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MATERIALS PROBLEMS IN DIRECT CONVERSION SYSTEMS

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MATERIALS PROBLEMS IN DIRECT CONVERSION SYSTEMS*

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ABSTRACT

Some of the potential problems of a materials-metallurgical-chemical nature which may arise in fusion reactors utilizing the magnetic mirror principle and direct conversion of charged particle energy to electricity are enumerated. The effect that the energetic particles, charged or neutral, may have on three main components are discussed. These components are: (1) the first wall; (2) the blanket; and (3) the collector elements of the direct converter. The complexity of problems in these areas are enumerated and some possible solutions offered which are considered worthy of further investigation.

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Mirror Reactors with Direct Conversion

Mirror machines with direct conversion represent a particular concept of a fusion reactor. This reactor has three main parts; a magnetically contained plasma volume in which fusion takes place, an ion injection and plasma heating system requiring electrical energy, and a combination thermal and direct energy converter system. We will be concerned only with the energy conversion system in looking at some of the materials problems. The thermal portion of the converter system converts the neutron kinetic energy to thermal energy in a blanket surrounding the plasma confinement zone. The blanket may or may not breed tritium depending on the fuel cycle selected. The second element of the energy converter system is the direct converter which accepts the charged particle energy fluxes escaping from the plasma confinement zone and converts them to high voltage dc power. Some fraction of this direct converter power is then fed back to the ion injection system to sustain the reaction and maintain the plasma. The reactor may be generally classified as a relatively low gain energy amplifier. This concept of combining thermal and direct conversion should be applicable to any fusion containment system; however, it is especially attractive for mirror systems because it furnishes a means to minimize end losses.

For mirror machines with direct conversion the fuel cycles shown in Figure 1 are possible; the D-T cycle, in which direct conversion is used in conjunction with the predominantly thermal conversion of the neutrons in a blanket which provides neutron multiplication and tritium breeding; the D-D cycle, where tritium breeding is not required but thermal conversion of the neutron energy is a necessary and not insignificant contribution to

the total power output; and the D-He³ cycle, in which charged particles ideally would be the only product and there would be no thermal converter. However, within this D-He³ cycle some D-D reactions and neutron production is inevitable and therefore a nominal blanket would be required to cope with some relatively small fraction of the total energy release.

1.	${}_1\text{D}^2 + {}_1\text{T}^3 \rightarrow {}_2\text{He}^4 (3.5) + n(14.1)$
2.	${}_1\text{D}^2 + {}_1\text{D}^2 \begin{cases} \rightarrow {}_2\text{He}^3 (.82) + n(2.45) \\ \rightarrow {}_1\text{T}^3 (1.0) + {}_1\text{H}^1 (3.02) \end{cases}$
3.	${}_1\text{D}^2 + {}_2\text{He}^3 \rightarrow {}_2\text{He}^4 (3.6) + {}_1\text{H}^1 (14.7)$
THE PRINCIPAL FUSION REACTIONS	

FIGURE 1

For the neutron energy to be recovered in any of these cycles the kinetic energy of the neutron must be converted to thermal energy which leads to a recognized, conventional process - the familiar heat engine. The Carnot limit for efficiency $(T_H - T_C)/T_H$ is applicable to this process. Operating temperatures for this kind of energy converter are materials limited; i.e., by allowable stress, creep, corrosion, etc. Overall efficiencies of 50% may be obtained within current technology although 40% is more representative of actual systems. Efficiencies of

60% may only be achieved by materials and metallurgical advances at a significantly higher and perhaps unreasonable cost per electrical kilowatt.

In contrast to the thermal conversion of the neutrons with its limited efficiency the utilization of the energy of the charged particles has the potential capability of much higher efficiencies because this direct conversion process itself is not Carnot limited since source temperatures are those of the charged particle, for example 400 KeV, and sink temperatures are the particles energy after deceleration.

