UCRL-51419

EFFICIENCY OF INJECTION OF HIGH ENERGY NEUTRAL BEAMS INTO THERMONUCLEAR REACTORS

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July 17, 1973

Prepared for U.S. Atomic Energy Commission under contract No. W-7405-Eng-48

LAWRENCE LIVERMORE LABORATORY

University of California/Livermore

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Printed in the United States of America
Available from
National Technical Information Service
U. S. Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22151
Price: Printed Copy $___*; Microfiche $0.95

*Pages	NTIS Selling Price
1-50	$4.00
51-150	$5.45
151-325	$7.60
326-500	$10.60
501-1000	$13.60

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Abstract

The efficiency of injection of energetic, neutral beams into thermonuclear reactors has a substantial effect on the overall reactor efficiency. Direct conversion of the unneutralized portions of the ion beam is used in modeling the injector system, and the injection efficiency is estimated from assumptions on the performances of the components of the injection system. Based on this model, deuterium or tritium atoms between 100 keV and 1000 keV, which have been generated from negative ions, can be injected into the reactor with an efficiency of 80 to 90%. Without direct conversion this efficiency will drop to 65 to 85%. For energies around 100 keV, D^+ ions can be used to obtain a system efficiency of about 75%, which is higher than can be obtained with either D_2^+ or D_3^+. The same model predicts the injection of ^3He atoms to be 80% efficient below 200 keV using $^3He^+$ ions, and less than 70% efficient between 200 keV and 700 keV using $^3He^-$ ions.

Introduction

A fusion power reactor based on the mirror principle of containment will probably require the continuous injection of high energy particle beams in order to maintain the plasma against end losses. The injector system efficiency has a great deal of leverage on the overall system efficiency of a mirror reactor system. For a mirror reactor system of the type discussed by Werner et al.[1], a 5% increase in the injector system efficiency, from 90 to 95%,results in a 12.5% increase in the overall reactor system efficiency (32 to 36%). In this report, which is an extension of a previous analysis,[2] we consider the "in principle," overall efficiency of the injection system for injecting high energy neutral beams formed from accelerated positive or negative ions into a plasma. For a D-T plasma, D (and T) neutrals are formed from accelerated D^+, D_2^+, D_3^+ and D^- (and T^+, T_2^+, T_3^+ and T^-) ions. For a D-^{3}He plasma, ^{3}He neutrals are formed from accelerated $^3He^+$, $^3He^-$, and $^3HeD^+$ ions.

The injection system discussed in the paper is conventional in the sense that it is a scale up of present neutral injection experiments such as Baseball II where neutral particles are produced outside the plasma and injected across the plasma.[3] For mirror-confined plasmas, neutral injection transverse to the magnetic field is particularly important because the trapped ions resulting from these injected neutrals are initially as far away in velocity space as possible from the mirror loss cone. This increases the plasma confinement time.

Hamilton and Osher[4] argue that the current density required at the ion source and in the accelerator in a conventional injection system may be higher than appears technically feasible. Therefore, they propose an injection scheme that directs negative ions along a magnetic guide field into the plasma. The advantage of the Hamilton-Osher injection scheme is that the area of the source can be much larger than the holes into the plasma container. However, the angle of trapping cannot be perpendicular to the magnetic field that contains the plasma so that the trapping fraction, and hence the overall injection efficiency, of the Hamilton-Osher scheme is less than that of a conventional neutral injection system using negative ions. Even though the Hamilton-Osher injection scheme may be technically less demanding than a conventional system, this paper is restricted to the analysis of a conventional neutral injection system because of efficiency considerations.

Some aspects of neutral injection as they relate to a conceptual, mirror fusion reactor are discussed in Ref. 5.

Discussion

INJECTION SYSTEM EFFICIENCY

General Efficiency

The injection system, as shown in Fig. 1, is a subsystem of Fig. 2 which shows a power-flow diagram for a fusion reactor with direct conversion. The power-flow diagram of the injector system shown in Fig. 1 is shown in Fig. 3. Positive ions are produced in a source and accelerated to an energy of E^+. These E^+ ions are passed through an alkali-metal-vapor cell which produces negative ions from the positive ions entering the cell. The negative ions are accelerated to the desired injection energy, neutralized, and the neutral atoms are injected into the plasma. The ions not neutralized are magnetically separated from the neutrals and guided into a direct converter where a fraction of the energy of the charged particles is recovered.

Some of the injected neutrals charge exchange with the trapped reactor plasma ions forming new neutrals, which escape from the plasma before ionization occurs. These neutrals deposit their energy over the reactor first wall. The portion of the injected beam which is not trapped in the reactor plasma and is not deposited on the first wall passes through a cell where the particles are stripped of an electron and the energy partially recovered in a second direct converter.

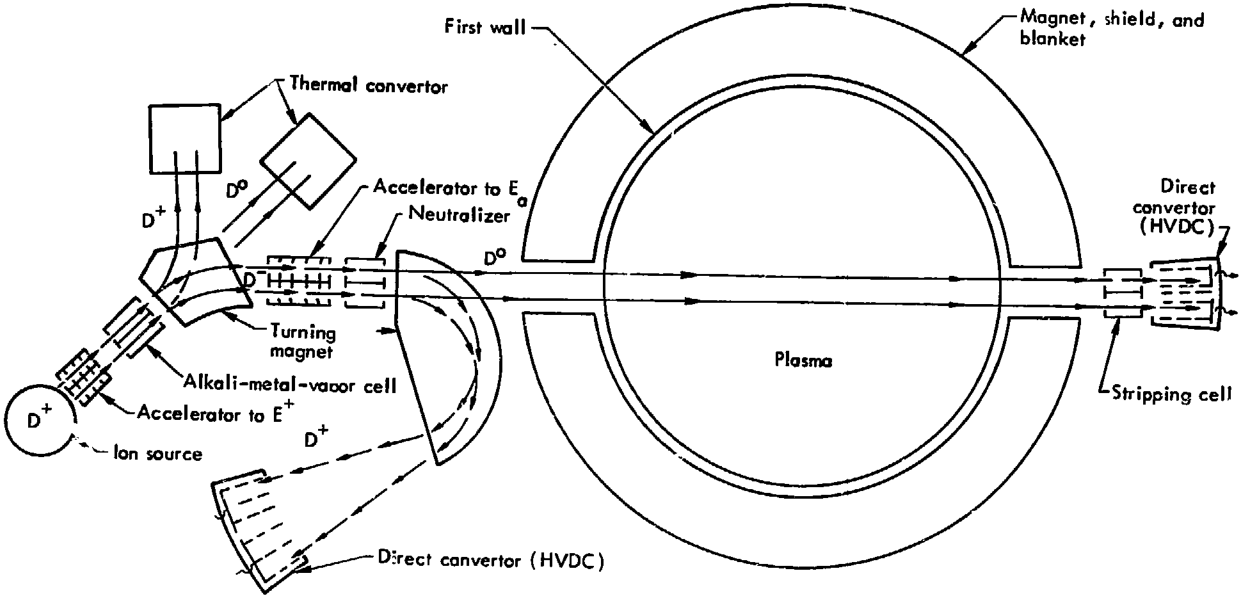

Fig. 1. Schematic of a neutral-beam injection system.

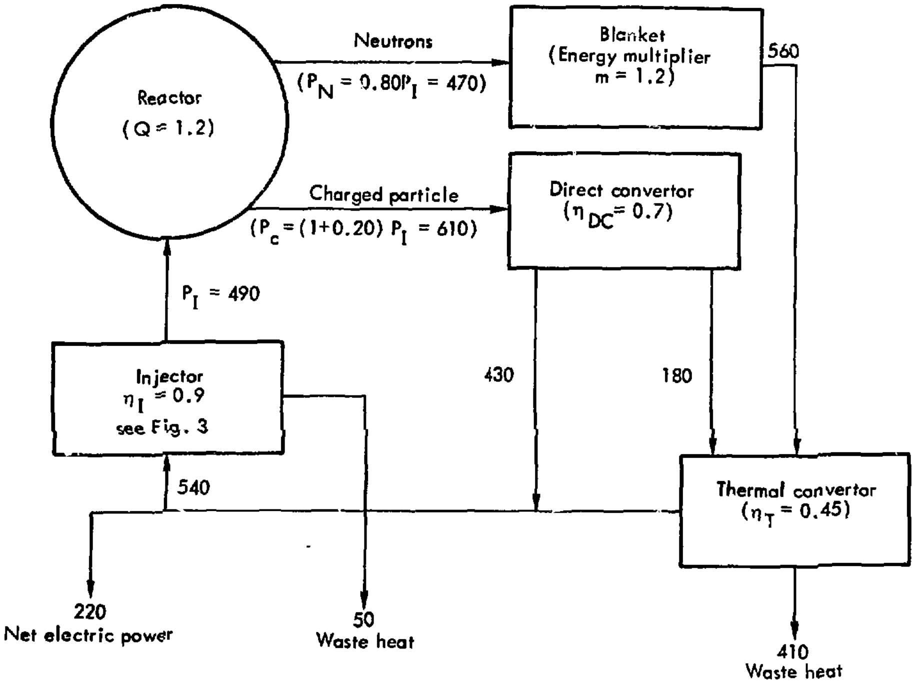

Fig. 2. Diagram of the power flow (in MW) for a D-T mirror reactor with direct conversion. The overall efficiency,

$$\eta_{sys} = \frac{[0.8Qm + (1 + 0.2Q)(1 - \eta_{DC})]\ \eta_T + 1\ (1 + 0.2Q)\ \eta_{DC} - \frac{1}{\eta_I}}{[0.8m + 0.2]\ Q} = 0.32,$$

and the variation of the overall efficiency as a function of the variation of the injector efficiency is

$$\frac{\delta\eta_{sys}}{\eta_{sys}} = \frac{\frac{\delta\eta_I}{\eta_I}}{\{[0.8Qm + (1 + 0.2Q)\ (1 - \eta_{DC})]\ \eta_T + (1 + 0.2Q)\ \eta_{DC}\}\ \eta_I - 1} = 2.51\ \frac{\delta\eta_I}{\eta_I}.$$

The overall injection efficiency is defined as

$$\eta_I = \frac{P_T}{P_{ex} - P_{rec}},$$

where P_T is the power trapped, P_{ex} is the power expended in producing the ions and accelerating them to the energy required for a given injection energy, and P_{rec} is the amount of power lost in the injection system components which is recovered in direct and thermal convertors. For the injection system shown in Fig. 3, the overall injection system efficiency is shown in Appendix A to be

$$
\begin{aligned}
\eta_i = \eta_{a2} f_n f_T \Bigg\{ 1 &+ \frac{q}{M\eta_{+-}\eta_{a1} E}(1 - \eta_{T1}) + \frac{E^+}{ME}\Bigg[\left(\frac{1 - \eta_{+-}\eta_{a1}}{\eta_{+-}\eta_{a1}}\right) \\
&+ (1 - \eta_{a2})\eta_{T4} - \left(\frac{1 - \eta_{a1}}{\eta_{a1}}\right)\frac{\eta_{T2}}{\eta_{+-}} - \left(\frac{1 - \eta_{+-}}{\eta_{+-}}\right)\eta_{T3}\Bigg] - (1 - \eta_{a2})\eta_{T4} \\
&- \eta_{a2}\Bigg[(1 - f_n)[\eta_{D1} + (1 - \eta_{D1})\eta_{T5}] \\
&+ f_n\Big[(1 - f_T - f_w)[\eta_{D2} + (1 - \eta_{D2})\eta_{T7}] + f_w\eta_{T6}\Big]\Bigg]\Bigg\}^{-1} ,
\end{aligned}
\tag{1}
$$

where E^+ is the energy of the formation of the negative ions in the alkali-metal-vapor cell, E is the energy of the injected atoms, and the other symbols are defined in Fig. 3.

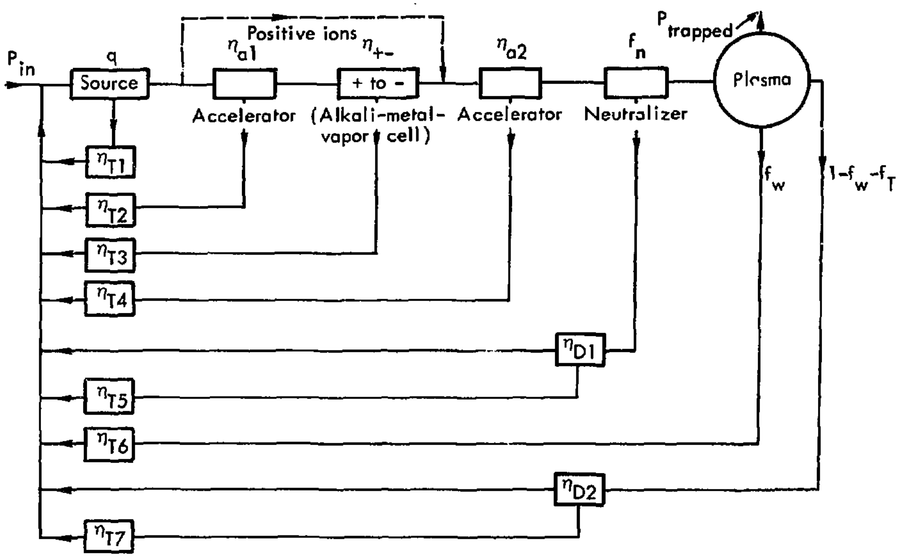

Fig. 3. Diagram of the power flow for the injector system.

For a neutral-beam injection system using positive ions ($\eta_{+-} = \eta_{a1} = 1$, and $E^+ = 0$), the above equation reduces to

$$\eta_i = \eta_{a2} f_n f_T \left\{1 + \frac{q}{ME}(1 - \eta_{T1}) - (1 - \eta_{a2})\eta_{T4} - \eta_{a2}\left[(1 - f_n)\left[\eta_{D1} + (1 - \eta_{D1})\eta_{T5}\right] + f_n\left[(1 - f_T - f_W)\left[\eta_{D2} + (1 - \eta_{D2})\eta_{T7}\right] + f_W \eta_{T6}\right]\right]\right\}^{-1}. \quad (2)$$

Note that if the negative ions are produced directly from the source, the overall injection system efficiency is also given by Eq. (2).

The performance of the components of the injection system are discussed below. These component performances probably represent an upper limit as they do not take into account some real effects such as removal of neutral gases from the system and beam divergence in the system.

COMPONENT PERFORMANCE

Ion Source

Ion sources for fusion reactors have been discussed in the literature.[6-9] Basically these sources consist of a plasma and an ion-extraction system. The control of the ion species is a problem in the source. Even with the arc and gas optimized for a single species the plasma composition of that species is generally only 50 to 80%.[10] For the purpose of this analysis, the source will be considered to form ions of a single species. The current density and divergence of the beam will not be considered in this in-principle study although they are very important in the design of the components of the injector system.

The source energy, q, required to produce an ion is estimated to be 500 eV.[11] The inefficiency of ion production and the initial ion-beam losses that result from defining the ion source emittance to fall within the acceptance of the accelerator column are taken into account in this value of q. Some of this energy can be recovered in a thermal converter with efficiency η_{T1} by using cooled high temperature electrodes in the ion source.

