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NEUTRAL BEAM REQUIREMENTS FOR MIRROR REACTORS

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NEUTRAL BEAM REQUIREMENTS FOR MIRROR REACTORS*

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ABSTRACT

The neutral beam requirements for mirror reactors as presently envisioned are 200 keV for the Field Reversed Mirror (FRM) and 1200 keV for the Tandem Mirror (TMR). The hybrid version of the Standard Mirror, FRM and TMR require 100-120 keV. Due to the energy dependence of atomic processes, negative ions should produce neutrals more efficiently than positive ions above some energy and below this energy, positive ions are probably more efficient. This energy is probably somewhere between 100 and 150 keV for D°, and 150 and 225 for T°. Thus we conclude that hybrid reactors can use D^+ ions but all of the fusion reactor designs call for D^- ions to make the neutral beams. Trends in the energy requirements are discussed. The hardening of neutral beams against neutron and gamma radiation is discussed.

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1. Introduction

Mirror reactors depend on non-thermal ion energy distributions which in all the reactor designs to date are produced by neutral beam injection. The electrons can be in thermodynamic equilibrium but the ions must be maintained in a nonthermal steady state. Because the ions cannot be allowed to come into thermodynamic equilibrium, heating methods which first heat electrons, which in turn heat ions, will not do. Ion cyclotron R.F. heating of ions in principle might be effective but so far has not been of much interest. The neutral injection in the mirror designs to date are the only heat source other than alpha particles; however, auxiliary heating could reduce the neutral beam energy and power requirements if that were desirable but could not eliminate their use.

In the discussion to follow, the beam requirements such as energy and power, are reviewed. The shielding requirements of the neutral beam components from neutron and gamma radiation are discussed, as well as a status of the past and future shielding design efforts.

REA

2. Mirror Reactor Conceptual Designs

The early reactor designs done at LLL (1970-73) were based on the standard mirror configuration (Yin-Yang coil, steady-state neutral beams, and direct energy conversion) and employed 600 keV injection due to the end loss direct converter understanding at that time. The hybrid reactor used 100 keV injectors. The next reactor design done in 1973-74 was on the FERF (Fusion Engineering Research Facility) whose purpose was primarily as a neutron source for material testing. It did not have a blanket or energy recovery as power production was not its purpose. The injection requirement was 65 keV D° and 97 keV T°.

The next design done in 1975 was a standard mirror hybrid with 100 keV D° injectors. Next was the standard mirror reactor design of 1976 with a careful optimization of all parameters to minimize the cost of power. Q came out to be only 1.1 and the injection energy, which was best, was 150 keV. This was essentially the first negative ion injector on a mirror reactor design. In 1976 and 1977, we designed the Field Reversed Mirror reactor (FRM) and the Tandem Mirror Reactor (TMR). The energy for the FRM was 200 keV and 1200 keV for the TMR. The hybrid version of the standard mirror, FRM and TMR were 120 - 125 keV. These parameters are summarized in Table 1. The ratio of gross electrical power to net electrical power (second column of Table 1) is an economic indicator discussed in the next section. The standard mirror is clearly uneconomical but still shown for completeness.

The standard mirror reactor is shown in Fig. 1, the FRM in Fig. 2, the TMR in Fig. 3, the standard mirror hybrid in Fig. 4, and the TMR hybrid in Fig. 5.

The injection energy for each reactor listed in Table 1 was arrived at by folding in the physics model current at LLL at the time, with the engineered system current at the time, in such a way that all free parameters and, in particular, injection energy were optimized to minimize electrical power. In the hybrid most of the electrical power came from fission reactors that burned the hybrid-produced fissile fuel.

The physics and engineering models which led to the quoted injection energies for the three cases is complex for each case, and will not be discussed here. However in Sec. 4 the trends are discussed which are likely to affect injection energy as mirror reactor concepts evolve.

TABLE 1

Injector Parameters for Mirror Reactors

	Q	P_{GROSS}/P_{NET}	η_i	$W_{D^\circ INJ}$	POWER PER UNIT	UNITS
STANDARD MIRROR	1.1	4.4	.8	150 keV	270 MW	4
FIELD REVERSED	5	1.5	.7	200	4	12
TANDEM TMR	5	1.7	.7	1200	120	4
STANDARD MIRROR HYBRID	.7	3.2	.7	120	360	4
FRM HYBRID	~2	~1.4	.7	~120	~4	12
TMR HYBRID	1.8	1.4	.7	125	70	2

