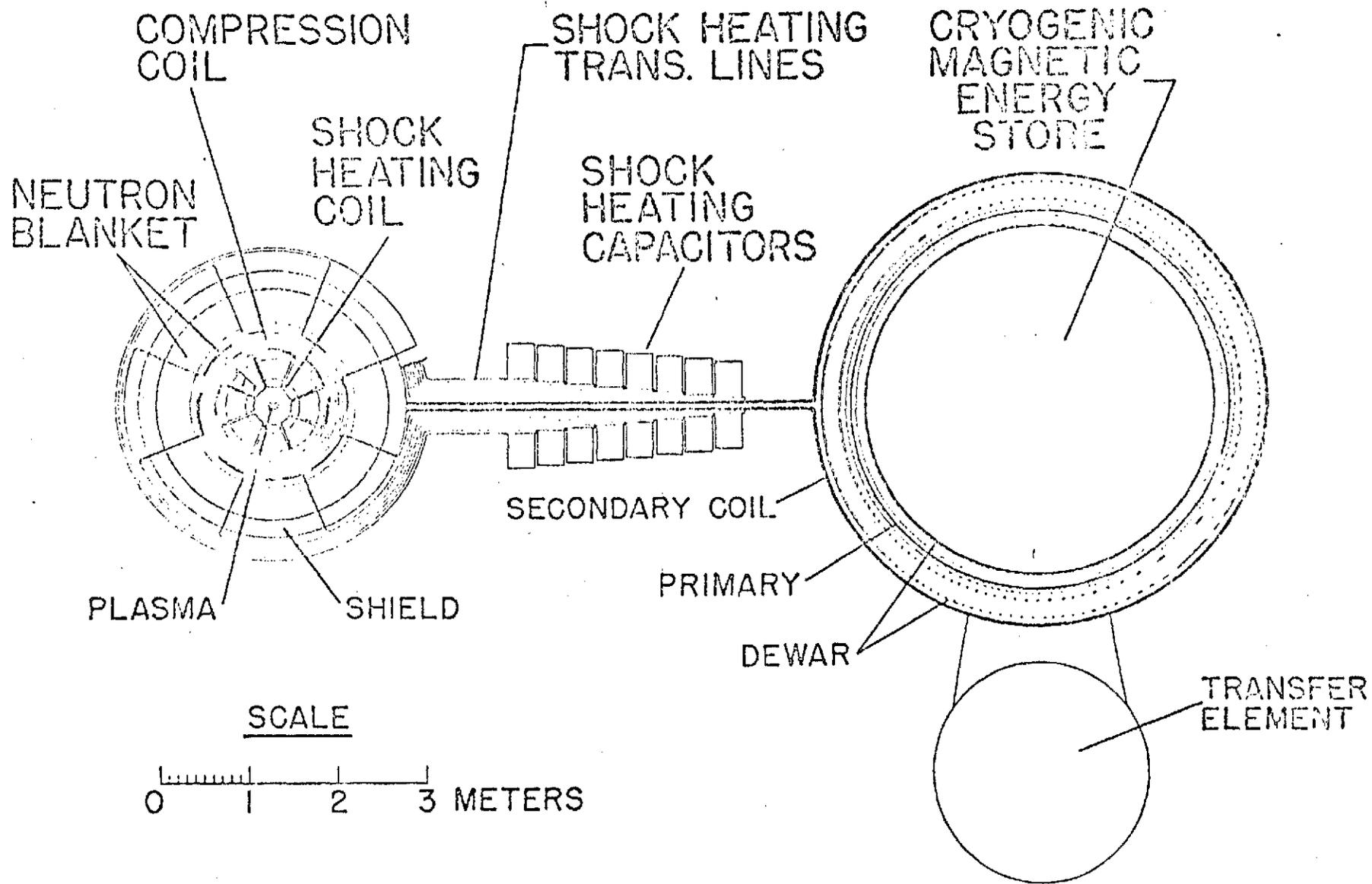


FIGURE 5. Theta Pinch Fusion Reactor (Cross-Section of a Torus). Source: WASH-1239

The laser program at LASL is directed towards the development of 100 joule carbon dioxide gas laser units with amplifiers and multiple path geometry. A multi-kilojoule unit is planned for operation before 1975, and will employ four to six beams. The associated engineering effort has comprised systems studies including blanket mechanical stress and neutronics analyses²¹. The LASL preliminary reactor design is summarized in WASH-1239:

"A schematic of a wetted-wall Inertial Confinement Thermonuclear Reactor (ICTR) is shown in Figure 6. A DT pellet is injected through a port, which penetrates the blanket, and is initiated at the center of the cavity by a laser pulse; the cavity is defined by the wetted-wall located at a radius of 1.0 m from the center. The subsequent (D+T) burn releases 200 MJ of energy. Within fractions of a microsecond, 50 MJ is deposited within the pellet and 152.5 MJ is generated within the blanket lithium and structural materials.

Within ~ 0.5 ms the pressure pulses generated by the interaction of the pellet with the lithium at the wetted-wall will subside. Within the next few milliseconds, the cavity conditions are equilibrated, ~ 1.6 kg of lithium are vaporized from the protective layer at the wall, and sonic flow conditions of the cavity gases are established at the outlet port.

The flow of hot gases through the cavity outlet port is expanded in a diffuser to supersonic conditions, and the gases are then condensed in a down stream length of duct where a finely atomized spray of liquid lithium is injected. (The spray of atomized droplets is recirculated from the liquid pool at the bottom of the condenser). Downstream of the condenser duct, the mixture of gas and liquid droplets, still at supersonic velocity, is decelerated by turbulent mixing created by a spray of large lithium droplets. (The coarse-droplet spray is provided from a side-stream of the 400°C return flow from the heat exchanger.) The kinetic energy of this mixture is finally absorbed by impacting with a pool of liquid lithium at the bottom of the condenser system.

After ~ 0.2 s, the pressure within the cavity decreases to less than atmospheric, and the blow-down continues during the remaining 0.8 x of the pulse cycle, reducing the cavity pressure to less than 133 N/m² (1.0 mm Hg). The cycle is then repeated with the initiation of another pellet.

The energy deposited within the blanket is removed by circulating the lithium through an external heat exchanger. Lithium, flowing at 400°C from the heat exchanger, is returned to a plenum between the 1.0 cm-thick wetted-wall and the 5.0 cm-thick inner structural wall, which serves to restrain the movement of the inner blanket boundary caused by the pressure waves generated within the blanket