Negative-Ion-Production Cell

It appears to be difficult to obtain high currents of negative ions directly from an ion source. However, a negative-ion beam can be produced from a positive-ion beam by electron capture in a gas or vapor cell. For high-current, negative-beam systems the alkali-metal-vapor cell is suitable for large-area application.[4] The conversion efficiency of deuterons (D^+ to D^-) has been determined to be a maximum of 0.21 ± 0.04 for a deuteron of energy 1.5 keV passed through a cesium-vapor cell having the product of gas density times cell thickness equal to 10^{15} to 10^{16} atoms per square centimeter.[12,13]

Osher[14] has suggested using a series of cesium-vapor cells to increase the efficiency of the effective positive to negative ion conversion. For a series of cells, the positive to negative ion conversion efficiency is given by Osher as

$$\eta_{+-} = \sum_{n=1}^{N} f_{+-} (1 - f_{+-})^{n-1} T^n, \tag{3}$$

where f_{+-} is the efficiency of the basic positive to negative ion conversion process, T is the transmission of each cell, and N is the number of cells. For a 21% conversion to negative ions and a 95% transmission in each cell,

$$\eta_{+-} = \sum_{n=1}^{N} 0.21\ (0.79)^{n-1}\ (0.95)^n.$$

Thus, the positive to negative ion-conversion efficiency is 20% and 54.6% for one and four cells respectively.

The fraction $(1 - \eta_{+-})$ of the positive ion beam entering the cesium cell is converted to deuterium atoms with an energy of 1.5 keV. In principle these neutrals could be ionized by stripping an electron, and their energy recovered in a direct convertor, but this is difficult at low energies. However, for this study, the energy of the neutrals is assumed to be recovered in a thermal conversion system with efficiency η_{T3}.

Accelerator

The ions must be accelerated to an energy of E_a per ion;

$$E_a = ME, \tag{4}$$

where E_a is the energy of the ion leaving the accelerator, M is the ratio of the mass of the ion to the mass of the injected neutral particle, and E is the energy of the injected neutral particle.

In a study of an injector system used to heat a toroidal plasma, Julian[15] estimated the achievable efficiency of an injector-type accelerator so that the accelerator power supply could be defined more closely. A breakdown of Julian's estimates for a 16.6-A beam of 3-MeV D_3^+ ions is given in Table 1 below:

The power losses by beam interception and the retrograde electron current were assumed to take place at the inlet side of the accelerator tube. The accelerator efficiency is defined as

$$\eta_a = \frac{\text{Power out}}{\text{Power out + Power loss}}$$

$$\eta_a = \frac{1}{1 + 0.087} \approx 92\%.$$

Table 1. Accelerator losses.

Item	Power loss/Output power
Interception of beam by electrodes	≈ 0.005
Retrograde electron current losses	≈ 0.002
X-ray production by electron currents	≈ 0.04
Heat losses of potential divider	≈ 0.04
Total	≈ 0.087

Julian notes that the losses estimated above, and thus the accelerator efficiency of 92% are based on "simple optimistic assessments." The losses in the accelerator can be recovered in thermal convertors with efficiencies η_{T2} and η_{T4} by using cooled electrodes, x-ray shields, and potential dividers capable of operating at high temperatures.

Neutralizer

For a neutral injection system, the high energy ions must be converted into high energy atoms. The energetic atoms are formed by the loss of an electron from a negative ion, the capture of an electron by a positive ion, or the dissociation of a molecular ion passing through a gas or plasma.

Riviere[16] has estimated the power efficiency f_n, defined as the ratio of the power in the atom beam leaving the neutralizer to the power in the ion beam entering the neutralizer, for deuterium atom production from D^+, D^-, D_2^+, and D_3^+ ions as a function of the energy of the deuterium atom for, in the case of D^- and D_2^+, both a gas and a plasma neutralizer cell. The computation of the plasma neutralizer performance was based on the assumption that the plasma behaves as an electron gas. This assumption tends to predict a higher neutralizer efficiency than a fully ionized plasma can deliver.[17] Riviere's results are shown in Fig. 4. The power efficiency of D^+ in the production of deuterium atoms of energy less than 50 keV is taken from Allison and Garcia-Munoz.[18] Riviere notes that ionization reduces the power efficiency for D^+, and increases the power efficiency for D_2^+ and D^- ions. Berkner et al.[19] measured the efficiency of the conversion of the kinetic energy of H_3^+ into neutral-beam kinetic energy in a hydrogen gas cell and found that the measured conversion efficiency is about 80 to 90% of that predicted by Riviere.

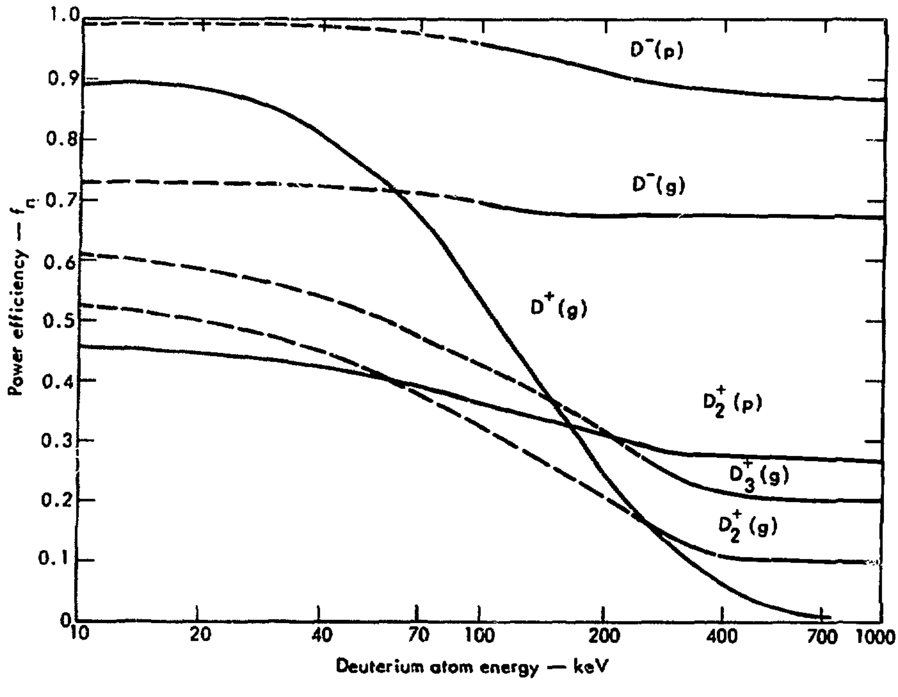

Fig. 4. The power efficiency of the neutralizer as a function of the energy of the deuterium atoms. The dashed lines represent extrapolated data, (p) = plasma neutralizer cell, and (g) = gas neutralizer cell.

The energy of the ions $(1 - f_n)$ that pass through the neutralizer can be partially recovered in a direct convertor topping cycle with efficiency η_{D1}, and the direct convertor losses can be partially recovered in a thermal convertor with efficiency η_{T5}.

Reactor

A fr:ction of the neutral beam that enters the reactor plasma is trapped in the plasma. The remainder of the neutral beam either penetrates through the plasma or charge-exchanges with the plasma ions where the neutrals formed, which do not undergo a reionizing collision, escape the plasma and deposit their energy over the reactor first wall. Thus

$$f_T + f_p + f_w = 1, \tag{5}$$

where f_T is the fraction of the neutral beam that is trapped in the reactor plasma, f_p is the fraction of the neutral beam that penetrates through the plasma, and f_w is the fraction of the neutral beam that charge-exchanges with the reactor plasma ions without undergoing a reionizing collision.

Riviere[20] has estimated the fraction of the neutral beam which penetrates a cylindrically symmetrical reactor plasma for atoms injected normal to the plasma axis as

$$f_p = \exp\left[-\int_0^D \frac{n\,\langle\sigma v\rangle_T}{v_0}\,dx\right], \tag{6}$$

where the beam diameter is less than the plasma diameter, D, n is the reactor plasma density, v_0 is the velocity of the injected atoms and $\langle\sigma v\rangle_T$ is the total reaction rate coefficient for collisional processes. If $\langle\sigma v\rangle_T$ is assumed to be constant, the integral can be replaced with $Dn\langle\sigma v\rangle_T/v_0$ where n is an averaged density.

Hunt[21] has estimated the fraction of the injected neutral beam which charge-exchanges with the reactor plasma ions and gives rise to somewhat randomly directed neutrals. These neutrals may escape the plasma before ionization occurs and deposit their energy on the first wall of the reactor. Hunt makes the assumption that the neutral atoms produced from the plasma ions that charge-exchange with the neutral beam pass through the plasma of uniform density n with a path length D/2 equal to the plasma radius. Hunt then estimates that the fraction of the injected beam striking the reactor first wall is given by the product of the fraction of the injected neutral beam that undergoes charge-exchange in the plasma times the probability that the neutrals formed by charge-exchange will not be reionized in the plasma, i.e.,

$$f_W = \left\{\frac{\langle\sigma v\rangle_{cx}}{\langle\sigma v\rangle_T}\left[1 - \exp\left(-\frac{Dn\langle\sigma v\rangle_T}{v_0}\right)\right]\right\}\exp\left[-\frac{1}{2}\left(\frac{Dn\,\langle\sigma v\rangle_T}{v_0}\right)\left(\frac{\langle\sigma v\rangle_i}{\langle\sigma v\rangle_T}\right)\right], \tag{7}$$

where $\langle\sigma v\rangle_{cx}$ is the total reaction rate coefficient for charge exchange, $\langle\sigma v\rangle_i$ is the total reaction rate coefficient for ionization by both ions and electrons, and

$$\langle\sigma v\rangle_T = \langle\sigma v\rangle_i + \langle\sigma v\rangle_{cx}.$$

Thus, combining Eqs. (5), (6), and (7), the fraction of the injected neutral beam that is trapped is given by

$$f_T = 1 - \exp\left[-\frac{Dn\langle\sigma v\rangle_T}{v_0}\right]\left\{1 - \frac{\langle\sigma v\rangle_{cx}}{\langle\sigma v\rangle_T}\exp\left[-\frac{1}{2}\left(\frac{Dn\langle\sigma v\rangle_T}{v_0}\right)\left(\frac{\langle\sigma v\rangle_i}{\langle\sigma v\rangle_T}\right)\right]\right\}. \tag{8}$$

For the case with

$$\gamma = -\frac{Dn\,\langle\sigma v\rangle_T}{v_0} = 3,$$

and using Riviere's[20] summary of reaction rate coefficients shown in Fig. 5 for a deuterium atom beam of energy E injected into a mirror reactor with an ion energy distribution from Kuo-Petravic et al.[22] the trapping fraction, wall fraction, and penetrating fraction of the injected beams are shown in Fig. 6. The trapping fraction and wall fraction do not include the effects of the alpha population in the reactor plasma. The effect of a plasma alpha population on the trapping fraction is discussed in Appendix B.

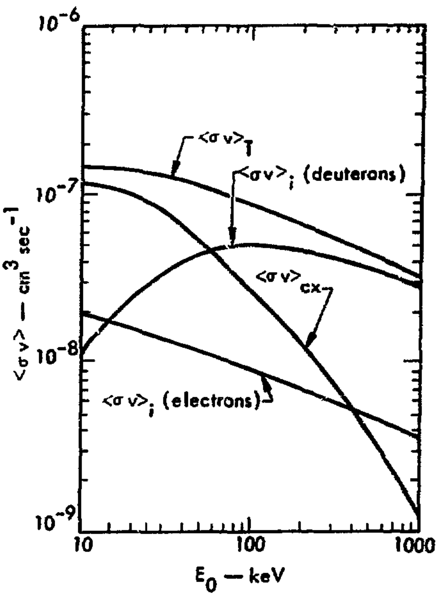

Fig. 5. Summary of the reaction rate coefficients for a deuterium-atom beam of energy E_0 which enters a mirror reactor plasma with an electron temperature of $E_0/7$ and has a mirror ratio of 3 and rejection of forward scattered neutrals, from charge exchange, within a cone semi-angle of 0.2.

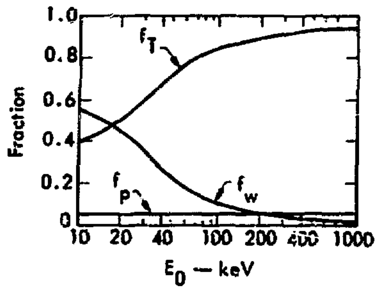

Fig. 6. The fate of the injected deuterium beam as a function of the atom energy for a mirror reactor with

$$\gamma = \frac{\langle\sigma v\rangle_T\, nD}{v_0} = 3.$$

The fraction of the beam which is trapped is denoted by (f_T), the fraction which penetrates the plasma by (f_P), and the fraction which charge-exchanges without reionization by (f_W).

The energy of the injected neutral atoms which impinge on the first wall of the reactor after a charge exchange with the plasma can be partially recovered in a thermal convertor of efficiency η_{T6}. The energy of the injected neutral beam that penetrates the plasma can be partially recovered by stripping an electron from the neutral particles, and capturing the ions formed in a direct convertor of efficiency η_{D2}. The direct convertor losses can be partially recovered in a thermal convertor of efficiency η_{T7}.

Energy Recovery System

Three schemes for recovering injector energy are considered in this paper. These recovery schemes will be denoted as cases A, B, and C. The component performances for each of the three cases are shown in Table 2. The efficiencies of the energy recovery components are assumed to be independent of the energy of the injected atoms.

Table 2. Injector system energy recovery performance.

Case	η_{Ti}, i = 1, 2, 3, 4	η_{Ti}, i = 5, 6, 7	η_{D1}	η_{D2}
A	0.45	0.45	0.9	0.9
B	0.25	0.45	0.9	0.7
C	0.0	0.45	0.9	0.0

For all three cases the direct conversion of the energy of the charged particles leaving the neutralizer is assumed to be 90%. An experimental direct convertor which consisted of a gridded Faraday Cup was tested. A direct conversion efficiency of 94.8% was obtained for a hydrogen ion energy of 1.8 keV[23] with a power density of 0.12 W/cm^2 and a current density of 0.07 mA/cm^2. However at higher power and current densities, and if the vacuum-pump power and other requirements are considered, the efficiency of the beam direct convertor may be only 90%. Another type of beam direct conversion, which uses a "Venetian blind" concept, has an estimated conversion efficiency of 90%.[24]

Also for all three cases, the thermal convertors backing the direct convertors and recovering the losses to the reactor first wall are assumed to be 45% efficient. This efficiency is based on a cycle operating at 60% of a Carnot cycle with source and sink temperatures of 900°C and 27°C respectively.

The injected atoms that penetrate the reactor plasma may be stripped of an electron and the energy partially recovered in a direct convertor. For the purpose of this study, the direct conversion efficiency may be either 70% (Case B), 90% (Case A), or zero (Case C). For Case C, the neutral atoms penetrating the reactor plasma are allowed to impinge directly on the reactor first wall, and the atom energy is partially recovered in a thermal convertor.

The losses that occur in the source, alkali-metal-vapor cell, and accelerators are assumed to be partially recovered in thermal convertors with efficiencies of 45% (Case A), 25% (Case B), and not recovered (Case C).

Because all the thermal convertor efficiencies are based on a 27°C sink temperature, no additional thermal conversion can be performed on the injector system.

