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✓ **FINAL REPORT**

**APPLICATION OF FUSION
PLASMA TECHNOLOGY**

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June 1976

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ABSTRACT

This report presents principal findings of studies conducted at Iowa State on Applications of Fusion Plasma Technology. Two tasks were considered. The first was to identify and investigate plasma processes for near term industrial applications of already developed plasma technology. The second was to explore the potential of reprocessing the fuel for fusion test facilities in a closed-cycle system.

For the first task, two applications were considered. One was alumina reduction in magnetically confined plasmas, and the other was uranium enrichment using plasma centrifuges.

For the second task, in-core and ex-core plasma purification were considered. Separation techniques that are compatible with the plasma state were identified and preliminary analysis of their effectiveness were carried out. The effects of differential ionization of impurities on the separation effectiveness are considered.

Possible technical difficulties in both tasks are identified and recommendations for future work are given.

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1. INTRODUCTION

This is a final report describing fusion research carried by Iowa State University for the Energy Research and Development Administration on "Applications of Fusion Plasma Technology" under Contract No. AT(11-1) - 2457 during the period April 1, 1974 to June 30, 1975.

The general purpose of this research was two-fold:

- (1) to investigate and identify plasma processes for near term industrial applications, and
- (2) to explore the potential of reprocessing the fuel for fusion test facilities in a closed-cycle system.

In section 2, the scope of the investigations is described.

Significant results obtained relevant to the tasks are discussed in section 3.

The studies have uncovered areas where more intensive research need to be carried. These areas are outlined in section 4.

Appendix A and B include papers published in national and international conferences and technical journals.

2. SCOPE OF INVESTIGATIONS

The general scope of investigations undertaken is the study of the chemical characteristics of high temperature plasma processes. Two major tasks have been considered thus far, namely:

TASK 1 Investigation of Plasma Processes for Near Future Industrial

Applications:

In this task emphasis is placed on applications in which present fusion technology can be used. The technology developed to date in the fusion program is to be applied to solve current industrial problems and to improve upon present industrial practices in areas of national priority. Special attention is given to industrial processes such as alumina reduction which are currently carried out in a manner accompanied by high energy consumption and intolerable waste production. The utilization of electromagnetically confined plasmas in the reduction of alumina is first considered. Results of this specific investigation can be generalized to similar processes.

TASK 2 Fuel Processing for Fusion Test Facilities in a Closed-Cycle

System:

Here, emphasis is given to the design of a closed-cycle fusion test facility. Thus, we investigate the reprocessing of the D-T plasma effluent in its plasma state from a fusion test facility. The intention is to obtain a recycle fuel stream containing an acceptable concentration of helium ash and impurities and a waste stream with minimal unburnt fuel concentration. If the reprocessing of fuel in its plasma state is proven to be compatible with the fusion power device, great improvements

in the overall energy balance of the facility can be achieved. This scheme would also limit the difficulties encountered in reaching ignition conditions to the first start-up phase only.

3. SIGNIFICANT RESULTS OBTAINED

TASK 1 Investigation of Plasma Processes for Near Future Industrial

Applications:

3.1. Reduction of Alumina by Electromagnetically Confined Plasmas

Processing of alumina by thermal plasma torches has faced several difficulties. One of the methods which has been experimentally investigated is to feed finely ground particles of alumina into a thermal plasma flame and, thus, vaporization, dissociation and ionization take place. Recombination of oxygen and aluminum is prevented by means of a fast quench in water. The low yield of aluminum in this process is attributed to several causes including the presence of vaporization and condensation barriers, poor mixing, need for heat exchange agent, and partial quenching at the boundaries of the hot plasma core.

Operating the plasma torch at temperatures and densities which are typical of thermonuclear plasmas is shown to provide the means to overcome the difficulties encountered in the use of thermal torches. The high specific enthalpies, electromagnetic containment and the presence of hydrogen isotopes as heat exchange agents would provide a great improvement in efficiency and production rates.

The use of rotating plasma devices for reduction of alumina is considered. High concentrations of aluminum at the plasma boundaries result from the centrifugal electromagnetic forces. Collection of the element can be achieved without the need for quenching stages. Separation factors in a single stage process exceed those achieved in other multi-stage processes. Thus, high production rates together with high product

purity are possible.

Energy consumption and environmental effects are compared with present industrial processes. Separation effects are obtained for different operating conditions and for several ionization states.⁽¹⁾

3.2. Uranium Enrichment Using Plasma Centrifuges

A viable separation technique for nuclear fuel processing and uranium enrichment akin to the widely noted gas centrifuge process is analyzed. The technique is based on transforming the feed material to plasmas and putting the plasma into rotation by means of a crossed electric and magnetic fields. Rotating plasma devices have been realized for other purposes⁽⁵⁾ and a variety of such devices are under operation on a laboratory scale. Mechanical limitations of moving parts do not exist and thus centrifugal accelerations unattainable in conventional centrifuges can be achieved. In contrast to earlier electromagnetic separation techniques, separation by plasmas does not involve problems of space charge forces, spread of velocity distribution, and neutralization. Reported collection rates in laboratory rotating plasmas are as high as 100 Amperes using a probe with a surface area of 1 cm^2 ⁽⁶⁾. High degrees of ionization are not required since ionized particles would exert a volume centrifugal force on the neutral particles putting them in rotation⁽⁷⁾ and consequently low energy expenditure can be assured.

Two types of rotation plasma devices are considered: an isorotational device in which the angular velocity of rotation, Ω , is space-independent and a device for which the ratio between the energy put into the rotation of a unit mass and the thermal energy per particle, θ ,

is constant. Separation factors are calculated for both situations. For isorotational plasma, Fig. 1 shows the simple process factor, α , as a function of the ratio of the outer to the inner radii, ξ . The parameter α gives the ratio of ^{235}U concentration to that of ^{238}U at a given radius. The ratio θ is evaluated at the inner radius of the plasma shell and hence the subscript o is used. The result is evaluated for different values of the ratio between the collection and separation rates, ψ . For the second type of rotating plasma devices, the values of α are less than isorotational devices.⁽⁸⁾

The separation factor is significant compared to present enrichment processes. In fact, very few stages can be used with such large separation effects. The simple process factor can also be improved if differential ionization of uranium isotopes is made possible.⁽⁹⁾

Fig. 1. Simple Process Factor for Separation of Impurities and Ash from Effluent of D-T Fusion System, $\epsilon_p = \epsilon_{p1} = 1$.