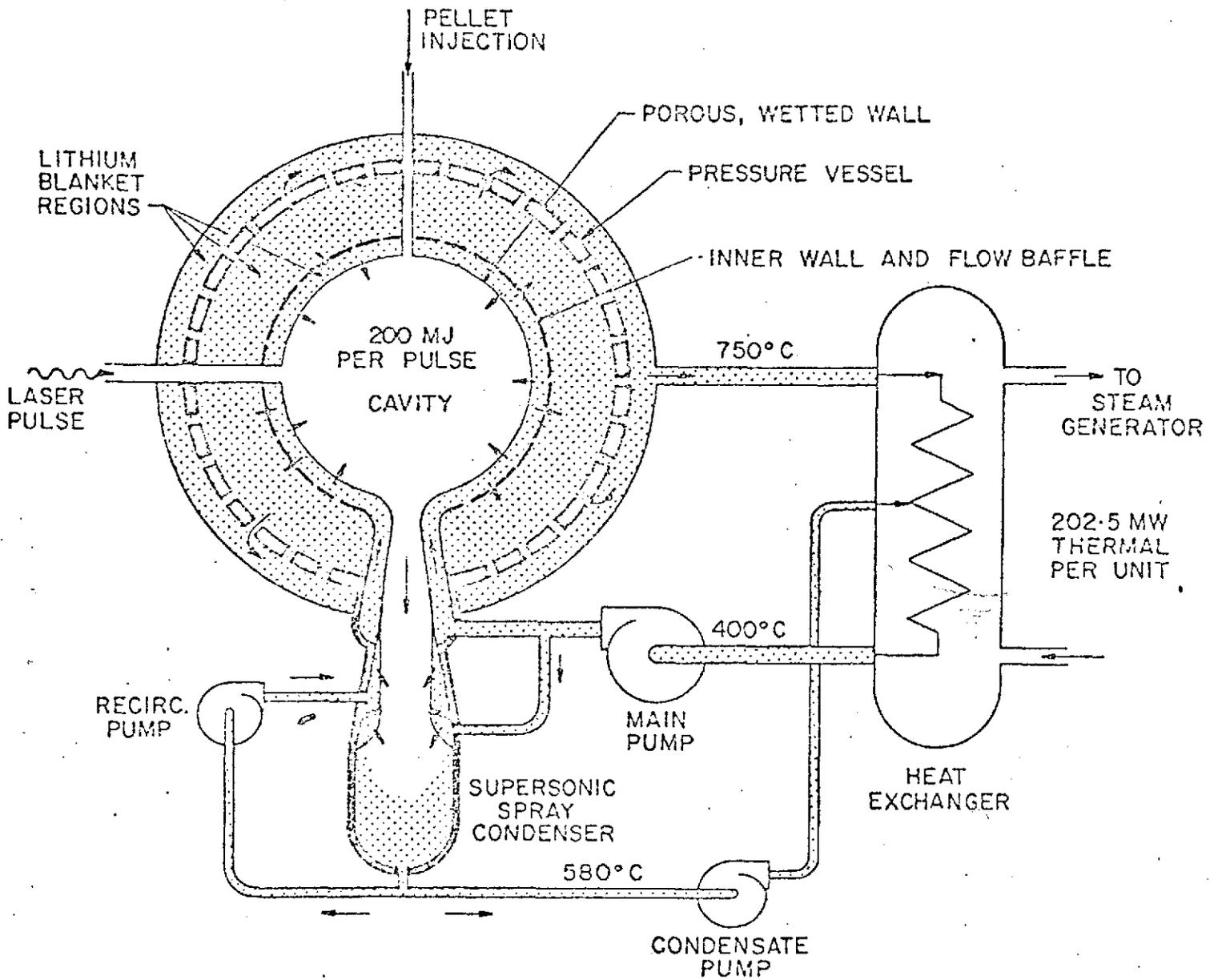


FIGURE 6. LASL Laser-Driven Fusion Reactor. Source: WASH-1239

and the cavity pressure. Located a few centimeters behind the wetted-wall, the inner structural wall also serves as a flow baffle for distributing the radial outflow. The wetted-wall moves along with the structural wall through hydrodynamic coupling, and, if needed, through mechanical attachments.

The minimum power level is based on a thermal output of ~ 200 MW, from one ICTR. Higher power levels may be obtained by combining several ICTRs in a reactor system, thereby increasing both the versatility and the overall ratio of actual operating power to full design power. The nominal thermal power level for a conceptual plant was arbitrarily chosen to be ~ 2000 MW, requiring ten modular ICTRs.

Lawrence Livermore Laboratory

Early work in compression of thermonuclear fuels to ignition temperatures for military applications prompted both magnetically confined and, later, inertially confined controlled fusion investigations at LLL as well as LASL. The program in magnetic confinement has included the Christofilos E-layer or Astron concept and the magnetic mirror concept investigated by Post and Coensgen, under the overall direction of T. K. Fowler. While now discontinued, some of the earliest reactor system designs evolved from the Astron group. At present, emphasis in magnetic confinement is on plasma tests with the 2XII mirror device. An associated reactor system study effort is in progress. The laser-induced inertial confinement technique is being developed under J. Nuckolls and includes advanced computer calculations as well as reactor system studies complementary to the LASL effort.

The magnetic confinement program has been described by Coensgen²². The outstanding characteristics of the mirror concept include the highest attained plasma temperatures to date - 10 keV is approached in some experiments. Plasma density is low - approximately $6 \times 10^{13}/\text{cm}^3$ in 2XII experiments using a titanium evaporator. Current emphasis is directed towards the enhancement

of confinement time and the demonstration of efficient, neutral beam heating techniques. Confinement times have been extended to approximately 2.2 milliseconds using minimum-B confinement techniques developed from the Ioffe hexapole geometry. Present neutral beam heating work is directed toward beam currents of order 10 amperes, with progression to 100 amperes projected. The basis for use of neutral beams in these mirror experiments is the positive potential developed within the plasma as electrons preferentially leak out the ends of the magnetic mirrors.

Fusion power reactor studies have been undertaken at LLL and incorporate both D-T and D-He³ fuel cycles. The magnetic field in the D-T systems are of the order 42 kg in the plasma, and for D-He³ systems 70 kg. The D-T reactor is described in WASH-1239:

"Designed to produce 500 MW(e), the LLL DT mirror reactor design may be considered as having three main parts: a magnetically contained plasma volume in which the fusion reactions take place, an ion injection and plasma heating system requiring electrical power input, and a combination thermal and direct energy converter system. The thermal portion of the converter system converts the neutron kinetic energy to thermal energy in a blanket surrounding the plasma confinement zone. The blanket breeds tritium for fuel replenishment. The second element of the energy converter system is the direct converter which accepts energetic charged particles which escape from the plasma confinement zone and it converts their energy to high voltage dc power. A fraction of this direct converter power is then fed back to the ion injection system to sustain the reaction and maintain the plasma. The reactor may be generally classified as a relatively low gain energy amplifier. This concept of combining thermal and direct conversion should be applicable to any fusion containment system; however, it is especially attractive for mirror systems because it furnishes a means to minimize the adverse effects of end losses. The direct conversion subsystem operates in a sequence of four steps: (1) expansion, (2) charge separation, (3) deceleration and collection, (4) conversion to a common potential. The first three steps of this process are as follows. The reaction products escape from the mirrors at a low ion density (10^8cm^{-3}) which is further decreased to 10^6cm^{-3} by expansion into a large, flat, fan shaped chamber. Expansion is accomplished by coupling an external radial magnetic field to the

mirror field and allowing the field to decrease from its high level at the mirrors (approximately 150 kilogauss) to levels of about 500 gauss. The expansion also converts particle rotational energy to translational energy in inverse proportion to the field change. At the end of this expander field, electrons are separated from the ions by abruptly diverting the field lines. The electrons behave adiabatically and remain on the field lines while the ions cross the field lines and enter the collector region.

The ions emerge from the expander with a considerable spread in energy. To recover this energy at high efficiency the ions are passed through a series of electrostatically focusing collectors within which they are progressively decelerated. The ions are decelerated to a low residual energy and then diverted into a collector. Experiments at LLL have demonstrated overall collection efficiencies in excess of 80% and further improvements are expected.

The final step of direct conversion is the transformation of the electrical energy to a common potential. This is accomplished by an inverter-rectifier system using commercially available equipment.

The approximate plasma conditions are as follows: average ion energy = 400 keV, average electron energy = 40 keV, total power output = 1330 Mw, plasma beta = 0.9, plasma density = 10^{14} cm⁻³, and plasma radius = 4.3 meters. A schematic of the system is shown in Figure 7.