CIRCULATING POWER AND CURRENT OF A NEUTRAL-BEAM INJECTOR SYSTEM

There are other aspects of neutral beam injector systems to be considered besides the injector efficiency. The first consideration is the circulating power within the injector system which is defined as the ratio of the accelerator power (P_{acc}) to the trapped power (P_T). The circulating power should be minimized to reduce the operating cost of the injector system. For the power-flow diagram of the injector system (in Fig. 3),

$$\frac{P_{acc}}{P_T} = \frac{1 + \frac{E^+}{ME}\left(\frac{1 - \eta_{+-}\,\eta_{a1}}{\eta_{+-}\,\eta_{a1}}\right)}{\eta_{a2}\, f_n\, f_T} .$$

For the injection system utilizing ions directly from the source,

$$\frac{P_{acc}}{P_T} = \frac{1}{\eta_{a2}\, f_n\, f_T} .$$

Another consideration is the circulating current which is defined as the ratio of the beam current from the source (I_S) to the beam current trapped in the plasma (I_T). The circulating current should be also minimized to reduce the cost of the injection components. For the injection system shown in Fig. 3

$$\frac{I_S}{I_T} = \frac{1}{\eta_{a1}\,\eta_{+-}\,\eta_{a2}\, f_n\, f_T\, M} ,$$

which reduces to

$$\frac{I_S}{I_T} = \frac{1}{\eta_{a2}\, f_n\, f_T\, M} = \frac{P_{acc}}{M\, P_T}$$

for an injection system utilizing ions directly from the source.

EFFECT OF PARTICLE SPECIES ON INJECTOR EFFICIENCY

Deuterium Atom Injection

The overall system efficiency of a deuterium atom injection system as a function of the energy of the injected deuterium atom for a variety of deuterium ion types is shown in Figs. 7 through 12. The results for energy recovery component performances

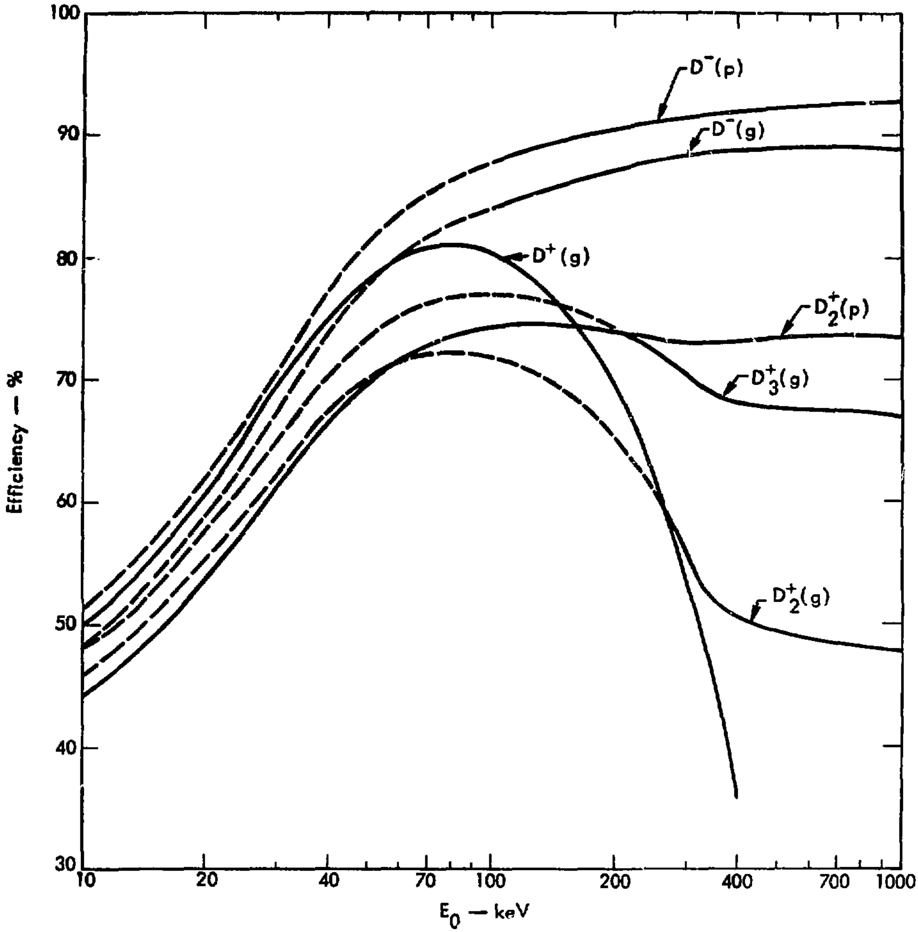

Fig. 7. The efficiency of the injection system as a function of the energy of the injected deuterium atoms, where $q = 0.5$ keV, $\eta_{Ti} = 0.45 (i = 1, \ldots, 7)$, $\eta_{D1} = \eta_{D2} = 0.9$, $\eta_{a2} = 0.92$, $\eta_{a1} = \eta_{+-} = 1$, $E^+ = 0$. The dashed lines indicate the use of extrapolated values of the neutralizer power efficiency in the calculation.

of Case A are shown in Figs. 7 and 8, for Case B in Figs. 9 and 10, and for Case C in Figs. 11 and 12. The dashed portions of these and subsequent curves indicate where extrapolated values of the neutralizer power efficiency were used.

The highest overall injection efficiency is obtained using negative deuterium ions produced in the source and neutralized in a plasma. However of the other ions, at low injection energies the positive deuterium ions have the highest overall injection system efficiency. At higher injection energies, the negative deuterium ions have the highest

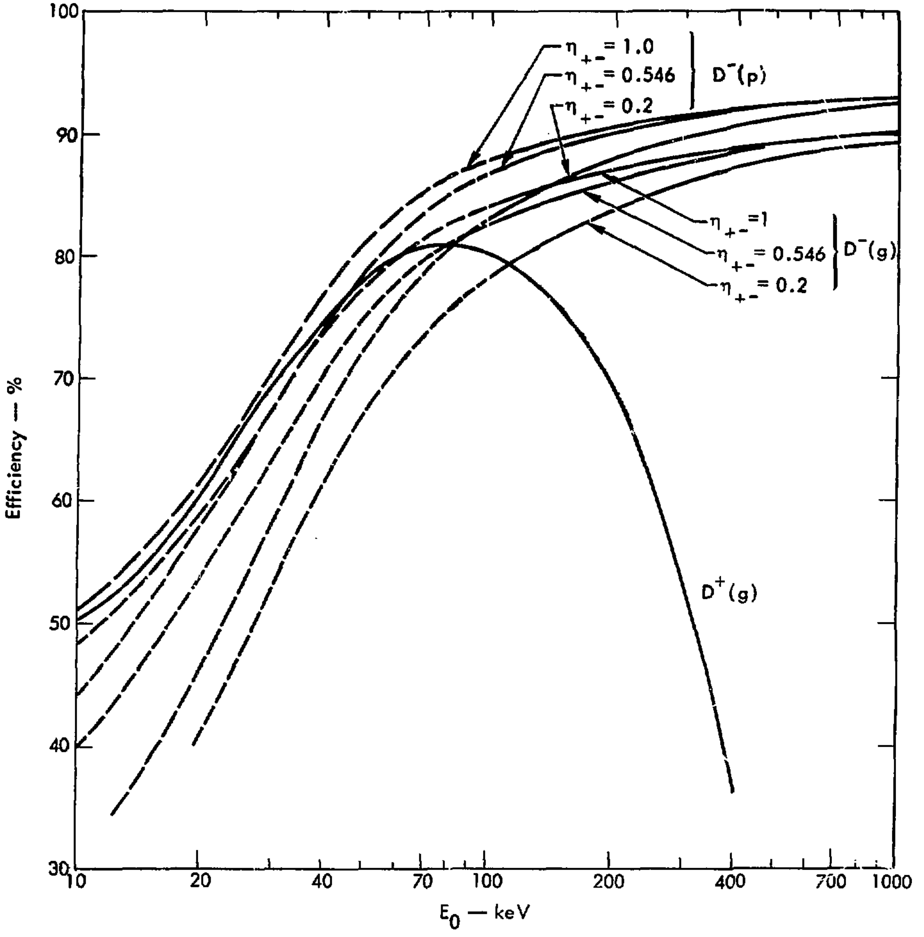

Fig. 8. The efficiency of the injection system as a function of the energy of the injected deuterium atoms, where $q = 0.5$ keV, $\eta_{Ti} = 0.45$ ($i=1, \ldots, 7$), $\eta_{D1} = \eta_{D2} = 0.9$, $\eta_{a1} = \eta_{a2} = 0.92$, and $E^+ = 1.5$ keV.

overall injection efficiency. At very high energies, the efficiency of the alkali-metal-vapor cell does not have much effect on the overall injection system efficiency. At high energies the neutralization of D_2^+ by dissociation in a plasma is so much better than in a gas that the neutralization of D_3^+ by dissociation in a plasma may be interesting. Unfortunately data on the neutralization of D_3^+ in a plasma is not yet available.

The ratio of the accelerator power to the trapped power of a deuterium atom injection system as a function of the injected deuterium atom energy for a variety of

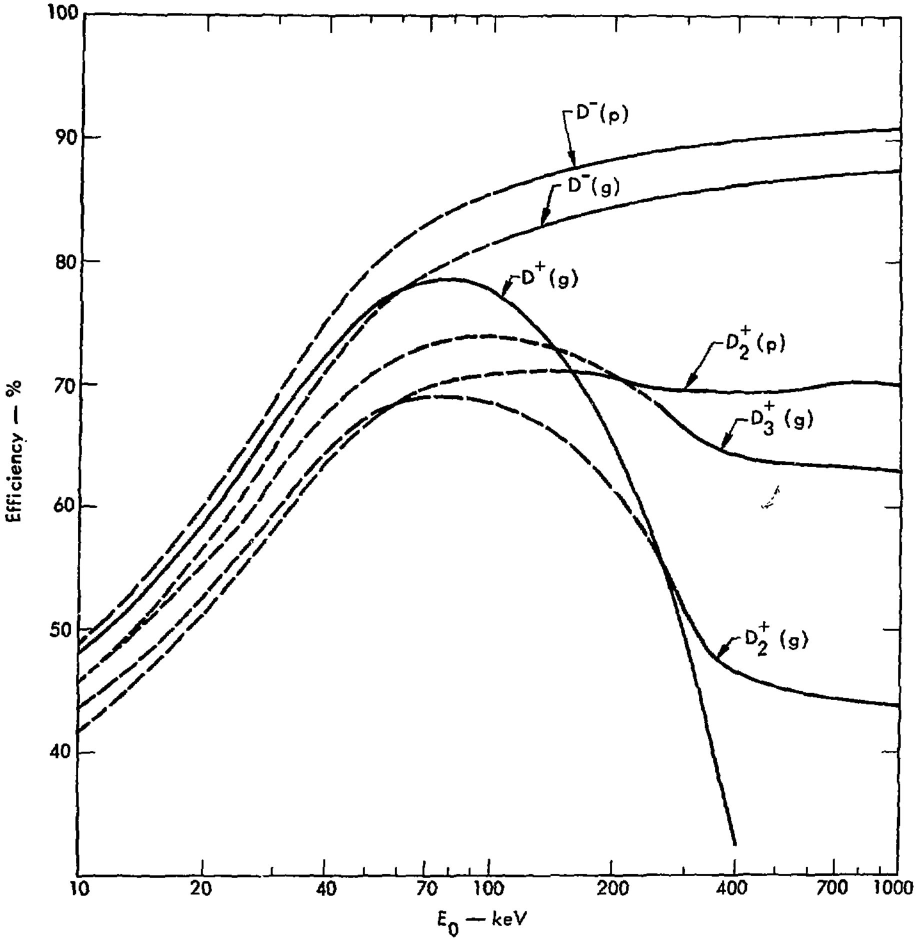

Fig. 9. The efficiency of the injection system as a function of the energy of the injected deuterium atoms, where q = 0.5 keV, η_{Ti} = 0.25 (i = 1, 2, 3, 4), η_{Ti} = 0.45 (i = 5, 6, 7), η_{D1} = 0.9, η_{D2} = 0.7, η_{a2} = 0.92, η_{a1} = η_{+-} = 1, and E^+ = 0.

deuterium ion types is shown in Figs. 13 and 14. To minimize the cost of operation of the injector system, the ratio of the accelerator power to the trapped power must be a minimum. As with the overall injector efficiency, the minimum circulating power occurs using negative deuterium ions produced directly in a source and neutralized in a plasma cell. For low injection energies, positive deuterium ions will require less circulating power than the other ions. At higher energies, the negative deuterium ions require the least circulating power. Again, as for the overall injection efficiency, at

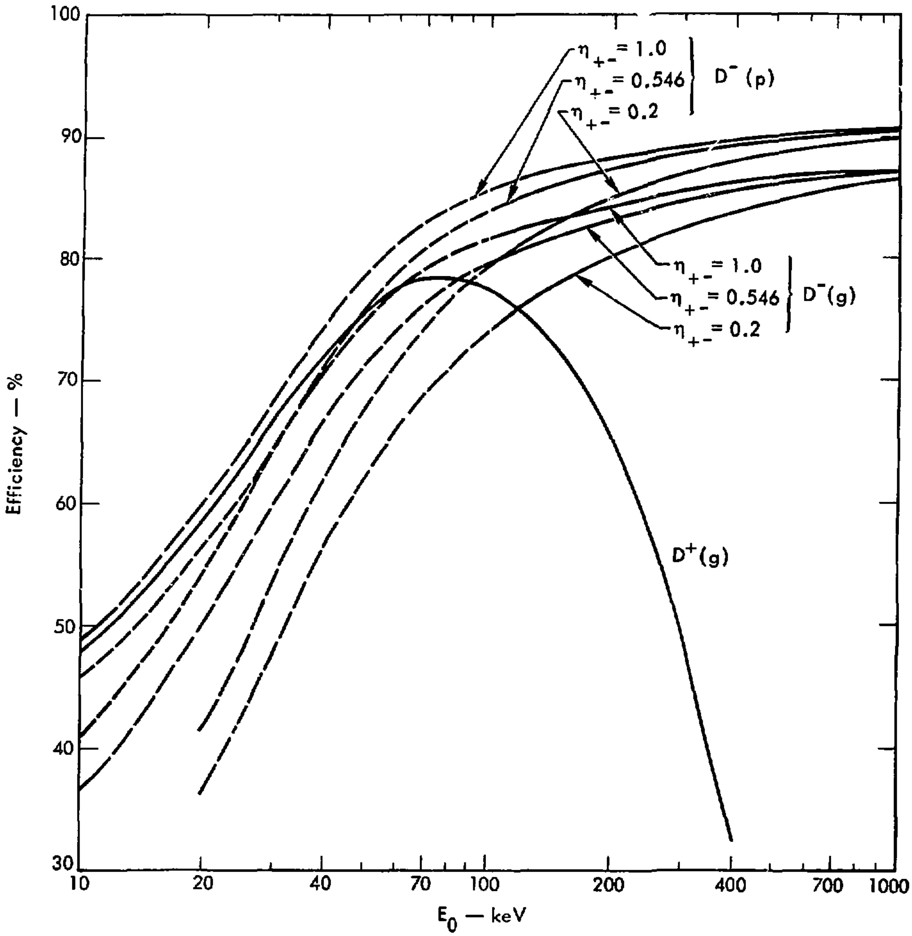

Fig. 10. The efficiency of the injection system as a function of the energy of the injected deuterium atoms, where q = 0.5 keV, η_{Ti} = 0.25 (i = 1, 2, 3, 4), η_{Ti} = 0.45 (i = 5, 6, 7), η_{D1} = 0.9, η_{D2} = 0.7, η_{a1} = η_{a2} = 0.92, and E^+ = 1.5 keV.

high energies the efficiency of the alkali-metal-vapor cell does not have a large effect on the circulating power of the injection system.