A method for direct conversion was formally proposed by Richard Post of the Lawrence Livermore Laboratory at the Culham Conference in September 1969.¹ Post, at that time, provided a complete, preliminary physics analysis of a total system. Since that time the original analysis has been refined and improved.² Using Post's original concept, the process of the conversion of this charged particle energy to electrical energy may be imagined to take place in a sequence of four steps:

1. Expansion
2. Charge separation
3. Deceleration and collection
4. Conversion to a common potential

The first three steps of this process are illustrated in Figure 2. The reaction products escaping from the mirrors at already low ion density (typically $10^8/\text{cm}^3$) are required to further decrease their density by expansion into a large, probably flat, fan shaped chamber where the density would be reduced to about $10^6/\text{cm}^3$. The density reduction is required because of space charge limits. Expansion is accomplished by coupling an external radial magnetic field to the mirror field and allowing the field to decrease

DIRECT CONVERSION FOR A MIRROR FUSION REACTOR

Figure 2

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

The ions emerge from the expander with a considerable spread in energy. To recover this energy at high efficiency the ions are passed through a series of electrostatically focusing collectors within which they are progressively decelerated. This is the third step of direct conversion. Figure 3 illustrates a computer calculation of various ion trajectories in the collector. The ions are decelerated to a low residual energy and then diverted into a collector. The collection efficiency for each particle is the electric potential of the collector divided by the initial energy of the ion. Experiments at LLL have demonstrated overall collection efficiencies in excess of 80% and further improvements are expected.'

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

System "Q" and Circulating Power

Depending principally upon the ratio of fusion power to net injected power (defined as the "Q" of the system) the efficiency of a mirror reactor with direct conversion can be quite high. Mirror machines are termed "driven systems" since energy is continually injected, the object being to produce

COLLECTOR GEOMETRY AND TYPICAL ION TRAJECTORIES

$$\phi = X \cdot \sum_{n=1}^{\infty} \sin(2\pi n X) \sinh(2\pi n Y) \\ C = 3$$

FIGURE 3

an incremental increase in energy over that which is injected. This injection power is needed to sustain and heat the plasma. This injected power will be quite high relative to the fusion power that is produced for small values of Q . Q 's ~ 0.2 for D-He³ to ~ 2.0 for D-T are currently representative.^{4,5}

The value of Q determines the amount of "circulating power" involved in systems using direct conversion. All of the energy except for the incremental increase due to the fusion reaction must be continuously recirculated. That is, all the plasma fuel ions that did not react must be recovered and their energy reused. Additionally, some of the fusion energy itself must be fed back to the system to make up for inefficiencies. The level or quantity of circulating power will influence to a large extent the materials problems in all of the reactor working elements. A mirror reactor power flow chart specifying these working elements is shown in Figure 4. Table 1 defines the circled numbers shown on the flow chart. We will discuss only three elements at this time: (1) the first wall, (2) the blanket, and (3) the collector element of the direct converter.

For our assessment of the materials problems in these three elements in direct conversion systems, we will consider two basic mirror reactor systems, one of which employs the D-T fuel cycle and the other the D-He³ fuel cycle. Table 2 shows the assumed plasma conditions. The initial element that will be considered is the first wall surrounding the plasma.

TABLE 1 - Key to Numbering System Used in Power
Flow Chart

1. Mirror Reactor Leakage	13. Neutron Induced Blanket
2. Plasma Radiation	14. Untrapped Beam Electric
3. Collector Ions	15. Untrapped Beam Thermal
4. Collector Electrons	16. Injector Input
5. Expander Heat	17. Injector Heat
6. Ion Coll. Electric	18. Exp+Col+Inj Heat
7. Ion Coll. Heat	19. Thermal to Electric
8. Electron Coll. Electric	20. Total Electric
9. Electron Coll. Heat	21. Auxillary (Assumed)
10. I-R Electric	22. Net Electric Output
11. I-R Heat	23. Fusion Power
12. Fusion Neutron	24. Waste Heat
	25. Neutral Beam Power

TABLE 2 - Assumed Plasma Conditions for Two Basic Mirror Reactor Systems

	<u>D-T Case</u>	<u>D-He³ Case</u>
$Q \equiv$ Fusion Power/Trapped Injected Power	1.0	0.4
$T_i \equiv$ Ave. Ion Energy	420 KeV	435 KeV
$T_e \equiv$ Ave. Electron Energy	52 KeV	53 KeV
$P_f \equiv$ Fusion Power	1390 MW	2150 MW
$P_n \equiv$ Fusion Neutron Power	1100 MW	320 MW
$B \equiv$ Magnetic Field	64 kG	70 kG
$\beta \equiv$ Plasma Pressure/Magnetic Pressure	0.9	0.9
$n_i \equiv$ Ion Density	$1.95 \times 10^{14} \frac{\text{ions}}{\text{cm}^3}$	$2.27 \times 10^{14} \frac{\text{ions}}{\text{cm}^3}$
$R_p \equiv$ Plasma Spherical Radius	3.15 meters	4 meters
$V_p \equiv$ Plasma Volume	130 m^3	268 m^3
$A_p \equiv$ Plasma Surface Area	125 m^2	200 m^2
$P_b \equiv$ Injected Beam Power	1420 MW	5500 MW
$E_b \equiv$ Injected Beam Energy	575 KeV	594 KeV