TASK 2 Fuel Processing for Fusion Test Facilities in a Closed-Cycle System:

In this task the investigations were directed towards finding means for in-core purification by enhancing certain diffusion mechanisms such that the plasma core may become self-purifying. Ex-core fuel purification was considered and a separation technique that is compatible with the plasma state was considered first. Rotating plasma devices which are capable of separating impurities in the plasma state are evaluated. The results indicate that this is an area that needs special research effort. The separation factors obtained for this technique are very high and the prospect of having a closed-cycle fusion device, rather than a big discharge, is a topic that needs further consideration.

3.3. Diffusion Processes in Plasmas and Their Use for Isotope Separation and Impurities Exclusion

3.3.1. Self-Purification of Thermonuclear Plasmas⁽¹⁰⁾

Spatial distribution of the density of impurities in a plasma device differs from the distribution of plasma constituents due to diffusion processes that depend on mass, charge or both. A favorable situation is one in which the concentration of impurities at the outer region of the plasma core is higher than their concentration in the center portion of the core. Conditions are sought for the realization of this type of self-purifying plasma. In rotating plasma devices the centrifugal forces tend to exclude impurities from the interior of the hydrogen plasma core. In tokamak devices, the separation effects are sensitive to the plasma density and temperature profiles. Four of the currently used profiles

are examined. High abundance of impurities is found to exist at the center of the plasma for all of the four models.⁽¹⁰⁾

3.3.2. Separation of Impurities by Plasma Rotation

The degree of separation of impurities has been evaluated in terms of the parameter α which is defined as the ratio of the abundance of impurities at some radius r in the plasma shell and the abundance of the impurities at the inner radius r_i of the plasma shell. Here, the abundance R refers to the ratio between the density of impurities and the density of the fusion fuel plasma. In general, the parameter α is used to describe the separation effects in a single stage process, and hence the parameter is referred to as the simple process factor. The reference line, which is selected here as the inner radius r_i , is usually taken as the line where the concentration of the species of interest is minimum. Consequently, $\alpha \geq 1$. In the presence of one singly ionized species of impurities, α is a function of the two parameters ξ and Θ , where $\xi = r/r_i$ and Θ is a characteristic parameter of the rotating plasma which is defined as the ratio between the energy stored in the mass rotation of a given species and the energy stored in the thermal motion of that species. For hydrogen plasmas Θ is given by

$$\Theta_p = \frac{\frac{1}{2} m_p \Omega^2 r^2}{\frac{3}{2} kT} \quad (1)$$

where subscript p refers to protons, m_p is the protonic mass, Ω is the angular velocity of rotation, k is the Boltzmann constant, and T is the kinetic temperature of the plasma ions. A value of $\Theta_p = 2$ is reported for

homopolar type experiments⁽¹¹⁾, and a value of $\Theta_p = 1$ is obtained from the Wisconsin rotating plasma source experiment.⁽¹²⁾

In our studies we have assumed that T is spatially independent, and we have considered five species of impurities, namely, C, O, Nb, Mo, and W. Values of α for other impurities can also be obtained or interpolated from the results given here. We have also considered the separation of the ^4He -ash from the plasma. Thus, the results cover a wide range of atomic masses. Figure 1 shows the calculated values of α versus ξ for $\Theta_p = 1$ and for rotating plasma devices in which the azimuthal velocity is constant; that is, $\Omega r = \Omega_i r_i$, where Ω_i is the value of Ω at r_i . The results corresponding to $\Theta_p = 2$ are shown in Fig. 2 for the same elements and for similar types of devices. We have also studied the separation of impurities by isorotational plasma centrifuges. These are devices characterized by a constant Ω , that is, $\Omega = \Omega_i$. The results are given in Figs. 3 and 4 for $\Theta_{pi} = 1$ and $\Theta_{pi} = 2$, respectively, where values of Θ_{pi} are evaluated at the inner radius of the plasma shell.

The separation effects are extremely high in the situations considered above. By extracting the impurities at the outer radius of the plasma shell, the level of these impurities will be greatly reduced. The fuel can be extracted at the inner region of the plasma shell with minimum concentration of impurities and ash. Luckily enough, the simple process factor α is the highest for heavy ions, and consequently, the concentration of these ions in the recycle fuel stream will be almost zero. Addition of a second stage would increase the degree of purity of the recycle stream.

Fig. 2. Simple Process Factor for Separation of Impurities and Ash from Effluent of D-T Fusion System, $\Theta_p = \Theta_{p1} = 2$.

Fig. 3. Simple Process Factor for Separation of Impurities and Ash from Effluent of D-T Fusion Systems by Isorotational Plasma Centrifuges, $\Theta_{pi} = 1$.

Fig. 4. Simple Process Factor for Separation of Impurities and Ash from Effluent of D-T Fusion Systems by Isorotational Plasma Centrifuges, $\Theta_{pi} = 2$.

Since a large value of Θ results in larger values of α , we have studied the possibility that $\Theta_{(D-T)i}$ at r_i for a D-T plasma is unity. Lower values of α are obtained in this case. The results are shown in Fig. 5 for $\Omega r = \Omega_i r_i$ and in Fig. 6 for isorotational plasma centrifuges. However, the separation factors are still very high even under this conservative assumption. A comparison between devices characterized by $\Omega r = \Omega_i r_i$ and isorotational plasmas and between the cases when $\Theta_{pi} = 1$ and $\Theta_{(D-T)i} = 1$ is shown in Fig. 7 for He and in Fig. 8 for Mo.

3.3.3. Dependence of Separation Effects on Machine Type

The simple process factor is sensitive to changes in the value of Θ_i as shown in Figs. 1 through 4 for the processing of the fusion experiment effluent. The value of the parameter Θ and its dependence on the atomic number of the plasma constituents is greatly affected by the type of rotating plasma machine. The presence of insulators as in the isorotational devices results in limitations on the dependence of Θ on the atomic number and may result in separation effects less than those predicted by the theory. Values of Θ in the range between 1 and 7 have been obtained for several elements by using an approximate heat balance between the ion-ion viscous energy dissipation and the heat conduction by electrons for a plasma slab.^(13,14) The dependence of α on the value of Θ_i is shown in Fig. 9 for a constant velocity rotating plasma and in Fig. 10 for isorotational systems at $\xi = 2$ for fusion reactor impurities, ash, and alumina. The variation of α as a function of Θ is more rapid in isorotational plasmas than in the case of plasma centrifuges with constant velocity. The difference in the dependence

Fig. 5. Simple Process Factor for Separation of Impurities and Ash from Effluent of D-T Fusion Systems, $\epsilon_{(D-T)} = \epsilon_{(D-T)1} = 1$.