Systems studies of the magnetic mirror concept center about the use of electrostatic conversion of the kinetic energy of the charged reaction products generated in He³-enriched fuel cycles. Sophisticated calculations of end loss phenomena have suggested that such He³-enriched systems may have marginal Q - that is, the ratio of power out to power in - and excessive circulating power. Thus systems studies include D-T fuel cycles which offer potentially higher Q, though most of the electrostatic direct conversion is traded for the inefficiencies of a thermal engine. In view of the potential attractiveness of the He³-enriched fuel cycles, from an environmental standpoint, ongoing research in electrostatic converters is in progress as well as efforts to reduce end losses and achieve a higher system Q. The latter effort requires a better understanding of the nature of microinstabilities within thermonuclear plasmas. Such an understanding has been greatly assisted

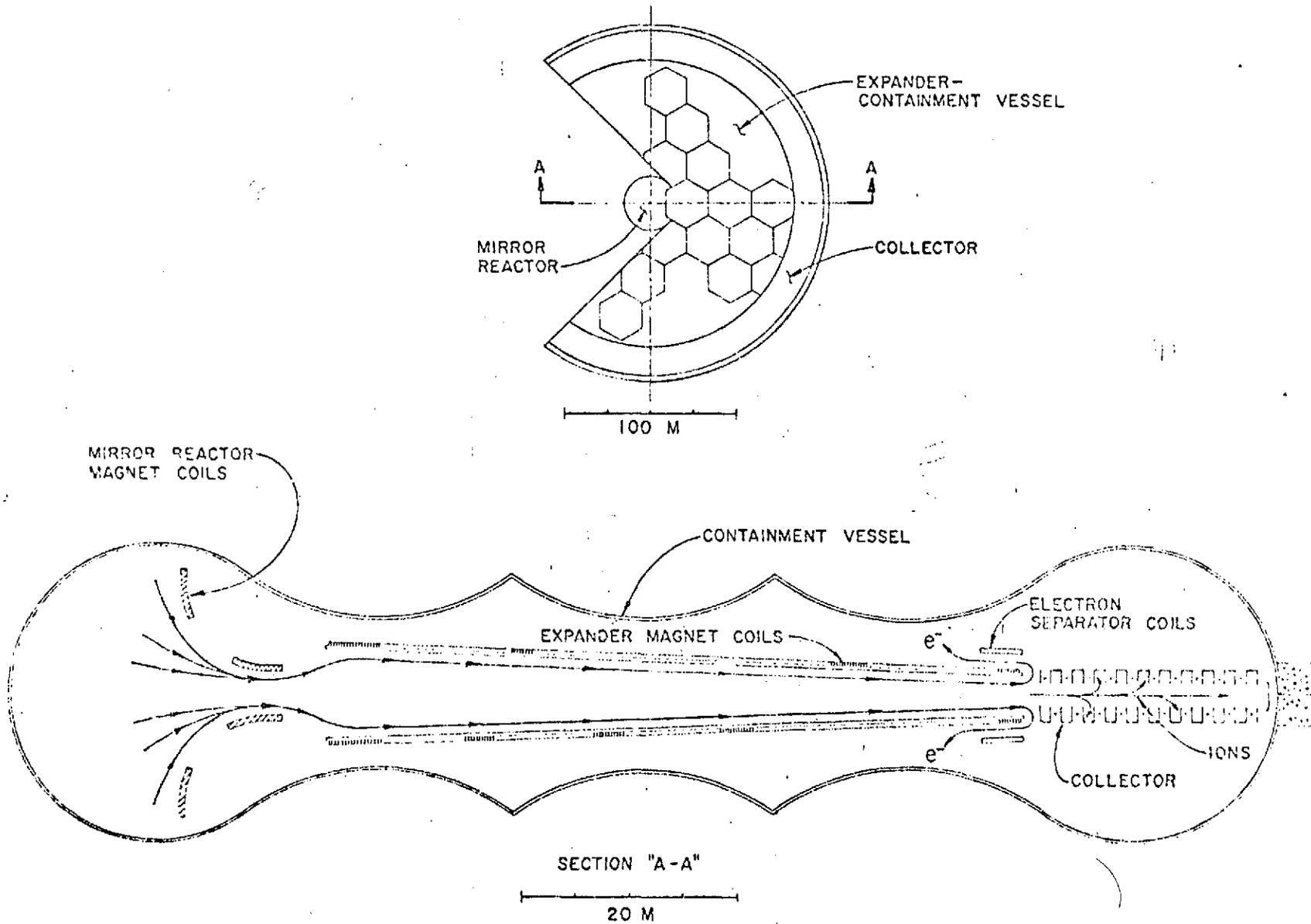


FIGURE 7. LLL Mirror Reactor With Direct Converter. Source: WASH-1239

by an ongoing program of computer simulation of such instabilities.

The LLL laser-fusion effort is described recently by Nuckolls.^{23,24} Key elements of the program include computer calculations of implosion phenomena, laser technology, and reactor studies. The computer program incorporates several physical phenomena including hydrodynamics, optical absorption, coulomb coupling of charged-particles species, suprathreshold electron spectra, thermal diffusion, magnetic field and MHD effects, photonics, nuclear reaction kinetics, and materials properties under extreme conditions of temperature and pressure. The laser technology effort at LLL includes a design study and funding request for construction of a 10 kilojoule neodymium glass laser system for subnanosecond spherical irradiation of pellets. It is expected that with such a system fusion power output equal to laser power input can be demonstrated. In addition to the neodymium-glass laser investigations, LLL is investigating the short-wavelength (1722 Å) xenon laser which offers the promise of better energy deposition and higher efficiency (25%) than either CO₂ or neodymium-glass lasers can obtain. In addition to the physics calculations and laser technology activity LLL works with LASL in the development of laser-driven fusion reactor concepts, which are presently in an earlier stage of evolution than the magnetically-confined fusion reactor system studies.

Oak Ridge National Laboratory

In addition to the early DCX experiment and fusion technology investigations ORNL carries out magnetic confinement investigations on both magnetic mirror and tokamak configurations. Advanced design of prototype fusion power plants in laser and tokamak form are being conducted, and the latter are amongst the most detailed studies to date on complete systems.

The principal magnetic confinement devices employed in ORNL experiments are the Ormak (Oak Ridge Tokamak) and the Elmo toroidal mirror. Recent results obtained on the Ormak device have been described by J. Clarke of the ORNL Thermonuclear Division²⁵. Topics presently under study include neutral beam injection and heating, the classical slowing down process, injection effects on plasma stability, and plasma relaxation mechanisms. Present plasma behavior exhibited by Ormak as well as the Soviet T-3 and Princeton ST devices confirms the principle of scaling according to the pseudo-classical diffusion theory, and Ormak is found to have the lowest collisionality of any existing machine in its class. Neutral beam injection has been tested and has demonstrated 20% heating increments over the ohmic limit. Four neutral beam injection units are to be installed with 120 kW beam power capability per unit in the present program. Immediate goal is to obtain 1 keV plasma temperatures.

Associated with the Oak Ridge tokamak plasma experiments are design studies of a prototype commercial fusion power plant. The current design study¹⁸ has formed the basis of the reference reactor for the WASH-1239 report. The summary description follows:

"The principal features of the conceptual design of a full scale tokamak chosen as the Reference CTR are shown in Figure 8. The torus structure is divided into six sectors to facilitate construction and maintenance. Four of these are shown assembled and positioned around the poloidal magnet core. In the left foreground a fifth is assembled and ready to be moved into position. In the right foreground partially assembled magnet coils for the sixth are illustrated. Note the massive steel reinforcing rings that contain the superconducting coils in their inner flanges. Figure 9 is a schematic of the approximately one meter thick blanket region which surrounds the toroidal plasma. It consists of a set of 60 segments, each of which consists of a 2.5 mm thick niobium shell. ...These segments contain a long, slender, central "island" of graphite surrounded by a lithium-filled duct. Lithium coolant would be circulated at about 30 cm/sec around this closed loop by an electromagnetic pump at one end. Tritium is bred by neutron absorption in the lithium. A typical breeding

