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Controlled Thermonuclear Research at LASL

los alamos
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of the University of California
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Present Status and Future Plans
for Feasibility and Reactor Experiments

by

Members of the LASL CTR Staff

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SECTION I

SUMMARY AND INTRODUCTION

R. F. Taschek

For the LASL CTR Staff

Recent scientific progress toward controlled thermonuclear fusion has been sufficiently encouraging to justify an acceleration of the effort to demonstrate scientific feasibility of this approach to power production and to consider now the problems of producing a demonstration reactor. It seems evident that even those experiments leading only to scientific feasibility are going to be very costly. If they and the follow-on demonstration reactor programs are to be accomplished within a time frame of national interest the reasons for these costs and the risks involved must be recognized and accepted and provisions made for implementing the programs on a sound basis.

In a sufficiently hot deuterium or deuterium and tritium gas, the thermal collisions between atomic nuclei cause them to undergo nuclear fusion reactions which release energy. A demonstration of scientific feasibility consists of heating and containing such a gas, which must be extremely hot by engineering standards, long enough for as much energy to be released from fusion reactions as is invested in heating the plasma. Since the rate of fusion reactions depends on the density of atoms in the reacting gas, it is the product of density, n, and containment time, τ, which must be made sufficiently large. If the reacting gas is half deuterium and half tritium then energy break even occurs when the product $n\tau$ is greater than about 4×10^{13}, where n is in ions per cubic centimeter and τ is in seconds. With pure deuterium the required value of $n\tau$ is higher. Typically n might be 10^{16} atoms per cubic centimeter and τ would then need to be longer than 10^{-2} seconds. The gas temperature must be at least five thousand electron volts (one electron volt is 11,000°C) and more realistically should be over ten thousand electron volts (usually written 10-keV). In order that a demonstration of scientific feasibility be credible as a basis from which to proceed to engineering and economic feasibility, it must be achieved in such a way that there is no known insurmountable technical or scientific obstacle to improve heating and containment beyond the above break-even conditions. For example, it might be possible in a particular kind of containment device to exceed $n\tau \approx 4\times10^{13}$ in a region 10 centimeters in diameter but not in a region one meter in diameter which might be required in an economic reactor. While this definition is somewhat subjective and there is some flexibility in the quantitative conditions, there is little doubt that when such scientific feasibility in this sense is demonstrated, it will be generally recognized by the scientific community.

The basic scientific problem which has beset controlled fusion is this: When a gas is heated to thermonuclear temperature it cannot be contained by a material pressure vessel. Because a gas at such temperatures is in the fully ionized, or plasma, state, and hence a good electrical conductor, it can in principle be contained by a magnetic field. However, matter in the plasma state has very different fundamental properties than it does in the ordinary gaseous state, in addition to its high electrical conductivity. In order to understand these often surprising properties well enough to succeed with the heating and subsequent stable confinement of a thermonuclear plasma it has been necessary to develop the almost completely new science of plasma physics. This has taken about twenty years, and while unsolved problems remain, considerable progress has been made. Early difficulties with heating and containment are beginning to be understood, and containment values of $n\tau$ near 10^{12} have been reached. At Los Alamos this has been done in θ pinches at a temperature of over 2 keV, while at a temperature of 5 keV, $n\tau = 2\times10^{11}$ has been achieved. Typical densities are a few x 10^{16}. It now seems quite possible that simple scaling of some present devices to larger size would be adequate to demonstrate scientific feasibility later in this decade, and that scientific work now in progress will make the job much easier.

Once the necessary containment and temperature are achieved in a scientific feasibility experiment, attention must be turned to engineering a fusion reactor which is economical of energy losses while providing magnetic field and plasma, and whose inner wall has sufficient cooling to tolerate the thermonuclear power flux on it. A device which provides an overall excess of thermonuclear power against total system input power will constitute a demonstration reactor. In the case of a D-T system it must incorporate a tritium and liquid-lithium handling system, as well as the generating plant and auxiliaries.

The basic Los Alamos approach to controlled fusion is conceptually simple. A cylindrical column of high temperature deuterium or deuterium and tritium plasma is produced by a rapid compression of relatively cold, but ionized, gas (preionized plasma). The compression heating is accomplished by the sudden application of a large magnetic field which pushes the preionized plasma inward away from the walls of the containment tube and subsequently holds the confined plasma near the center of the tube out of contact with material walls. Such a plasma heating and containment device is called a pinch. There are two basic types of pinches depending on the direction of electric current flow which provides the magnetic field to contain the plasma column; in a z-pinch the current flows along the plasma column and in a θ pinch the current flows around the plasma column.

At the present time there are two active programs at Los Alamos which are directed toward experimental demonstration of the scientific feasibility of controlled fusion within this decade, and toward a later demonstration reactor if the scientific and technical results warrant.

Section II is a self-contained description of the experimental effort on straight and toroidal theta pinches which has culminated in the 15-meter Scyllac device, part of which is now in operation. Fewer scientific questions remain to be answered before proceeding with a scientific feasibility demonstration in a straight theta pinch than in a toroidal one. However, the toroidal system, if proven in Scyllac, leads to a smaller, less expensive system and, in the case of a reactor, to one with a smaller minimum output power. Two options now appear: (1) On the basis of present theory a toroidal theta-pinch feasibility demonstration would be possible in a torus having a major diameter of about 50 meters and an overall cost of about $30 million. (2) The only way observed so far in which plasma escapes from a long, straight theta pinch is through unavoidable holes in the magnetic containment system at the ends of the device. By using established methods to minimize this end loss, it is expected that scientific feasibility could be achieved with a one-kilometer-long theta pinch at a cost of about $90 million on a somewhat longer time scale than in the toroidal case. The general features of a theta-pinch pulsed reactor core and plant, as indicated by feasibility studies over the past several years, are also discussed in Section II.

Section III describes the Los Alamos toroidal z-pinch program. It is expected that the ZT-1 device now under construction will show significant improvements in toroidal confinement, as indicated by recent straight z-pinch experiments. However, only a toroidal z-pinch is being considered as a controlled fusion device. Given suitable progress in this area, scientific feasibility could be domonstrated in a toroidal z-pinch at a program cost of $15 million.

Underlying these major experiments there is required a continuing mathematical and experimental effort to understand the physics of thermonuclear plasmas. This effort is built on the accumulated experience of twenty years of research in plasma physics at Los Alamos and is now making increasingly effective use of the outstanding Los Alamos computer facilities.

At present, pre-feasibility experiments are in progress, but much more work is needed on long lead time technological developments to support the feasibility experiments. In particular it is believed that capacitor energy storage will be impractical for the θ-pinch feasibility experiment and will need to be replaced by cryogenic magnetic energy storage. Section IV is a description of the work that is needed in this area and the exceptional capabilities of the Los Alamos cryogenics group for doing this work. It follows of course that such energy storage technology, which may be necessary for feasibility experiments, will be essential for a fusion reactor. It might be possible to use capacitors for a z-pinch feasibility experiment.

Other long lead time scientific and technical work are required to support possible fusion reactor systems. Section V discusses neutron radiation damage, which will certainly be a serious problem, and which can be expected to be different from that encountered in fission reactors. Section VII discusses the metallurgical radiation effects problem and the scientific program which will have to be undertaken if the problem is to be overcome. It is essential that realistic radiation sources be used. For instance the properties of radiation in a fusion reactor are very different from radiation in fission reactors, and, therefore, fission reactor studies are only partially applicable. A specialized accelerator which could be used in laboratory testing is suggested as a source of radiation for performing such studies. Los Alamos has unique facilities and experience for supporting such work.

Fusion reactors are going to require wall materials for the containment tube or chamber which must withstand extraordinary abuse, not only from the neutron radiation which also penetrates the blanket, but also from the plasma's ultraviolet and x-radiation, and from the electrical discharge during initial plasma heating. They will also be exposed to elevated temperatures, perhaps 1000°C. In θ-pinch or Z-pinch devices the wall is subjected to large electric field stresses during the initial heating phase, and must maintain good dielectric properties in spite of the harsh environment. The problem is less severe in a scientific feasibility experiment which may have a very low duty factor but there will have to be further major technical development between scientific feasibility and a demonstration reactor.

In a D-T reactor there will be a closed tritium-handling cycle for recovering tritium generated in the blanket and purifying it for reinjection. LASL presently has an extensive tritium-handling facility and many years of experience in all aspects of this field. LASL can presently handle the inventory of a controlled thermonuclear reactor.

Section VI describes neutronics and radiation calculations which are needed for the design of fusion reactors, and a description of the Los Alamos capability for performing these calculations is given.

At this time, before scientific feasibility has been shown, it is difficult to estimate the time-and-cost scale for producing a demonstration reactor. However, the following remarks may be made. The scientific feasibility experiments, if successful, would necessarily embody many of the essential technological ingredients of fusion reactors. The difficult technology which would have to be developed between scientific feasibility and a demonstration reactor and finally an economical power-producing fusion reactor will require diligent work over a considerable period of time. Optimistically it could be done in a period of ten years after scientific feasibility demonstration, placing the demonstration reactor in the late 1980's. This very short time scale would, however, require immediate support of technological studies and CTR budgets, increasing by approximately a factor 2 every two years or so into the range of several hundred million dollars per year for the U. S. program.

Although it has been stressed above, it bears repeating that the Los Alamos Scientific Laboratory has an extensive and unique combined capability for fusion reactor development.

In the following reports the categories mentioned above are discussed in detail by experts in each field.

A ten-year financial forecast for the Los Alamos CTR effort leading to scientific feasibility experiments and beyond is given in Table I.

TABLE I

BUDGET SUMMARY
(Dollars in Thousands)

	FY 72	FY 73	FY 74	FY 75	FY 76	FY 77	FY 78	FY 79	FY 80	FY 81	FY 82
05-07-01-01											
Research											
Scientific Man Years	8	9	9	10	11	12	13	14	14	15	15
Total Direct Personnel	10	12	13	15	17	18	19	21	22	21	24
Hardcore Costs	425	525	580	705	820	945	1,065	1,230	1,340	1,500	1,630
Device Procurement	25	55	60	65	70	75	75	80	80	90	90
Total Costs	450	580	640	770	890	1,020	1,140	1,310	1,420	1,590	1,720
05-07-01-02											
Development*											
Scientific Man Years	16	18	25	27	25	24	25	26	26	29	29
Total Direct Personnel	29	36	55	59	57	52	55	58	58	65	65
Hardcore Costs	1,060	1,345	2,115	2,405	2,420	2,385	2,655	2,950	3,120	3,710	3,930
Device Procurement	-0-	305	325	375	400	425	325	350	350	350	350
Total Costs	1,060	1,650	2,440	2,780	2,820	2,810	2,980	3,300	3,470	4,060	4,280
05-07-02-01-1											
Open Confinement Systems**											
Scientific Man Years	7	8	3	3	2	2	2	2	2	2	2
Total Direct Personnel	25	19	3	3	2	2	2	2	2	2	2
Hardcore Costs	750	670	160	170	110	120	130	140	150	160	170
Device Procurement	150	75	-0-	-0-	-0-	-0-	-0-	-0-	-0-	-0-	-0-
Total Costs	900	745	160	170	110	120	130	140	150	160	170

*After FY-1977 the majortiy of "Development" will be charged to 05-07-03 "Fusion Power and Energy Conversion Technology".

**After FY-1972 Open Confinement Research will be theoretical studies.

TABLE I (Continued)

BUDGET SUMMARY
(Dollars in Thousands)

	FY 72	FY 73	FY 74	FY 75	FY 76	FY 77	FY 78	FY 79	FY 80	FY 81	FY 82
05-07-02-01-2											
Closed Confinement Systems											
Theta Pinch Program											
Scientific Man Years	14	20	23	28	34	41	43	45	47	45	46
Total Direct Personnel	36	58	73	88	100	123	129	135	139	132	133
Hardcore Costs	1,180	1,980	2,550	3,280	4,050	5,130	5,700	6,300	6,980	6,955	7,475
Device Procurement	250	825	800	600	900	750	750	800	650	675	775
Total Costs	1,430	2,805	3,350	3,880	4,950	5,880	6,450	7,100	7,630	7,630	8,250
Z-Pinch Program											
Scientific Man Years	10	12	17	19	21	23	24	24	26	28	29
Total Direct Personnel	15	21	29	35	41	45	48	48	54	56	59
Hardcore Costs	580	820	1,210	1,500	1,830	2,120	2,400	2,550	2,980	3,310	3,680
Device Procurement	80	200	200	100	200	250	300	300	350	350	400
Total Costs	660	1,020	1,410	1,600	2,030	2,370	2,700	2,850	3,330	3,660	4,080
Grand Total Costs (Million Dollars)	4.5	6.8	8.0	9.2	10.8	12.2	13.4	14.7	16.0	17.1	18.5
(M D F Costs Within Total Costs)		400	300	100	400	400	300				
Total Scientific Man Years	55	67	77	87	93	102	107	111	115	119	121
Total Direct Personnel	115	146	173	200	217	240	253	264	275	276	283

SECTION II

PULSED, HIGH-β, THETA-PINCH EXPERIMENTS AND REACTOR SYSTEMS

F. L. Ribe

1. Properties of High-β Plasmas The quantity β is the ratio of plasma pressure to that of the containing magnetic field. In present θ-pinch experiments and in the corresponding eventual fusion reactors both pressures are hundreds of atmospheres. High-β plasmas react strongly on the confining magnetic field, pushing it aside instead of being almost completely permeated by it, as in the low-β case. In a θ pinch a cylindrical rod of plasma is confined by a longitudinal magnetic field (i.e., one parallel to the plasma axis), and one defines β by the pressure balance shown in Fig. 1. The particle pressure makes an appreciable "dent" in the magnetic field whose pressure would otherwise be uniform and have the value $B_0^2/8\pi$.

The factor β^2 measures how efficiently magnetic field is utilized in a fusion reactor. All feasibility studies indicate that β itself must be greater than about 10% if the magnetic fields in a fusion reactor are to be small enough to accommodate present superconductor technology (i.e., not much more than 100,000 gauss). In θ pinches β has values between 50 and 100 percent.

2. Plasmas in Theta Pinches For the past 13 years high-beta research has been carried out predominantly with the theta pinch in Los Alamos and in Great Britain and West Germany. These devices produce plasmas at near reactor conditions. The ion temperatures are as large as 5 keV (50,000,000°K), and the densities are in the range of 10^{16} to 10^{17} particles per cc. The plasma densities are typically 1000 to 10,000 times greater than those in low-β experiments (Tokamaks and mirror devices). The containment times are correspondingly shorter (2 to 10 microseconds, as

$$\beta(r) = \frac{nk(T_e + T_i)}{B_0^2/8\pi}$$

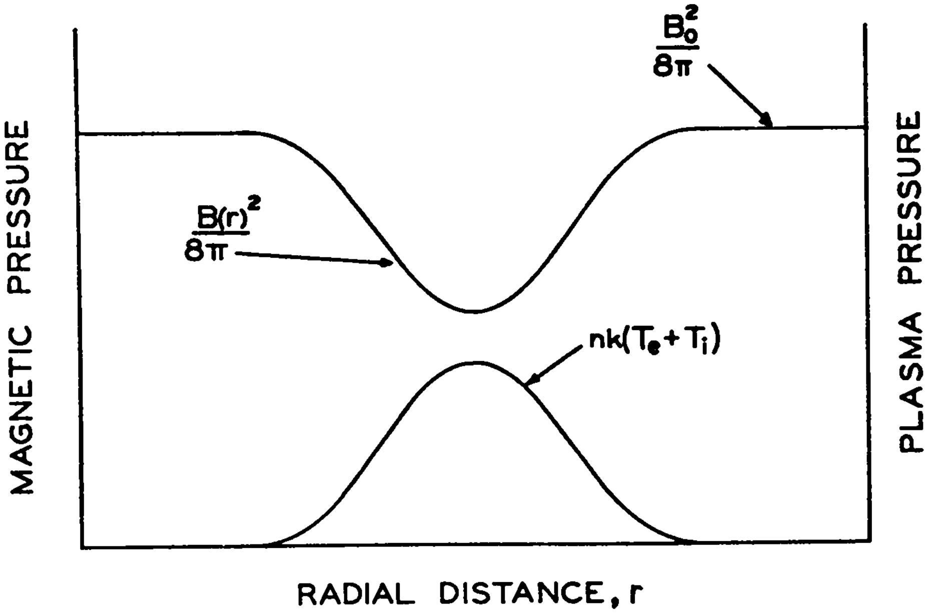


Fig. 1. Illustrating plasma and magnetic pressures for a high-β plasma. The axis of the plasma cylinder is in the center of the graph.

opposed to tens or hundreds of milliseconds). Beta values are typically 0.5 to 0.9. These experiments have progressed over the years from very short lengths of about 1/10 meter to lengths in present experiments of many meters (15 meters for Scyllac at Los Alamos). $n\tau$ values presently achieved are 4×10^{11} cm^{-3} sec.

3. Operation of θ-Pinch Experiments A θ-pinch experiment (Scylla IV-3), capable of producing a 3-meter column of thermonuclear plasma, is shown in Fig. 2. The compression coil shown below is made of thick aluminum to withstand the high magnetic pressures. It is fed by the white coaxial cables from some 300 capacitors, each with a spark-gap switch.

As an illustration of diagnostic measurements on a θ-pinch plasma we show an end-on interferogram in Fig. 3. It was made with a ruby laser by means of the holographic technique illustrated at the bottom. Here two beams, one through the discharge tube and one through air, produce an interference pattern on the photographic plate. Refraction by the plasma modifies this pattern (or hologram) to produce the circular fringes. The plasma density is obtained by simply counting the fringes. This case of measurement is typical of work at high densities, where the plasma is conveniently luminous, as well as refractive to visible light.

4. The Containment Limitation in Linear θ Pinches is the flow of plasma out the ends. The end loss time is closely related to the time of flight of an ion at its thermal speed from the center of the plasma to an end. By the use of mirrors (regions of increased magnetic field) at the ends, the flow can be constricted and the containment time increased.