Material Problems in the First Wall

The first wall of a mirror reactor, i.e., the surface in view of the plasma, is subjected to neutron fluxes and neutral particle fluxes and to photon radiation.⁶ Charged particle impingement on the first wall can be neglected because the rate of charged particle leakage into the mirror loss cone is much greater than diffusion across the walls.

The neutrons, of course, are produced by the D-T and D-D reactions as was indicated in Figure 1.

The neutral atoms which hit the first wall are produced by both charge exchange of plasma ions with the injector neutrals and by the charge exchange of plasma ions with gas atoms that leak into the reaction chamber from the beam neutralizer. In mirror machines creating and maintaining the plasma is accomplished by the injection of neutrals and their ionization in the plasma region for capture. Particles are injected at high energy (hundreds of KeV) to provide plasma heating and penetration. This fueling technique affords plasma density and temperature control plus fuel mixture control. The advantage of injecting neutral particles is that they can cross field lines and enter the plasma. The disadvantage is that particles must first be accelerated as ions and then neutralized before injection. The process must be highly efficient and the beam neutralizer design must allow a minimum of gas leakage into the plasma from the neutralizer.

Photons are produced by bremsstrahlung (x-ray energy range) and synchrotron radiation (infrared energy range).

Table 3 lists the fluxes on the first wall from these three sources for the two cases, D-T and D-He³.

TABLE 3 - Fluxes on the First Wall of A Mirror Reactor

RADIATION (ENERGY RANGE)	D-T Case		D-He ³ Case	
	# Flux (#/cm ² -sec)	Energy Flux (w/cm ²)	# Flux (#/cm ² -sec)	Energy Flux (w/cm ²)
<u>Neutrals Atoms</u> (420-435 KeV) (deuterium & tritium)				
Source leakage gas	9.7×10^{11}	0.063	1.4×10^{11}	0.01
Source neutral beam	1.2×10^{14}	8.1	2.7×10^{14}	19
Totals	1.2×10^{14}	8.2	2.7×10^{14}	19
<u>Photons</u>				
Bremsstrahlung (x-ray)	-	15.5	-	44.6
Synchrotron	-	11	-	18
Totals	-	26.5	-	62.6
<u>Neutrons</u>				
DT fusion (14.1 MeV)	3.9×10^{14}	870	2.4×10^{13}	53
DD fusion (2.45 MeV)	1.0×10^{14}	16	2.7×10^{14}	107
Totals	5×10^{14}	890	2.9×10^{14}	160

From a materials damage standpoint we can consider the photons as sources of thermal energy only which will probably not directly affect the first wall except as a problem in heat transfer. It is possible that this photon energy as a surface heating phenomena could alleviate radiation damage if it causes the first wall surface temperature to be sufficiently high to anneal out damage. This can be true if the wall is thin (~ .1 cm). Conversely, if the first wall were to be significantly thick, then radiation damage could

be aggravated by the substantial temperature gradient which would exist across the wall producing differential swelling. Both of these possibilities are suggested in Figure 5 where it can be seen that material volume changes (a measure of failure) go through a maximum as a function of temperature with a steep gradient on either side.⁷

It can be seen from Table 3 that the particle flux of neutrons on the first wall for a D-He³ reactor is the same order of magnitude as the neutron particle flux for the D-T case. However, the neutron energy is principally 2.45 MeV for the D-He³ (D-D source) compared to 14.1 MeV for the D-T case. Consequently, some alleviation of neutron damage to the first wall materials in a D-He³ reactor can be expected compared to a D-T reactor; but order of magnitude improvements are not likely. According to S. Blow, the rates of damage density at 14 MeV to that at 1 MeV is ~ 3.5 to 1.0.⁸ From his data one would then estimate the damage ratio for 14 MeV vs. 2.45 MeV as approximately 2.0 to 1.0. Thus there are some positive gains to be made in reducing neutron damage by using the D-He³ reaction.

