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SOURCE DRIVEN BREEDING THERMAL POWER REACTORS

Part II. USING LITHIUM-FREE NEUTRON SOURCES

Ehud GREENSPAN

March 1978

(כולל כותרת ותקציר בעברית)

ABSTRACT

The feasibility of fusion devices operating in the semi-catalyzed deuterium (SCD) mode and of high energy proton accelerators to provide the neutron sources for driving subcritical breeding light water power reactors is assessed. The assessment is done by studying the energy balance of the resulting source driven light water reactors (SDLWR) and comparing it with the energy balance of the reference light water hybrid reactors (LWHR) driven by a D-T neutron source (DT-LWHR). The conditions the non-DT neutron sources should satisfy in order to make the SDLWR viable power reactors are identified. It is found that in order for a SCD-LWHR to have the same overall efficiency as a DT-LWHR, the fusion energy gain of the SCD device should be at least one half that of the DT device. The efficiency of ADLWRs using uranium targets is comparable with that of DT-LWHRs having a fusion energy gain of unity. Advantages and disadvantages of the DT-LWHR, SCD-LWHR and ADLWR are discussed.

Work performed at the Department of Nuclear Engineering, Ben-Gurion University of the Negev, Beer-Sheva and at the Nuclear Research Centre - Negev, Beer-Sheva;

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כורי-כוח תרמיים דוגרים המופעלים על-ידי מקור

חלק II. שימוש במקורות ניטרונים החופשיים מליתיום

א' גרינשפן

אדר תשל"ח - מרץ 1978

תקציר

נחקרת ההיתכנות של השימוש במתקני מיזוג המבוססים על מחזורי דלק של דויטריום ובמאיצי פרוטונים לאנרגיות גבוהות כמקורות ניטרונים להפעלת כורי-כוח תת-קריטיים דוגרים, המואטים על-ידי מים קלים. ההערכה מתבססת על מחקר מאזן האנרגיה של כורי המים הקלים המופעלים על-ידי מקורות הניטרונים הנדונים, והשוואתו עם מאזני האנרגיה של כורים תת-קריטיים של מים קלים המופעלים על-ידי מתקני מיזוג המבוססים על מחזור ה-D-T. מוגדרים התנאים שמקורות הניטרונים שלא מסוג D-T צריכים למלא על-מנת שהכורים אותם הם מפעילים יהיו כורי-כוח יעילים. נמצא שעל-מנת שהנצילות הכללית של הכורים המופעלים על-ידי מקור ניטרונים המבוסס על הדויטריום תהיה שווה לנצילות המתקבלת משימוש במקורות ניטרונים מסוג D-T, הכפלת האנרגיה במתקנים העובדים עם דויטריום צריכה להגיע לפחות למחצית ערכה במתקני המיזוג מסוג D-T. הנצילות הכללית של כורי מים קלים המופעלים על-ידי מקור ניטרונים ממאיץ שבו משמש האורניום כמטרה, דומה לזו המתקבלת מכור המופעל על-ידי מתקן מיזוג מסוג D-T אשר הכפלת האנרגיה שלו היא יחידה. נדונים יתרונות וחסרונות של כורי מים קלים המופעלים על-ידי כל אחד משלושת מקורות הניטרונים הנבדקים.

העבודה נעשתה במחלקה להנדסה גרעינית באוניברסיטת בן-גוריון בנגב ובקריה למחקר גרעיני - נגב;

הוכן עבור הסדנה הבינלאומית לעבודה-חשיבה בנושא קונספטים חדשים של מערכות מתקדמות של אנרגיה גרעינית, גרץ, אוסטריה, 29-31 במרס 1978.

מוצא לאור ללא עריכה מדעית של יה"ם/מה"ל

PREFACE

The nuclear energy economy is facing nowadays a number of difficulties associated with (1) the need to significantly improve the utilization of the nuclear fuel resources (i.e., to assure breeding), (2) non-proliferation issues, and (3) safety and environmental issues. Fusion reactors have the potential of alleviating all of these difficulties. The problem is, of course, that there is a long (and not so clear) way to go before they could become available, and be commercial.

"Fuel factories" are recently being proposed(1-8) to provide the make-up fissile fuel for non-breeding thermal reactors, thus providing a solution to problem number 1 of the nuclear economy (the fuel utilization problem). These fuel factories are subcritical fission systems ("blankets") driven by intense neutron sources. They can be characterized by the type of blanket and driver. Two general types of drivers are commonly considered - fusion devices (usually neutral beam driven) based on the D-T fuel cycle, and high energy proton (or deuteron) accelerators(9-12) providing neutrons via spallation reactions.

The most popular blankets proposed so far(2-16) are fast blankets, usually gas cooled. These blankets are characterized by a high fissile fuel production per unit power generated in the blanket, and per driving neutron. A nuclear power economy based on such fuel factories needs a dual fuel cycle - one for the fuel production step and one for the power generation step.

We have taken a different approach to the conception of source driven systems: rather than using these systems to make up for the fuel defficiency of the critical thermal reactors, we propose to utilize the source neutrons to make up, directly, for the neutron defficiency of the thermal fission systems, thus upgrading their performance and alleviating difficulties of the nuclear energy economy while relying on the most developed fission reactors technology.

Of the thermal fission systems we have identified light water moderated systems to be the most promising. Chronologically, we have started investigating the characteristics and promise of Source Driven Light Water Reactors (SDLWR) by considering fusion devices operating on the D-T fuel cycle for the driving neutron source. Most of our investigation of SDLWR so far concentrated on this concept of Light Water Hybrid Reactors (LWHR). More recently we have examined the promise of two additional types of neutron sources to drive SDLWRs - a fusion device that operates in a semi-catalized deuterium mode, and a high energy proton accelerator.

The blankets of SDLWRs driven by a D-T neutron source are required to breed tritium, in addition to their primary goal - power generation and, possibly, fissile fuel production. The blankets driven by the other two types of neutron sources are free from the need to breed tritium and can be considered as a subset of the light water blankets. Moreover, the possible contributions of SDLWRs to the nuclear energy economy can be identified with respect to the D-T driven LWHRs.

Consequently, we have divided the report on the properties and promise of source driven thermal power reactors into two parts: in the first part we discuss the properties of subcritical thermal fission systems, describe the characteristics expected from LWHR blankets and discuss the potential contribution of LWHRs to the nuclear energy economy. In the second part we examine the possibility of driving the light water blankets with Semi-Catalyzed Deuterium (SCD) fusion devices - novel fusion neutron sources and with high energy proton accelerators. The three types of SDLWRs: the DT-LWHRs (i.e., LWHRs driven by a fusion device operating with the D-T fuel cycle), SCD-LWHRs and ADLWR (i.e., Accelerator Driven Light Water Reactors) are also intercompared in Part II.

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1. INTRODUCTION

The need to breed tritium reduces the energy multiplication and fissile fuel production ability of the hybrid reactor blankets. It also introduces technological and safety related difficulties associated with the need to incorporate large amounts of lithium in the blanket and to extract and handle the tritium produced.

Neutron sources not based on the D-T fusion reaction are free from the need to breed tritium. All known types of such sources the technology of which might be available before fusion power reactors become commercial are less energy-efficient than D-T sources; they require more energy investment per neutron produced and, in several of these sources, the neutrons are of a lower energy and therefore are less effective than a 14 MeV neutron. Can the improvement in the energy multiplication of the blanket, resulting from designing it to be lithium-free, compensate for the extra energy investment required for the neutron generation?

The thermal blankets of the type considered for the LWHRs described in Part I of this work(1) appear to be most compatible with non-D-T neutron sources, and for the following reasons:

(a) Their gain in energy multiplication resulting from reducing the tritium breeding requirement is high.

(b) Their energy multiplication (and fuel production ability) is less sensitive to the energy of the driving neutron.

In this part of the work we shall estimate the performance characteristics expected from lithium-free water blankets that are driven by two types of non D-T neutron sources:

(1) Fusion devices operating with deuterium fuel (Section 2).

(2) High energy proton accelerators producing neutrons via spallation reactions (Section 3).

The properties of these lithium-free SDLWRs are compared, in Section 4, with those of the reference LWHRs - those driven by D-T fusion devices. It should be emphasized that the evaluation of the properties of SCD-LWHRs and of ADLWRs is even more preliminary in nature than the corresponding evaluation of DT-LWHRs (Part I). In the above and the following, we denote SDLWRs driven by a D-T fusion device, a fusion device operating in the semi-catalyzed-deuterium (SCD) mode, or a high energy accelerator by, respectively, DT-LWHR, SCD-LWHR or ADLWR.

```
I    R    I      Z     I       T     I
I   8.84  I     0.00   I     0.000   I      I   8.84  I   110.00  I   111.107  I
I   8.84  I     2.00   I    28.003   I      I   8.84  I   112.00  I    94.990  I
I   8.84  I     4.00   I    53.798   I      I   8.84  I   114.00  I    76.099  I
I   8.84  I     6.00   I    76.099   I      I   8.84  I   116.00  I    53.798  I
I   8.84  I     8.00   I    94.990   I      I   8.84  I   118.00  I    28.003  I
I   8.84  I    10.00   I   111.107   I      I   8.84  I   120.00  I     0.000  I
I   8.84  I    12.00   I   125.774   I
I   8.84  I    14.00   I   139.491   I
I   8.84  I    16.00   I   152.275   I
I   8.84  I    18.00   I   163.899   I
I   8.84  I    20.00   I   174.297   I
I   8.84  I    22.00   I   183.700   I
I   8.84  I    24.00   I   192.460   I
I   8.84  I    26.00   I   201.769   I
I   8.84  I    28.00   I   208.566   I
I   8.84  I    30.00   I   215.669   I
I   8.84  I    32.00   I   222.003   I
I   8.84  I    34.00   I   227.692   I
I   8.84  I    36.00   I   232.951   I
I   8.84  I    38.00   I   237.893   I
I   8.84  I    40.00   I   242.451   I
I   8.84  I    42.00   I   246.474   I
I   8.84  I    44.00   I   249.890   I
I   8.84  I    46.00   I   252.789   I
I   8.84  I    48.00   I   255.336   I
I   8.84  I    50.00   I   257.616   I
I   8.84  I    52.00   I   259.562   I
I   8.84  I    54.00   I   261.032   I
I   8.84  I    56.00   I   261.955   I
I   8.84  I    58.00   I   262.407   I
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I   8.84  I    62.00   I   262.407   I
I   8.84  I    64.00   I   261.955   I
I   8.84  I    66.00   I   261.032   I
I   8.84  I    68.00   I   259.562   I
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I   8.84  I    94.00   I   200.769   I
I   8.84  I    96.00   I   192.460   I
I   8.84  I    98.00   I   183.700   I
I   8.84  I   100.00   I   174.297   I
I   8.84  I   102.00   I   163.899   I
I   8.84  I   104.00   I   152.275   I
I   8.84  I   106.00   I   139.491   I
I   8.84  I   108.00   I   125.774   I
```

branch does not undergo the D-^{3}He fusion reaction.