5. Near-Classical Diffusion of θ-Pinch Plasmas A central problem in obtaining the long-time confinement of plasma which is necessary to a fusion reactor is to be sure that the rate at which plasma diffuses across the confining magnetic field is sufficiently low. The lowest limiting rate is the "classical" rate, caused by collisions of electrons and ions. The highest limiting rate is that caused by collisions of electrons with charge fluctuations in the plasma. This is called the Bohm rate of diffusion and

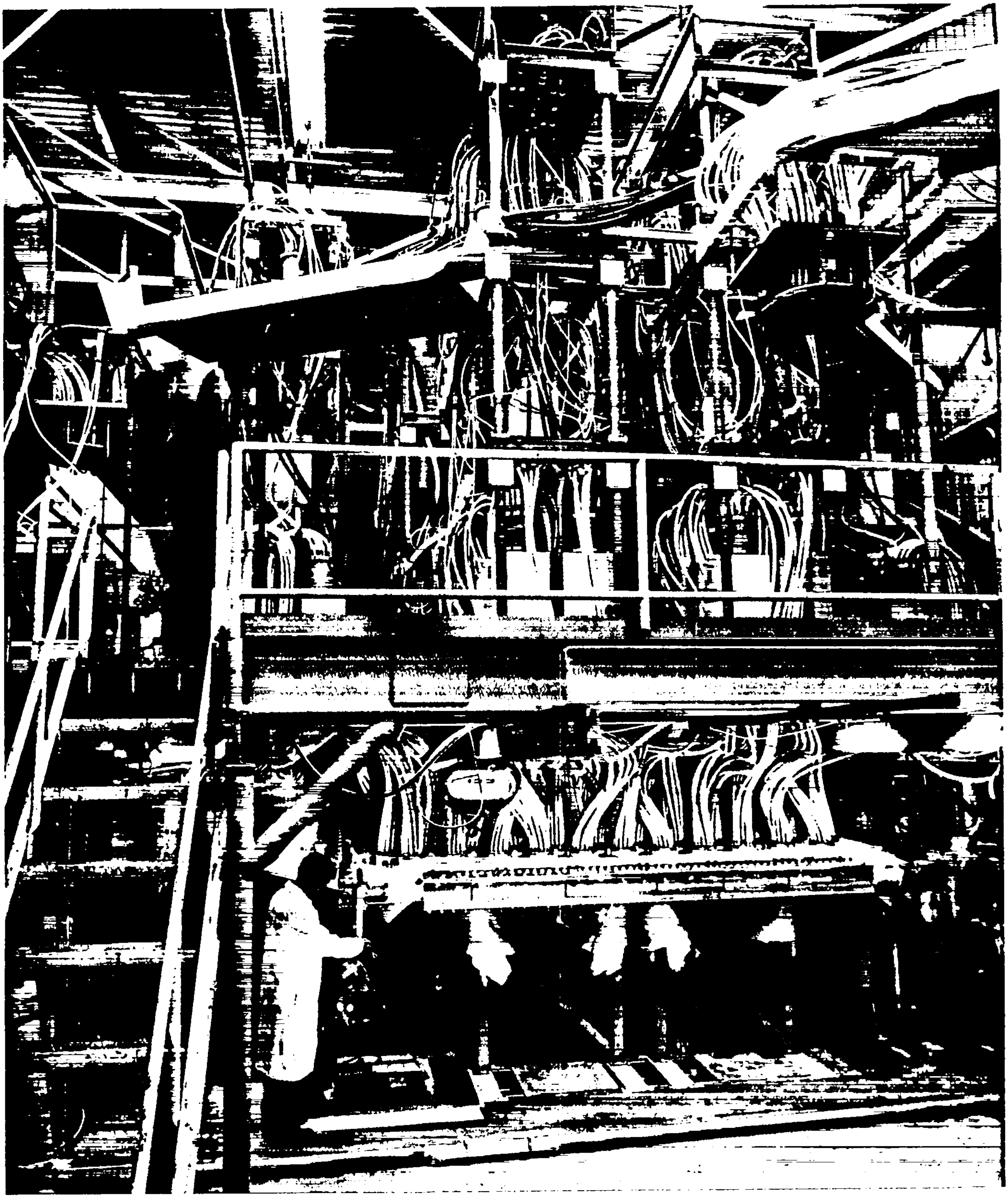


Fig. 2. Three-meter θ-pinch Scylla IV at Los Alamos.

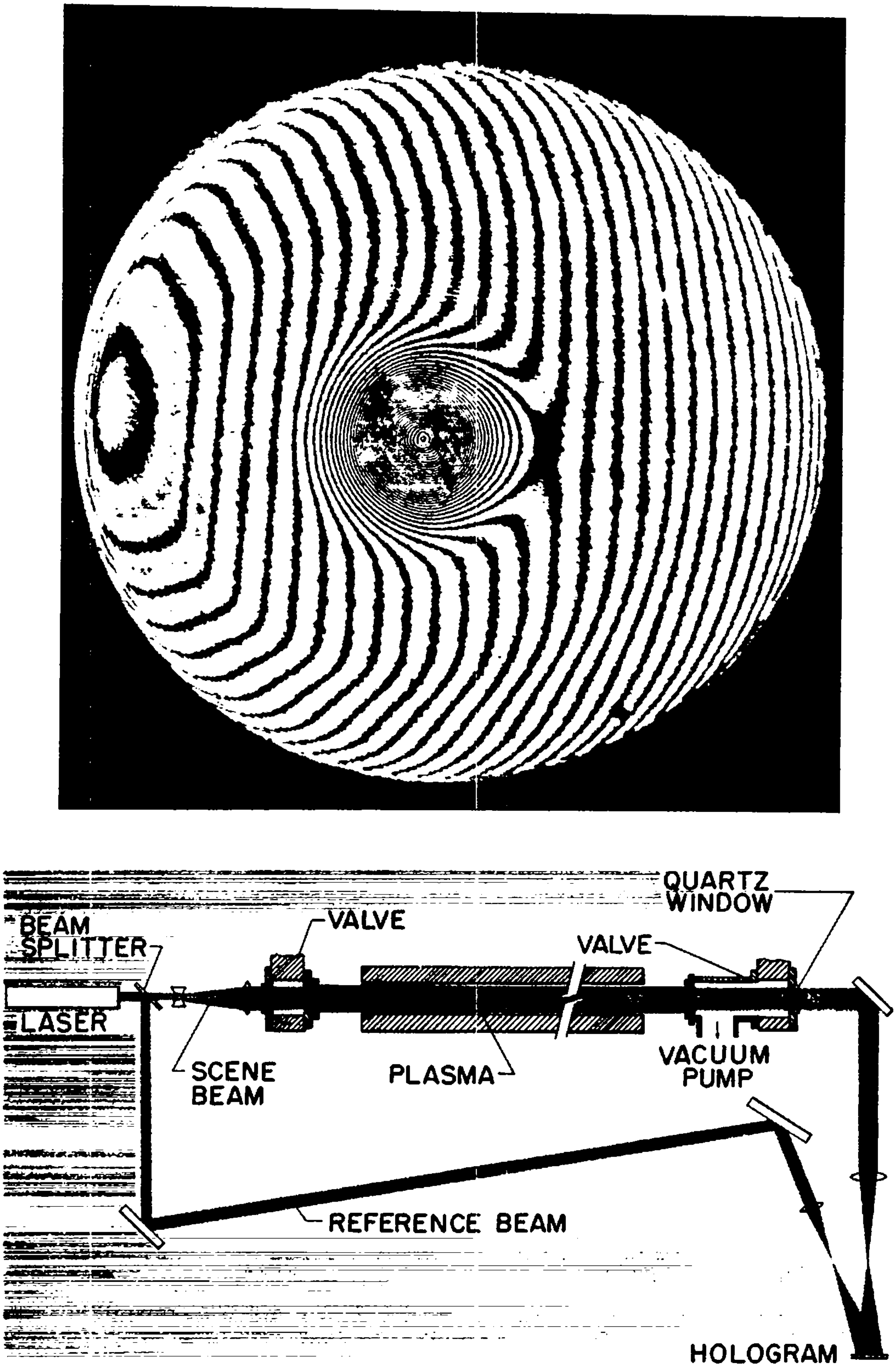


Fig. 3. a) End-on interferogram of plasma in the Los Alamos 3-meter θ pinch. b) Schematic view of apparatus using holography to produce interferograms.

is excessive for a reactor.

One of the most striking results on plasma diffusion was obtained in 1968 by the Culham group using an 8-meter theta-pinch plasma column with $\beta = 0.5$. They showed that the observed diffusion is slower than Bohm diffusion by a factor of at least 100 and may indeed be classical.

6. Toroidal High-β Systems In view of the end-loss containment limitation in linear systems major attention in the high-β laboratories has turned toward producing systems without ends---toroidal systems.

Figure 4A shows a section of the toroidal plasma which would occur if one simply bent a linear θ pinch into a torus. The plasma experiences an outward toroidal force of expansion (called F_R) because the magnetic lines are bent and therefore stronger on the inside than the outside. This force must be cancelled in order to keep the plasma in the torus.

In the Scyllac system to be described below the lines are made to vary periodically so that the plasma surface is helical, but with greater helical excursions on the inside than the outside, as shown in Fig. 4B. This produces a magnetic force (called F_δ) which cancels the toroidal force.

7. The 15-Meter Scyllac θ Pinch at Los Alamos In 1968, after a favorable report by an Ad Hoc panel of the CTR branch of AEC Division of Research, construction funds were authorized by Congress for a θ pinch capable of producing a 15-meter-long thermonuclear plasma, eventually in the form of a torus of 5-meter diameter. The capacitor bank and switching are such that magnetic fields of 100,000 gauss can be produced and held in the compression coil, decaying in about 0.25 msec. With modified switching, if plasma containment is sufficiently successful to warrant it, the magnetic field can be held for about 2.5 msec. The corresponding effective plasma containment times τ would be about 0.1 msec and 1 msec and the densities about 5×10^{16} ions per cc. The corresponding products $n\tau$, which measure the approach to plasma energy breakeven (at a value of about 10^{14} cm^{-3} sec, see below) would be 5×10^{12} and 5×10^{13} respectively. Success in the

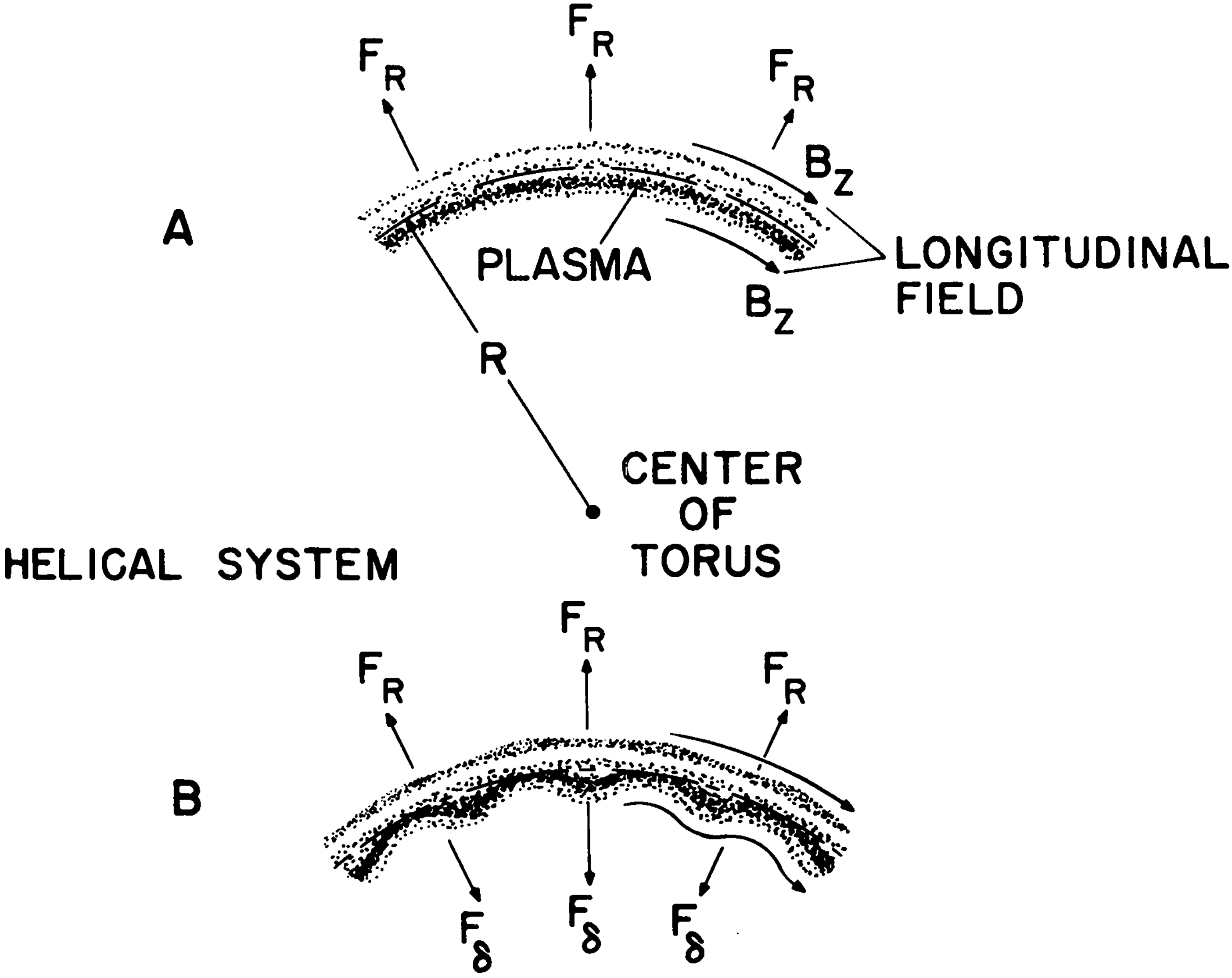


Fig. 4. Illustrating the helical toroidal system.

toroidal experiment at high β and thermonuclear temperature for the 1 msec containment time would closely approach energy breakeven.

a) Initial Configuration Figure 5 shows the initial configuration of Scyllac, now under construction. It consists of a 5-meter toroidal sector and a 5.5-meter linear θ pinch with 2:1 mirrors (end regions where the magnetic field is increased by a factor of 2, to nearly 200,000 gauss).

b) 5-Meter Toroidal Sector In the 5-meter toroidal sector a test will be made of the $\ell = 1$ helical high-β equilibrium. Even though this system is still end-loss limited, there will be ample time, with this long length, to observe the attainment of toroidal equilibrium and the growth of any MHD instability which needs to be feedback stabilized. This system (Fig. 6) is now in operation.

c) The 5.5-Meter Linear System The linear system has as its primary objects to test (a) diffusion rates; (b) end-loss scaling in simple geometry, using thermonuclear collisionless plasma; (c) the effects of high-β mirrors; and (d) thermal-conductivity losses along magnetic lines.

By using mirrors we can, according to theory, gain a factor of 2.5 in containment time, owing to the constriction of the effective end region through which plasma can be lost. This gives the effect of a 12-meter device for the 5.5-meter length. With this system we expect to achieve $n\tau$ values between 1 and 2×10^{12} cm^{-3} sec. It is important to see if the mirrors themselves will introduce instability in the presence of the end-loss plasma. The mirrors would greatly simplify the problem of producing a reactor based on the linear θ pinch.

(d) Final Toroidal Configuration Figure 7 shows Scyllac in its 15-meter toroidal form into which it will be rearranged when experiments in the initial configuration are complete, and if the toroidal experiments in the sector warrant.

8. Conditions Required for a Scientific Feasibility Demonstration and for a Fusion Reactor In order to proceed from present high-β plasma experiments, we must contain the plasma for considerably longer times. This is

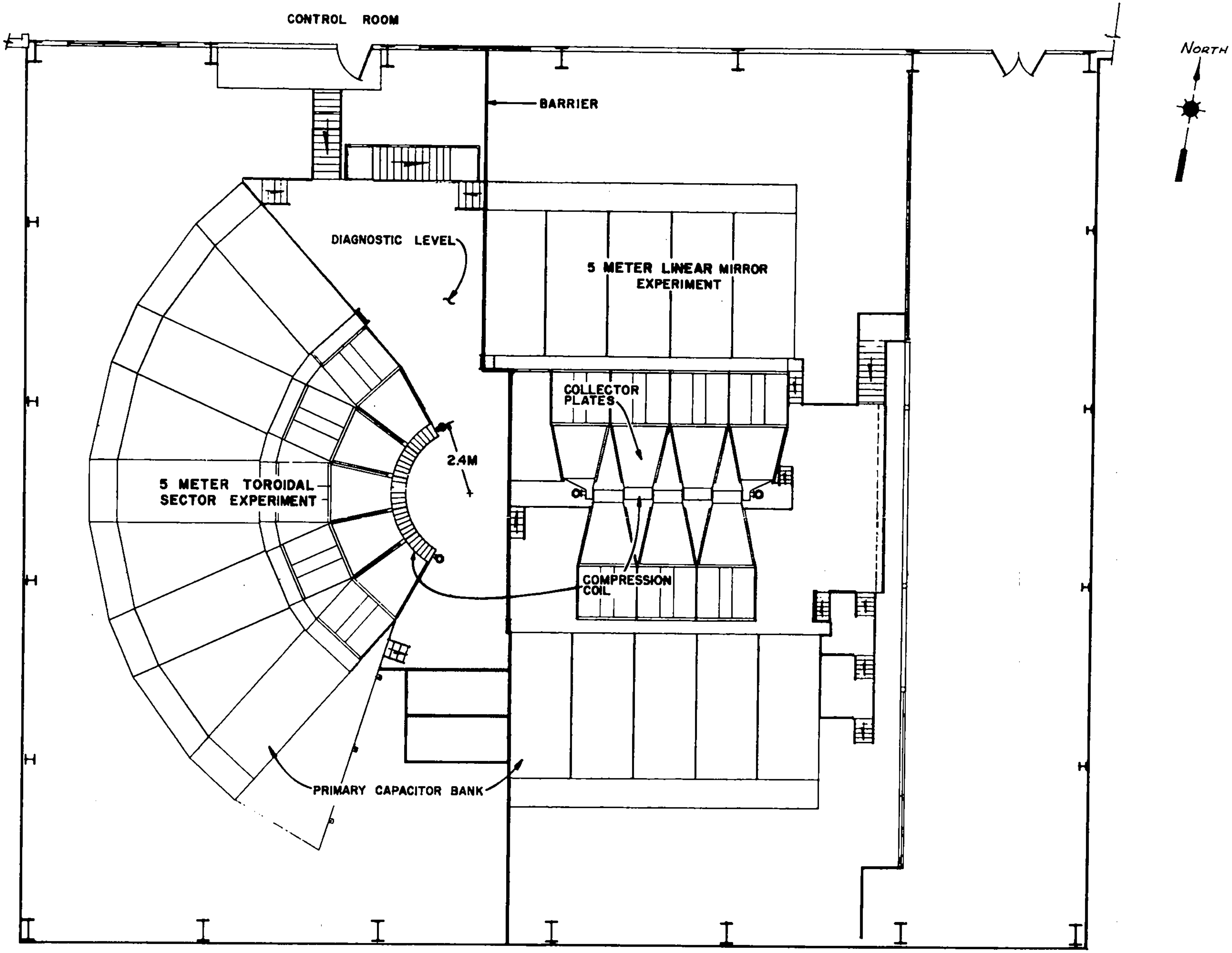


Fig. 5. Initial configuration of the Scyllac θ pinch at Los Alamos.