The ratio of the source beam current to the trapped beam current of a deuterium atom injection system as a function of the injected deuterium atom energy for a variety of deuterium ion types is shown in Figs. 15 and 16. To minimize the number and size of the injection system components, the circulating current must be at a minimum. The minimum circulating current occurs using negative deuterium ions produced in

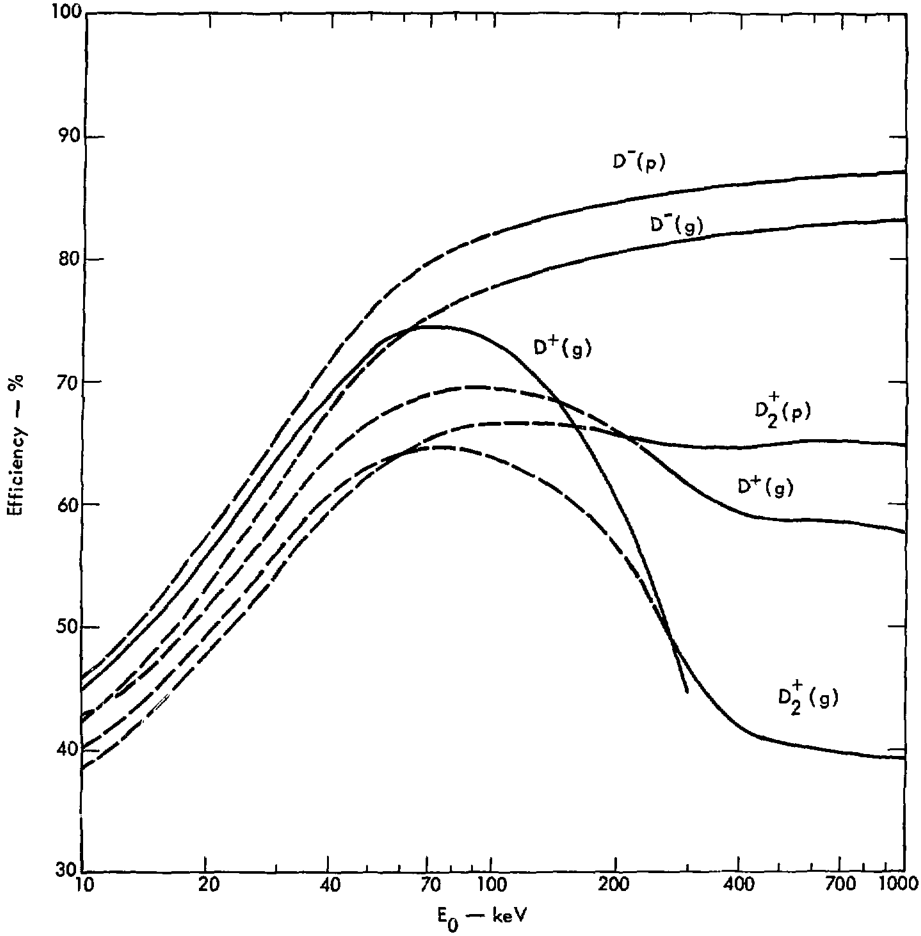

Fig. 11. The efficiency of the injection system as function of the energy of the injected deuterium atoms, where q = 0.5 keV, η_{Ti} = 0.0 (i = 1, 2, 3, 4), η_{Ti} = 0.45 (i = 5, 6, 7), η_{D1} = 0.9, η_{D2} = 0, η_{a1} = η_{+-} = 1.0, and E^+ = 0.

the source and neutralized in a plasma, but at low energies the D_3^+ ion results in a smaller circulating current than the other ions. At higher energies the smallest circulating current was obtained for negative deuterium ions coming directly from the source. If alkali-metal-vapor cells are used to produce the negative deuterium ions, the circulating current becomes very large resulting in a decrease in the efficiency of the alkali-metal-vapor cell.

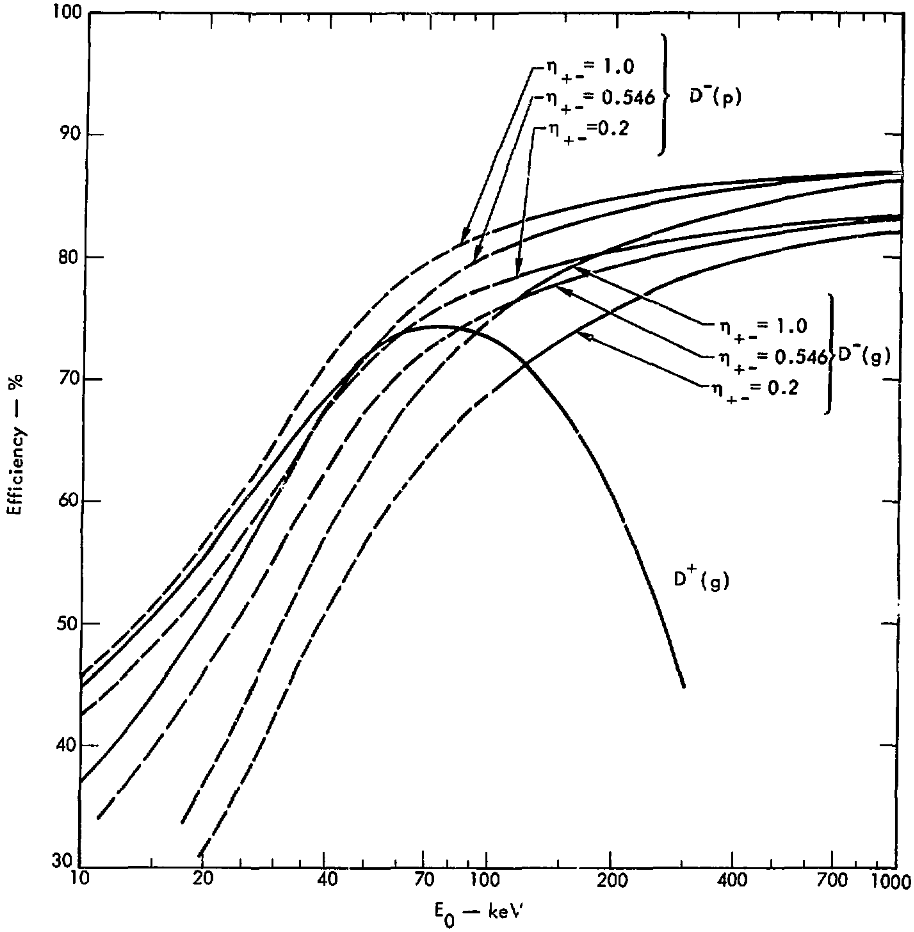

Fig. 12. The efficiency of the injection system as a function of the energy of the injected deuterium atoms, where q = 0.5 keV, η_{Ti} = 0 (i = 1, 2, 3, 4), η_{Ti} = 0.45 (i = 5, 6, 7), η_{D1} = 0.9, η_{D2} = 0, η_{a1} = η_{a2} = 0.92, and E^+ = 1.5 keV.

Tritium Atom Injection

Assuming that the fraction of neutrals formed in a neutralizer from a given hydrogen isotope is dependent only on the velocity of the entering ion, tritium ions will have a greater fraction of ions neutralized than deuterium ions of the same energy. If the reaction rate coefficients for charge exchange and ionization of the injected atoms in the plasma are dependent only on the velocity of the entering atom, the fraction of atoms trapped will be lower for tritium than for deuterium atoms of the same energy. Thus, at low injection energies, the efficiency of a tritium, neutral-beam injector

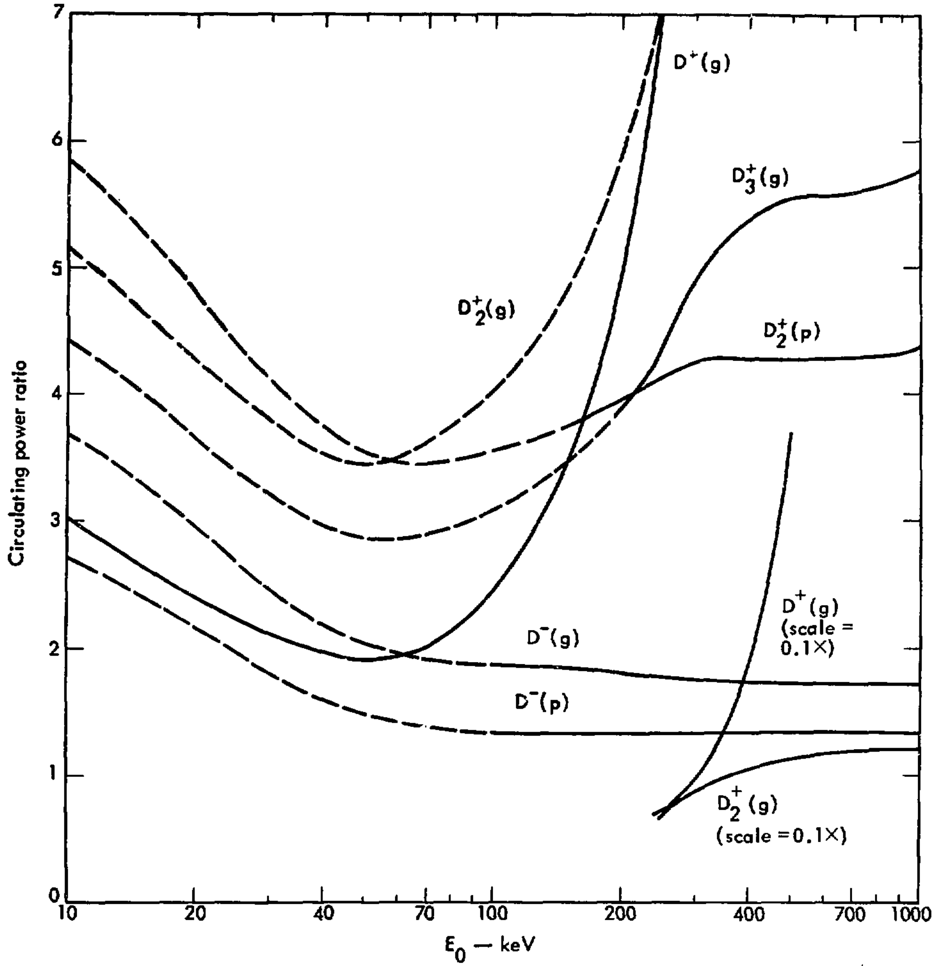

Fig. 13. The ratio of accelerator power to trapped power as a function of the energy of the injected deuterium atoms, where $\eta_{a2} = 0.92$, $\eta_{a1} = \eta_{+-} = 1.0$, and $E^+ = 0$.

system will be less than that of a deuterium, neutral-beam injector for the same energy of injected beam. The tritium, neutral-beam injection system is more efficient than the deuterium, neutral-beam injection system only at energies where the fraction of deuterium ions neutralized decreases with energy more rapidly than the trapping fraction increases with energy.

The overall system efficiency of a tritium-atom injection system as a function of the injected tritium atom energy for a variety of tritium ion types is shown in Figs. 17

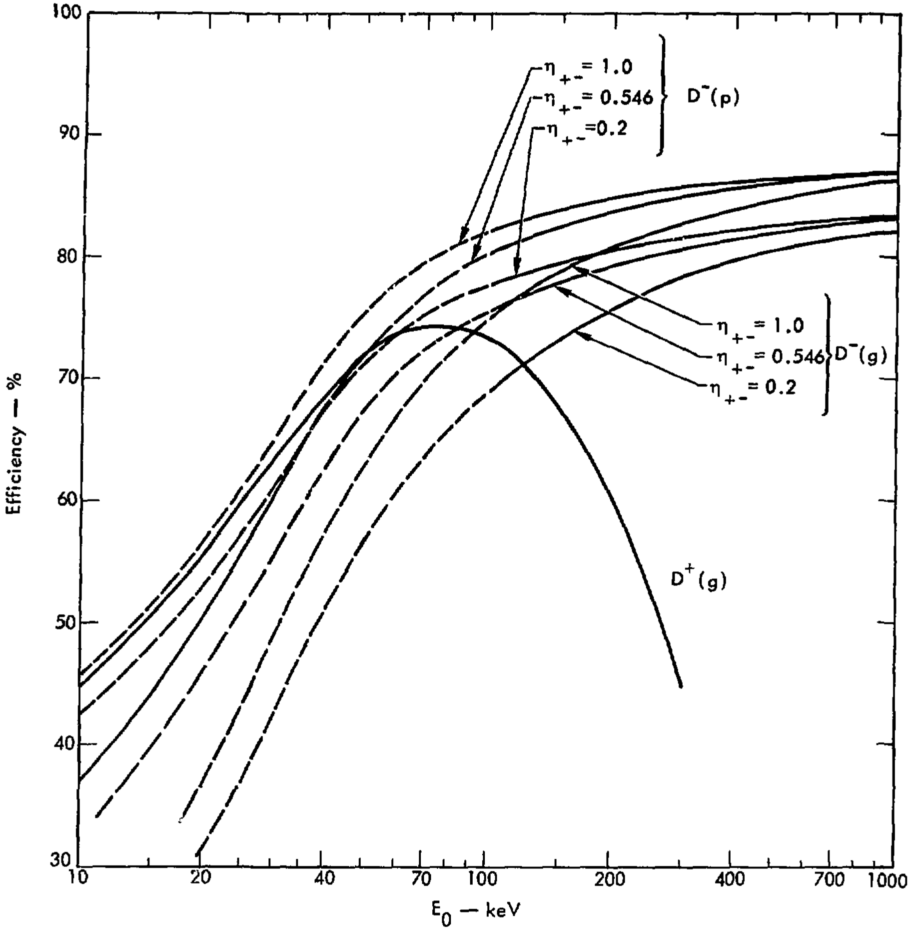

Fig. 12. The efficiency of the injection system as a function of the energy of the injected deuterium atoms, where q = 0.5 keV, η_{Ti} = 0 (i = 1, 2, 3, 4), η_{Ti} = 0.45 (i = 5, 6, 7), η_{D1} = 0.9, η_{D2} = 0, $\eta_{a1} = \eta_{a2}$ = 0.92, and E^+ = 1.5 keV.

