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Capabilities of a DT tokamak fusion neutron source for driving a spent nuclear fuel transmutation reactor

W.M. Stacey

Fusion Research Center, Georgia Institute of Technology,
Atlanta, Georgia, United States of America

Abstract. The capabilities of a DT fusion neutron source for driving a spent nuclear fuel transmutation reactor are characterized by identifying limits on transmutation rates that would be imposed by tokamak physics and engineering limitations on fusion neutron source performance. The need for spent nuclear fuel transmutation and the need for a neutron source to drive subcritical fission transmutation reactors are reviewed. The likely parameter ranges for tokamak neutron sources that could produce an interesting transmutation rate of 100s to 1000s of kg/FPY (where FPY stands for full power year) are identified ($P_{fus} \approx 10$–100 MW, $\beta_N \approx 2$–3, $Q_p \approx 2$–5, $R \approx 3$–5 m, $I \approx 6$–10 MA). The electrical and thermal power characteristics of transmutation reactors driven by fusion and accelerator spallation neutron sources are compared. The status of fusion development vis-à-vis a neutron source is reviewed.

1. Introduction

There is an ongoing worldwide planning, analysis and R&D activity dedicated to mitigating the nuclear waste problem by neutron transmutation of long lived actinides and fission products in spent nuclear fuel. The objective of neutron transmutation of spent nuclear reactor fuel is to reduce the amount (70 000 t will have been produced in the USA by 2015) and the time of high radiotoxicity (from hundreds of thousands to hundreds (or thousands) of years) of the material that must be stored in high level radioactive waste repositories. Such a reduction in the amount and the time of high radiotoxicity of stored high level waste could eliminate the one remaining obstacle — waste disposal — to the full-scale deployment of nuclear power to meet the world's growing energy demands without dramatically increasing CO_2 levels. At the same time, the destruction of actinides by fission would eliminate a potential proliferation risk and produce electrical power, which would provide a source of revenue to offset the operating cost of the transmutation facility.

The OMEGA project motivated the largest international R&D activity since 1988 on separation and transmutation of actinides and fission products, with Japan and France as the principal participants. Further motivation was provided by an IAEA Meeting in 1991 and the GLOBAL Meeting in Seattle in 1993. The major elements of this R&D have been systems studies to evaluate transmutation scenario options and the development of technologies for separating actinides and fission products from the waste stream of reprocessed fuel. A formal program of information exchange among OECD countries, under the auspices of the OECD Nuclear Energy Agency (NEA), has produced five International Information Exchange Meetings on the subject in the past decade, each with about 100 participants and proceedings [1, 2].

In the USA, there has been considerable interest in the use of accelerator spallation neutron sources in conjunction with subcritical transmutation reactors for the transmutation of spent nuclear fuel (see, e.g., Refs [3–5]). This interest has led to the establishment of the accelerator transmutation of waste (ATW) activity [5], in which the major emphasis is on the use of a subcritical reactor driven by an accelerator spallation neutron source.

In contrast to the US ATW activity, the international OECD/NEA activity has emphasized recycling of spent fuel first in commercial light water reactors (LWRs) and then in dedicated fast reactors. However, there is a general consensus that, even with extensions of the presently available aqueous processing technology, critical reactors alone cannot achieve sufficient levels and rates of net actinide destruction to qualitatively change the waste disposal issue and that subcritical reactors driven by neutron sources are needed to achieve this goal. While accelerator spallation neutron sources have been mentioned in most such studies, fusion neutron sources could play the same role.

The physics [6] and technology [7–13] design basis for a good tokamak DT fusion neutron source exists today and will be advanced over the next few years. The 'conventional' tokamak physics database (including the more than 10 MW level of DT operating experience in TFTR (USA) and JET (EU)) and the existing technology database (including the technology which has already been demonstrated on existing tokamaks and the advanced technology which has been developed and tested in the US M\$750 ITER R&D programme) are sufficient to allow the design and construction at present of neutron sources with modest annual neutron fluence capability. The 'advanced tokamak' physics database that is rapidly accumulating is extending the design basis for continuous operation, reduced cost and annual neutron fluence accumulation.

A limited number of studies (see, e.g. Refs [14–19]) of transmutation systems with fusion neutron sources have been performed. These studies and other considerations would seem to indicate that the minimum requirements for a tokamak DT fusion neutron source for a transmutation facility are energy amplification $Q \approx 2$–5, neutron wall load $\Gamma < 1$ MW/m^2, very long pulse operation and availability $\approx$40–50%. The present tokamak physics and technology database is sufficient to design a device satisfying the Q and Γ requirements (which are less demanding than those for ITER). A substantial advance in the database for long pulse operation will be supplied by KSTAR (Republic of Korea), but without the integration needed with burning plasma phenomena. However, a prototype tokamak experiment that integrates the burning plasma physics, long pulse physics and advanced technology is required, particularly to provide the design database for achieving 40–50% availability. Such a prototype would necessarily be almost at the ITER [20] level, and that device would in fact serve as a prototype for a tokamak neutron source for a transmutation facility. Furthermore, it would be technically feasible to test prototypical transmutation reactor modules (without fissionable material or fission products) in ITER.

Several fuel/moderator/coolant and processing/separation technologies are being developed and/or evaluated in the ATW process [5] and in the OECD/NEA R&D activities [1, 2], based on extensions of nuclear reactor technology and taking into account the accumulated experience with nuclear safety and nuclear licensing requirements. For a fusion driven transmutation facility, an additional technical issue is the adaptation of these technologies to tokamak geometry and to achieving tritium self-sufficiency. The evaluation of fusion driven transmutation facilities based on the adaptation of the same 'nuclear' technologies (fuel/moderator/coolant and processing/separation technologies) that are being developed/evaluated in the ATW and OECD/NEA activities remains to be done.

Some idea of the 'window of opportunity' for developing a fusion neutron source for transmutation applications can be obtained by considering the schedule for the development of an accelerator spallation neutron source for this application [5]. The ATW activity initiated a six year programme in f.y. 2000 to perform scenario systems studies and to evaluate 'reactor' technology options. This initial programme is intended to be followed by about ten years of R&D and technology testing, which would in turn be followed by the construction, operation and continual upgrading of a demonstration plant over a period of 15 years, leading to an accelerator neutron source based transmutation facility coming on-line in about 30 years.

If ITER is constructed and operated more or less on schedule, or if a different neutron source prototype on a somewhat smaller scale is built and operated on about the same schedule, then it should be possible to design and construct a tokamak fusion neutron source based transmutation facility to come on-line within about 30 years, consistent with the present ATW schedule, particularly if the design was performed and validated during the prototype operating period.

The transmutation of spent nuclear fuel could be an important, intermediate term, international mission for magnetic fusion which directly contributes to the long term objective of fusion energy. A tokamak fusion neutron source could be as suitable, perhaps more suitable, as an accelerator spallation neutron source for the transmutation of spent nuclear fuel in a subcritical reactor, and the further R&D needed for a tokamak fusion neutron source that meets the requirements for a transmutation facility may be no more than the R&D required for an accelerator neutron source that meets the same requirements, given the recent internationally funded (7.5×10^8 US dollars) ITER R&D activity and the possibility that an internationally funded ITER could serve as the prototype fusion neutron source. It is important that both the accelerator spallation and the fusion neutron source technologies be fully evaluated for this application.

Since the neutron spectrum in a subcritical reactor driven by a neutron source will depend more on the moderating and absorption properties, and hence on the material composition, of the subcritical reactor than on the energy spectrum of the source neutrons, the material composition in the subcritical reactor can be optimized for the transmutation task at hand, without the criticality and safety constraints that would be present in a critical reactor. Thus, the physics characteristics of a subcritical reactor should be more or less independent of whether a fusion or an accelerator spallation neutron source is used. The engineering design and the economics, however, will surely depend on the choice of neutron source.

The purpose of this article is to characterize the capabilities of a DT tokamak as a fusion neutron source for a subcritical reactor for the transmutation of spent nuclear fuel. The need for transmutation of spent nuclear fuel and the need for neutron sources to drive subcritical fission reactors is reviewed in Section 2. The thermal and electrical power characteristics of neutron sources based on DT fusion and on accelerator spallation are compared in Section 3. Physics and engineering limitations on the capabilities of a tokamak fusion neutron source for driving a subcritical transmutation reactor are discussed in Section 4, and a likely range of tokamak neutron source parameters is presented. The status of DT tokamak neutron source development, vis-à-vis the requirements identified in Section 4, is reviewed in Section 5. Finally, some conclusions are presented in Section 6.

2. Transmutation of spent nuclear fuel

The once through cycle (OTC), in which slightly enriched UO_2 fuel (^{235}U increased from 0.72% in natural U to 3–5%) is irradiated to 30–50 GW d/t (gigawatt days per metric ton) in a commercial reactor and then disposed of totally as high level waste (HLW), is the reference nuclear fuel cycle in the USA and a few other countries. With the present low U prices, this is the cheapest fuel cycle, in the short term. Moreover, the present US government policy against reprocessing, motivated by proliferation concerns, is consistent only with OTC. However, the long term implications of OTC are rather unfavourable. The potential energy content of residual fissile material (about 1% each Pu and ^{235}U) and of the ^{238}U (>90%) in spent fuel, which constitutes more than 90% of the potential energy content of mined uranium, is lost in the OTC. Moreover, all the nuclides that can contribute to the potential radiotoxicity of the spent fuel are retained together with a much greater volume of depleted U (mostly ^{238}U), which makes a relatively small contribution to the potential radiotoxicity, resulting in the largest possible volume of HLW, which must be stored in geological repositories for hundreds of thousands to millions of years.

At the current level of nuclear energy production in the USA using OTC, a new repository on the scale of the presently proposed Yucca Mountain site would have to be installed about every 30 years. The objective of transmutation of spent fuel is to reduce both the mass of HLW that must be stored in geological repositories and the time of high radiotoxicity of that HLW, thus reducing the requirements for both the number of repositories and the duration of secured storage. A National Research Council (NRC) study [21] recently concluded that the need for a geological repository could be reduced, but would not be eliminated, by transmutation.

The short term radiotoxicity of the spent fuel is dominated by fission products, but after 300–500 years only long lived radionuclides (particularly ^{99}Tc and ^{129}I, but also ^{135}Cs, ^{93}Zr, etc.) remain [22] — unfortunately some of these are relatively mobile and contribute disproportionately to the potential radiological hazard from spent fuel. However, the long term potential radiotoxicity of spent fuel arises principally from the presence of transuranic actinides (Pu and the so-called minor actinides Np, Am, Cm, etc.) produced by transmutation–decay chains originating with neutron capture in ^{238}U, which constitute a significant radiation source for hundreds of thousands of years.

