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FUSION DEVICES

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FUSION DEVICES

T. K. Fowler

In this talk, I will emphasize the expected developments in fusion research over the next five years. This will be the formative period for fusion in the foreseeable future. It will also be a formative period in national energy policy that will impact many years to come. As the previous speakers have said, we believe that fusion is a matter of great interest to the electric utilities. We need your support and your guidance in this critically formative period.

I will give a brief description of the three mainline activities of the research program in fusion. These include two magnetic systems, one called the Tokamak and one called the mirror machine, and also laser fusion. While I am going to concentrate on these three mainline activities, they are not the only possibilities. Fusion is a rich subject with many possible outcomes, all of which may be interesting to the utilities. However, the first ways that fusion will be made practical will, I think, come from the approaches I will describe, simply because each of these concepts already has behind it a long history of scientific development that should culminate in the next five years.

Tokamak

I will begin with the Tokamak, which is in fact the largest fusion program, both internationally and in the U.S. The Tokamak is a magnetic device in the shape of a torus or doughnut as shown in Figure 1. The figure is a sketch of the toroidal vacuum chamber that contains the hot plasma in which fusion reactions will take place. In the photograph the lighted region is a halo of light emitted in a cool thin plasma surrounding the hot plasma, which is so hot that it does not emit light. In this case the hot plasma temperature is around ten million degrees Kelvin.

The toroidal plasma is maintained in position by strong magnetic fields that act on the plasma because it is fully ionized. In the magnetic fusion energy program, we deal with plasmas at particle densities much less than the densities of air in the room, many thousands of times less. The reason for atoms or, in the case of a plasma, ionized atoms, or ions and electrons. In the PLT it is hoped that temperatures will approach the forty or fifty million degree range *by the time these experiments* are *completed*.

One can already say with some confidence that the above goal will be met in PLT in the next twelve months. The final beam power will be about three megawatts. The first of several beams has been installed and has resulted in an increase in the temperature of the ions from eight million degrees without beam heating to about fifteen million degrees with four hundred kilowatts of beam input at this writing.

Success in increasing the temperature in PLT bodes well for the next major Tokamak step already in preparation. This is called the Tokamak Fusion Test Reactor (TFTR), also at Princeton. It will be a very large facility, at a cost of two hundred thirty million dollars. Figure 4 shows a model of the TFTR. Again, note the characteristic toroidal shape. This facility should be in operation around 1981. The goal of this machine is to actually produce fusion energy from a mixture of deuterium and tritium. It will be heated by neutral beams, the same process that is now being tested in the PLT. The objective is to produce about as much fusion power out as the beams inject into the plasma, what one might call a scientific "breakeven" demonstration but one that will, by the way, produce over ten megawatts of actual fusion power for periods of a second or so at a time. This would be a substantial achievement scientifically, but also a substantial achievement technologically. The TFTR will have many of the ingredients of a working reactor. As to scale, the minor diameter of the vacuum chamber is about two meters. The magnetic field strength will be about fifty kilogauss and the total beam injection capability is around twenty mega watts. *Figure 5 shows a full scale model* of the machine in cross section.

Figure 6 is a sketch of a full-scale Tokamak reactor of the future. Such attempts at reactor design serve mainly as problem-finding exercises at this stage. I show you this complicated sketch mainly to indicate that people are, in fact, trying to address designs in detail. The basic toroidal machine can be seen in the middle of the reactor. The fusion reactor itself only produces heat that runs a steam electric generation plant in the usual manner. In tank, that have produced over six megawatts of heating power for one-hundredth of a second. With this powerful heating method record ion temperatures have been obtained in the 2XIIB, well in excess of one hundred million degrees. This result was first obtained in 1975.

Besides achieving high temperatures, the 2XIIB experiments have exhibited a ten-fold improvement in plasma confinement time as predicted theoretically. As a bonus, it was also found that the device could confine very high plasma pressures with relatively weak magnetic fields. In fusion jargon, this is called high beta, beta being a term for the ratio of pressure to the magnetic field strength squared. Higher pressure implies higher fusion power output from a given magnet. This is, of course, quite important because much of the capital cost of magnetic devices is in the magnet and associated gear.

We are now ready to move on from these accomplishments to a larger mirror machine, called the Mirror Fusion Test Facility (MFTF); see Figure 10. Though tritium operation is not intended, in many respects the MFTF serves for the mirror approach a role comparable to the TFTR for Tokamaks; namely, the MFTF should be the last scientific step before embarking upon an experimental mirror reactor in the 1980's. It embodies the main technologies of a mirror reactor, including more powerful neutral beams (80 kV) and a superconducting magnet. Ultimately, all magnetic fusion devices will employ superconducting magnets because they require very little power to operate (mainly refrigeration). Today I think it is fair to say that whether one chooses to build a superconducting magnet or not is largely a matter of economics and experimental convenience and not one of technological capability. In our case, partly because we already have experience in building superconducting magnets, and partly because we are interested in very long periods of operation, the MFTF will use superconductors and hence the magnet itself will be DC. The MFTF magnet will weigh two hundred tons. It will use a commercially available niobium-titanium conductor. The MFTF should become operational in late 1981, about the same time as the TFTR.

One outcome of the 2XIIB mirror experiments has been new ideas. Our aim is to produce relatively small reactors operating in steady state. The linear geometry and high beta capability of mirror systems offer unique possibilities toward these ends, but thus far the mirror system is more "leaky" than the Tokamak in that the latter has confined plasmas for much longer times. The new ideas offer ways to plug up the leaks. The evolution of these ideas is sketched in Figure 11.

One of the new ideas, called the Field Reversed Mirror, might lead to reactors at the hundred megawatt level and experimental reactors at tens of megawatts. I must caution you that this is by no means certain but it is something to which we are giving serious attention and it is one of the focuses of our mirror experimental program today. Field reversal is just another mode of operating the same machine. It builds upon the high beta capability of mirror machines in two ways. First, as I have explained, high beta means that with a relatively weak field one can hold high plasma pressures. Conversely, with very high fields, one can hold very very high pressure. Thus it turns out that there would be a possibility of producing power at power densities that are a hundred or more times what would be possible in other magnetic fusion schemes. That is one virtue of high beta. The other possible virtue is that the diamagnetic plasma current at high beta may become so strong that the magnetic lines close, as shown in the figure. In this way the high beta plasma would plug up its own leaks since the plasma would now have to cross the closed magnetic lines in order to escape. Such a mode of operation would combine some of the good features of the mirror machine with some of the good features of the Tokamak, resulting in a rather compact and small reactor cell producing ten or twenty megawatts of fusion power in a plasma volume of a few litres. One can imagine a reactor consisting of a string of five or ten such cells adding up to a hundred megawatts output.

Another new idea we are pursuing is the Tandem Mirror. It represents a return to the original mirror idea of a long solenoid terminated by mirrors that plug up the ends of the solenoid. In the Tandem Mirror, the end plugs are mirror machines of the magnetic well type similar to the 2XIIB and the MFTF. Theoretically, based on plasma properties verified in 2XIIB, this scheme would enhance the confinement of plasma in the solenoid by a large factor. The principles of this concept will be tested in a new experiment called TMX (see Figure 12).

A reactor based on the tandem mirror concept would have many interesting features, as sketched in Figure 13. Most of the fusion power would be produced in the long solenoid, which is the simplest conceivable magnetic fusion device - circular coils, modular construction, easier maintenance. The high technology would be relegated to the smaller end plugs.

peak power. Each system undertaken represented a major step in laser technology. Shown also in Figure 15 are the expected target gains for each system, with the actual target performance to date.

Janus, a small two-beam laser system, produced 0.4 TW of power. With Janus, laser-driven deuterium-tritium implosions yielded 10^7 neutrons and allowed first proof of the thermonuclear nature of the reaction. Cyclops was the developmental test bed for Janus, Argus, and Shiva. It was the first laser worldwide to deliver 1 TW. Argus II, designed as a 3-TW system, actually has delivered 4.6 TW. Neutron yields with Argus II exceeded 10^9, permitting for the first time confirmation of thermonuclear nature of the D-T reaction with neutron time-of-flight spectroscopy. Argus IV was not built because of funding limitations. Shiva, to be finished this year, is expected to achieve significant thermonuclear burn by the end of 1978.

To prove the scientific feasibility of laser fusion Shiva Nova is designed to provide the power needed to drive high energy gain microexplosions. Its technological base has been systematically developed by preceding lasers. It will produce 10-15 times the power and 20-30 times the energy of Shiva, by using more beams (40 to 50) of larger diameter (30 to 40 cm) with amplifiers made of new, advanced fluorophosphate laser materials.

Figure 16 is a photograph of the Argus facility. The laser is laid out on tables around the room in this case. Again, this facility has produced the best laser fusion results anywhere. Figure 17 is a model of the Shiva with its twenty beams, and Figure 18 is Shiva Nova.

Figure 19 sketches a conceptual laser fusion reactor. The basic idea is similar to a magnetic fusion reactor. However, whereas the magnetic system produces energy at a more or less continuous rate, like a furnace, in the laser system pellets are fired repeatedly, about once a second. The energy release from any one pellet might be as much as a thousand kilowatt-hours. With DT fuel, most of this energy is released as energetic neutrons that must be absorbed in the walls of the reactor vessel. Figure 20 illustrates a different kind of reactor vessel concept, called the lithium waterfall, that would greatly reduce the damage to the vessel by neutron bombardment. In this novel approach, the first structural wall is shielded by a thick flow of

DR. WOODSON: We have time for a couple of questions.

VOICE: The lithium waterfall concept looks like a closed cycle system. What do you do with the tritium that you produce in the lithium?

DR. FOWLER: I would like to defer to Dr. John Emmett who heads the laser fusion program at Livermore.

DR. EMMETT: The idea behind the lithium waterfall is the decoupling of the thermonuclear yield from the first wall. Tritium is made in the lithium and removed from it in the lithium pumping system, to be used in another pellet fabrication.

DR. FOWLER: Thank you. Another question?

VOICE: What kind of cooling temperatures are we looking at in the various devices?

DR. FOWLER: There is flexibility on that point. The design choice is closely coupled to the lifetime of the material against neutron damage. Some data suggests that if the temperature of the "first wall" facing the plasma is cooler, damage is less. Thus one might design with a temperature gradient, cooler at the surface and hotter in the interior where the neutrons deposit most of their energy. In any case, I think we are not necessarily talking about highly advanced materials but the actual choices vary with the design.