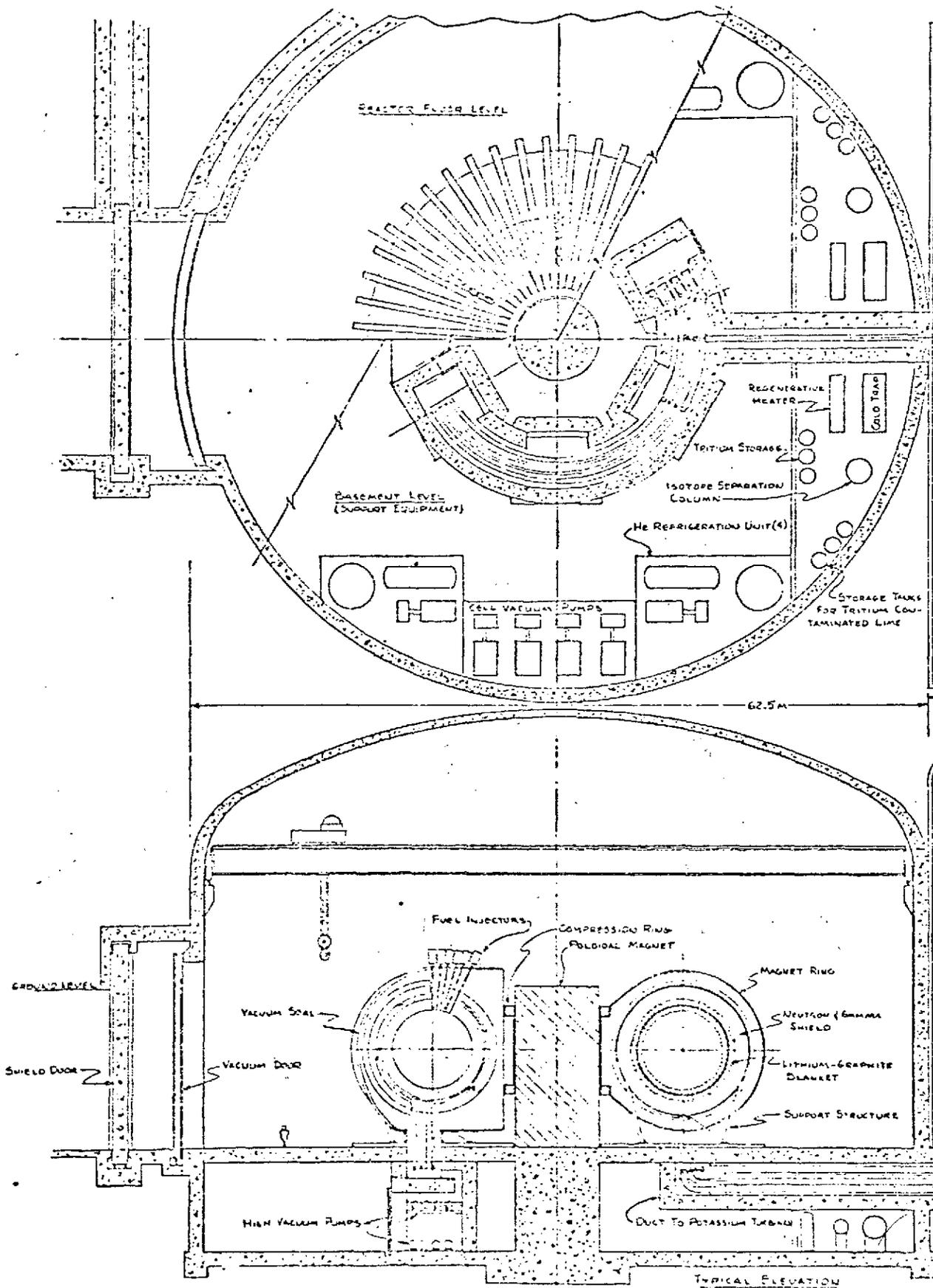


FIGURE 8. Reference CTR: ORNL Concept. Source: WASH-1239

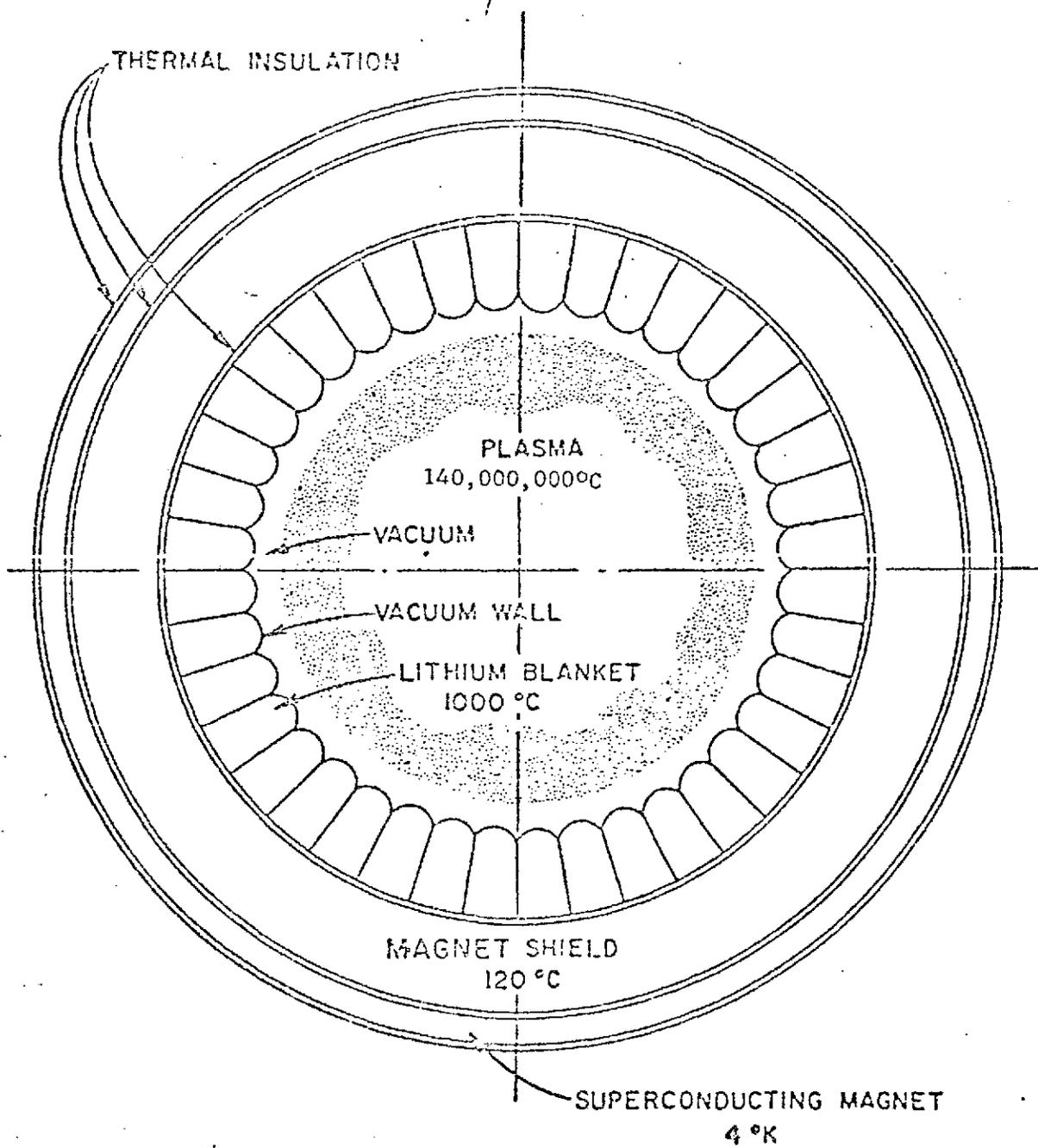


FIGURE 9. Section Through Toroidal Core of ORNL Design. Source: WASH-1239

ratio is 1.3, giving a doubling time of about a month. (Addition of neutron absorbers can easily reduce this ratio when excess tritium is no longer needed). A set of tubes installed in the lithium blanket utilized the heat generated in the blanket to boil potassium. One set of the ring-shaped manifolds would carry the liquid potassium feed to the blanket from pipes in a duct beneath the reactor floor, and the other set carries potassium vapor to vapor pipes that extend around under the reactor and out to a potassium vapor turbine in the adjacent turbine hall (see Figure 10).

A magnet shield about 1 m thick attenuates radiation leaking from the blanket region into the liquid helium-cooled superconducting magnets so that the radiation energy deposited in them would be about 1 kW(t), and hence the power required for the liquid helium refrigeration system can be held to about 2 MW(e).