Table 1 summarizes the total energy and neutron balance for the two types of catalyzed D systems considered along with those for the regular D system. Both catalyzed systems provide twice as many neutrons per beam-plasma reaction as the regular D one. An approximate estimation of the fusion energy gain attainable from deuterium beam driven fusion devices operating in the three modes considered is shown in Fig. 1.

TABLE 1: Number of Neutrons and Energy Generated per Beam Induced D-D Reaction.

MODE	Number of Neutrons	Fusion Energy (MeV)	
		Charged Particle	Total (E_f)
Regular	½(2.45)[a]	2.43	3.65
Semi-Catalyzed	½(2.45+½(14.1)	4.19	12.44
Catalyzed	½(2.45)+½(14.1)	13.36	21.61

[a] Neutron Energy (MeV)

A fundamental question concerning the feasibility of a beam driven catalyzed dueterium reactor is the equilibrium concentration of tritium and helium required for operating in the catalyzed modes. This equilibrium concentration depends on the plasma temperature (throughout the work we shall assume that the plasma electrons and background ions have the same

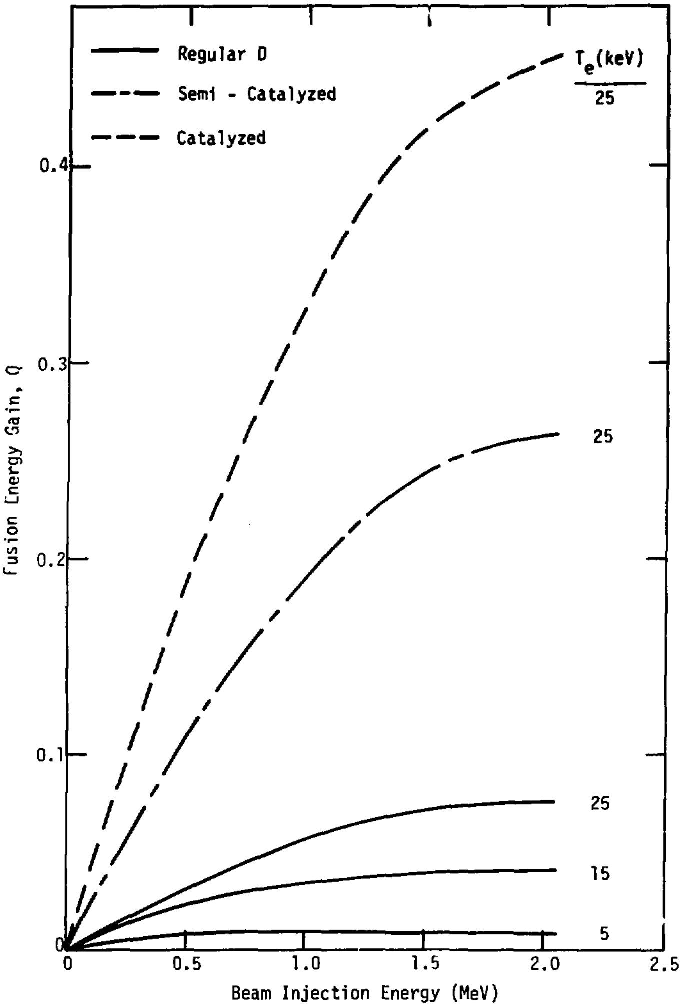

Fig. 1. Fusion Energy Multiplication Dependence on Beam Energy (W_b) for Several Temperatures (T_e) and Three Types of Deuterium Systems.

temperature) and beam injection energy W_b. We have estimated this equilibrium concentration using a simplified model$^{(10)}$. Fig. 2 shows our estimates for a tokamak reactor having an alongated plasma ($\kappa = 3$) and a maximum field intensity of $B_M = 9.5$ Tesla. The corresponding plasma pressure is 0.93 J/cm^3. The partial pressure of the beam ions is taken to equal that of the bulk plasma $\Gamma = 1$. The steep increase in n_T/n_e as the plasma temperature decreases below about 10 keV reflects the sensitivity of the D-T reactivity $\langle\sigma v\rangle_{DT}$ to temperature in the range considered. It is concluded that semi-catalyzed systems are conceivable, in the beam driven mode of operation, even for plasma temperatures as low as about 5 keV. Above 10 keV the equilibrium tritium concentration is only a few percent of the plasma ion population.

The reactivity of the D-^{3}He reaction is smaller, in the range of temperatures considered, by more than two orders of magnitude compared to $\langle\sigma v\rangle_{DT}$. To arrive to an equilibrium situation, the reactor will have to have either a high content of ^{3}He in its plasma, or to recirculate the ^{3}He and inject it along with the D. In either of these circumstances the neutron yield from the catalyzed reactor will be lower than that from a semi-catalyzed one (operating at a similar T_e and W_b). The ^{3}He produced in the semi-catalyzed reactors might be used in satellite fusion power reactors operating on the D-^{3}He fuel cycle recently proposed by Miley et al.$^{(5)}$

The neutron production ability of the semi-catalyzed system is illustrated in Fig. 3. Half of these neutrons are D-D (2.45 MeV) neutrons while the other half are D-T (14.1 MeV) neutrons. It is observed that the lower the plasma temperature, the higher is the source intensity attainable. This

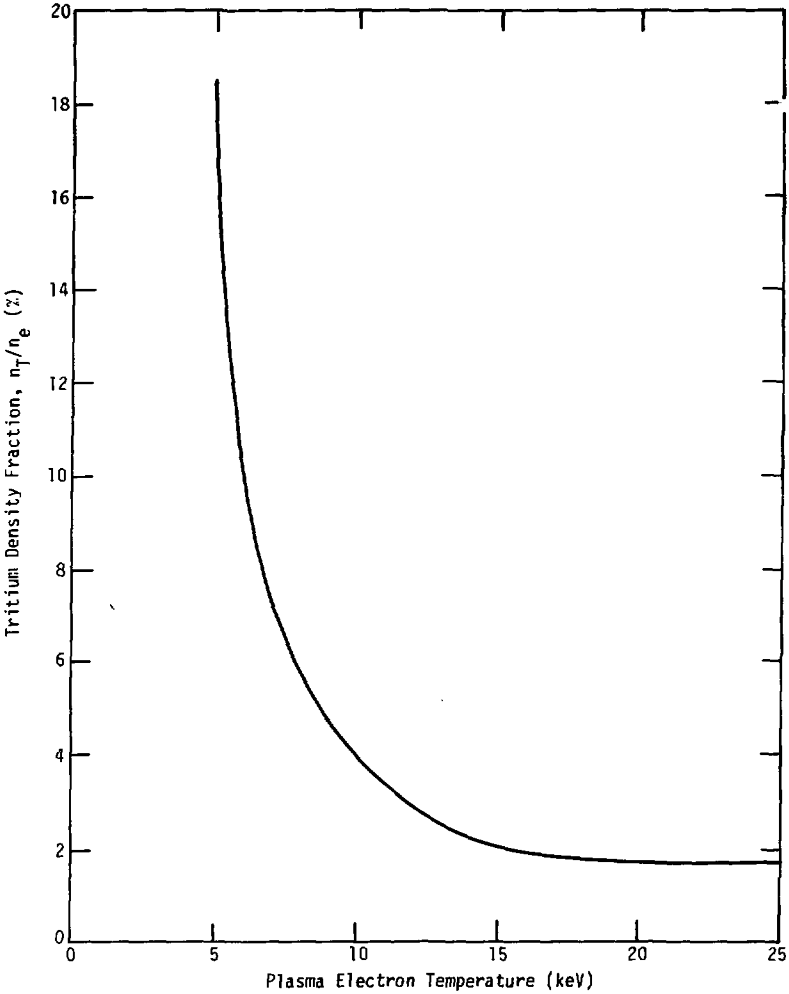

Fig. 2. Relative Equilibrium Tritium Concentration in the Plasma as a Function of the Plasma Temperature (calculated for a total plasma pressure of 0.93 J/cm^3 and $\Gamma = 1$).