VOICE: I believe you stated that developing small reactors was a goal at Livermore, one I am highly in favor of. There is probably some optimum size that is a compromise between the flexibility of smaller sizes and the economy of scale. Can you comment on this?

DR. FOWLER: My primary concern is the development phase. I think it may well turn out that the market is a variable thing for fusion in which

Figure 1: Halo of light surrounding the hot plasma core in a Tokamak experiment.

Figure 2: Geometry of the Tokamak showing the toroidal plasma chamber and magnetic field geometry.

Figure 3: Photograph of the Princeton Large Torus (PLT) that has reached record plasma confinement -- 0.1 second at about 10 million degrees.

Figure 4: Model of the Tokamak Fusion Test Reactor (TFTR) to operate in the early 1980's, it will be the first magnetic fusion device to produce substantial fusion power by D-T reactions.

Figure 5: A full scale model of the TFTR.

Figure 6: Princeton Reactor.

Figure 7: Glowing plasma outlines the fan shape of magnetic lines in a mixer or machine.

Figure 8: Mirror Coils with Ioffe Bars that create a stable "magnetic well" configuration.

Figure 9: Photograph of the 2XIIB Mirror Machine that created record ion temperatures over one hundred million degrees.

Figure 10: Artist's rendering of the MFTF mirror experiment showing the superconducting magnets, neutral beams and vacuum tank.

Figure 11: Evolution of Mirror Fusion Ideas.

Figure 12: Sketch of the Tandem Mirror experiment (TMX).

Figure 13: A conceptual Tandem Mirror Reactor.

Figure 14: Laser Fusion Concept.

Figure 15: Laser development schedule and fusion energy yield projections with actual performance to date.

Figure 16: Argus Laser Facility that has produced a billion neutrons per shot.

Figure 17: Model of the Shiva Laser Facility soon to be completed.

Figure 18: Shiva Nova Laser Laboratory Facility.

Figure 19: Conceptual Laser Fusion reactor.

Figure 20: Laser Fusion Reactor incorporating the Lithium Waterfall Concept.

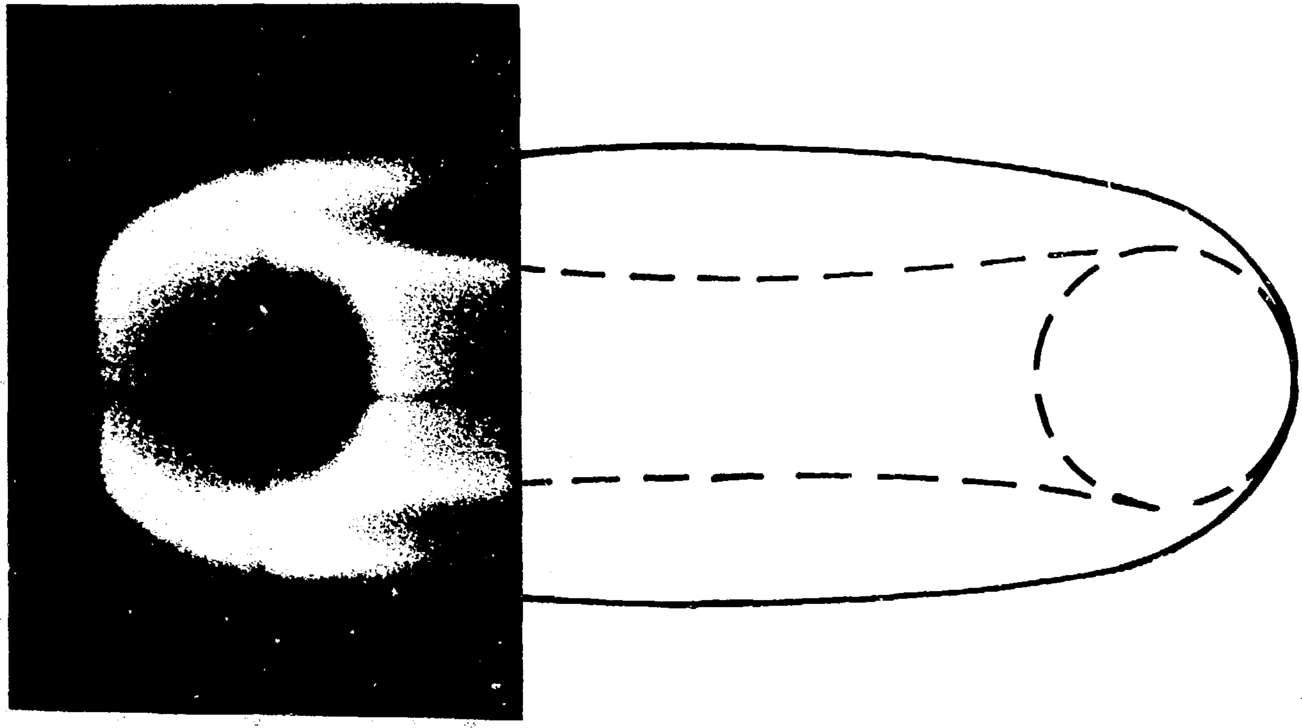


Fig. 1

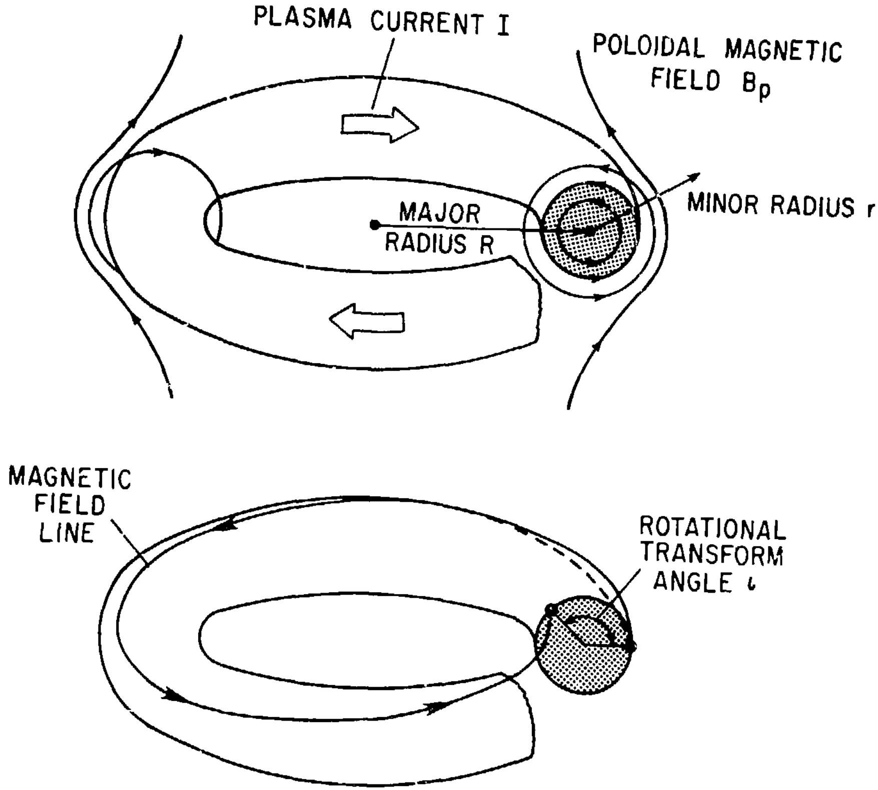

PLASMA CURRENT I
POLOIDAL MAGNETIC FIELD B_p
MAJOR RADIUS R
MINOR RADIUS r
MAGNETIC FIELD LINE
ROTATIONAL TRANSFORM ANGLE ι