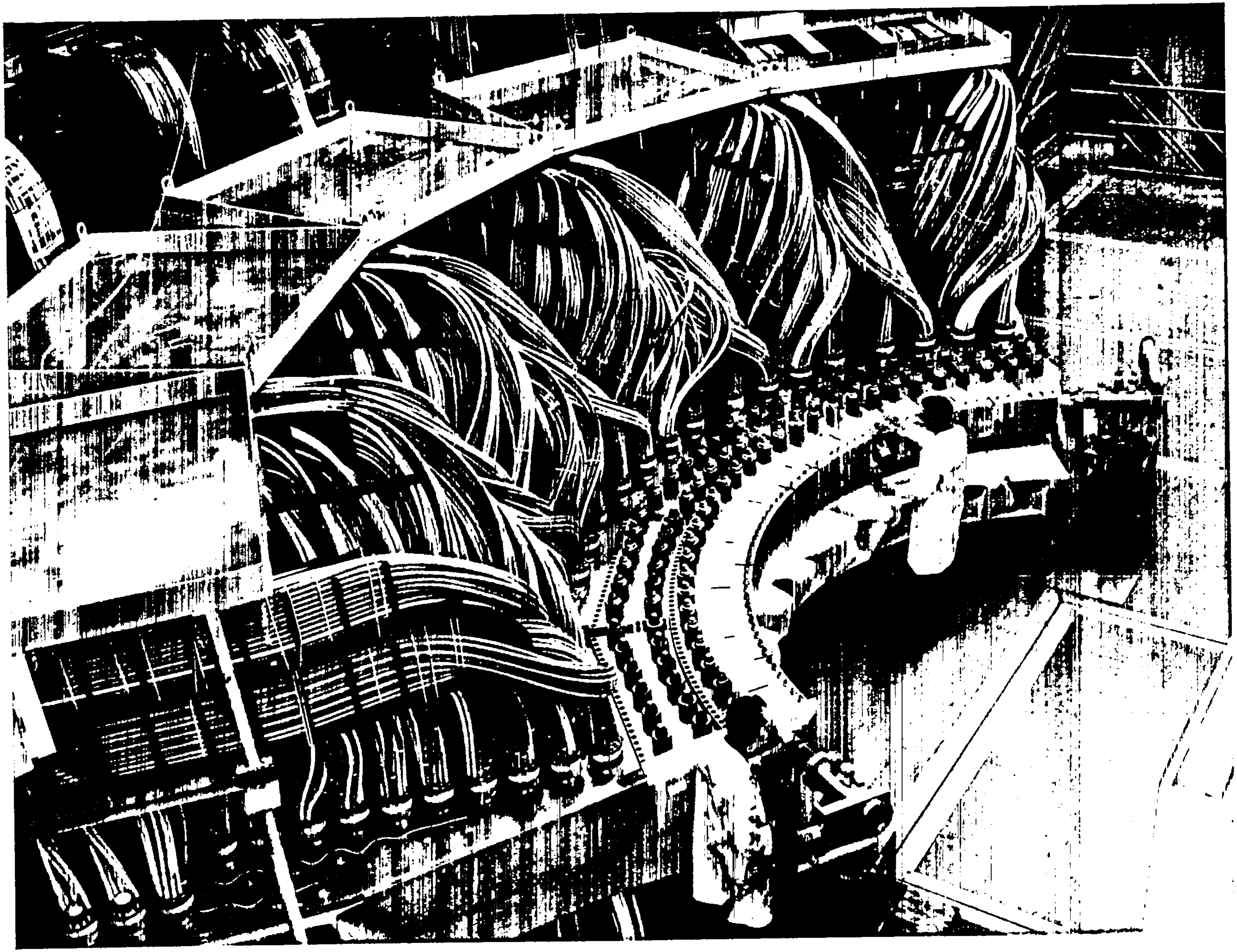


Fig. 6. The toroidal-sector Scyllac experiment.

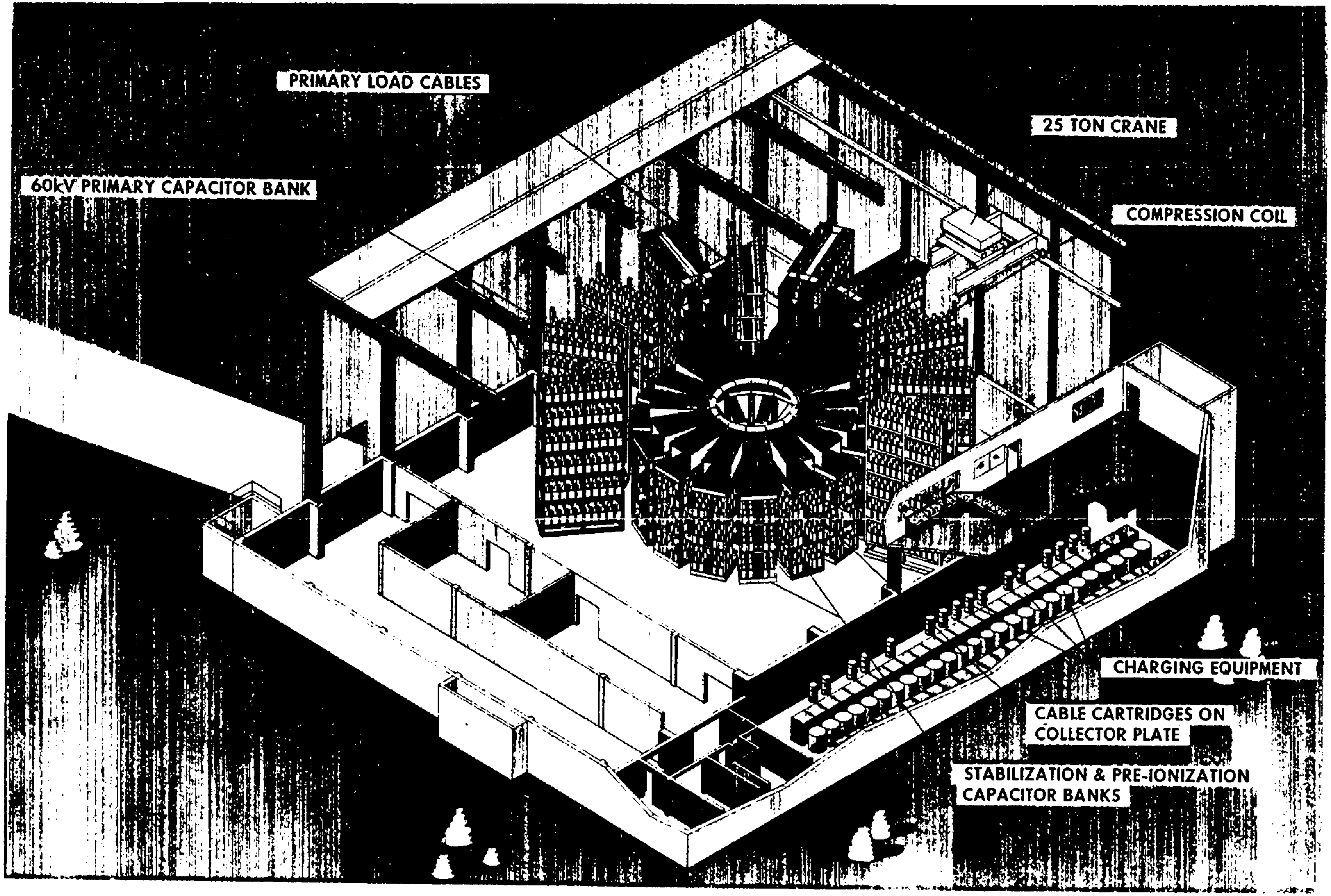


Fig. 7. 15-meter toroidal configuration of Scyllac.

necessary to achieve the degree of plasma fuel burnup necessary for the fusion energy release to overcome the losses incurred in producing the plasma (energy breakeven at which $n\tau = 4 \times 10^{13}$ cm^{-3} and fuel burnup is 1%). This condition can be taken as the criterion for a demonstration of scientific feasibility if it is achieved in a configuration which has technological components similar to those of a reactor.

Once the necessary burnup is achieved, attention must be turned to engineering a fusion reactor which is economical of energy losses in providing magnetic field and plasma and whose first wall has sufficient cooling for the thermonuclear power flux on it. A device which provides an overall excess of thermonuclear power against total system input power will constitute a demonstration reactor. In the case of a D-T system it must incorporate a tritium and liquid-lithium handling system, as well as the generating plant and auxiliaries.

9. Magnets for Pulsed Reactors and Feasibility Experiments In one respect these present a less stringent problem than for the steady-state case because of the smaller energies and sizes involved. However, there is the unique problem of changing the field in a superconducting storage coil as energy is transferred out of it to the compression coil of the reactor which can be at a much higher temperature.

The problem of maintaining superconductor stability and minimizing energy losses under transient conditions is under investigation at Los Alamos. We have an active program involving the use of very finely divided superconducting strands in small stabilizing copper wires, braided to give magnet windings of minimum loss and maximum stability under transient conditions involving times of 1 to 10 msec. A 30-kJ superconducting magnet, capable of fast switching and energy transfer is being constructed as a first step to investigate the transient problems involved in the large (100 MJ to 100 GJ) systems required for next generation feasibility experiments and for reactors.

10. Switching of Pulsed Magnets

a) Reactor Systems In the final reactor, where good energy balance and consequent low circulating power are important, it appears necessary to use variable inductors (rotating machinery with fields furnished by superconductors) to provide energy transfer from storage magnet to compression coil.

b) Use of Superconducting Switches in Scientific Feasibility Systems

In the next generation of fusion experiments successful systems such as the theta pinch must be produced in sizes and configurations which model reactor plasma parameters and techniques and produce appropriate plasma burning conditions and times. In this case large magnets and compression coils can be most appropriately switched by resistive elements consisting of normal-going superconductors (see Fig. 8 below). Even though 50% of the energy is lost, the capital cost of magnetic field in the plasma compression coil is nevertheless greatly lowered over that for capacitor banks, such as are presently used in Scyllac. Cryogenic magnetic energy storage and switching are necessary to make large-scale scientific feasibility experiments practicable.

c) Development of Superconducting Switches for Transferring Large Amounts of Magnetic Energy There is an active program underway at Los Alamos to investigate this problem, and results have already shown normal-going transitions in superconductors carrying multi-kA currents in times as small as a fraction of one μsec. The work is being extended to the 30-kJ, 1-kA magnet mentioned above, and it is anticipated that progressively larger experimental systems will follow, leading to the θ-pinch feasibility experiment discussed below.

A circuit with a superconducting storage magnet is illustrated in Fig. 8. Here the primary inductance is a NbTi solenoid operating at about 30 kA and 20 kG, divided into sections, each of which is closed by a length of superconductor. When the superconductor closure is driven normal by a small pulse of current, it assumes a value R_{SC} and causes the current in the solenoid section to decay to zero. The parallel resistor R_B ($R_B < R_{SC}$) takes most of the dissipated energy at room temperature. The secondary is at room temperature and has current and voltage induced in it from the superconducting primary. It in turn energizes the θ-pinch compression coil on the left.

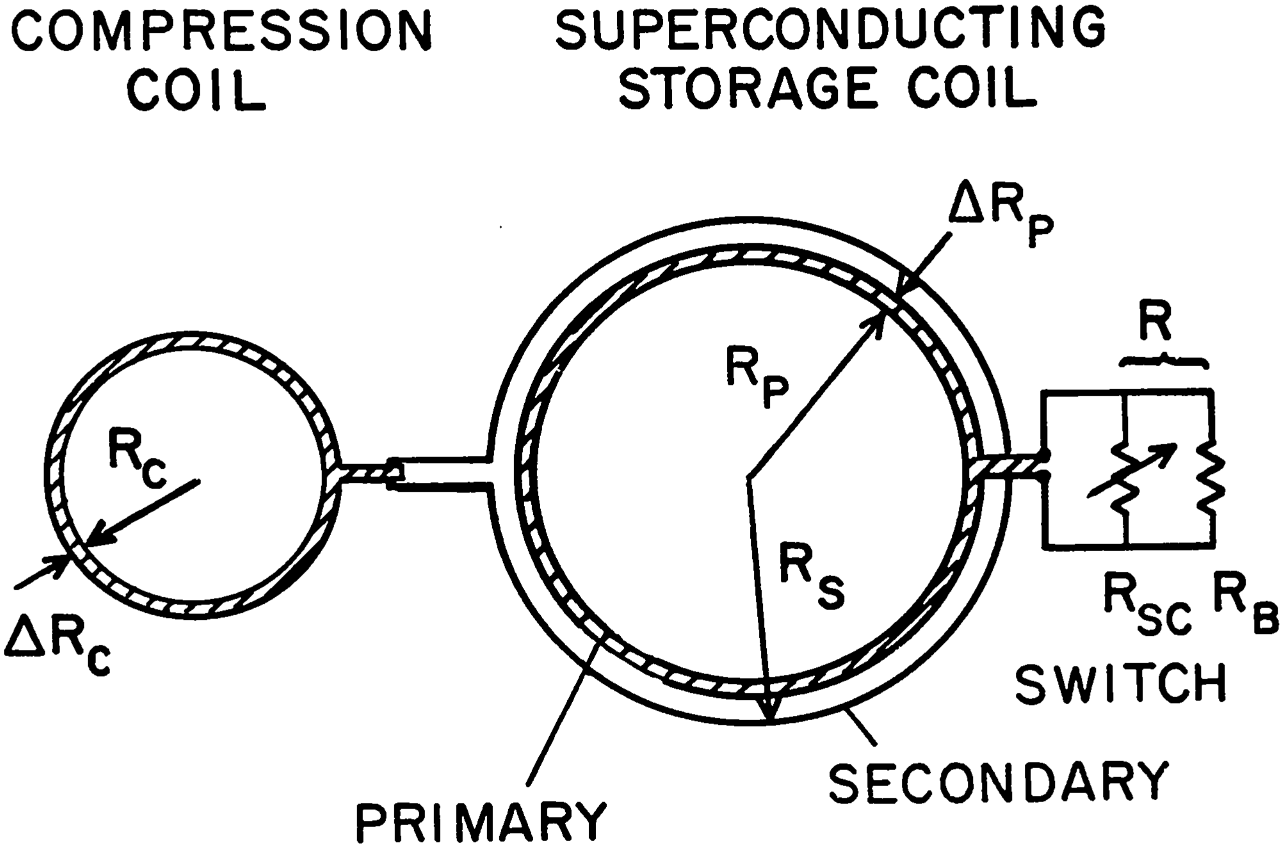


Fig. 8. Superconducting storage coil switched by means of a normal-going superconductor R_{SC} into the compression coil of a separated-shock θ pinch.

11. θ-Pinch Scientific Feasibility Experiments

a) The Separated-Shock θ Pinch For economic reasons it is essential to replace the capacitors which presently furnish the slow compression fields by cryogenic magnets, as discussed above. In order to accommodate this change, high-voltage electrostatic energy in much smaller amounts than the compression energy (about 1%) must be used to shock heat the plasma to 1 or 2 keV in a separate operation, followed by the slow magnetic compression whose energy source need not provide such shock heating. Thus the θ pinch has two distinct energy sources, one for shock heating and one for adiabatic compression, rather than one as at present. This is the principle of the separated-shock θ pinch.

In the separated-shock device a thin, single-turn coil is driven by charged Blumlein transmission lines according to established techniques, as shown in Fig. 9A. To prolong the fast-rising ramp of magnetic field from the line which shock heats the plasma the transmission line is backed with a few capacitors and "crowbar" switches (Fig. 9B). This allows time for the shock-heated plasma to be "picked up" by the more slowly rising compression field which is powered by the cryogenic magnets. A composite view of a separated-shock θ pinch, with the superconducting solenoid shown at the right, is shown in Fig. 10. The normal-going superconductor switches (not shown) would probably consist of lengths of coaxial conductor coiled inside the cryostat.

b) Time Schedules and Scientific Goals A time scale for development of the shock heating and cryogenic energy storage and separated-shock experiment (possibly using the LASL Zeus bank for slow compression) is shown in the lower portion of the pert chart of Fig. 11. This separated shock experiment and the superconducting store would be prototypes for the toroidal scientific feasibility experiment to be discussed below.

Table I gives cost schedules for the developments leading to the Scientific Feasibility experiment. The Cryogenic Magnetic Energy Storage development is discussed in Sec. IV.

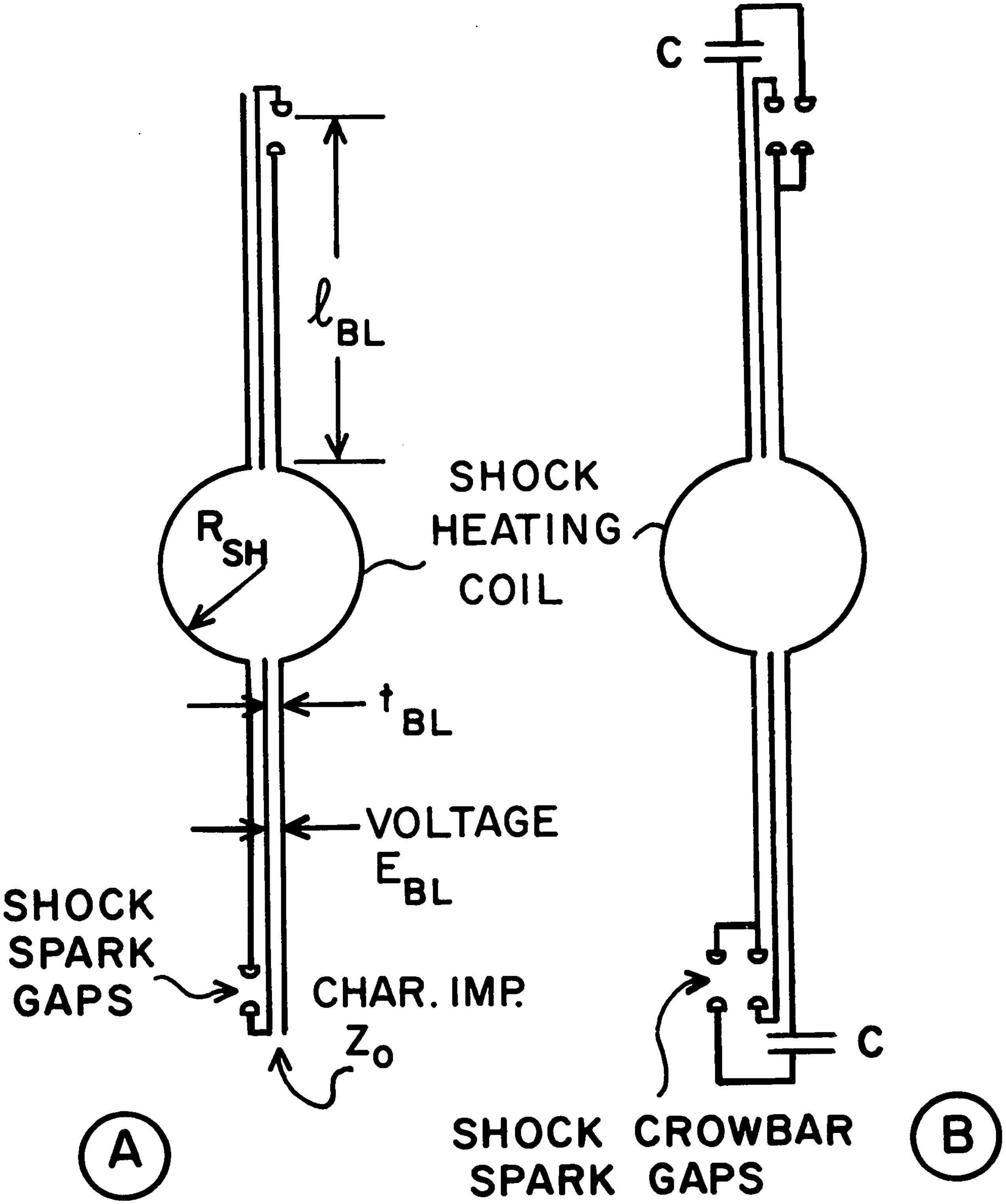


Fig. 9. Circuits for separately shock heating a θ pinch. The vertical lines represent Blumlein transmission lines.