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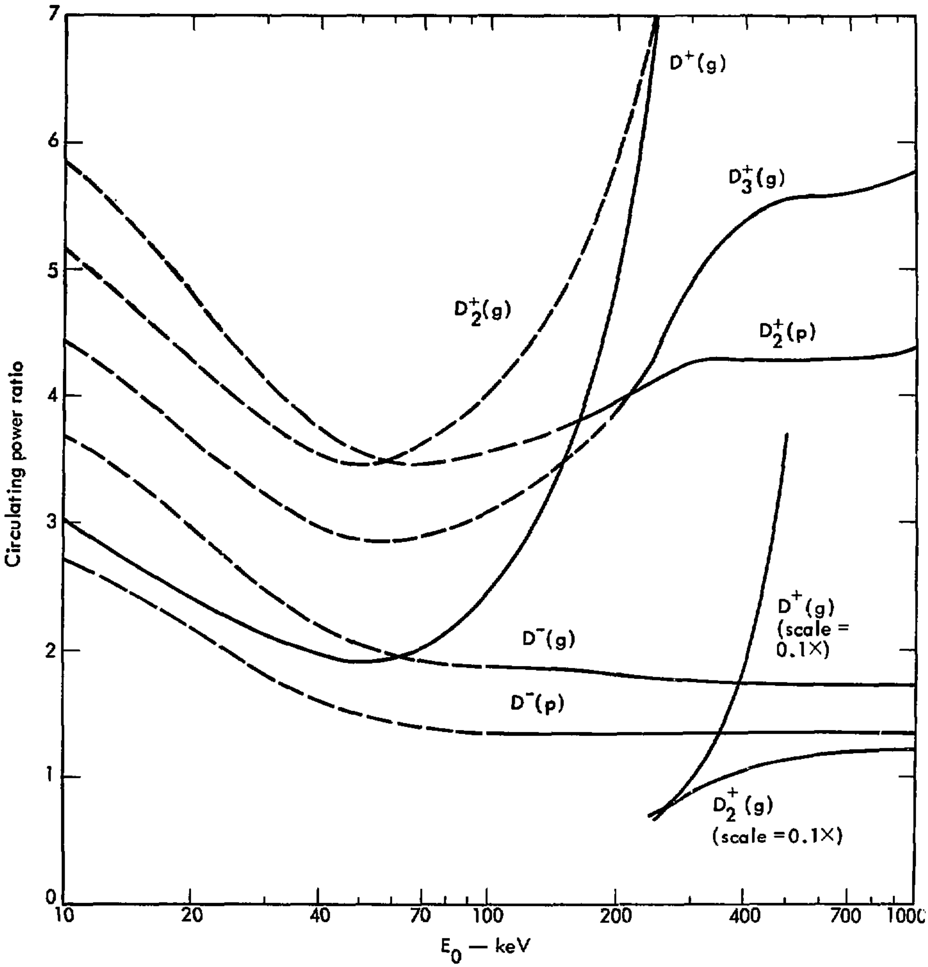

Fig. 13. The ratio of accelerator power to trapped power as a function of the energy of the injected deuterium atoms, where $\eta_{a2} = 0.92$, $\eta_{a1} = \eta_{+-} = 1.0$, and $E^+ = 0$.

system will be less than that of a deuterium, neutral-beam injector for the same energy of injected beam. The tritium, neutral-beam injection system is more efficient than the deuterium, neutral-beam injection system only at energies where the fraction of deuterium ions neutralized decreases with energy more rapidly than the trapping fraction increases with energy.

The overall system efficiency of a tritium-atom injection system as a function of the injected tritium atom energy for a variety of tritium ion types is shown in Figs. 17

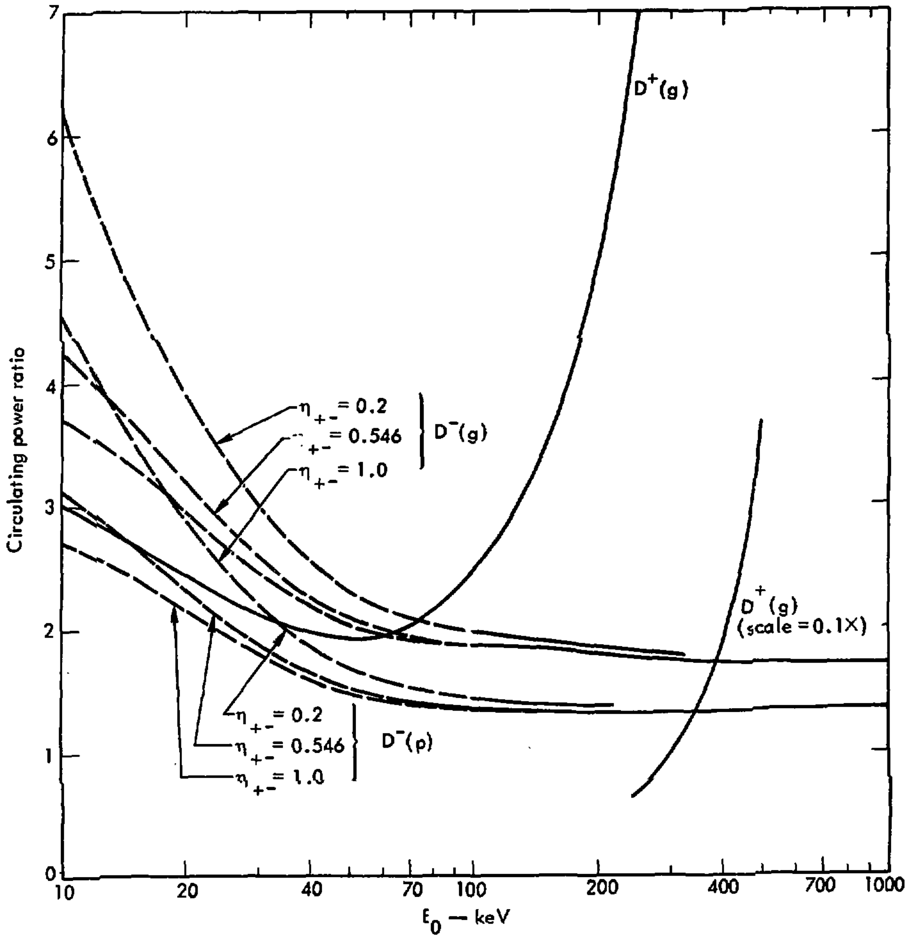

Fig. 14. The ratio of accelerator power to trapped power as a function of the energy of the injected deuterium atoms, where $\eta_{a1} = \eta_{a2} = 0.92$ and $E^+ = 1.5$ keV.

and 18 for Case B, energy-recovery component performances. The ratio of the accelerator power to the trapped power of a tritium atom injection system as a function of the energy of injected tritium atoms for a variety of tritium ion types is shown in Figs. 19 and 20. The ratio of the source beam current to the trapped beam current of a tritium atom injection system as a function of the energy of injected tritium atoms for a variety of tritium ion types is shown in Figs. 21 and 22.

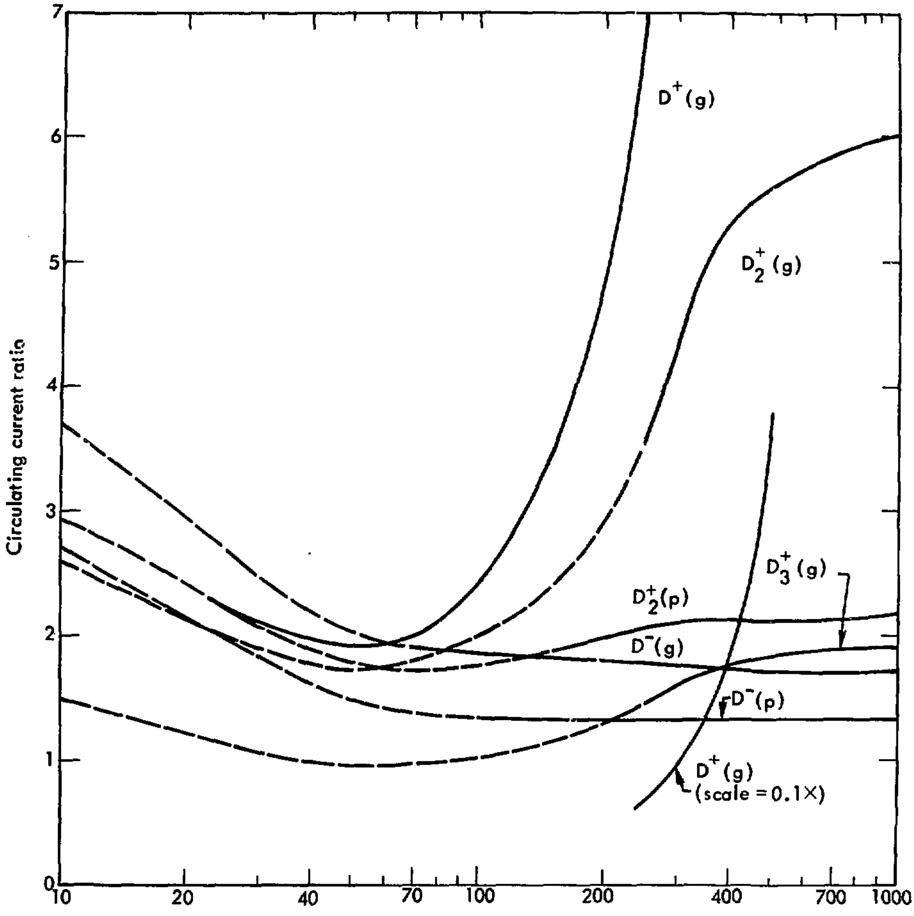

Fig. 15. The ratio of the source beam current to the trapped beam current as a function of the energy of the injected deuterium atoms, where η_{a2} = 0.92 and $\eta_{a1} = \eta_{+-}$ = 1.

^{3}He Injection

The injection of ^{3}He is of interest since ^{3}He is a fuel for some advanced fusion cycles.[25,26] Negative ^{3}He ions can be produced in an alkali-metal-vapor cell from 2.25-keV positive ^{3}He ions with a 1.2% positive to negative ion conversion fraction.[27] Thus from Eq. (3), for a cell transmission of 95%, the positive to negative ion conversion efficiency is 1.14% for one cell and 4.16% for four cells.

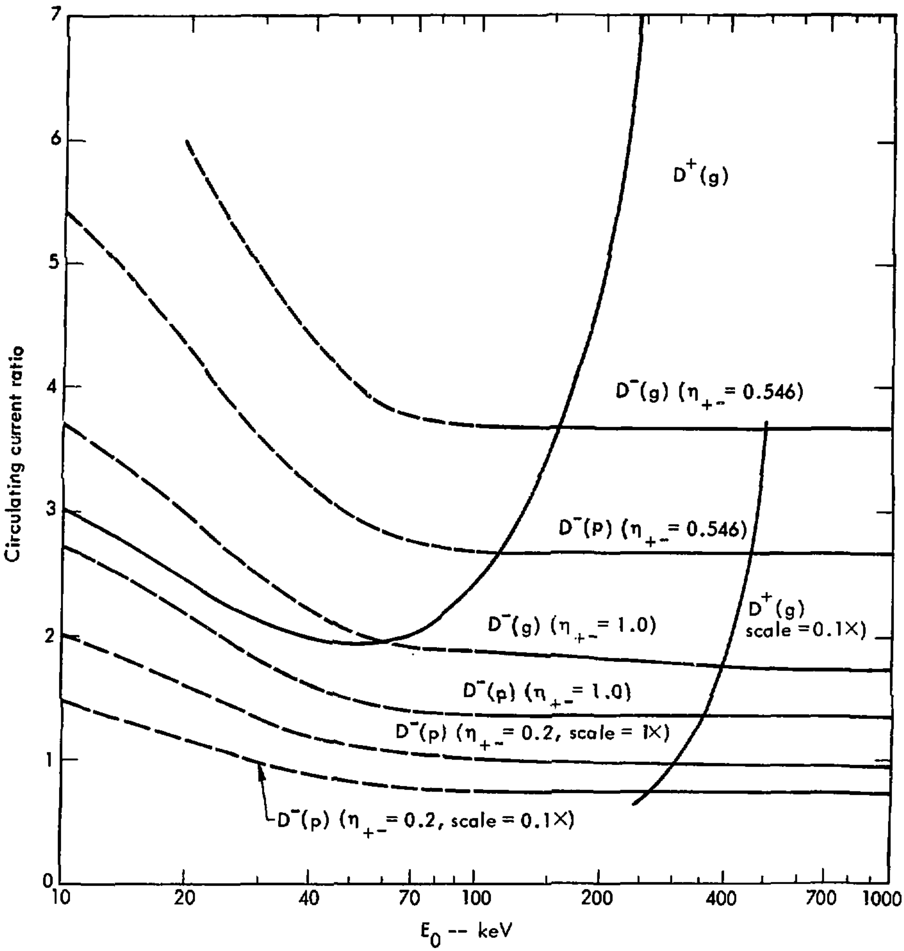

Fig. 16. The ratio of the source beam current to the trapped beam current as a function of the energy of the injected deuterium atoms, where $\eta_{a1} = \eta_{a2} = 0.92$.

The power neutralization efficiency of positive ^3He ions shown as a function of ^3He energy in Fig. 23 is taken from Allison and Garcia-Munoz[18] for ^4He in a helium gas cell, with the yield assumed to be dependent only on the velocity of the helium isotope entering the cell. Riviere discusses the breakup of $^3HeH^+$ and gives data from Wilson[28] which indicates a 12% neutralization at a ^3He energy of 340 keV. Berkner et al.[29] indicate a 25% neutral ^3He yield at a ^3He energy of 300 keV for $^3HeH^+$ at 400 keV in an optimized gas cell. Thus, the power neutralization efficiency of $^3HeD^+$

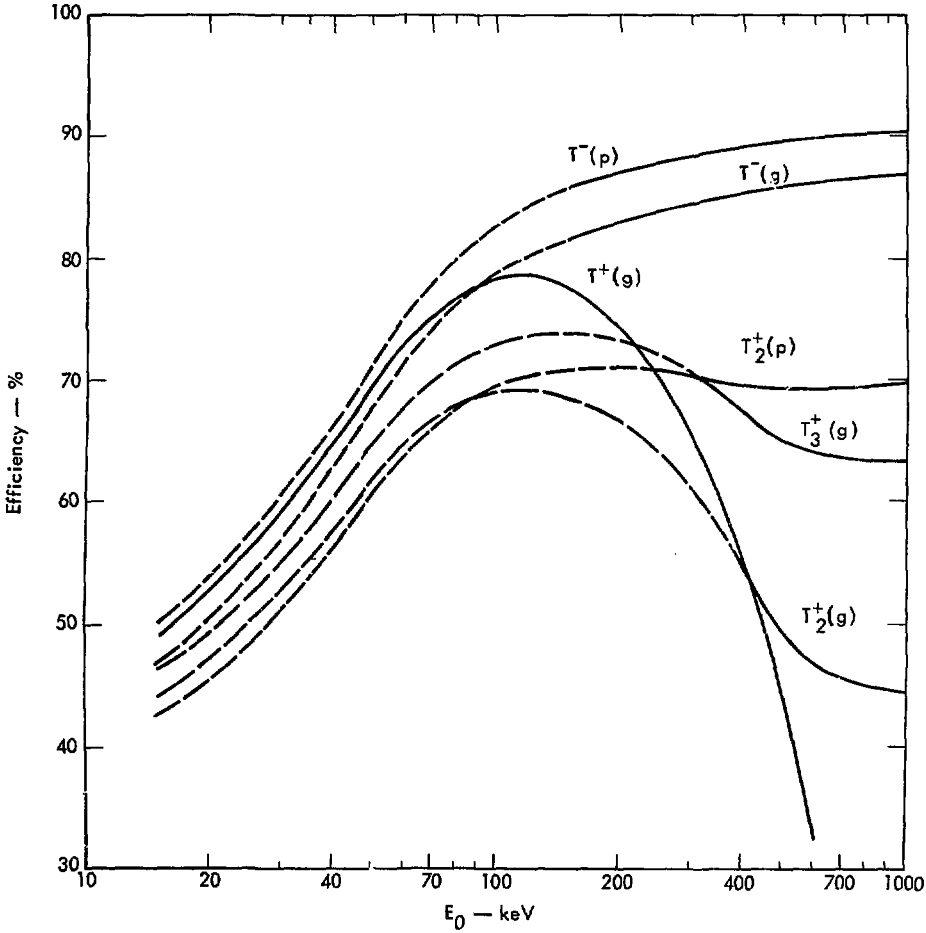

Fig. 17. The efficiency of the injection system as a function of the energy of the injected tritium atoms, where q = 0.5 keV, η_{Ti} = 0.25 (i = 1, ...4), η_{Ti} = 0.45 (i = 5, 6, 7), η_{D1} = 0.9, η_{D2} = 0.7, $\eta_{a1} = \eta_{+-}$ = 1.0, and E^+ = 0.

ions is 7.2 and 18.8% and for $^3HeH^+$ ions is 9 and 15% at a ^3He energy of 340 and 300 keV. Berkner et al.[30] measured the dissociation cross section of $^3HeH^+$ at higher energies than measured by Wilson. Since the cross sections decrease with energy, the neutralization efficiency will also decrease with energy. For negative ^3He ions a power neutralization efficiency of 95%, which may be accomplished in a gas or plasma cell or by field ionization, is assumed for this paper.