Fig. 2

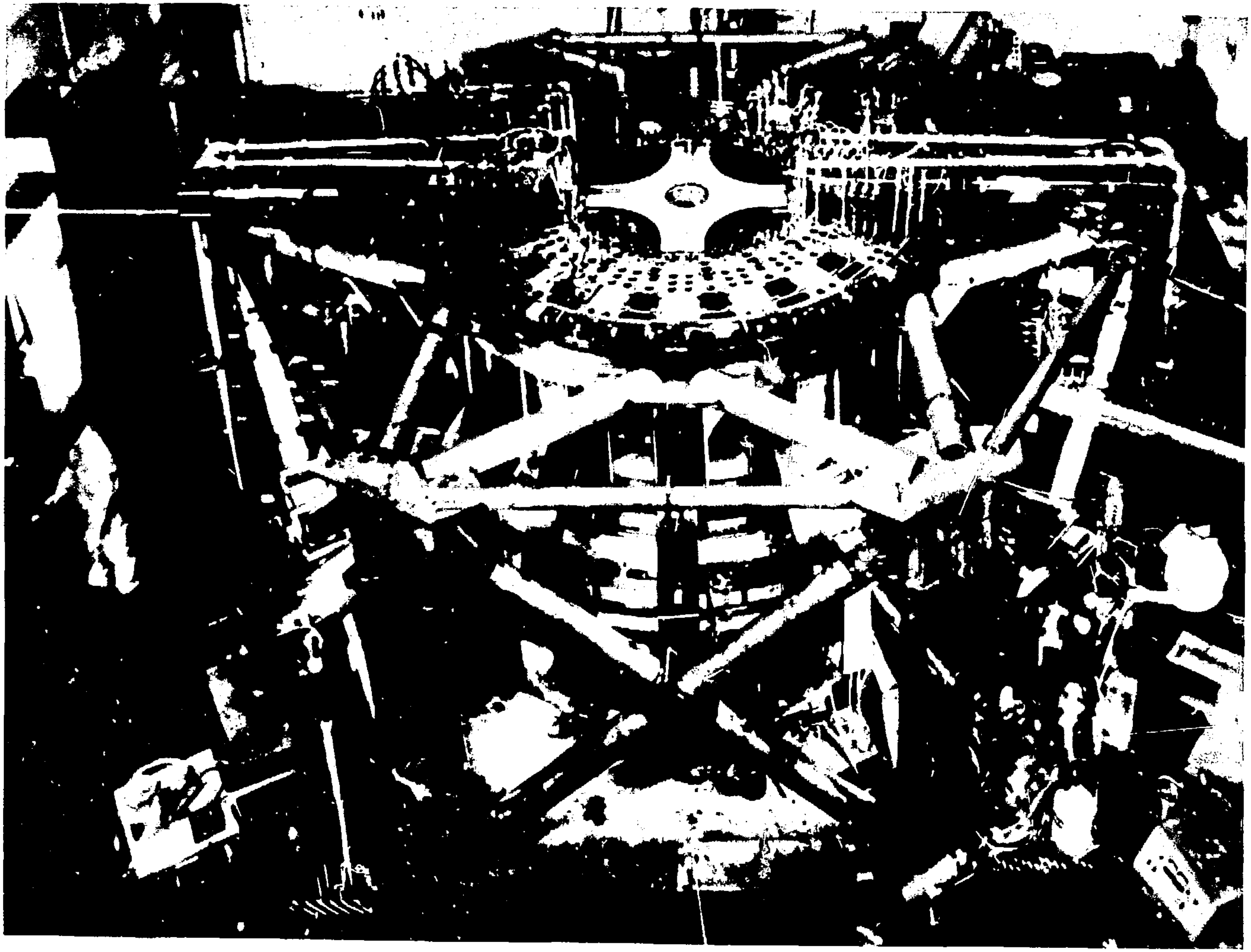


Fig. 3

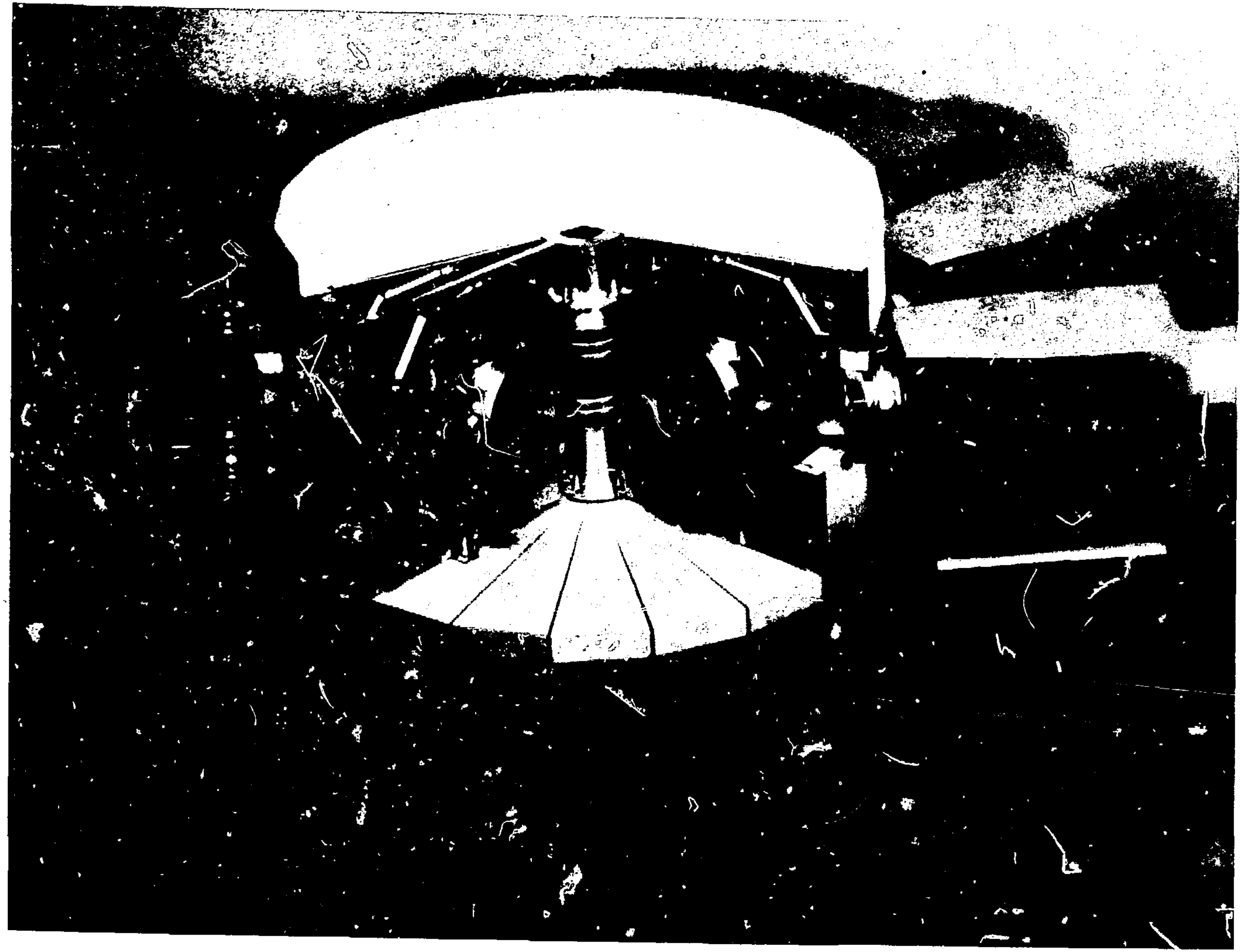


Fig. 4

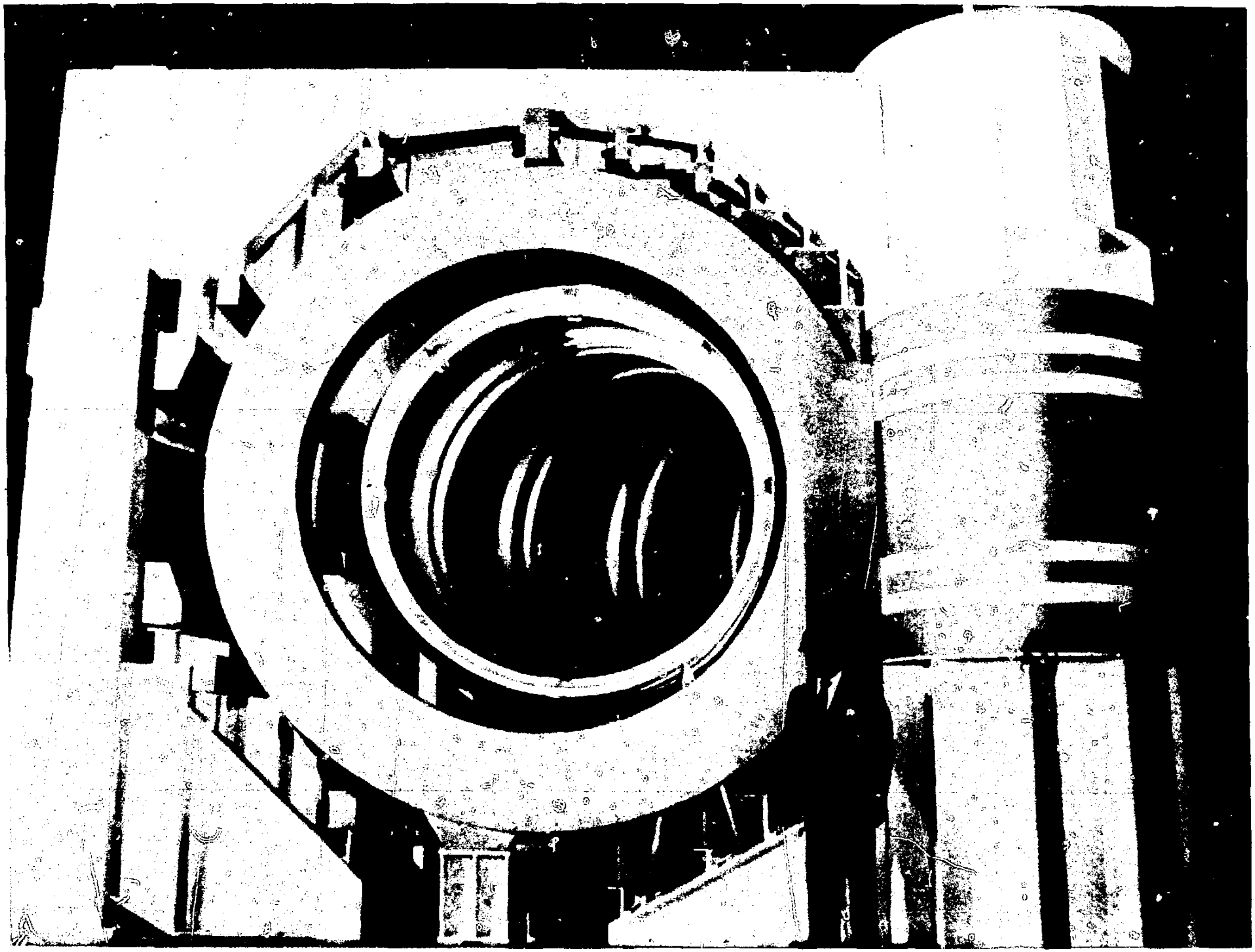


Fig. 5

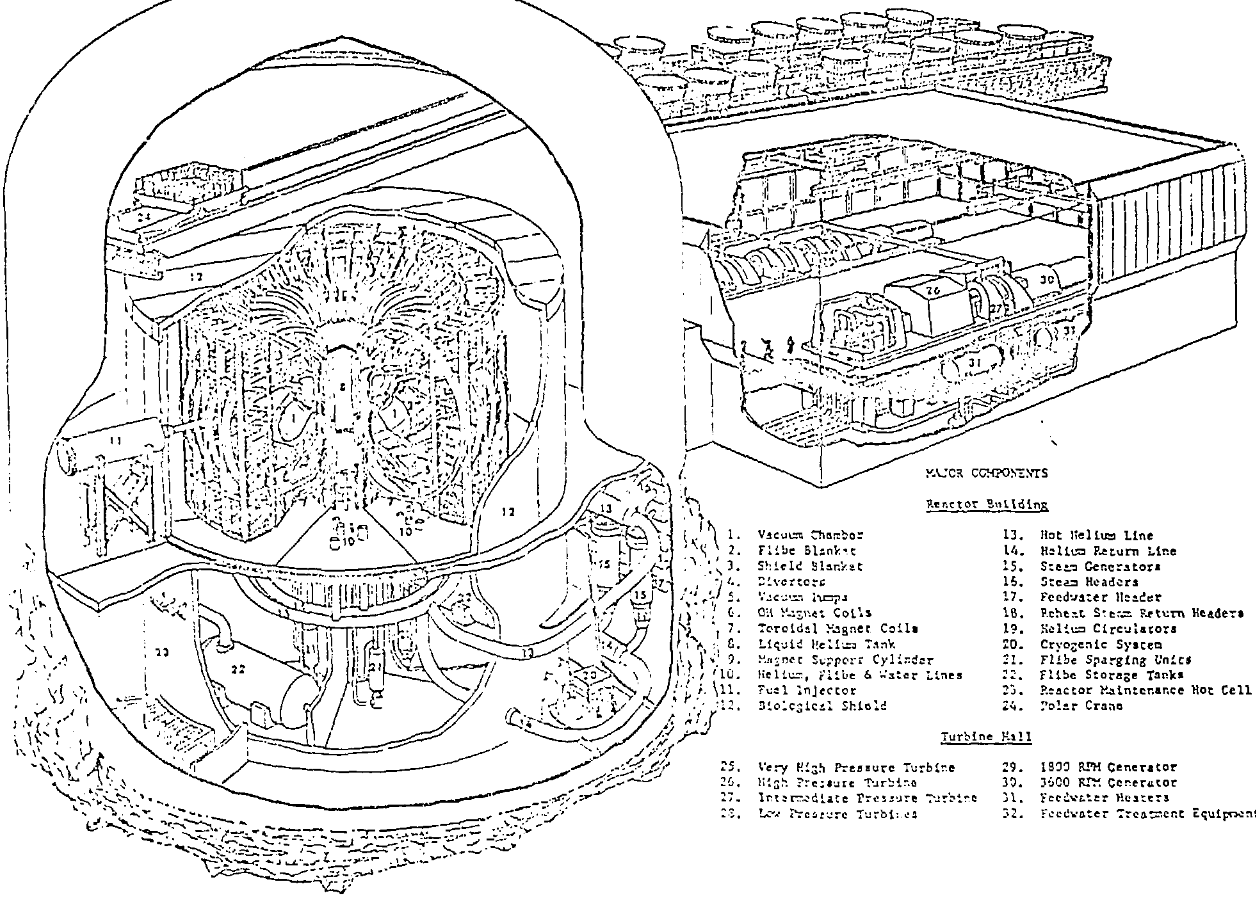

MAJOR COMPONENTS
Reactor Building
1. Vacuum Chamber
2. Flibe Blanket
3. Shield Blanket
4. Divertors
5. Vacuum Pumps
6. OH Magnet Coils
7. Toroidal Magnet Coils
8. Liquid Helium Tank
9. Magnet Support Cylinder
10. Helium, Flibe & Water Lines
11. Fuel Injector
12. Biological Shield
13. Hot Helium Line
14. Helium Return Line
15. Steam Generators
16. Steam Headers
17. Feedwater Header