Materials which are considered for the first wall, such as niobium, which are subjected to these energetic neutrons, may suffer substantial damage. The degree of this damage is highly uncertain at this time and assessing this damage and modeling the system is one of the most important, if not the most important fusion technology problem. Numerous papers are available on this subject. The principal damage mechanisms are transmutations and lattice atom displacements. In niobium, which is a prime candidate for the first wall at this time, the principal transmutation reactions produce hydrogen, helium, yttrium, and zirconium. Hydrogen diffuses readily and the amount that is formed is relatively low. Yttrium and zirconium form

FIGURE 5

Void Induced Swelling in Refractory Metals After Bombardment to Approximately 5 dpa

solid solutions with niobium at acceptable levels within the life span of the vessel. No particular problems seem to be created by these three transmutation products. However, the helium atoms can be expected to effect the physical properties severely. The migration and agglomeration of helium to form bubbles within the base metal results in swelling and possible fracture of the host material by separation of grain boundaries under stress. The lattice atom displacements caused by the neutron bombardment have been shown to result in swelling by the formation of void cavities in certain temperature ranges (Figure 5) and above certain critical fluences (Figure 6).

In mirror machines, as mentioned previously, the charged particles do not diffuse to the wall but neutral atoms whose source is the injector beam will strike the wall. It can be seen by referring back to Table 3 that the number flux of these neutrals is the same order of magnitude as the neutron flux. It can be assumed that the probability of He^3 undergoing two charge exchanges to become a neutral is infinitesimal. Therefore, the neutrals striking the wall are either deuterons or tritons. The energy of these neutrals is significant, ~ 400 KeV, and two main material damaging processes may be generated as a consequence of impact; surface sputtering and/or sub-surface penetration. The sputtering coefficient for 400 KeV deuterons on niobium is $< .004$ per incident deuteron from which it may be shown that a surface recession of ~ 30 microns per year will occur.⁹ This is approximately 3% wall loss/year and implies a wall replacement time period greater than 10 years. Sputtering from neutrals is therefore not a serious problem with the wall, although it may be with the plasma itself. The sub-surface penetration for the 400 KeV deuterons or tritons is ~ 2.5

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FIGURE 6. Swelling in AISI 304 SS

microns.¹⁰ With this particle range and the given flux level it remains to be determined if diffusion rates will be sufficiently high to remove the deuterons and tritons or whether the flux level is higher than diffusion rates can handle. If the latter is the case, then spalling will occur in the region of the 2.5 μ interface because of gas buildup.

First Wall Heat Transfer

The energy sources creating heat transfer design problems at the first wall are either the neutrons causing internal heat generation or the photons as an energy deposition effect on the surface. The energy removal is by convection heat transfer to the coolant. The coolant may be lithium or a lithium salt, or flowing helium with stationary lithium. In the case of lithium as a coolant and using an assumed wall loading of 10 MW/m^2 , convective heat transfer need not be a problem even considering the effect of B fields on laminarizing flow. The principal requirement is that first wall thicknesses be limited to values $\sim 1 \text{ mm}$ so that internal heat generation is sufficiently low. In the case where lithium salt is used as a coolant, the pressure drop problem, inherent with pumping lithium in a B field, is eliminated but the B field influence may cause the flow to be laminar in which case the system will be heat transfer limited. Further analytical and experimental work is required in this area, principally in getting good property data. Neutronically inert helium seems an adequate coolant.

Material Problems in the Blanket - Blanket Cooling/Tritium Breeding

It is likely that the chemical/materials problems within the blanket volume for mirror machines are substantially the same as those for closed

systems, such as Tokamaks, both in degree and in number for D-T reactors where tritium breeding is necessary.

The present candidates for the combined coolant and moderator in the mirror machine blanket are:¹¹

1. Lithium metal
2. Lithium salts, Li_2BeF_4 (flibe)
3. Helium with non-flowing lithium

The general considerations in blanket design allowing a choice of one of these coolants are:

1. MHD effects
2. Neutronics - tritium breeding, transmutations and gamma ray generation
3. Heat transfer
4. Chemical corrosion
5. Electrolytic corrosion
6. Tritium removal and processing
7. Structural requirements
8. Impurity effects

Lithium

With lithium as a coolant, the major problem is pumping this electrically conducting fluid in a high magnetic field region when there is a field component perpendicular to the flow. Pressure drops may be very high and depend in detail on individual flow paths. This pressure drop can be reduced significantly by development of an electrically insulating material surrounding the flow paths.