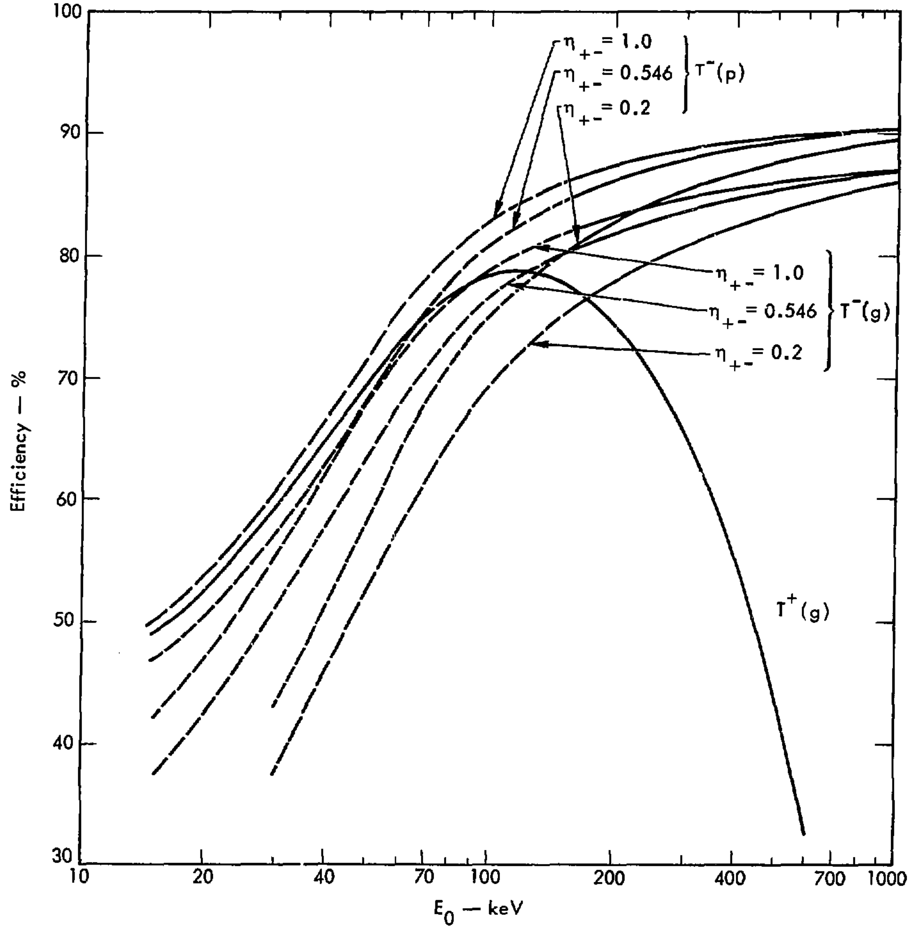

Fig. 18. The efficiency of the injection system as a function of the energy of the injected tritium atoms, where q = 0.5 keV, η_{Ti} = 0.25 (i = 1, 2, 3, 4), η_{Ti} = 0.45 (i = 5, 6, 7), η_{D1} = 0.9, η_{D2} = 0.7, $\eta_{a1} = \eta_{a2}$ = 0.92, and E^{+} = 2.25 keV.

The effect of charge-exchange on the injected ^{3}He atoms by reactor plasma is assumed to be very small ($\langle \sigma v \rangle_T \approx \langle \sigma v \rangle_i$). Thus from Eqs. (5) and (6),

The overall system effeciency of a ^{3}He-atom injection system as a function of the energy of the injected ^{3}He atoms is shown in Fig. 24 for a variety of ^{3}He ion types and Case-B, energy-recovery component performances. The ratio of the accelerator power to the trapped power and the ratio of the source beam current to the trapped current of a ^{3}He-atom injection system are shown in Figs. 25 and 26

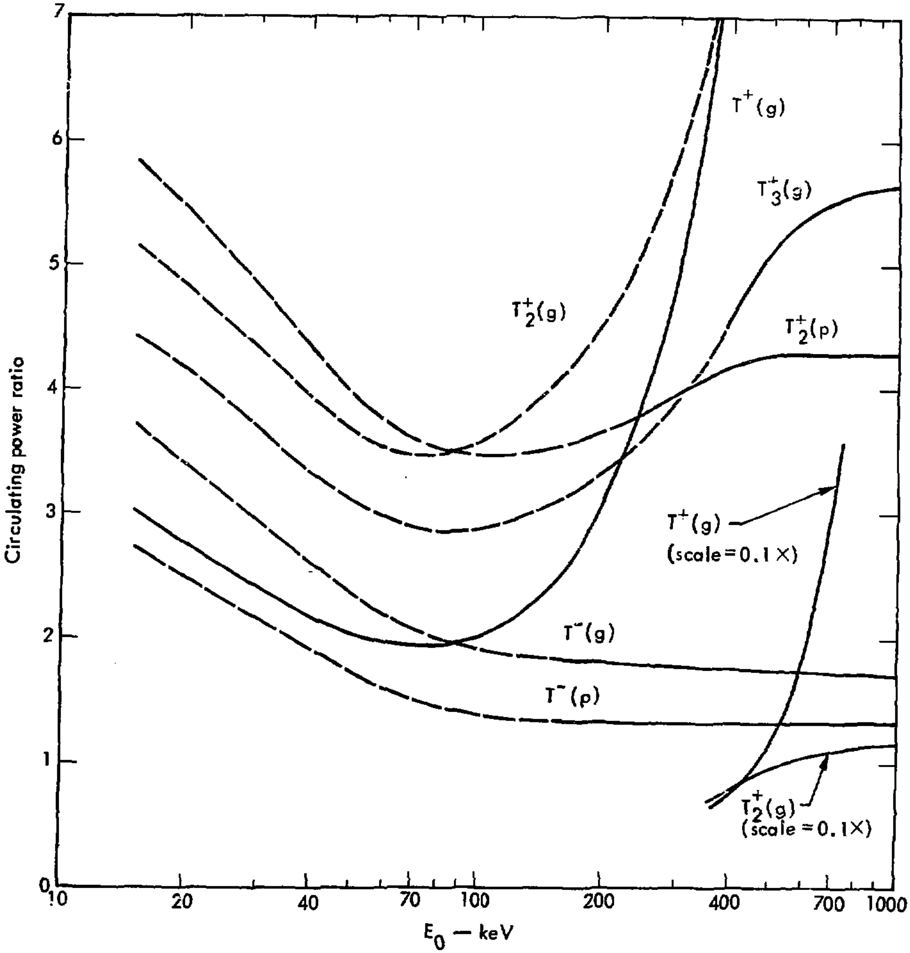

Fig. 19. The ratio of accelerator power to trapped power as a function of the energy of the injected tritium atoms, where $\eta_{a2} = 0.92$, $\eta_{a1} = \eta_{+-} = 1.0$, and $E^+ = 0$.

respectively as functions of the energy of the injected ^3He atoms for a variety of ^3He ion types.

$$f_t \approx 1 - \exp\left[\frac{-Dn\langle\sigma v\rangle_T}{v_0}\right] = 0.95$$

$$f_p = \exp\left[-\frac{Dn\langle\sigma v\rangle_T}{v_0}\right] = 0.05,$$

and

for

$$\gamma \equiv \frac{Dn\langle\sigma v\rangle_T}{v_0} = 3.$$

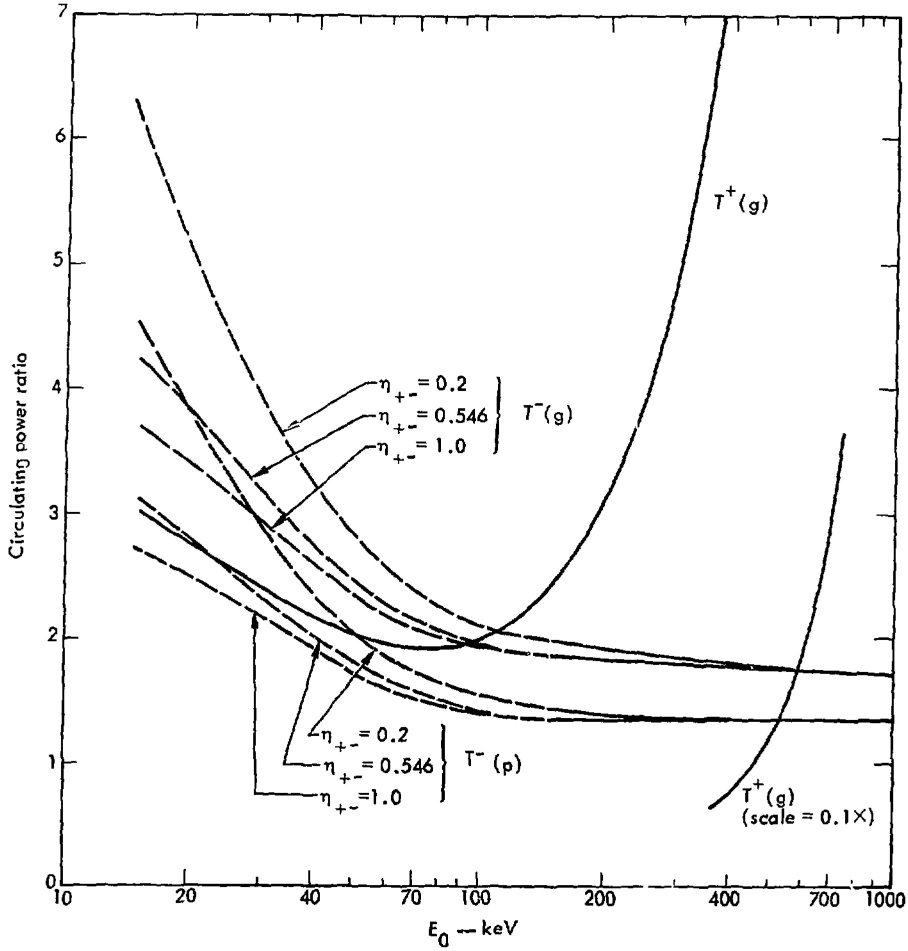

Fig. 20. The ratio of accelerator power to trapped power as function of the energy of injected tritium atoms, where $\eta_{a1} = \eta_{a2} = 0.92$ and $E^+ = 2.25$ keV.

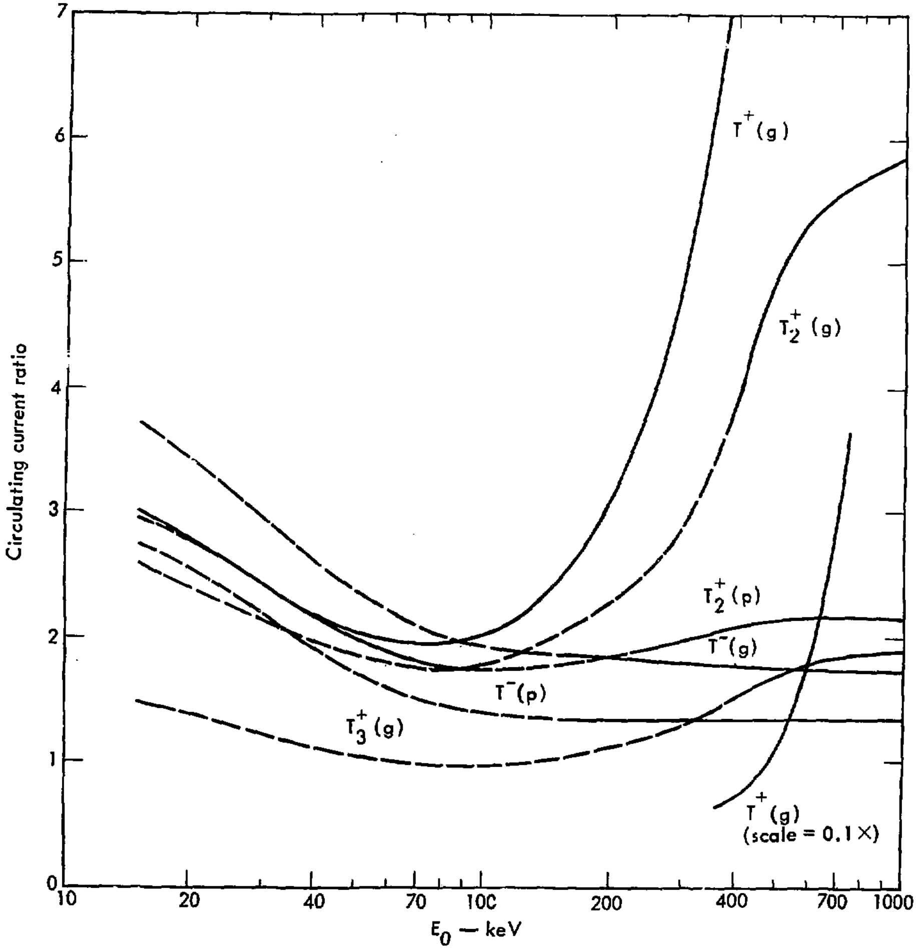

Fig. 21. The ratio of the source beam current to the trapped beam current as a function of the energy of the injected tritium atoms, where $\eta_{a2} = 0.92$ and $\eta_{a1} = \eta_{+-} = 1$.

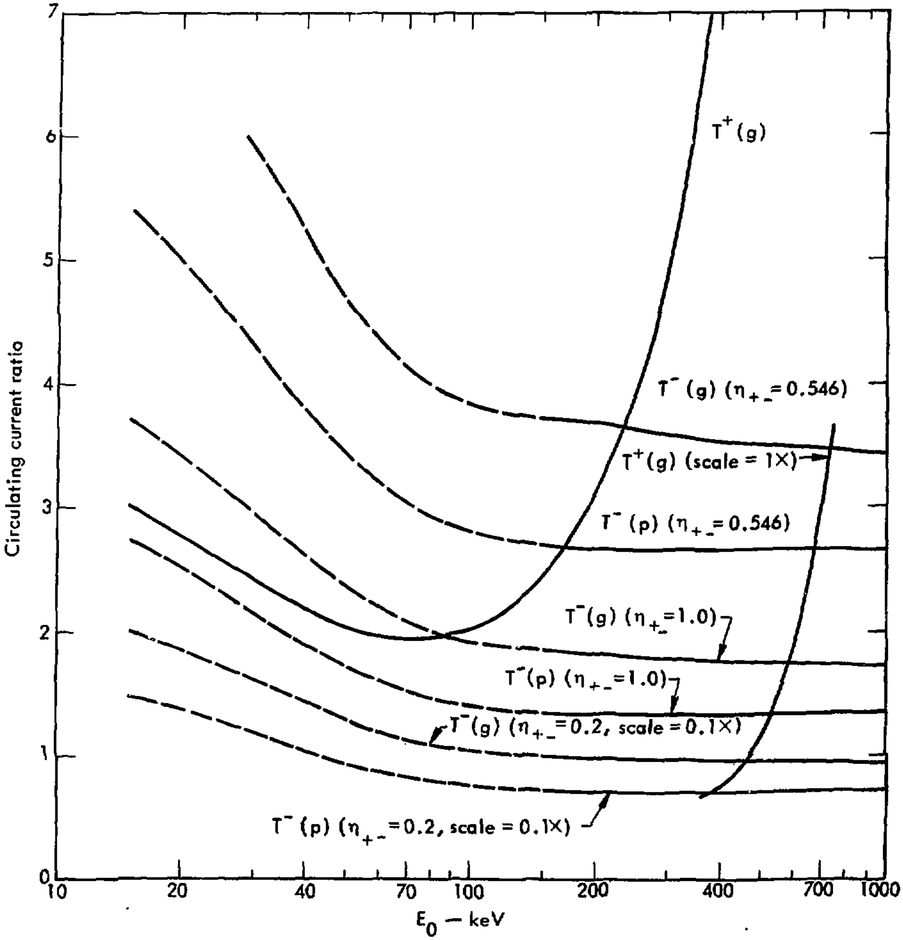

Fig. 22. The ratio of the source beam current to the trapped beam current as a function of the energy of the injected tritium atoms, where $\eta_{a1} = \eta_{a2} = 0.92$.