18. Reheat Steam Return Headers
19. Helium Circulators
20. Cryogenic System
21. Flibe Sparging Units
22. Flibe Storage Tanks
23. Reactor Maintenance Hot Cell
24. Polar Crane
Turbine Hall
25. Very High Pressure Turbine
26. High Pressure Turbine
27. Intermediate Pressure Turbine
28. Low Pressure Turbines
29. 1800 RPM Generator
30. 3600 RPM Generator
31. Feedwater Heaters
32. Feedwater Treatment Equipment

Fig. 6

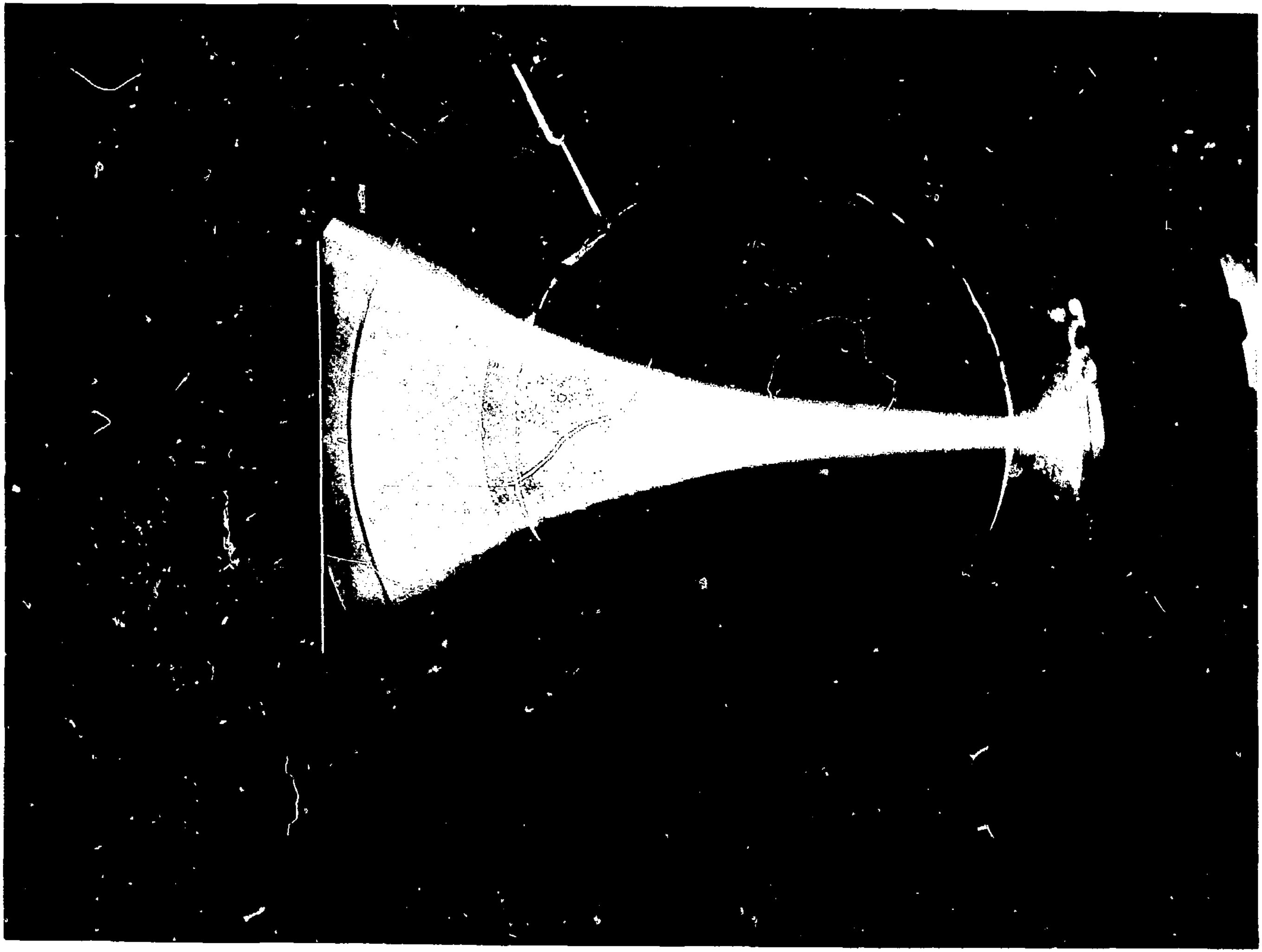
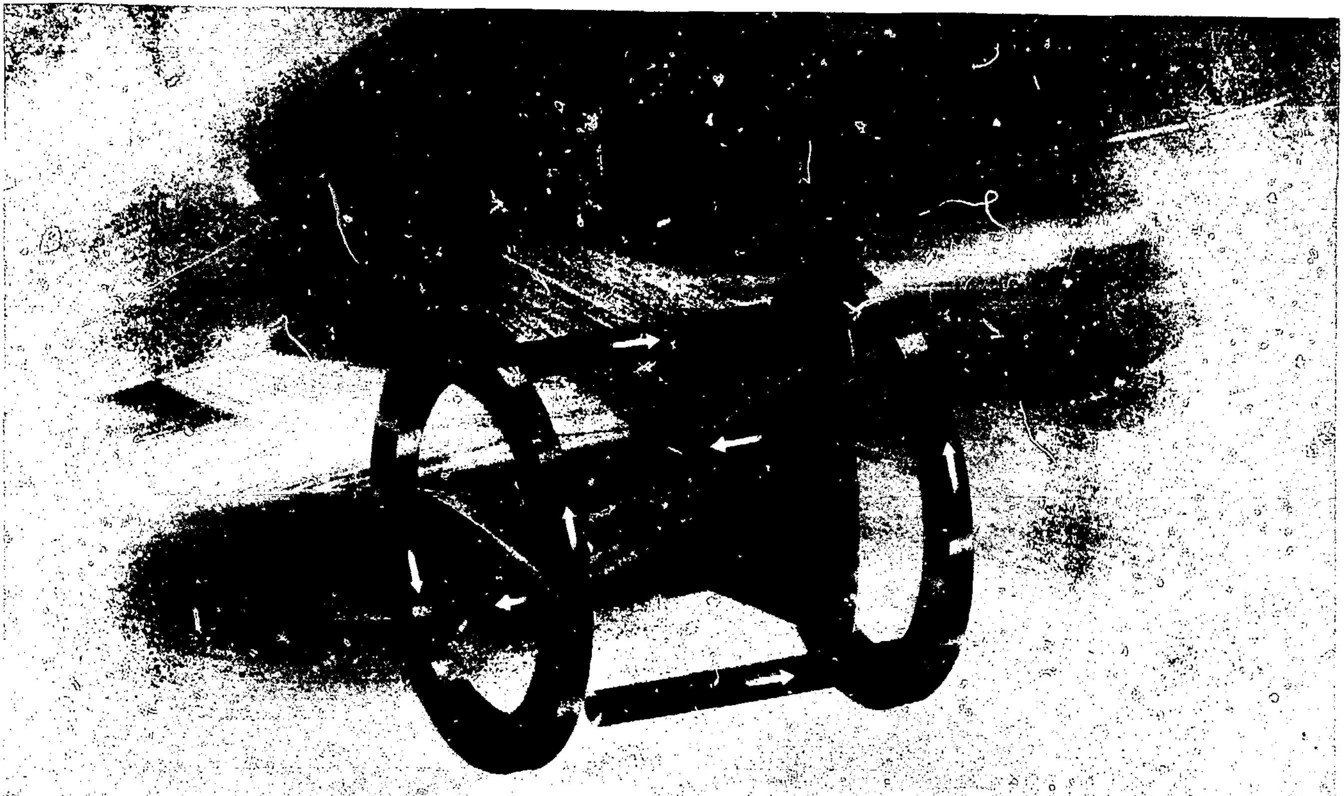


Fig. 7



"MAGNETIC WELL" created by surrounding a mirror-type magnetic field by four rods carrying current.