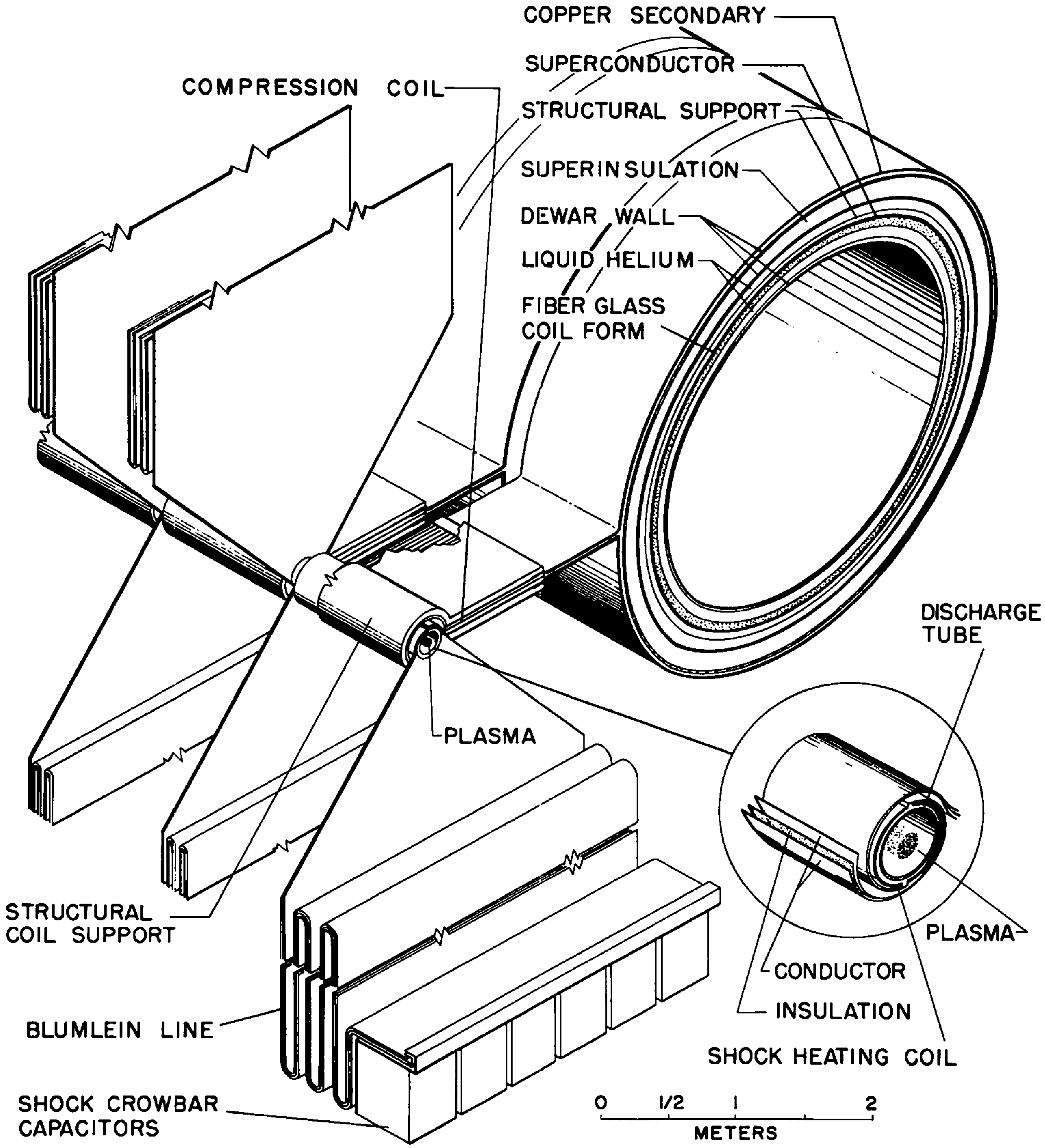


Fig. 10. Separated shock θ-pinch feasibility experiment. The shock heating circuit is on the left and the superconducting magnet is on the right.

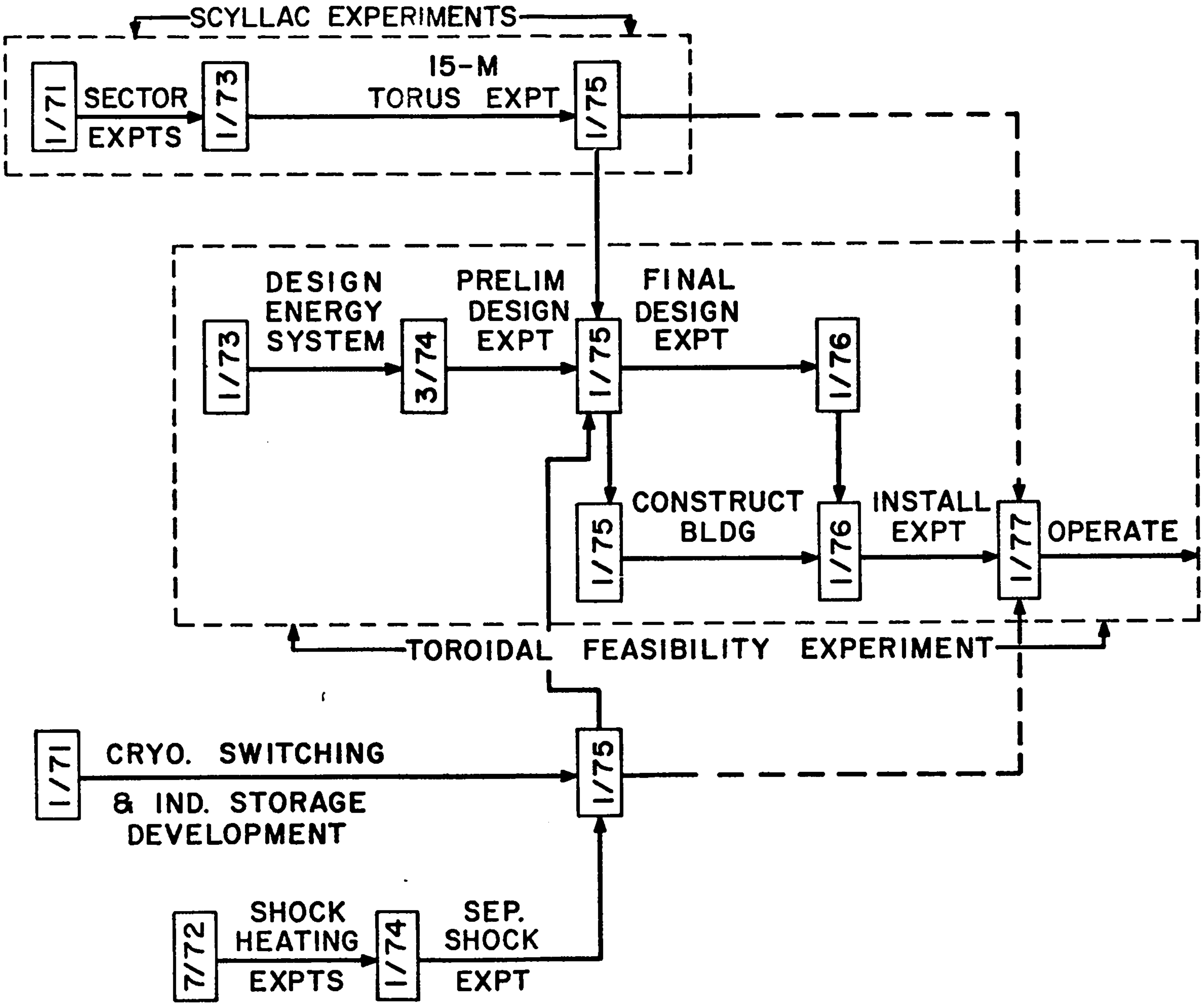


Fig. 11. Pert diagram of (top) toroidal Scyllac experiment, (bottom) prototype separated-shock experiment with cryogenic inductive storage, and (center) toroidal scientific feasibility experiment.

TABLE I

SCYLLAC TOROIDAL FEASIBILITY PROGRAM FORECAST

OPERATIONS ONLY

(Dollars in Thousands)

	FY 72	FY 73	FY 74	FY 75	FY 76	FY 77	FY 78	FY 79	FY 80	FY 81	FY 82
05-07-02-01-2											
Shock Heating											
Scientific Man Years	-0-	2	5	8	8	2	2	2	1	-0-	-0-
Total Direct Personnel	-0-	4	13	21	21	10	10	10	5	-0-	-0-
Hardcore Costs	-0-	150	475	810	850	375	400	420	225	-0-	-0-
Procurement Costs	-0-	75	100	100	100	50	50	50	50	-0-	-0-
Total Operations Cost	-0-	225	575	910	950	425	450	470	275	-0-	-0-
05-07-01-2											
Cryogenic Inductive											
Storage Developement											
Scientific Man Years	4	5	10	10	8	6	6	6	6	6	6
Total Direct Personnel	5	11	24	24	18	12	12	12	12	12	12
Hardcore Costs	210	400	900	950	770	560	600	630	675	710	750
Procurement Costs	-0-	150	200	250	250	300	200	200	200	200	200
Total Operations Cost	210	550	1,100	1,200	1,020	860	800	830	875	910	950
05-07-02-01-2											
Feasibility Device											
Scientific Man Years	-0-	-0-	-0-	2	2	15	16	17	20	23	24
Total Direct Personnel	-0-	-0-	-0-	2	6	40	43	46	58	63	64
Hardcore Costs	-0-	-0-	-0-	160	240	1,720	1,950	2,210	2,900	3,400	3,700
Procurement Costs	-0-	-0-	-0-	100	400	400	300	350	450	600	700
Total Operations Costs	-0-	-0-	-0-	260	640	2,120	2,250	2,560	3,350	4,000	4,400
Total Costs	210	775	1,675	2,370	2,610	3,405	3,500	3,860	4,500	4,910	5,350
(M D F Costs Within Total Costs)		400	300	100	400	400	300				

c) Toroidal Scientific Feasibility Experiment Figure 12 shows a toroidal version of Fig. 10 which is the scientific feasibility experiment. Both this and the linear version described below are designed for a Blumlein-line voltage of 50 to 75 kV (200 to 300 kV around the shock heating coil) and a compression field of 85 to 100 kG, having a risetime of a few msec and a plasma duration of 5 to 10 msec at a temperature of 5 to 10 keV and a density of a few times 10^{16} cm^{-3}. Lower densities, higher temperatures and longer times may be possible in the toroidal experiment by choices of lower filling densities.

Because of the use of cryogenic magnetic energy storage this device would cost about 5 cents per joule of compression-coil energy, as opposed to 60 cents per joule for Scyllac. In arriving at the circumference of the feasibility experiment, we project a system which utilizes the (ℓ = 1, ℓ = 0) configuration of Fig. 4B, which is the Scyllac system. The aspect ratio and ratio of plasma and wall radii (0.4) are chosen to give MHD stabilization by the wall of the shock heating coil at a beta value of ~ 0.8. The circumference is about 150 m and the plasma diameter about 6 cm.

The construction costs of the toroidal feasibility system are summarized in Table II. This table corresponds to the construction portion of the central portion of the PERT diagram of Fig. 11. The cost of the construction line item for the toroidal scientific feasibility experiment is $19M. Table II also summarizes associated operating costs.

d) Linear Experiment The linear θ pinch, because of its inherent simplicity and demonstrated success, could possibly provide the means of making an energy-breakeven demonstration experiment which involves the least scientific uncertainty. It would also test the feasibility of massive cryogenic energy storage and low-energy shock heating in a separated-shock experiment. Such an experiment is sometimes urged because it could probably be done on the basis of established scientific principles without further elaboration.

A schematic diagram of such a system is shown in Fig. 13. If 2.3:1 mirrors (as measured in vacuum) were used its length would be about 1 km.

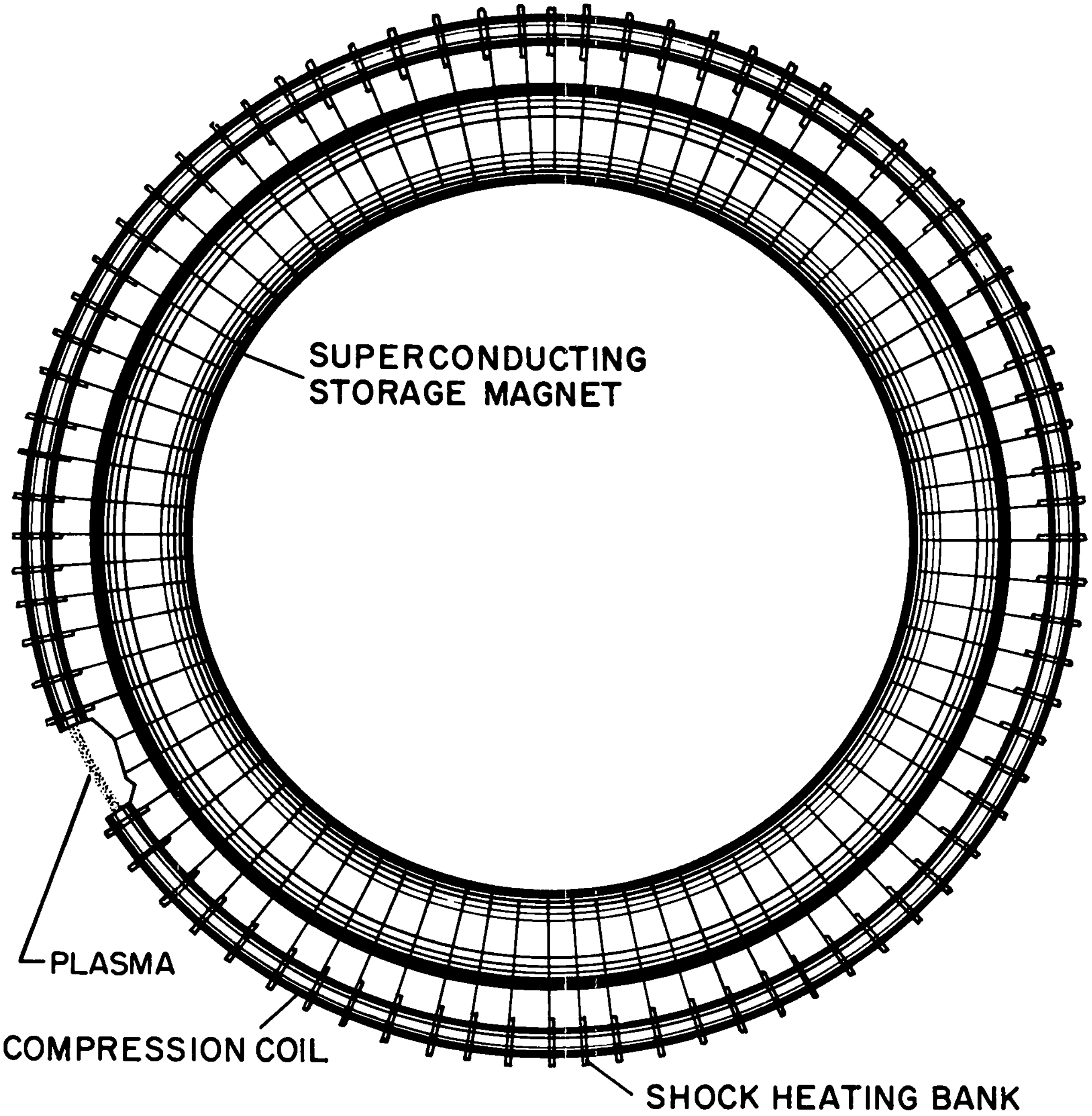


Fig. 12. Toroidal separated shock theta-pinch scientific feasibility experiment.

TABLE II

SCYLLAC TOROIDAL FEASIBILITY PROGRAM FORECAST SUMMARY

(Dollars in Thousands)

	FY 72	FY 73	FY 74	FY 75	FY 76	FY 77	FY 78	FY 79	FY 80	FY 81	FY 82
Operations											
Total Scientific Man Years	4	7	15	18	18	23	24	25	27	29	30
Total Direct Personnel	5	9	37	47	45	62	65	68	75	75	76
Total Costs	210	775	1,675	2,370	2,610	3,405	3,500	3,860	4,500	4,910	5,350
(M D F Costs Within Total Costs)		400	300	100	400	300	300				
Construction Budget											
Arch-Engn. Costs			300	50	50						
Building Costs				1,500	3,000						
System Engn. Costs			100	400	200	100					
Equipment Costs			500	4,500	2,000	1,000					
Installation Costs				600	1,000						
Contingency						3,700					
Total Construction Costs			900	7,050	6,250	4,800					
Total Costs	210	775	2,575	9,420	8,860	8,205	3,500	3,860	4,500	4,910	5,350

Total Operations Cost FY-1972 - FY-1982	33,065
Total Construction Cost FY-1974 - FY-1977	19,000
Total Program Cost FY-1972 - FY-1982	52,065

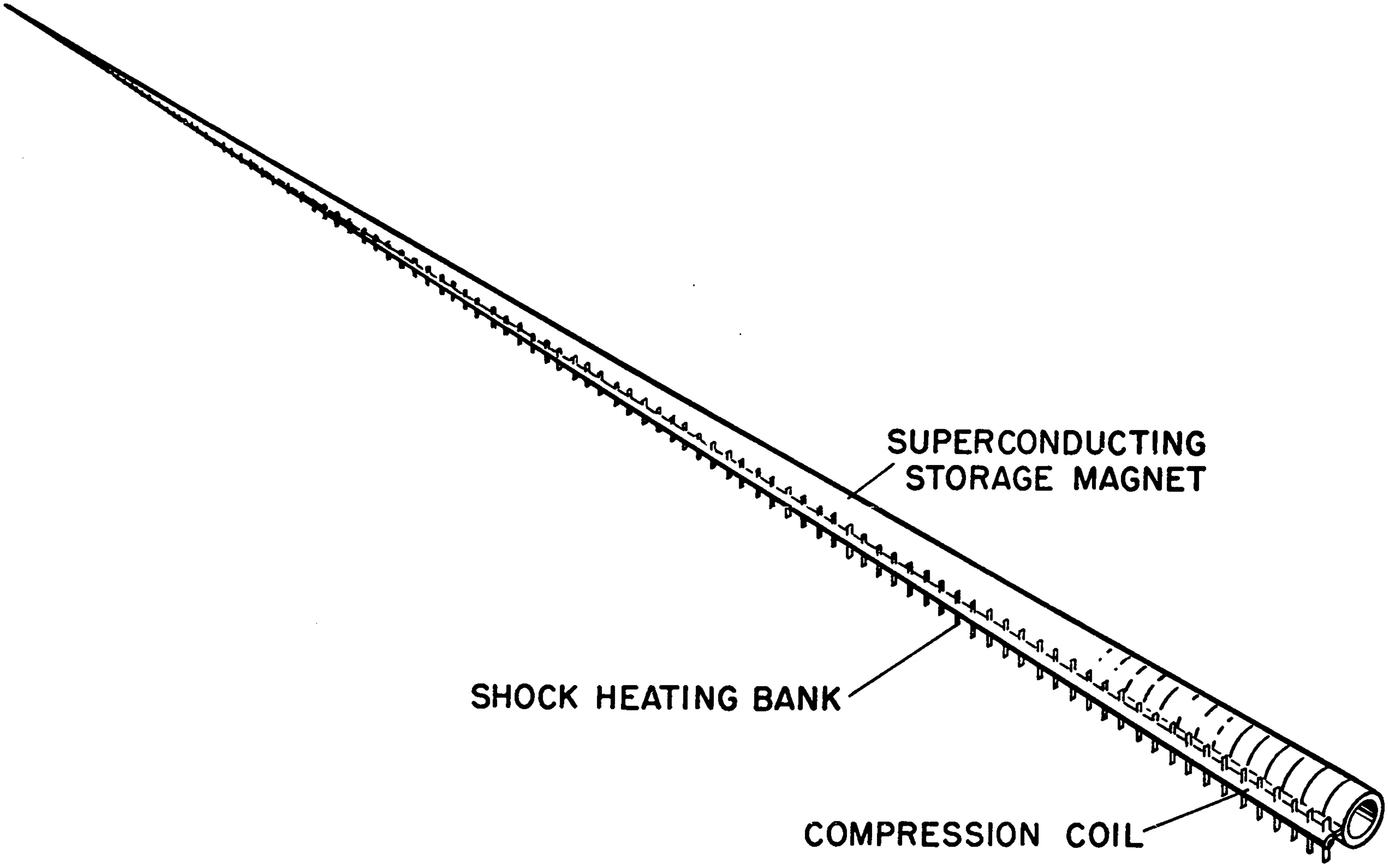


Fig. 13. Linear version of the separated-shock theta pinch for $n\tau = 10^{14}$ cm^{-3} sec.