Processing of spent UO_2 fuel to recover the residual U and Pu reduces the potential long term radiotoxicity of the remaining HLW (minor actinides, fission products, activated structure, etc.) by a factor of 10 and reduces the volume by a much larger factor, and aqueous processing technology (PUREX) capable of 99.9% efficient recovery of U and Pu is commercially available in a number of countries (UK, France, Japan, India, Russian Federation and China). A fuel cycle in which the recovered Pu and U was recycled as a mixed oxide (MOX) UO_2–PuO_2 commercial reactor fuel has been envisioned since the beginning of the nuclear energy era, and at present a number of commercial reactors are operating with recycled Pu in Western Europe. (Reprocessed U is not being significantly recycled because of the low cost of fresh U which does not contain the neutron absorbing ^{236}U that decreases the reactivity of recycled U.) Taking into account the further production of minor actinides and fission products in the recycled Pu, a single recycle of the Pu in spent fuel reduces the potential radiotoxicity of the HLW associated with the original spent fuel only by a factor of 3 (rather than 10). Repeated recycling of the MOX fuel is technically feasible and would result in better fuel utilization, but the potential radiotoxicity of the HLW associated with the original spent fuel would actually increase relative to that of OTC because of the further production of minor actinides and fission products [1].

It is clear from the above discussion that in order to reduce the potential radiological hazard associated with spent fuel or the length of time that hazard exists, it is necessary

(a) To destroy the actinides (Pu and the minor actinides),
(b) To destroy the potentially hazardous long lived fission products.

The destruction of the minor actinides and long lived fission products, as well as the Pu, by neutron transmutation implies the requirement for separation of these nuclides from the waste stream of processed spent fuel for recycling with subsequent fuel loadings. Effective separation of Pu with 99.9% efficiency is achieved commercially with the PUREX process. The effective separation of Np is technically feasible with a modified PUREX process, but practical separation methods for Am, Cm and the long lived fission products are still in the research stage. The pyrometallurgical (PYRO) separation technology presently under development would, unlike the PUREX process, allow separation of Np, Am and Cm along with Pu into a co-deposited metallic product that could be recycled in a metal fuel fast reactor, resulting in a waste stream essentially free of actinides.

Since all actinides are potentially radiotoxic and since neutron capture (n,γ) reactions in actinides just produce other actinides, the only effective way to destroy actinides is by neutron fission (n,f) reactions. Some of the actinides are effectively not fissionable in a thermal neutron spectrum such as exists in almost all commercial nuclear reactors, and the probability of fission per neutron absorbed is greater for all the actinides in a fast neutron spectrum [22]. The neutron absorption cross-sections for the troublesome long lived fission products are small in a thermal neutron spectrum and even smaller in a fast neutron spectrum, implying the advantage of a very high flux of thermal neutrons for their effective destruction (effective destruction of ^{135}Cs may prove impractical because of the presence of other neutron absorbing Cs isotope fission products).

Several studies of minor actinide transmutation in nuclear reactors have been performed (see, e.g., Refs [1, 2, 5]). They indicate that recycling of industrial levels of minor actinides as well as of Pu in thermal neutron spectrum commercial reactors does not significantly reduce the overall radiotoxicity and requires an increase in fuel enrichment, with a corresponding increase in the cost of energy. On the other hand, recycling minor actinides as well as Pu in fast reactors is predicted to reduce the overall radiotoxicity of HLW, but the maximum loading of minor actinides is limited by reactor safety considerations. The possibility of recycling Pu and the minor actinides first in thermal neutron spectrum commercial LWRs and then in dedicated fast reactors has been calculated to be able to reduce the radiotoxic inventory in HLW by a factor of about 100 relative to that of OTC [1].

Such studies generally indicate that the transmutation of Pu, minor actinides and fission products in critical nuclear reactors would be ultimately limited by criticality or safety constraints. While fast reactors could, in principle, burn the mixture of Pu plus minor actinides and some of the fission products, the available PUREX process does not separate the minor actinides with the plutonium from the waste stream for recycling. Moreover, it would be difficult to fabricate MOX fuel containing the highly radioactive minor actinides in existing facilities. This has led in Europe and Japan to consideration of remote fuel fabrication facilities to supply fuel containing minor actinides for destruction in dedicated subcritical 'transmuter' reactors driven by accelerator spallation neutron sources, while the Pu would be consumed in dedicated fast reactors [1].

The US ATW concept [5] is to use remote fabrication of fuel containing separated Pu plus minor actinides, but no ^{238}U, for destruction in a critical 'transmuter' reactor driven by an external neutron source. A variant of this concept would involve first irradiating this Pu plus minor actinide fuel by repeated recycling in a critical reactor before the final irradiation in a subcritical 'transmuter' reactor.

The small delayed neutron fraction of the minor actinides and the generally positive reactivity coefficient of fast reactors without ^{238}U dictates that these actinide destruction, or 'transmuter', reactors must remain well below subcriticality. The reactivity coefficient could be made negative by the addition of ^{238}U, which would allow the possibility of actinide destruction in critical fast reactors, but that would lead to the production of additional Pu and minor actinides by transmutation of ^{238}U, and hence to a decreased net actinide destruction rate.

The development of the PYRO separation technology would allow separation of Np, Am and Cm along with Pu, all of which could be recycled in a metal fuel fast reactor, resulting in a waste stream essentially free of actinides. However, it would be necessary to include ^{238}U (or another resonance absorber) in the fuel to avoid the safety problems mentioned in the previous paragraph, which would reduce the net destruction rate of actinides.

Thus, safety or net destruction rate constraints on the transmutation of actinides in critical reactors could be relaxed by operating the reactors subcritically with a neutron source. Several studies of subcritical reactors driven by accelerator spallation neutron sources [1–5] and a few studies of subcritical reactors driven by fusion neutron sources [14–19] have predicted significantly higher levels of Pu, and minor actinide and/or long lived fission product destruction than those that are predicted to be achievable in critical nuclear reactors. The optimum scenario for recycling Pu, minor actinides and long lived fission products in commercial thermal neutron spectrum reactors, in dedicated fast neutron spectrum reactors and in subcritical transmutation reactors driven by neutron sources remains the subject of active investigation.

It should be noted that there will be significant technical challenges associated with the implementation of fission waste transmutation in either fusion or accelerator based neutron source subcritical facilities, and, indeed, in critical fission reactor transmutation schemes. There will be a tendency to large power density swings during the transmutation cycle due to changes in fissionable fuel density and composition. There will be materials damage and materials compatability issues to be addressed, and there will be safety issues associated with high power densities and large fission waste inventories. These concerns will be present for any transmutation system. Detailed studies are required to address these issues and to evaluate both which transmutation scheme offers the best solution and whether or not any transmutation system is superior to long term monitored retrievable storage.

3. Comparison of electrical power characteristics of fusion and accelerator neutron source transmutation facilities

3.1. Computational model

We use a simple, global particle balance to model source driven subcritical reactors. The point kinetics model describing the dynamics of the total neutron population N in a nuclear reactor with an external source S is [23]

$$\frac{dN}{dt} = \frac{k-1-\beta}{\ell}N + \sum_{i=1}^{I}\lambda_i C_i + S \qquad (1)$$

and

$$\frac{dC_i}{dt} = \frac{\beta_i N}{\ell} - \lambda_i C_i, \quad i = 1, ..., I \qquad (2)$$

where the C_i represent the population of fission products of species i which decay with half-life $t_{1/2} = \sqrt{2}/\lambda_i$ to release 'delayed' neutrons, β_i is the fission yield of delayed neutron precursor species i, $\beta = \sum \beta_I$, k is the multiplication constant of the reactor assembly and $\ell = 1/(v\sum_a)$ is the prompt neutron lifetime, where v is the average neutron speed and $\sum_a$ is the macroscopic absorption cross-section averaged over the neutron energy distribution. The asymptotic solution of Eqs (1) and (2) yields the equilibrium neutron population in the reactor,

$$N = \frac{S\ell}{1-k} = \frac{S/(v\sum_a)}{1-k}. \qquad (3)$$

The effective multiplication constant can be written as the ratio of the neutron production rate to the neutron destruction rate,

$$\begin{aligned} k &= \frac{(\nu\sum_f + 2\sum_{n,2n} + 3\sum_{n,3n})}{\sum_a^F + \sum_a^{Li} + \sum_a^P} P_{NL} \\ &\equiv \frac{\nu\gamma\sum_f P_{NL}}{\sum_a^F + \sum_a^{Li} + \sum_a^P} \end{aligned} \qquad (4)$$

where ν is the average number of neutrons per fission, the factor γ takes into account the neutrons produced in (n,2n) and (n,3n) reactions, P_{NL} is the non-leakage probability that a neutron remains in the reactor to be absorbed, and $\sum_a^x$ is the macroscopic absorption cross-section for the fissionable material ($x =$ F), the lithium needed to breed tritium for the fusion neutron source ($x =$ Li), and for absorption in the structure and other parasitic material ($x = p$).

We assume that with the fusion neutron source it is necessary to produce tritium fuel, which requires a tritium breeding ratio (TBR) greater than unity,

$$\mathrm{TBR} = \frac{\Sigma_a^{Li} N v}{S} > 1. \tag{5}$$

Combining Eqs (3) and (5) yields

$$\Sigma_a^{Li} = \Sigma_a (1-k)\mathrm{TBR} \tag{6}$$

which can be used with Eq. (4) to relate the effective multiplication constant with no Li present (k_0 for TBR $= 0$) to the effective multiplication constant when Li is present in a reactor that is otherwise identical,

$$k_0 = k[1 + (1-k)\mathrm{TBR}] \tag{7}$$

The effective transmutation (fission) rate (TR) is defined as

$$\mathrm{TR} = v\Sigma_f N = \frac{S}{1-k}\frac{\Sigma_f}{\Sigma_a} \simeq \frac{Sk}{\nu(1-k)} \tag{8}$$

since the non-fission capture of a neutron by an actinide essentially just converts that actinide into another actinide.

3.2. Input electrical power requirement

The input electrical power required to produce S spallation neutrons per second is

$$\begin{aligned} P_{in,e}^{atw} &= \frac{E_{spall} S_{atw}}{\eta_b^{atw}} + \frac{P_{aux}^{atw}}{\eta_{aux}^{atw}} \\ &= \frac{E_{spall} S_{atw}}{\eta_b^{atw}} \left[1 + \left(\frac{P_{aux}^{atw}}{E_{spall} S_{atw}}\right)\left(\frac{\eta_b^{atw}}{\eta_{aux}^{atw}}\right)\right] \end{aligned} \tag{9a}$$

where E_{spall} is the energy on target per spallation neutron produced, η_b^{atw} is the ratio of electrical energy to energy on target (i.e. the beamline efficiency), P_{aux}^{atw} is the power required to operate the auxiliary systems for the accelerator spallation neutron source transmutation facility and η_{aux}^{atw} is the efficiency of delivery of this energy to end use.