The use of lithium as a thermonuclear reactor blanket moderating fluid and coolant has some decided advantages. In the D-T reaction it is neutronically superior to the lithium salts such as lithium fluoride or lithium-beryllium fluoride because of higher tritium breeding capability. It is also an extremely good heat transfer fluid having high heat capacity, high thermal conductivity, low viscosity, and high latent heat of vaporization. At the same time lithium has two principal disadvantages. It is highly corrosive and thus can only be contained within selected materials, and as mentioned, because it is a liquid metal, there can be severe pressure drop pumping problems associated with transporting the lithium across high magnetic fields. These two problems of pumping and corrosion are coupled since a tolerable pressure drop can probably only be achieved by insulating the walls of the tube carrying the lithium with a material resistant to corrosion. This insulation would be needed in the region where there is any significant transverse B field.

Carlson and Hoffman have shown that for the flow of an electrically conducting fluid in a circular tube in a transverse magnetic field the pressure drop can be represented by an equation of the form:¹²

$$\Delta P = \frac{1.3 \eta_L \bar{u}}{a^2} \left[\frac{H^2 \tanh H}{H - \tanh H} + \frac{H^2 C}{1 + C} \right] + \Delta P_0$$

where

L = tube length, m

η_L = fluid viscosity Ns/m^2

$\bar{u}$ = fluid velocity m/sec

a = tube radius m

ΔP_0 = ordinary laminar flow pressure drop

H = Hartmann number

C = conductance ratio

These two nondimensional parameters are defined as follows:

$$\text{Conductance Ratio} \equiv C \equiv \frac{\sigma_w t_w}{\sigma_L a}$$

and

$$\text{Hartmann No.} \equiv H \equiv Ba \sqrt{\frac{\sigma_L}{\eta_L}}$$

where

σ_L = electrical conductivity of liquid mho/m

σ_w = electrical conductivity of tube wall, mho/m

t_w = tube wall thickness, m

B = magnetic field strength tesla

The parameter, C, is a measure of the ease with which magnetically induced currents can leak through the tube walls; the wall current leakage is zero when $C = 0$ and increases to a maximum as $C \rightarrow \infty$.

The Hartmann number, H, is essentially the ratio of magnetic to viscous forces in the fluid. It is a measure of the strength of magnetically induced current loops in the fluid. When $H = 0$, there is only the ordinary viscous, incompressible boundary-layer pressure; as H increases, the pressure drop increases as a function of both H and C.

For reactors that are presently considered to be representative, the values of the terms in the Hartmann number are:

$$B = 1 - 10 \text{ tesla}$$

$$a = .02 \text{ meters}$$

$$\sigma_L = 2.5 \times 10^6 \text{ mho/meters}$$

$$\eta_L = 2.2 \times 10^{-4} \frac{\text{Newton seconds}}{\text{meter}^2}$$

Therefore, values of $H = 10^3 - 10^4$ are applicable and the pressure drop equation can be simplified and rewritten as:

$$\Delta P = \frac{1.3 \ln \bar{u}}{a^2} \left[H + \frac{H^2 C}{1 + C} \right] + \Delta P_0$$

The preceding equation can be rewritten in nondimensional form as:

$$P_H = H + \frac{H^2 C}{1 + C} + P_0$$

The influence of C , the conductance ratio between the wall and the fluid, can be clearly seen in this modified form of the equation. (The P_0 term is quite small.) This Hartmann pressure drop is plotted in Figure 7 for different values of C over a range of Hartmann numbers.

For materials that are likely candidates for blanket structure the metal conductance is approximately equal to the fluid conductance so that $C = t_w/a$. Based on satisfying structural requirements for tube wall thickness versus radius the value of C is likely to be ~ 0.1 for an uninsulated tube. Clearly evident from Figure 7 is that for conductance ratios of ~ 0.1 the flow perpendicular to the B field will suffer a severe pressure drop penalty since the Hartmann number $H = 10^3 - 10^4$ for $B = 1 - 10$ tesla. If the flow of lithium can conform to the field lines so that the B_z component is small the problem is less critical. For instance, if the flow were 5 degrees off of conformity the pressure drop would decrease about 2 orders of magnitude compared to fully perpendicular flow.

The other possibility for decreasing pressure drop is to provide the tube wall with an insulating or semiconducting coating so that the value of C is decreased.