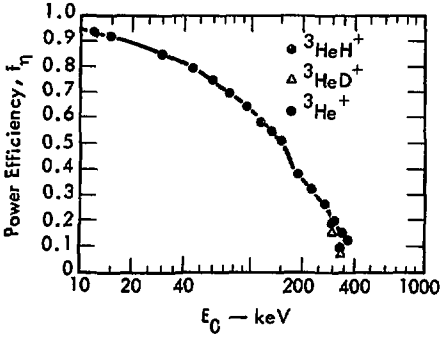

Fig. 23. The power efficiency of the neutralizer as a function of the energy of the ^3He atoms for a helium gas cell.

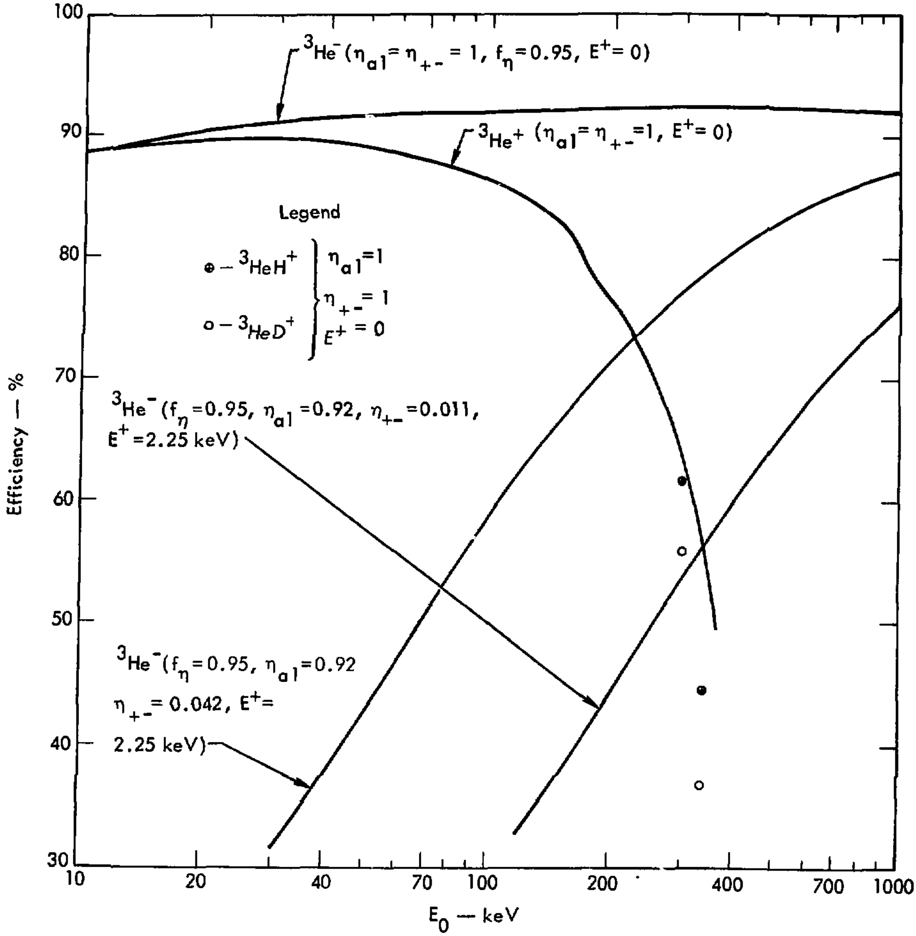

Fig. 24. The overall efficiency of the injection system as a function of the energy of the injected ^3He atoms, where $q = 0.5$, $\eta_{Ti} = 0.25$ ($i = 1, 2, 3, 4$), $\eta_{Ti} = 0.45$ ($i = 5, 6, 7$), $\eta_{D1} = 0.9$, $\eta_{D2} = 0.7$, and $f_T = 0.95$.

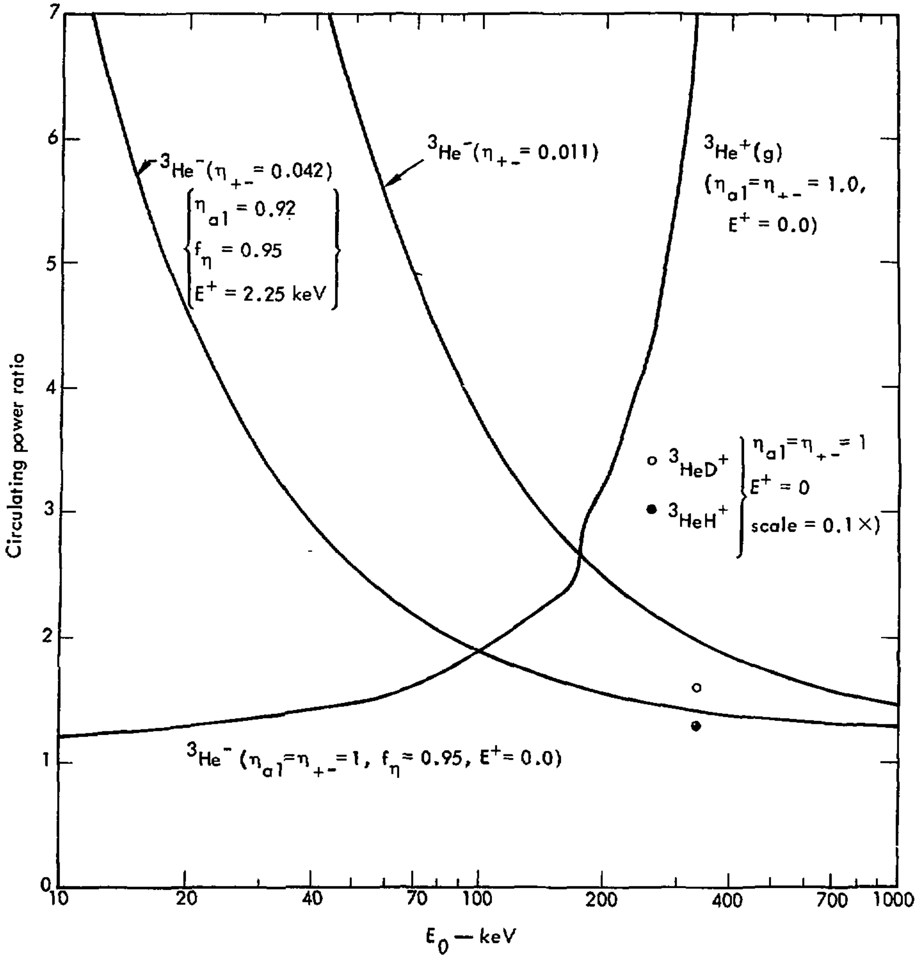

Fig. 25. The ratio of accelerator power to trapped power as a function of the energy of the injected ^{3}He atoms, where $f_T = 0.95$ and $\eta_{a2} = 0.92$

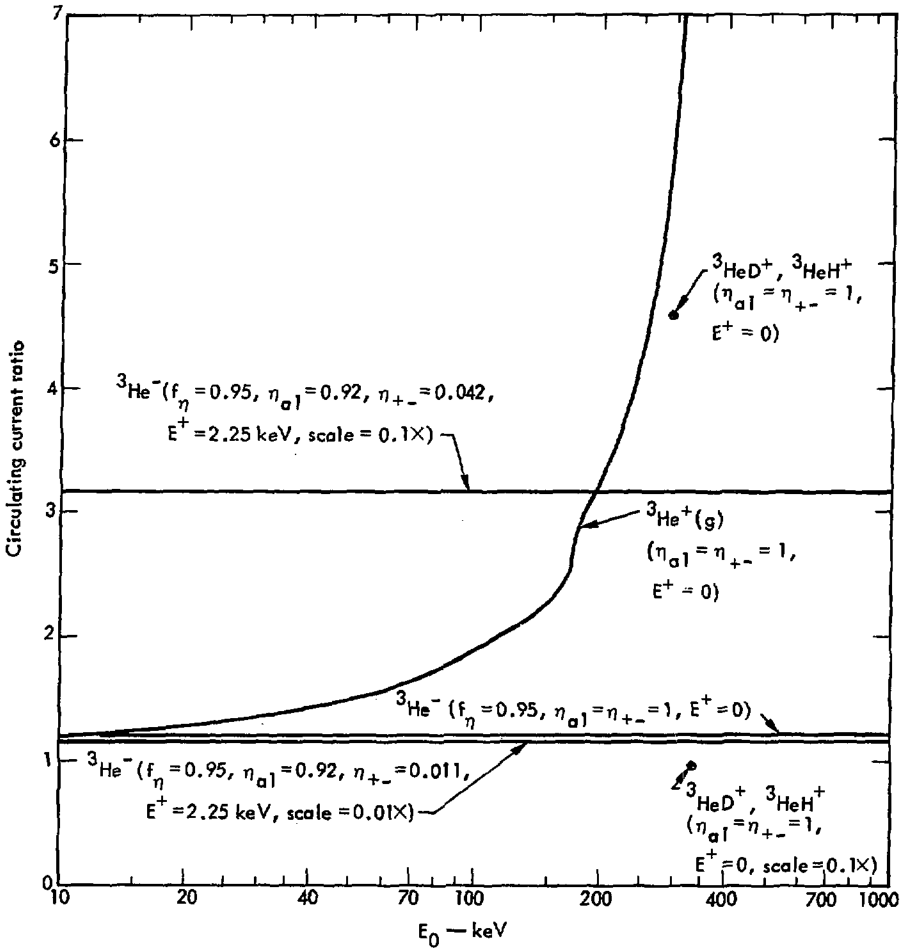

Fig. 26. The ratio of the source beam current to the trapped beam current as a function of the energy of the injected ^3He atom (95% trapping fraction).

Conclusions

Under the assumptions made in this study, the following important generalizations can be made:

For neutral-hydrogen-isotope injection,

1. The highest overall injection efficiency and the lowest circulating power can be achieved when negative ions are produced in the source and neutralized in a plasma cell.
2. For injection energies above 100 keV, the use of negative ions can achieve overall injection efficiencies in the range of 80 to 90%.
3. Around 100 keV (180 keV for T^+), D^+ ions give a higher overall injection efficiency than the D_2^+ and D_3^+ ions studied.
4. Below 100 keV the overall system efficiency decreases due to the loss of plasma ions by charge-exchange with the neutral beam.
5. The circulating power for injection energies above 100 keV is about 1.5 times the trapped power for negative hydrogen isotopes, and much greater for the other types of hydrogen isotope ions investigated.
6. The circulating current for injection energies above 100 keV is about 1.5 times the trapped current for negative hydrogen isotopes produced in the source, but is strongly dependent on the method of production of negative ions, varying inversely with the efficiency of the alkali-metal-vapor cell.
7. Dissociation cross-section measurements should be made for D_3^+ in a plasma since this molecular ion may be injected with a high efficiency and low circulating power and current.
8. The cross section for the conversion of D^- to D^0 in a plasma and a gas should be measured, since D^- can be injected with the highest efficiencies of the deuterium molecular and atomic ions investigated, and since the neutralizer power efficiency curves for the D^- ion are based only on calculated cross sections.

For neutral ^3He injection,

1. The use of $^3He^+$ below injection energies of 200 keV may allow the achievement of overall injection system efficiencies of 80%.
2. The use of $^3He^-$ between 200 and 700 keV results in an overall system efficiency of less than 70% because the conversion of helium from positive to negative ions is only about 1% efficient. For higher injection efficiencies, a multistage conversion system or source that emits $^3He^-$ is required.

This study of a neutral injector system predicts an overall injection efficiency of about 90% for deuterium and tritium injection. High energy ^3He injection is predicted to be less than 70% efficient. These efficiencies may decrease when the many practical aspects of an injection system are considered. The sensitivity of the injection efficiency to perturbations in the performance of the system components are reported elsewhere.[31]

The injection of high energy neutrals into a thermonuclear reactor requires large energy conversion and vacuum systems and efficient accelerators which are complex and costly. A conceptual design of a neutral injector system should be the next step in the development of high energy neutral injector systems for thermonuclear reactors.

Acknowledgments

We would like to thank J. E. Osher for discussions especially related to the use of negative ions, A. L. Hunt for the discussion of the fraction of the injected neutral beam which charge-exchanges with the reactor plasma ions giving neutrals that escape the plasma before ionization occurs, and R. W. Werner for his helpful comments. We would also like to thank R. F. Post and T. K. Fowler for their support.

Appendix A:
Derivation of the Expression for the Efficiency of a Neutral-Beam Injection System

The power-flow diagram of a neutral-beam injection system for a thermonuclear reactor is shown in Fig. 3. The ion source produces a current I_0 of ions with an energy loss of q per ion emitted by the source. For simplicity, we assume that only one species of ion is produced by the source. The ion is accelerated to an energy E^+ with an accelerator efficiency η_{a1}, where

$$\eta_{a1} = \frac{\text{accelerator output current}}{\text{accelerator input current}} .$$

Thus the beam current from the first stage accelerator is

$$I_1 = I_0 \, \eta_{a1} .$$

The alkali-metal-vapor cell converts the charge of the incoming ion from positive to negative with a beam efficiency of η_{+-}, where the efficiency of the alkali-metal-vapor cell is defined as the ratio of the positive-charge beam current entering the cell to the negative-charge beam current leaving the cell. Thus, the output current from the alkali-metal-vapor cell is

$$I_2 = \eta_{+-} \, I_1 = \eta_{+-} \, \eta_{a1} \, I_0 .$$

The ion beam is then accelerated to M times the desired injection energy with an efficiency of η_{a2}, where M is the ratio of the mass of the source-ion produced to the mass of the ion trapped in the reactor plasma and η_{a2} is defined in the same way as η_{a1}. Thus the ion beam current from the second accelerator is given by

$$I_3 = \eta_{a2} \, I_2 = \eta_{+-} \, \eta_{a1} \, \eta_{a2} \, I_0 .$$

The gas or plasma neutralizer cell converts a fraction f_n of the current I_3 of ions of mass M to neutrals of unit mass. The output current of the neutralizer is

$$I_4 = f_n \, M \, I_3 = \eta_{+-} \, \eta_{a1} \, \eta_{a2} \, f_n \, M \, I_0 .$$

The fraction $1 - f_n$ of the ion beam entering the neutralizer remains charged. This beam, having an output current of

$$I_4' = (1 - f_n) \, I_3 = \eta_{+-} \, \eta_{a1} \, \eta_{a2} \, (1 - f_n) \, I_0 ,$$

is magnetically separated from the neutral beam. The energy of this charged beam is partially recovered in a direct convertor with efficiency η_{D1}.