The input electrical power required to produce S fusion neutrons per second is

$$\begin{aligned} P_{in,e}^{fus} &= \frac{E_{fus} S_{fus}}{\eta_b^{fus} Q_p} + \frac{P_{aux}^{fus}}{\eta_{aux}^{fus}} \\ &= \frac{E_{fus} S_{fus}}{\eta_b^{fus} Q_p} \left[1 + \left(\frac{P_{aux}^{fus}}{E_{fus} S_{fus}}\right) Q_p \left(\frac{\eta_b^{fus}}{\eta_{aux}^{fus}}\right)\right] \end{aligned} \tag{9b}$$

where E_{fus}/Q_p is the injected plasma heating energy per fusion neutron produced, η_b^{fus} is the ratio of electrical energy into the heating system to the energy into the plasma (i.e. the heating efficiency), P_{aux}^{fus} is the power required to operate the auxiliary systems for the fusion neutron source transmutation facility and η_{aux}^{fus} is the efficiency of delivery of this energy to end use.

We will evaluate the ratio of input electrical power required for fusion and accelerator spallation neutron source transmutation facilities that produce the same transmutation rate

$$\begin{aligned} R_{in} \equiv \frac{P_{in,e}^{fus}}{P_{in,e}^{atw}} &= \left(\frac{E_{fus}}{E_{spall}}\right)\left(\frac{\eta_b^{atw}}{\eta_b^{fus}}\right)\left(\frac{\xi_{fus}}{Q_p}\right) \\ &\times \left\{ \frac{\left[1 + \left(\frac{P_{aux}^{fus}}{E_{fus} S_{fus}}\right) Q_p \left(\frac{\eta_b^{fus}}{\eta_{aux}^{fus}}\right)\right]}{\left[1 + \left(\frac{P_{aux}^{atw}}{E_{spall} S_{atw}}\right)\left(\frac{\eta_b^{atw}}{\eta_{aux}^{atw}}\right)\right]} \right\} \end{aligned} \tag{10}$$

$E_{fus} = 17.6$ MeV/n and we use $E_{spall} = 25$ MeV/n, corresponding to the production of 40 spallation neutrons per 1 GeV ion. We assume the same efficiencies for the plasma heating and accelerator systems, so that $\eta_b^{fus}/\eta_b^{atw} = 1.0$. We assume $\eta_b^{fus}/\eta_{aux}^{fus} = \eta_b^{atw}/\eta_{aux}^{atw} = 0.8$. We assume that 50 MW auxiliary power is needed for a transmutation system that produces 2.5×10^{19} n/s and use $P_{aux}/S = 12.5$ MeV/n for both the fusion and the accelerator spallation transmutation systems.

The requirement to breed tritium in the fusion transmutation facility consumes neutrons that could otherwise be used for transmutation. We consider two different scenarios with regard to the treatment of this tritium breeding requirement. In the first scenario, it is assumed that the transmutation facility used with the fusion neutron source differs from the transmutation facility used with the accelerator spallation neutron source only by the addition of sufficient Li to achieve TBR $= 1.05$. Thus, if the fusion transmutation facility has a multiplication constant k, the ATW facility has a larger multiplication constant k_0 given by Eq. (7), and the fusion facility must produce a neutron source larger by the factor

$$\xi_{fus} \equiv \frac{S_{fus}}{S_{spall}} = \frac{1-k}{1-k_0} = \frac{1 + (1-k)\mathrm{TBR}}{(1-k)\mathrm{TBR}} \tag{11}$$

in order for both facilities to have the same transmutation rate. We use $\gamma = 1.05$, $\nu = 2.9$ and $P_{NL} = 0.95$

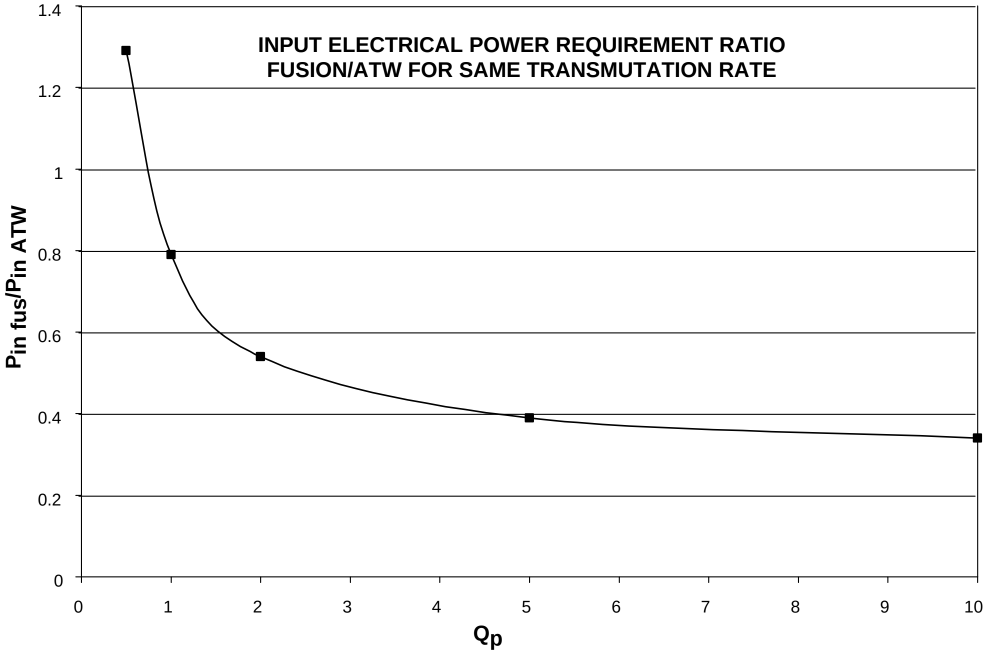

Figure 1. Ratio of input electrical power required for the operation of fusion and ATW neutron sources which produce the same transmutation rate in a subcritical transmutation reactor. ($E_{spall} = 25$ MeV/n, $E_{fus} = 17.6$ MeV/n, $P_{aux}/S = 12.5$ MeV/n, $\nu = 2.9$, $\gamma = 1.05$, $\eta_b^{fus} = \eta_b^{atw} = \eta_e^{fus} = \eta_e^{atw} = 0.40$, $\eta_e^{fus}/\eta_e^{blkt} = \eta_e^{atw}/\eta_e^{blkt} = 0.9$, $\eta_b^{atw}/\eta_{aux}^{atw} = \eta_b^{fus}/\eta_{aux}^{fus} = 0.8$: $k = 0.90$ is the same with fusion and ATW neutron sources.)

to calculate k_0 and ξ_{fus}. In the second scenario, we assume that the transmutation reactors used with the fusion and accelerator neutron sources have the same multiplication constant k, and hence the same neutron source levels to produce the same transmutation rates. This would be accomplished by replacing a parasitic absorber with Li or by increasing the fissionable material in the transmutation reactor for the fusion neutron source relative to the ATW facility.

The ratio of input electrical powers required to produce the same transmutation rates in fusion and accelerator spallation neutron source transmutation facilities is shown as a function of plasma gain for the second of the above Li scenarios in Fig. 1, for the above parameters and $k = 0.90$. (The results for $k = 0.85$ and 0.95 differ only slightly.) For a plasma gain Q_p greater than about 1.0–1.5, the required input electrical power is less for a fusion neutron source transmutation facility than for a similar ATW which produces the same transmutation rate. At $Q_p > 5$, the input electrical power requirement for a fusion transmutation facility is about half or less the requirement for an ATW with the same transmutation rate, for the parameters assumed above, and the improvement is slight for $Q_p > 5$. The results shown in Fig. 1 are in semi-quantitative agreement with the results of a similar analysis based on a somewhat simpler model [24].

3.3. Comparison of waste thermal energy

The thermal energy dissipated in the ATW and fusion neutron sources are $E_{spall}S_{atw}$ and $(1 + 1/Q_p)E_{fus}S_{fus}$, respectively, and the thermal energy generated by the fission and other exoergic processes in the transmutation reactor is $(1+\varepsilon)E_{fis}S_x/(1-k_x)$, where $x =$ fus or atw, and ε is the ratio of energy produced by other (than fission) exoergic reactions to the energy produced by fission. The ratio of the amount of thermal energy that must be removed from transmutation facilities with fusion and accelerator spallation neutron sources which produce the same transmutation rate is

$$R_{th} = \frac{P_{fus,th}/S_{atw}}{P_{atw,th}/S_{atw}} = \xi_{fus}\left(1+\frac{1}{Q_p}\right)\frac{E_{fus}}{E_{spall}}$$

$$\times\left(\frac{\left[1+\frac{(1+\varepsilon)}{(1-k_{fus})}\frac{k_{fus}}{\nu}\left(\frac{E_{fis}}{E_{fus}}\right)\left(\frac{1}{1+1/Q_p}\right)\right]}{\left[1+\frac{k_{atw}}{\nu}\frac{(1+\varepsilon)}{(1-k_{atw})}\left(\frac{E_{fis}}{E_{spall}}\right)\right]}\right)$$

$$\equiv R_{th}^{source}\left(\frac{\left[1+\frac{(1+\varepsilon)}{(1-k_{fus})}\frac{k_{fus}}{\nu}\left(\frac{E_{fis}}{E_{fus}}\right)\left(\frac{1}{1+1/Q_p}\right)\right]}{\left[1+\frac{k_{atw}}{\nu}\frac{(1+\varepsilon)}{(1-k_{atw})}\left(\frac{E_{fis}}{E_{spall}}\right)\right]}\right). \tag{12}$$

The ratio $R_{th}^{source} = \xi_{fus}(1 + 1/Q_p)E_{fus}/E_{spall}$ of the thermal energies dissipated in the fusion and accelerator neutron sources has been calculated for the two scenarios discussed earlier for treating the tritium breeding requirement for the fusion neutron source. A fusion neutron source will dissipate somewhat more thermal energy at low Q_p (<2) and somewhat less thermal energy at higher Q_p than an accelerator neutron source, when both sources are driving subcritical reactors with the same k values that are producing the same transmutation rates ($k_{fus} = k_{atw}$).

The thermal energy produced in the transmutation reactor by fission (E_{fis} = 195 MeV/fission) is so much greater than the thermal energy produced in the neutron source that the ratio of the total thermal energy produced in fusion and accelerator spallation neutron transmutation facilities with the same transmutation rate, given by Eq. (12), is essentially unity.