Fig. 6. Simple Process Factor for Separation of Impurities and Ash from Effluent of D-T Fusion System, $\Omega = \Omega_i$, $\epsilon_{(D-T)i} = 1$.

Fig. 7. Comparison of Simple Process Factors for Separation of He from D-T Plasma; (I) $\epsilon_p = \epsilon_{pi} = 1$, (II) $\epsilon_{pi} = 1$, $\Omega = \Omega_i$, (III) $\epsilon_{(D-T)} = \epsilon_{(D-T)i} = 1$, and (IV) $\epsilon_{(D-T)i} = 1$, $\Omega = \Omega_i$.

Fig. 8. Comparison of Simple Process Factors for Separation of Mo from D-T Plasma: (I) $\epsilon_p = \epsilon_{pi} = 1$, (II) $\epsilon_{pi} = 1$, $\Omega = \Omega_i$, (III) $\epsilon_{(D-T)} = \epsilon_{(D-T)i} = 1$, and (IV) $\epsilon_{(D-T)i} = 1$, $\Omega = \Omega_i$.

Fig. 14. The Simple Process Factor vs. Θ For $\xi = 2$ and $\Omega_r = \Omega_{r1}$.

Fig. 15. The Simple Process Factor vs. ξ in Isoretational Systems for $\xi = 2$.

of α on Θ in both systems is displayed in Fig. 11 for He, in Fig. 12 for Mo, and in Fig. 13 for alumina at $\xi = 2$. These results, together with Figs. 7, 8, and 13, show that the separation degree depends on whether the plasma separator is isorotational or not. In general, theoretical prediction and experimental evaluation of Θ for a given rotating plasma device and for specific elements is essential for determining accurate values of the simple process factor, separation power, and energy consumption in impurity extraction and in separation processes by plasma centrifuges.

3.4. Effects of Differential Ionization on Separation

In the above analysis of separation of impurities from the recycle stream of a D-T fusion system, the impurities and the ash are assumed to be singly ionized. This situation would be favorable from the point of view of energy consumption in the separation process. Nevertheless, we have examined the case when impurities or He-ash are ionized to higher levels. The separation effects are examined when He is doubly ionized, that is, the He charge number $Z_{\text{He}} = 2$. Assuming that $\Theta_{(\text{D-T})i} = 2$, the simple process factor is plotted against ξ for $Z_{\text{He}} = 1$ and 2, for $\Omega r = \Omega_i r_i$ devices in Fig. 14 and for isorotational devices in Fig. 15. The decrease in the value of α at the outer radius of the plasma shell is rather significant, especially in the case of isorotational plasma centrifuges. In the case of heavy impurities, the effect on the separation factor of the increase in the ionization level is extremely important since the abundance of the impurities at the outer boundary of the plasma shell may become less than the abundance at the inner

Fig. 16. Simple Process Factor vs. $\Theta_{(D-T)i}$ for He Separation from D-T Fusion System, $\xi = 2$.

Fig. 17. Simple Process Factor vs. $(D-T)_i$ for Mo Separation from D-T Plasma, $\xi = 2$.

Fig. 18. Simple Process Factor vs. θ_{O_i} for $\xi = 2$ in the Case of Alumina Reduction.

Fig. 19. α vs. ξ for He in D-T Plasma of $\Omega r = \Omega_i r_i$, $\Theta_{(D-T)i} = 2$.

Fig. 20. α vs. ξ for He Separation of D-T Isorotational Plasma with $\Theta_{(D-T)i} = 2$.

boundary; that is, the impurities peak shifts from one side to the other. This is in addition to the decrease in the magnitude of α . Thus, it is important to control the level of ionization of the impurities in order to assure high simple process factors and to be able to predict the location of the high impurities concentration in the plasma shell.

The effect of differential ionization of the alumina constituents on separation is also investigated. The results are reported in a paper to be published in Plasma Physics. The paper is included as Appendix A.

4. RECOMMENDATIONS FOR FUTURE WORK

The two tasks considered in this research project need to be separated and evaluated individually. The studies carried have answered some questions, but have also generated several other questions that need to be considered before any conclusions can be reached about either tasks. The following are some areas that need more in-depth considerations.

Task 1: Investigation of Plasma Processes for Near Future Industrial Applications

The two applications that have special promise are

1. Alumina Reduction
2. Isotope Separation in Plasma Centrifuges

both applications do not require plasma parameters that exceed the present state of the plasma technology. The analysis of the element separation in the plasma state⁽¹⁾ show that differential ionization of the two elements can either enhance or reduce separation. The degree of ionization depends on the plasma temperature which in turn affect plasma energy losses by bremsstrahlung radiation. The optimum conditions for alumina reduction need to be evaluated based on energy expenditure and aluminum yield. Possible technical difficulties in the design and operation of the plasma centrifuges for the above applications need to be evaluated with special emphasis on extraction of the separated element.

Task 2: Fuel Processing for Fusion Test Facilities in Closed Cycle System

The studies conducted up to now concentrated on in-core and ex-core impurity reduction.

The in-core purification is done by enhancing certain diffusion mechanisms and modifying temperatures and density profiles to exclude impurities from the center of the core. Means of achieving these modifications need to be studied and their impact on the system design need to be explored.

The ex-core plasma purification was evaluated based on using plasma rotation in a centrifuge. Figures 16 and 17 show a schematic of the proposed system. Similar systems were used for plasma propulsion.⁽¹⁵⁾ Separation factors in the centrifuge are very promising and make it worthwhile considering the systems further. However, no final conclusions could be reached without considering the following questions:

How much reduction in exhaust temperature is allowed to make the system compatible with the rotating plasma separator and at the same time attractive from overall energy saving considerations? The temperature of the plasma core exhaust may be reduced by mixing it with fresh fuel, thus preheating the fuel. However, the effect of the connection region on the plasma stability in the reactor core need to be evaluated. There is a question on whether to connect the plasma purification system before or after the divertor and what is the impact of this connection on the overall reactor design? The feasibility of separating the impurities at high plasma temperature need to be evaluated and different separation techniques need to be considered and compared.

Fig. 16. Fuel Reprocessing System for Toroidal Fusion Reactors.

Fig. 17. Fuel Reprocessing System for Open-ended Fusion Reactor.