Fig. 7 Hartmann Pressure Drop for Circular Pipe (Eq. 7)

The relative values of resistivity that will assist in material selection for this coating are as follows:

Good Conductor (cu)	- 10^{-6} ohm - cm
Good Insulator	- 10^{12} ohm - cm
Semiconductor	- 10^{-3} - 10^6 ohm - cm
Lithium	40×10^{-6} ohm - cm

From this list it can be seen that the value of C will become very close to zero by the use of materials for a tube coating that have the resistivity of a semiconductor. Thus the required coating need only be a relative nonconductor compared to lithium to be effective. The gains to be realized in reducing C from .1 to close to zero are at least two orders of magnitude reduction in pressure drop at Hartmann numbers > 1000.

The general considerations for selecting the material for the non-conducting wall are:¹³

1. Compatibility with lithium
2. Effect of irradiation
3. Compatibility with substrate
4. Economics
5. Electrical resistivity

The potential materials using the preceding criteria are:

1. $\text{Sn}_2 \text{O}_3$
2. Th O_2
3. Ti C
4. Zr C
5. $\text{Y}_2 \text{O}_3$
6. $\text{Th O}_2 - \text{Y}_2 \text{O}_3$

There may be other materials that were not evident in the preliminary survey. Of these potential materials, Y_2O_3 appears to offer the most promise from a compatibility with lithium standpoint which seems to be the greatest difficulty. Available data are limited, however, and an analytical/experimental program is in order.

A final comment on lithium is that additional data are needed on the equilibrium and characteristics of the lithium-tritium system at low tritium partial pressures. This can influence significantly the holdup and doubling time of tritium in the system.

Lithium Salts, Li_2BeF_4 (flibe) Coolants

Neutronically, tritium breeding is poorer in the lithium salts and gamma ray production is higher than for lithium but the use of the salt provides a means of avoiding the MHD pumping problem since the electrical resistivity is several orders of magnitude higher.

The compatibility of the lithium salt with vanadium is unknown and with niobium the presence of a range of fluorides through, for example NbF to NbF_5 , may produce mass transfer problems. Transmutation reactions of Li (n, α) and Be ($n, 2n$) will release fluorine and hydrofluoric acid. Fluorine has an n, α cross section < 14 MeV and this will produce nitrogen which decays to oxygen with a short half-life. The transmutation reactions are:

Tritium fluoride (like HF) may be highly corrosive to the material in which it is contained. For instance:

In addition to these three transmutation reactions and the problems they may cause, there is a further possible problem with MHD induced electrolytic corrosion when using lithium salts. That is, a potential difference across the lithium salt is created ($E = v \times B$) which may cause a mass transfer problem; that is electrolysis if the potential is large enough.

Blanket Cooling with Helium Containing Lithium Vapor

Because of MHD effects with liquid metals flowing in B fields and other problems associated with the lithium salts, there is an increasing interest in using helium as a primary blanket coolant removing energy from non-flowing lithium instead of using lithium as a combined flowing coolant and moderator.¹⁴

Implicit in the use of helium for this application is that it is chemically inert and will not therefore prove detrimental to the blanket structural materials. That this is not so in cases where niobium alloys or vanadium is used as structural material can be demonstrated by a rather simple illustration. It has been observed that vacuum systems containing Nb 1% Zr must be maintained at pressures less than 1×10^{-6} torr to avoid serious deterioration of the mechanical properties of the niobium when it is operated at typical blanket temperatures (~ 1000 K) for time periods as short as

months.¹⁵ The degradation of the niobium is due to the formation of a solid solution of oxygen in the niobium causing embrittlement. The total residual vacuum pressure of 10^{-6} torr is a measure of the steady state level of all the contaminants in the system and oxygen is a strong contributor. For our purposes in blanket design, lifetimes of years instead of months are necessary and so quite evidently the 10^{-6} torr system pressure would be too high a contaminant level. Let us assume however that it is acceptable and determine what it implies in terms of helium purity requirements if an overpressure of helium were used instead of the vacuum. The following is Jack DeVan's (of ORNL) "Vacuum Analog" which illustrates the severity of the problem.¹⁶

If

$$p = \text{contaminant pressure} = 1 \times 10^{-6} \text{ torr}$$

and

$$P = \text{helium pressure} = 300 \text{ psi (TYP.)} = 1.5 \times 10^4 \text{ torr}$$

then the ratio of contaminant to helium is:

$$\frac{p}{P} = \frac{\frac{n_c RT}{m_{\text{He}} RT}}{1.5 \times 10^{10} \text{ helium atoms}} = \frac{1 \text{ contaminant atom}}{1.5 \times 10^{10} \text{ helium atoms}}$$