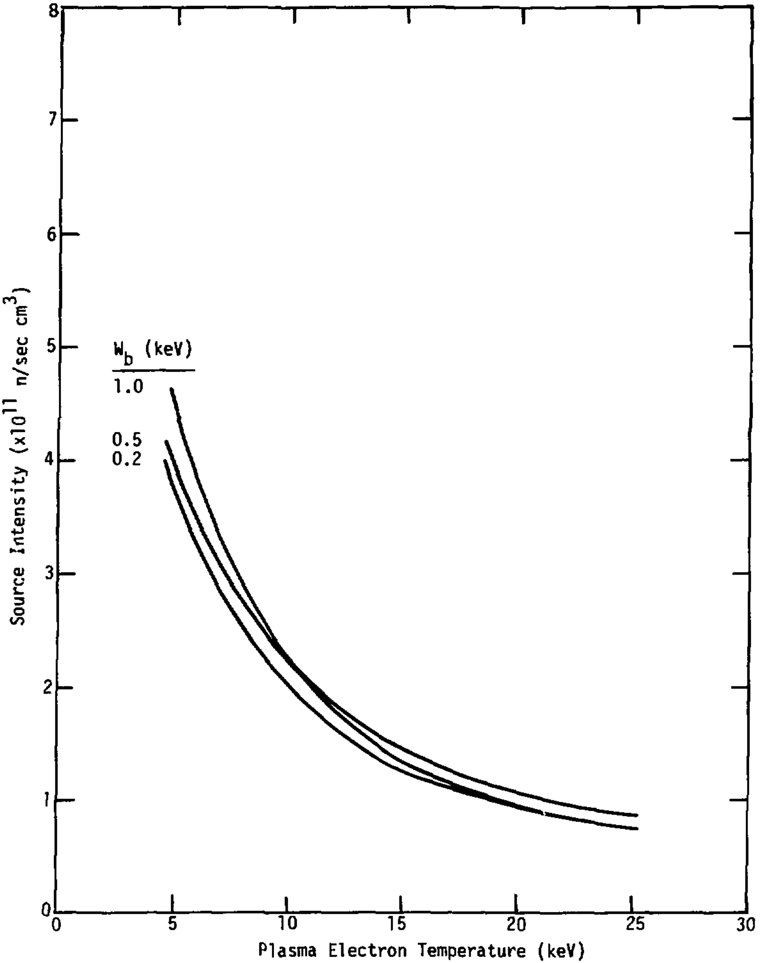

Fig. 3. Fusion Neutron Source Intensity Attainable from a Beam-Driven Semi-Catalyzed Device (P_{max} = 0.93 J/cm^3; Γ = 1).

is due to the higher intensity of the beam ions that can be injected into the plasma under the constraint of $\Gamma = 1$ and is in agreement with the predicted performance of TCT machines based on the D-T fuel cycle(11). Even though the neutron production density increases, the Q value decreases as the plasma temperature goes down. The best operating temperature is therefore a matter for optimization.

Following Ref. (12), we derived(10) the following simplified expression for the relative plant efficiency of hybrid reactors

$$\frac{\eta_p}{\eta_{th}} = 1 - \frac{\frac{1}{Q}\left(\frac{1}{\eta_I \eta_{th}} - 1\right) - \psi_c \psi_R \left(\frac{\eta_{dc}}{\eta_{th}} - 1\right)}{1 + N(B_{eff}/E_f)} \quad . \qquad (1)$$

where

E_f is the average fusion energy liberated per beam-induced fusion reaction (see Table 1).

N - The number of neutrons generated per beam-induced fusion reaction (see Table 1).

B_{eff} The thermal energy (mostly of fission origin) released in the blanket per average fusion neutron generated.

ψ_c - The fraction of the fusion energy carried by the charged reaction products.

ψ_R - The fraction of the charged reaction products energy that does not go into radiation (i.e., that can be converted directly into electrical energy).

η_{dc} - The efficiency for direct conversion of charged particle energy into electricity.

The effects of the ion beam injection energy and of the plasma electron temperature on the relative plant efficiency attainable from a semi-catalyzed driven hybrid power reactor (characterized by their blanket energy generation) are shown, respectively, in Figs. 4 and 5). The results of these figures correspond to the assumptions that $\psi_R = 0$, $\eta_{th} = 0.35$ and $\eta_I = 0.7$ or 0.6 for, respectively, the D-T and SCD fusion devices. It is observed (Fig. 4) that there is not much efficiency to be gained by increasing the beam energy above 1.5 MeV. For the high energy producing blankets, even 1 MeV beams will provide close to the maximum attainable plant efficiencies. The plasma electron temperature should be as high as possible.

2.2. The Energetics of LWHRs

The energy that can be generated per source neutron in either tritium breeding or lithium free blankets is estimated using a modified version fo the simple model$^{(1)}$ which allows for the effect of neutron leakage through port holes and other sections of the plasma chamber not covered by the blanket, as well as for the effect of utilizing part (or all) of the leaking neutrons to produce tritium:

$$B_{eff} = 200\left\{\frac{k_{eff}/\nu}{(1-k_{eff})}\left(\beta_{eff} - T_{eff}\right) + \gamma_{eff}\right\} . \qquad (2)$$

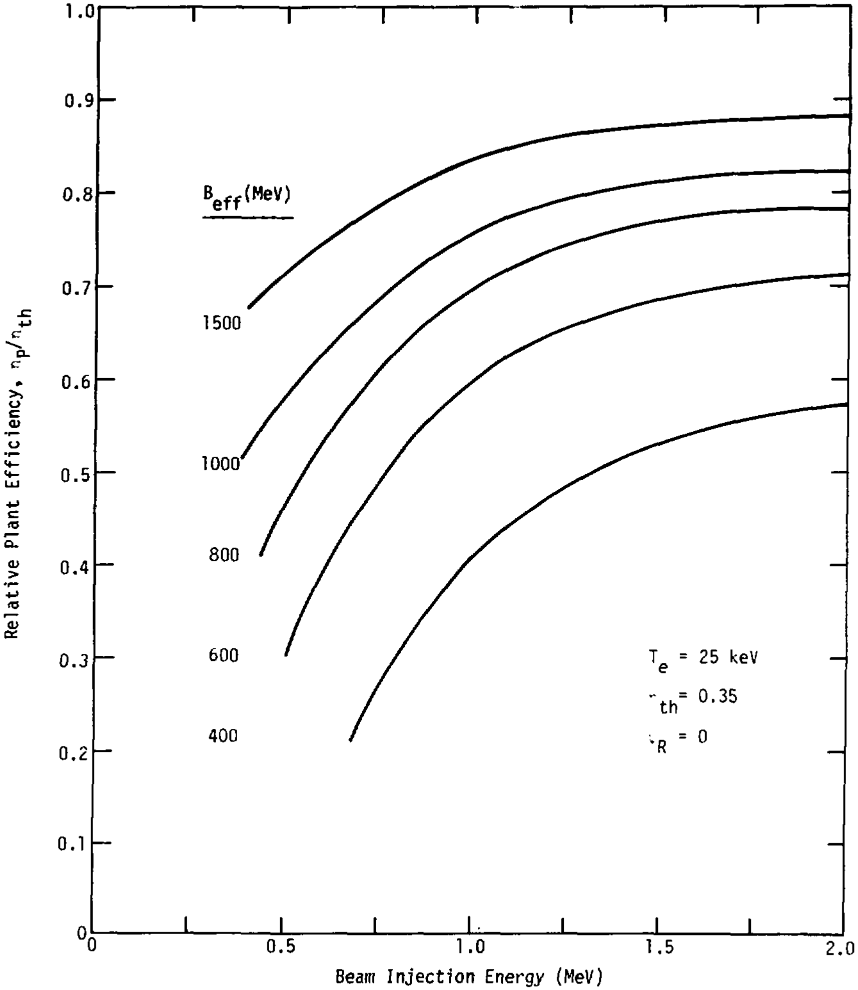

Fig. 4. Effect of Beam Injection Energy on the Relative Plant Efficiency of Semi-Catalyzed Driven Hybrid Reactors.

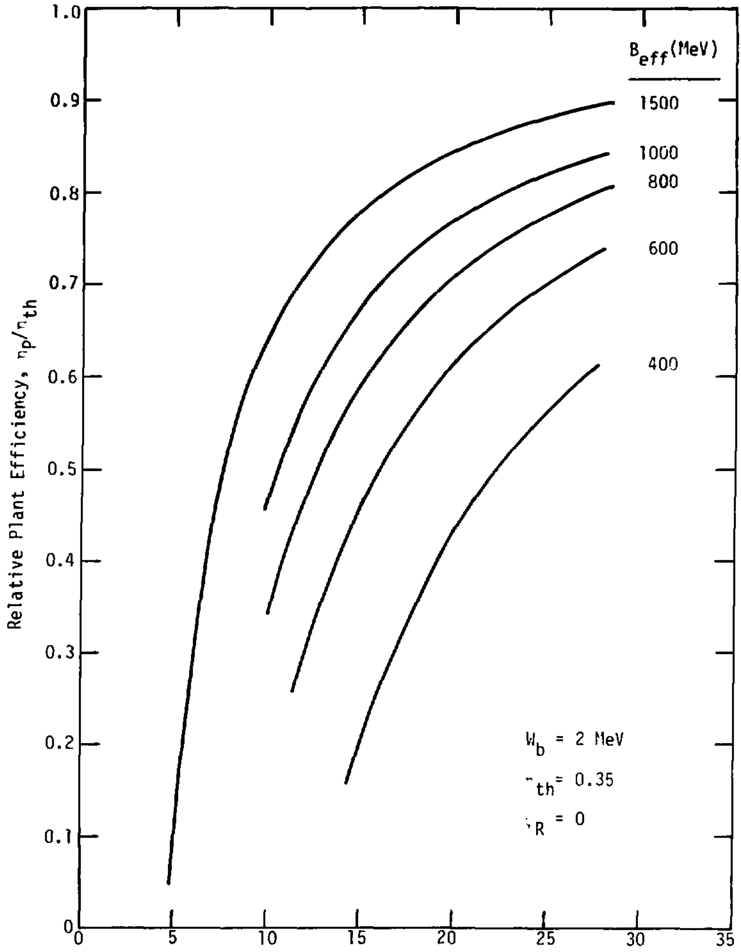

Fig. 5. Effect of Plasma Electron Temperature on the Relative Plant Efficiency of Semi-Catalyzed Driven Hybrid Reactors.