Its cost would be about \$90M. A version with no mirrors would have a length of about 3 km and cost about \$250M. Owing to its greater length, the added construction time of this experiment would be about two years longer than for the toroidal feasibility experiment.

12. Auxiliary Long-Lead Efforts Needed to Support the θ-Pinch Feasibility Experiment

a) Cryogenic Magnetic Energy Storage and Switching As discussed above, this program is of paramount importance to the θ pinch scientific feasibility experiment. See the section entitled "Superconductivity and Magnetic Energy Storage in Controlled Thermonuclear Systems." A beginning has been made on this work, but more support is essential in FY 1971-72 and thereafter.

b) θ-Pinch Shock Heating Experiments This experiment (Fig. 9) is also crucial to the θ-pinch feasibility experiment and has not yet begun because of the press of the Scyllac and other programs. A coordinated effort between the θ-pinch, toroidal-Z-pinch, and theoretical groups should be pursued as soon as possible, beginning at the latest in FY 1973.

13. Auxiliary Long-Lead Efforts Needed to Support the Power-Plant Program

a) Non-Dissipative Energy Transfer from Cryogenic Magnetic Energy Storage The toroidal feasibility experiment of Fig. 12 uses dissipative superconducting energy transfer to make it technically and economically feasible. However, a pulsed θ-pinch reactor must have non-dissipative, reversible means of energy transfer in order to provide the necessary energy balance. In Fig. 8 this means replacing the resistors R_{sc} and R_B by means of rotating machinery which removes magnetic energy from the superconducting primary and stores it reversibly as mechanical energy over a period of tens of ms and then restores the magnetic energy to the primary. During this process magnetic field is pumped into and out of the compression coil of the reactor. In addition to LASL this development could be done by industry, who should become familiar with the pulsed-reactor energy transfer problem as soon as practicable.

b) Development of High-Voltage Insulation Techniques Suitable for High-Temperature Environment In the reactor case the shock-heating coil of Figs. 9, 10, and 12 will probably operate with liquid metal cooling at temperatures of the order of 1000°C. Thus insulation in a reactor must involve only refractory metals and ceramics, such as Nb and Al_2O_3. There is a need to mock up a shock-heating coil in an environment involving liquid-metal contact and to perform high-voltage tests in this environment. Liquid-metal capability exists at Los Alamos and could be built up for this purpose, with suitable financial support for staff and equipment.

c) Sputtering and Electron Emission Problems Associated with High Ion and X-Ray Fluxes In a reactor ions will be sputtered into the region near the vacuum wall where they will be ionized by low density plasma electrons outside the central core and by thermal x-rays from the hot central plasma. It is important to see if the resulting heavy ions will remain in the vicinity of the wall or possibly diffuse across the magnetic field to the central plasma where they would increase its radiation loading. The effects of secondary-emission electrons should also be investigated. The same hot-metal facility discussed above could be bombarded with accelerator ions and x-rays in the presence of high-voltage pulses, even in the absence of plasma, to investigate such loading effects in a preliminary way.

d) Neutronic and Radiation Calculations for Thermonuclear Reactors In assessing any reactor structure (e.g., Fig. 14) it is essential to know how well the magnet coils are shielded from neutrons and gamma rays, what the tritium breeding is, and where the nuclear energy is deposited. Work of this sort has been done at Los Alamos since 1965 and extensive capability exists which can be built up specifically for CTR engineering studies. A proposal is made in the section entitled "A Program of Neutronic and Radiation Calculations for Thermonuclear Reactors."

e) Radiation Damage This problem is of paramount importance in all thermonuclear reactors. It is discussed in the section entitled "Preliminary Proposal for a Los Alamos 14-MeV Neutron Effects Facility."

f) Tritium Processing and Handling In a D-T reactor there will be a closed tritium-handling cycle for recovering tritium generated in the blanket and purifying it for reinjection. LASL presently has an extensive tritium handling facility and many man years of experience

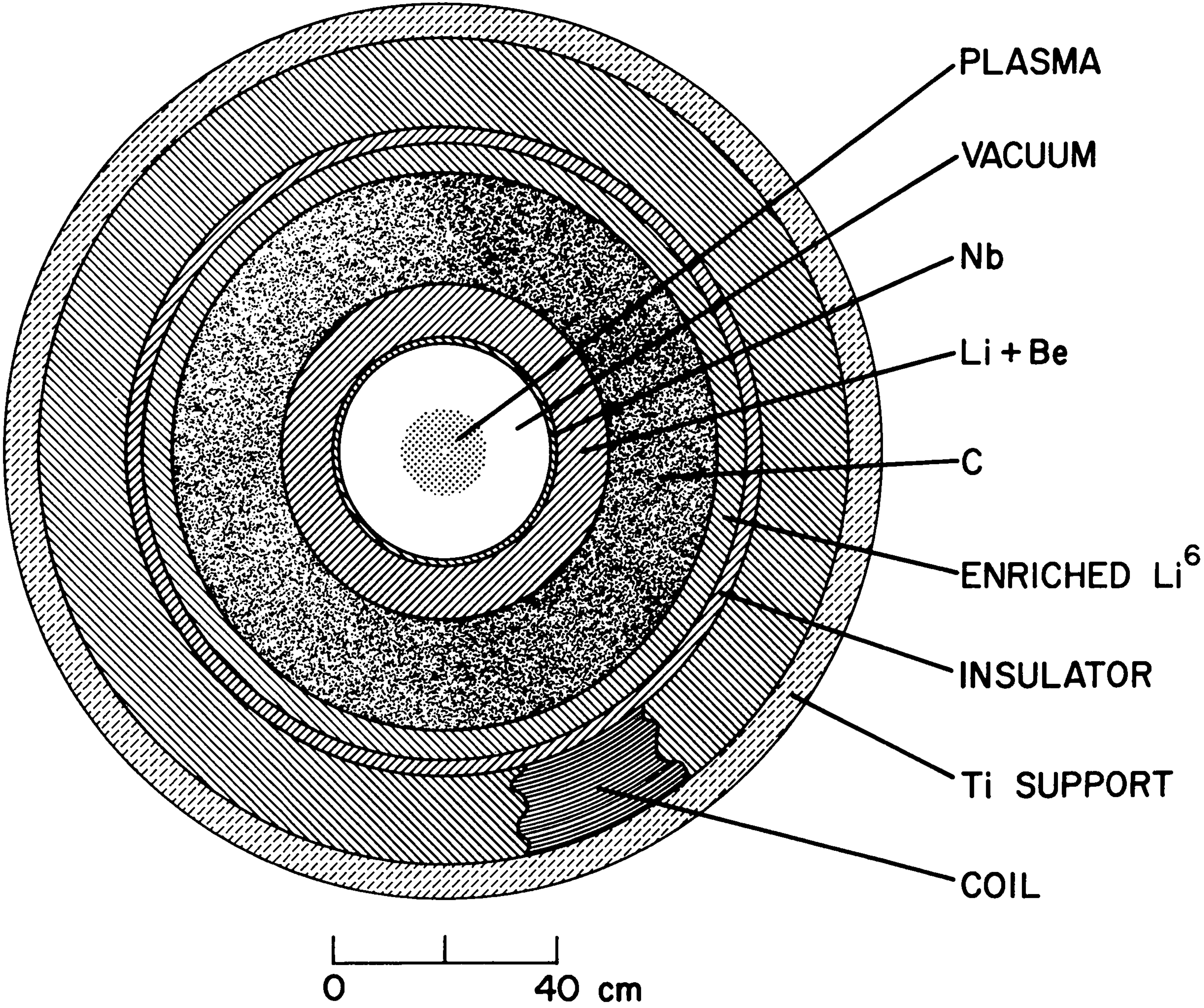


Fig. 14. Schematic cross section of theta-pinch D-T reactor core.

in all aspects of this field.

14. Pulsed Thermonuclear Reactors

a) General Characteristics Pulsed thermonuclear reactors will operate at much higher plasma densities and β values (although at comparable magnetic fields) than steady-state reactors. In order to maintain sufficiently low thermal flux through the smaller plasma-chamber wall the more intense thermonuclear energy pulses are spaced in time. Thus the duty factor produces the same acceptable wall loading as in the steady-state case, where larger sizes are necessary to accomplish this. The pulse (which compress and contain the plasma) have rise times and durations of the order of a few tens of ms and occur about once a second. In a conceptual pulsed reactor (Fig. 15) superconducting or other cryogenic material is used in a separate magnetic-energy storage coil, outside the compression coil which contains the plasma. Magnetic field is pulsed from the external coils into the reactor compression coil. Note that this system has large aspect ratio (i.e., it has a skinny torus) so that parts of the reactor plant are inside the ring, as opposed to a Tokamak, for example, where only an iron core would occupy this area.

b) Core Parameters Figure 14 illustrates a typical schematic cross section of the core of a pulsed θ-pinch reactor based on the separated-shock principle which is illustrated above in Figs. 10 and 12. The plasma of radius $R_p = 8$ cm is situated inside a Nb first wall of radius $R_w = 20$ cm. The Nb cylinder illustrated in Fig. 14 assumed also to represent the shock-heating coil for purposes of neutronic calculations. Between this and the multiturn multilayer copper coil of mean radius $R_c = 68$ cm is a neutron blanket, followed by a region of insulation to keep the coil at room temperature. Outside the coil is a structural support of titanium at room temperature.

c) The Neutron Blanket considered here consists of three regions: (1) an inner region of normal Li plus about 25% Be, assumed to be "poisoned" by 4% of Nb, necessary for laminar flow channeling of the liquid lithium plus encapsulation of the Be. This region serves to regenerate tritium,

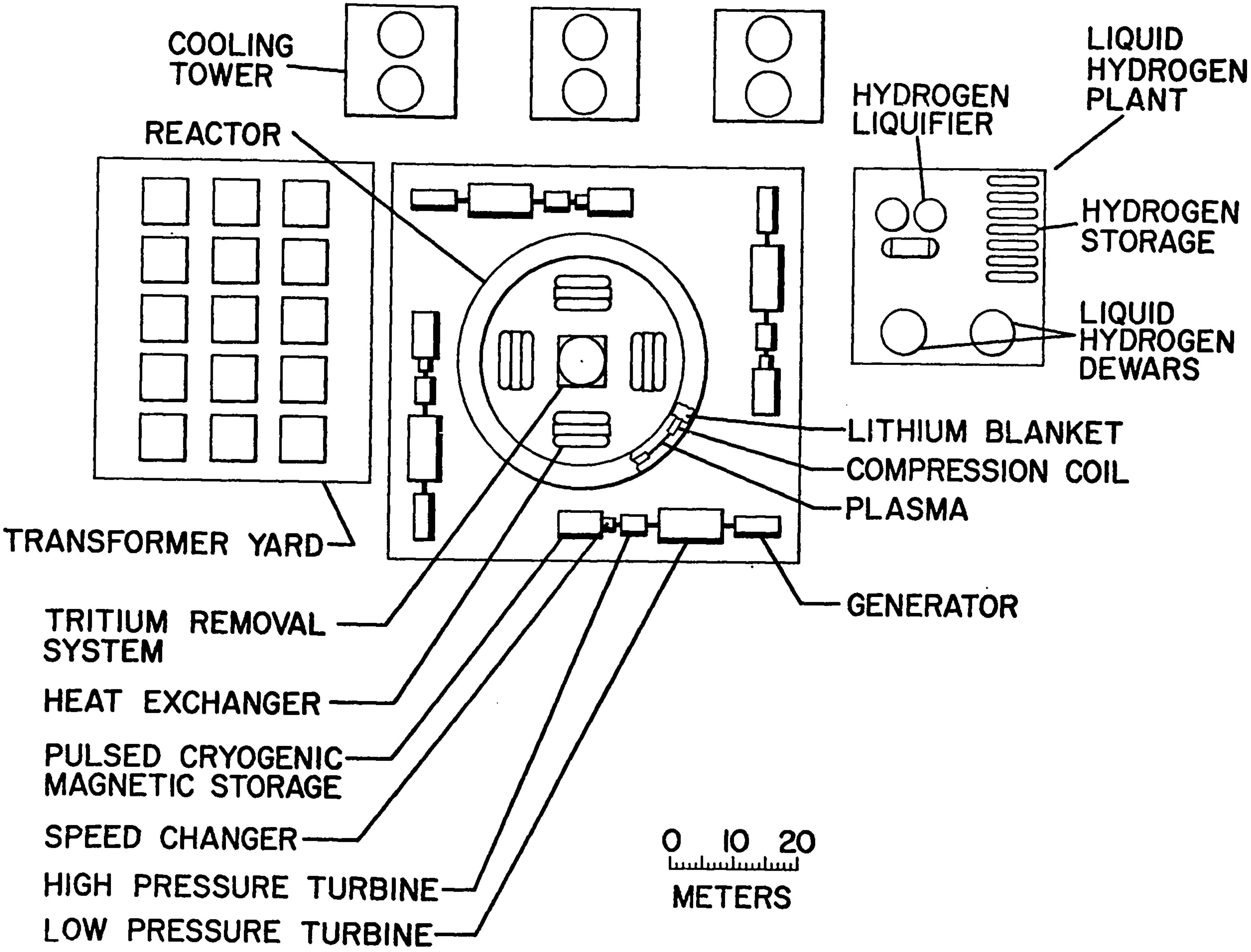


Fig. 15. Conceptual fusion reactor based on the toroidal θ pinch.

largely by the $Li^7(n,n'T)He^4$ reaction, and to cool the Nb inner wall. The liquid lithium runs at about 1000°C. (2) The region of carbon slows the neutrons further in preparation for their capture by (3) the 95% enriched Li^6 of the thin outer blanket region where tritium is produced primarily by the $Li^6(n,T)He^4$ capture reaction. The overall breeding ratio in this small blanket is about 1.15 tritons per neutron.

A major function of the blanket considered here is to reduce the nuclear energy deposition in the copper coil to about 1% of what it would be if the copper were inside a blanket next to the plasma. The coil fast-neutron radiation damage is reduced by roughly a factor of 25. In view of the duty factor of about 2% (see below) the nuclear energy deposition in the copper coil is neglibible.

d) The Copper Coil is made of ordinary square bar stock cooled in the normal manner with laminar flow of water through central channels. The bar stock thickness is smaller than the skin depth δ_E corresponding to the plasma burning time $\tau_T = 0.025$ sec. Thus eddy current losses are small and the joule heating of the coil is approximately that of a d-c coil during the time τ_T for which current is pulsed into it from the superconducting inductive storage supply (not shown in Fig. 14). The coil is assumed to produce a peak compressive magnetic field B = 141 kG. The joule losses and magnetic field of the shock phase are negligible.

e) The Excess Energy Production of the D-T reactions over plasma losses involves a number of factors in the energy balance.[1,2] However, it reduces approximately to a comparison of the instantaneous thermonuclear energy P_T produced by the plasma (assumed to have $\beta \approx 1$ and kT = 10-15 keV) and the joule-heating power dissipation W_E/τ_T, where W_E is the joule-heating energy loss in the copper coil during its current pulse. From the equation

$$M = P_T \tau_T/W_E \tag{1}$$

we calculate a typical energy excess M for the parameters and materials mentioned so far (assuming the copper coil to have a thickness 10 times the skin depth and a volume filling factor $\lambda = 0.7$). The resulting value is M = 9.

The duty factor is given as the ratio of permissible average thermonuclear power through the first wall (taken as 2 kW/cm^2) and the thermonuclear flux during the actual burning time τ_T. It turns out to be about 2%. Thus the repetition rate of the compression and burning pulses is about one per second.

f) Plant Output Power, Plant Efficiency and Circulating Power

On the basis of the simple energy balance of Eq. (1) the average output power is

$$P_{out} = (\epsilon_T/\xi)P_T(1 - M^{-1}). \quad (2)$$

Here $\xi = 44$ is the inverse of the duty factor and ϵ_T is the thermal conversion efficiency for producing electrical output which is taken to be 0.5, corresponding to the use of the high-temperature lithium in the thermal cycle. Corresponding to the instantaneous thermonuclear power $P_T \approx 1.1$ GW per meter of reactor length we find an average output power of 11 MW/m. The plant efficiency on the basis of joule losses alone would be

$$\epsilon_p = (1 - M^{-1})\epsilon_T \approx 44\%, \quad (3)$$

based on a circulating-power fraction M^{-1} of 12% from the generators necessary to furnish only the joule losses. Other circulating power requirements may raise the total figure to 20%, resulting in an overall plant efficiency of about 40%.

g) Fuel Burnup and Fueling For the parameters considered thus far one calculates a plasma density $n = 2 \times 10^{16}$ cm^{-3} (at $kT \approx 12$ keV) and a corresponding $n\tau_T = 5 \times 10^{14}$ cm^{-3} sec. The approximate fuel burnup is $f \approx \frac{1}{2} n\tau_T \overline{\sigma v}$, where $\overline{\sigma v}$ is the Maxwell average of the D-T cross section and relative ion velocity. For $kT \approx 12$ keV one calculates a burnup fraction of about 5%. This does not take account of plasma heating and expansion owing to deposition of energy by the α particles accompanying burnup.[3] This will have the effect of lowering the burnup and $n\tau$ values given above by perhaps 20%.

