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ELECTRICAL INSULATOR REQUIREMENTS FOR MIRROR FUSION REACTORS

R. H. Condit

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October 30, 1977

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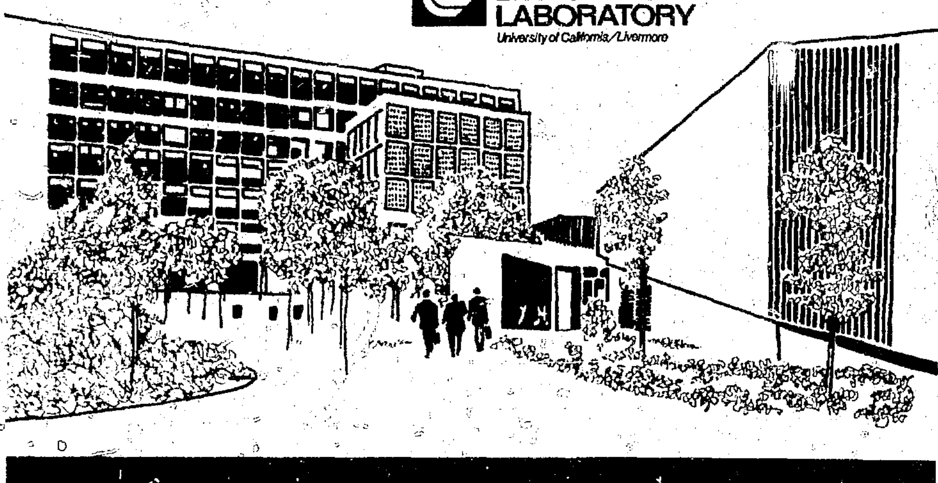

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ABSTRACT

In this report, we discuss the requirements for mirror fusion electrical insulators. Insulators will be required at the neutral beam injectors, injector power supplies, direct converters, and superconducting magnets. Insulators placed at the neutral beam injectors will receive the greatest radiation exposure, 10^{14} to 10^{16} neutrons/m^2·s and 0.3 to 3 Gy/s (10^5 to 10^6 R/h) of gamma rays, with shielding. Direct converter insulators may receive the highest temperature (up to 1300K), but low voltage holding requirements. Insulators made from organic materials (e.g., plastics) for the magnet coils may be satisfactory. Immediate conductivity increases of all insulators results from gamma irradiation. With an upper limit to gamma flux exposures of 300 Gy/s in a minimally shielded region, the conductivity could reach 10^{-6} S/m. Damage from neutron irradiation may not be serious during several years' exposure. Surface changes in ceramics at the neutral beam injector may be serious. The interior of the injector will contain atomic hydrogen, and sputtering may transfer material away from or onto the ceramic insulators. We are also concerned about unknown and potentially damaging interactions between irradiation, electric fields, temperature gradients, cycling of temperature, surface and joint reactions, sputtering, polarization, and electrotransport in the dielectrics. Materials research to deal with these problems is needed.

INTRODUCTION

All mirror fusion reactors will require electrical insulators. In this report, we discuss the requirements for insulators in mirror fusion machines and the adequacy of insulator materials under the conditions we expect.

Mirror fusion reactors are being developed in stages, which are now progressing from preliminary physics experiments to an ultimate experimental power reactor (Table 1). Operating conditions we envision for these reactors are shown in

Table 1. Characteristics of mirror fusion machine.

Machine	Construction by	Total neutron flow/s	Duty cycle	Remarks
2 × IIB	Finished	Small	Short	Demonstrates energy scaling.
BB II-T	Finished	Small	Short	Demonstrates steady state.
MFTF (Formerly MX)[4]	1978–1981	10^{17}	1–2 s	Prototype for FERF.
FERF[1,2]	1985	3.6×10^{18}	Continuous	For reactor engineering studies.
Hybrid	1985	2.1×10^{20}	Continuous	A 600 MWe machine, generates 700 kg Pu/y.
Experimental power reactor	1990	7.2×10^{20}	Continuous	A 100 MWe machine, makes use of FERF technology to increase efficiency.
DT, reference design	?	10^{22}	Continuous	This 500 MW machine sets a goal for all previous machines.

Table 2.[1-5] The basic geometry of the magnetic coils and enclosed plasma common to all mirror fusion machines is shown in Fig. 1; more detailed features of mirror machines are illustrated in Figs. 2 through 6. These machines require electrical insulation at four locations.

1. Neutral beam injector, which supplies fuel to the plasma.
2. Beam injector power supplies.
3. Direct converters that convert ion leakage from the plasma into useful current.
4. Superconducting magnets to confine the plasma.

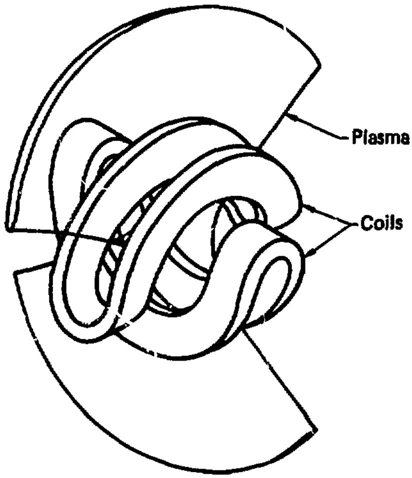

Fig. 1. The yin-yang geometry of the magnet coils and plasma common to all mirror fusion machines.

Table 2. Radiation fluxes[a] at three positions in mirror fusion machines.

Machine	Injectors	Converters	Magnets
MFTF (formerly MX)	Small	None	Small
FERF Hybrid	Neutrons: 10^{16} at end wall	Not applicable for FERF; possible for hybrid-like experiment power reactor.	Neutrons: 10^{12} Gammas: 3×10^{-3}
Experimental power reactor	Neutrons: 8×10^{16} (unshielded) 10^{14}-10^{16} (shielded) Gammas: 20-300 (unshielded) 0.3 to 3 (shielded)	Neutrons: trapped out Ions: 0.25 MW/m^2. Gammas: 3.	Neutrons: 10^{13} Gammas: 0.15
Reference design	Similar to experimental power reactor.		

[a]Neutron fluxes measured in $n/m^2 \cdot s$; gamma ray fluxes are in Gy/s (1 Gy/s = 3.6×10^5 R/h).

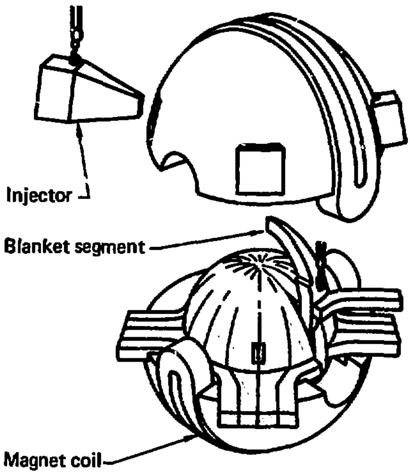

Fig. 2. A mirror reactor, showing essential features. Blanket segments with attached conduits that would lead from the blanket segments to the turbines are shown.

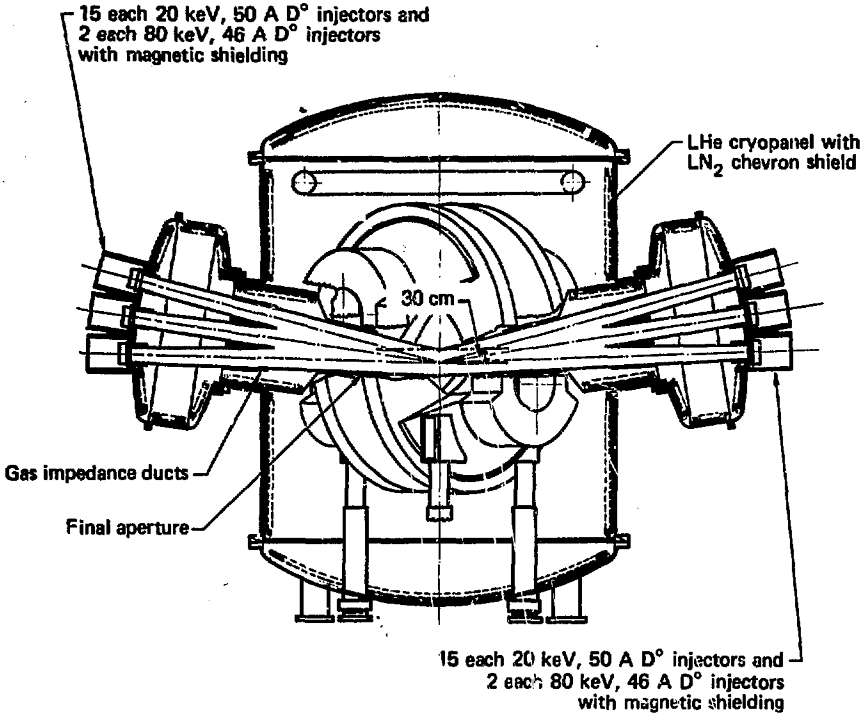

Fig. 3. Configuration of the neutral beam injectors for the MFTF (MX) main chamber. Injectors will be similarly positioned for other mirror machines. Start-up beam energies would be 20 keV. Continuous operation would be at 80 keV.