Or a purity level requirement for the helium equivalent to the 10^{-6} torr must be $\sim 1.0 \times 10^{-5}$ ppm. Not only can this not be achieved in any practical way, it cannot be measured! System leaks, helium makeup, etc. would surely provide many orders of magnitude more contaminant than would be acceptable. Thus we are faced with the problem of either providing an impermeable interface between the niobium and the helium or providing a getter that will preferentially and strongly react with the oxygen contaminant before it embrittles the niobium. I would like to offer the latter as a possible solution, and

specifically propose that lithium vapor be used as the gettering material.

Consider a representative coolant tube of perhaps 2 centimeters in diameter. Per unit length the surface area of the tube is $2\pi \text{ cm}^2$. The volume of the tube is $\pi \text{ cm}^3$, and the area to volume ratio = $2 \text{ cm}^2/\text{cm}^3$.

The lithium vapor pressure @ 1000 K = $5. \times 10^{-3}$ bars, and the number of atoms of lithium per unit volume is

$$n_{\text{Li}} = \frac{6. \times 10^{23} \times 5. \times 10^{-3}}{2.24 \times 10^4} \frac{400}{1000} = 0.5 \times 10^{17} \frac{\text{atoms}}{\text{cm}^3}$$

If we assume that the kinetics of the reaction causing the niobium embrittlement by the oxygen to be generated at the niobium surface, then we can assume a monolayer of niobium to calculate the number of atoms available to react with the oxygen. The atomic radius of niobium is $\sim 1.46 \text{ \AA}$, so its diameter is approximately $3 \text{ \AA}$. The number of atoms per unit area is $n = 1 \times 10^{15} \text{ atoms/cm}^2$. The ratio of lithium atoms to niobium atoms is:

$$\frac{1.34 \times 10^{17}}{2 \times 10^{15}} = \frac{100}{1}$$

Three reactions and their free energies can be written that seem applicable to the niobium, oxygen and lithium system:

Additionally, a solid solution (interstitial) of oxygen in the niobium will exist at low mole fractions of oxygen. The energies involved in the production of the solid solution are not known.

The number of O_2 in the system is proportional to the helium pressure. We will assume an equilibrium O_2 population in the helium of 1 ppm. Then:

$$n_{O_2} = \frac{20 \text{ atm} \times 6. \times 10^{23} \times 1 \times 10^{-6}}{2.24 \times 10^4}$$

$$= 6 \times 10^{13} \text{ } O_2/\text{cm}^3$$

The population distribution for the four constituents of interest is approximately:

O_2	Li	Nb	He
1	1×10^5	1×10^3	1×10^{11}

It is known that niobium is deoxidized (reaction 2) by exposure to lithium at 600°C or above in cases where lithium is in the liquid state and in physical contact with the niobium. It must be determined if the reaction kinetics remain the same when lithium is replaced by lithium vapor. The efficiency of the lithium vapor compared to the liquid as a getter must be proportional to the ratio of the respective pressures. Therefore, the vapor effectiveness must be roughly three orders of magnitude less than the liquid. Whether this is sufficient is not known by the author and perhaps can only be determined by experiment. The free energies involved and the population distribution both favor the gettering reaction.

Effects of Helium and Hydrogen on Collector Elements

As mentioned previously, the ions, whose energy is to be directly converted to electricity energy, emerge from the expander with a considerable spread in energy. To recover this energy at high efficiency, the ions enter a collector region where decelerating fields extract their kinetic energy and guide them to collect electrodes at high DC potential. These ions are made up of not only reaction products but also of unreacted fuel ions. Thus collectors have impinging on their surfaces hydrogen and helium ions and their isotopes.

To properly design the collectors of a direct converter, it is necessary to understand the rate controlling and equilibrium processes that will govern the hold up and release of hydrogen and helium. It is expected that these processes are materially different for the two species. It must be determined if the processes for the two ion species, hydrogen and helium, can be mathematically decoupled and separate analytical expressions derived for each.

The probable level of ion fluxes (type and energy) impinging on the collector elements of a direct converter for a conceptual 1000 MW_e reaction using D-T or D-He³ is shown in Table 4.

Helium Isotopes

The helium hold up and damage question appears to be a big problem both in our ability to analyze the problem and the probable results.