In the above P_{eff} stands for the value a parameter P will have with the effect of leakage taken into account. Denoting by ψ_B the average probability for a blanket born neutron not to leak out through blanket-free sections of the machine and by ψ_S the corresponding non-leakage probability for the source neutrons we have

$$\beta_{eff} = \psi_S \beta \tag{3}$$

$$\gamma_{eff} = \psi_S \gamma \tag{4}$$

$$k_{eff} = \psi_B k_\infty \,. \tag{5}$$

Let ε be the probability that a leaking neutron will bring about the production of one triton (to be referred to as the "neutron efficiency"). Then the tritium breeding condition is

$$T_{eff} + \varepsilon[1+\psi_B]\frac{(\beta_{eff} - T_{eff})}{(1 - k_{eff})} + \varepsilon[1 - \psi_S] = T \tag{6a}$$

or, in rearranged form, the number of tritons that have to be produced in the fission blanket (excluding special lithium containing sections) per fusion neutron is

$$T_{eff} = \frac{[T - \varepsilon(1 - \psi_S)] - \varepsilon\beta_{eff}[(1-\psi_B)/(1-k_{eff})]}{1 - \varepsilon(1-\psi_B)/(1-k_{eff})} \,, \tag{6b}$$

where T is the total tritium breeding ratio requirement (taken, for the present analysis, to be 1.1).

To apply Eq. (2) for estimating the energy generation in the lithium-free blankets of SCD-LWHRs, we set $T = 0$ and replace β and γ (in Eqs. (3) and (4)) by $(1+\beta)/2$ and $\gamma/2$, respectively. The change in β and γ reflects our assumption that the 2.45 MeV neutron from the D-D reaction has no direct fast fission effects; That it is as effective as an average fission-born neutron.

Figure 6 compares the energy generation (averaged over an irradiation cycle of 30,000 MWD/T) attainable from leakage-free LWHR blankets driven by a SCD or a DT neutron source. The blankets consist of U_3Si-H_2O lattices in the pressure tube design described in Part I(1) (each pressure tube houses a cluster of 37 fuel rods, each rod is 1 cm in diameter and cladded with Zircaloy). To each water-to-fuel volume ratio, V_m/V_f, there corresponds a specific equilibrium fissile fuel content(1,14). This fissile fuel content varies from 0.7% in the $V_m/V_f = 2$ blankets to about 5.5% in the $V_m/V_f = 0.5$ blankets.

In evaluating the energetics of the LWHRs we shall assume throughout that $\psi_R = 0$, $\eta_I^{DT} = 0.7$, $\eta_I^{SCD} = 0.6$, $\eta_{th} = 0.29$ (corresponding to the efficiency of the CANDU type reactors which use similar pressure tubes) and that ψ_S equals ψ_B. The latter will be referred to as the blanket coverage efficiency.

The effect of the blanket coverage efficiency on the relative plant efficiency, η_p/η_{th}, of DT-LWHRs and SCD-LWHRs is shown in, respectively, Figs. 7 and 8. The fusion energy gain of the respective neutron sources

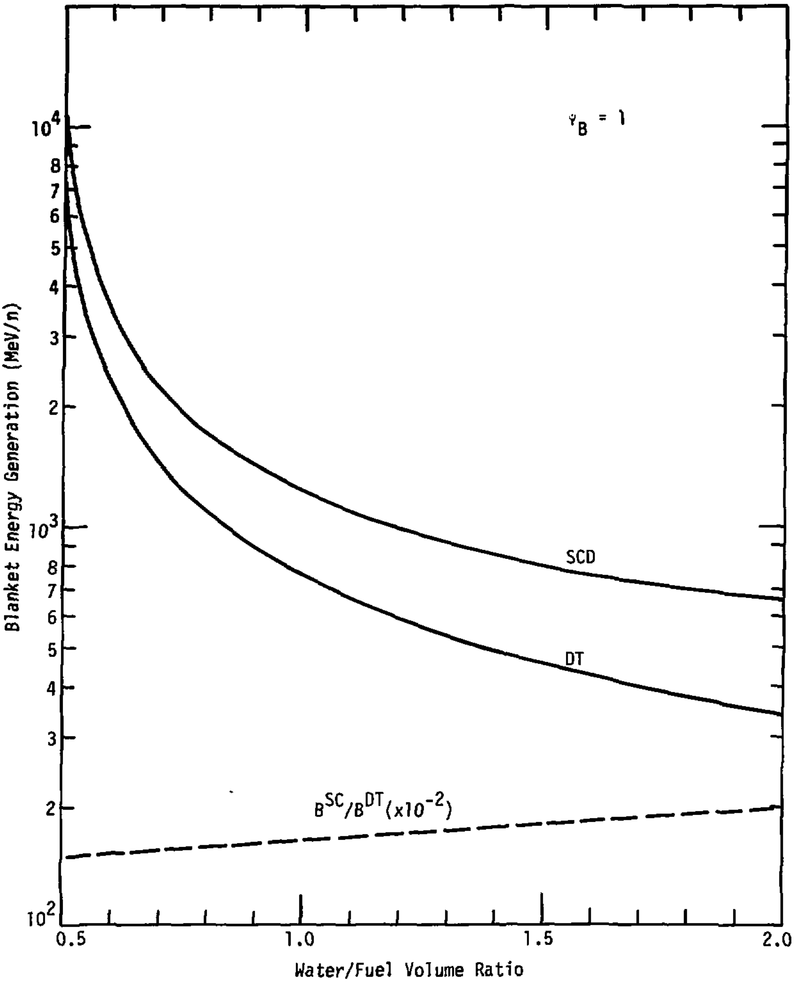

Fig. 6. Energy Generation by a Semi-Catalyzed-Deuterium Neutron in Lithium-Free Blankets and by a 14 MeV Neutron in a Tritium Breeding Blanket (T = 1.1).

is 1 and 0.25. The latter corresponding to a SCD fusion device having a plasma temperature of about 25 keV and a beam injection energy exceeding 1.5 MeV (see Fig. 1). It is observed that the efficiency of both types of LWHRs is very sensitive to the blanket coverage efficiency, with the SCD-LWHR being more sensitive of the two. This observation is in contradiction to an earlier one(10). The present observation relies upon a more accurate estimation of the energy multiplication attainable from a tritium breeding blanket for LWHRs (the ratio B^{SC}/B^{DT} for the $V_m/V_f = 2$ blanket is estimated now to be about 2 (see Fig. 6) versus 4.5 estimated in Ref. (10)) as well as upon a more accurate treatment of the effect of neutron leakage on the blanket multiplication properties.

The sensitivity of the plant efficiency of the DT-LWHRs to the blanket coverage efficiency might be significantly reduced could the leaking neutrons be utilized for the production of tritium. This is illustrated in Fig. 9 which together with Fig. 7 show that much of the loss in the plant efficiency incurred by the neutron leakage might be recovered if the DT-LWHR could be designed to have ε close to one. The termination point of the curves in Fig. 9 (those curves which terminate at $\varepsilon < 1$) correspond to the value of ε which is necessary for all the tritium breeding to come from the special lithium (blanket free) sections. At these points there is no need to produce tritium in the blanket itself. Had we designed a DT-LWHR to have a higher ε, its tritium production rate would have exceeded the tritium breeding requirements of that LWHR. It

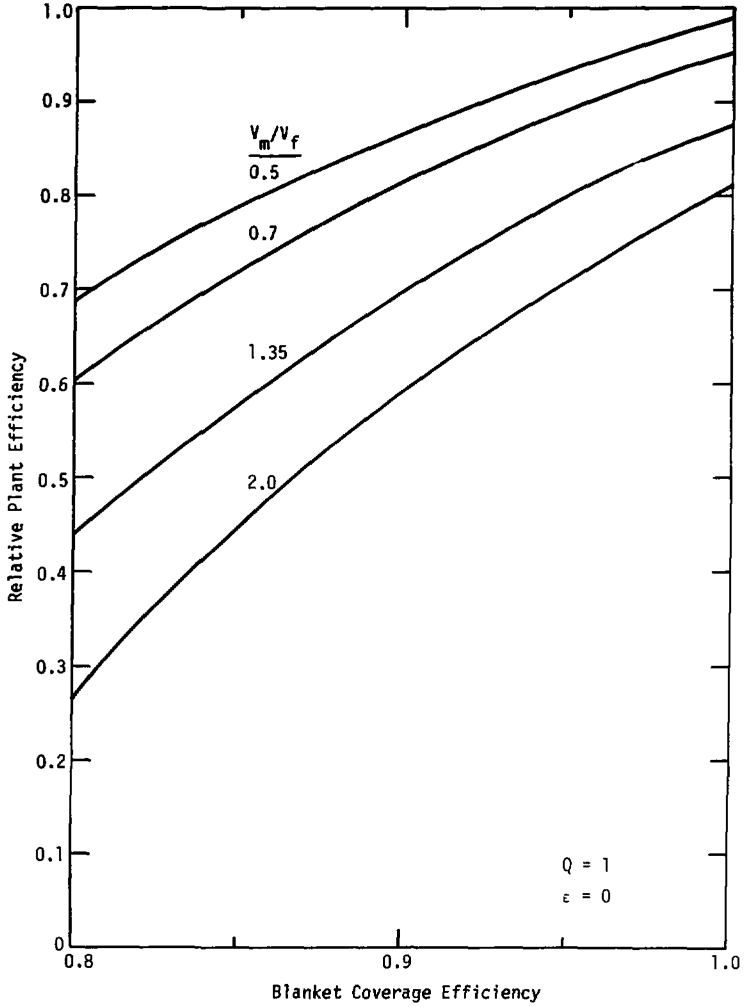

Fig. 7. Effect of the Blanket Coverage Efficiency on the Plant Efficiency of LWHRs Driven by a Q = 1 DT Fusion Device. Neutron Efficiency ε = 0.