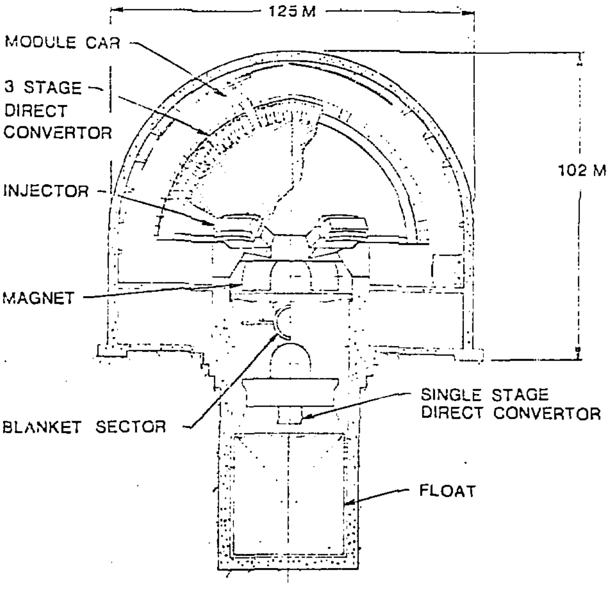


Figure 1. Mirror Fusion Reactor

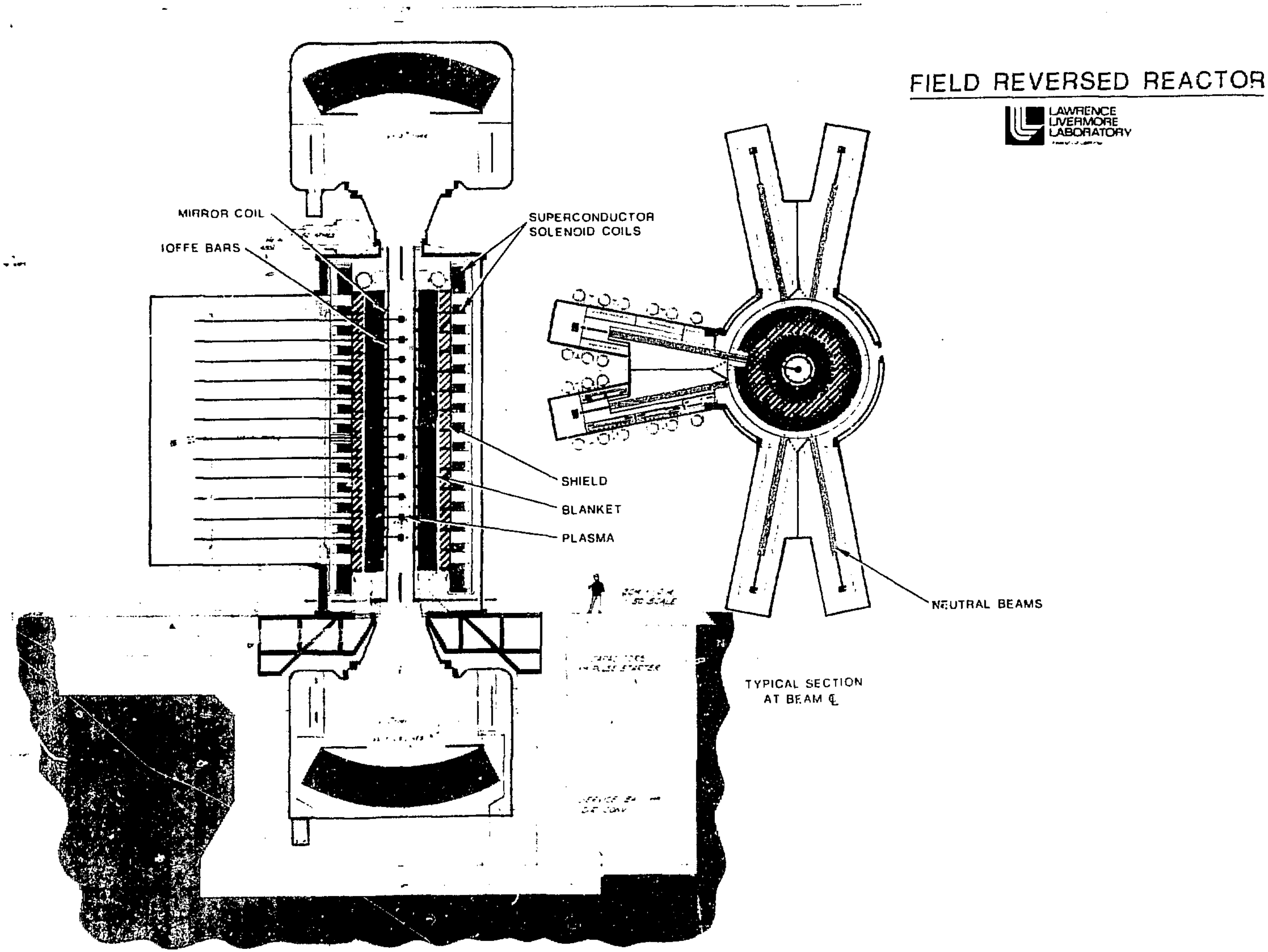

FIELD REVERSED REACTOR
LAWRENCE LIVERMORE LABORATORY
MIRROR COIL
IOFFE BARS
SUPERCONDUCTOR SOLENOID COILS
SHIELD
BLANKET
PLASMA
NEUTRAL BEAMS
TYPICAL SECTION AT BEAM ℄

Figure 2.