Since helium is insoluble, gas bubbles will build up internally until the resultant pressure physically ruptures the material causing layers to spall off. Experiments have been run in which spallation of micron thick material was observed at helium (300 KeV) doses of $\sim 10^{18}$ ions/cm². Since

TABLE 4

ION FLUXES EXPECTED IN DIRECT CONVERTERS

FOR D-T AND D-He³ REACTORS

Element (temp °C)	Area (cm ²)	Flux (ions/sec-cm ²)					Ion Energy Range (KeV)	Ave Thermal Flux (w/cm ²)
		ϕ_H	ϕ_D	ϕ_T	ϕ_{He^3}	ϕ_{He^4}		
Collector Surfaces (~ 700° C)	7.2×10^8	1.7×10^{11}	1.2×10^{13}	For D-T Reactor		6.7×10^{11}	10 - 100 ($E_{ave} \sim 50$)	0.2
				1.2×10^{13}	1.7×10^{11}			
Collector Surfaces (~ 700° C)	1.1×10^9	1.1×10^{12}	6×10^{13}	For D-He ³ Reactor		5.5×10^8	10 - 100 ($E_{ave} \sim 60$)	0.9
				5.5×10^8	6.7×10^{12}			

Conceptual reactor models described in Madison paper, UCRL #72883.

our total helium fluxes are $\sim 1. \times 10^{12}$ ions/cm²-sec damage time may be as short as 10^6 seconds or - 300 hours.

Hydrogen Isotopes

Unlike helium, hydrogen is soluble in most metals and at temperatures of interest for collector elements it will readily diffuse. And since diffusion is driven by a concentration gradient the upper limit to hydrogen transport by diffusion is determined by the hydrogen ion's range and the maximum concentration permitted by the hydrogen solubility limit. If the hydrogen flux is above this transport limit, the hydrogen could form bubbles and act much like helium does. Unfortunately the presence of helium in the metal complicates the hydrogen transport question. Helium in the lattice might reduce the diffusion coefficient and helium bubbles might reduce the area and increase path length for diffusion.

The spalling or physical damage of the collector element surfaces has two important side effects: (1) the spalled material can hold up substantial amounts of tritium which must be recycled, (2) the spall may cause severe arcing of the collector elements.

In an attempt to circumvent the physical damage, holdup and electrical problems, it has been suggested that the surfaces could be coated with a low vapor pressure liquid metal such as gallium or tin which should allow the helium and hydrogen to escape without damaging the surface. This may be an acceptable solution but the problems of liquid metal wetting, vaporization, and sputtering must be evaluated. Clearly, substantial research is required in this area.

Summary

We have touched on probably what is only a small fraction of the potential problems in fusion reactors that might be classed as being metallurgical/chemical in nature. Furthermore, we looked at only three reactor elements, the first wall, the blanket and the direct converter collectors. Yet those potential problems that were mentioned are almost certainly representative of the total kinds one would expect to encounter and it is doubtful if any new problems will be subsequently disclosed that are either of a higher level of difficulty or of a different, new class. Certainly, radiation effects on the first wall, sputtering, spalling, swelling, etc. seem to be the most severe of the problems, both in our analytical ability to assess the problem and in our experimental ability to simulate the environmental condition short of building a fusion reactor. It is also evident that the choice of a coolant for the blanket is not clear cut. Of the candidate materials mentioned, each has its particular limitations - MHD effects with lithium, transmutation and possible electrolysis effects with the lithium salts, and oxygen embrittlement problems with helium. Fortunately these problems are tractable and can be resolved by well planned analytical-experimental programs. In the direct converter section the energetic ions falling on the collectors surfaces may cause spalling and/or sputtering. There are side effects to both of these phenomena that are not strictly metallurgical in nature but may require a metallurgical solution. One of these problems is that individual collectors are at very high potentials, as high as a million volts, and are highly sensitive to electrical discharge. The sputtering or spalling could very easily trigger this discharge and therefore surfaces must be

designed that either eliminate the problem or bring it within control. Another indirect problem with spalling of collector surfaces is that the spalled platelet will probably contain substantial amounts of tritium that must be recovered. On spalling, the temperature of the platelet will decrease so that diffusion will be of no practical help in this case. Thus, if spalling is allowed to occur and does not have other adverse effects, it will still be necessary to periodically recover the spalled material for processing. Experiments are planned in this area. Since ion impingement is not limited to collectors but can also be expected to occur in closed systems on first walls or divertor surfaces, the problem is of general interest and importance.

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