Fig. 8

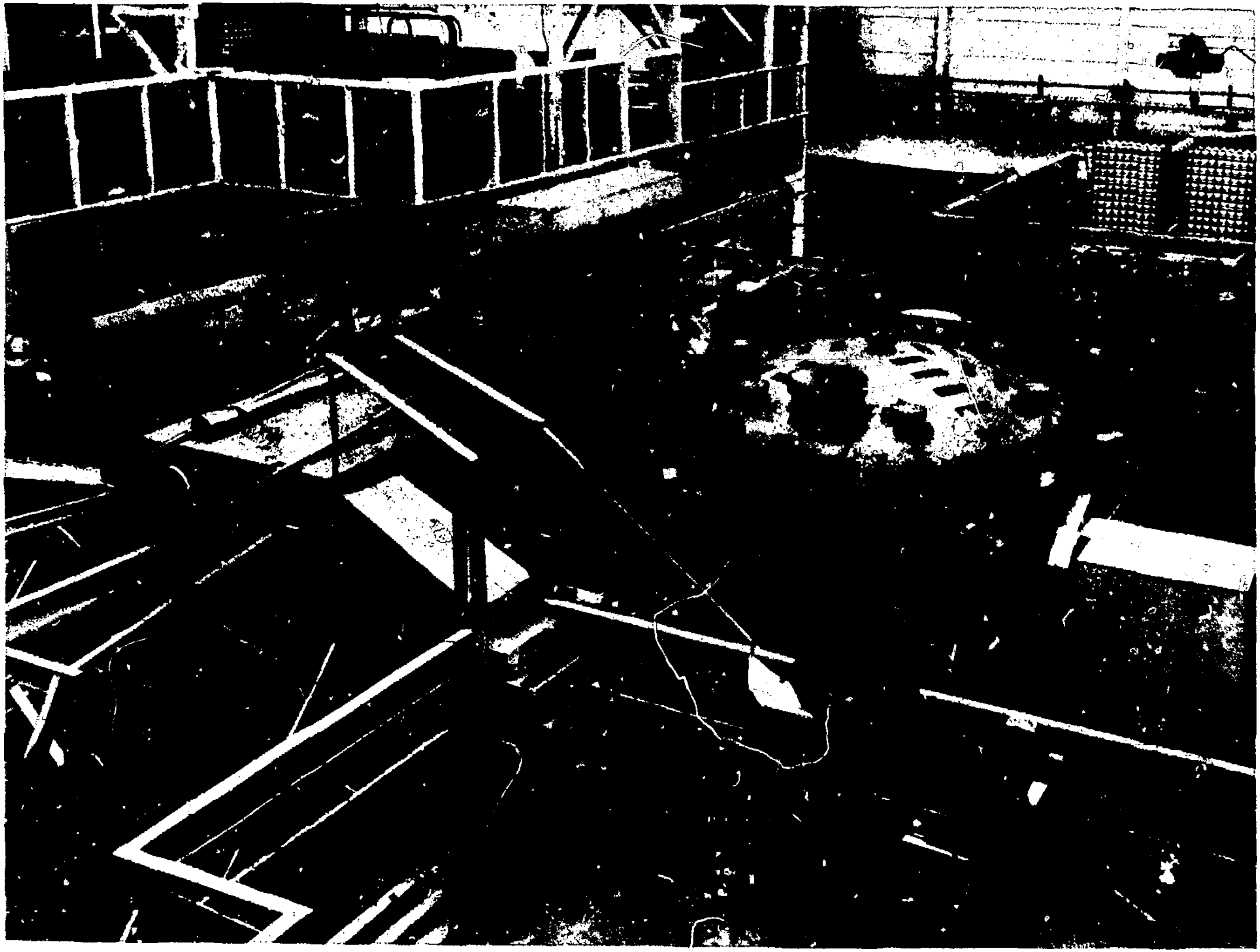


Fig. 9

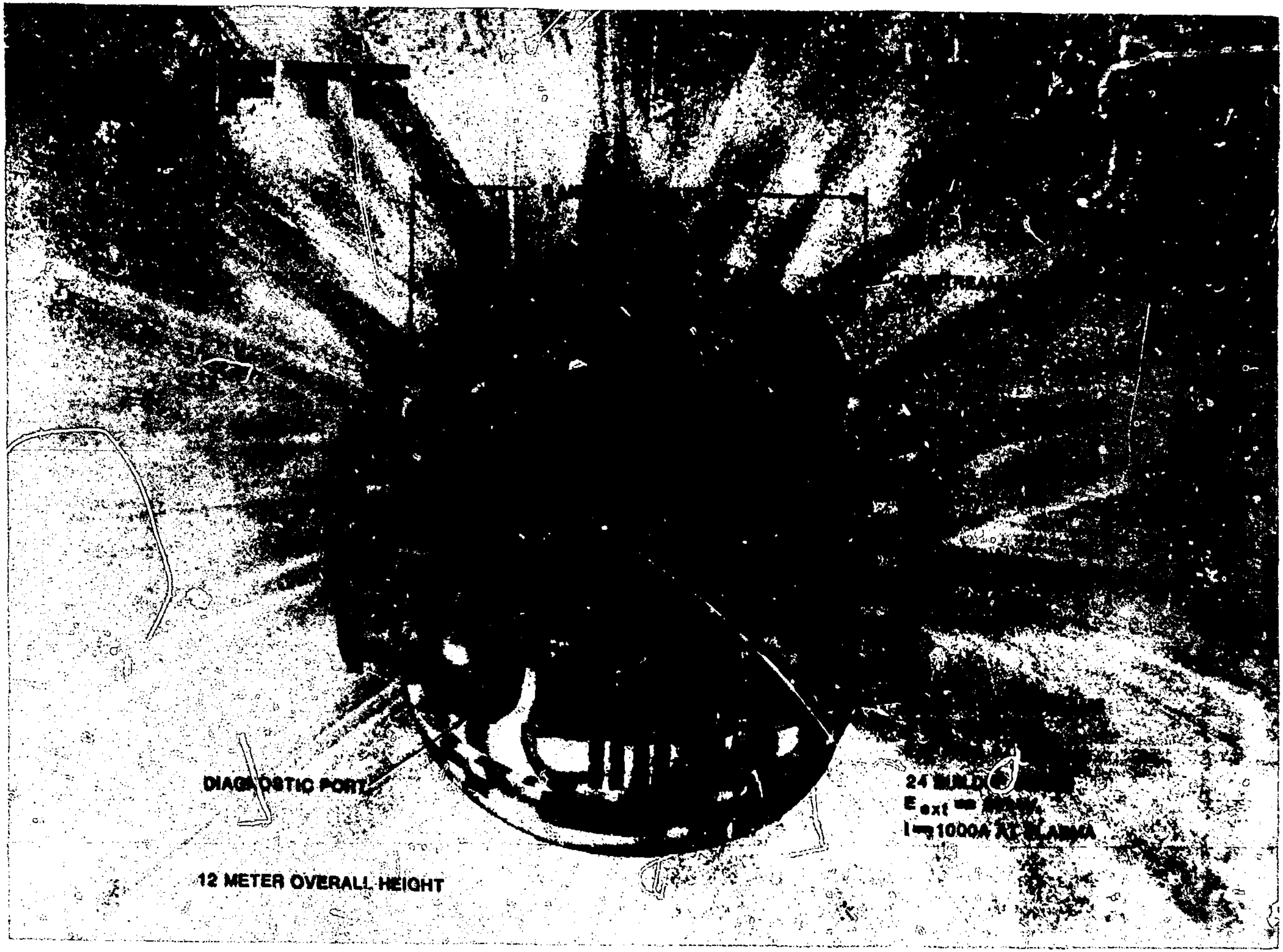


Fig. 10

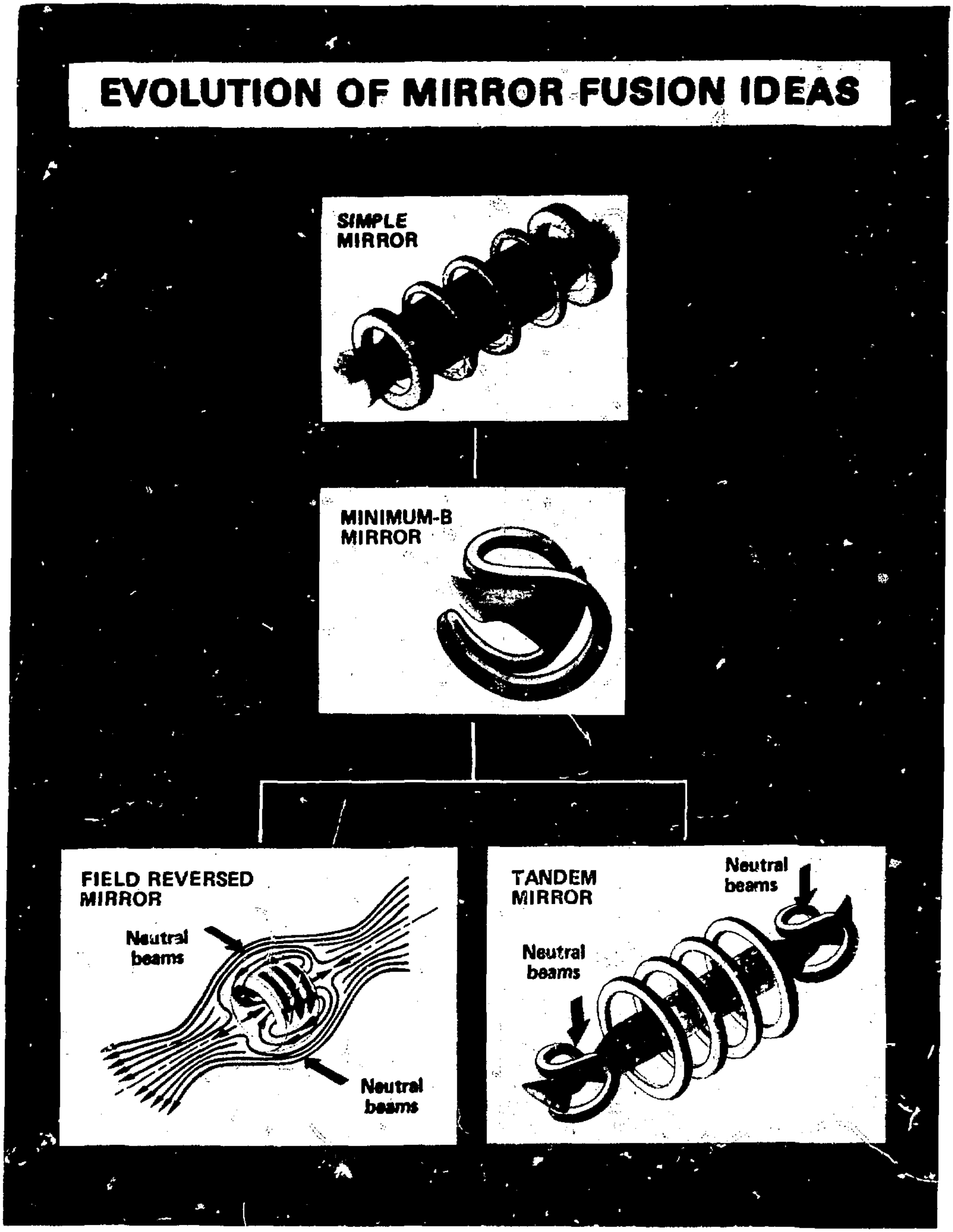

EVOLUTION OF MIRROR FUSION IDEAS
SIMPLE MIRROR
MINIMUM-B MIRROR
FIELD REVERSED MIRROR
Neutral beams
Neutral beams
TANDEM MIRROR
Neutral beams
Neutral beams