In designing mirror fusion reactors, scientists previously thought that electrical insulation would also be necessary to reduce the currents generated by flowing liquid lithium used as a metal breeder material. However, the proposed use of a non-conducting lithium compound such as solid lithium beryllate, ($Li_2Be_2O_3$) as a reaction fuel has eliminated the need for this insulation.

Insulators at the four main locations must meet special requirements as a result of the neutron and gamma ray radiation and other unusual conditions described below. The requirements for insulators we outline below should only be regarded as guidelines

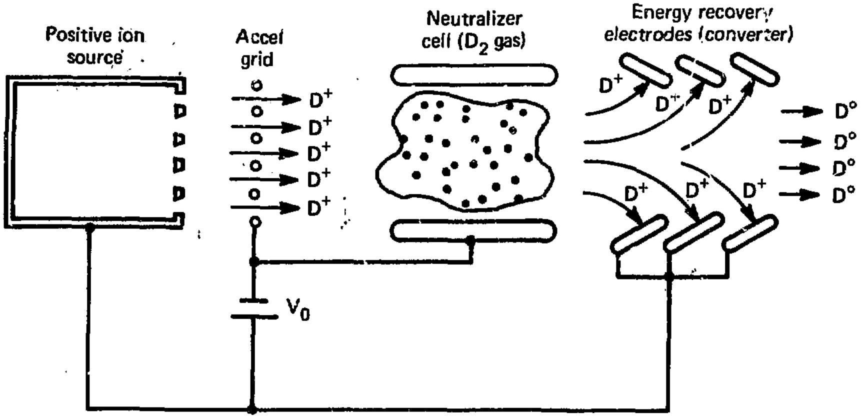

Fig. 4. Schematic of typical neutral-beam positive ion injection system being constructed for the MFTS and Tokamak mirror machines. Instead of a direct converter, a sweep magnet will be used in MFTF to clean unneutralized ions out of the neutral beam.

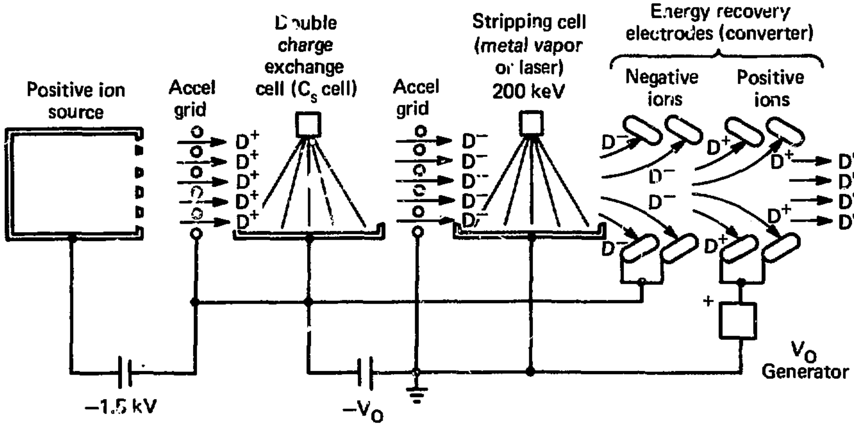

Fig. 5. Neutral beam injector negative ion system.

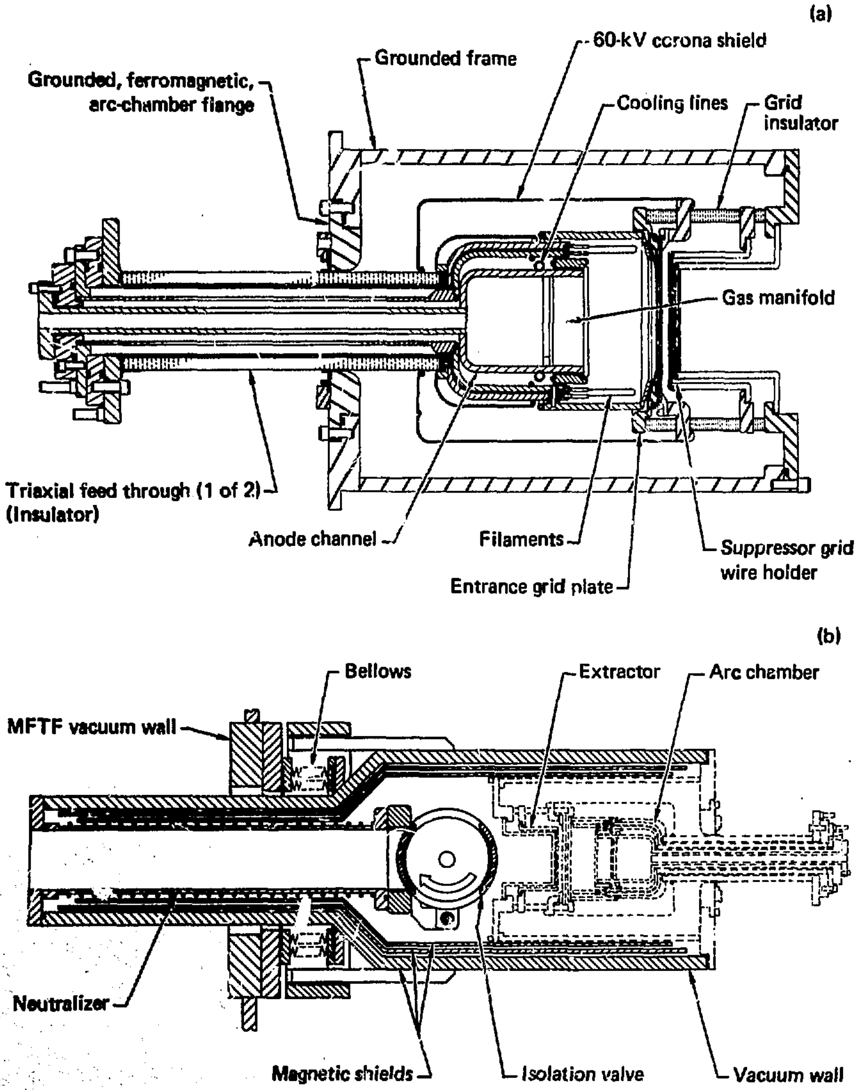

Fig. 6. A current design for a neutral beam injector to be used with the Tokamak Fusion Test Reactor or the MFTF. In (a), the arc chamber shown is designed to occupy a minimum cross-sectional area. In (b), the placement of the arc chamber within the outer magnetic shield is shown. The grid insulators will need to support 80 kV; filament insulators would need only support 50 V.

because they are being continually changed and the designs can be modified to accommodate available materials. Alternatively, the unusual combination of influences such as electric fields, radiation, mechanical constraints, and surface bombardment by atomic hydrogen may sometimes cause deterioration in ways we have not previously encountered. On the other hand, more completely understanding such interactions may uncover new applications for insulators. The problems we anticipate with insulators are outlined below.

Four Insulation Needs

Neutral Beam Injectors

The positions of the neutral beam injectors around one mirror machine are shown in Fig. 3. They will face the most severe radiation exposure because they are closest to the plasma.

The neutral beam injectors supply energized D and T atoms as fuel to the plasma. These atoms are first given a high kinetic energy as ions and are then neutralized without diminishing their energy. In one injection scheme (Fig. 4), positive ions are first accelerated followed by electron exchange as they pass through a region of D neutral atoms.

In another scheme (Fig. 5), the positive D and T ions are converted to negative ions when passed through Cs vapor at a pressure of 0.04 to 0.4 Pa(3×10^{-4} to 3×10^{-3} Torr). These negative ions would be accelerated to high energy and the excess electron stripped off the D^- or T^- ion by passage through a second stripping gas or by a photon stripping using laser light irradiation. When greater neutral beam energies are needed, this scheme becomes more attractive than the method based on D^+ or T^+.