3.4. Comparison of plant electrical energy gain

If the waste energy from the spallation neutron production (i.e. target heating) is collected and converted to electricity with efficiency η_e^{spall} and the energy of the fission and other exoergic reactions in the subcritical transmutation reactor is collected and converted to electricity with efficiency η_e^{blkt}, the output electrical energy from a transmutation facility driven by an accelerator spallation neutron source is

$$P_{out,e}^{atw} = \left(E_{spall}\eta_e^{atw} + \frac{k_{atw}}{\nu}\frac{(1+\varepsilon)E_{fis}\eta_e^{blkt}}{1-k_{atw}}\right)S_{atw} \tag{13a}$$

where $\varepsilon = 0.05$ accounts for the enhancement of the fission energy release by other exoergic reactions.

Assuming that the efficiency η_e^{blkt} of collecting and converting to electricity the energy produced in the subcritical reactor assembly is the same with the fusion and accelerator spallation neutron sources, the output electrical energy from a transmutation facility driven by a fusion neutron source is

$$P_{out,e}^{fus} = \left[E_{fus}\eta_e^{fus}\left(1+\frac{1}{Q_p}\right) + \frac{k_{fus}}{\nu}\frac{(1+\varepsilon)E_{fis}\eta_e^{blkt}}{1-k_{fus}}\right]S_{fus} \tag{13b}$$

where η_e^{fus} is the efficiency of collecting and converting to electricity the plasma heating energy and the energy produced by fusion.

If the input power, fusion power and fission power are recovered and converted to electricity, the ratio of the output electrical power to the input electrical power

$$Q_e^x \equiv \frac{P_{out,e}^x}{P_{in,e}^x} \tag{14}$$

is known as the electrical Q value, or gain, of the system. For a fusion neutron source transmutation facility this expression becomes

$$Q_e^{fus} = \eta_e^{fus}\eta_b^{fus}$$

$$\times\left(\frac{\left\{1+Q_p\left[1+\frac{k_{fus}}{\nu}\frac{(1+\varepsilon)}{(1-k_{fus})}\left(\frac{E_{fis}}{E_{fus}}\right)\left(\frac{\eta_e^{blkt}}{\eta_e^{fus}}\right)\right]\right\}}{\left[1+Q_p\left(\frac{P_{aux}^{fus}}{S_{fus}E_{fus}}\right)\left(\frac{\eta_b^{fus}}{\eta_{aux}^{fus}}\right)\right]}\right). \tag{15}$$

We assume the same efficiencies for collecting and converting fusion and spallation heat, so that $\eta_e^{fus}/\eta_e^{atw} = 1.0$, and we assume somewhat better heat recovery from the transmutation blanket than from the spallation target or the fusion plasma, so that $\eta_e^{blkt}/\eta_e^{fus} = \eta_b^{blkt}/\eta_e^{atw} = 0.9$. The quantity Q_e^{fus} is plotted in Fig. 2, for three different values of the multiplication constant of the transmutation reactor. Clearly, net electrical power ($Q_e > 1$) is possible for Q_p values even much below unity, for the parameters discussed above.

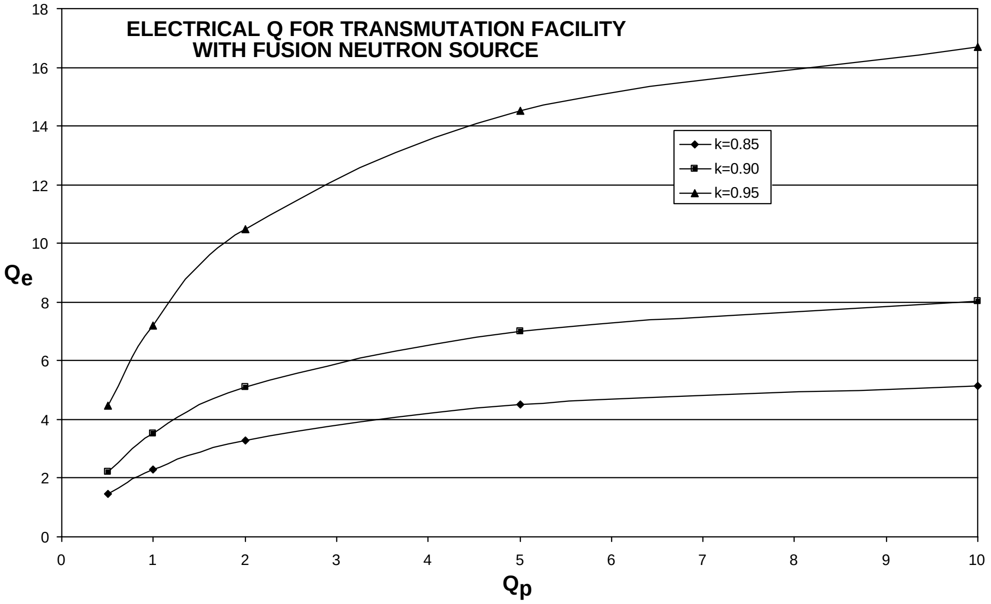

Figure 2. Electrical energy gain Q_e^{fus} for a subcritical transmutation reactor plant with fusion neutron source. ($E_{fis} = 195$ MeV/fis, $E_{fus} = 17.6$ MeV/n, $P_{aux}/S = 12.5$ MeV/n, $\nu = 2.9$, $\gamma = 1.05$, $\varepsilon = 0.05$, $\eta_b^{fus} = \eta_e^{fus} = 0.40$, $\eta_e^{fus}/\eta_e^{blkt} = 0.9$, $\eta_b^{fus}/\eta_{aux}^{fus} = 0.8$.)

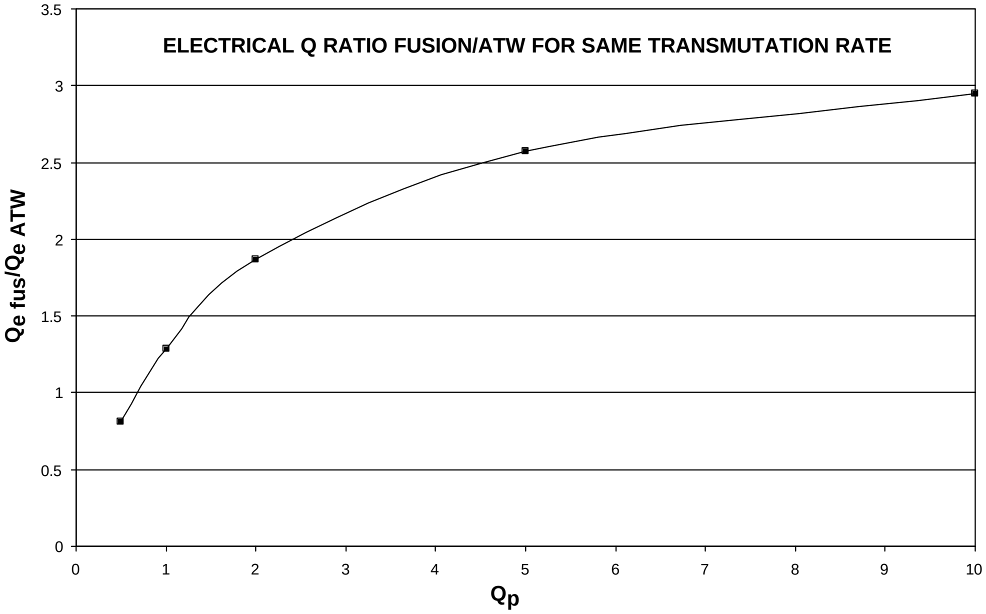

Figure 3. Ratio of subcritical transmutation reactor plant electrical energy gain for the same transmutation rate with fusion and ATW neutron sources. ($E_{fis} = 195$ MeV/fis, $E_{spall} = 25$ MeV/n, $E_{fus} = 17.6$ MeV/n, $P_{aux}/S = 12.5$ MeV/n, $\nu = 2.9$, $\gamma = 1.05$, $\varepsilon = 0.05$, $\eta_b^{fus} = \eta_b^{atw} = \eta_e^{fus} = \eta_e^{atw} = 0.40$, $\eta_e^{fus}/\eta_e^{blkt} = \eta_e^{atw}/\eta_e^{blkt} = 0.9$, $\eta_b^{atw}/\eta_{aux}^{atw} = \eta_b^{fus}/\eta_{aux}^{fus} = 0.8$; $k = 0.90$ is the same with fusion and ATW neutron sources.)

The ratio of the electrical gains for fusion transmutation and ATW reactor systems which achieve the same transmutation rates is given by

$$\frac{Q_e^{fus}}{Q_e^{atw}} = \left(\frac{\eta_e^{fus}}{\eta_e^{atw}}\right)\left(\frac{\eta_b^{fus}}{\eta_b^{atw}}\right)$$
$$\times\left(\frac{\left\{1+Q_p\left[1+\frac{(1+\varepsilon)}{(1-k_{fus})}\frac{k_{fus}}{\nu}\left(\frac{E_{fis}}{E_{fus}}\right)\left(\frac{\eta_e^{blkt}}{\eta_e^{fus}}\right)\right]\right\}}{\left[1+\frac{(1+\varepsilon)}{(1-k_{atw})}\frac{k_{atw}}{\nu}\left(\frac{E_{fis}}{E_{spall}}\right)\left(\frac{\eta_e^{blkt}}{\eta_e^{atw}}\right)\right]}\right)$$
$$\times\left(\frac{\left[1+\left(\frac{P_{aux}^{fus}}{E_{spall}S_{atw}}\right)\left(\frac{\eta_b^{atw}}{\eta_{aux}^{atw}}\right)\right]}{\left[1+Q_p\left(\frac{P_{aux}^{fus}}{E_{fus}S_{fus}}\right)\left(\frac{\eta_b^{fus}}{\eta_{aux}^{fus}}\right)\right]}\right). \qquad (16)$$

This ratio is plotted in Fig. 3 for the parameters described above and for $k_{fus} = k_{atw}$. For these parameters, the plant electrical gain is greater for fusion transmutation plants with $Q_p > 1$ than for ATW plants with the same transmutation rate. These results are in good semiquantitative agreement with the results obtained in a similar analysis using a somewhat simpler model [24].

We have checked the sensitivity of the calculations to some of the input parameters. Doubling the auxiliary power per neutron reduces the Q_e ratio by about 33% at high Q_p, but has little effect at low Q_p. Increasing η_b^{atw} from 0.4 to 0.45 or decreasing η_e^{spall} from 0.4 to 0.35 reduces this ratio by about 15% at high Q_p, but has little effect at low Q_p, and changing both the ratios $\eta_b^{fus}/\eta_{aux}^{fus}$ and $\eta_b^{atw}/\eta_{aux}^{atw}$ a like amount has a negligible effect. Thus, the general nature of the comparisons of fusion and accelerator spallation neutron source transmutation facilities shown in Figs 1 and 3 would seem to be relatively insensitive to modest uncertainties in plant parameter values, although a parameter such as the electrical Q_e for either system will vary linearly with η_e and η_b.