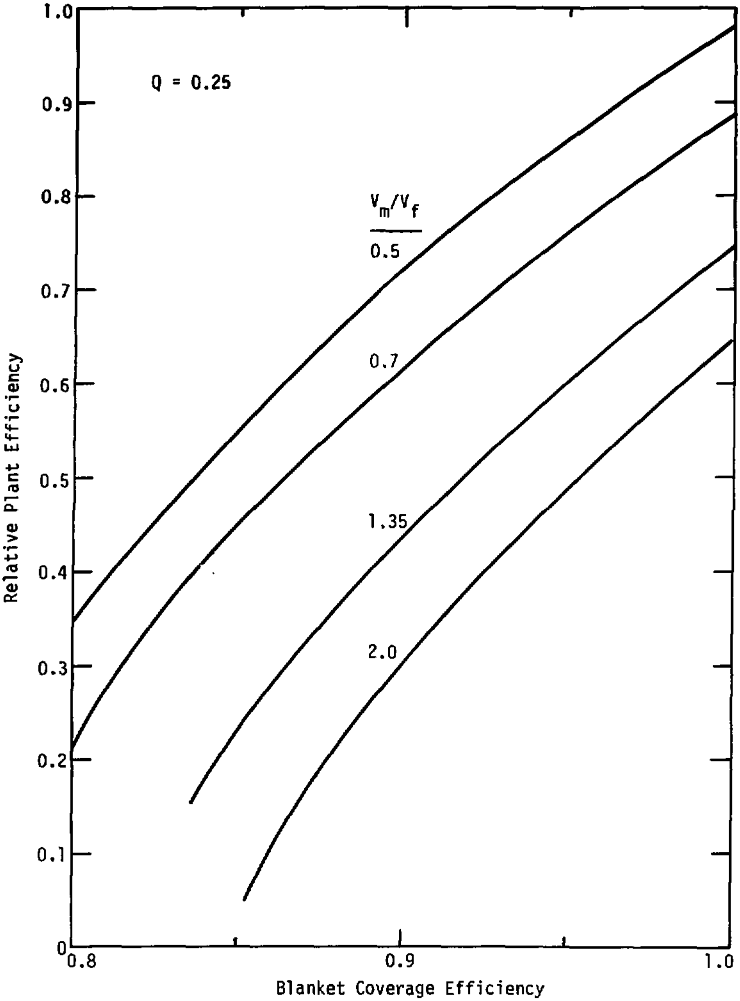

Fig. 8. Effect of the Blanket Coverage Efficiency on the Plant Efficiency of LWHRs Driven by a Q = 0.25 SCD Fusion Device.

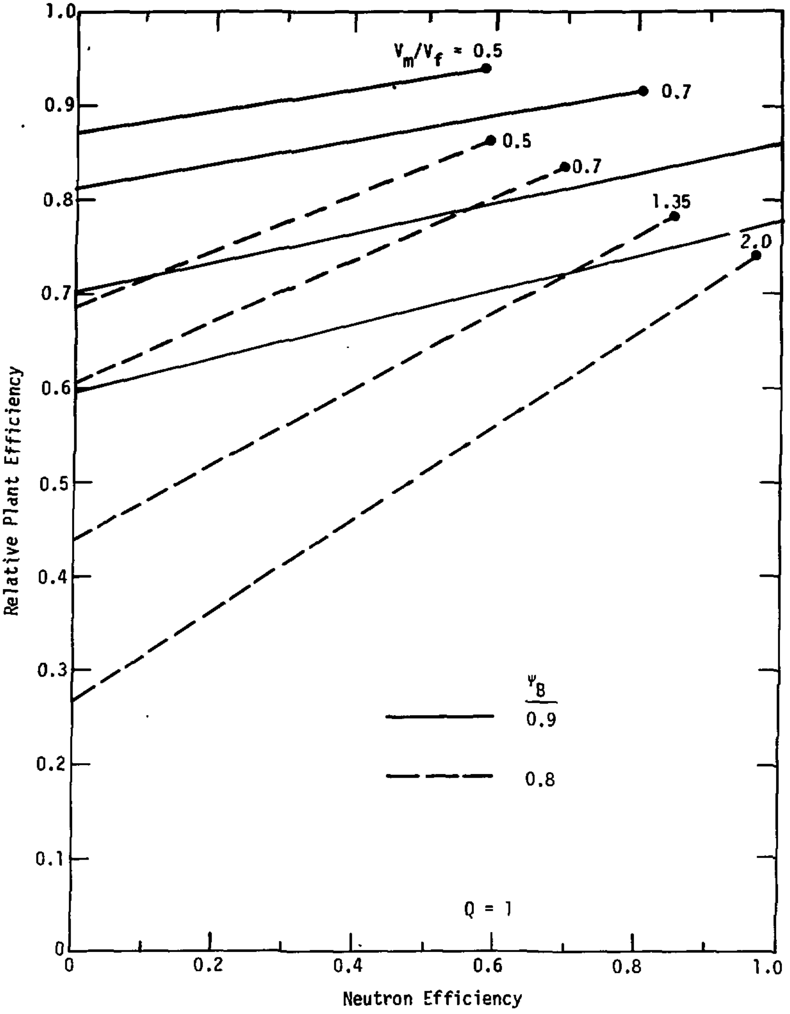

Fig. 9. Effect of Neutron Efficiency on the plant Efficiency of LWHRs Driven by a Q = 1 DT Fusion Devices.

should be emphasized that all the results about the effect of leakage on the performance of SDLWRs presented in this work are based on a very simple model and therefore they are not expected to be quantitatively accurate.

Figures 10 and 11 compare the relative plant efficiency of a family of LWHRs (defined by their blanket V_m/V_f) driven by DT or SCD fusion devices having different fusion energy gains. The results corresponding to $\psi_B = 1$ (Fig. 10) provide the upper limit estimation for η_p/η_{th} attainable from the specific blanket types and neutron sources (characterized by their Q value) under consideration. The $\psi_B = 0.9$ results (Fig. 11) may be considered as the upper limit for practical designs of LWHRs. Assuming, arbitrarily, that $\eta_p/\eta_{th} \gtrsim 0.7$ is the regime for plant efficiencies of practical interest, it is observed that D-T fusion devices having $Q = 1$ might provide viable LWHRs provided their blankets are restricted to the $V_m/V_f \lesssim 1.35$ range. D-T neutron sources having $Q \gtrsim 1.5$ open the entire V_m/V_f range to be of interest for power reactor applications (see also Fig. 9). It should be mentioned that the $Q \gtrsim 1.5$ regime is considered to be accessible with beam driven Tokamak fusion devices(11).

Considering $Q = 0.25$ a close to the maximum fusion energy gain expected from beam-driven SCD neutron sources, these sources appear to be only marginally suitable for power reactor applications. The SCD-LWHRs may be viable power reactors only for blankets having a multiplication similar to that of the $V_m/V_f = 0.5$ blanket considered. Such an energy

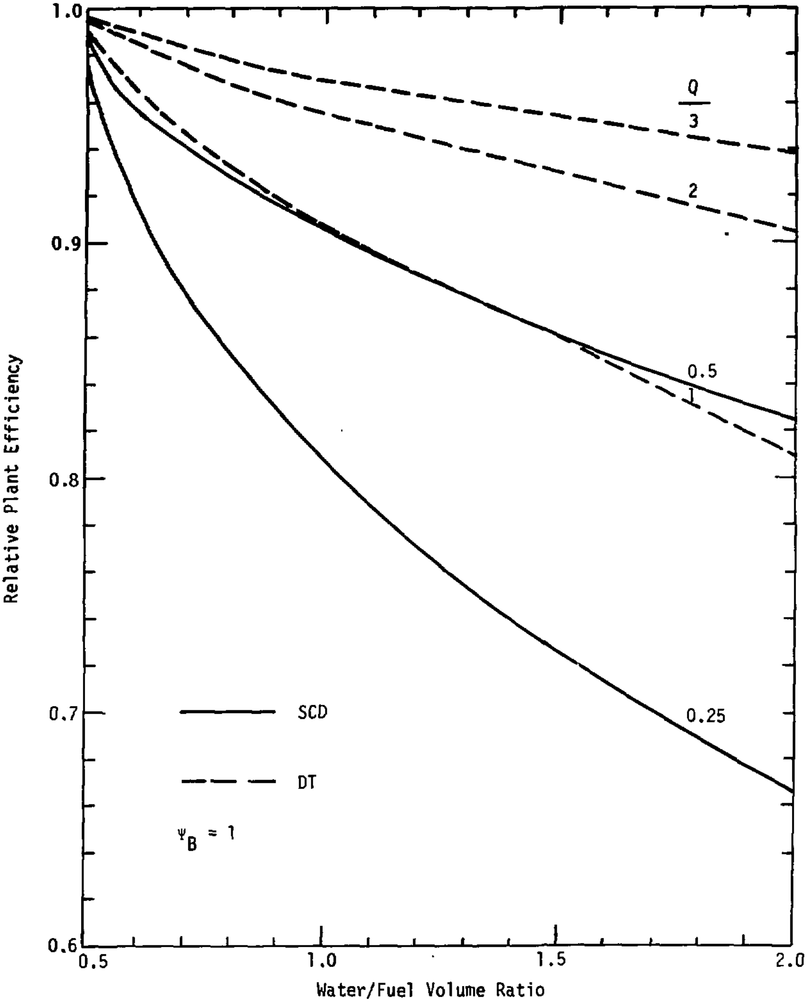

Fig. 10. Upper Limit of Plant Efficiencies Attainable from LWHRs Driven by Different SCD or DT Fusion Devices.