One tentative design for the injector includes a direct converter for the recovery of energy from that part of the ion beam that has not been neutralized. This converter (Fig. 5) is different from the direct converter placed some distance from the reactor core and fed from plasma leakage as discussed below. The direct converter within the injector would be exposed to the highest neutron flux because it would be at that end of the injector closest to the thermonuclear plasma.

The problems facing the neutral beam injectors are:

- Highest neutron and gamma flux of the four main insulator locations.
- Hydrogen plasma and scattered hydrogen atoms may attack surfaces of oxide ceramic insulators.

• Cesium vapor may attack oxide ceramic insulators.

Injector Power Supplies

We would best locate the injector power supplies (Fig. 7) nearest the injectors to minimize Ohmic heating losses in the bus bars. However, these supplies will incorporate solid-state components such as silicon-controlled rectifiers, zener diodes, and ceramic insulators. Because such solid-state components are several orders of magnitude more sensitive to radiation than ceramic components, their limits of radiation

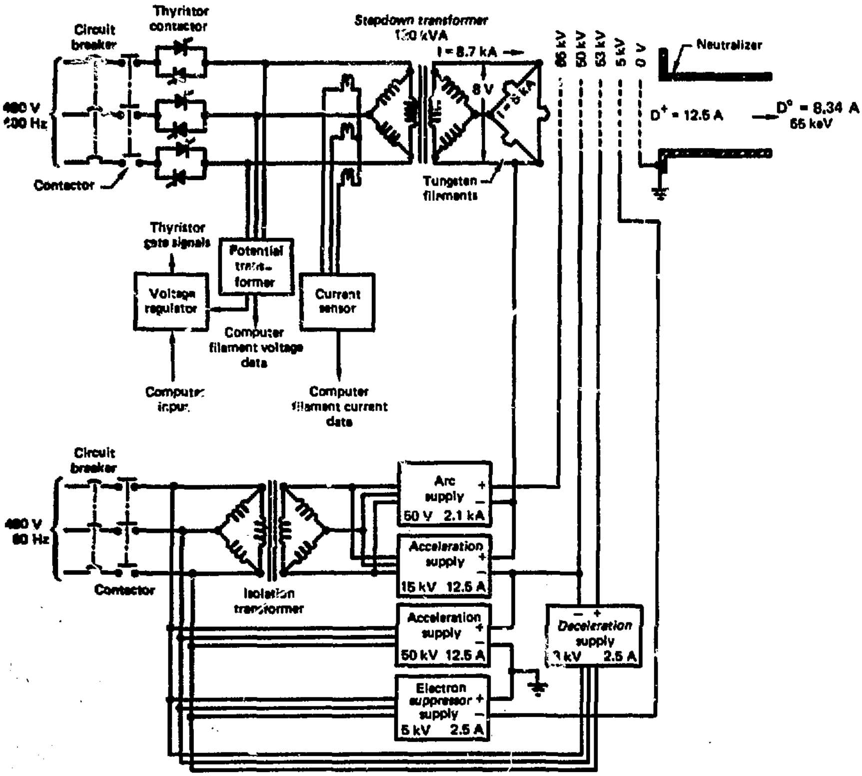

Fig. 7. Proposed electrical circuits for the FERF neutral beam power supply. Solid state components will limit the exposure tolerance and require shielding for most of the FERF system, but should be as close as possible to the tungsten filaments to reduce line losses.

dosage will determine the degree of shielding for the power supplies, and the insulators will be used within their exposure tolerances.

Direct Converters

The direct converter is designed to recover energy from ions that leak from the plasma. Figure 8 illustrates the energy distribution (flux) of these ions.[6] The position of the direct converter is shown in Fig. 9; it is relatively remote from the reactor, and the flux of neutrons is suppressed by a neutron trap. The converter diverts the ions magnetically but traps the uncharged neutrons. Neutron and gamma radiation fluxes in the direct converter will therefore be low. The charged particle fluxes will be reduced to a tolerable level by magnetic expansion that increases the cross section of the leaking plasma.

The direct converter recovery scheme is shown in Figs. 10 through 12. In the converters, the α-energies may reach ~4 MeV. The range of such

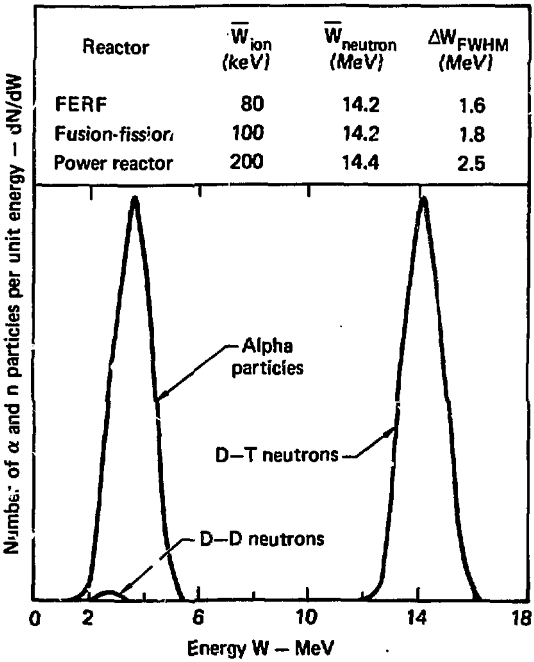

Fig. 3. Fluxes of ions and neutrons from D-T plasma. $\bar{W}$ ion and $\bar{W}$ neutron are average ion and neutron energy, ΔW_{FWHM} is the spread of neutron energy, full width at half maximum.

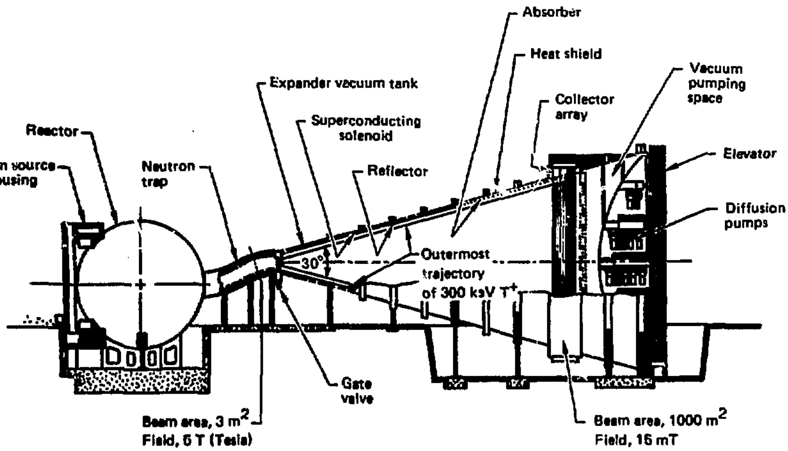

Fig. 9. Elevated view of single converter (collector array) unit with part of vacuum tank cut away to show internal features.

ions in iron is about 5 μm so they can be easily stopped before reaching the insulators, where they might otherwise cause surface damage. The average energy of D and T ions in the power reactor is expected to be ~200 keV, and they can also be shielded out.

Insulators in the direct converters may have to operate at a high temperature, ~1273K (1000°C). Part of the ion energy may be recovered as heat so a heat exchanger and turbine would be used. To obtain a high thermodynamic efficiency, we may need this high operating temperature. Here, we would be concerned with thermal effects, such as the runaway conduction caused by Ohmic self-heating. However, there is available space in this part of the machine to include many different insulator types. For example, it is possible to use large insulators with relatively small voltage gradients.