We recognize that a comparison of transmutation efficiency and neutron cost, as well as a comparison of electrical and thermal power characteristics, is needed to fully evaluate a fusion neutron source vis-à-vis an accelerator neutron source for spent fuel transmutation. However, a comparison of efficiency and neutron cost depends not only on the neutron source but also on the subcritical transmutation facility, and is beyond the scope of this article. We have, however, begun such a study.

4. Limitations on fusion neutron source capabilities for transmutation reactors

The factors determining the effect of possible neutron source limitations on the transmutation rate in a subcritical transmutation reactor can be understood by examining Eq. (8). This equation can be put into different forms to illustrate the effect of various possible limitations of the neutron source capability on the transmutation rate. We stress that we are examining only limitations on transmutation rate that would be caused by limitations in neutron source capability, not by engineering and safety constraints on the transmutation reactor itself.

4.1. Radiation damage limits to the first wall

Writing the neutron source in terms of the power P_n of $E_n = 14$ MeV neutrons through the first wall relates the neutron source strength to the neutron wall load, or flux, Γ_n and first wall area A_w,

$$S = \frac{P_n}{E_n} = \frac{(P_n/A_w)A_w}{E_n} = \frac{\Gamma_n^{av}A_w}{E_n}. \qquad (17)$$

This relation may be used in Eq. (8) to write the transmutation rate as

$$\mathrm{TR} = \frac{S}{1-k}\frac{k}{\nu} = \frac{\Gamma_n^{av}A_w(k/\nu)}{E_n(1-k)} \qquad (18a)$$

from which the annual transmutation rate TRA (kg/FPY) may be written in terms of the annual fluence, the area of the first wall and the effective multiplication constant of the transmutation reactor

$$\mathrm{TRA}\,[\mathrm{g/FPY}] = \frac{5.55(k/\nu)(\Gamma_n^{av}t)\,[\mathrm{MW\text{–}FPY/m^2}]\,A_w\,[\mathrm{m^2}]}{1-k} \qquad (18b)$$

where FPY refers to full power year.

A given transmutation rate can obviously be achieved in a number of ways by making trade-offs between neutron wall load and first wall area on the one hand and the effective multiplication constant on the other. The upper limit on the effective multiplication constant is set by safety considerations; k should be sufficiently less than unity that no credible event could cause a reactivity increase Δk that would make the transmutation reactor prompt critical; i.e. $k + \Delta k$ must remain less than $1 + \beta$ for any credible accident, where β is the delayed neutron fraction ($\beta = 0.0020$ for ^{239}Pu, 0.0029 for ^{240}Pu and 0.0054 for ^{241}Pu). The wall area depends on the size of the neutron source, of course, which can be made as large as desired for a fusion neutron source.

The first wall will fail when the accumulated neutron fluence $\Gamma_n^{max}t$ reaches some limiting value (1–3 MW FPY/m^2 for existing austenitic stainless steel and considerably more for advanced structural alloys presently under development). A practical requirement might be that the first wall lifetime be as long as the refuelling interval for the transmutation reactor. Assuming a 1 FPY refuelling interval and taking a limiting neutron fluence of 2 MW FPA/m^2 and a first wall area of 450 m^2 (representative of an $R \approx 5$ m tokamak), a transmutation reactor with $k = 0.90$ driven by a fusion neutron source would be limited by materials damage to a transmutation rate of TRA $\approx$ 50 000 kg/FPY. Assuming a first wall area of 100 m^2 (perhaps representative of advanced confinement concepts in the early stages of development), radiation damage in an austenitic stainless steel first wall would limit the transmutation rate to TRA $\approx$ 10 000 kg/FPY. Such large transmutation rates are unrealistic for other reasons (handling the engineering challenges of such a large thermal power output and the safety challenges of such a large mass of fissile material in the transmutation reactor being foremost among them). As a point of reference, the present ATW plan is to fission less than 2000 kg/FPY of actinides in a single transmutation reactor, and studies of critical fission transmutation reactors typically have transmutation rates of less than 1000 kg/FPY. The main points are that:

(a) A practical fusion neutron source is unlikely to be limited by radiation damage to the first wall, even for the presently available austenitic stainless steels;

(b) A fusion neutron source for transmutation could meet its objectives operating at rather low neutron wall loads ($\ll$1 MW/m^2).

We will make a more quantitative investigation of these points later in this section.

4.2. Thermal limits to the first wall

The thermal power P_{th} which must pass through the first wall of the fusion neutron source is the sum of $E_\alpha = 3.5$ MeV alpha particle energy per fusion and the input plasma heating power, which may be related to the fusion power $P_{fus} = SE_{fus}$ by $Q_p = P_{fus}/P_{heat}$. A fraction f_{div} of this power will be exhausted in the divertor, and a fraction $1 - f_{div}$ will be incident on the first wall of the neutron source as a heat flux. Thus, the fusion neutron source may be written as

$$S = \frac{P_{th}}{(E_\alpha + E_{fus}/Q_p)(1 - f_{div})} = \frac{\Gamma_{th} A_w}{E_{fus}\left(\dfrac{E_\alpha}{E_{fus}} + \dfrac{1}{Q_p}\right)(1 - f_{div})} \tag{19}$$

and the corresponding form for the transmutation rate becomes

$$\mathrm{TR} = \frac{(k/\nu)S}{1-k} = \frac{(k/\nu)\Gamma_{th} A_w}{E_{fus}\left(\dfrac{E_\alpha}{E_{fus}} + \dfrac{1}{Q_p}\right)(1-k)(1-f_{div})}. \tag{20a}$$

In terms of transmutation rate per FPY this becomes

$$\mathrm{TRA}\,(\mathrm{kg/FPY}) = \frac{4.44(k/\nu)\Gamma_{th}\,[\mathrm{MW/m^2}]\,A_w\,[\mathrm{m^2}]}{\left(\dfrac{1}{Q_p} + \dfrac{1}{5}\right)(1-k)(1-f_{div})}. \tag{20b}$$

The maximum surface heat flux for an austenitic stainless steel first wall is about 0.5 MW/m^2. Taking an average heat flux of half this value to account for peaking, assuming a diverted heat fraction of $f_{div} = 0.5$ and assuming $Q_p = 5$, $A_w = 450$ m^2 and $k = 0.90$, the transmutation rate would be limited to about 25 000 kg/FPY by first wall heat flux removal limitations. Assuming instead $A_w = 100$ m^2, the first wall thermal limit on the transmutation rate for austenitic steel is about 5500 kg/FPY. Again, these are quite large transmutation rates, and the point is that thermal limitations on an austenitic stainless steel first wall of the neutron source should not limit the transmutation rate achievable in a transmutation reactor driven by a fusion neutron source. This point will be investigated more quantitatively in Section 4.3.

4.3. Tokamak physics limits

The plasma physics of the fusion neutron source also imposes certain constraints on the realizable source performance. The existing physics basis for a tokamak neutron source is well characterized by the tokamak physics database compiled for ITER [6]. For our purposes, we can consider five such physics constraints to characterize the physics limitations on a tokamak neutron source.

Assurance of MHD stability of existing tokamak plasmas can be characterized by the requirement that the normalized beta parameter

$$\beta_N = \frac{\beta_{\%}}{I_{MA}/a_m B_T} \tag{21}$$

does not exceed 2.5–3.0 and that the safety factor evaluated at the 95% flux surface

$$q_{95} = \frac{5B_T R_m}{2A^2 I_{MA}}[1+\kappa^2(1+2\delta^2-1.2\delta^3)] \times \left(\frac{1.17-0.65/A}{1-A^{-2}}\right) \tag{22}$$

be not less than about 3. Here B_T is the toroidal magnetic field in teslas, I_{MA} is the plasma current in megamps, $A = R/a$ is the ratio of the plasma major to minor radii, κ is the elongation of the plasma, δ is a parameter known as the triangularity which characterizes the degree of D shape of the plasma and β is the ratio of the plasma kinetic pressure to the pressure of the magnetic field,

$$\beta = \frac{n_{DT}T_{DT} + n_e T_e + n_{imp}T_{imp} + n_f E_f}{B^2/2\mu_0}. \tag{23}$$

The DT ions, electrons (e), impurities (imp) and fast (f) beam and alpha particles contribute to the kinetic pressure of the plasma.

The plasma must have adequate energy confinement to achieve a power balance between the self-heating from the fusion alpha particles plus any auxiliary (NBI or RF) heating and losses due to transport and radiation. Consideration of the plasma power balance indicates that the energy confinement time must be about $\tau_{ign} = 5$ s to maintain the power balance at about 10 keV average temperature in the absence of auxiliary heating and that the energy confinement time must be about $\tau_{ign}/(1+5/Q_p)$ when auxiliary heating is present. The tokamak database for ELMy H mode discharges is well correlated to the tokamak parameters by the ITER-98H scaling law $\tau = \tau_{98}(I, B, P_{fus}, ...)$. Thus, achieving sufficient energy confinement to maintain power balance imposes the confinement constraint

$$\frac{\tau_{ign}}{1+\dfrac{5}{Q_p}} = 0.05H\, I_{MA}^{0.91} B_T^{0.15} n_{19}^{0.44}\left[P_{fus}\left(\frac{1}{5}+\frac{1}{Q_p}\right)\right]^{-0.65} \times R^{2.05}\kappa^{0.72}M^{0.13}A^{-0.57} \tag{24}$$

where H is the confinement enhancement factor, M is the plasma ion mass in amu, A is the ratio of the major to minor axes of the tokamak, n_{19} is the density in units of 10^{19} m^3, P_{fus} is in megawatts and the units of the other quantities are indicated by the subscripts.

The fusion power

$$P_{fus} = \tfrac{1}{4}n_{DT}^2\langle\sigma v\rangle U_\alpha(\pi\kappa a^2)(2\pi R) \tag{25}$$

not only depends on the density, which is constrained by the MHD and confinement constraints, but is also involved in the confinement constraint, so that Eq. (25) is actually a fourth physics constraint. Here, $\langle\sigma v\rangle$ is the Maxwellian averaged fusion rate and $U_\alpha = 3.5$ MeV is the energy of the DT fusion alpha particle which remains in the plasma to heat it.

A fifth physics constraint, thought to be due to thermal instabilities in the plasma, is an upper limit on the achievable plasma density. This upper limit on the density can be correlated remarkably well over a wide range of tokamak experiments with the simple ‘Greenwald limit’,

$$n \le n_{GW} \equiv \frac{I_{MA}}{\pi a_m^2} \tag{26}$$

although there are many examples of tokamak operation well above (up to about twice) the Greenwald limit.