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APPENDIX A

Technical Papers Published Reporting Work Supported

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SELF-PURIFICATION OF THERMONUCLEAR PLASMAS

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ABSTRACT

Spatial distribution of the density of impurities in a plasma device differs from the distribution of plasma constituents due to diffusion processes that depend on mass, charge or both. A favorable situation is one in which the concentration of impurities at the outer region of the plasma core is higher than their concentration in the center portion of the core. Conditions are sought for the realization of this type of self-purifying plasma. In rotating plasma devices the centrifugal forces tend to exclude impurities from the interior of the hydrogen plasma core. In tokamak devices, the separation effects are sensitive to the plasma density and temperature profiles. Four of the currently used profiles are examined. High abundance of impurities is found to exist at the center of the plasma for all of the four models.

Reduction of impurities in hydrogenic thermonuclear plasma can be achieved to a limited extent by divertors,¹ effusers,² porous barriers,³ or neutral gas blankets⁴ and by adequate design and manufacturing of the first walls and the vacuum system. These methods do not provide for a perfectly-pure plasma and consequently massive high-Z particles are likely to exist in the plasma interaction zone with a finite concentration. This is in addition to the impurities which may be wittingly introduced into the plasma for control purposes. As pointed out in an earlier paper, the high-Z impurities can be excluded from the reaction volume in a fusion reactor by selective enhancement of one of the various diffusion processes in plasmas.⁵ By such enhancement, effective separation can take place under fusion conditions leading to self-purification of the plasma. This is favorable provided the separation does not upset the confinement or cause undesirable changes in the operation parameters.

In this work, we explore the possibility of separating impurities in plasmas. The main emphasis here is devoted to tokamak devices; however, a discussion of self-purification in rotating plasma machines is included. Evaluation of the spatial distribution of impurities relative to that of the plasma particles is essential in determining the radiation losses. It is also important in the evaluation of the control capabilities in the case of injecting high-Z control particles into the plasma.

For the purpose of this analysis we assume that the plasma confinement is cylindrically symmetric and that the plasma is quasineutral. Also we assume that there is no plasma bulk motion; that is, no extraction or injection and hence the separation factors correspond to static equilibrium conditions. Convective plasma motion can be taken into account; however, the separation factors in this situation are usually determined in terms of the equilibrium factors. Furthermore, the axial gradients of the concentration and the kinetic tempera-

ture of any species, ν , is considered much smaller than the corresponding radial gradients. Thus, the separation equation of the ν -th species in a multi-component plasma is given by⁶

$$n \frac{\partial N_\nu}{\partial t} = - \frac{1}{r} \frac{\partial}{\partial r} \sum_Y \sum_\mu \left\{ (\delta_{\nu Y} - N_Y) \frac{n^2 N_{\nu\mu}}{\rho N_Y} \right. \\ \times [D_{Y\mu r}] r \left[\frac{\partial N_\mu}{\partial r} + (N_\mu - T_\mu) \frac{\partial \ln p}{\partial r} \right. \\ \left. \left. - \rho_Y \omega_\mu \frac{\Omega r}{p} \right] - \frac{n N_\nu}{\rho T_Y} \left[D_{Yr}^T \right] r \frac{\partial \ln T}{\partial r} \right\} \quad (1)$$

where n , T , T , and p are the plasma number density, mass density, kinetic temperature, and kinetic pressure, respectively; m_ν , T_ν , and N_ν are the mass, mass concentration, and number concentration, respectively, of species, ν ; $\delta_{\nu Y}$ is the Kronecker delta; $D_{Y\mu r}$ and D_{Yr}^T are the radial diffusion and thermal diffusion coefficients, respectively; ω_μ is the cyclotron frequency of species, μ ; and Ω is the angular speed of the plasma in presence of centrifugal motion. To determine the separation effects, Eq. (1) is used to give the separation equations for each of the plasma components. Simultaneous solution of these equations gives the spatial distribution of the concentration of the species of interest relative to that of the other components. This is usually expressed in terms of a separation process factor, α , which is defined as the ratio between the abundance of the species of interest at some point and that at a reference point. The choice of the reference point depends on the geometry of the system.

Let us first consider the case of a rotating plasma in the form of a concentric plasma shell. For simplicity we may assume that the plasma consists of deuterons, tritons, and one singly-ionized species of impurities. The dependence of separation on the degree of ionization is treated elsewhere.⁷ The separation process factor, in this case, is defined as the ratio, N_I/N_t , where the subscripts I and t are used to refer to the impurities species and triton, respectively. Solving Eq. (1) for the concentration of the impurities, α , is obtained as a function of the dimensionless parameters ξ and θ . Here, $\xi = r/r_1$, where r_1 is the inner radius of the plasma shell. The parameter, θ , is the ratio between the energy stored into the rotation of a proton at an angular speed, Ω , and the kinetic energy of the proton. For the purpose of the present analysis the value of θ at the inner radius of the plasma shell is taken as 2. Also, a flat temperature profile is assumed.

For rotating plasmas, the dominant term in Eq. (1) is that arising from the presence of the centrifugal force; namely, the term proportional to Ωr . This force enhances diffusion processes which result in separation that leads to the exclusion of impurities from hydrogenic plasma cores.⁸ This type of self-purifying plasma can be realized by adequate selection of the design parameters of the machine.⁶ Figure 1 shows the behavior of the separation factor, α , as a function of ξ for aluminum and iron impurities in the case of isorotational plasma devices for which Ω is spatially-independent. The graph shows that impurities tend to concentrate at the peripheries of the plasma shell. Collection of such impurities at the outer boundaries could minimize the density of the impurities in the plasma interaction zone. Separation of the iron exceeds that of the lighter aluminum impurities. Thus, one expects that wall-originated impurities tend to have higher separation factors than those of iron. This is due to the fact that the wall is likely to be constructed of heavier elements. Figure 2 shows the corresponding behavior in a rotating plasma device having a spatially-independent θ . The separation factors are much lower than those of Fig. 1. This indicates that the isorotational type of plasma devices has less

impurities concentration within the plasma core than devices with uniform θ . In absence of forced diffusion; separation factors are rather sensitive to the plasma density and temperature profiles. The following general profiles are considered for toroidal plasma devices:

$$n = n_0 (1 + \beta \xi^2) \quad (2)$$

and

$$T = T_0 (1 + \gamma \xi^2) \quad (3)$$

where $\xi = r/a$, a is the minor radius of the plasma, n_0 and T_0 are the plasma density and temperature, respectively, at $r = 0$, and β and γ are constants which are characteristic of the reactor model. To examine the spatial distribution of impurities in this case, we may consider a steady state ternary plasma composed of electrons, deuterons, and a trace of a single species of impurities of charge number Z . Neglecting thermal diffusion and writing Eq. (1) for impurities concentration, N_I , a simplified separation equation is obtained for the impurities. With the aid of the profiles given by Eqs. (2) and (3), the separation equation can be integrated twice using the cylindrical symmetry condition and taking N_{I0} to be the concentration at $r = 0$. The result is then rearranged to give the separation factor,

$$\alpha = [1 + (2\beta + \gamma)\xi^2 + (\beta^2 + 2\beta\gamma)\xi^4 + \beta^2\gamma\xi^6]^{Z-1} \quad (4)$$