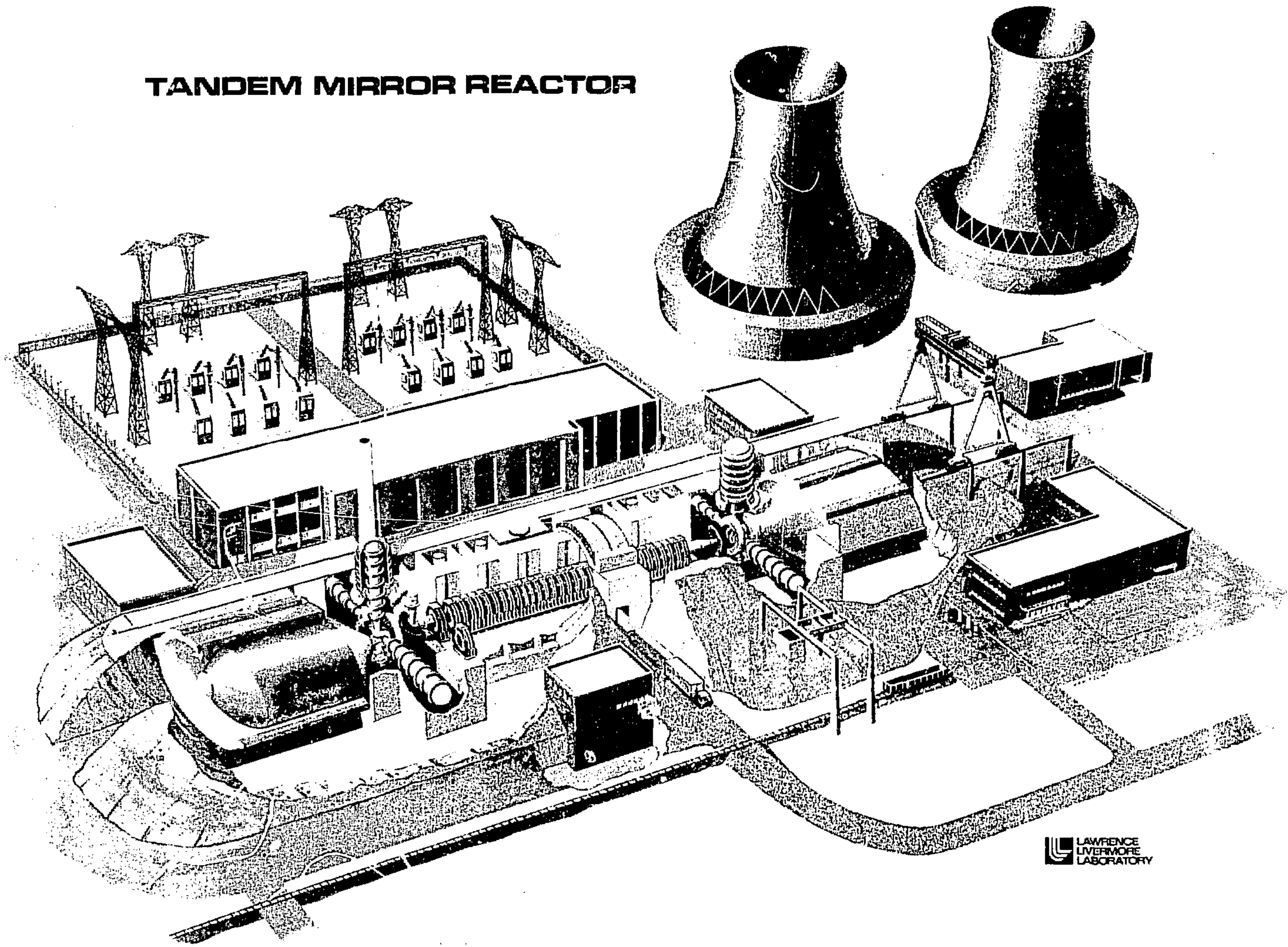


Figure 3.