Six neutral beam injectors for plasma heating and refueling are mounted near the top of each sextant so that fuel injection takes place through the parting planes between sextants.

Magnetic mirror developments pursued at ORNL have evolved to the so-called bumpy torus (Elmo) concept, in which the end losses inherent to mirror confinement devices are circumvented by arranging a series of mirror cells in a circular geometry. In the current year construction of such a device has been partially completed. Basic plasma studies relevant to the mirror approach have been conducted in the related IMP device.

Reactor studies for laser-driven fusion have been conducted at ORNL and incorporate the rotating lithium vortex concept of A. Fraas²⁶. A summary description of the BLASCON system is contained in the WASH-1239 report and is excerpted as follows:

"If lasers can be economically utilized to ignite DT pellets to give small thermonuclear explosions, it may be possible to build reactors for central stations, ships, and spacecraft propulsion. Analyses and model tests indicate that, by igniting the pellets in the cavity of a vortex formed in a pool of liquid lithium, the explosion can be contained in conventional pressure vessels at a vessel capital cost of only about \$10/kw(e). The neutron economy would be excellent -- the breeding ratio could be 1.3 to 1.5. If applied to reactors for central stations or ships, the concept would permit the construction of economic, thermonuclear reactors

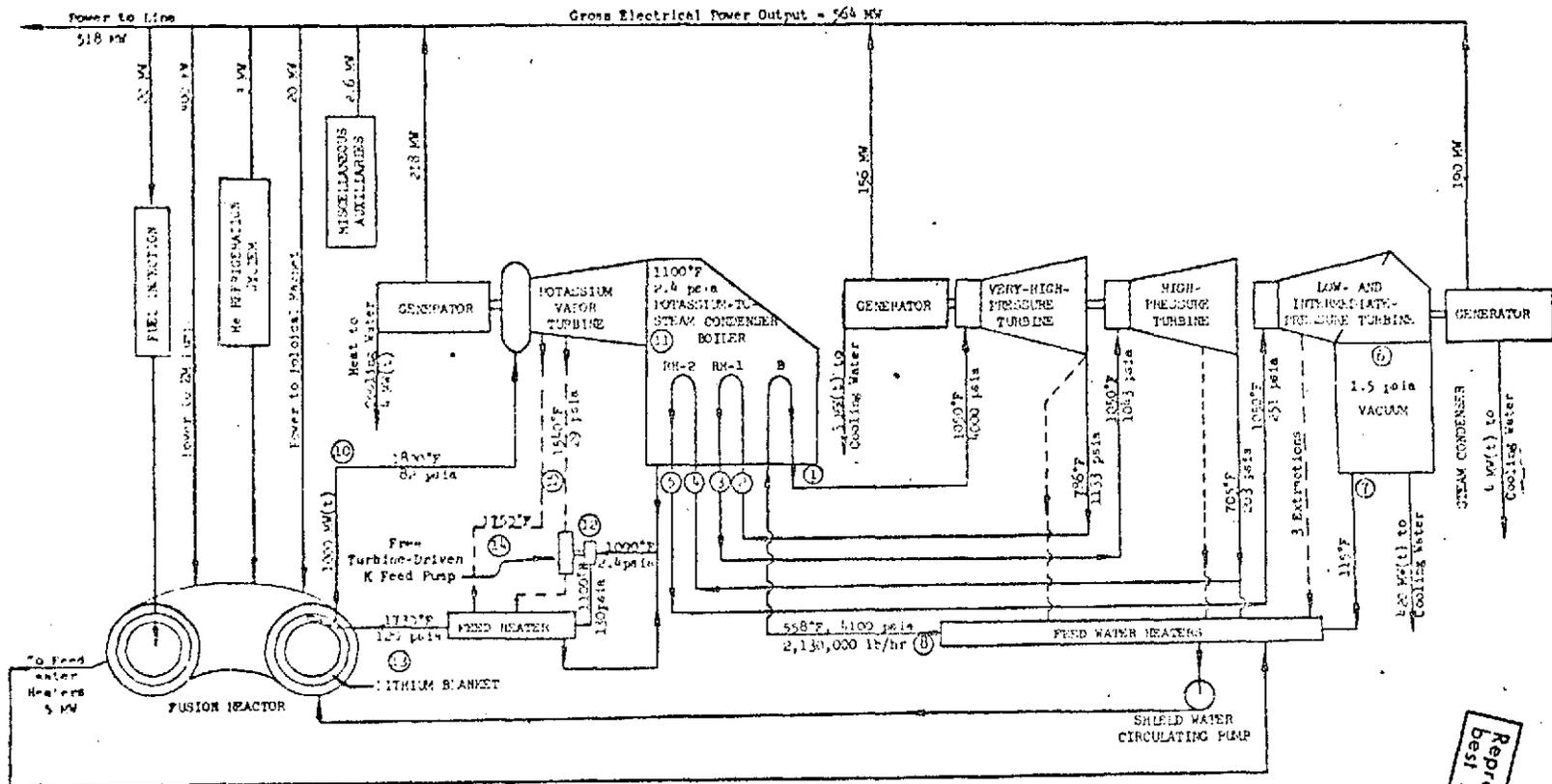


FIGURE 10. Potassium-steam Binary-Vapor Cycle Energy Conversion System For ORNL Fusion Reactor. Source: WASH-1239

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in sizes possibly as small as 100 MW(t). There would be no need for large cryogenic magnets, and no problem with fast neutron damage or neutron activation of structure. If applied to spacecraft propulsion the laser-exploded pellets might give a system whose propellant requirement for a typical Earth-Mars-Earth mission would be only about 10% those of a Rover-type nuclear rocket.

Frozen DT particles could be ignited at intervals of 10 to 20 sec and the energy of the explosions absorbed in a rapidly swirling pool of molten lithium contained in a massive pressure vessel perhaps 10 or 15 ft. in diameter having a configuration similar to that of Figure 11. With a sufficiently high swirl velocity, a free vortex would form at the center of the swirling pool to provide a cavity into which a deuterium-tritium pellet could be fired. When the pellet approached the bottom of the cavity in the vortex, a laser beam could be triggered to ignite the pellet, and the energy released in the subsequent fusion reaction could be absorbed in the molten lithium. Drawing off the lithium from the bottom of the pressure vessel would help stabilize the vortex. The lithium would be circulated to heat exchangers that could serve either to boil the working fluid for a Rankine cycle or heat the gas of a Brayton cycle. Other thermodynamic cycles could of course be employed, but the Rankine and Brayton cycles appear to be the most attractive. The lithium would be returned through pumps to tangential nozzles in the perimeter of the pressure vessel to maintain the desired vortex so that particles would be injected to a point close to the center of mass of the lithium. The operating temperature of the lithium would depend in part on the choice of containment system material, e.g., about 900°F if a chrome-moly steel were used and perhaps 1800°F if niobium were employed.

Key to the success of the BLASCON concept has involved current experiments with bubble injection for attenuation of the hydrodynamic shock wave resulting from pellet ignition. Experiments with a lucite model employing water have demonstrated an eightfold reduction of shock intensity by means of bubble injection and using a capacitor discharge for simulation of the pellet impulse. As a result it is expected that reduction in wall thickness of the reaction chamber outer wall from 80 cm to 10 cm may be possible for minimum-burn pellets in actual reactors.