Here, α is defined as the ratio between the impurities abundance at r , N_I/N_D , and their abundance at $r = 0$, N_{I0}/N_{D0} ; where N_{I0} is the concentration of impurities at $r = 0$, and N_D and N_{D0} is the concentration of deuterons at r and $r = 0$, respectively. When impurities are present in the plasma only as a trace, $\alpha \approx N_I/N_{I0}$. The expression for α in Eq. (4) is independent of the diffusion coefficients and the plasma composition; however, α depends to a great extent on the density and temperature spatial distributions. Actually, $\alpha = 1$ for flat plasma density and temperature profiles and the concentration of the impurities is constant over the radial direction.

The concentration of the impurities at the center of the plasma core will be less than that at the boundaries if $\alpha > 1$ at $r > 0$. Thus a self-purifying plasma can be realized if the spatial distribution of its density, pressure, and temperature are such that

$$\beta^2 + 2\beta + \gamma/(1 + \gamma) > 0 \quad (5)$$

Several values have been suggested for these constants. For a steady state tokamak, Golovin, Knestrovsky, and Kormarov⁹ assumed $\beta = -0.5$ and $\gamma = -0.9$. In this case, condition (5) is not satisfied and the concentration of the impurities at the center of the plasma is

$$\alpha = (1 - 1.9\xi^2 + 1.15\xi^4 - 0.225\xi^6)^{Z-1} \quad (6)$$

For $Z = 2$, the concentration of the impurities at the center of the plasma is 40 times the concentration at the boundaries. For higher values of Z the impurities become much more concentrated at the inner portion of the plasma core. Studies of similar profiles show that high Z particles occupy the hottest region of the plasma. Departure from the simple parabolic profiles could provide proper conditions for the reduction of impurities concentration at the active region of the plasma.

Yoshikawa¹⁰ suggested two different profiles which could be suitable for tokamaks with poloidal divertors. For both cases, condition (5) is not satisfied. In one case,

$$\beta = -0.5 \text{ and } \gamma = 0, \text{ thus } \alpha = (1 - \xi^2 + 0.25\xi^4)^{Z-1}. \quad (7)$$

For $Z = 2$, the ratio between the concentration at $r = a$ and that at $r = 0$ is 0.25. This would result in less radiation losses compared to the results corresponding to Eq. (6) if the temperature profile is not flat. In the second case the temperature profile is also flat while $\beta = -1$, thus

$$\alpha = (1 - \xi^2)^{2(Z-1)}. \quad (8)$$

At $\xi = 1$, $\alpha = 0$; that is, the impurities are completely trapped in the plasma center.

The most favorable profiles among those suggested for tokamaks are the flat density and temperature profiles which have been proposed by Carruthers.¹¹ This corresponds also to a flat impurities density profile. Syntheses of density, pressure and temperature profiles for self-purifying plasmas need to be carried out. The results of these syntheses would provide the grounds to modify the above proposed profiles so that reduction of the impurities in the plasma active region can be achieved. Although separation effects are considered in this work for the plasma core only, it is necessary to explore the spatial concentration of impurities in the divertor and the surrounding vacuum region.

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Fig. 1. Spatial Concentrations of iron and aluminum impurities relative to plasma tritium concentration in a rotating plasma ($\Omega = \text{constant}$, $\theta = 2$).

Fig. 2. Spatial concentrations of iron and aluminum impurities relative to plasma tritium concentration in a rotating plasma ($\theta = \text{constant} = 2$).

SOME CONSIDERATIONS IN THE PROCESSING OF D-T PLASMA EFFLUENTS

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ABSTRACT

The processing of D-T plasma effluent in gaseous form to obtain a recycle fuel stream containing an acceptable concentration of helium and a waste stream with minimal tritium concentration is not yet well established. Potential limitations in terms either of excessive tritium holdup or of inadequate separation of fuel and waste species can be identified in all processes thus far identified as usable in gaseous effluent processing. If a reasonably effective partitioning scheme functioning on-line, either in the reacting or exhausting plasma, or after collection of the effluent, and yielding partial separation of helium from deuterium and tritium, can be used to feed a two stream effluent handling system, an acceptable trade off of power derating against tritium holdup with high ultimate tritium utilization appears to be obtainable. A gaseous effluent processing system based on these concepts would be appropriate for tokamak or stellerator systems fueled by neutral beam injection or background gas take-up or for currently envisioned theta pinch power reactors.

INTRODUCTION

The near term prospects for commercial development of fusion power are limited to rather few alternatives, all based on the relatively favorable characteristics of deuterium-tritium fusion. It is conceded that a viable fuel cycle can be based on the production of tritium by neutron-induced reactions in a suitably designed lithium bearing blanket surrounding the reaction region. Extensive effort has been invested in recent years in estimating the tritium breeding ratio for various blanket configurations and in devising methods for extracting the tritium so produced from the blanket with minimum holdup and loss. Significant work has also been done in identifying and developing capabilities for fueling the reacting plasma and for removing residual materials from the reaction chamber. By comparison, relatively little effort has as yet been directed toward questions regarding the processing of the plasma effluent to separate reusable fuel material from reaction waste products and other contaminants.

Johnson(1) has reported that if D-T droplet or pellet injection is utilized as the method for fueling the plasma, and therefore that liquefaction and perhaps solidification of the fuel components of the effluent are necessary parts of the fuel cycle, very effective isolation of noble gases and, to a degree, protonic hydrogen can be achieved in the liquefaction process and in subsequent fractional distillation. Corresponding assurances of high separation capability in gas fueled reactors, i.e., in neutral beam injection systems for tokamaks, stellators or mirrors or in self-fueling tokamaks or gas-fueled theta pinches, have not yet been provided. Since effective and efficient handling of D-T fusion effluents is essential if even the comparatively simple D-T fuel cycle is to prove to be commercially acceptable, and since the method of fueling (or, in fact, the method of confinement) has yet to be firmly established, we feel it appropriate here to review a few important aspects of D-T plasma effluent processing with a view toward gas fueling, as opposed to pellet or droplet fueling, systems.