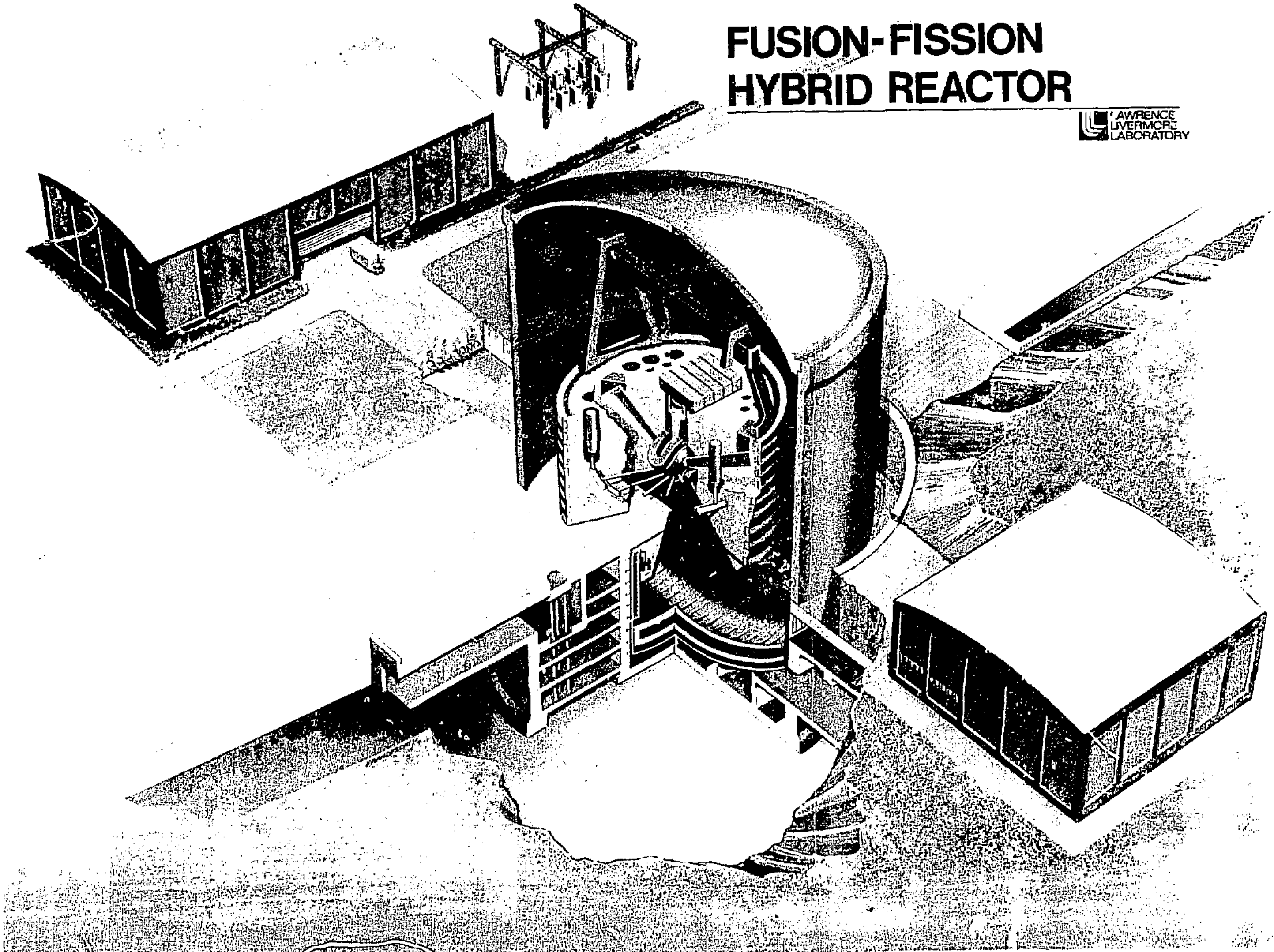

FUSION-FISSION
HYBRID REACTOR
AWRENCE
LIVERMORE
LABORATORY

Figure 4.

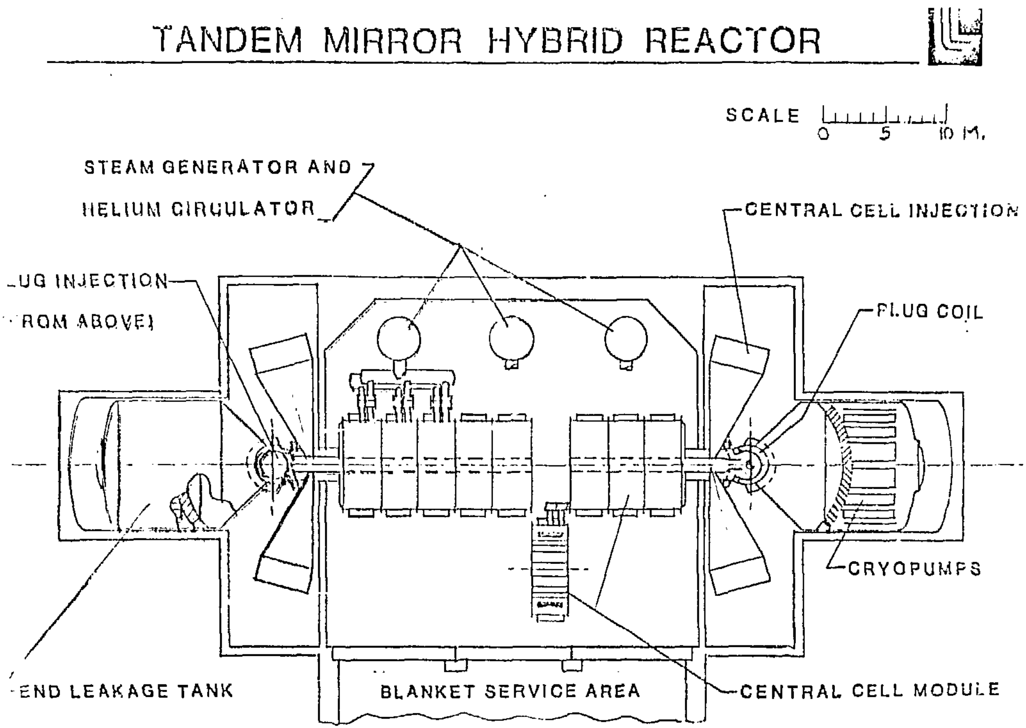

TANDEM MIRROR HYBRID REACTOR
SCALE
0 5 10 M.
STEAM GENERATOR AND
HELIUM CIRCULATOR
CENTRAL CELL INJECTION
UG INJECTION
ROM ABOVE)
PLUG COIL
CRYOPUMPS
END LEAKAGE TANK
BLANKET SERVICE AREA
CENTRAL CELL MODULE

Figure 5.