The neutral beam enters the reactor plasma. A fraction f_T of this beam is trapped and a fraction f_w of the beam charge exchanges with the plasma ions, with some of the neutrals formed by the charge exchange escaping to the reactor first wall. The fraction $1 - f_T - f_w$ of the neutral beam which passes through the reactor plasma without being trapped may be stripped and the energy recovered in a direct convertor with efficiency η_{D2}.

Thus the trapped beam current is

$$I_T = f_T I_4 = \eta_{+-} \eta_{a1} \eta_{a2} f_n f_T M I_0 .$$

The neutral beam current (from charge exchange) that impinges on the reactor first wall is

$$I_w = f_w I_4 = \eta_{+-} \eta_{a1} \eta_{a2} f_n f_w M I_0 .$$

The neutral beam current that penetrates the plasma is

$$I_p = (1 - f_T - f_w) I_4 = \eta_{a1} \eta_{+-} \eta_{a2} f_n (1 - f_T - f_w) M I_0 .$$

The power of the neutrals which are trapped is

$$P_T = I_T E = \eta_{+-} \eta_{a1} \eta_{a2} f_n f_T M I_0 \left(\frac{E_a}{M}\right) = \eta_{a1} \eta_{+-} \eta_{a2} f_n f_T I_0 E_a, \qquad \text{(A-1)}$$

where E_a is the energy of the ions entering the neutralizer and E is the injection energy of the neutrals.

The power expended to form the ion and to accelerate it to an energy E_a is given by

$$P_{ex} = I_0 (q + E^+) + I_2 (E_a - E^+) = \left[1 + \frac{q}{\eta_{+-} \eta_{a1} E_a} + \frac{E^+}{E_a} \left(\frac{1 - \eta_{+-} \eta_{a1}}{\eta_{+-} \eta_{a1}}\right)\right]$$

$$\times \eta_{+-} \eta_{a1} I_0 E_a. \qquad \text{(A-2)}$$

Consider that the power losses in each of the injector components are partially recovered by the direct and thermal convertors shown in Fig. 1. Then the power recovered is

$$P_{rec} = \eta_{T1} q I_0 + (1 - \eta_{a1}) \eta_{T2} I_0 E^+ + (1 - \eta_{+-}) \eta_{T3} I_1 E^+$$

$$+ (1 - \eta_{a2}) \eta_{T4} I_2 (E_a - E^+) + (1 - f_n) [\eta_{D1} + (1 - \eta_{D1})\eta_{T5}] I_3 E_a$$

$$+ f_w \eta_{T6} I_4 E + (1 - f_T - f_w) [\eta_{D2} + (1 - \eta_{D2}) \eta_{T7}] I_4 E. \qquad \text{(A-3)}$$

Noting that $E = \frac{E_a}{M}$,

$$P_{rec} = \left[\frac{\eta_{T1}\, q}{M\eta_{+-}\, \eta_{a1}\, E} + \frac{E^+}{ME}\left[\left(\frac{1 - \eta_{a1}}{\eta_{a1}\, \eta_{+-}}\right) \eta_{T2} + \left(\frac{1 - \eta_{+-}}{\eta_{+-}}\right) \eta_{T3} - (1 - \eta_{a2})\, \eta_{T4}\right] + (1 - \eta_{a2})\, \eta_{T4} + \eta_{a2}\left((1 - f_n)\left[\eta_{D1} + (1 - \eta_{D1})\, \eta_{T5}\right] + f_n\left\{f_w\, \eta_{T6} + (1 - f_T - f_w)\left[\eta_{D2} + (1 - \eta_{D2})\, \eta_{T7}\right]\right\}\right)\right] M\, \eta_{+-}\, \eta_{a1}\, I_0\, E. \quad \text{(A-4)}$$

The injection system efficiency is defined as

$$\eta_i = \frac{P_T}{P_{ex} - P_{rec}} . \quad \text{(A-5)}$$

Thus, combining Eqs. (A-1), (A-2), (A-3), (A-4), and (A-5) the injection system efficiency is

$$\eta_i = \eta_{a2}\, f_n\, f_T \left[1 + \frac{q}{M\eta_{+-}\, \eta_{a1}\, E}(1 - \eta_{T1}) + \frac{E^+}{ME}\left[\left(\frac{1 - \eta_{+-}\, \eta_{a1}}{\eta_{+-}\, \eta_{a1}}\right) + (1 - \eta_{a2})\, \eta_{T4} - \left(\frac{1 - \eta_{a1}}{\eta_{a1}\, \eta_{+-}}\right)\eta_{T2} - \left(\frac{1 - \eta_{+-}}{\eta_{+-}}\right) \eta_{T3}\right] - (1 - \eta_{a2})\, \eta_{T4} - \eta_{a2}\left((1 - f_n)\left[\eta_{D1} + (1 - \eta_{D1})\, \eta_{T5}\right] + f_n\left\{(1 - f_T - f_w)\left[\eta_{D2} + (1 - \eta_{D2})\, \eta_{T7}\right] + f_w\, \eta_{T6}\right\}\right)\right]^{-1} . \quad \text{(A-6)}$$

For the case where the alkali-metal-vapor cell is not used to change the ion charge from positive to negative, the above equation reduces to

$$\eta_i = \eta_{a2}\, f_n\, f_T \left(1 + \frac{q}{ME}(1 - \eta_{T1}) - (1 - \eta_{a2})\, \eta_{T4} - \eta_{a2}\left\{f_n\left[f_w\, \eta_{T6} + (1 - f_T - f_w) \times \left[\eta_{D2} + (1 - \eta_{D2})\, \eta_{T7}\right]\right] + (1 - f_n)\left[\eta_{D1} + (1 - \eta_{D1})\, \eta_{T5}\right]\right\}\right)^{-1} . \quad \text{(A-7)}$$

Note that in Eqs. (6) and (7) the energy is the injected neutral energy.

The neutral beam enters the reactor plasma. A fraction f_T of this beam is trapped and a fraction f_w of the beam charge exchanges with the plasma ions, with some of the neutrals formed by the charge exchange escaping to the reactor first wall. The fraction $1 - f_T - f_w$ of the neutral beam which passes through the reactor plasma without being trapped may be stripped and the energy recovered in a direct convertor with efficiency η_{D2}.

Thus the trapped beam current is

$$I_T = f_T I_4 = \eta_{+-} \eta_{a1} \eta_{a2} f_n f_T M I_0 .$$

The neutral beam current (from charge exchange) that impinges on the reactor first wall is

$$I_w = f_w I_4 = \eta_{+-} \eta_{a1} \eta_{a2} f_n f_w M I_0 .$$

The neutral beam current that penetrates the plasma is

$$I_p = (1 - f_T - f_w) I_4 = \eta_{a1} \eta_{+-} \eta_{a2} f_n (1 - f_T - f_w) M I_0 .$$

The power of the neutrals which are trapped is

$$P_T = I_T E = \eta_{+-} \eta_{a1} \eta_{a2} f_n f_T M I_0 \left(\frac{E_a}{M}\right) = \eta_{a1} \eta_{+-} \eta_{a2} f_n f_T I_0 E_a, \qquad \text{(A-1)}$$

where E_a is the energy of the ions entering the neutralizer and E is the injection energy of the neutrals.

The power expended to form the ion and to accelerate it to an energy E_a is given by

$$P_{ex} = I_0 (q + E^+) + I_2 (E_a - E^+) = \left[1 + \frac{q}{\eta_{+-} \eta_{a1} E_a} + \frac{E^+}{E_a} \left(\frac{1 - \eta_{+-} \eta_{a1}}{\eta_{+-} \eta_{a1}}\right)\right] \times \eta_{+-} \eta_{a1} I_0 E_a. \qquad \text{(A-2)}$$

Consider that the power losses in each of the injector components are partially recovered by the direct and thermal convertors shown in Fig. 1. Then the power recovered is

$$P_{rec} = \eta_{T1} q I_0 + (1 - \eta_{a1}) \eta_{T2} I_0 E^+ + (1 - \eta_{+-}) \eta_{T3} I_1 E^+ + (1 - \eta_{a2}) \eta_{T4} I_2 (E_a - E^+) + (1 - f_n) [\eta_{D1} + (1 - \eta_{D1})\eta_{T5}] I_3 E_a + f_w \eta_{T6} I_4 E + (1 - f_T - f_w) [\eta_{D2} + (1 - \eta_{D2}) \eta_{T7}] I_4 E. \qquad \text{(A-3)}$$

Noting that $E = \frac{E_a}{M}$,

$$P_{rec} = \Bigg[\frac{\eta_{T1}\, q}{M\eta_{+-}\,\eta_{a1}\, E} + \frac{E^+}{ME}\Bigg[\left(\frac{1-\eta_{a1}}{\eta_{a1}\,\eta_{+-}}\right)\eta_{T2} + \left(\frac{1-\eta_{+-}}{\eta_{+-}}\right)\eta_{T3}$$

$$- (1-\eta_{a2})\,\eta_{T4}\Bigg] + (1-\eta_{a2})\,\eta_{T4} + \eta_{a2}\Big((1-f_n)\left[\eta_{D1} + (1-\eta_{D1})\,\eta_{T5}\right]$$

$$+ f_n\left\{f_w\,\eta_{T6} + (1-f_T-f_w)\left[\eta_{D2} + (1-\eta_{D2})\,\eta_{T7}\right]\right\}\Big)\Bigg]\, M\,\eta_{+-}\,\eta_{a1}\, I_0\, E. \qquad \text{(A-4)}$$

The injection system efficiency is defined as

$$\eta_i = \frac{P_T}{P_{ex} - P_{rec}} . \qquad \text{(A-5)}$$

Thus, combining Eqs. (A-1), (A-2), (A-3), (A-4), and (A-5) the injection system efficiency is

$$\eta_i = \eta_{a2}\, f_n\, f_T \Bigg[1 + \frac{q}{M\eta_{+-}\,\eta_{a1}\, E}(1-\eta_{T1}) + \frac{E^+}{ME}\Bigg[\left(\frac{1-\eta_{+-}\,\eta_{a1}}{\eta_{+-}\,\eta_{a1}}\right) + (1-\eta_{a2})\,\eta_{T4}$$

$$- \left(\frac{1-\eta_{a1}}{\eta_{a1}\,\eta_{+-}}\right)\eta_{T2} - \left(\frac{1-\eta_{+-}}{\eta_{+-}}\right)\eta_{T3}\Bigg] - (1-\eta_{a2})\,\eta_{T4} - \eta_{a2}\Big((1-f_n)\Big[\eta_{D1}$$

$$+ (1-\eta_{D1})\,\eta_{T5}\Big] + f_n\left\{(1-f_T-f_w)\left[\eta_{D2} + (1-\eta_{D2})\,\eta_{T7}\right] + f_w\,\eta_{T6}\right\}\Big)\Bigg]^{-1} . \qquad \text{(A-6)}$$

For the case where the alkali-metal-vapor cell is not used to change the ion charge from positive to negative, the above equation reduces to

$$\eta_i = \eta_{a2}\, f_n\, f_T \Big(1 + \frac{q}{ME}(1-\eta_{T1}) - (1-\eta_{a2})\,\eta_{T4} - \eta_{a2}\Big\{f_n\Big[f_w\,\eta_{T6} + (1-f_T-f_w)$$

$$\times\left[\eta_{D2} + (1-\eta_{D2})\,\eta_{T7}\right]\Big] + (1-f_n)\left[\eta_{D1} + (1-\eta_{D1})\,\eta_{T5}\right]\Big\}\Big)^{-1} . \qquad \text{(A-7)}$$

Note that in Eqs. (6) and (7) the energy is the injected neutral energy.

Appendix B:
Effect of Alpha Particles on Neutral-Beam Trapping in the Reactor Plasma

As noted earlier the effect of alpha particles in the reactor plasma was neglected in estimating the maximum trapping fraction and the minimum fraction of the randomly directed neutrals reaching the first wall from charge exchange of the neutral beam without subsequent reionization. Equations (7) and (8) can be used to estimate the fraction of the neutral beam striking the first wall and the fraction of the neutral beam trapped by letting

$$\begin{aligned} \langle\sigma v\rangle_{cx} &= (1 - x)\,\langle\sigma v\rangle_{cxD} + x\,\langle\sigma v\rangle_{cx\alpha} \\ \langle\sigma v\rangle_{i} &= (1 - x)\,\langle\sigma v\rangle_{iD} + x\,\langle\sigma v\rangle_{i\alpha} \\ \langle\sigma v\rangle_{T} &= (1 - x)\,\langle\sigma v\rangle_{TD} + x\,\langle\sigma v\rangle_{T\alpha}\,, \end{aligned} \qquad \text{(B-1)}$$

where x is the ratio of the density of alpha particle in the plasma to the total plasma density. From Riviere's curves[20] for deuterium atom energies above 150 keV,

$$\frac{\langle\sigma v\rangle_{T\alpha} - \langle\sigma v\rangle_{i\alpha}}{\langle\sigma v\rangle_{T\alpha}} < 0.1\ .$$

Thus, for a given

$$\gamma \equiv \frac{Dn\,\langle\sigma v\rangle_{T}}{v_0} = \frac{Dn[(1 - x)\,\langle\sigma v\rangle_{TD} + x\,\langle\sigma v\rangle_{T\alpha}]}{v_0}\,,$$

the effect of the alpha particles in the plasma on the trapping of the deuterium atoms should be small for deuterium atom energies greater than 150 keV, and the effect will increase with a decrease in deuterium atom energy for an alpha particle density less than 10% of the plasma density. The results for a deuterium atom energy of 20 keV with $\gamma = 3$ are shown in Fig. B-1 as a function of the plasma alpha particle density.

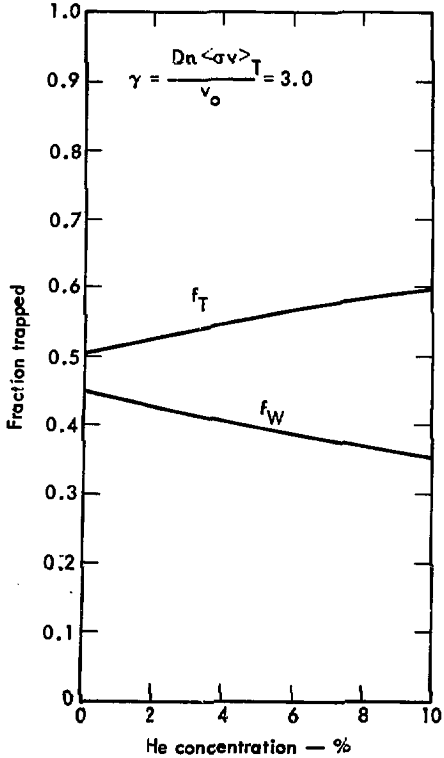

Fig. B-1. The effect of the concentration of helium in the plasma on the fraction of an injected, 20-keV, deuterium atom beam that is trapped and on the fraction of the beam lost to the reactor first wall by charge-exchange without reionization.

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