The result of each 25-ms burning pulse is to leave an expanded hot plasma with about 5% of α-particle "ash" in it. Since a second elapses between burning pulses, refueling might be accomplished by a simple continuous flow of D-T gas to dilute the ash to a level below 1%, interrupting the flow only during the burning pulse. The spent plasma from each pulse could probably be cooled and purified without divertors in this way.

h) Size of Plant The pulsed D-T reactor discussed above has an electrical output of about 11 MW per meter (about 27 MW/m thermal). Its total output depends on its length. This in turn depends upon scientific factors yet to be determined in the Scyllac experiment and the subsequent scientific feasibility experiment. On the basis of present theory a reactor with a cross section like that of Fig. 14 may require a plasma length of about 350 m for MHD stability. Its electrical output would then be 3800 MWE. Scientific principles yet to be tested may allow considerable shortening of the reactor, but an electrical output in the 1000-MWE range is to be expected.

15. Time-Scale and Cost Estimates for a Demonstration Reactor

At this time, before scientific feasibility has been shown, it is difficult to estimate the time and cost scale for producing a demonstration reactor. However, the following remarks may be made. The scientific feasibility experiment of Fig. 12, if successful, would have the essential technological ingredients of a reactor. It would require pursuit of the technological tasks outlined in Sec. 13 above to allow its transformation into a power-producing reactor. This could probably occur within 10 years after the scientific feasibility experiment, placing its date in the late 1980's. This would require immediate support of technological studies and CTR budgets increasing by a factor of 2 every two years or so into range of several hundred million dollars per year for the U. S. program.

16. Acknowledgments The advice and participation of the following LASL staff in preparing the material of this report is gratefully acknowledged: G. I. Bell, F. J. Edeskuty, J. P. Freidberg, E. L. Kemp, H. L. Laquer, R. L. Morse, W. E. Quinn, G. A. Sawyer, and D. M. Weldon.

References

1. F. L. Ribe, T. A. Oliphant, Jr., and W. E. Quinn, Los Alamos Report LA-3294-MS (1965), p. 34, Eq. (83).

2. F. L. Ribe, Proceedings of the 5th Intersociety Energy Conversion Engineering Conference, Energy 70, Las Vegas, Nevada, September, 1970. Fusion Technology Monographs, p. 1-13, Eq. (2).

3. T. A. Oliphant, Proceedings of the BNES Nuclear Fusion Reactors Conference, Culham, England (1969). p. 306.

SECTION III

Z-PINCH

I. DEVELOPMENT OF THE Z-PINCH PROGRAM AT LASL

The CTR program at LASL started in 1952 with the z-pinch in which a plasma column is confined by the B_θ magnetic field of an axial current. The Z-pinch has a unique position in magnetic confinement in that 1) it is the only system which does not communicate all the plasma pressure to the laboratory, and 2) it has the largest amount of magnetic pressure per unit of magnetic energy.

The simple pinch was found very quickly to be unstable. In (1956 - 58) a sharp boundary theory was developed which predicted stability for z-pinches containing a longitudinal field (B_z) and having a conducting wall close to the pinch. Experiments at LASL and elsewhere confirmed these predictions but

1) Several μsecs after initiation of the discharge high frequency fluctuations in the magnetic fields were observed.

2) Magnetic fields diffused faster than predicted by classical resistivities, i.e. the resistivities were 'anomalously' high. As a consequence the sharp boundary between the plasma and magnetic field could not be maintained.

3) Plasma temperatures were limited to $\leq$ 100 eV and very high energy loss rates (~ 1,000 Joules/μsec) were measured in ultra-violet line radiation from partially ionized impurity ions.

These difficulties were considered so fundamental that the z-pinch program at LASL was terminated in 1961 in favor of other approaches.

Since that time further information has been obtained. The toroidal experiment at General Atomic (1963) showed that the fluctuations of magnetic fields could be suppressed by programming the external fields, e.g. reversal of the B_z field and z-current outside the central pinch column. The (1964) observation in Zeta (U.K.) of a quiescent period during which approximately classical resistivities inferred from the diffusion rate of magnetic fields. Diffuse magnetic field profiles were found which are theoretically stable and which confine high plasma pressures ($\beta \lesssim 40\%$).

In 1966 we reviewed our investigations of z-pinches and addressed ourselves to the temperature limitation in earlier experiments. θ-pinches are initially heated by a strong shock produced by a rapidly rising magnetic field and this opened up the possibility of heating z-pinches in a similar way. Fast rising fields require high voltages and low inductance electrical circuits.

A new technology, that of magnetic energy storage, Fig. 1 was used. A low voltage ($\lesssim$ 14 kV) capacitor bank initially discharges through the storage inductor and fuse. At high currents the fuse melts and its resistance becomes large. The inductor tries to keep the current constant with a resulting high voltage (40-60 kV) induced across the fuse. Closing the transfer switch, S in Fig. 1, applies the high voltage to the discharge tube.

In a linear z-pinch experiment magnetic fields have been produced which rise two to three times faster than in current θ-pinch experiments. Measurements yield plasma temperatures ($T_i + T_e$) of 750 eV at ion densities $\sim 3 \times 10^{16}$/cc. In addition the plasma column is stable for times of the experiment ($\sim$ 8 μsec).

The status of the z-pinch has then changed dramatically. The results of the linear shock heated z-pinch experiment demonstrate that high temperatures, high density, plasmas can be produced. At these temperatures line radiation from impurities is small. Further, diffuse magnetic field profiles such as shown in Fig. 2 are theoretically completely MHD stable, i.e. stable against all modes including kinking and interchange.

With these encouraging results, a toroidal z-pinch experiment ZT-1 is being assembled at LASL. The torus (Fig. 3) has a major diameter of 76 cm and a minor diameter of 10 cm. A 0.5 M Joule inductive energy storage system develops $\sim$ 80 kV across each quadrant of the torus and z-pinch currents of $\lesssim$ 300 kA are induced in the plasma secondary. The toroidal z-pinch has marked advantages,

1) Azimuthal symmetry and stable equilibria.

2) The B_z stabilized z-pinch can in principle exceed by orders of magnitude the current limit of other toroidal devices such as the Tokamaks.

The experiment will determine if the required field profiles can be established and the plasma confinement time. In the initial experiment with the current decaying in $\sim$ 10 μsec, a value of $n\tau \approx 3 \times 10^{10}$ sec cm^{-3} will be obtained. The future program for this toroidal experiment is outlined in Section II.

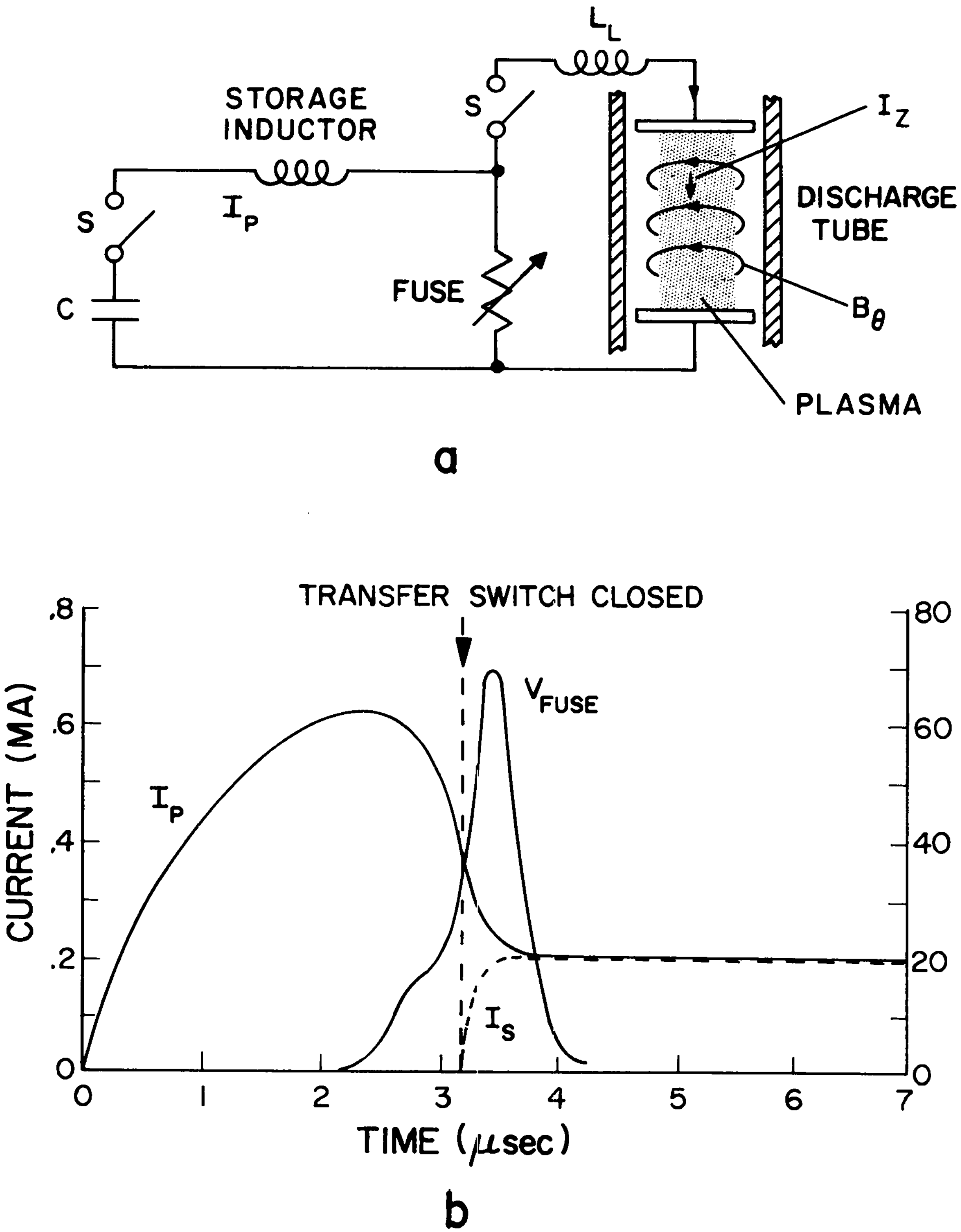

L_L
STORAGE INDUCTOR
S
S
S
I_P
C
FUSE
I_Z
DISCHARGE TUBE
B_θ
PLASMA
a
TRANSFER SWITCH CLOSED
CURRENT (MA)
VOLTAGE (kV)
.8
.6
.4
.2
0
80
60
40
20
0
V_{FUSE}
I_P
I_S
0
1
2
3
4
5
6
7
TIME (μsec)
b

Figure 1

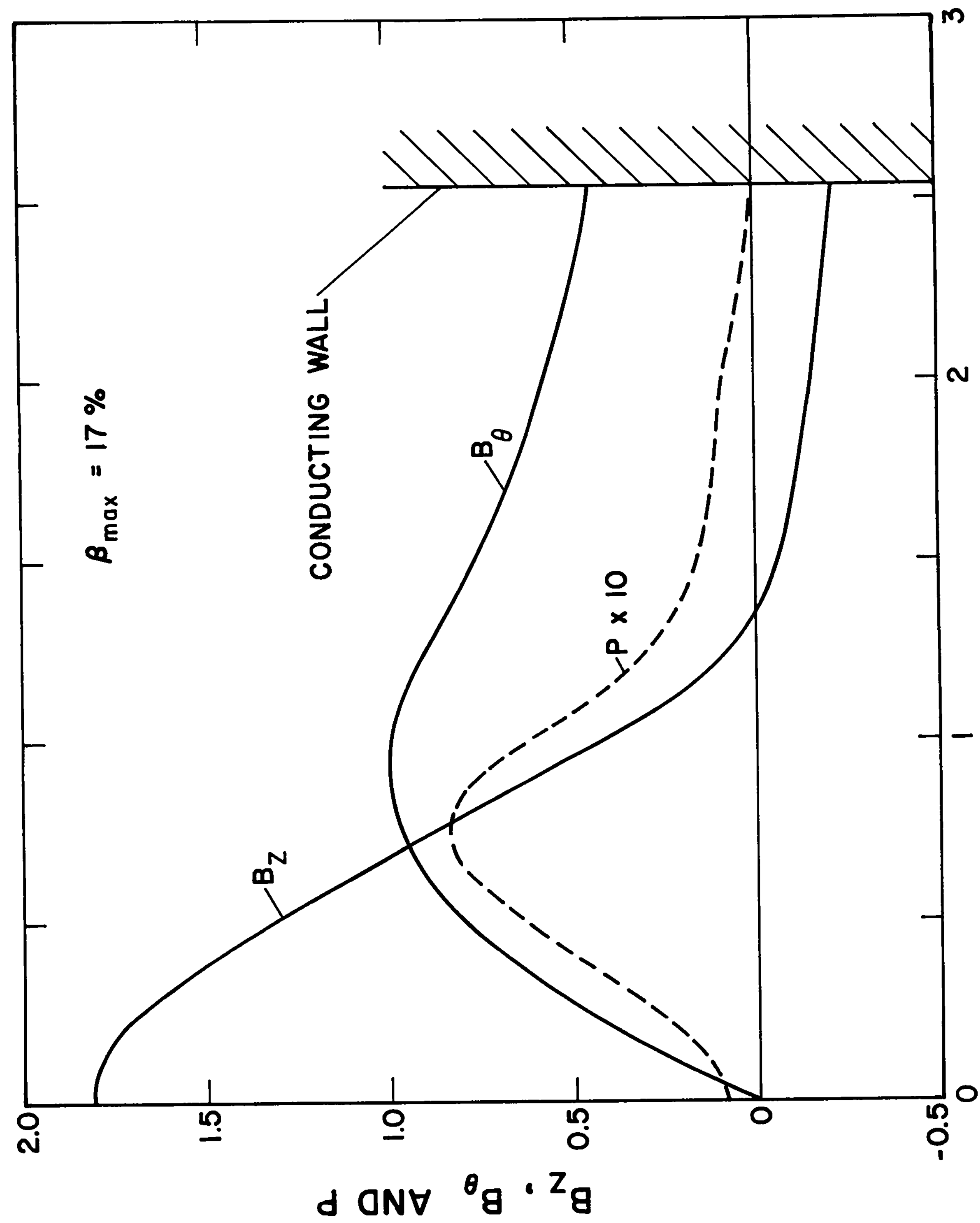

β_{max} = 17 %
CONDUCTING WALL
B_θ
B_Z
P x 10
RADIUS
0
1
2
3
2.0
1.5
1.0
0.5
0
-0.5
B_Z, B_θ AND P

Figure 2

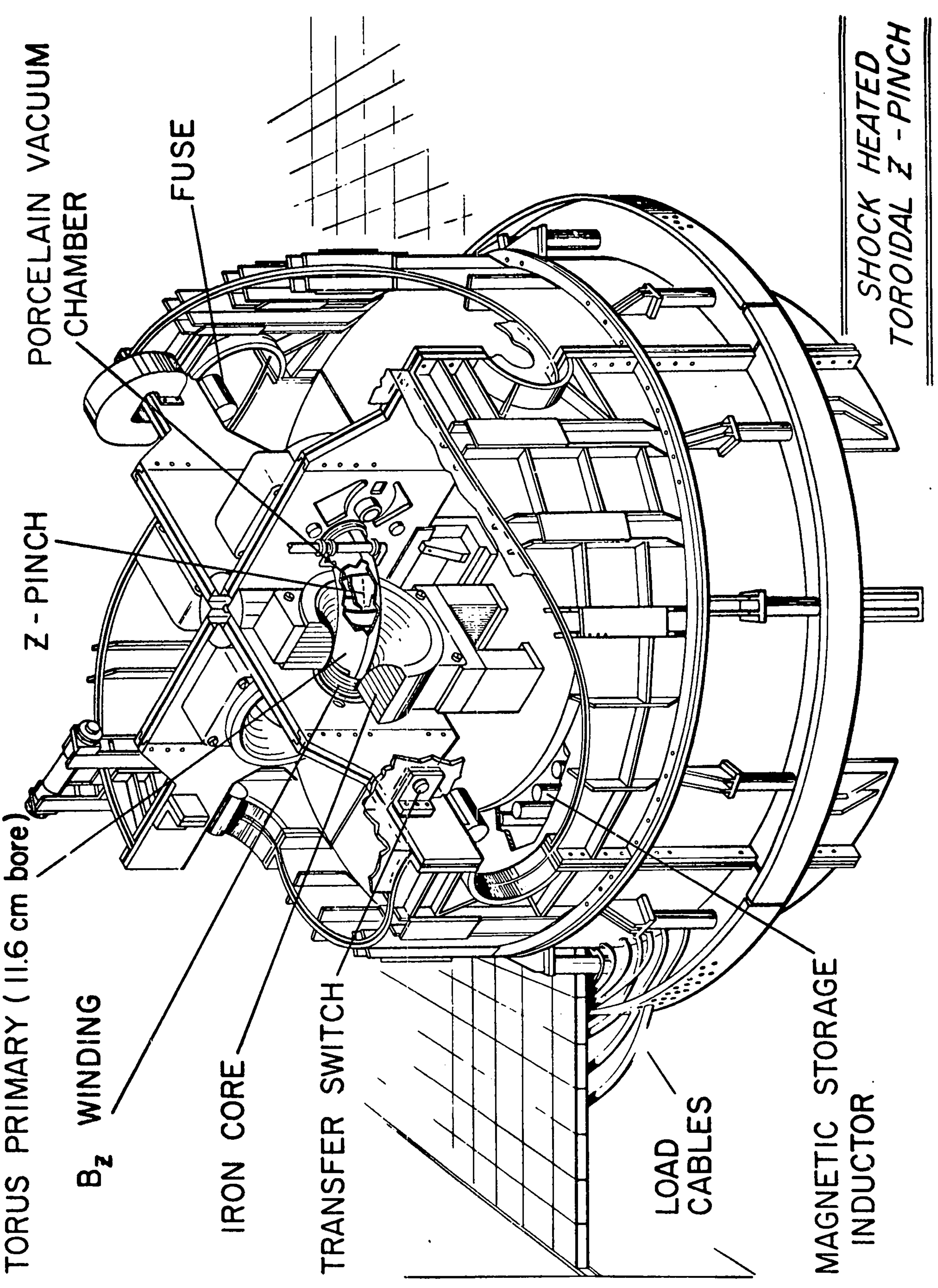

SHOCK HEATED TOROIDAL Z-PINCH
PORCELAIN VACUUM CHAMBER
FUSE
Z-PINCH
TORUS PRIMARY (11.6 cm bore)
B_z WINDING
IRON CORE
TRANSFER SWITCH
LOAD CABLES
MAGNETIC STORAGE INDUCTOR

Figure 3

II. ACCELERATED PROGRAM FOR THE SHOCK HEATED TOROIDAL Z-PINCH

A. Steps to demonstrate scientific feasibility with assumption of optimum success in each phase.

1) Scientific feasibility defined as;

Plasma confined for $n\tau \approx 10^{14}$ at a temperature of ~ 10-15 keV.

2) Principal characteristics;

Toroidal plasma column confined by the magnetic field of an axial (z-) current passing through the plasma. Exact equilibrium of z-pinches exists in toroidal geometry. MHD stability is given by a conducting wall and an internal longitudinal B_z magnetic field. The B_z field outside the pinch column is small and negative. Plasma shock heated by the magnetic field of the rapid rising z-current.

3) Experiments:

a) ZT-1. 10-cm bore and 76-cm major diameter. Discharge current $\lesssim$ 300 kA, with main capacitor bank 0.5 MJ. Experiment under construction. Expected parameters, $T_i \approx T_e \approx 1$ keV, $n \approx 3 \times 10^{15}$/cc.