We shall begin by stating for the record the more obvious requirements imposed on a D-T plasma effluent processing system. We shall then consider what appears to be the most convenient of the various gas separating systems, the oxidation-electrolysis process, and point out a potential difficulty in that system. Then we shall explore alternative approaches, provide some indication of possible trade-offs, and close by observing that there remains much still to be done.

REACTOR EFFLUENT PROCESSING REQUIREMENTS

The effluent from the reaction region of a D-T fueled fusion power reactor will consist of unburned deuterium and tritium, plus helium-4, rather small amounts of protonic hydrogen and helium-3, perhaps a moderate amount of argon or a similar material if a radiant is purposely injected for temperature control, and minor contaminants arising either from surface erosion of the first wall or from imperfect purification of the fuel stream prior to injection. Practical considerations require that the deuterium and tritium be recycled until high burnup is achieved. However, unless the undesirable contaminants in the effluent stream are at least partially extracted, under constant plasma pressure constraints, the contaminants (notably helium-4) will gradually displace the fuel species as the effluent is recycled and the fusion reaction rate will deteriorate to an economically unacceptable level. Further, plasma control considerations may dictate that the concentration of any temperature stabilizing specie that is present be easily and rapidly adjusted in order to maintain control and insure stability. Thus, high separation of argon or the equivalent, if present, must also be obtained. We conclude, therefore, that effective partitioning of the noble gases from the hydrogenous fuel species in D-T reactor effluents is a necessary condition for successful operation of a commercially viable fusion power reactor.

PREVIOUSLY PROPOSED EFFLUENT PROCESSING SYSTEMS

If liquefaction of the hydrogenous component of the plasma effluent is either an essential or an acceptable stage in the effluent processing system, quite acceptable separation of deuterium and tritium from helium and heavier noble gases can be obtained, at least under equilibrium conditions, by taking advantage of the relative volatilities of the constituents of the effluent as functions of temperature(1). Argon, if present, will condense out of the effluent at temperatures on the order of 100°K, depending on the liquefaction pressure. The hydrogens follow at temperatures in the vicinity of 20°K, leaving gaseous helium. The vapor pressures of the hydrogens under liquefaction conditions are sufficiently low that tritium concentrations of 0.001 mole fraction in the helium waste stream, together with virtual elimination of helium from the liquefied deuterium-tritium, are anticipated(1).

If hydrogen liquefaction is unnecessary and undesirable in the D-T effluent processing system, an obvious and frequently suggested process for obtaining the required separation of the noble gases from the hydrogenous fuel species is that of oxidation followed by electrolysis, both of which draw on current, well established technologies. A typical effluent processing system based on an oxidation/electrolysis scheme is sketched in Fig. 1. For simplicity we assume that protonic hydrogen and helium-3 occur in concentrations sufficiently low that their presence can be ignored. We also assume that wall material present in the effluent is recovered almost immediately as temperatures are reduced toward ambient in the processing systems. We are thus concerned, in the main, only with the deuterium-tritium-noble gas mixture as effluent processing proceeds.

The deuterium and tritium are catalytically burned in nearly stoichiometric oxygen to yield D_2O , DTO and T_2O . The various heavy waters are then condensed to separate them from the noble gases and are subsequently electrolyzed to yield oxygen that is recycled to the catalytic combiner and a mixed deuterium-tritium gas for final processing and re-injection into the reactor. Examination of published solubilities of helium and argon in water(2) and of the purity of the cathodic gases evolved in electrolysis(3,4) shows clearly that virtually complete elimination of helium, oxygen and argon from the deuterium-tritium gas in the recycle stream can be expected. Hydrogen purities of at least 99.5% and usually 99.9% are routinely obtained in current commercial facilities(3,4). The oxygen stream collected at the anodes of the electrolytic cells is somewhat less pure, ranging from 98.0% to 99.8% in commercial installations(4). The major impurities are hydrogenous gases; tritium escaping by this route could constitute a serious loss in a fusion fuel cycle. However, since the oxygen stream bearing the "lost" deuterium and tritium is recycled directly back into the catalytic combiner, very little actual loss occurs. Heavy water vapors escaping in both the anodic and cathodic gas streams are recondensed and returned to the electrolytic cell. Hence, we conclude that the methods of effluent processing currently proposed are, in principle, entirely adequate for realistic projected D-T power reactor applications, at least insofar as the purity of the recycled fuel stream and the potential for loss of the evolved tritium are concerned.

The sizes of the equipment required even for a large fusion reactor installation prove to be quite modest. The hydrogenous component of the effluent of a typical power reactor depends on the operating parameters of the reactor according to the proportionality:

$$\frac{\text{kg}}{\text{day}} \text{ of D-T effluent} \propto [\text{plant electric power level}] \times \left[\frac{1}{\eta M}\right] \times \left[\frac{1-f}{f}\right]$$

where η is the net station thermal efficiency, f is the burnup fraction, and M is the blanket energy multiplication factor. If we take as a convenient example the parameters of the Princeton Reference Design of a Fusion Reactor Plant(5) we obtain:

$$\frac{\text{kg}}{\text{day}} \text{ of D-T effluent} = 0.44 \times 10^{-3} \times \text{MWe} \times \left(\frac{1-f}{f}\right)$$

At a fractional burnup of 10% we anticipate a D-T effluent rate of 7.9 kilograms per day or about 0.73 pounds of DT gas per hour or 0.88 standard cubic feet of DT gas per minute. At 3% burnup the equivalent numbers are 28.4 kilograms per day, 2.62 pounds per hour or 3.16 standard cubic feet per minute. The catalytic recombiner in a typical large fission reactor installation is rated at about 3 cubic feet of hydrogen per minute with at least 98.5% oxidation of the hydrogen supplied. Currently available commercial equipment is thus adequate to handle the throughput requirements of a large D-T reactor, even at a comparatively low burnup fraction. A two stage combiner backed by an effective hydrogen adsorber would probably prove necessary to minimize tritium loss.

The electrolytic cells in the secondary train of the Trail, British Columbia heavy water plant operated at an electrolysis rate of 0.74 pounds of heavy water (D_2O) per hour or 0.15 pounds of D_2 gas evolution per hour(3,6). Thus, between four and perhaps twenty cells of the Trail secondary plant design should suffice to meet the electrolysis requirements of a 2000 Megawatt (electric) fusion plant. Therefore, no serious difficulties are anticipated in terms of throughput requirements or practical equipment sizes.