3. Q Requirements for Mirror Reactors

The recirculation of power in power plant tends to degrade the economic competitiveness. A plant which can sell 0.5 unit of power for 1.0 unit of power generated will enjoy an overwhelming competitive edge over a plant that can sell only 0.5 units of power, if everything else is the same. We can quantify the above example and then make several observations.

We take an injected reactor which amplifies injected power by a factor of 1 + Q, where Q is the fusion power divided by the injected power. We assume the neutrons deposit M-times their kinetic energy in the blanket. The direct converter recovers the injected power plus the alpha particle power with an efficiency, η_{DC}. The undirect converted power and the blanket power is converted to gross electrical power, P_{Gross} with an efficiency, η_{th}. A fraction of the gross power, $f_{recirculation}$, is fed back to the injector which converts this electrical power to plasma energy with an efficiency, η_i. The ratio of gross-to-net electrical power, G is given below:

$$G = \frac{P_{gross}}{P_{net}} = \frac{1}{1 - f_{rec.}}$$

Based on judgement of the kind of performance that seems likely, we have chosen the following parameters as typical:

$\eta_i = 0.7$, $\eta_{DC} = 0.5$, $\eta_{th} = 0.4$. Under the above simplifying assumptions the G versus Q values for three cases are plotted in Fig. 6. . Case 1 is a fusion reactor where M is chosen to be 1.2. Case 2 is a hybrid reactor designed to produce ^{233}U as well as some ^{239}Pu with M = 5. Case 3 is a hybrid designed to produce ^{239}Pu with M = 10.

The curves each have a vertical and horizontal asymptote. The vertical asymptote occurs at break-even values for Q. The horizontal asymptote shows the idea of diminishing returns for further increases in Q.

For example, a fusion reactor, under the above assumptions which are felt to be reasonable by the author, must have Q ≈ 2 to break even and Q values above 10 result in small further improvements. For a Pu producing hybrid, the break-even Q is about 1/4 and Q above 1.8 results in small further improvements. For ^{233}U, the Q values are about 1/2 and 3.4.

For G > 2 the reactor is uneconomical. For G < 1.2, the Q value is high enough so that it is not a major issue in economics. The value of 1.2 is, of course, an arbitrary cutoff of a continuous variable.

Based on the Q values for the conceptual designs to date, as shown in Table 1, we conclude:

- The mirror fusion reactor Q of 5 seems somewhat low and 10 is probably needed*.
- The hybrid Q value of 2 is already high enough.
- The standard mirror hybrid with Q of 0.7 has a somewhat large economic penalty.

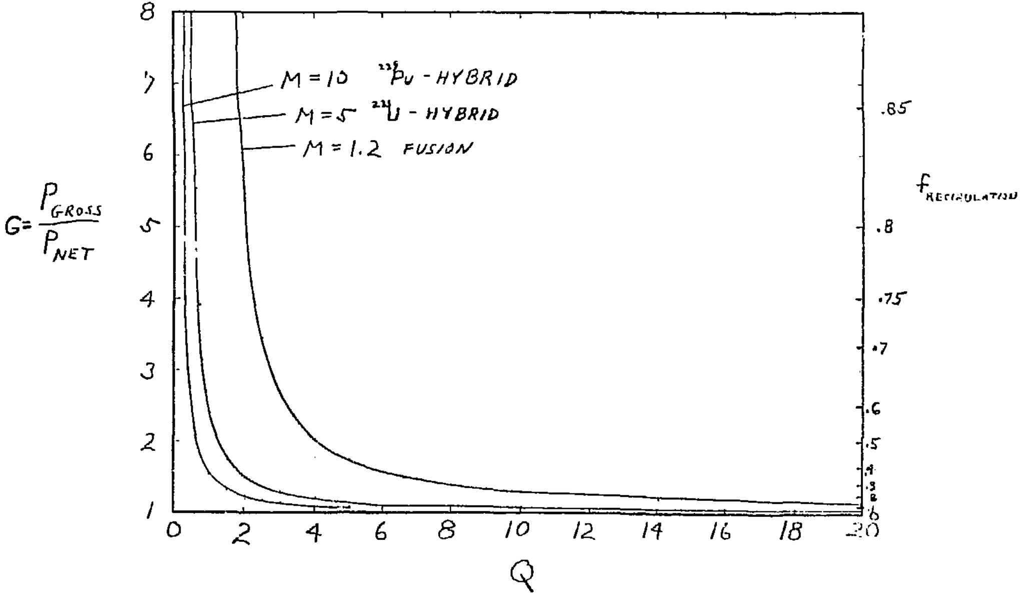
The hybrid because its saleable product is fissile fuel as well as electricity can perhaps tolerate a somewhat lower Q than shown above, but not by much due to the incipient rise of the curve for falling Q values.