The experiment will have three stages of operation;

1) ZT-1A. Maximum plasma confinement time 10-15 μsec determined by the time constant of the power supply.

2) ZT-1B. The primary of the transformer is crowbarred with an L/R time constant of ~ 1 millisec for the discharge current which would extend the time scale of the experiment to ~ 100 μsec.

3) ZT-1C. A power crowbar which maintains the discharge current constant and extends the experimental time to $\lesssim$ 6 millisec. This would allow the experiment to be extended to an $n\tau \sim 2 \times 10^{13}$.

The projected confinement times for ZT-1B and ZT-1C are calculated from the electrical characteristics of the experiment with the assumption that the plasma pinch behaves. We expect that at some time, perhaps ≈ 100 μsec, wall effects will become important and plasma confinement will be lost. An increase in discharge current and discharge tube diameter would then be necessary to extend plasma lifetimes.

   b) ZT-2. 40-50 cm bore, and 4 meter major radius, discharge current 3-5 MA, with $T_i \simeq T_e \approx 5$ keV, and designed to achieve an $n\tau \approx 10^{14}$.[1]

4) Supporting experiments and developments.

   a) Shock heating experiments.

   Increase plasma temperature from ~ 1 keV to ~ 10-15 keV by raising the rate of rise of magnetic fields. Estimate Z-electric fields of ~ 20-30 kV/cm and currents ~ 3 MA will be required. Energy supply to consist perhaps of cables whose length gives a transient time one half the required pulse length. Capacitors would support the discharge current until the main capacitor bank is switched on. Voltage is graded along the discharge tube so that not more than ≈ 200kV appears across an insulator.

   b) Development of plasma discharge tubes. Extended the present linear metal discharge tube design to toroidal geometry. Fabricate tubes having optimum neutron characteristics and minimum bremsstrahlung effects.

   c) Development of components for energy storage and energy transfer. Research directed primarily at; a) very high voltage pulses for shock heating and; b) long term extension of MA currents for 10's of millisec. Evaluate power supplies, as capacitor versus magnetic energy storage systems, for the ZT-2 experiment. Research and development times of each will be important in the overall time scale for completion of ZT-2.

5) The time scale for accomplishing the feasibility experiments.

   A bar chart is shown in Fig. 4.

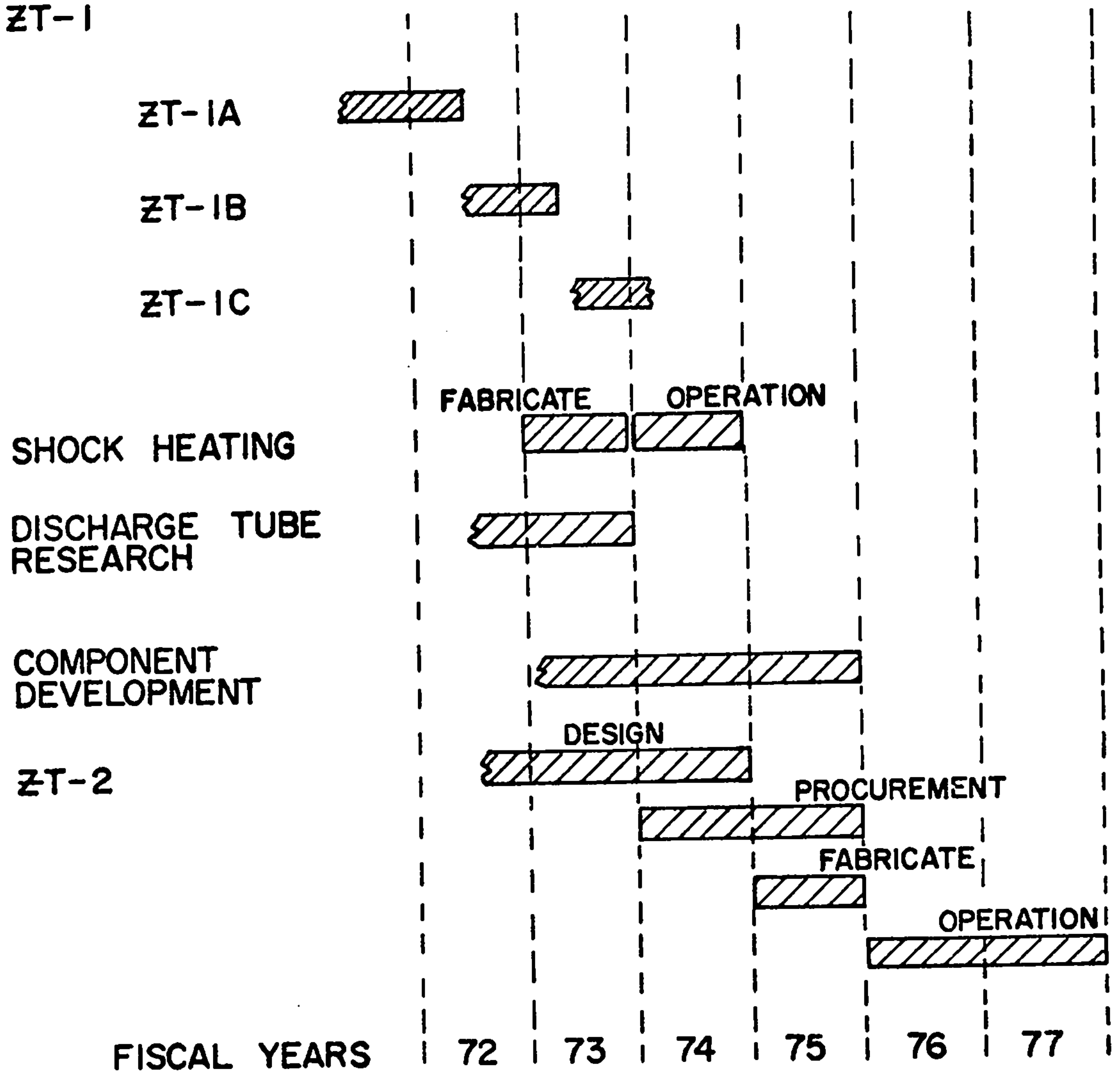
6) Costs of tasks above present level of support is shown in Fig. 5. It will be noted that there is an item for a building at ~ 2 M \$. This building would have a 100' x 100' space for ZT-2 plus offices and machine shops.

B. Long lead efforts required in FY 1972.

   a) Shock heating experiment.

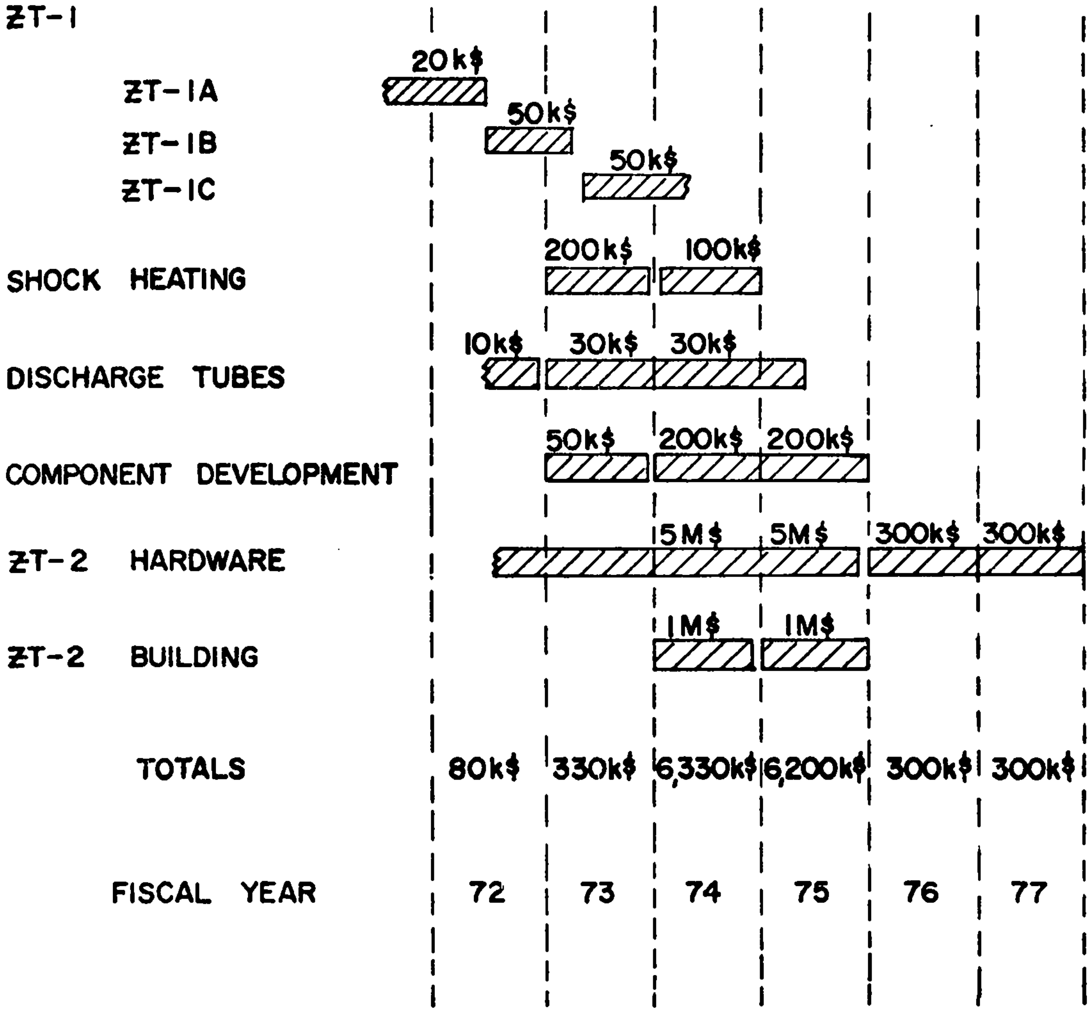
   b) High voltage techniques.

   c) Engineering techniques for switching and insulation.



TIME SCALE TO FEASIBILITY EXPERIMENT.

Figure 4



HARDWARE COST ESTIMATES TO FEASIBILITY EXPERIMENT.

Figure 5

C. Demonstration fusion power plant.

With a successful operation of ZT-2 the next experiment would produce power. Little can be said at this time of design parameters. General consideration show, however, that the major diameter to be 10-20 meters, minor diameter 20-50 cm, discharge currents 10-20 MA, and output ~ 1-5 GW (E).

SECTION IV

Superconductivity and Magnetic Energy Storage in Controlled Thermonuclear Systems

E. F. Hammel, W. E. Keller, H. L. Laquer and F. L. Ribe

I. MAGNETS AND SWITCHING FOR PULSED, HIGH-β CTR SYSTEMS

A. Pulsed Thermonuclear Reactors

Pulsed thermonuclear reactors will operate at much higher plasma densities and β values (although at comparable magnetic fields) than steady-state reactors (Section II). In order to maintain sufficiently low thermal flux through the smaller plasma-chamber wall the more intense thermonuclear energy pulses are spaced in time. Thus the duty factor produces the same acceptable wall loading as in the steady-state case, where very much larger sizes are necessary. In the pulsed case magnetic volumes and energies smaller by an order of magnitude or more can be used. The pulses (which compress and contain the plasma) have rise times and durations of the order of a few tens of ms and occur about once a second. In a conceptual pulsed reactor super-conducting material is used in a separate magnetic-energy storage coil, outside the coil which compresses and contains the plasma (cf. Fig. 8 of the chapter on High-β Theta-Pinch Systems).

B. Magnets for Pulsed Reactors

In one respect these present a less stringent problem than for the steady-state case because of the smaller energies and sizes involved. However, there is the unique problem of changing the field in a superconducting storage coil as energy is transferred out of it to the compression coil of the reactor which can be at a much higher temperature.

The problem of maintaining superconductor stability and minimizing energy losses under transient conditions is in the early stages of investigation. At Los Alamos we have an active program involving the use of very finely divided superconducting strands in small stabilizing copper wires, braided to give magnet windings of minimum loss and maximum stability under transient conditions involving times of 1 to 10 ms. A 30-kJ superconducting magnet, capable of fast switching and energy transfer is being constructed as a first step to investigate the transient problems involved in the large (100 MJ to 100 GJ) systems required for next generation experiments and for reactors.

C. Switching of Pulsed Magnets

(1) Reactor Systems In the final reactor, where good energy balance and consequent low circulating power are important, it appears necessary to use variable inductors (rotating machinery with fields furnished by superconductors) to provide energy transfer from storage magnet to compression coil.

(2) Use of Superconducting Switches in Scientific Feasibility Systems In the next generation of fusion experiments successful systems such as the theta pinch must be produced in sizes and configurations which model reactor plasma parameters and techniques and produce appropriate plasma burning conditions and times. Such experiments, which demonstrate "Scientific Feasibility," need not be primarily concerned with such things as overall energy balance, circulating power, and tritium breeding. In this case large magnets and compression coils can be most appropriately switched by resistive elements consisting of normal-going superconductors. Even though energy transfer efficiency is in principle about 50%, the capital cost of magnetic field in the plasma compression coil is nevertheless greatly lowered over that for capacitor banks, which presently are used. Cryogenic magnetic energy storage and switching are necessary to make large-scale scientific feasibility experiments financially practicable.

(3) Development of Superconducting Switches for Transferring Large Amounts of Magnetic Energy There is an active program underway at Los Alamos to investigate this problem, and results have already shown normal-going transitions in superconductors carrying multi-kA currents in times as small as a fraction of one μsec. The work is being extended to the 30-kJ, 1-kA magnet mentioned above, and it is anticipated that much larger systems will follow. By transformer coupling one can produce much larger currents to a load. Such a magnetic system would be a prototype section for a θ-pinch feasibility experiment, as well as later reactor systems. (See section entitled "Projection of Pulsed High-Beta Theta-Pinch Systems to Scientific Feasibility Experiments and Demonstration Reactors.")

(4) Development of Rotating Machinery for Magnetic Energy Transfer In an actual reactor system the burning times and energy transfer times will pass from the range of a few ms (in the case of the feasibility experiment) to tens of ms. Under these conditions rotating machinery such as homopolar generators operating in the field of the superconducting storage solenoid, or more conventional motor generators which provide a variable-inductor energy transfer will be appropriate. This type of energy transfer is a long-leadtime development best left to industry, which presently has superconducting homopolar generators and alternators under development.

D. Application to Slowly-Pulsed Systems

At even slower rates (hundreds of ms) such as are encountered in pulsing the toroidal current of Tokamak devices, the concepts outlined above are also applicable. The relaxed time scale eases the technical difficulty.

II. MAGNETS IN STEADY-STATE THERMONUCLEAR REACTORS

A. Steady-State Magnets

In a conventionally conceived steady-state reactor the longitudinal (or toroidal) field is generated by a very large superconducting solenoid operating at 4°K. Typically the bore of this magnet is 6 meters (approximately 20 ft); and the volume of magnetic field is about 1000 m^3. The magnet cost comprises about one third of the reactor capital cost.

B. Application of Present Superconductors

Present conceptual designs make use of NbTi (NbZr in some cases) or similar substances as the superconductor and limit the longitudinal field to about 80 or 90 kG. Even though small magnets (volume < 1 liter) are being produced at fields of 150 kG in Nb_3Sn, it is unlikely that fields in excess of 100 kG can be produced over the large volumes necessary for reactors because:

> When the field is increased to values near the critical field (~ 200 kG for Nb_3Sn) the current density j_c must be lowered since j_c decreases with increasing field, and hence the amount of costly superconductor required increases more than linearly with field.

C. An Important Question of Scientific Feasibility Bearing on Superconductor Choice

Present encouraging experimental results in the Tokamak have occurred at low β values (< 1%), i.e., at plasma pressures which are less than 1% of the longitudinal (toroidal) magnetic pressure. In order that a Tokamak (or low-β Stellarator) remain below the critical β (about 5%) above which the static magnetohydrodynamic stability characteristic of these devices is lost, the longitudinal magnetic field must be raised above the value which can reasonably be expected, in a large reactor system, from NbTi superconductors or the like. With the presently available superconducting materials the values of β must be in the 10 to 30 percent range, and new physics of feedback stabilization, cross section shaping, or toroidal field programming is required. Although these techniques may indeed have application, they can be probably avoided by the use of higher toroidal magnetic fields.

D. Bearing of Recent Superconductor Discoveries on These Problems

New superconducting materials discovered at the Los Alamos Laboratory in Group CMB-3, stimulated by Matthias's work, have shown transition temperatures as high as 19.8°K with prediction of critical fields as high as 700 kG at 4°K. These materials presently exist only in ingot form or as small grains, and development is urgently needed to produce ribbon or wire so that high-field magnets can be built. Such development could have major impacts on the development of CTR magnets for steady-state, as well as pulsed reactors, as follows: (a) The current density allowed at 4°K would increase a factor of at least 3, reducing the superconductor volume requirements (and probably the cost), correspondingly. (b) The raising of current density would relieve structural problems and costs. (c) At fields around 100 kG the operating temperature could rise, appreciably reducing refrigerator costs or reducing blanket thickness requirements. (d) Perhaps most important, the working fields could feasibly rise to greater than 150 kG, allowing the low-β physics at which "Scientific Feasibility" may foreseeably be achieved in Tokamaks or low-β Stellarators to be applied in reactors without having to develop new physics for containing the plasmas against static MHD instability.

III. LASL CRYOGENIC CAPABILITIES IN APPLIED SUPERCONDUCTIVITY

A. Cryoengineering

The cryoengineering section of the Los Alamos Scientific Laboratory cryogenic group presently consists of four chemical engineers, two mechanical engineers, one electrical engineer, and five cryogenic technicians. In total this represents about 200 man-years of cryoengineering experience in such areas as cryogen fluid flow; heat transfer; large-scale refrigerators for operation at temperatures between

1 and 30°K; dewar design (for systems up to 10^6 gal. liquid H_2 capacity); structural analysis; mechanical properties of materials at low temperature; testing and evaluation of cryogenic equipment and hardware; electronic instrumentation for measurement and control of cryogenically important variables and for process automation; and safety considerations for handling large amounts of cryogens. In the past five years, members of the cryoengineering section have published 83 papers in scientific journals.

B. Low Temperature Physics Research

The remainder of the permanent staff consists of 14 Ph.D. chemists and physicists, working in the broad areas of thermodynamic properties of materials at very low temperature; superfluid hydrodynamics; solid state physics at very low temperatures; nuclear physics at very low temperatures; and superconductivity. These efforts represent over 250 man-years of research activity. Members of the research section have published 181 papers in scientific journals during the past five years.

C. Cryogenic Facilities

Approximately 16,000 square feet of laboratory and office space are in use by the cryogenic group. Extensive storage and handling facilities are available for liquid hydrogen, liquid helium, and liquid nitrogen.