A matter of some concern, however, is the holdup of tritium in practical oxidation/electrolysis systems, specifically in the electrolyte of the electrolysis cell. One Trail secondary electrolysis cell contained in excess of 100 pounds of heavy water under normal full load operating conditions(3). If one (optimistically) assumes a 50-50 deuterium-tritium mix in the cell, the tritium content is about 15 pounds or nearly 7 kilograms of tritium in a fully charged cell. With four cells in service the tritium holdup in the electrolyte would be 25-30 kilograms for 2000 MWe generation at high burnup (10% to 12%) and more than 100 kilograms at low burnup (~3%). The electrolysis rate is dependent on total electric current flow through the cell. Current flow, in turn, is dependent on electrode area and spacing, both of which had been optimized for minimum heavy water holdup in the Trail secondary plant facility. Hence, the potential tritium holdup indicated here is already somewhere near a practical minimum. The actual tritium holdup in the electrolytic cell might well be higher than the amount just estimated by a factor of as much as two because of isotopic separation by electrolysis, unless specific efforts are made to suppress such natural separation. Several factors are known to reduce the isotopic separation factor(3,7,8). Among them are high electrolyte temperature, entrainment and foaming of the electrolyte, poor electrode surfaces and electrode polarization. Thus, the natural isotopic separation process can be inhibited and tritium holdup can be held to something like the theoretical minimum provided the electrolysis facility is designed and operated with these considerations in mind. It is to be emphasized, however, that even under favorable conditions the tritium holdup in the electrolytic cells of the effluent processing system, as presently envisioned, is larger by a factor of at least several more than the total holdup previously anticipated for the entire plant(5,9,10,11,12). Taken either from the point of view of initial tritium requirements at plant startup or from considerations of potential release of radioactive material in the event of damage to the cells, this large holdup of tritium cannot be ignored and should, if possible, be significantly reduced; preferably, however, not at the expense of ultimate tritium utilization.

SOME QUANTITATIVE CONSEQUENCES OF IMPERFECT EFFLUENT PROCESSING

We shall briefly re-examine the requirements that are, in fact, imposed on the plasma effluent processing system with a view toward identifying an alternative approach that could lead to a reduction in the tritium holdup in the processing facility for a gas effluent handling system. We assume as a convenient reference a magnetically confined, pressure limited plasma in at least quasi-steady state with plasma temperature dictated either by a radiant (argon or equivalent) to maximize $\langle \sigma v \rangle / T^2$ or by the characteristics of the staged pinch of a theta pinch system. The helium-4 partial pressure in the plasma is divided conceptually into a component due to the helium-4 particles produced as reaction products in a given cycle and a component due to recycled helium-4 produced in earlier cycles. The direct reaction product is viewed as an unavoidable component of the total plasma pressure as is the effect of the radiant that may be introduced for temperature control. The partial pressure of recycled helium-4 is taken to be a variable in our analysis with the partial pressures of deuterium and tritium being adjusted accordingly to maintain a constant composite.

If the separation of the hydrogenous species from the noble gases in the plasma effluent is incomplete, two points are of immediate interest: the actual

effect under fixed plasma pressure constraints of recycled contaminants on plasma power level, and the consequences of loss of tritium during effluent processing and fuel recycling. Taking these in reverse order, if some portion of the tritium follows the helium waste stream and is permanently removed from the processing system, fuel is lost and the tritium breeding requirements on the blanket increase. Figure 2 shows the influence of tritium recovery efficiency in the plasma effluent processor on ultimate tritium utilization for various values of fractional burnup. The axes could as well be labeled in terms of deuterium; however, the consequences of loss of deuterium are so far less than those for loss of tritium that the deuterium losses need not be considered. Since tritium not utilized in fusion must be replaced with excess tritium bred in the blanket, it is evident that even in high burnup machines a very high tritium recovery factor is essential if undue constraints in blanket design and operation are to be avoided. Even at fractional burnups as high as 10%, for example, recovery efficiencies of 0.99 or better, per pass, are in order if tritium breeding ratios of 1.10 to 1.15 in the blanket are to be tolerated. Note that we are considering a simple equilibrium fuel cycle in a high fractional burnup reactor. If the fractional burnup is lower or if excess tritium is to be produced to fuel a new reactor coming on line, significantly higher blanket tritium breeding ratios are required and blanket design and operation are the more severely constrained.

The effect of incomplete extraction of helium from the deuterium-tritium recycle stream is shown in Fig. 3. We assume that total plasma pressure is held constant at a level set by the confining and stabilizing magnetic fields, and that temperature is held constant either at the value that maximizes the quantity $\langle \sigma v \rangle / T^2$ or at the level produced by a staged theta pinch. Then, recycled helium necessarily displaces fuel in the plasma and so reduces the fusion reaction rate and the plant power level. The derating factor plotted in Fig. 3 is the ratio of the power level obtainable with recycled helium-4 in the plasma to that obtainable if helium is totally removed from the deuterium-tritium recycle streams. It is noteworthy that the loss in power generation capability is not large, even at high fractional burnup, if a reasonable helium extraction efficiency can be maintained. Apart from the obvious considerations of potential release of radioactive materials, recovery of tritium from the plasma effluent stream appears to be of greater importance in establishing an economically feasible D-T fusion power system than is extraction of undesirable reaction products from the fuel recycle stream.

CONSIDERATION OF ALTERNATIVES

Apart from the oxidation-electrolysis process, several other schemes for obtaining at least a partial separation of hydrogenous species from the noble gases can be identified. Several of the apparently likely candidates are shown schematically in Fig. 4. A few comments regarding these respective alternatives are in order.

Separation of effluents either by permeation or by any of the diffusion-effusion processes that are driven by partial pressure differences is necessarily incomplete. The unavoidable existence of a partial pressure of each of the plasma constituents on the inlet side of the separation barrier and the requirement that the rejected species, either fuel or waste, be continuously removed from the inlet side at a rate proportional to the inlet rate of that component insures that the tails stream will contain fuel material. The heads stream may also contain noble gases, as in diffusion or effusion processes. Two important diffusion-permeation type processes not shown explicitly in Fig. 4 should be noted. Gas centrifuge separation processes operate on a principle that is somewhat different from that of diffusion or effusion but nonetheless can be viewed as being analogous to gaseous diffusion, at least in this application, since the driving force in the centrifuge is again partial pressure. Selective extraction of helium by permeation through fused silica or

glass barriers under conditions of high pressure and temperature may provide an important balance for the selective permeation of hydrogenous species through suitable metal membranes. A composite permeation cell with separate barriers of fused silica and palladium, if properly sized and if operated under suitable conditions of temperature and pressure, could provide nearly complete separation of helium from deuterium and tritium. Argon, if present, would be unable to permeate either barrier very effectively and so could constitute a serious contaminant in the cell. All such permeation-diffusion processes can be tailored to obtain separation of protonic hydrogen from deuterium and tritium and, in general, of helium-3 from helium-4 and all processes can be improved to achieve virtually any degree of overall separation of the plasma effluent components if multi-stage configurations are used, but only at the price of sharply increased tritium holdup.