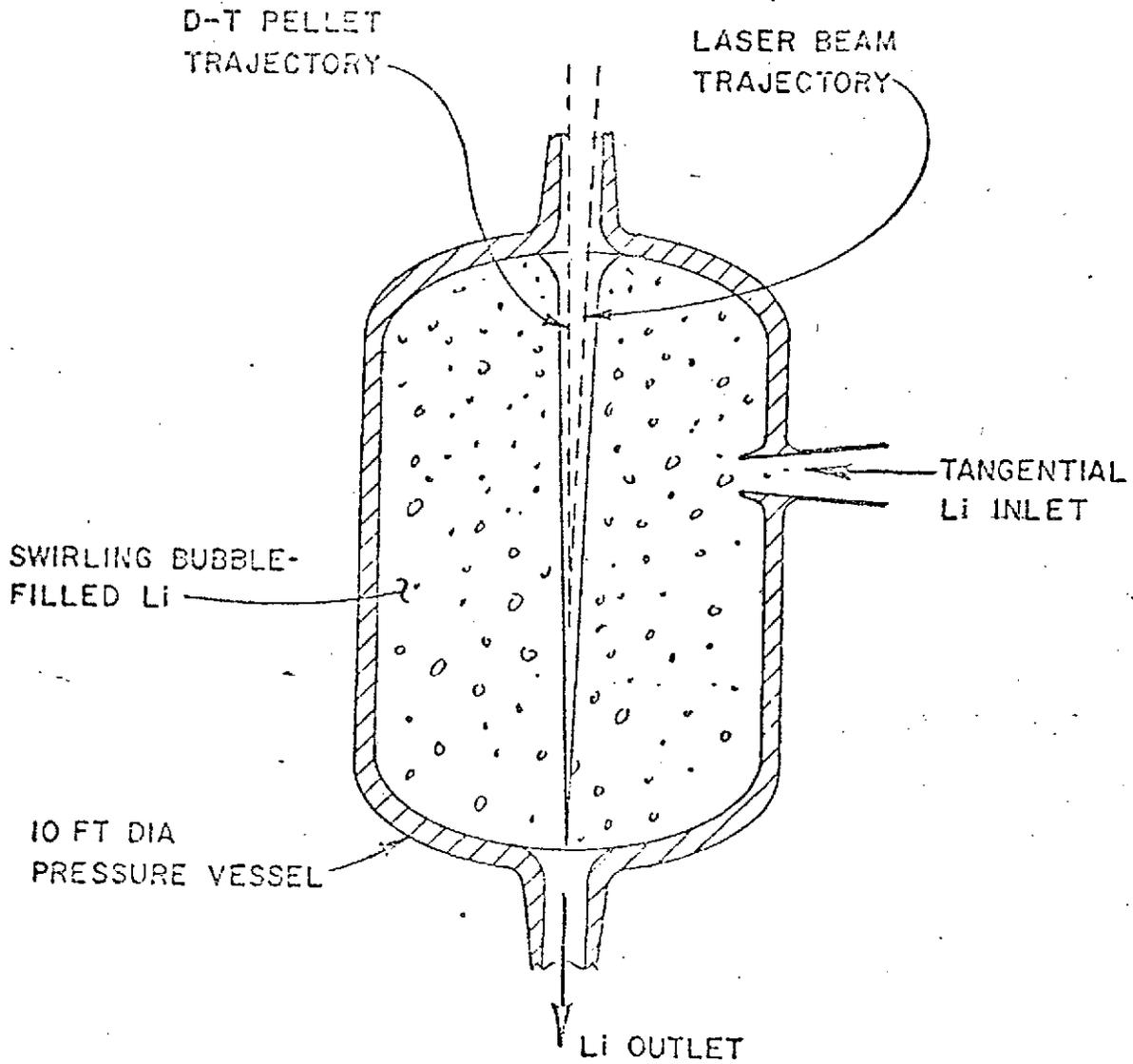


FIGURE 11. ORNL Laser-Driven Fusion Reactor Concept. Rotating Lithium Vortex. Source: WASH-1239

Argonne National Laboratory

An interdisciplinary working group in controlled fusion at Argonne National Laboratory is collaborating with LASL in the detailed investigation of prototype theta pinch power reactor concepts. Materials research in support of fusion technology underway at ANL includes superconducting magnet research, insulator research, and ionic impact studies. In addition, ANL is investigating magnetohydrodynamic conversion of fusion energy.

Lewis Research Center

The fundamental problem of rocket propulsion has historically been an energy problem, and amongst the concepts investigated at NASA Lewis Research Center since the 1958 Geneva Conference has been the feasibility of thermonuclear rocket propulsion. A comparison of the technological problems involved in fusion space propulsion and fusion power generation has been performed by J. R. Roth, W. D. Rayle, and J. J. Reinmann²⁷. Mission analyses indicate the potential of fusion propulsion for both interplanetary²⁸ and possible interstellar²⁹ missions.

Analytical work on the D-He³ fuel cycle performed at NASA Lewis Research Center has contributed to our understanding of this environmentally promising fuel system³⁰. Studies of energy transfer in thermonuclear plasmas³¹ bear on the feasibility of magnetohydrodynamic conversion of fusion power for electric power generation. Experimental work on plasmas and superconducting magnet systems has accelerated the state-of-the-art in fusion confinement systems.³² Present investigations at Lewis center about the toroidal mirror concept, shown in Figure 12. Exhaust thrust would be obtained by means of a plasma

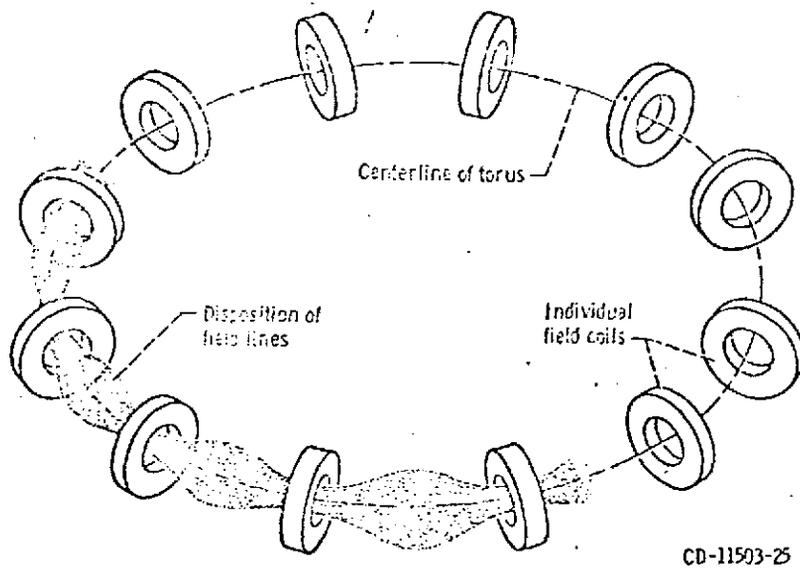


FIGURE 12. Bumpy-torus Confinement Concept. Source: NASA TN D-7353

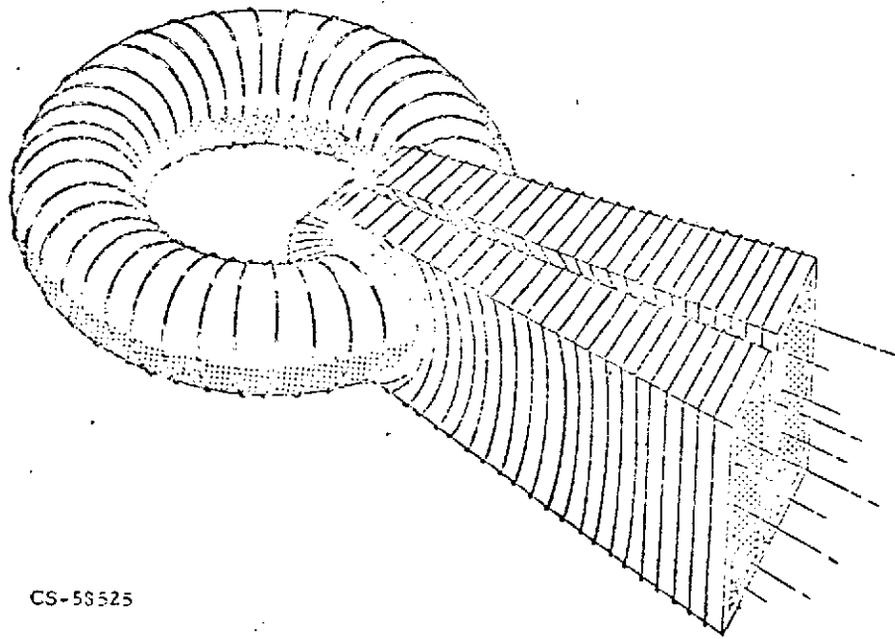
divertor similar to that contemplated for ash and impurity cleanup in a power producing reactor. The concept is shown in Figure 13. Remarking on the lower duty-cycle and the economics of space propulsion, Teller³³ has remarked that space propulsion applications of nuclear fusion might actually precede terrestrial power applications.