Fig. 11

Fig. 12

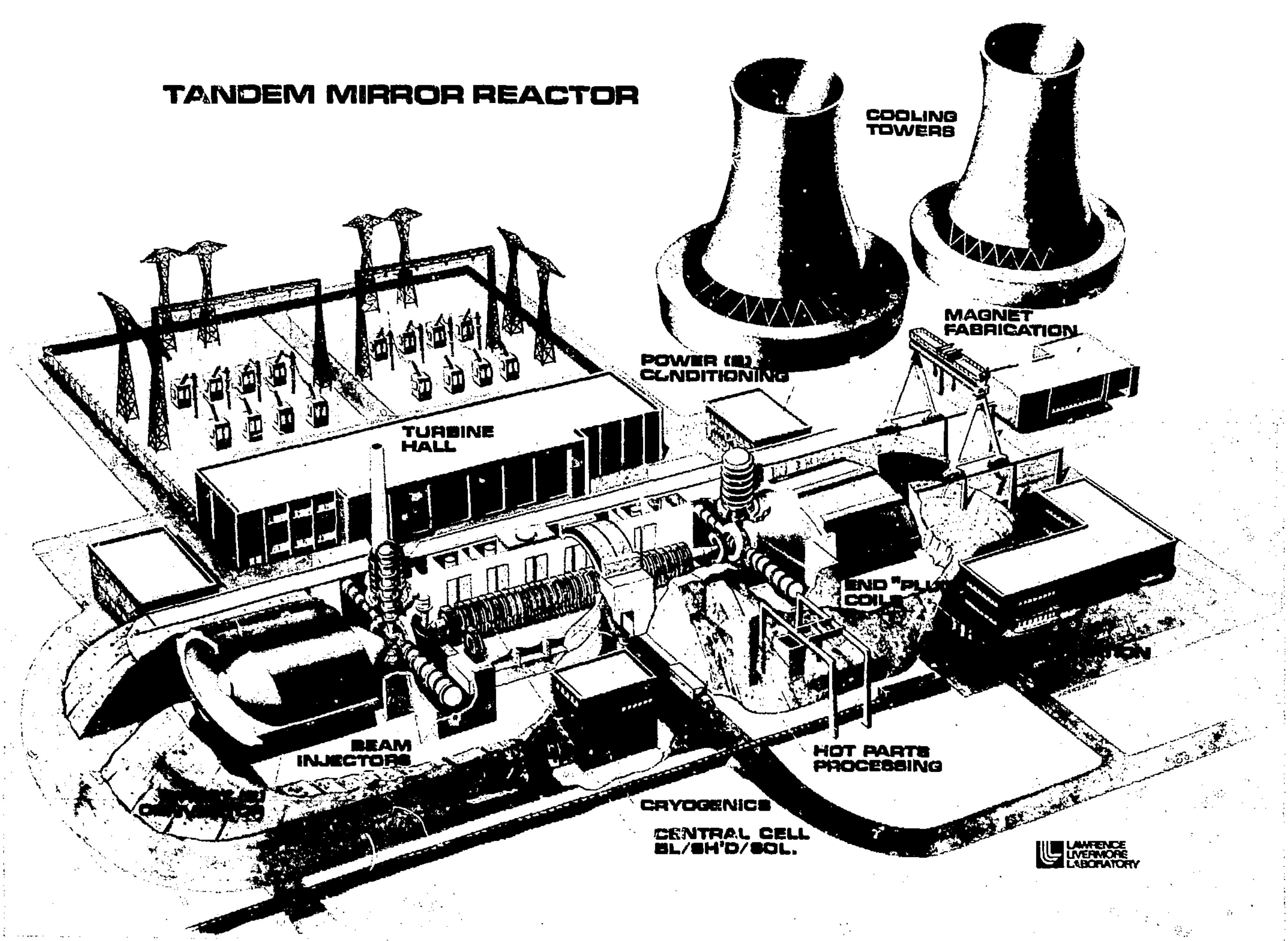
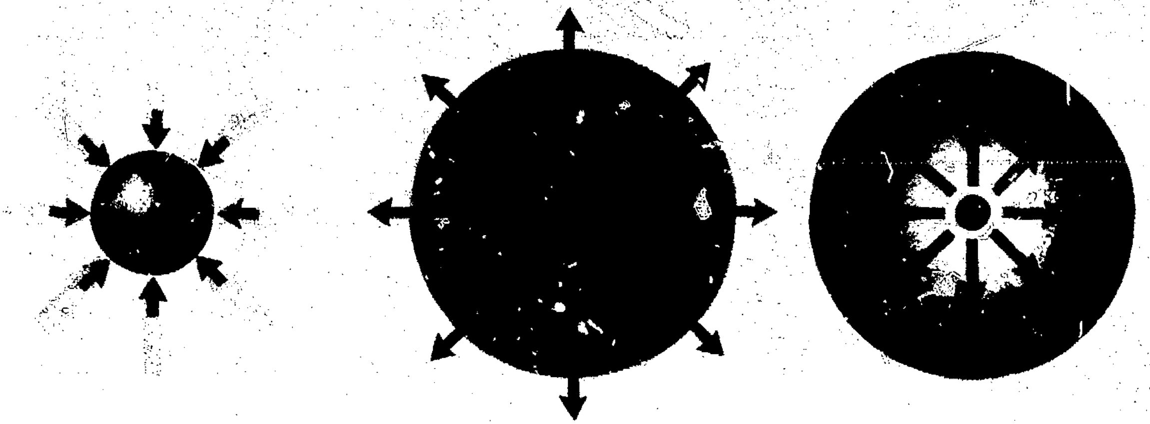

TANDEM MIRROR REACTOR
COOLING TOWERS
MAGNET FABRICATION
POWER (E) CONDITIONING
TURBINE HALL
BEAM INJECTORS
HOT PARTS PROCESSING
CRYOGENICS
CENTRAL CELL BL/SH'D/SOL.
LAWRENCE LIVERMORE LABORATORY

Fig. 13

INERTIAL FUSION CONCEPT



Laser or particle beams rapidly heat the surface of a fusion target

Fuel is heated and compressed by rocket-like blow-off of surface material

When the central core of the fuel reaches a temperature of 100,000,000°C and high density, the fusion reaction ignites.

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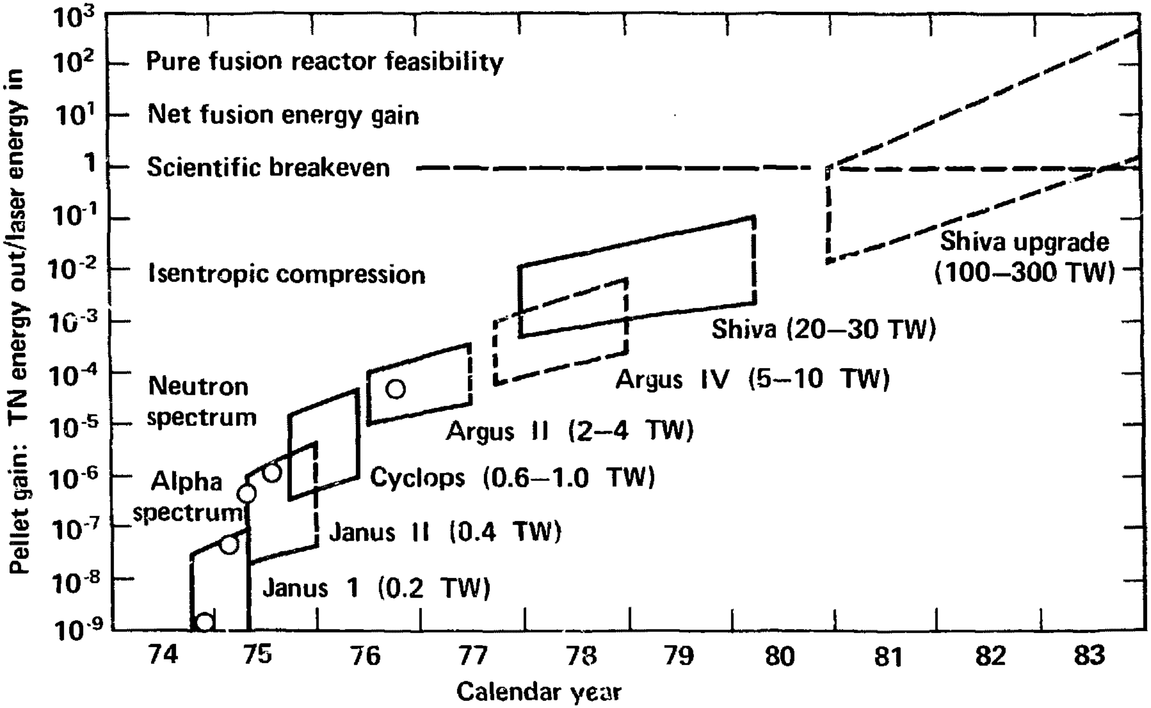
Fig. 14