Magnets

Superconducting magnets will provide the magnetic field for confining the plasma. Between the magnet coil windings, the preferred insulators are made from organic materials such as epoxy-fiberglass and polyethylene teraphthalate (Mylar), or polyimides (Vespel and Kapton). The voltage gradients in the magnets will be small, and they will be shielded

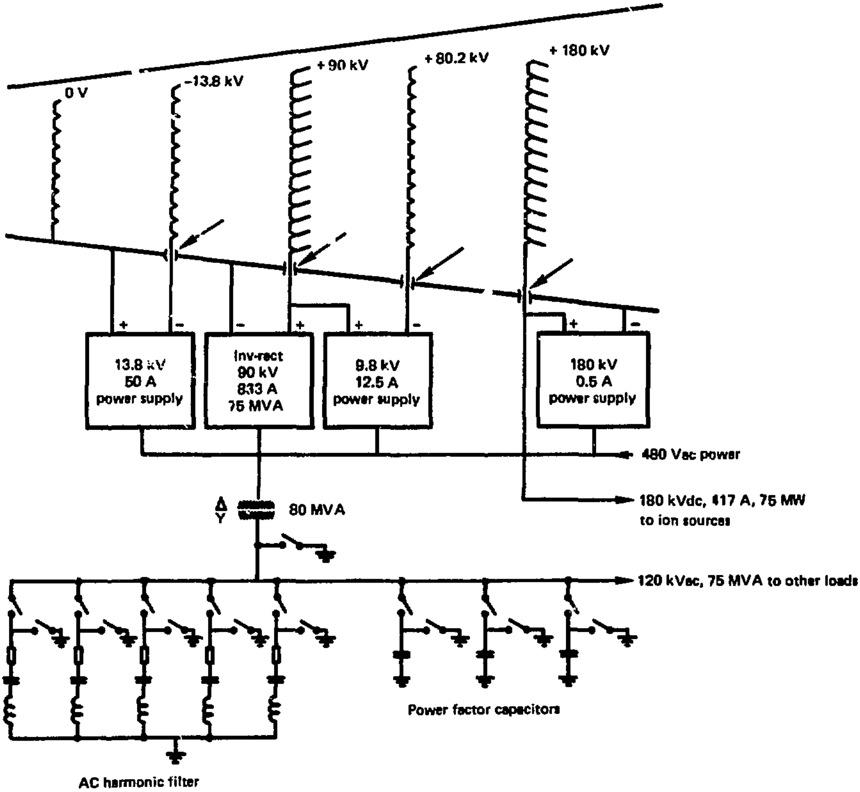

Fig. 10. Schematic representation of electrical circuits of direct converter. The 90-kV venetian-blind power is converted to alternating current by solid-state inverters and transformers to 120 kV. Arrows indicate positions requiring electrical insulators.

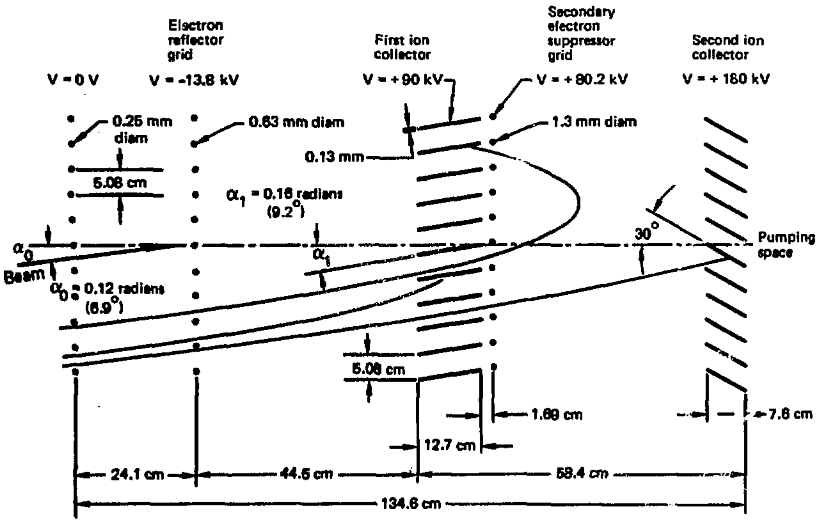

Fig. 11. Collector and grid array. The wire grids at the left (dotted lines) reflect the electrons and allow ions to pass through the venetian-blind collector. The blind appears transparent to the incoming ions but opaque to the ions reflected by the second collector.

against direct radiation. Radiation levels are shown in Table 3. Ceramic materials will be considered only if such organic insulators prove to be unsatisfactory.

One problem we may encounter is the buildup of stored energy in the insulator polymers from neutron and gamma irradiation. This energy might appear as free chemical radicals, which would be unreactive at cryogenic temperatures but explosively reactive on heating. Occasional annealing of the insulators may avoid this problem.

Two other problems that must be solved are first, radiolysis-induced release of gases, which may foul the helium in the refrigeration system or fracture the insulator from internal pressure when the system is warmed above the gas evaporation point, and second, a loss of mechanical integrity (crumbling) of the insulators leading to clogging of coolant channels.

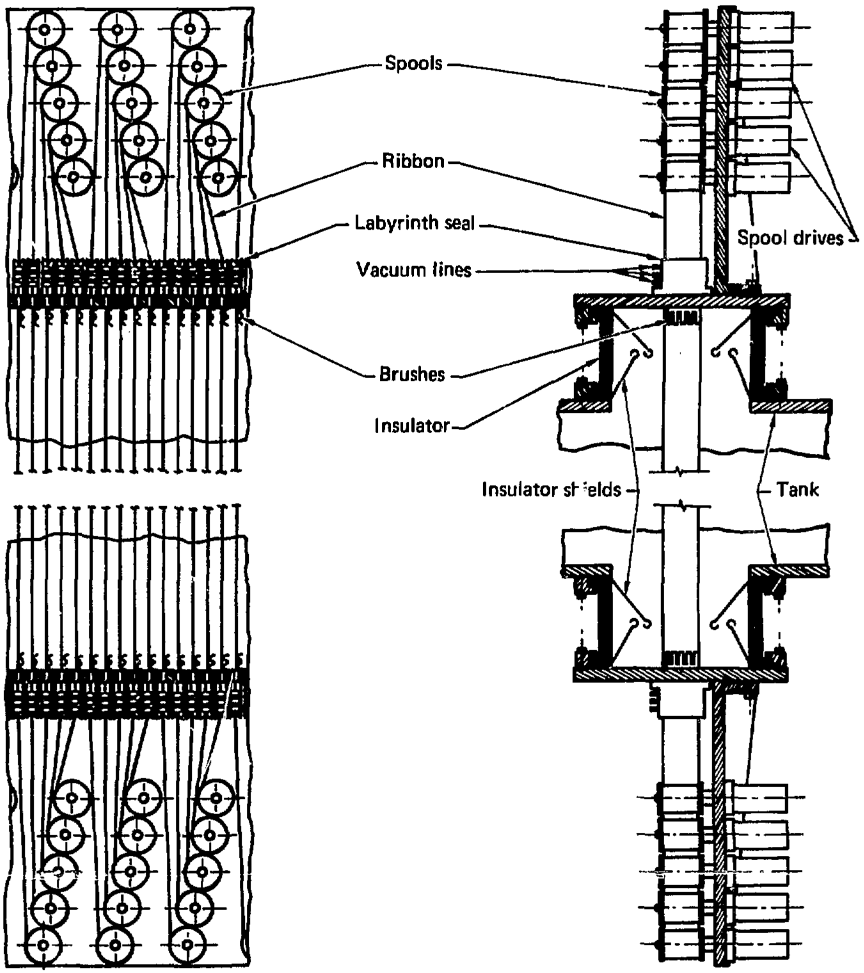

Fig. 12. A proposed termination of venetian-blind ribbons showing vacuum seals, brushes to remove current, spools and drives. Old blistered ribbons can be replaced without shutting down the converter.

Table 3. Energy deposition and fluence of neutrons and gammas in FERF magnet.

Radiation	Flux	Max fluence (30 y)
>10 MeV neutrons	0.3×10^{13} n/m^2·s	0.3×10^{22} n/m^2
All neutrons	9.6×10^{13} n/m^2·s	9.6×10^{22} n/m^2
>0.5 MeV gammas	1.4×10^{22} γ/m^2·s	1.4×10^{22} γ/m^2
	(3×10^{-3} Gy/s)	
Max. energy deposited in magnet		
	MW/m^3 × 10^{-6}	%
Neutrons	32	22
Gammas	113	78
Max. energy deposited in materials		
Lucite		
Neutrons	130	89
Gammas	16.8	11
Fiberglass/epoxy		
Neutrons	31	56
Gammas	24	44
Copper		
Neutrons	18	13
Gammas	125	87

NEUTRAL BEAM INJECTOR INSULATORS

In the present conceptual designs of mirror reactors, fueling is accomplished by injecting neutral atoms of D and T into the system (Figs. 3-7).[7,8] In Table 4, we list the injection energies of three reactors.

Neutral beams will be energized by ionizing D and T, and accelerating, focusing, and neutralizing them

Table 4. Energies of neutral D and T atoms injected into plasma.