In order to understand how these physics limits might constrain the performance of a fusion neutron source for a subcritical transmutation reactor, we have fixed various parameters ($B = 5.5$ T, $q_{95} = 4$, $A = 3$, $T = 12$ keV) and solved Eqs (21), (22), (24) and (25) for (I, n, R, P_{fus}) as a function of Q_p and δ_N. For this purpose we assumed $\beta = 2.1n_{DT}T_{DT}/(B^2/2\mu_0)$. We carried out the calculations with a set of confinement and shape parameters characteristic of the present tokamak database ($H = 1$, $\kappa = 1.7$, $\delta = 0.5$) and with a second ‘advanced’ set characteristic of improved confinement regimes presently under intensive investigation and a higher degree of shaping ($H = 1.5$, $\kappa = 2.0$, $\delta = 0.8$). We considered several values of the parameter β_N, including values within the presently established database of $\beta_N < 3$ and values within the advanced range $\beta_N > 3$ that is presently under investigation.

In order to relate these calculations of physics performance to the transmutation rate, we write

$$\mathrm{TRA} = \frac{(k/\nu)S}{1-k} = \frac{4.44(k/\nu)P_{fus}\,(\mathrm{MW})}{1-k}(\mathrm{kg/FPY}). \tag{27}$$

We choose $k = 0.90$ for the calculations because this value of the multiplication constant provides a large margin to criticality and allows for the processing

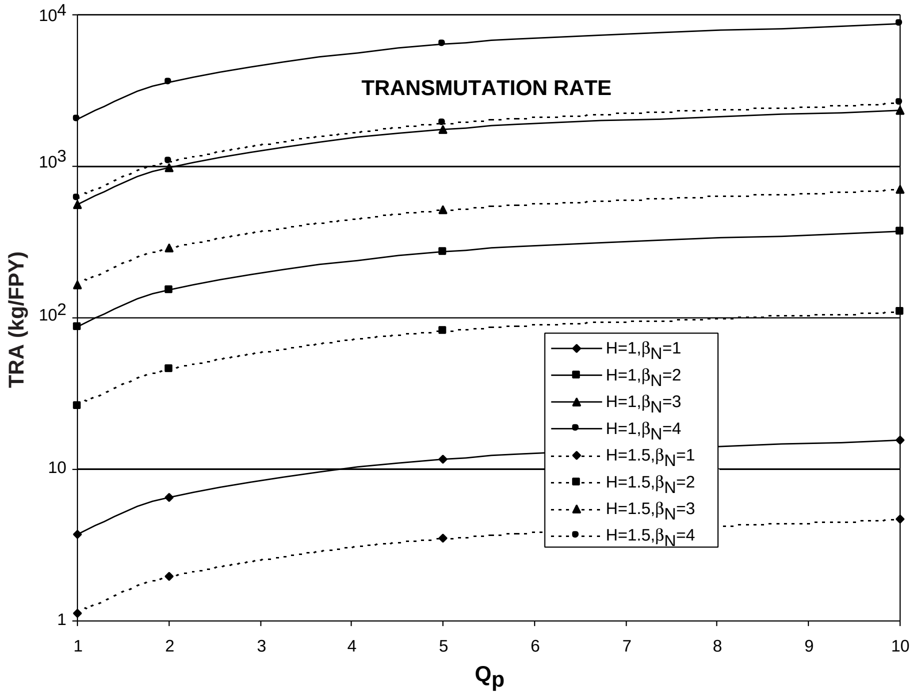

Figure 4. Transmutation rate in subcritical transmutation reactor driven by a tokamak fusion neutron source ($k = 0.90$, $B = 5.5$ T, $q_{95} = 4$, $\tau_{ign} = 5$ s, $T = 12$ keV).

of spent fuel with large concentrations of parasitic absorbers present. The transmutation (fission) rate is, of course, directly related to the fission thermal power production rate in the transmutation reactor

$$P_{fis} = \frac{k}{\nu}\frac{P_{fus}}{1-k}\frac{E_{fis}}{E_{fus}} = \frac{11.1}{1-k}\frac{k}{\nu}P_{fus}. \tag{28}$$

Each kg/FPY transmutation rate corresponds to a fission thermal power production rate of about 2.48 MW, when $k = 0.90$.

In order to relate the physics performance to the neutron wall load/radiation damage limit and the thermal limit on the first wall discussed above, we write

$$\Gamma_n = \frac{\frac{4}{5}P_{fus}}{\sqrt{\frac{1}{2}(1+\kappa^2)}(2\pi a)(2\pi R)} \tag{29}$$

and

$$\Gamma_{th} = \frac{\frac{1}{5}P_{fus}(1-f_{div})}{\sqrt{\frac{1}{2}(1+\kappa^2)}(2\pi a)(2\pi R)} \tag{30}$$

and carry out the calculation for $f_{div} = 0.5$.

The results of these calculations are plotted in Figs 4–10, study of which leads to several interesting conclusions. Foremost among these is the conclusion that parameters routinely achieved in operating tokamaks (i.e. those that are part of the present tokamak database ($H = 1$, $\beta_N = 2$–3)) are sufficient for a tokamak neutron source operating with densities below the Greenwald limit to produce transmutation rates of several hundred to several thousand kg/FPY in a reactor with $k = 0.9$. Such tokamak neutron sources would have major radii in the range $R = 3$–5 m, produce fusion power in the range $P_{fus} = 10$–100 MW and drive transmutation reactors that produce fission thermal power in the range $P_{fis} \approx 1000$–10 000 MW. Achieving improved confinement ($H = 1.5$) will enable these same transmutation rates to be achieved with smaller (and presumably less expensive) neutron sources.

As a point of reference, the proposed ATW plant would use two 45 MW proton beams to produce 840 MW thermal energy in each of eight target transmutation assemblies, for a total thermal power output of 6720 MW, in order to produce a transmutation rate of 1760 kg/FPY.

A second important conclusion is that $Q_p = 2$–5 is adequate for the neutron source, since the transmutation rate increases only slowly above $Q_p = 5$ but drops sharply below $Q_p = 2$. Furthermore, the input electrical power requirement and the waste heat production rate for a fusion neutron source, relative to an accelerator spallation neutron source,

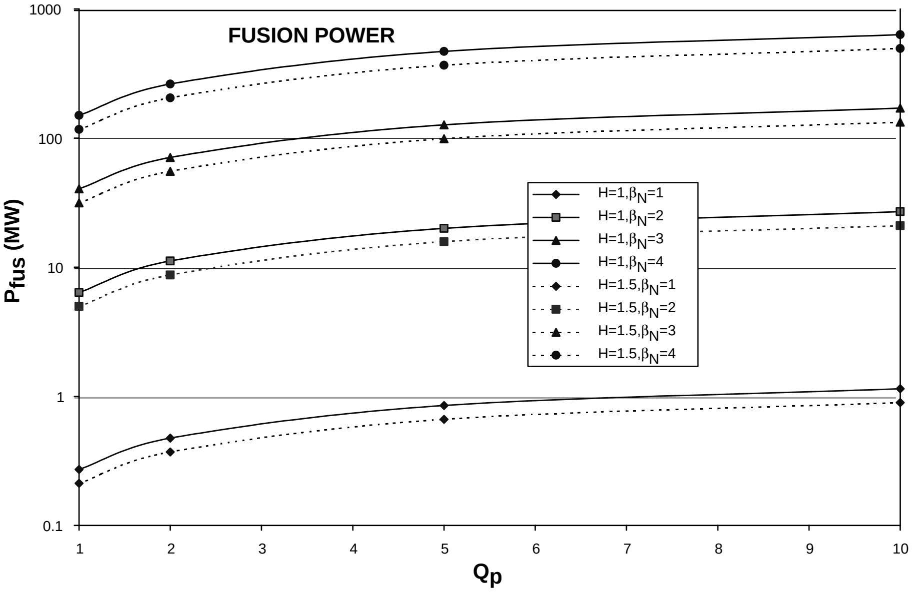

Figure 5. Fusion power in tokamak fusion neutron sources for subcritical transmutation reactors ($k = 0.90$, $B = 5.5$ T, $q_{95} = 4$, $\tau_{ign} = 5$ s, $T = 12$ keV).

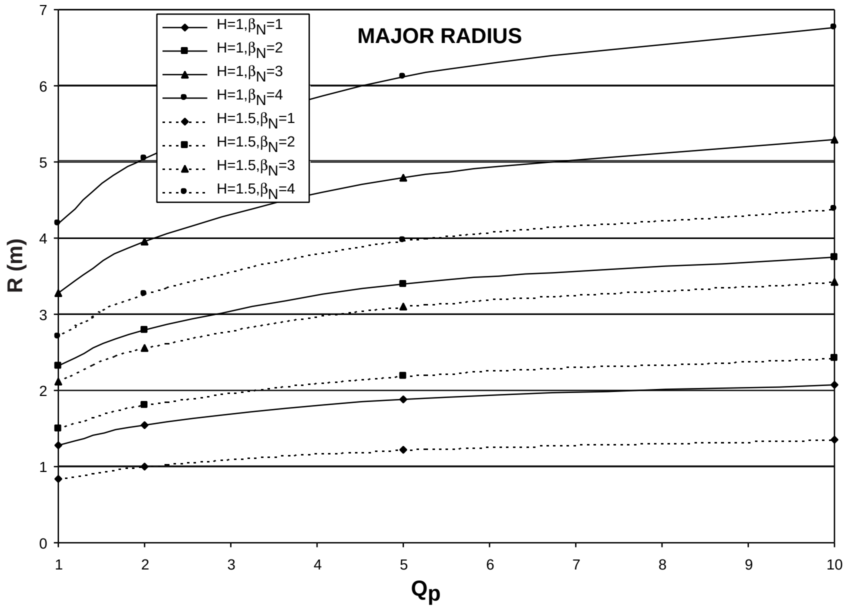

Figure 6. Major radii of tokamak fusion neutron sources for subcritical transmutation reactors ($k = 0.90$, $B = 5.5$ T, $q_{95} = 4$, $\tau_{ign} = 5$ s, $T = 12$ keV).

both become much more favourable above about $Q_p = 1.5$–2 but are relatively insensitive to further increases in Q_p beyond about 5.