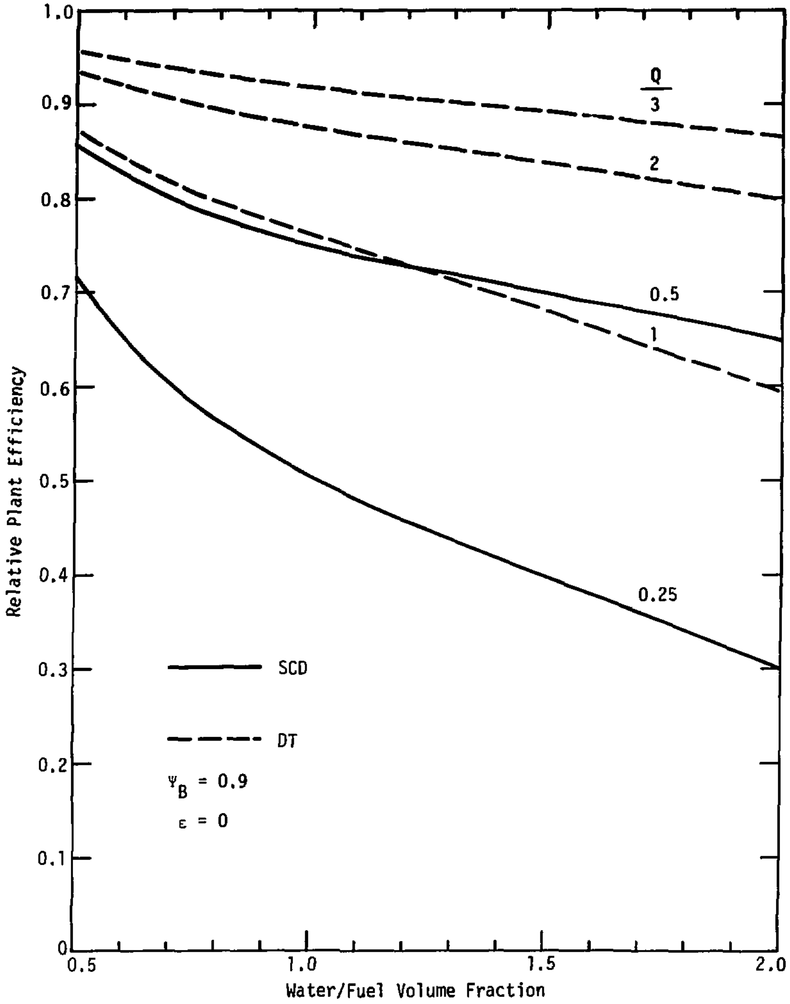

Fig. 11. Plant Efficiency Attainable from LWHRs the Blanket Efficiency of which (ψ_B) is 0.9 and Neutron Efficiency of which (ε) is Zero.

multiplication may be provided by $V_m/V_f > 0.5$ blankets using either different lattices or different operational modes(1,14) than those assumed for the present assessment.

If deuterium based fusion devices could be designed to have a Q of 0.5, they could have provided useful neutron sources for driving LWHRs; the efficiency of a Q = 0.5 SCD-LWHR is seen (Figs. 10 and 11) to be comparable to that of a Q = 1 DT-LWHR. Had the ^{3}He produced in the hybrid reactors been utilized to provide additional energy by the D-^{3}He fusion reaction (either in the same hybrids or in the satellite reactors(5)), the effective Q value would have been almost doubled as compared with that of the SCD-LWHRs (see Table 1 and Fig. 1). The fusion energy gain the semi-catalyzed (or the catalyzed) deuterium neutron source should have in order for the plant efficiency of the SCD-LWHR to break-even with that of a DT-LWHR of a given Q is summarized in Fig. 12. It is interesting to notice that if the DT-LWHRs could be designed to have a high utilization of the leaking neutrons for tritium breeding ($\epsilon \to 1$), the Q values the SCD should have in order for the SCD-LWHR to break-even, energy-wise, with the DT-LWHRs is comparable with the Q value of the DT fusion device. But the neutrons leaking from the deuterium based fusion devices could also, in principle, be utilized to produce tritium which, if burned in the same devices, could improve their energy balance.

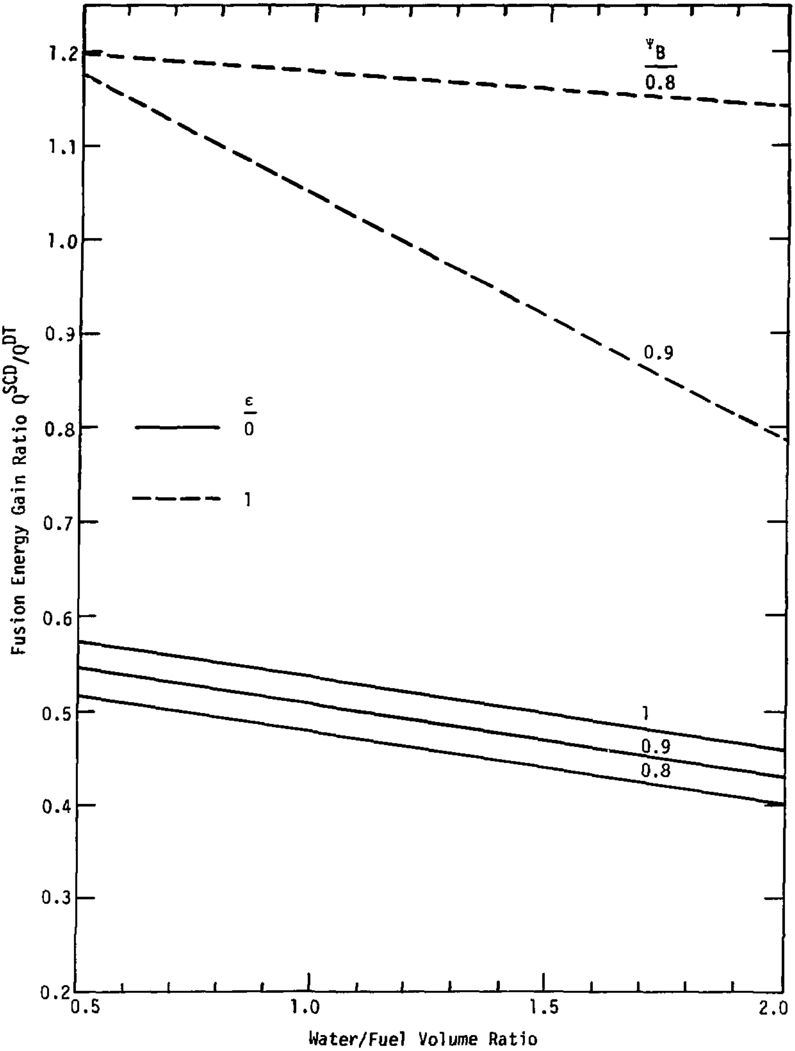

Fig. 12. Ratio of the Fusion Energy Gain of a SCD Fusion Device to that of a DT Fusion Device which Provides the Same Plant Efficiency for the Respective LWHRs.

3. ACCELERATOR DRIVEN LIGHT WATER REACTORS (ADLWR)

Most of the spallation based intense neutron sources that have been proposed(15-21) call for the use of proton beams accelerated to energies of the order of 1 GeV. The neutron yield strongly depends on the target material and, in the proton energy range considered, has a linear dependence on the proton energy. The energy investment required for the generation of a spallation neutron in uranium or lead target is approximately 20 MeV and 50 MeV respectively. For the following analysis we shall assume(13,18,20) that a 1-GeV proton produces, on the average, 22 or 42 neutrons in lead or uranium targets respectively. The energy deposited in the respective targets is 1 GeV and 4 GeV per 1-GeV proton.

The nautre of the spectrum of the spallation neutrons is illustrated in Fig. 13 which shows the spectrum of the spallation neutrons emitted at 90° from a beam of 1-GeV protons impinging on a Pb-Bi target(20). It is observed that the spallation neutron source has a tail of very high energy neutrons. These energetic neutrons are expected to be quite effective in causing fast fissions and other neutron multiplying reactions in ^{238}U (of the blanket). We did not calculate the direct fast fission effects (β and γ, see Section 2) induced by an average spallation neutron in the blanket. Instead, we shall assess the potential of SDLWRs by assuming

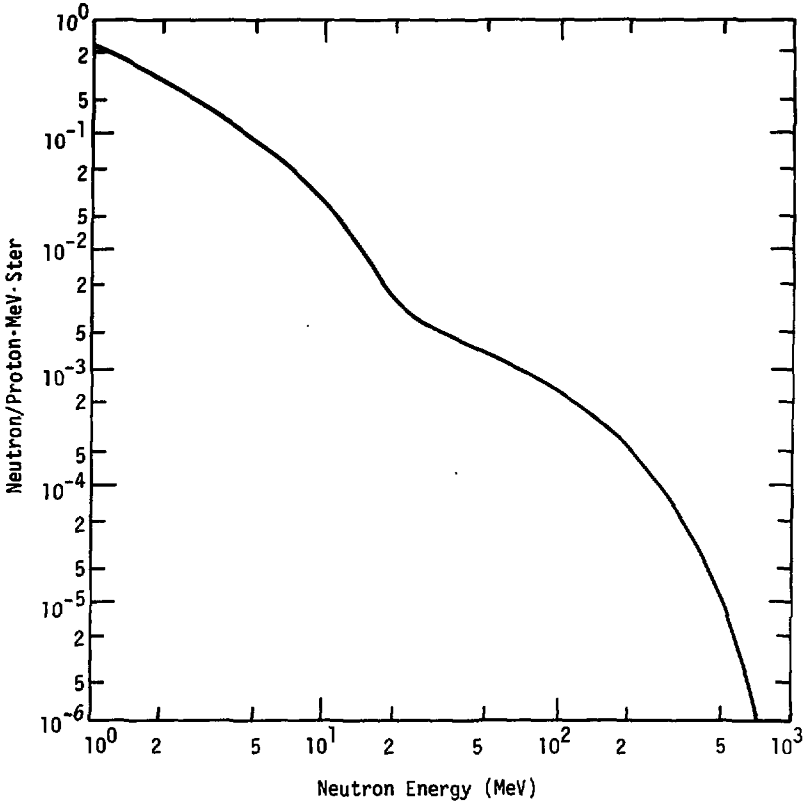

Fig. 13. Spectrum of the Spallation Neutron Source at 90° from a 1-GeV Proton Beam Impinging on a Pb-Bi Target.

that the direct fast fission probability of an average neutron from an accelerator neutron source is either one-half or the same as that of a 14-MeV neutron. That is, the accelerator neutron source is taken to be as effective as neutron from either a SCD or a DT fusion device.