LASER FUSION ENERGY YIELD PROJECTIONS



12/76

Fig. 15

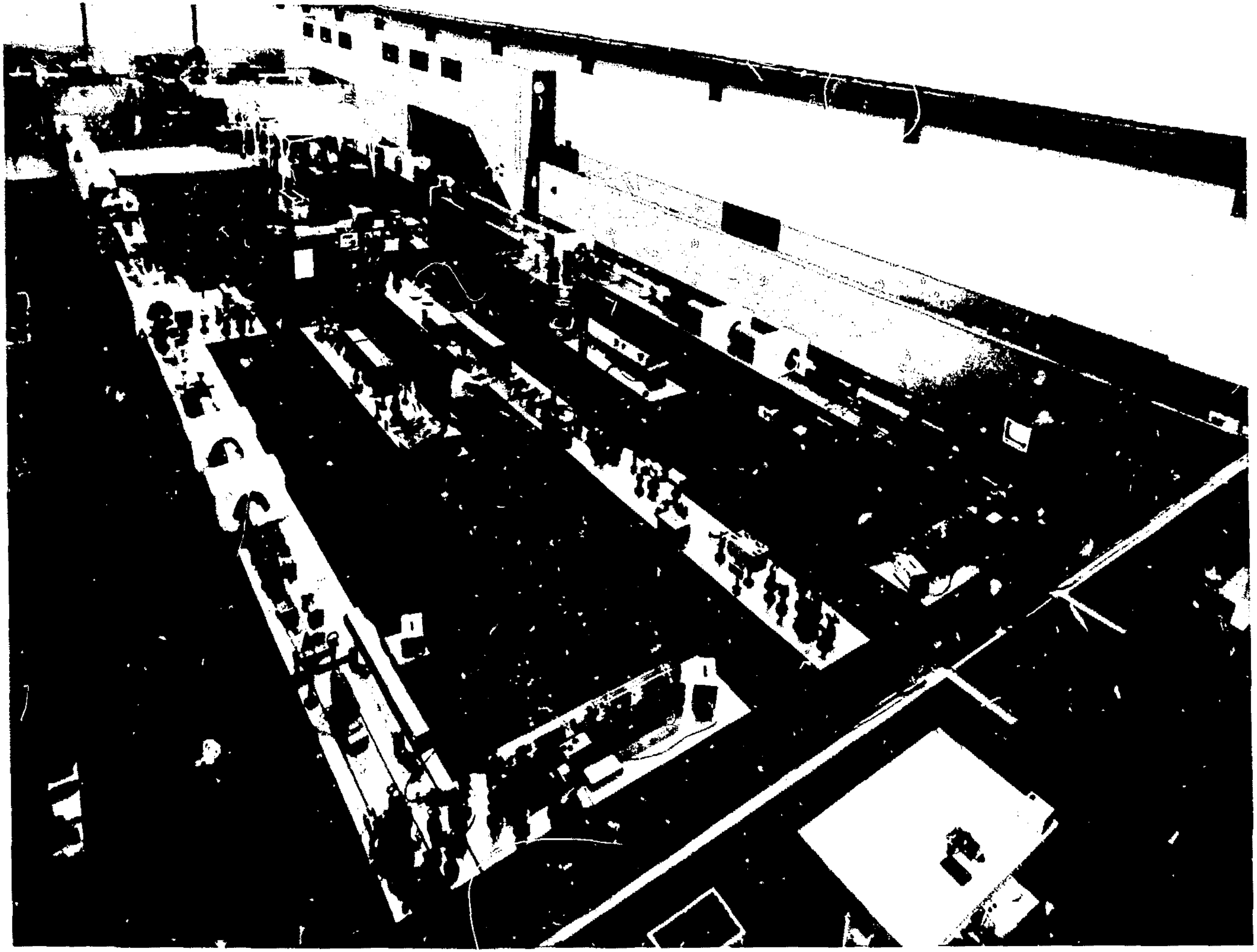


Fig. 16

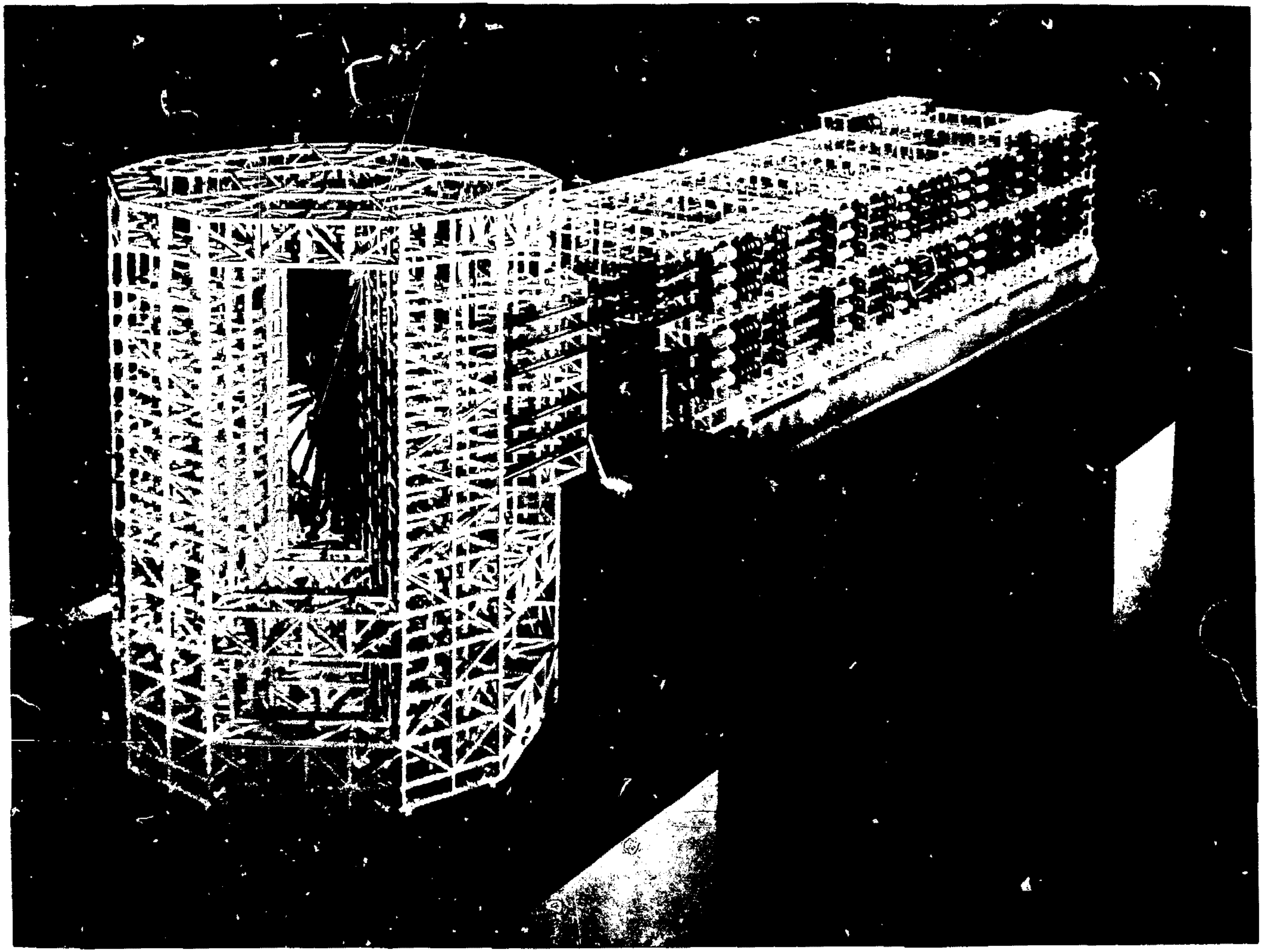
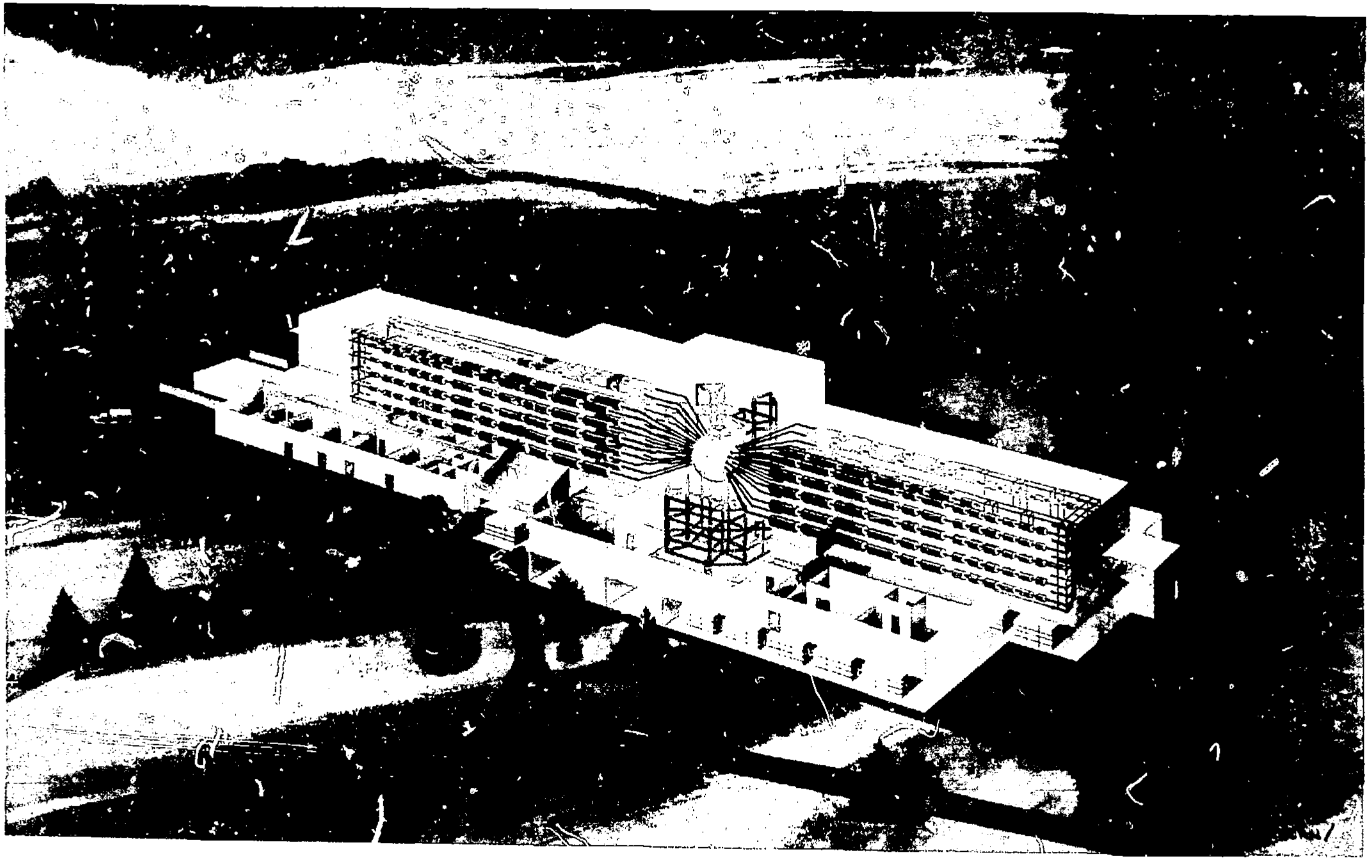