A third important conclusion is that $\beta_N = 2$–3 seems to be the correct range for achieving these interesting transmutation rates (with $k = 0.9$), since $\beta_N = 1$ leads to transmutation rates that are too low to be interesting and $\beta_N = 4$ leads to transmutation rates that are so large as to imply large size, fissile inventory and heat removal challenges in the design of the transmutation reactor. We note in this regard that since the transmutation rate shown in Fig. 6

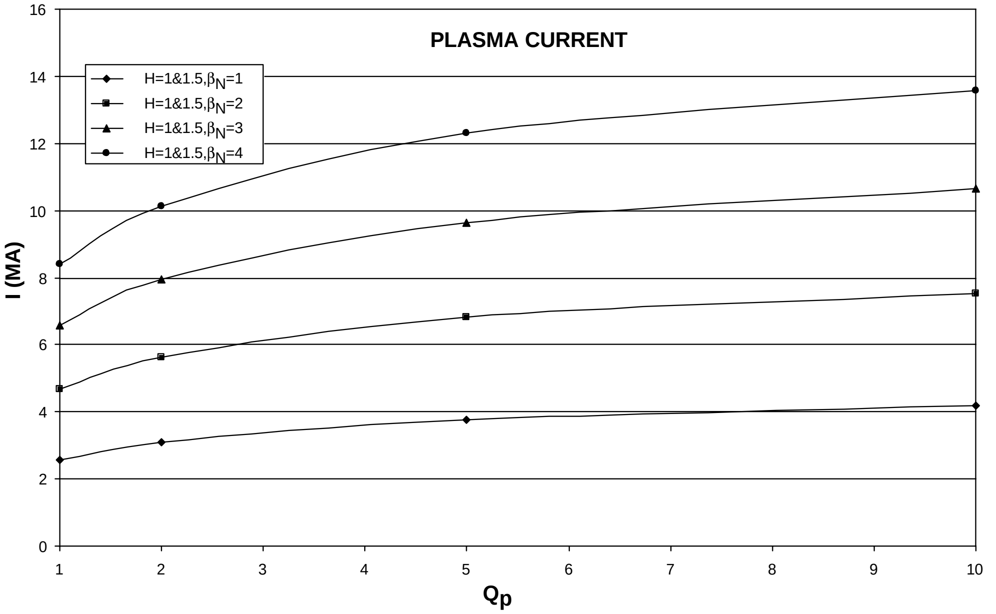

Figure 7. Plasma current in tokamak fusion neutron sources for subcritical transmutation reactors ($k = 0.90$, $B = 5.5$ T, $q_{95} = 4$, $\tau_{ign} = 5$ s, $T = 12$ keV).

scales as $(1 - 0.9)k/0.9(1 - k)$, interesting transmutation rates could also be achieved at $\beta_N < 2$ in transmutation reactors with $k > 0.9$ and at $\beta_N > 3$ in transmutation reactors with $k < 0.9$.

The basis of these calculations, the estimated characteristic parameters allowed by physics constraints for tokamak neutron sources based on nominal ($H = 1$) and advanced ($H = 1.5$) confinement physics is summarized in Table 1.

4.4. Engineering limits on a tokamak fusion neutron source

The smaller end of the size range indicated in Fig. 6 and Table 1 would have to use copper magnetic technology rather than superconducting magnet technology, and even then some of the cases shown may be excluded by engineering limits. For example, at $R = 2$ m and $a = 0.67$ m ($A = 3$), a 5 MA inductive current capability (for backup and testing) would require about 8.5 V/s, which would necessitate a flux core radius $a_{fc} \approx 0.5$ m at a maximum field of 10 T in the ohmic heating coil, leaving only $2-0.67-0.5 = 0.83$ m for the ohmic heating coil, the toroidal field coil and any inboard section of the transmutation reactor, which at most would be just a very thin neutron shield. (See Ref. [25] for a discussion of the engineering limitations on the size of tokamaks.) With such a small-R neutron source, that the fraction (perhaps 20%) of the neutrons directed inwards (towards the major axis of the tokamak) would be absorbed in the copper magnets and shield, effectively reducing the neutron source to the transmutation reactor proportionately.

Table 1. Characteristic parameters of tokamak fusion neutron sources that produce transmutation rates of hundreds to thousands of kg/FPY in transmutation reactors with $k = 0.9$

Parameter	Nominal database	Advanced database
H confinement	1.0	1.5
β_N	2–3	2–3
Q_p	2–5	2–5
B (T)	5.5	5.5
τ_{ign} (s)	5	5
κ, δ	1.7, 0.5	2.0, 0.8
q_{95}	4	4
n/n_{GW}	0.4–1.0	0.2–0.6
R (m)	3–5	2–3
I (MA)	6–10	6–10
P_{fus} (MW)	10–100s	10–100s
Γ_n (MW/m^2)	0.1–0.3	0.15–0.5
Γ_{th} (MW/m^2)	0.02–0.09	0.03–0.15

At $R = 4$ m and $a = 1.33$ m, a 5 MA inductive current capability would require about 35 V/s, which would necessitate $a_{fc} \approx 1.05$ m, leaving about

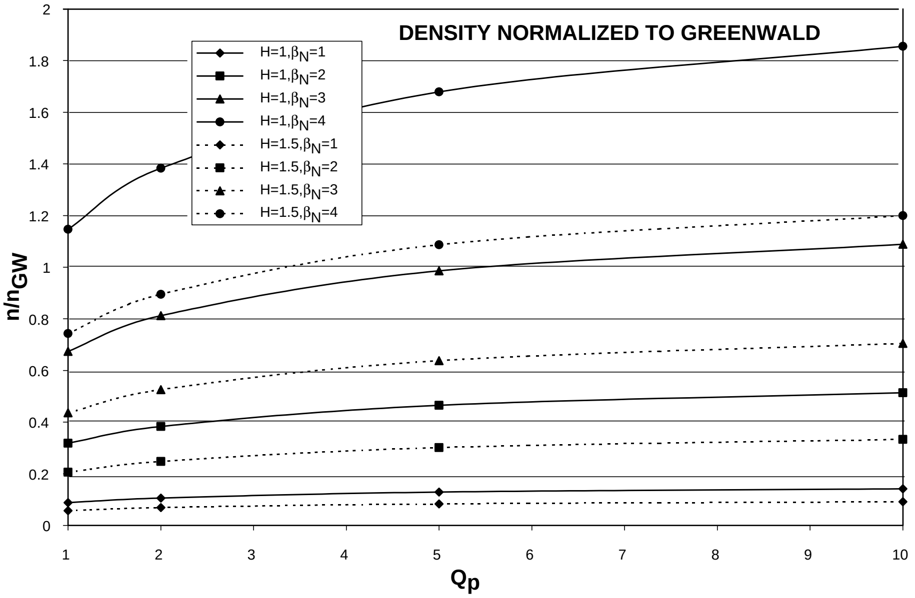

Figure 8. Greenwald normalized densities in tokamak fusion neutron sources for subcritical transmutation reactors ($k = 0.90$, $B = 5.5$ T, $q_{95} = 4$, $\tau_{ign} = 5$ s, $T = 12$ keV).

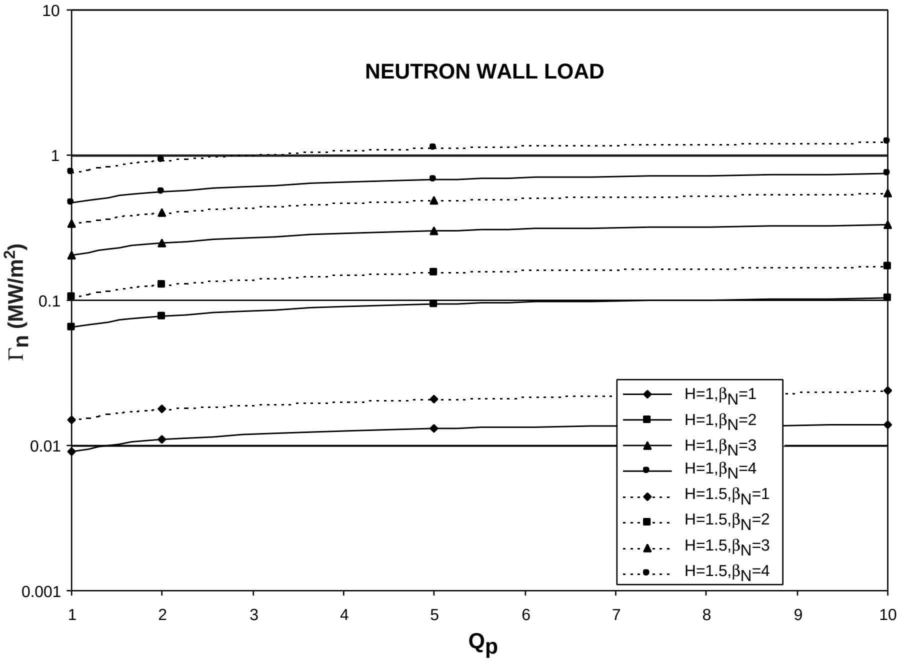

Figure 9. Neutron wall loads in tokamak fusion neutron sources for subcritical transmutation reactors ($k = 0.90$, $B = 5.5$ T, $q_{95} = 4$, $\tau_{ign} = 5$ s, $T = 12$ keV).

1.6 m on the inboard side for the ohmic and toroidal coils and the shielding. This is still neither enough space on the inboard side for shielding to enable use of superconducting magnet technology nor enough space for placing transmutation assemblies on the inboard ≈20% of the neutron source. Thus, the effective neutron source for transmutation would again be reduced by ≈20%.

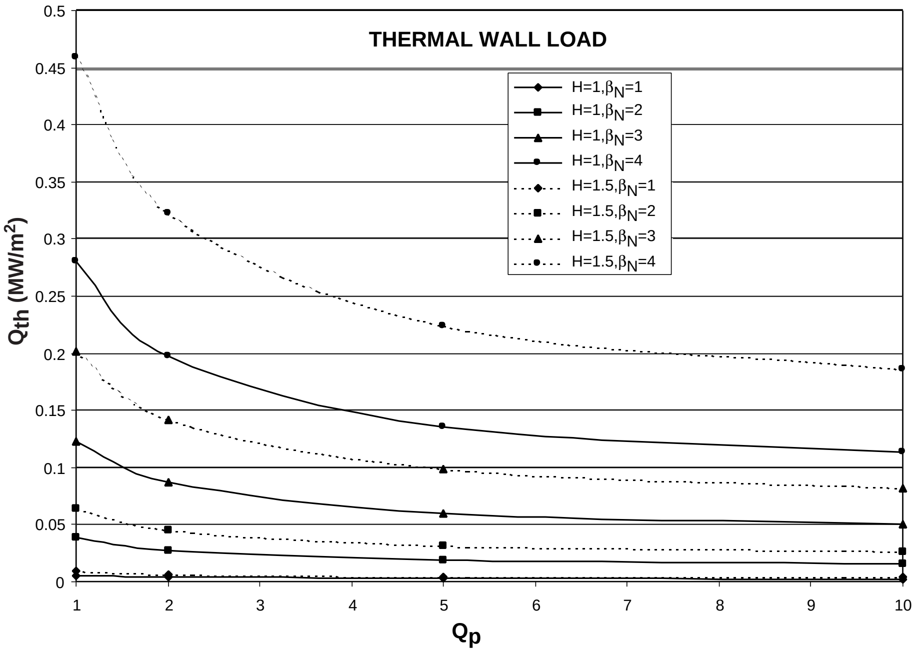

Figure 10. Thermal wall loads in tokamak fusion neutron sources for subcritical transmutation reactors ($k = 0.90$, $B = 5.5$ T, $q_{95} = 4$, $\tau_{ign} = 5$ s, $T = 12$ keV).