The volume of the target required to stop a 1 GeV proton beam can, in principle, be quite small; a typical target size considered for the Intense Neutron Generator(20) is 10 cm in diameter and 50 cm in length. Heat removal considerations, however, may dictate a larger volume for the spallation neutron source. Nevertheless, the spallation neutron source may be considered as a "point source" when compared, for example, with the volume of an equal intensity fusion neutron source from magnetically confined plasmas.

Thermal-hydraulic considerations impose an upper limit on the blanket power density and through it, on the maximum current of source neutrons permitted to reach the blanket (per surface area of the blanket). Consequently, the total power output the SDLWR is designed for dictates the minimum total blanket surface area (as well as the total intensity of the neutron source) and, through it, on the size of the central blanket cavity. For SDLWRs for a 1000 MWe, for example, the minimum dimension of the central cavity is estimated(13) to be about 6 meters. Such a large cavity provides much flexibility for the design of the target assembly(13), and its heat removal system. In this regard our ADLWR concept differ from other accelerator driven systems proposed (see, for example, references 17 and 18) in which the target is actually imbedded inside the fission blanket, very close to it.

A variety of geometries for laying-out the blanket around the spallation neutron source may be conceived(13). One of the simplest and most convenient of them is the cylindrical geometry illustrated schematically in Fig. 14. To avoid excessive streaming of neutrons through the bases of the central cavity, it might be necessary to design such blankets to have a large height-to-diameter ratio or else, to add blanket sections to close at least part of the bases.

Figure 15 shows schematically two basic pressure tube design approaches for the blanket of ADLWRs. The single water system design of Fig. 15b appears to be the preferable approach as, in addition to the inherent advantages of the single water system arrangement(1), it is free of an inner wall.

Following the approach used for assessing the energetics of LWHRs (Section 2.2), we define the overall efficiency of an ADLWR power plant, η_p, using a simplified energy conservation condition

$$\eta_p[m_t W_b + N_t B_{eff}] = \eta_{th}[(m_t + 1)W_b + N_t B_{eff}] - W_b/\eta_b \qquad (7)$$

from which we get an expression for the relative plant efficiency

$$\frac{\eta_p}{\eta_{th}} = 1 - \frac{(\eta_b \eta_{th})^{-1} - 1}{m_t + N_t B_{eff}/W_b} \; . \qquad (8)$$

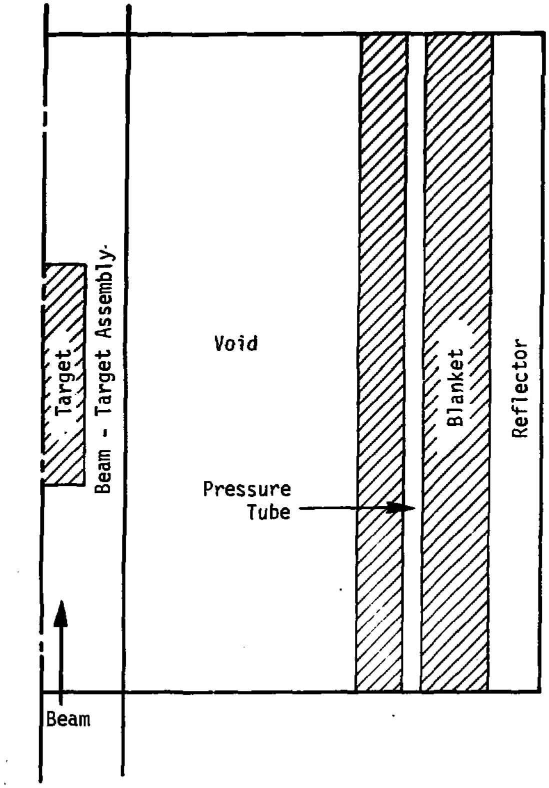

Fig. 14. A Schematic Layout of a Cylindrical ADLWR.

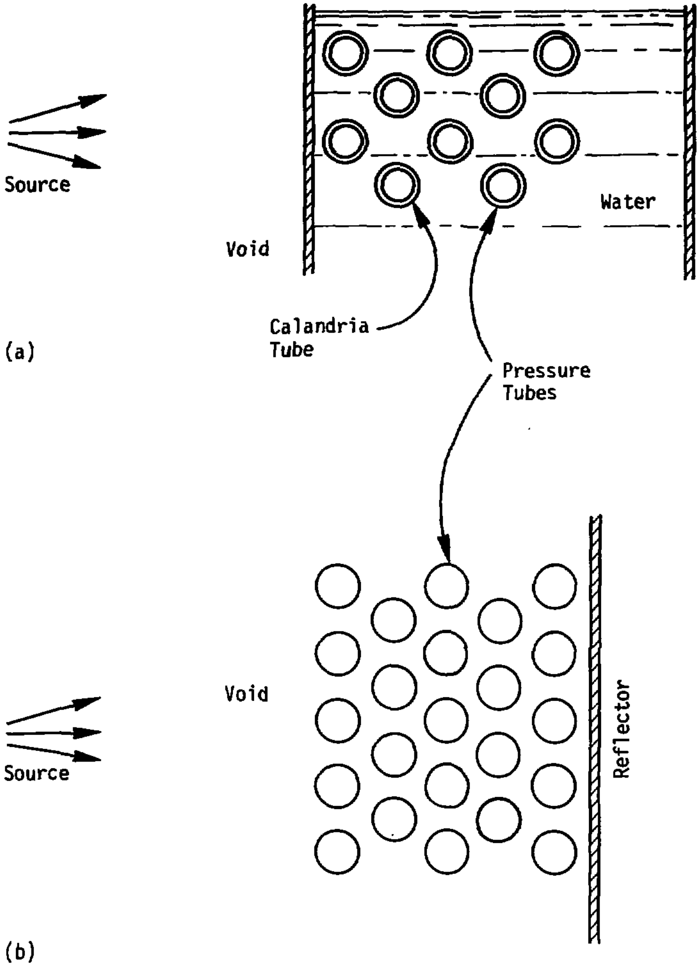

Fig. 15. Schematic Layouts of ADLWR Blankets Having a Pressure Tube Design.

In the above,

W_b is the beam proton energy,

η_b is the efficiency for the conversion of electrical energy into the proton kinetic energy. It will be assumed$^{(18)}$ to be 0.5,

N_t is the number of neutrons generated in the target per proton, and

m_t is the target energy multiplication defined here to be the nuclear energy generated in the target per proton, in units of W_b. It is assumed to be 0 or 3 for the lead or uranium targets respectively.

Figure 16 defines the range of the relative plant efficiencies that might be attainable with ADLWRs based on accelerator neutron sources the performance of which was described above. Comparing the results of Fig. 16 with those of Figs. 7 and 8 it is observed that with uranium target, the plant efficiency of ADLWRs is significantly better than that of SCD-LWHRs with $Q = 0.25$ (Fig. 8); it is comparable with the plant efficiency of DT-LWHRs having $Q = 1$ and $\epsilon = 0$ (Fig. 7). With lead target, however, the efficiency of the ADLWR is comparable with that of a $Q = 0.25$ SCD-LWHR. The results reported here on plant efficiency of ADLWRs should be considered more reliable than those reported previously$^{(13)}$ as they account for the leakage effect on the blanket performance more accurately.