Fig. 17



SHIVA NOVA LABORATORY FACILITY

Fig. 18

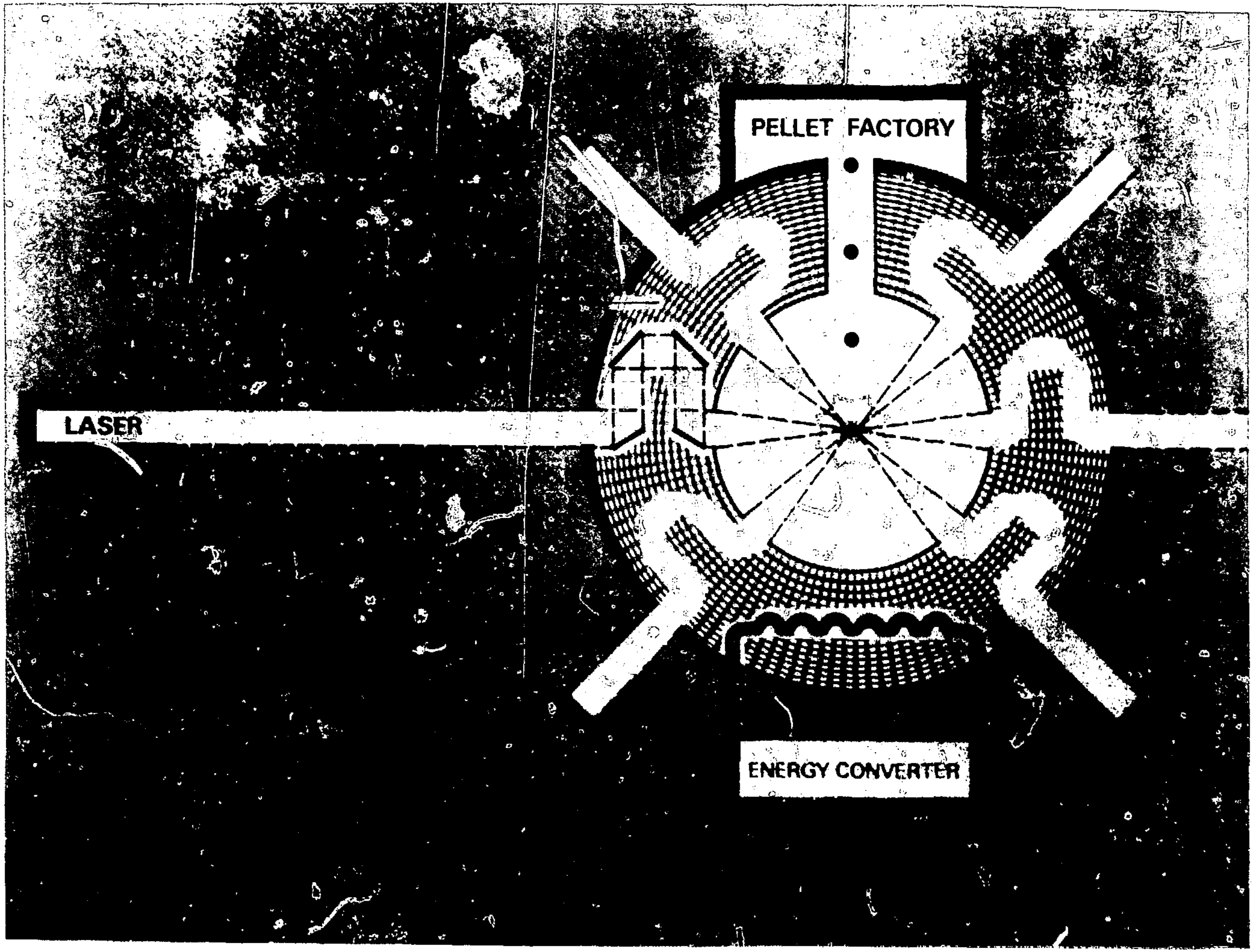


Fig. 19

LASER FUSION REACTOR: LITHIUM WATERFALL CONCEPT

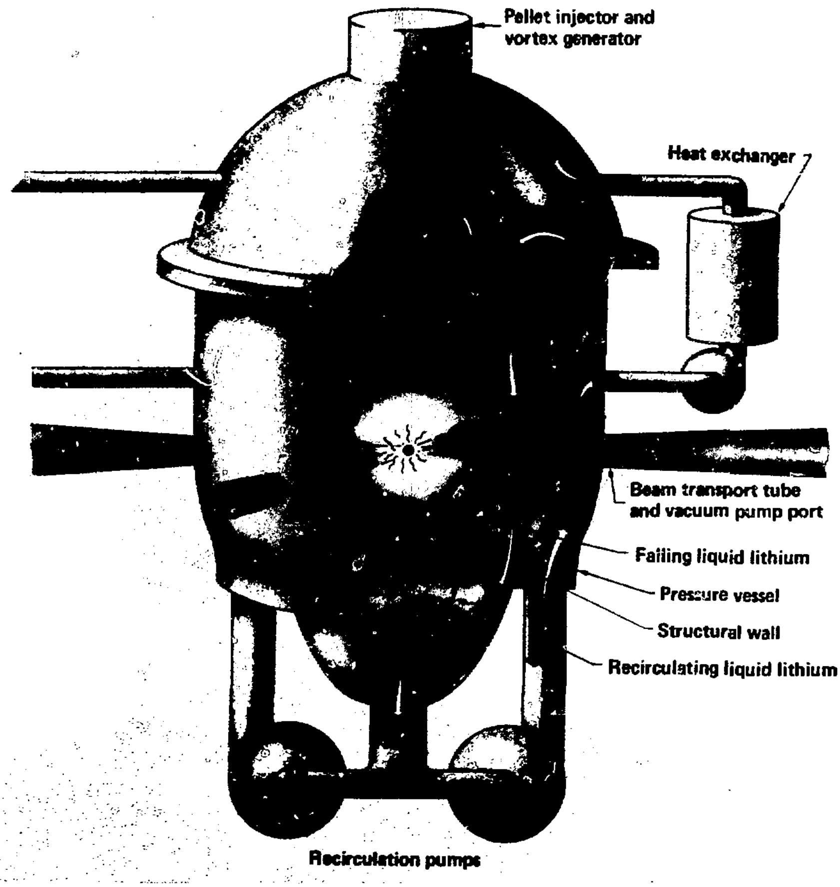


Fig. 20

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Laser Fusion

I would now like to turn to my third topic, Laser Fusion. Whereas in magnetic fusion the idea is to contain a low density plasma for a very long time in order that fusion reactions occur, in laser fusion the density is very high and the time is very short, just the billionth of a second or so during which a tiny pellet of burning fuel blasts apart.

The concept is sketched in Figure 14. A pellet of solid deuterium and tritium is rapidly heated to a temperature of one hundred million degrees or more by a powerful laser beam. The density is further increased by the rocket action of ablated material that compresses the pellet to densities much higher than those in normal liquids or solids, ultimately to many thousands of times normal densities. At such high densities, the fuel "burns" so rapidly that efficient burn is achieved before the pellet blows apart. The process is similar in principle to thermonuclear explosions; for this reason laser fusion has been able to draw heavily on the scientific knowhow of nuclear weapon research. However, I hasten to add that firing a laser fusion pellet is an explosion in the mildest sense. We call it a microexplosion. The pellets are very tiny, the width of a human hair in present experiments. So this is an explosion only by analogy.

While laser fusion is the primary approach, in principle microexplosions may be driven by other high-power sources. Options include heavy ion accelerators, deuteron beams, and electron accelerators. Collectively these approaches are called "inertial confinement". To a large extent it is possible to divide the inertial confinement fusion problems into two parts: development of an appropriate driver source, and demonstration of the fusion physics. Thus the achievement of high energy gain microexplosives with a laser driver should prove scientific feasibility for inertial confinement fusion. The development of an efficient driver for a reactor capable of achieving the same pellet conditions should proceed in parallel.

Detailed calculations showed that high-energy-gain microexplosions would require 200 to 300 terawatts (TW) of laser power. This was far beyond the capabilities of existing lasers,so the Lawrence Livermore Laboratory initiated the laser development program shown in Figure 15. Neodymium glass lasers were chosen because they were the farthest advanced with respect to producing high liquid lithium. The lithium fall attenuates the fusion neutrons, protecting the target chamber structure which will now last the lifetime of the plant. The flowing lithium also serves as the heat exchange medium and the source of tritium fuel.

At the beginning of this talk, I set out to describe the three main lines of fusion research with emphasis on the next five years. As you have seen, each of these approaches - the Tokamak, the Mirror Machine and Laser Fusion - has made good progress over the last several years and each is now embarking on a major facility to be completed over the next five years or so. To review, these are the TFTR Tokamak facility at Princeton, the MFTF mirror machine at Livermore, and the Shiva Nova laser facility, also at Livermore. The scientific results from these three major facilities, all to begin operation in the early 1980's, will set the course of engineering development of fusion reactors in the foreseeable future.

Thank you.

more than one size, more than one type, more than one fuel cycle is a desirable end product. But even if the ultimate commercial size were a gigawatt or half a gigawatt, it seems to me that it would be desirable to gain actual operating experience in a utility system with reactors as small as tens of megawatts. In this way one can begin collaboration with the utilities sooner and at less risk because one can take more steps more quickly with a smaller investment.

DR. WOODSON: As the chairman, I want to remind you that Prof. Rose said the reactor designs that you have seen here are not blue prints for reactors, but they are problem finders. You are going to buy something that is unknown at the moment.

DR. FOWLER: I couldn't agree more. But these designs are also pathfinders because we are also looking for the solutions.