	Injection energy, keV	
	D	T
MFTF (formerly MX)	80	—
FERF	65	100
Power reactor	200	200

at high energy. Future designs will provide for trapping unneutralized ions or recovering their energy in a direct converter.

High-voltage insulators will be required for the cathodes and accel-decel electrodes of the ion sources. These insulators must be vacuum tight, must not outgas too much, and must insulate enough that leakage currents do not cause serious power loss or overheating. The insulators in the ion source and the direct converter may be unshielded from the neutrons originating in the reaction plasma. If necessary, some shielding could be provided or bends in the beam line may obstruct a direct line of sight between the ion source and the plasma. Thus, we must be flexible to design a machine that can be modified to meet whatever limitations the materials may present.

Geometry

The fuel injectors in the experimental power reactor will have several common insulator needs.

- Feedthrough insulators will isolate the terminals that supply current to the cathodes. These will be hollow cylinders, a few centimeters in diameter and length.

- Bushings will be used to insulate the throughbolts holding the ion source electrodes together. These will be hollow cylinders with shoulders. The dimensions will be a few centimeters in diameter and several hundred millimeters in length.

- The electrodes in the accel-decel stack will be isolated from each other by insulators with the general shape of an automobile valve cover-gasket. The size will be several tenths of a meter up to a meter on a side, by a few millimeters to centimeters thick. Grooves will be cut perpendicular to the potential gradient to lengthen the surface leakage path.

Operating Conditions

Radiation Fields

We plan to position the injectors so that they will have a free path to the center of the plasma; however, the insulators need not be in a direct line of sight. In the FERF, they will be located ~5 m from the plasma. In the larger mirror power reactors, this distance is ~20 m. For the FERF, the direct flux of 14 MeV neutrons (n) on the insulators will be between 10^{14} and 10^{16} $n/m^2 \cdot s$, depending on their location and the amount of shielding afforded them by structural supports. The direct, unshielded 14-MeV neutron flux in the power reactor would be about 10^{17} $n/m^2 \cdot s$. Shielding will reduce this flux to 10^{14}-10^{16} $n/m^2 \cdot s$. The insulators will also be exposed to lower energy neutrons resulting from scattering, gamma rays, and secondary x rays. These fluxes are presently being calculated. The insulators can be protected from most ion and electron bombardment by properly designing the electrodes. Electrode shielding like that shown in Fig. 12 would be possible. Other geometrical variations should be possible within the available space so that the insulators would stand off the voltage while being protected from the full flux of unshielded neutrons.

Temperature

The heat load on the insulators originates from the filament, the arc, accelerated ion impinging on the electrode grids, blackbody radiation from the plasma, and nuclear heating from gamma and x rays. We may wish to keep some electrodes hot to allow for the release of H and He atoms embedded in them from the reaction plasma because if they remain embedded, they would cause blistering of the metal surface. Although the exact operating temperatures are not known, we plan to water cool the area near the contacts between the insulators and the metal parts. Temperature gradients within the insulators can be reduced by shielding to control heat input and by distributing heat sinks.

Surrounding Medium

Inside the ion sources there will be a pressure of 1 Pa (10^{-2} Torr) of D or T. In the injector direct converter, pressure will be 10^{-1} to 10^{-2} Pa. The ion beam density may reach 100 to 500 A/m^2 (6×10^{21} to 3×10^{22} $ions/m^2 \cdot s$). If any appreciable fraction of these ions are scattered or impart some of their kinetic energy to residual H or Cs atoms by collision, the exposed electrode and insulator surfaces will erode from sputtering. Sputtered material from metals or insulators will change the characteristics of the insulator surfaces onto which they are thrown. Surface conduction of such modified surfaces may be seriously increased.

In the charge-exchange portion of the reactor, the Cs vapor density of 0.04 to 0.4 Pa corresponds to the vapor pressure over the liquid metal at 370 to 400K; i.e., this vapor will condense on exposed surfaces cooler than these temperatures. Thus, insulators may be subject to coating by Cs vapor or possibly streaming liquid Cs metal (melting point 312K). This may etch the surface or render it conducting.

The external environment has not yet been established. It may either be atmospheric or pressurized CO_2 or SF_6 gas. The external gas will be partly ionized by the radiation fields. The dissociation products from SF_6 might include F atoms that would react chemically with almost any material surface. Such dissociation in an energetic neutron field will likely differ from dissociation in an x-ray field, where the usefulness of SF_6 has been established.

Stresses

Compression stresses in the injectors will be maintained high enough to hold a vacuum seal with metal gaskets. Large thermal stresses may be avoided by careful design, i.e, choosing metals with proper thermal expansion coefficients.

Electrical Requirements

The potential gradients along the surfaces of the insulators may be as high as several kilovolts per millimeter. Breakdown should be prevented and leakage minimized both in the bulk and over the surface. The conductivity should not exceed about 10^{-6} S/m ($10^{-8}/\Omega\cdot$cm) if Ohmic heating is not to be serious under the expected voltage gradients.

Cycling Time

The temperature and voltages may be cycled several times each day in the FERF. To recycle the cryogenic pumps on the injector system in a power reactor, it may be necessary to shut down the ion source. Not all injectors would be running at any moment; some might be in a cryogenic pumping mode while others might be recycling, i.e., being cleaned out. The possibility of recycling is now under discussion.

Lifetime

An injector lifetime of at least six months is desired; it is difficult and dangerous to change ion sources because tritium contamination and neutron activation will occur.

Suitable Materials

In much of the following discussion, aluminum oxide (Al_2O_3) is used as a reference material. Al_2O_3 is better characterized than most other ceramic materials in terms of its behavior under irradiation, and it is a principal ingredient of the more expensive commercial insulator ceramics. The behavior of alumina and other commercial ceramic materials under radiation exposure has been reviewed by Bauer and Bates,[9] who include data on BeO, MgO, HfO_2, SiO_2, Y_2O_3, AlN, BN, Si_3N_4, glasses, and other materials.

EVALUATION OF THE PROBLEM

The main questions we need to answer are first, for how long will the insulators support the potential gradients on the accel-decel stacks (electrical properties) and second, how long will they remain vacuum tight (mechanical properties)? We will first discuss effects of flux and then those of fluence (flux over time). Flux will affect the electrical but not the mechanical properties. Fluence will affect both.

Initial Voltage Holding Capability—Flux Effects

Assuming the neutral beam injector insulators operate satisfactorily in the absence of the radiation fields, we should consider whether the presence of the fields will have any serious prompt effects — that is, effects that depend on the instantaneous flux and not upon the accumulated fluence over time. Such possible effects are: (1) increased bulk conductivity due to ionization and nuclear heating within the insulator, (2) reduced breakdown strength, and (3) increased conductivity due to ionization in the gas shunting the insulators.

Bulk Conductivity

Rapid changes in bulk conductivity (photo conductivity) result primarily from the ionization due to gamma radiation (photoelectric effect and Compton scattering). This has been studied extensively for Al_2O_3.[10-13] The increase in conductivity σ can be directly related to the exposure dose rate ϕ. The conductivity increase at room temperature is given by $\sigma = 4$ to $250 \times 10^{-11}\ \phi$, where conductivity is expressed in S/m, and dose rate ϕ is expressed in Gy/s. In equivalent units, $\sigma' = 1.1$ to $70 \times 10^{-18}\ \phi'$, where conductivity is $(\Omega\cdot cm)^{-1}$, and dose rate ϕ' is R/h. The roentgen R is defined as 10^2 Gy, 10^{-5} J/m^3, or 6×10^{13} eV/cm^3. This range in the coefficient σ' reflects the results of different authors and material purities. For comparison, the normal ionic conductivity of Al_2O_3 at room temperature is ~10^{-12} to 10^{-10} S/m, depending on purity. For gamma rays of 1 MeV, 1 Gy/s (3.6×10^5 R/h) is equivalent to a flux of 2×10^{15} photons/m$^2\cdot$s. In this relationship, we take into account the range of gamma rays and the fact that they deposit only part of their energy at one point. For 0.5 MeV gamma rays, 1 Gy/s is equivalent to 3.6×10^{15} photons/m$^2\cdot$s.

Assuming a gamma flux of 300 Gy/s (1.1×10^8 R/h), an upper reasonable limit for the Reference Design Mirror Fusion Reactor, with an energy of 1 MeV and a coefficient of 2.5 $\times 10^{13}\ \phi$, the photoconductivity at room temperature could be $\sigma = 1.0 \times 10^{-6}$ S/m.