It might be very difficult to design uranium targets that will meet acceptable safety criteria. The particular approach for the design of the ADLWR which call for a central blanket cavity of large dimensions provides, nevertheless, for the utmost flexibility in the design of the

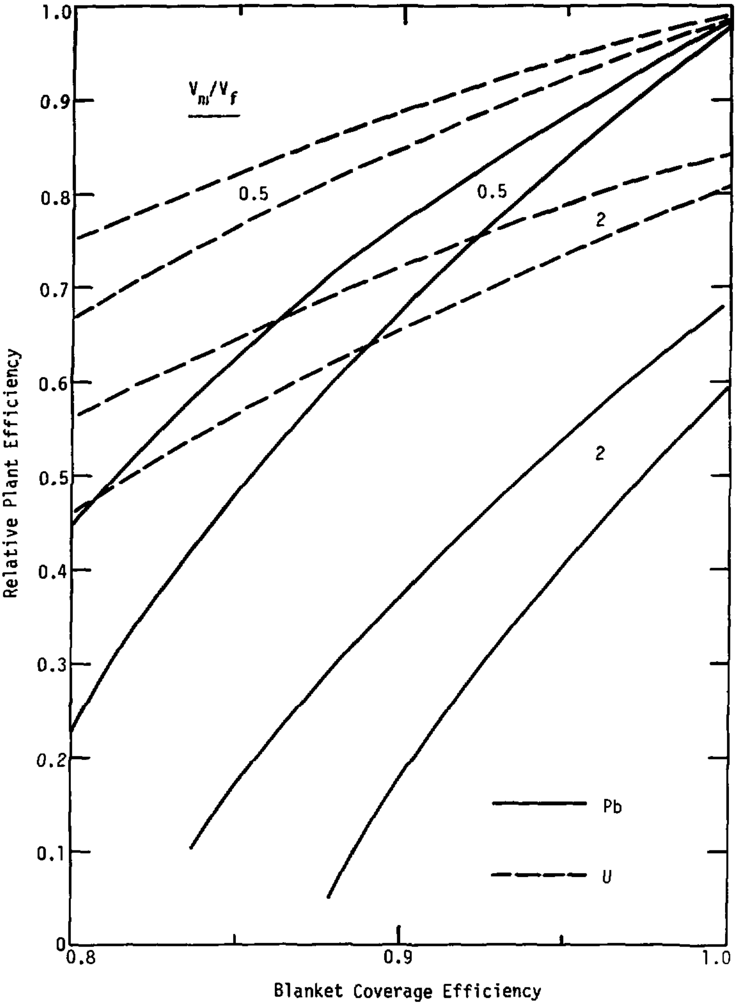

Fig. 16. Plant Efficiencies of ADLWRs as a Function of the Blanket Coverage Efficiency and Type of Target. The Lower Curve of Each Pair Corresponds to β and γ Values of SCD Neutrons. The Upper Curve Corresponds to β and γ of DT Neutrons.

target assembly (as compared with other concepts of accelerator driven fission systems). Moreover, as compared with other accelerator driven fission systems, the blanket of the ADLWR has the advantages of significantly lower radiation damage rates and maximum-to-average power densit' (that is, relatively small power density gradients).

4. COMPARISON OF SOURCE DRIVEN LIGHT WATER REACTORS

Both types of SDLWRs which are free from the need to breed tritium that were examined in this work - the SCD-LWHR and ADLWR, are found to offer useful alternatives to the reference DT-LWHR. All three types of SDLWRs might provide, under certain conditions, overall efficiencies for the conversion of nuclear into electrical energy which are within 80% of the efficiency of a power plant based on the corresponding critical fission system. The most meaningful criterion for comparing the different SDLWRs is the economical one. Such a comparison is, however, beyond the scope of this work (and, in fact, can not be done reliably before additional extensive R & D work has been completed). We shall, nevertheless, compare qualitatively several properties of the SDLWRs. The fusion devices considered are assumed to be beam driven with no contribution from thermonuclear reactions. The comparison is done category by category whereby for each category the three types of SDLWRs are ranked in order of descending advantage (from left to right). The notation DT, SCD and AD is used for, respectively, DT-LWHRs, SCD-LWHRs and ADLWRs.

(1) Energetics DT, AD, SCD

The DT-LWHRs have a clear lead over the other types of SDLWRs, as far as the attainable plant efficiencies are being considered. The lead of the

DT-LWHR stems, primarily, from the relatively low energy required to invest for the production of a 14 MeV neutron.

The energy balance of ADLWRs using lead targets appears to be comparable with that of $Q = 0.25$ SCD-LWHRs. But hybrid reactors based on the deuterium fuel cycle have the potential of becoming more energy-efficient than ADLWRs (even with uranium targets).

(2) Technology AD, DT, SCD

The technology of high energy accelerators is considered (see, for example, reference 15) to be more developed than that of fusion devices. The extrapolation from the present accelerator technology to that required for SDLWR applications is thought to be modest.

(3) Tritium Inventory AD, SCD, DT

Even though the ADLWR and SCD-LWHR are completely free from the need to incorporate lithium in the blanket, the SCD device has non-negligible amounts of tritium in its plasma system. It is estimated(10) that the tritium inventory in the SCD-LWHR is smaller than that in a DT-LWHR of comparable power by more than two orders or magnitude.

(4) Fissile Fuel Inventory DT, AD, SCD

The tritium breeding blanket for the DT-LWHR can be designed(1) to have significantly smaller thickness for the fission zone and significantly higher average-to-maximum power density as compared with lithium-free blankets. Consequently, the fissile fuel inventory of the DT-LWHR can be smaller than that of the other types of SDLWRs.

(5) Flexibility in Blanket layout AD, DT, SCD

The small size of the target assembly of the accelerator neutron source, and the relatively large dimensions of the central blanket cavity provide much flexibility in the design of the blanket for the ADLWRs. The access port required for the ADLWR beam-target assembly are expected to be significantly smaller than that required for the neutron source of the LWHRs. This, along with the fact that the ADLWR neutron source does not have to be surrounded with magnetic field coils, assures that the blanket coverage efficiency ADLWRs could be designed with will be higher than those of the LWHRs. Moreover, the ADLWR blanket is expected to be simpler, cheaper and easier to maintain than the LWHR blankets.

Of the fusion devices, the need to breed tritium, along with the possibility of separating the functions of the power generating and tritium breeding blankets, provide more flexibility in the layout of the DT-LWHR blanket.

(6) Sensitivity to Blanket Coverage Efficiency DT, SCD, AD

The possibility to utilize part of the leaking neutrons to produce tritium in the DT-LWHRs (see discussion above) can make the DT-LWHR the least sensitive to the blanket coverage efficiency of all other SDLWRs. Neutrons leaking from SCD devices might also be utilized to produce tritium which, if used in the SCD reactor, could improve its energy balance. Neutrons leaking from ADLWRs might be used for a variety of applications but not for improving its energy balance.

(7) First Wall Loading AD, SCD, DT.

The blanket of the ADLWR does not have to have an inner wall at all (see Section 3). The maximum permissible (from blanket power removal considerations) first wall loading of the SCD-LWHR is lower than that of the DT-LWHR by at least a factor of four.

(8) Flexibility in Blanket Power Control DT, SCD, AD

In the DT-LWHRs it is possible(1) to use the lithium system for adjusting the blanket power output and, in the lithium-in-lattice blanket design(1), also the power shape. In the lithium-free SDLWR one could use parasitic absorbers to perform similar functions. Of the SDLWRs, the SCD-LWHR is more suitable for lithium control as the tritium produced could contribute to the overall energy balance of the reactor.

(9) Benefit to Cost Ratio DT, SCD, AD

The development of fusion devices for SDLWR (or any other types of hybrid reactors) might be viewed as a spin-off of the R & D effort aimed at the development of fusion power reactors. Assuming that the R & D aimed at the commercialization of fusion power reactors will be financed in any case, the extra investment required for the development of hybrid reactors is expected to be relatively small.

5. SUMMARY AND CONCLUSIONS

(a) The improvement in the energy generation ability of LWHR blankets made possible by relieving them from the need to breed tritium could compensate for the extra energy investment required for the generation of neutrons in SCD fusion devices provided the latters could be designed to have fusion energy gains which are about one half the Q value of the corresponding DT fusion devices.

(b) If DT-LWHRs could be designed to have most of the neutrons leaking from the blanket (assumed to have a coverage efficiency smaller than 0.9) to produce tritium, their average blanket energy generation ability will be comparable with that of lithium-free blankets driven by SCD neutron sources.

(c) SCD-LWHRs may, nevertheless, be viable power reactors. To have acceptable plant efficiencies the fusion energy gain of the SCD device should be at least 0.25. The attainment of $Q \simeq 0.25$ requires plasma electron temperatures of about 25 keV or higher and beam injection energies of at least 1.5 MeV. The $Q = 0.25$ SCD-LWHRs could be viable power reactors only with blankets having very high energy multiplication - comparable to that attainable with the water-to-fuel volume ratio of 0.5.

The lowest useful limit of the fusion energy gain for practical SCD-LWHRs appears to us to be about $Q \simeq 0.5$. The contribution of the D-^{3}He reactions to the energy balance of deuterium based fusion devices could be very useful even for hybrid reactor applications.

(d) The overall energy balance of ADLWRs that use uranium targets is comparable to that of a DT-LWHR using a $Q = 1$ fusion device. In other words, the improvement in the energy generation ability of LWHR blankets which are free from the need to breed tritium just about compensates for the extra energy investment (relative to a $Q = 1$ DT fusion device) for the generation of neutrons in high energy accelerators using uranium targets. The development of safe and environmentally acceptable uranium targets may, however, be very difficult.

(e) With lead targets, the energy balance of ADLWRs is comparable to that of SCD-LWHRs using $Q \approx 0.25$ fusion neutron sources.

(f) The possibility for utilizing the neutrons that escape the blanket of a DT-LWHR for the production of tritium (in separate lithium zones not accessible for fission blankets) can significantly improve the energy balance of the DT-LWHRs relative to the other types of SDLWRs having the same blanket coverage efficiency.

(g) Other advantages of DT-LWHRs (in addition to the possibility of getting the highest plant efficiencies) include:

- Lowest fissile fuel inventory
- Highest average-to-maximum power density
- Flexibility in blanket power control

- Relative to the SCD-LWHRs also less demanding fusion reactor technology and more flexibility in the blanket layout.

(h) Advantages of ADLWRs include:

- Lowest radiation damage problems in the blanket (even though there might be severe radiation damage problems to the target assembly).
- Freedom from tritium (except for very small amounts from fission products).
- Flexibility in the blanket layout and simplicity of the blanket design. Consequently it is likely that the blanket of an ADLWR could be designed to be the cheapest, to have the highest coverage efficiency and easiest maintenance.

(i) Advantages of SCD-LWHRs relative to DT-LWHRs include:

- Lower first wall loading
- Lower tritium inventory
- Simpler (and also cheaper) blanket design.

ACKNOWLEDGMENT

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