Ways should be found to increase Q to about 10 for the Tandem and Field Reversal concepts which do not sacrifice too much other economic factors like power density. Recently there is encouragement for larger size FRM's when measured in gyroradii. Reduced power density and increased injection energy for penetration may result. Heating electrons (ECRH, RF, e-beams) in the TMR may result in increased Q values.

* A conclusion D. Steiner came to previously.

P_{GROSS} VERSUS Q

FIG 6



4. Trends likely to effect injection energy

a. Higher Q

As discussed in Sec. 3, Q as high as 10 may be needed for an economical reactor. Stating this goal and obtaining it are two different things; however, new ideas and improvements in old ideas seem to be yielding results as exemplified in the TMR. Assuming a way can be found to achieve $Q \sim 10$ without giving up other factors, like power density, then considerable alpha particle heating will occur and, perhaps, almost completely remove the heating role of neutral beams. Then the neutral beam would play the more single-purpose role of maintaining the non-thermal ion energy distribution, such as circulating current in the FRM and end plugs for the TMR. What effect this will have on injection energy is not clear, but the likelihood of the injection energy dropping much below 150 keV seems unlikely.

b. Beam Penetration

In order to penetrate a thick plasma, the beam energy must be high. The FRM, which is 5-ion orbits across, requires as high as 200 keV due in part to penetration. There is some indication that plasma stability may permit a larger plasma size (10 orbits across). This will have the beneficial effect of substantially raising Q from its present 5 but, at the same time, force the injection energy up to permit adequate beam penetration. On the other hand, other means of penetrating plasmas should be explored, such as ion cross-field flow, for example, which would allow more optimal energies like ~100 keV.

c. TMR - auxiliary electron heating

The plug injection as now designed requires 1200 keV beams. Logan thinks auxiliary electron heating could reduce this injection energy to as low as 400 keV. The heating could be R.F., ECRH, or e-beam, but must be efficient 50-70% and low-cost, ~0.3-0.5 $/W.

d. *Power density versus energy*

The power density is proportional to $\frac{\langle \sigma v \rangle}{T^2}$ and peaks at about 20 keV and falls rapidly above 20 keV. The reaction rate parameter $\langle \sigma v \rangle$ peaks at about 100 keV and falls as $W^{-1/2}$. From this one observes that the ions have no energetic need in the plasma to be at energies above 100 keV. If injection is at energies much above 100 keV, the reason is to heat electrons or to penetrate or maintain non-thermal velocity distributions as in FRM and TMR for confinement. The above observation is, in my opinion, profound but meaningless if one does not have the freedom to apply it, e.g. TMR vitally needs high-injection energy for the end stoppering.

e. Ignition

Ignition trades a heating problem for a fueling problem (a bargain!) but usually results in low-power density which is a serious economics penalty and must be dealt with. The TMR, as we now understand it, can ignite ($Q \sim 10$ for 2000 MWe) but the minimum cost power occurs for the driven TMR with $Q \sim 5$ due to a tradeoff with power density. Similar tradeoffs have been discussed by Jassby for the slightly-driven Tokamak.

5. *Hardening of neutral beams for neutron and γ radiation*

An important requirement in design of neutral beam injectors is the protection of the injector components against the hostile radiation environment. Because neutrals must have line-of-sight to the fusing plasma, the neutrons can stream up the beam line. In principle, the ion source and accelerator structure can be located out of line-of-sight with bending magnets to guide the beam around a corner. This seems bulky and likely to run into severe beam-optics problems. Thus the line-of-sight injectors will necessarily be in a rather intense radiation environment. The vulnerable components are insulators, semiconductor devices, and cryopanels. Proper shielding designs can adequately protect the vulnerable components and the metal electrodes that see the highest radiation loads are not expected to be a problem, because the flux is low (100 times lower than at the blanket) due to geometry and distance from the source, causing a dilution.

Insulators: Dielectric breakdown due to high levels of ionizing radiation must be avoided. Structural damage due to accumulated radiation doses will determine replacement time.

Semiconductors: Solid-state lasers and rectifiers used in some injector designs must be well shielded.

Cryopanels: These are made of metal and although not subject to radiation damage, will suffer from nuclear heating which must be shielded to reduce refrigeration power to practical values.

Over the past 5 years at LLL increasing attention by the reactor-study group has been given to the effects of radiation on neutral injectors. The evolution of neutral beam hardening will be given briefly.

In 1973, the first reactor injector design was done by G. Hamilton for a FERF (Fig. 7). Shielding was provided primarily for the magnet as shown in Fig. 8. T. Wilcox then made a detailed analysis using Monte Carlo codes, to calculate neutron and gamma fluxes at many locations. The model is shown in Fig. 9. The point labeled '9' is the location of the source with its vulnerable high-voltage insulators. The neutron dose rate there is 2×10^{8} rem/h(1.3×10^{12} n cm^{-2} sec^{-1}), and the gamma rate is 1×10^{6} rem/hr. This corresponds to 0.05 W cm^{-3} in stainless steel.