Selective adsorption offers a potentially viable alternative to permeation or effusion/diffusion as a means of separating noble gases from hydrogenous species and also of obtaining some degree of isotopic separation among the hydrogens. Very extensive work has been done on the general characteristics of adsorption of gases on solids(13). The specifics of hydrogen-helium separation and of isotopic separation in hydrogen by atomic adsorption on palladium sponge at near ambient temperatures, followed by elution of isotopic gases in sequence at higher temperatures, has been the subject of relatively recent studies(14-16). The noble gases are only weakly adsorbed on palladium so that at least partial concentration of helium and argon, if present, in the gas phase is achieved. Scale-up of laboratory systems remains to be done.

Chemical and isotopic separation of gases following selective adsorption of tuned laser radiation has been proposed (17,18,19) and is currently being pursued in several proprietary development programs as a means of obtaining uranium enrichment. Assessments of the potential for large scale (i.e. fusion power reactor) applications of laser driven processes for effluent separation appear not to have been published as yet.

The thermal effusion/permeation scheme of extracting fusion reaction products from the plasma chamber while replenishing the background fuel gas appears to have potential for self-fueled tokamaks and for theta pinch systems. This approach, originally suggested several years ago(20) has recently been re-evaluated and extended(21). From our immediate point of view the effusion/permeation extractor does not alleviate the eventual fuel-noble gas separation requirement; the separation must still be accomplished at another point in the overall fuel cycle.

Internal partitioning of the plasma, either by natural or centrifugally enhanced diffusion processes in steady state or quasi-steady state toroidal systems, has been examined in a recent series of papers(22,23,24). Preliminary indications are that effective separation of the fuel species and the reaction products can be achieved if suitable temperature and particle density distributions can be achieved or if the effluent leaving the reaction chamber can be made to rotate in an appropriately designed diverter-extractor.

Thus, alternatives to the oxidation-electrolysis process exist. However, while single stage applications of each of these alternatives provides some degree of separation of fuel species from waste effluents, almost none shows the potential for achieving virtually complete partitioning of the fuel and waste species even in a D-T fueled fusion power reactor. In most cases (excluding the effusion/permeation extractor and the in-plasma separation processes) the overall separation factor can be improved by using multi-stage processors, but only at the cost of increased tritium holdup in the processing system.

An interesting possibility for exploiting the trade off between low helium

removal in single or few stage processes and high tritium holdup in multi-stage or oxidation-electrolysis systems can be found in the use of a dual stream effluent handling system as sketched in Fig. 5. The partitioning device can be a single or few stage application of any of the separation processes indicated in Fig. 4. The fuel recycle stream, depleted in helium, is returned directly to the fuel injector with effectively no tritium holdup chargeable to the effluent handling system. The helium enriched process stream is passed on to a cleanup processor, quite likely an oxidation-electrolysis system, that yields virtually complete removal of helium with minimal tritium loss and comparatively low tritium holdup since the quantity of effluent actually oxidized and electrolyzed is reduced. If tritium holdup in the partitioner is neglected, the trade-off between power level derating due to the partial pressure of recycled helium and holdup of tritium in the effluent handling system can be quantified as in Figs. 6 and 7. Here we plot the power derating factor against the fractional reduction in tritium holdup, compared to a total oxidation-electrolysis system, achievable with the dual stream concept. The plots are appropriate for high (10%) and low (3%) fractional burnup systems, respectively, and show parametrically the influence of the helium separation factor and the process stream flow fraction on the trade-off between power derating and tritium holdup. We assumed in preparing these plots that the injected fuel consists of equal atom fractions of deuterium and tritium plus recycled helium and that the electron and ion temperatures are the same. Similar plots for other conditions of deuterium-tritium ratios and for differences in ion and electron temperatures can readily be prepared. Since tritium either is directly recycled with virtually no loss or is recovered with minimal loss in the oxidation-electrolysis process, overall tritium utilization, in the sense of Fig. 2, is sufficiently high that the residual penalty on the fuel cycle can be readily accepted.

CONCLUSIONS

We conclude that gas effluent handling systems for D-T fueled fusion power reactors can be developed; if liquefaction of deuterium and tritium is not required for fuel injection purposes, the entire fuel cycle can be based on processes that exploit the particular properties of hydrogenous and noble gases. A few of the candidate methods of gas partitioning (e.g. gaseous diffusion and effusion) have already been scaled up from laboratory to industrial applications, although not for fusion fuel cycle purposes. Other methods show promise at the laboratory level but have not been applied under conditions comparable to those anticipated in fusion power reactors. Several of the methods are as yet speculative; further investigation and development are in order if the eventual potential of these processes is to be evaluated.

The use of a dual stream effluent handling system offers the prospect of an effective trade-off between power derating and high tritium holdup and/or low tritium utilization. The actual trade-off that can be obtained depends very strongly on both the degree of separation that can be obtained in the partitioning process and the characteristics, specifically the fractional burnup, of the reacting plasma. Again, although viable alternatives to liquefaction or oxidation-electrolysis appear to exist, it remains to be demonstrated that at least one of these alternatives can be utilized in practical situations.

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Figure 1. Schematic Diagram of an Oxidation-Electrolysis Plasma Effluent Processor

Figure 2. Effect on the Tritium Utilization Factor of Tritium Loss during Effluent Processing

Figure 3. Effect on Plasma Specific Power of Incomplete Helium Removal from the Fuel Recycle Stream

Separation by Permeation

Separation by Diffusion/Effusion

Separation by Adsorption and Elution

Separation by Photon Momentum Transfer

Separation by Plasma Rotation
(from Reference 23)

Figure 4. Alternative Non-Cryogenic Effluent Separation Processes

Figure 5. Dual Stream Gas Effluent Processing System

Figure 6. Trade Off of Power Level Against Tritium Holdup for Incompletely Separated Plasma Effluent at 10% Fractional Burnup

Figure 7. Trade Off of Power Level Against Tritium Holdup for Incompletely Separated Plasma Effluent at 3% Fractional Burnup