The assumed gamma flux is larger than we expect for most exposed insulators (Table 2). With such a flux, however, the conductivity is still within the range allowable if Ohmic heating is not to be too great. In a design of an injection system by Hamilton *et al.*,[14] the steepest voltage appears to be a 58 kV/0.03-m gap for which the current I through the insulator at room temperature would be about

$$I = \frac{V\sigma\ A}{l} \ ,$$

where A and l are area and length. Solving,

$$I = \frac{(58 \times 10^3\ V)\ (1.0 \times 10^{-6}\ S/m)\ (1\ m)\ (0.02\ m)}{0.03\ m}$$

$$= 40\ mA.$$

A current of 40 mA (a small fraction of the power supply capability) amounts to ~2 kW of Joule heating in the insulator, or $\sim 3\ MW/m^3$. Other oxide insulators are comparable[12] to Al_2O_3, at least at gamma fluxes of $\sim 5 \times 10^6$ R/h; the magnitude of the Compton effect is not sensitive to material.

Another source of heating is from gamma rays. Assuming 1 MeV gamma rays, the heating in Al_2O_3 is given approximately by

$$P\ (MW/m^3) \simeq 2 \times 10^{-8}\ \phi\ (photons/m^2 \cdot s).$$

For a flux ϕ of 10^{18} photons/$m^2 \cdot s$, this amounts to 2 MW/m^3, about half as much as from Joule heating. However, the temperature increase from both causes will lead to higher electrical conductivity and to more Joule heating. There will be additional heat input from the filament, arc, and accelerated ions striking the grids. The operating temperature of the insulators will be established by a balance between the heat put into the system and the conduction of heat away from it.

Breakdown

The electrical conductivity of oxides in radiation fields increases rapidly with temperature by the following expression[15]

$$\sigma = \overbrace{\sigma_{01}\ \exp(-u_1/kT)}^{(1)} + \overbrace{\sigma_{02}\ \exp(-u_2/kT)}^{(2)} + \overbrace{A\phi T^{3/2}\ \exp(-u_3/kT)}^{(3)} \ ,$$

where (1) represents ionic conductivity, (2) represents impurity conductivity, and (3) represents photoconductivity. From this, there is a rough exponential increase in electrical conductivity with decreasing 1/T. The thermal conductivity, on the other hand, *decreases* with temperature approximately as 1/T. If the heat input from all sources (nuclear, Joule, and heat conducted and radiated into the insulator) exceeds the heat conducted away, a catastrophic thermal breakdown (runaway conduction) will occur. During runaway conduction, the temperature rises rapidly until electrical breakdown occurs. It is difficult to calculate the conditions for this without a detailed knowledge of the system's geometry, thermal environment, and radiation fluxes. Experimental results[16] indicate that this process is important above ~800K in Al_2O_3.

Below this temperature, breakdown can occur by electron valanches. In a strong field, a few electrons may gain enough energy to impart some of their energy to the valence electrons in the solid and to inject them into the conduction band. In turn, these may excite other valence electrons, causing the avalanche. The effect of radiation on this process has not been studied, and it is difficult to make predictions about it.

Gaseous Conductivity

Assuming the injector contains pure hydrogen at 10^{-4} Pa pressure, and the electrode spacing is set to prevent avalanche ionization in the gas, the electrodes and spaces between will act as integrating ionization chambers. Neglecting gaseous diffusion and recombination, the current collected inside the injector is given by

$$I(A) = 4.3 \times 10^{-7} \cdot \text{volume } (m^3) \times \phi \text{ (Gy/s)}.$$

For a volume of 10^{-3} m^3 and a dose rate of 500 Gy/s at 1 MeV, the current would be ~0.2 μA, which is insignificant compared to the dielectric leakage (up to 50 mA, in 6×10^{-4} m^3 as calculated previously). If the environment outside the injector were 1×10^5 Pa (1 atm) of dry air, the density of ion pairs would be 7.6×10^4 greater. The current in this situation would be considerably larger, but not by this full amount, because it does not take into account ion recombination. This should be investigated further for the gas to be used.

Long-Term Voltage Holding—Fluence Effects

The next problem is the effect accumulated radiation may have on the voltage holding of insulators. Possible effects from accumulated radiation include (1) changes in the bulk electrical conductivity, (2) change in thermal conductivity that will affect the onset of runaway electrical conduction, (3) reduced breakdown strength from retained damage, and (4) increased surface conductivity caused by hydrogen isotopes injected into the insulators and metal atoms sputtered onto the insulator surfaces.

Bulk Electrical Conductivity

Results of studies on bulk conductivity changes in irradiated insulators are conflicting[10,14]; such changes depend on insulator material purity and grain size. The conductivity in alumina has been reported[14] to increase by one order of magnitude over 700–1100K after irradiation with 10^{26} n/m^2. Prompt conductivity changes (Compton effect) will probably dominate the changes for most or all of the usable lifetime of the insulator.

Thermal Conductivity and Runaway Conduction

The thermal conductivity of many ceramic materials is decreased after irradiation.[9] This effect decreases at high temperatures, where the intrinsic thermal conductivity then tends to decrease. Moreover, annealing of radiation damage may occur at high temperatures (above ~50% of the insulator melting temperature). However, at 973K and 8×10^{25} n/m^2, thermal conductivity in alumina may decrease threefold.[17,18] Thus, runaway conduction may occur at only one-third of the power input, which would otherwise have caused such electrical breakdown in alumina not exposed to radiation.

Avalanche Breakdown

We have not found published information on this topic. If avalanche breakdown is the dominant process (likely below 800K), the presence of fractures and bubbles of helium may reduce breakdown strength by concentrating the electric field at interfaces, or increase it by reducing the mean free paths of avalanche electrons.

Surface Conductivity

Injected hydrogen raises the surface conductivity of oxides.[19] The injector insulators now used, however, could be shielded from H^+ bombardment. Sputtered metal will likely become a problem, but little is known about the total sputtering rates from neutrons.

Vacuum Tightness

Neutron fluence can cause vacuum leaks from insulator swelling. Data on swelling of insulators is presented in Fig. 13 for fission neutron spectra.[9,20] Expansion of metals might typically be ~1% at 10^{26} n/m^2, but in metals and ceramics, expansion depends upon temperature, composition, grain size, neutron energy spectrum, and fluence.

For ceramics with a noncubic crystalline structure (Al_2O_3 and BeO), radiation-induced growth in a particular crystallographic direction can lead to separation of the individual grains, and hence, to intergranular fissures. Also, when a ceramic is constrained, radiation-induced swelling can produce increased

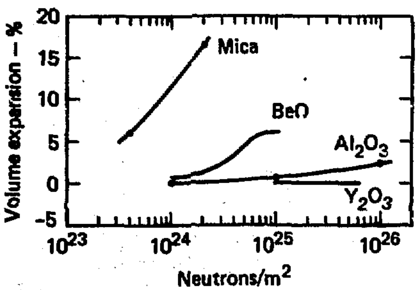

Fig. 13. Swelling of some materials as a function of neutron irradiation. Data is mostly for E > 0.1 MeV and room temperature. Data for BeO, Al_2O_3 and Y_2O_3, from Ref. 9. Data for mica from Ref. 20.

stresses in the material and lead to gross fractures. These effects have been studied in the thermionic power generation program.[18,21] The main differences for our application are (1) the temperature of operation, which should be lower for the injectors, (2) the neutron spectrum which contains a 14-MeV component, and (3) the increased helium generation in the ceramic due to the higher (n,α) cross sections at higher neutron energies.

The swelling and grain separation of Al_2O_3 under neutron bomdardment depends strongly on the material temperature, purity, and grain size.[9] Best results are obtained with high purity and small grain size. For temperatures below 373K, grain boundary separation is not observed up to doses of ~8 × 10^{25} n/m^2 (E > 0.1 MeV), assuming a Watt (pure fission) neutron spectrum. The volume swelling is about 2% at the highest neutron fluence. From 383 to 598K, grain boundary separation begins at a fluence of about 3 × 10^{25} n/m^2 (E > 0.1 MeV). At a fluence of about 7.5 × 10^{25} n/m^2 (E > 0.1 MeV), swelling is more severe, reaching more than 5%.

The damage effectiveness of the fusion neutron spectrum will be greater than that of a fission spectrum. In the absence of data, we will use a factor of 3 for Al_2O_3. Under these conditions, there is a fluence limit of about 10^{25} n/m^2 for Al_2O_3. For a helium production cross section of ~1.2 b (120 fm^2), the He concentration (assuming 1/8 of the neutrons are in the 14 MeV peak) would be about 300 ppm Al_2O_3 at this fluence. The helium will probably have a small effect on swelling and pore formation at this concentration for temperatures not much above 373K.