The machine was designed with the idea that the machine itself including the sources were part of neutron-damage studies.

The next injector was designed by Fink, Hamilton, and Barr in 1975 for the hybrid reactor. The individual beams were separated just enough to put shielding in between the individual beams as shown in Fig. 10. This added shielding essentially eliminated line-of-sight bombardment of cryopanels and direct converter insulators and somewhat attenuated the radiation seen by the ion sources. The neutron flux at the sources was estimated to 10^{13} n $cm^{-2}sec^{-1}$, however no detailed Monte Carlo calculations were made.

The next injector design done in 1976 by Fink, Barr, and Hamilton, was a 150 keV O^- neutral injector shown in Fig. 11. The major change in this design from the point of view of shielding, was to recess the high-voltage insulators into the shielding block, thus eliminating any line-of-sight (14 MeV neutrons) and greatly attenuating the radiation environment. Low-voltage insulators which are essentially non-load-bearing and can take relatively high doses remain in the source. This design uses a photodetachment neutralizer. The solid-state lasers are recessed into the shielding also. Again no Monte Carlo shielding calculations were done but rather estimates made. The next injector study, done in 1977 by Fink, Bender, and colleagues (Fig. 12) further develops the shielding. A Monte Carlo calculation on a ^3He injector is underway.

An assessment of "Electrical Insulator Requirements for Mirror Fusion Reactor" has been made by R. H. Condit and R. A. VanKonynenburg. The table of contents follows which gives an idea of the substance of this study.

Future Work

In FY 78 we plan to carry out two injector studies; one based on D^+ of about 120 keV and the other based on D^- at $\sim$1 MeV. Both will place heavy emphasis on shielding design and analysis with the extensive use of Monte Carlo codes.

"Electrical Insulator Requirements for Mirror Fusion Reactor"
by R. H. Condit and R. A. Van Konynenburg.

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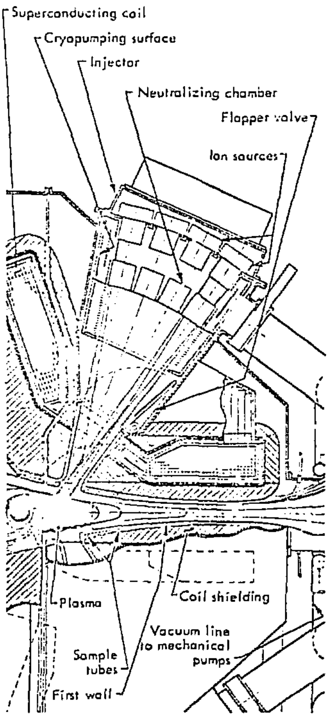
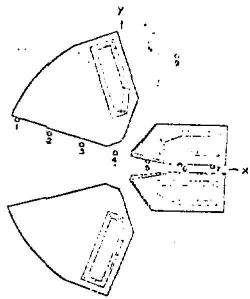


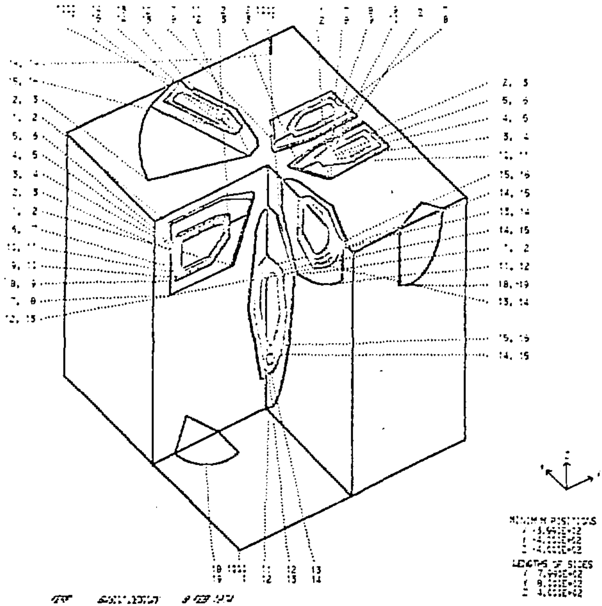
Detail from Fig. 1 showing typical section of one of the injector points.

Figure 7.



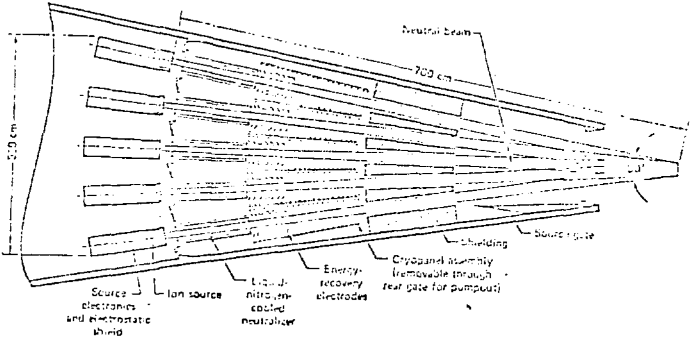
Cross-sectional view of the geometry model used for shielding calculations (z = 0 plane).