Non-Profit Research Institute Efforts

Activities of the non-profit research institutes encompass a variety of tasks related to the development of controlled nuclear fusion, from plasma physics work to technology development to systems studies. Thus experimental laser development at Battelle Memorial Institute has progressed to the point where fusion feasibility experiments have been planned. The present Battelle laser system, a Hadron neodymium-glass seven-stage device, incorporates a large multihead amplifier and beam splitting system. At 900 to 1500 joules the system is reported to be the world's most powerful laser. Full potential of the twelve-beam system is said to be 2500 to 3000 joules and is to be available in coming months. At this level it is expected that the conversion of 5 to 10 percent of the laser energy to fusion energy can be demonstrated in two years. The Battelle work includes development of theoretical models and computer codes.³⁴

In an assessment of California power needs Stanford Research Institute³⁵ has provided an independent evaluation of the prospects for fusion power. Highlights of this evaluation are extracted below:

"The SRI study team believes that 20 to 50 years of development work will be required before fusion reactors are freely accepted by utilities in the United States. This conclusion is based partly on the history of fission reactor development and partly on the timetable suggest by analogous events in the fusion development as tabulated below (see Figure 14).



CS-53525

FIGURE 13. Application of Plasma Divertor to Space Propulsion.
Source: NASA TM X-67826

FIGURE 14. Comparative Historical Development of Fission and Fusion Power

<u>Action</u>	<u>FISSION</u>		<u>FUSION</u>	
	<u>Year</u>	<u>Participant</u>	<u>Year</u>	<u>Participant</u>
Observed	1934	Fermi, accelera- tor particle bombard- ment	1920	Eddington, solar reactions
Identified	1939		1929-39	Other Sources
Sustained Reaction	1942	CP-1	1976-80 or 1976-85	--
Power Extracted	1952	--	1985-90	
Utility Acceptance	1953	Central Electric Generating Board	2000-30	
	1960-67	Southern California Edison		
	1963-69	Jersey Central Power and Light		

Source: SRI (Ref. 35)

It also appears that the materials problems arising from the intense, high energy neutron flux and the difficulties caused by the extremely high temperature plasma reactions in a confined space will require lengthy and expensive research and testing. The economic size of these plants is expected to be substantially larger than that of current fission reactors. Sizes of 3000 to 10,000 MW are mentioned as minimum economic ones. The utility grid or regional demand must be large before plants of such size can be accommodated. Locations which guarantee adequate cooling (7,500 to 25,000 MW of heat must be rejected) will also pose some problem...

The first generation of fusion reactors will be limited in ultimate capacity by the availability of lithium. The world lithium supply, if used in this way, is estimated as the equivalent in energy content to all fossil fuels. The availability of lithium, as with many other materials, depends on the assumed worth. Higher values would undoubtedly result in discovery of more lithium...

Advanced fusion reactors may extract electric power directly from the flowing plasma as a magnetohydrodynamic generator does. Such a system could have efficiencies as great as 80%, thus reducing the heat rejection requirements by factors of 3 to 6, and reducing fuel requirements by a factor of 2 or more.

This estimate of fusion availability by SRI is consistent with AEC goals and includes the period from demonstration plant operation to utility acceptance c. 2000-2030. It is consistent with the AEC estimate in WASH-1239 that "fusion could then have a significant impact on electrical power production by the year 2020." The estimate of thermal output must be tempered with the understanding that laser or electron beam driven fusion may permit power plants of as little as 100 MW thermal output.

The newly formed Electric Power Research Institute is expected to provide a utility-sponsored perspective on the question of controlled fusion. In this perspective it is reasonable to expect further consideration of economic factors governing the introduction of fusion power.

Private Efforts

The principal private efforts in nuclear fusion are those at General

Atomic Company and KMS Fusion. In addition Exxon Nuclear Company has recently begun investigations under Harold Forsen.

General Atomic is presently conducting experiments with two major plasma confinement devices, the dc Octopole and Doublet II. Planning for another major confinement experiment, Doublet III, is in progress. Fusion technology studies are presently being expanded. The basic theme of present experiments at General Atomic is the exploration of tokamaks with a noncircular cross-section. Insight into the noncircular cross-section is due to T. Ohkawa of General Atomic. Recently, T. Jensen of General Atomic has described the basis of noncircular cross-section experiments.³⁶ Plasma theory for tokamak devices shows that a high value of the parameter q is desirable, where $q = B_t r / B_p R$. Here B_t and B_p are the toroidal and poloidal components of the magnetic field, r and R are the minor and major radii of the torus, respectively. Thus it is desirable to have a minor radius as large as possible, as suggested by the comparatively "thick" cross-sections of the circular tokamak designs. But there are engineering limits to such a trend, i.e. space requirements for the neutron shielding, magnet coils, blanket, and structural support. Accordingly, it is proposed to increase the effective minor radius of the tokamak by using an elliptiform cross-section.

It was remarked earlier that the Battelle laser has operated at up to 1500 joules. At KMS Fusion an 80 mm driver laser is used with an output energy of 250-350 joules. Using a G.E. laser amplifier system, input at 200 joules (3 ns pulsewidth), KMS have obtained a measured output from the first six modules of about 840 joules at 8 kV flashing voltage. This is said to compare to a best Soviet value of 600 joules. KMS claim to have delivered on target 550 joules, compared to the Soviet figure 360 joules.

The predicted output of the KMS laser using seven modules flashed at 8 kV is about 990 joules, and at 9 kV is about 1400 joules - comparable to the Battelle number.³⁷

In target experiments begun in October 1973, KMS had illuminated deuterated polyethylene spheres about 0.1 mm in diameter and had produced about 0.5×10^6 neutrons per pulse. The D-D neutrons, identified by their characteristic velocity, are believed to have originated in collective and not thermal processes. A significant observation at KMS is that light reflection by the plasma is considerably less than originally predicted.³⁸

For years Physics International Company has supplied the defense community with large, pulsed electron beam machines, and it was proposed as early as 1965 to employ such beams to drive fusion reactions. Experimental programs are presently under way at the Naval Research Laboratories, Sandia Laboratories, Cornell University, Lawrence Livermore Laboratory, Air Force Special Weapons Laboratory, North Carolina State University and laboratories in the Soviet Union.

Using 11 kilojoules investigators at LLL have measured 1.7×10^{10} neutrons per pulse from deuterated targets. As in laser experiments the neutrons do not arise entirely from thermal processes but are in part due to ions accelerated in the electric field. Typically, electron beam machines store up to 200 kilojoules which is delivered in 30-80 nanoseconds. The largest available machine, "Aurora", built by Physics International and operated by Harry Diamond Laboratories in White Oak, Maryland can deliver 2.5-3.0 megajoules in 125 nanoseconds.

Thus, while electron beam devices appear to develop greater total energy than presently available lasers, the pulse width is excessive on the nanosecond scale of pellet implosion which is required by calculations.

Efforts are presently under way at Maxwell Laboratories in San Diego to develop equipment with a shorter pulse.³⁹

University Efforts

In addition to the large program at Princeton Plasma Physics Laboratory (PPPL), active programs are being pursued at M.I.T., University of Texas, Cornell, Rutgers, University of Wisconsin, University of Illinois, and the University of Rochester. In total some thirty colleges and universities are involved.