Therefore, for a flux of 10^{16} n/m^2 s (the high estimate for the neutral beam injector components) the insulators might maintain their vacuum tightness for one or more years.

Outgassing

Gases will be produced in the insulators as a result of n,p and n,α reactions and chemical breakdown (radiolysis) of the oxide material. This may not be a serious problem because the amount of gas will be small compared with the volume of D and T put through the injector. However, oxygen atoms have a stronger affinity for electrons than hydrogen or cesium atoms, and the electron transport in slightly contaminated DT plasmas might differ from transport in pure gases.

MATERIALS RESEARCH

It is yet difficult for us to predict the behavior of insulator materials in the environments of proposed mirror fusion reactors. Over time, there will be changes in thermal conductivity, composition (contamination by transmutation products), microstructure, surface properties, and stored energy resulting from radiation damage. Cycling the temperature, electric field, and radiation flux may cause changes different from steady-state operation. Gradients in temperature, mechanical stress, radiation damage, and changes in conductivity may produce damage in a location of a reactor that we would not expect. Interactive effects between processes such as these may produce phenomena that have not previously been studied. For example, electrical charges known to exist on crystal dislocations may modify their motion through a solid in an electric field to produce a new type of creep behavior, or radiation damage in a dielectric exposed to a high electric field may differ from that in an electrically unstressed material. Joints between metals and ceramics will require special attention in radiation fields. We do not know if the different densities of material in a gamma field induce electric charge distributions that give fields different from those expected.

In the following sections, we discuss those areas for which we feel new research is needed.

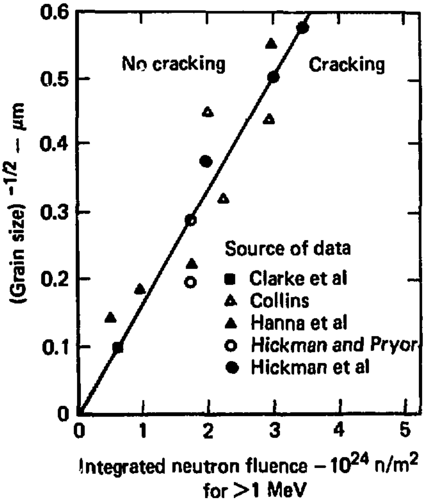

Fig. 14. Neutron dose required to produce microcracks in BeO during irradiation at 323-373K as a function of grain size.

Radiation Flux and Fluence

The dielectric breakdown strength of typical ceramic materials should be measured as a function of radiation flux and fluence. We are not aware that such measurements have been made. Studies of the alkali halides as model materials might be helpful since they have been well-characterized in other ways.

Amorphous Materials

The radiation sensitivity of amorphous materials needs to be studied further. Figure 14 shows a correlation between radiation sensitivity and grain size.[22] The data taken from several sources[23-27] suggest that material with zero grain size might be only slightly radiation-sensitive. Aside from this, grain boundaries can serve first, as paths for accelerated diffusion and ion migration in an electric field, and perhaps second, as points for precipitation of electrolytically formed metals in a polarizing field.

Dopants

Recent experiments suggest that selected doping may suppress radiation damage in MgO[28] (Fig. 15). Studies of the effects of hydrogen

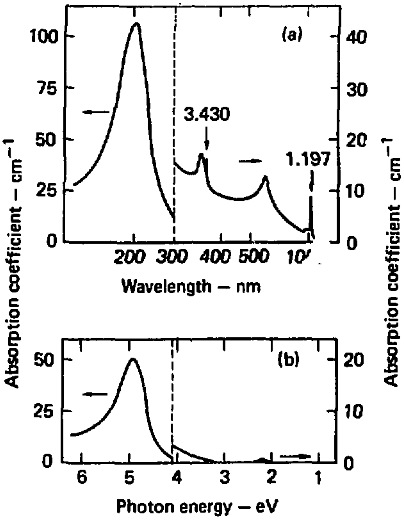

Fig. 15. Optical absorption spectra at 77K of (a) pure and (b) Li-doped MgO crystals, both irradiated to a dose of 6.4×10^{20} n/m^2.

on the radiation sensitivity of silica glass suggest strong effects of dopants, but there are conflicts in the results: soaking a specimen in high-pressure hydrogen before irradiation has been found to enhance[29] and suppress[30,31] its sensitivity to the radiation.

Other results[32] suggest that hydrogen soaking can reduce the concentration of damage centers in materials by 2 to 3 orders of magnitude. In this study, it was found that silica purity influences the extent of damage. In Fig. 16, the spin densities measured by electron spin resonance (ESR) are plotted as a function of γ-ray radiation, reactor neutron fluence, and 14 MeV neutron fluence. Two silica types were studied: Suprasil 1 containing 100 ppm OH, 100 ppm Cl, and ~1 ppm metallic impurities, and Suprasil W1, containing 0.4 ppm OH, 200 ppm Cl, and ~1 ppm metallics. The differences between the slopes indicate that the two silica types are damaged differently from radiation.

Radiation Types

The effects of different types of radiation need to be differentiated. As illustrated in Fig. 17, gamma rays and slow neutrons produce a different damage ESR signal than than produced by 14 MeV neutrons in Suprasil W1. This figure shows the appearance of a new ESR line in neutron-bombarded Suprasil W1 compared with γ-bombarded Suprasil W1. Small differences have been observed in the damage produced in Al_2O_3 between reactor and 14 MeV neutrons.[33] These fluences are small compared with those expected in a fusion reactor, and the meaning of this result is yet unclear. However, we expect that the He and H buildup in materials exposed to 14 MeV neutrons will contribute to radiation damage in ceramics in ways that do not normally occur with lower energy neutrons.

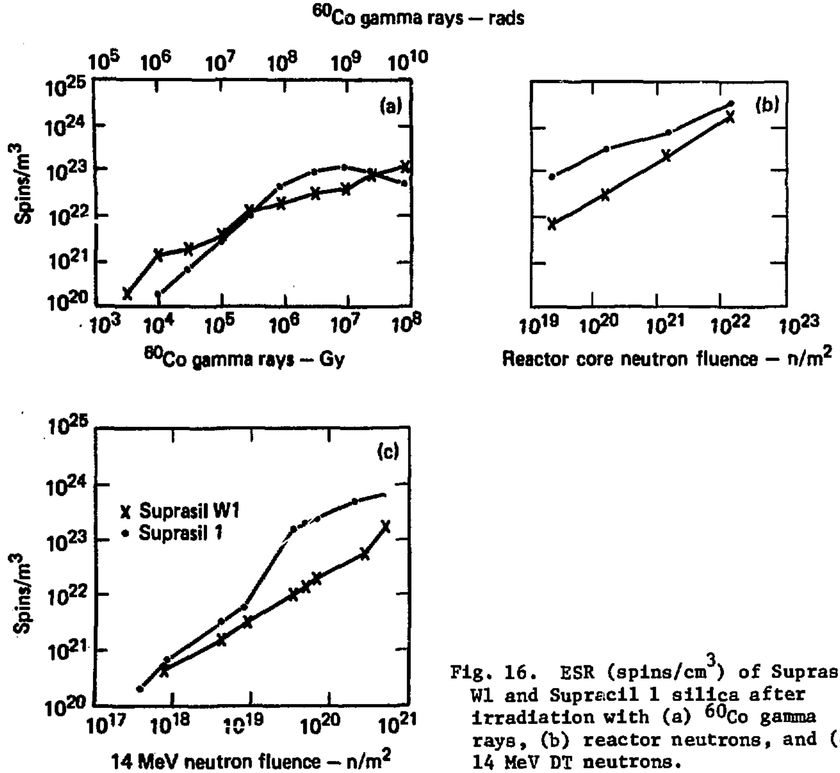

Fig. 16. ESR (spins/cm^3) of Suprasil W1 and Supracil 1 silica after irradiation with (a) ^{60}Co gamma rays, (b) reactor neutrons, and (c) 14 MeV DT neutrons.

Surfaces and Interfaces

The behavior of insulator surfaces and interfaces needs to be studied. The effects of atomic hydrogen on the oxides of magnesium and aluminum have been noted[19] and are illustrated in Fig. 18. As hydrogen bombardment time is increased, the resistance of both oxides similarly decreases. Subsequent to bombardment, it was found that the electrical resistance could recover to the original value on exposure to air. Other hot atom reactions may be important, such as reactions of He^+ or Cs^+ adsorbed on surfaces. Sputtering that transports material from one surface to another will surely affect surface leakage.