Figure 8.



Computer illustration of geometry model used in shielding calculations. Numbers refer to material compositions and statistical regions.

Figure 9.



100 keV D° INJECTOR FOR HYBRID (1975)

Figure 10.

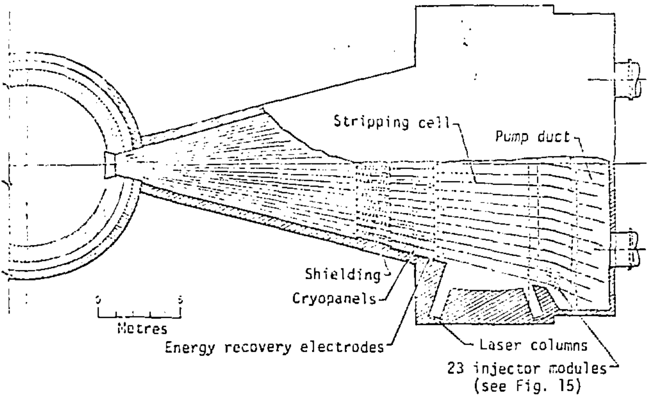


Fig. 11a. Proposed neutral beam injector delivering 1800 A of 150-keV deuterium and tritium atoms.

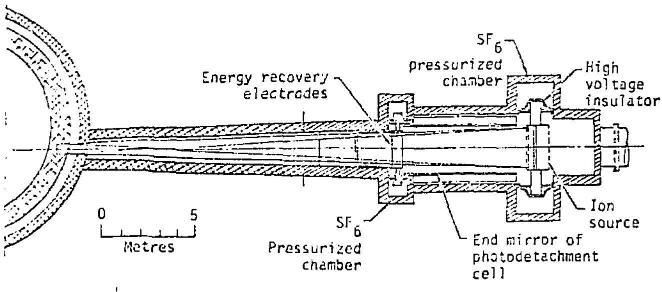


Fig. 11b. Vertical cross section of proposed neutral beam injector.

POSITIVE ION INJECTOR SOURCE DETAILS

120 keV HYBRID INJECTOR (1977)

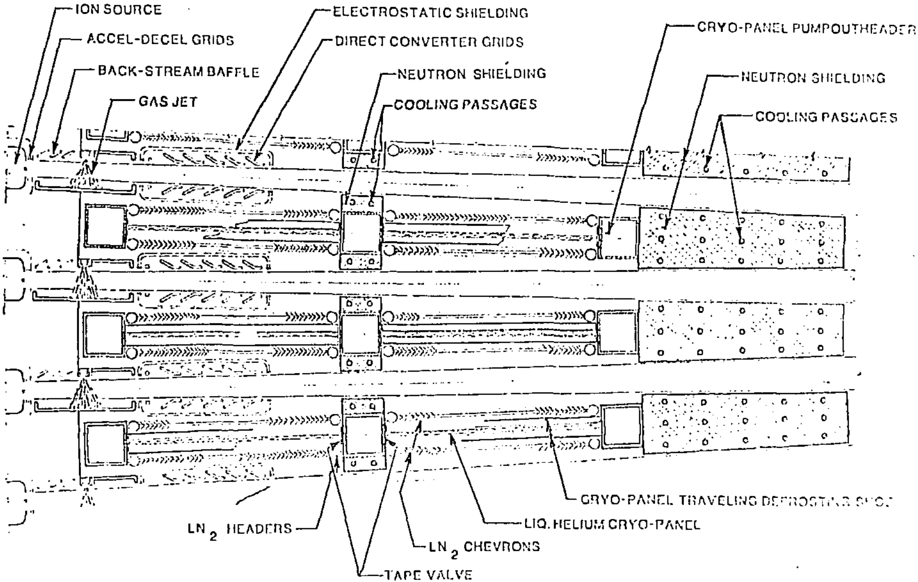


Figure 12.

6. Conclusions

Mirror fusion reactor designs carried out to date call for high-injection energy (standard mirror -150 keV, FRM - 200 keV, Tandem mirror - 1200 keV) which can be met by D^- beams but due to low efficiency, not by D^+ beams. Hybrid mirror reactors (standard, FRM, Tandem) use 100 - 125 keV injectors and can use D^+ ions.

If a reactor concept calls for injection above ~100 keV, the reason is not based on maximizing the reaction rate parameter $\langle\sigma v\rangle$, or the power density ($\propto \frac{\langle\sigma v\rangle}{t^2}$) but rather on some other requirement, such as penetration, heating, and plugging, maintaining plasma currents. If the beam is used for both heating and fueling simultaneously, then injection over 100 keV incurs disadvantages. On the other hand, heater beams seem to prefer high energy, requiring less current (especially to preferrentially heat electrons); in fact, the higher, the better, and 3.5 MeV He is an excellent heater; that is, ignition or near ignition is desirable.

If the confinement concept calls for high-injection energy, effort should be placed on evolving the concept towards lower energies as well as figuring out how to supply such high energies.