D. Special Techniques Applicable to Superconducting Magnet Systems

Work on cryogenic and superconducting magnets and associated problems such as flux pumps has been pursued at Los Alamos since 1955. Some of the highlights are: (a) The first routinely operating 80-kG liquid hydrogen-cooled electromagnet; (b) United States and foreign patents on two different types of flux pumps as means of generating high currents in a superconducting circuit without introducing them through leads from room temperature, thereby avoiding heat losses in the cryogenic region of about 2 W/kA; (c) A complete operating 3 kG/cm superconducting quadrupole doublet system; (d) 10-kV test of liquid hydrogen-cooled energy storage coil; (e) Present work on pulsed superconducting coils and switches.

IV. PROPOSED CRYOGENIC ENERGY STORAGE PROGRAM

The proposed Los Alamos program in cryogenic energy storage magnets, to keep pace with the schedule of feasibility and reactor experiments, will require extensive development of pulsed inductive storage and switching techniques and supporting research on cryogenic materials technology. The program will be planned to develop approximately 750-MJ of storage for a 150-MJ feasibility experiment by 1975.

The estimated staff needed to accomplish this development is:

4 cryogenic and plasma physicists
5 engineers (cryogenic, mechanical, instrumentation, etc.)
1 computer data analyst
1 secretary
13 technicians (mechanical, electrical, draftsmen, etc.)

A staff of this size will cost approximately $1,200,000 per year. In addition, procurement of major equipment might run as much as $300,000 per year. A cost summary is given in Table I of Section II .

SECTION V

14 MeV Neutron Effects Facility

H. Dreicer and D. B. Henderson

LASL Sherwood personnel believe that important ingredients of forthcoming technical fusion feasibility studies are

1) the demonstration that reactor wall materials can maintain their structural integrity when bombarded by the intense flux of neutrons produced in a D-T fusion reactor, and
2) the demonstration of efficient tritium breeding blankets.

The main obstacle presently preventing these demonstrations is the non-existence of a neutron source whose neutron flux and primary neutron spectrum is comparable to that emitted by a D-T burning fusion reactor, i.e., approximately 10^{15} neutrons-cm^{-2}-sec^{-1} at 14 MeV.

Our recent survey of neutron sources is summarized in Table I and compared with a fusion power reactor. Of all possible sources considered and listed in Table I only an Ion Accelerator, which utilizes a dense gas target for neutron production from the D-T reaction, can satisfy all of the conditions required for the demonstration and study of neutron effects. As one measure of the efficiency of each of the neutron sources listed, Table I gives the rate of helium build-up due to (n,α) reactions in niobium for each source and compares it with the helium production expected for fusion reactor neutrons. Table I shows that only the gas target Ion Accelerator would be comparable to the fusion reactor in this respect. All other sources are several too many orders of magnitude too weak, and may have an incorrect neutron spectrum as well.

TABLE I

NEUTRON SOURCE	SPECTRUM D-T	SPECTRUM Type	FLUX n/cm^2-sec	HELIUM ppm/month
Fusion Power Reactor	Yes		1×10^{15}	30.
Ion Accelerator - Gas Target	Yes		3×10^{14}	9.0
- Metal Target	Yes		5×10^{11}	.015
LAMPF Beam Dump	No	Copper	2×10^{12}	.017
Dense Plasma Focus IX	Yes		1×10^{12}	.030
Experimental Breeder Reactor II	No	Fission	3×10^{15}	.008
Electron Limac (e, γ, n)	No	Uranium	6×10^{11}	.0001
Boosted Electron Linac	No	Fission	6×10^{12}	.0003
			n/cm^2	ppm
Thermonuclear Bomb	Yes		1×10^{17}	.0012
minimum needed for metallurgy				.001

Our conception of the gas target Ion Accelerator, shown schematically in Fig. 1, utilizes a one ampere tritium ion beam from an ion source of the type developed at Oak Ridge National Laboratory, a standard 300 keV accelerator column (design codes for which exist at LASL from the Meson factory (LAMPF) development), a dense (~ 10^{19} molecules-cm^{-3}) deuterium gas target in the form of a supersonic jet directed across the ion beam to minimize differential pumping requirements, and a tritium recovery dump which utilizes the existing LASL Tritium Facility for recovery and processing to allow reuse of the tritium (Tritium cost = \$14 x 10^3/gm). Our preliminary design of the target features a supersonic wind tunnel capable of Mach 5 with entrance and exit holes for the tritium beam protected by differential pumping sections.

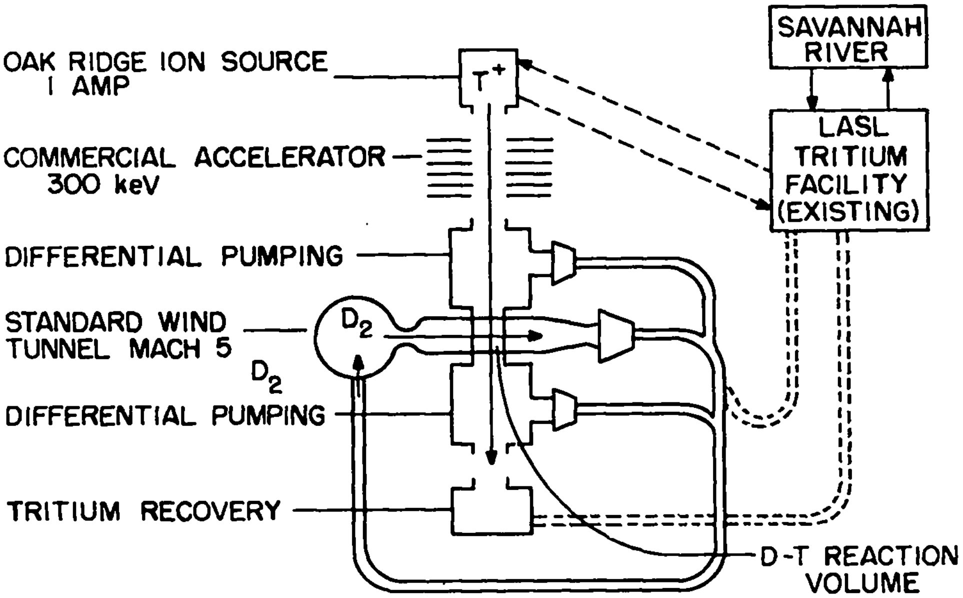


Fig. 1. LASL 14 MeV Intense Neutron Facility

Although we have not yet optimized our design we conclude that this neutron facility can produce 8×10^{14} neutrons-sec^{-1} in a 1 cm^3 reaction volume by using a 500 horsepower wind tunnel compressor, 500 horsepower for the differential vacuum pumps, a 300-500 kW ion source power supply, and a cryosorb tritium recovery pump as a dump for the 50 keV tritium beam which emerges from the gas target. This leads to the flux, 3×10^{14} neutrons-cm^{-2}-sec^{-1}, given in Table I.

The schedule for developing and placing this facility into operation is shown in Fig. 2. The major technical developments required for the facility are the Ion Beam Development and the Dense Gas Target Development. We expect to profit strongly from the ongoing beam development programs at ORNL and LRL which have already produced 1 amp beams at 50-100 keV. The

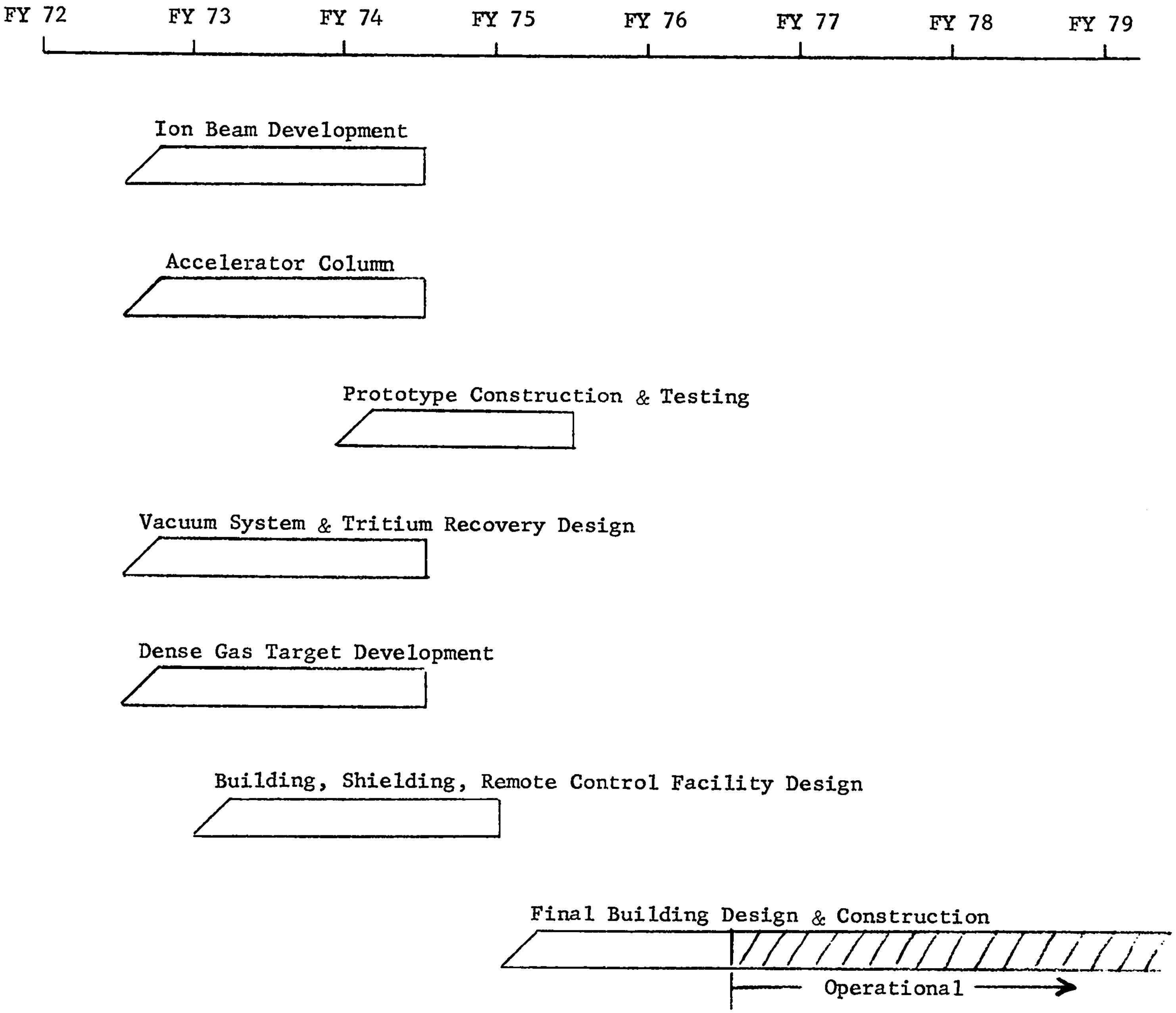


Fig. 2. Schedule For Proposed Neutron Effects Facility

primary developments which therefore remain in this area involve the increase to 300 keV and the focusing of the beam through differential pumping ports of 1-2 cm diameter, two developments which are considered to be technically feasible. It is noteworthy that the neutral injection program at ORNL and LRL depend upon focusing requirements which actually are more stringent than ours. We therefore expect that the beam development programs at these laboratories will provide a technical solution to this common problem. The increase of beam energy to 300 keV, also required at LRL, is expected to stiffen the beam and thus to simplify the problem.

LASL's major developmental effort between mid FY-72 and mid FY-74 would be concentrated on development of the supersonic dense gas target. Since supersonic gas jets of the type described have already been achieved, the development will center on system design and testing with view towards realiability, efficiency of operation, and minimization of the differential pumping problem. LASL's traditional expertise in the handling of intense neutron fluxes, tritium and other radioactive materials will help to make this neutron effects facility operational about 4 years after initiation of this project. A construction cost projection is given in Table II.

TABLE II

14 MeV NEUTRON EFFECTS FACILITY
(Dollars in Thousands)

	FY 72	FY 73	FY 74	FY 75	FY 76	FY 77
Construction Budget						
Development and Design						
Scientific Man Years		4	10	10	10	6
Costs		250	620	700	650	450
Facility						
Building Costs				400	600	
Device Costs			200	400	200	200
Total Costs		250	820	1,500	1,450	650

Total Costs FY-1973 - FY-1977 4,670

SECTION VI

A PROGRAM OF NEUTRONIC AND RADIATION CALCULATIONS FOR THERMONUCLEAR REACTORS

G. I. Bell

1. Scope of the Calculational Program In the design of CTR blankets, there are at least three important considerations. First of all, in a reactor with DT fuel, the blanket must be designed to breed tritium; that is, more than one triton must be produced in the blanket per triton consumed (and 14-MeV neutron produced) in the thermonuclear plasma. Second, provision must be made for removal of the heat which is generated in all regions of the blanket including vacuum and structural walls, coils, etc. If refrigerated or cryogenic coils are used to supply the containing magnetic fields, then the blanket must effectively shield these coils from fluxes of neutrons and gamma rays which would otherwise lead to excessive heating. Finally, consideration must be given to radiation damage in blanket materials and vacuum wall so that adverse changes in material properties can be minimized or at least anticipated.

In CTR blanket design studies, (whether for DD or DT fuel) neutron and gamma-ray transport and energy deposition are computed within the blanket using Monte Carlo or other numerical methods of solving the transport equation. Members of the LASL have much experience in the solution of such transport problems and have made preliminary blanket design studes[1,2,3] using existing computer codes and personnel.

A comprehensive calculational program for CTR blanket design could be readily established to make use of existing computer programs, computing facilities (CDC 7600 and 6600 computers), and experience in the solution of similar problems. Additional personnel would be required in order to give due emphasis to problems of special importance to CTR blanket design and in order to carry out the design calculations of interest to various kinds of thermonuclear reactors. The sorts of work which would be required may be grouped under three headings: (1) cross-section data evaluation and handling; (2) modification of computer programs; and (3) blanket and shielding design studies, including heat deposition and residual radioactivity.

2. Cross Section Evaluations Experimental neutron cross sections of materials of special interest to CTR systems should be critically examined and supplemented by theoretical calculations where required. Not only the neutron interaction cross sections but also the secondary reaction products (e.g., gamma rays and/or charged particles) and their energies must be specified. Additional experimental measurements may be indicated.

Evaluated nuclear data must be arranged and made available in computer files. Existing data handling facilities at LASL could be used for this work.

3. Modification of Computer Programs A variety of computer programs have been developed and are in use at LASL for solving complicated neutron and gamma-ray transport problems. In particular, numerical solutions of the neutron and gamma transport problem are readily obtained in simple one-dimensional geometry (plane, sphere, or infinitely long cylinder) by the DTF IV program.[4] Analagous codes exist for solving two dimensional problems. The Monte Carlo programs MCN(neutron) and MCG(gamma) are routinely used for solving transport problems in complicated geometry, for example toroidal regions of elipsoidal cross section can be treated. Other Monte Carlo programs, such as ANDYMG3,[5] are likewise available.

Modifications and extensions of these programs would be required in order to carry out an extensive series of CTR blanket and core calculations. In particular, neutron and gamma transport should be done in the same computer program using cross sections generated from a central nuclear data file. Progressively more realistic geometries would also be included.

Modified computer programs would be documented and made available to all interested persons.

4. Blanket and Shielding Design Studies Using existing cross sections and computer programs, it is possible to study simple and preliminary blanket and shielding designs both for pulsed and steady-state reactors. If the evaluated nuclear data and modified computer programs indicated in (2) and (3) were available, more reliable and accurate studies could be made on a variety of designs. Moreover one could better delineate the areas of greatest uncertainty where experimental effort should be concentrated.

5. Cost Estimates An agressive, continuing program of CTR blanket design calculations would require approximately the following level of effort:

(CP = ceiling point ≈ $40K per year).

a) Cross section evaluation and handling (two staff members)	1 CPS
b) Modification and extension of computer programs (two staff members)	1 CPS
c) Blanket design and shielding studies* (two staff members and two assistants)	3 CPS
Computer charges (~ 100 hours per year of CDC 7600 time or equivalent at $300/hour if charged at same rate as to governement agencies)	$30,000

A cost summary is given in Table I.

* About half this effort would suffice for those calculations of direct interest to LASL.

TABLE I

NEUTRONIC AND RADIATION CALCULATIONS
(Dollars in Thousands)

	FY 72	FY 73	FY 74	FY 75	FY 76	FY 77	FY 78	FY 79	FY 80	FY 81	FY 82
Scientific Man Years	-	3	4	5	5	5	5	5	5	5	5
Costs	-	150	210	280	300	315	330	350	375	400	425

References

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SECTION VII

STUDIES OF HIGH TEMPERATURE RADIATION DAMAGE TO FUSION REACTOR MATERIALS

D. J. Dudziak, W. V. Green, and E. G. Zukas

One of the key technological problems to be overcome prior to constructing a prototype fusion reactor is that of high temperature radiation damage. In Section V sources of neutrons for such studies are discussed. In addition to ordinary radiation damage 14 MeV neutrons will generate unusually large amounts of helium by $(n, x\,\alpha)$ reactions. Helium production, neutron irradiation and creep will each contribute to the total material damage. High temperature irradiation leads to material swelling as follows. Displaced atoms and vacancies are generated in equal numbers. Some, but not all, of the displaced atoms, return to normal lattice sites by refilling the vacant sites. This process causes no damage. A small fraction of the displaced atoms attach themselves to dislocations via climb, which leaves a small number of excess vacancies. These excess vacancies form vacancy clusters and eventually pores, which are typically 25 to 400 Å in diameter. The pore density ranges from 10^{14} to 10^{16} per cm^3. This process causes high temperature radiation damage swelling.

Helium, being a noble gas and therefore inert, is quite insoluble in metals. It collects in the pores under high pressure. This pressurization stabilizes small pores against collapse under the influence of surface tension forces. Helium production thereby modifies the size and spacing of the pores. This has not been adequately studied under conditions where the ratio of the number of helium atoms to displacement atoms is large, as will be the case in fusion reactors.

The material constraints or swelling in a reactor will generate stresses, as will design loads and magnetic field changes. Sustained stresses at high temperatures cause time dependent deformation or creep. Microstructural changes that accompany creep include grain boundary pore formation, cracking, migration and sliding, and large increases in dislocation density within the grains. All of the structural changes are expected to modify radiation swelling. Most significant might prove to be the increased dislocation density, which can amount to a 10,000 times increase. The excess vacancy production, and therefore the swelling rates would be increased. Creep and radiation induced pores would interact. Grain boundary migration would tend to sweep the pores into the grain boundaries, thereby reducing the strain and time to failure.

It is impossible to predict damage rates from theory but it is feasible to explain those rates, and to even modify them, in a thorough experimental program. Such a program must include electron transmission and light microscopy, and test sequences of (a) creep damage followed by radiation damage, (b) radiation damage followed by creep damage, and (c) simultaneous creep and radiation damage. This is what we propose to do.

Base line creep studies would begin as soon as possible on molybdenum, niobium, and vanadium. A few niobium samples are actually available for test now. We need to establish creep curve shape, the stress and temperature dependences of the creep rate and the dislocation density at various stresses and creep strains. It is also necessary to study grain boundary cavitation, migration and sliding in creep for these will affect radiation swelling.

The area of theoretical and calculational work in transport theory and dosimetry is one of the primary competences of LASL. A program of creep studies of refractory metals has been in progress since 1956 at LASL. Thus the required experience and competence presently exist at LASL.

KT/ep: 125 (100)