The interaction of the insulator surface with the field gradients in the neutral beam injector may have

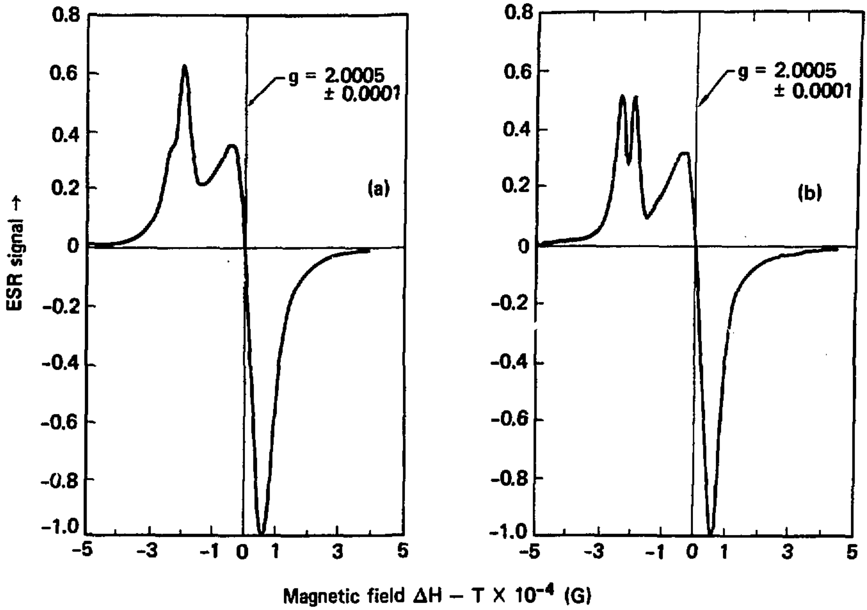

Fig. 17. ESR spectrum of Suprasil W1 irradiated with (a) reactor neutrons and (b) 14.8 MeV neutrons. Shown is g, the free electron "g" factor.

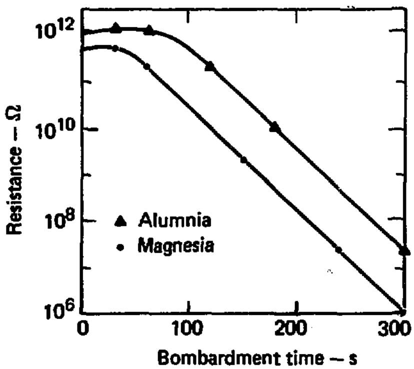

Fig. 18. Effects of H^+ bombardment on the resistance of aluminum and magnesium oxides. Ion source 300 μA, 500 eV proton beam with 10^{-1} μm penetration.

an important effect on the quality of beam focusing. Secondary electron emission from surfaces bombarded with ions and electrons from the region of the beam path may change surface potentials and potential gradients. A common procedure for controlling surface arcing is to add a thin layer of a semiconducting material (chromate, titanate, stannate) to bleed off local charge buildup. Such materials may have an effect on the secondary electron emission, and this needs to be studied.

Interfaces between ceramics and metals should be studied in the 14 MeV neutron environment. Enhanced reactivity of materials under fission neutron irradiation has been observed.[34] Recoil atoms from neutron collisions or neutron sputtering can implant material to a depth of nearly 1 µm from one part of a couple into the other. Surfaces treated in this way can be chemically more reactive than the initial surface. On exposure of such surfaces to the atmosphere during occasional shutdown for repairs, the adsorption of moisture and other impurities from the air could be much greater then anticipated with the result that long vacuum pumpdown and bakeout would be necessary before the outgassing level was low enough for useful operation of the neutral beam injector.

Internal surfaces in polycrystalline materials (grain boundaries), and external surfaces may become centers for helium precipitation, precipitation of transmutation products, and paths for relatively rapid ion migration in an electric field.

Mechanical Constraints

Effects of mechanical constraints on insulators should be studied since they may become important if the insulators swell under irradiation. Pressures exerted by swelling materials can reach 100 to 200 MPa or more. As shown in Fig. 19, these pressures are large enough to change the conductivity of some metal oxide varistors.[35] If the conductivity of

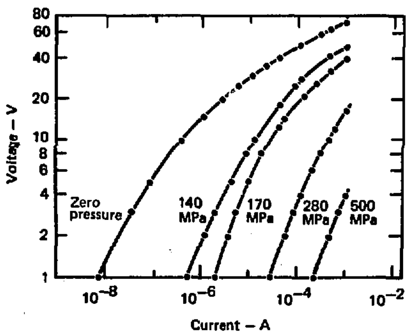

Fig. 19. Effect of pressure on electrical properties of 2- to 3-mm thick ZnO + 1/2% Bi_2O_3 varistor specimen.

an insulator around an angular metal joint is not homogeneous, the isopotential lines may become distorted and produce local voltage gradients that are larger than anticipated.

Polarization

Polarization of insulators subjected to radiation and continuous electric fields should be measured. Electrolytic decomposition of dielectrics in strong fields while being irradiated may occur, producing perturbation at the interfaces of initially clean metal-ceramic interfaces.

It has been shown[36] that the combined effect of an electric field and a temperature gradient is to produce a nonlinear field gradient with the peak field shifted to regions where the strong fields may least be tolerated. This results from the temperature-dependent mobility of the current carriers.

Composite Materials

Composite materials often have attractive properties, i.e., greater strength in certain stabilized zirconias, easier fabrication in machinable glasses, etc. The behavior of these under irradiation needs to be studied because their interesting properties often result from their microstructure, which might be changed. Machinable glass, for example, contains mica particles, but as shown in Fig. 13, swelling of mica is larger than many other materials during neutron irradiation.

Theoretical Limits Estimates

It would be worthwhile to estimate the theoretical limitations on insulators without regard to specific materials. Low-Z materials would be useful for insulators because their low electron density make them less sensitive to gamma-induced conductivity (Compton effect) and because they often have good thermal conductivity. One such material is BeO. On the other hand, low-Z materials tend to have large cross-sections for n,α reactions. Such general parametric studies may suggest other directions for materials research on insulators for fusion reactor radiation fields.

DISCUSSION

The development of adequate insulator materials for fusion reactors will be an iterative progression. At present, the geometry is not clearly defined, but it can probably be modified to accommodate the needs of the materials available. New materials may relax shielding or other geometry requirements. This may then shift the danger of possible component failure to another part of the machine. In this report, we have been concerned with phenomena in materials, but the fabrication of materials in the sizes required for large machines will also be a serious problem. All of these considerations indicate a need for involved and coordinated effort for the development of effective insulators.

The system as a whole will have to be studied. For example, we have mentioned the possible effect of the insulator surface conduction and secondary electron emission on neutral beam injector focusing. Other component interactions must be taken into account. Will the partial deterioration of one component lead to the breakdown of another? If breakdown does occur, will the release of the large stored energy and high voltage with large stored charge cause damage to critical parts?

Materials research has progressed to a point where information is available on single effects such as swelling as a function of a single variable such as radiation. More complex relationships are being investigated as parts of studies of magnetohydrodynamics (MHD) power research (electrical and high temperature), thermionic reactor fuel elements (radiation and electric fields), and ceramic fuel elements in fission reactors (transmutation and temperature gradient effects). The phenomena observed in these studies will all appear in some of the components of fusion reactors. A long history of experience in materials behavior will determine the reliability and success of these components of mirror machines. Materials research would clarify the uncertainties discussed in this report and guide us in coping with yet unknown problems.

CONCLUSION

With the materials commercially available, it is conceivable that we can build the necessary insulators for mirror fusion machines that will withstand the extreme radiation and temperature we anticipate. In those portions of the reactors with the most severe environments, we may be able to modify the exposure to further protect the insulators. Nevertheless, we must allow for occasional breakdown and replacement. The proper design of an insulating system for mirror fusion machines will require further study because too little is presently known about the interactions between processes such as electrical breakdown, ionic migration, radiation damage, effects of electrical fields, temperature and stress gradients, interfaces and surfaces, and high energy neutron radiation.

The materials research that would help us to assess the effects of radiation and temperature on mirror fusion insulators should be initiated soon. This complex evaluation is a crucial preliminary step in mirror fusion reactor design.

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