The role of university programs has been recently described by B. Miller.⁴⁰ Outside of the large hardware program at PPPL, most of the university effort is subsumed within the Research branch of the Division of Controlled Thermonuclear Research. Of the approximately \$7 million in the Research budget, about \$4.2 million is allocated to the AEC laboratories and about \$2.8 million to the thirty university or "off-site" locations. General categories of research are: 1) plasma properties, 2) plasma physics, 3) plasma diagnostics, 4) computer techniques, 5) exploratory concepts, and 6) atomic physics. Reversing the trend of previous years the budget allocated to these programs is expected to increase in the current year, both in theoretical and experimental areas. Plasma diagnostics and computer techniques, particularly, are expected to increase rapidly. In general, university efforts will be directed towards progress in confinement goals and on new departures, with primary emphasis on the former.

The large effort at Princeton Plasma Physics Laboratory, which operates largely on an AEC contractor basis, has culminated in the proposal to construct PLT (Princeton Large Torus). This device, basically a tokamak with added flexibility in the form of specially shaped and programmed transverse fields,

is in the beginning of the construction phase and is scheduled for completion in mid-1975, at a cost of \$13 million. At about the same time the Soviet Union is expected to complete T-10, roughly the same size as PLT. The PLT has a plasma minor radius of 45 cm, coil bore of 90 cm, and a major radius of 140 cm. Plasma current will be about 1.6 megamperes, which compares to the current record of 230 kiloamperes obtained in the Soviet T-4 and French TFR. Plasma temperatures of 2-3 keV are expected with a confinement time of about 0.3 second. Magnetic field will be about 50 kilogauss on-axis.

As an extension of the PPPL toroidal confinement program, a prototype fusion power reactor design has been developed. The design is superficially similar to the ORNL concept (Figure 8) but incorporates a plasma divertor, uses stainless steel instead of niobium in the first wall, uses flibe ($2 \text{ LiF} \cdot \text{BeF}_2$) instead of elemental lithium, and employs helium gas instead of potassium vapor to cool the blanket. The design is further detailed in WASH-1239:

The guiding principles on which this design was based were as follows:

1. The maximum magnetic field at the superconductor of the toroidal field coils was to be limited to 160 kilogauss. This field strength is somewhat higher than the present state-of-the-art level.
2. A divertor was to be included since the reactor was expected to operate essentially on a steady state basis.
3. Inexpensive, readily available materials and common techniques were to be utilized as much as possible.
4. The "safety factor", q , was chosen to be 2.0, a reasonable expected improvement over present experimental accomplishments.
5. The aspect ratio, A , was expected to exceed 3.0; the plasma ion density to approximate 10^{14} cm^{-3} ; the plasma temperature to be about 15 keV. The plasma composition was assumed to be equal parts of D and T. The reactor's electrical output was expected to be about 2000 MW(e) and a thermal cycle efficiency of 40% was assumed.

The resulting design (Figure 15) in part reflects the difficulty in placing a divertor on a tokamak reactor. The divertor windings

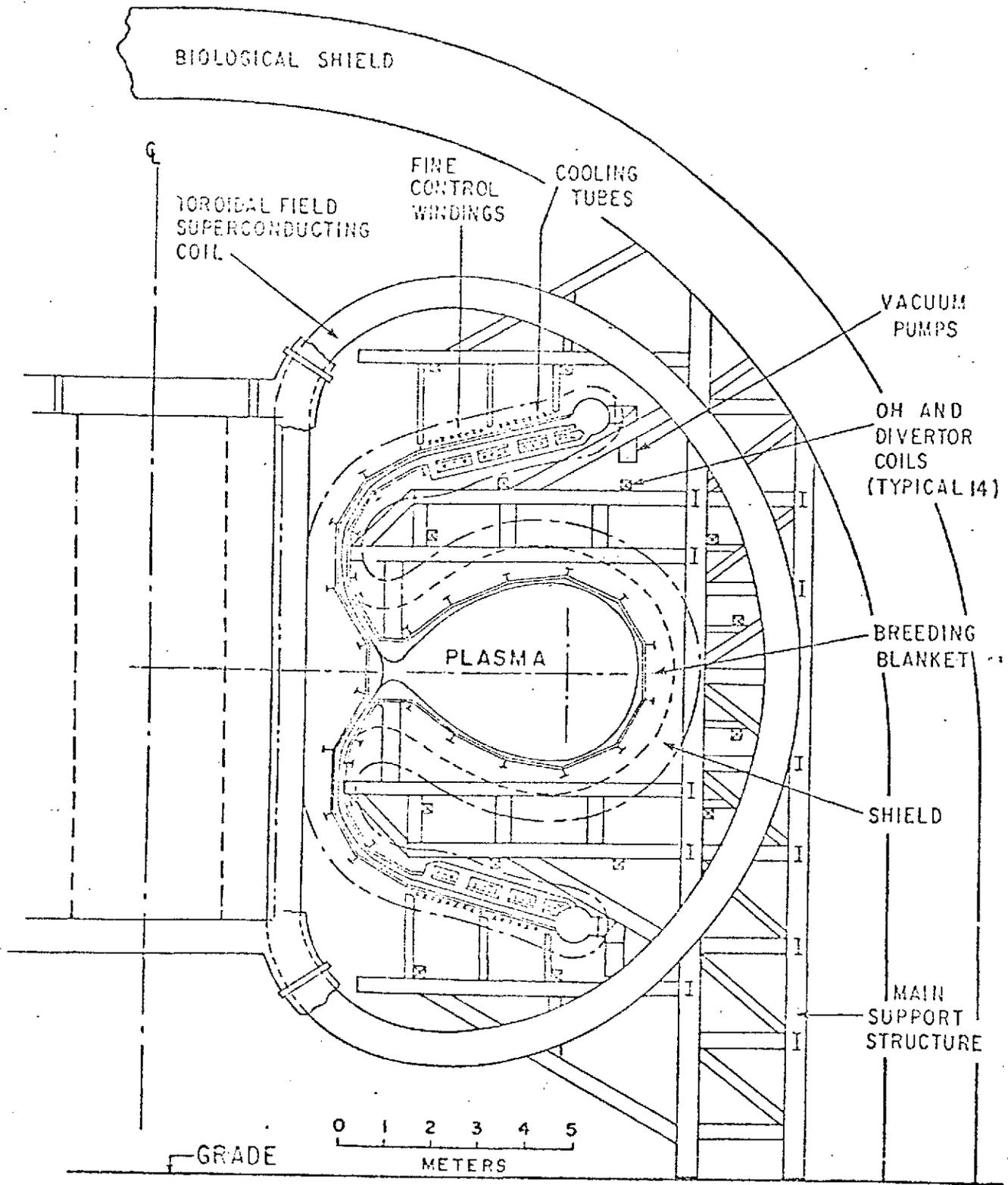


FIGURE 15. Princeton Fusion Reactor Design. Source: WASH-1239

were placed outside the neutron shield in order for them to be either superconducting or cryogenically cooled. The divertor windings also provide the vertical magnetic field that is necessary for plasma equilibrium. Furthermore, the size scale had to be sufficient to permit adequate neutron shielding between the reacting plasma and the superconducting toroidal field coils thereby limiting the heat deposition in the coils by the neutrons to acceptable levels.

In keeping with Item 3 above, stainless steel is the chief construction material. The vacuum wall is constructed of stainless steel plates welded on a steel framework. Liquid lithium is not used as a coolant to avoid associated MHD problems, but lithium in the form of flibe is used for tritium breeding. The blanket is cooled by helium gas which in turn is used to drive helium gas turbines.

The use of stainless steel limits the blanket operating temperatures to about 550°C. Thence the design foregoes the advantages of higher thermal cycle efficiencies that can be achieved with higher operating temperatures. However, the use of higher temperatures would require the use of a refractory metal, such as niobium, which is not in common use today.

The use of helium coolant has been proposed in several other fusion reactor prototypes.

New University Programs

In addition to the programs at Princeton and the schools listed previously, new university curricula reflect growing interest in nuclear fusion as an alternative energy source. At Georgia Institute of Technology, the School of Nuclear Engineering presently offers curricula in Thermonuclear Engineering. Work in progress includes fusion reactor neutronics calculations, advanced fusion energy conversion studies, and comparison of fusion power with alternate energy sources.

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