At $R = 5$ m and $a = 1.67$ m, a 5 MA inductive current capability would require about 44 V/s, which would necessitate $a_{fc} \approx 1.18$ m, leaving about 2.15 m on the inboard side for ohmic and toroidal coils and an inboard transmutation blanket or shield. At this size, superconducting technology could be used if a shield was place on the inboard ≈20% of the tokamak surface, once again reducing the neutron source to the transmutation reactor by ≈20%. Alternatively, copper magnet technology could be used and some of this inboard volume could be occupied by transmutation assemblies.

Thus, except for the larger end of the range of R shown in Table 1 and Fig. 6, the effective neutron source to the transmutation reactor would be reduced by as much as about 20% by engineering limitations on the inboard ‘radial build’ of the tokamak neutron source. Even with this reduction in effective neutron source level, the transmutation rates for the range of devices indicated in Table 1 remain very interesting for transmutation reactors.

5. Status of fusion development vis-à-vis a neutron source

Substantial progress has been made in recent years in achieving the plasma conditions required for a tokamak fusion neutron source. Using DT fuel, fusion powers exceeding 10 MW have been produced in both TFTR and JET. DT plasmas in these devices have approached the conditions required for $Q_p = 1$. Operating with deuterium plasmas, JT60-U has reached parameters exceeding those required for $Q_p = 1$.

These recent experimental accomplishments reflect a rapid growth in the understanding of the physics of anomalous transport in thermonuclear plasmas and of other aspects of tokamak behaviour. Coupled with an extensive tokamak physics database gathered from dozens of tokamaks around the world [6], there now exists a knowledge base sufficient to design tokamak reactors or neutron sources that will achieve $Q_p \gg 1$, with high confidence.

Several concepts have been proposed for machines capable of reaching $Q_p \gg 1$ or even ignition, where the power produced by alpha particles in DT fusion reactions balances all energy losses from the plasma. While economic considerations dictate that electricity producing fusion reactors operate with very large energy gain $Q_p \gg 10$, fusion neutron source applications such as spent nuclear fuel transmutation require only modest Q_p to be competitive. As we saw in the last section, $Q_p \approx 2$–5 is needed for a fusion neutron source coupled to a transmutation reactor with $k = 0.9$, and even smaller values of Q_p could be used with larger values of k. An upgrade of the JET facility has been proposed which, if approved, could achieve $Q_p \sim 2$ within a few years. From the plasma performance standpoint, fusion has demonstrated a level of performance where fusion neutron source applications can be seriously considered. The remaining physics development required is associated with achieving higher annual neutron fluence accumulation, which involves a combination of achieving much longer burn pulses and higher reliability/availability.

The classical tokamak is a pulsed device with the current driven inductively. Although inductive burn pulses of 1000 s or more can be envisioned in a reactor size ($R > 5$–6 m) tokamak, the plasma discharge must ultimately be terminated while the inductive coil is recharged. High fluence accumulation applications requiring very long pulse or nearly steady state operation, such as may be the case for transmutation of spent fuel, require that inductive current drive be supplemented, if not entirely replaced, by some form of non-inductive current drive.

Non-inductive methods for driving current in tokamaks on the basis of injection of energetic particles or RF waves are well developed. Since such methods are less efficient than inductive current drive, a central issue is the achievable gain Q_p. By optimizing the conditions favourable to the generation of the bootstrap current driven by pressure gradients, the current required to be driven by RF or beam sources can be minimized, greatly enhancing the possibility of achieving $Q_p \gg 1$. Significant progress has been made in developing well confined tokamak operational regimes with high bootstrap current fraction. Extending these regimes to true steady state provides the focus for much of present day tokamak research. The status of resolving this most important (availability relies upon it) remaining physics issue is summarized in Ref. [26].

It is planned to build the successor to the present generation of large tokamaks, ITER [20], through an international collaboration supported by the governments of Europe, Japan and the Russian Federation. The present ITER design is for a device that can operate in DT with an energy gain $Q_p \geq 10$ in the inductive mode and $Q_p \sim 5$ in the non-inductive or steady state mode. The inductive mode is based on the type of tokamak operation that resulted in the high performance regimes obtained in JET and JT-60U. Non-inductive operation is based on the steady state operating modes that are now in an advanced state of development. Total fusion power in either case will be ~500 MW and the neutron wall loading will be 0.5 MW/m^2. These ITER plasma performance parameters are considerably more demanding than those identified in the previous section for a tokamak fusion neutron source for spent nuclear fuel transmutation (fusion power ≈10–100 MW, neutron wall loading ≈0.1–0.5 MW/m^2).

A substantial (7.5×10^8 US dollars) tokamak technology R&D programme for ITER has been carried out in parallel with the design effort. All technologies required for steady state operation of a burning DT plasma were developed and tested in (near full scale for ITER, larger than full scale for a neutron source) test facilities, including superconducting magnets, plasma heating, DT fuel processing, vacuum vessel fabrication, remote maintenance and both plasma and nuclear heat removal systems. Successful validation of these technologies has provided a high degree of confidence that a machine in the ITER class (and a smaller neutron source) can be built and reach its design performance parameters.

The timescale for construction of ITER is about 10 years, and the capital cost is expected to be in the range of $(3\text{–}4) \times 10^9$ US dollars. Should this device be built, it would demonstrate the integration in a single facility of the critical fusion physics and technologies required for a tokamak fusion neutron source for the spent nuclear fuel transmutation application. Should ITER not be built, a (smaller) neutron source prototype would be necessary to integrate the physics and technology, and to demonstrate the potential for high availability operation.

Existing austenitic steels which could be used for the first wall between the plasma and the surrounding material are estimated to have a lifetime against material damage by 14 MeV neutrons of 1–3 MW a/m^2, and ferritic steels and vanadium alloys which are under development for this application may have a considerably longer lifetime. Our estimates of the minimum first wall 14 MeV neutron annual fluence needed from a fusion neutron source for a subcritical transmutation reactor are ≤0.5 MW FPY/m^2 (as low as 0.05 MW a/m^2), which are significantly lower than the annual fluence requirements (~1–2 MW a/m^2) which are usually projected for an electric power demonstration tokamak reactor [25]. However, there will be a significant fluence of fission neutrons on the first wall, as well as the 14 MeV fusion neutrons. Nevertheless, it would seem that existing austenitic stainless steel should be adequate for the structural material in a fusion neutron source for a transmutation reactor, and it does not appear that a materials development programme for advanced first wall materials would be required in support of a fusion neutron source for a transmutation reactor.

The nuclear (fuel, coolant, separation) technology being evaluated and developed in the ATW [5] and OECD/NEA [1] activities must be adapted to provide for tritium self-sufficiency of the fusion neutron source and to accommodate the tokamak neutron source geometry. For Pb–Bi coolant, one of the leading candidates under consideration, the addition of Li would seem to be a relatively straightforward adaptation, although the safety implications remain to be examined. Moreover, MHD effects for a liquid metal in a magnetic field is an additional issue that must be resolved. In any case, the requirement is to adapt technology otherwise being developed in the ATW nuclear programme, not to take on the entire development of such technology.

6. Conclusions

The most significant conclusion of this study is that the parameters routinely achieved in operating tokamaks (i.e. are part of the present tokamak database ($H = 1$, $\beta_N = 2$–3)) are sufficient for a tokamak neutron source operating with densities below the Greenwald limit to produce transmutation rates of several hundred to several thousand kg/FPY in a transmutation reactor with $k = 0.9$. Such tokamak neutron sources would have major radii in the range of 3–5 m, produce fusion power in the range of tens to thousands of megawatts and drive transmutation reactors that produce fission thermal power in the range $\approx 10^3$–10^5 MW. Achieving improved confinement ($H = 1.5$) will enable these same transmutation rates to be achieved with smaller (and presumably less expensive) neutron sources.

A second important conclusion is that $Q_p = 2$–5 is adequate for the neutron source, since the transmutation rate increases only slowly above $Q_p = 5$ but drops sharply below $Q_p = 2$. Furthermore, the input electrical power requirement and the waste heat production rate for a fusion neutron source, relative to the same quantities for an accelerator spallation neutron source, both become much more favourable above about $Q_p = 1.5$–2 but are relatively insensitive to increases in Q_p beyond about 5.

A third important conclusion is that $\beta_N = 2$–3 seems to be the right range for achieving these interesting transmutation rates (with $k = 0.9$).

Fusion plasma performance and technology have now been developed and demonstrated to a level where fusion neutron source applications can be seriously considered. The remaining physics development required is associated with achieving higher annual neutron fluence accumulation, which involves a combination of achieving much longer burn pulses by means of non-inductive current drive and achieving higher reliability/availability. The principal remaining technology development needed for using a fusion neutron source to drive a subcritical fission transmutation reactor is associated with adapting the transmutation reactor nuclear technology to produce the tritium fuel needed for the fusion neutron source and to accommodate the tokamak geometry. Existing austenitic stainless steel should suffice as the structural material for a fusion neutron source. A prototype experiment to integrate the physics and technology and to demonstrate the potential for high availability operation is needed prior to construction of a fusion neutron source for a transmutation reactor.

A DT fusion neutron source operating in the range $Q_p = 2$–5 would require significantly less electrical input power but would produce greater thermal energy than an accelerator spallation neutron source which produces the same transmutation rate in a transmutation reactor. If the thermal energy is converted to electricity, a transmutation reactor driven by a DT fusion neutron source operating in the range $Q_p \gtrsim 2$ would have a significantly larger plant electrical energy gain than a similar transmutation reactor driven by an accelerator spallation neutron source.

Other than availability/reliability considerations, the requirements for a fusion neutron source for spent fuel transmutation are significantly lower than the requirements for an electrical power demonstration plant [25]. This conclusion suggests that such a fusion neutron source would be an appropriate intermediate term objective in the international fusion programme. This would utilize fusion for an important international project, while at the same time providing a less costly (in the near term) path for advancing the status of fusion development towards the ultimate goal of electrical power production.

We conclude with a recognition that the ‘devil is always in the details’ and that detailed studies are needed to confirm the promising characteristics of tokamak fusion neutron sources for spent nuclear fuel that have been identified by the rather broad analysis of this article.

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E-mail address of W.M. Stacey:
weston.stacey@me.gatech.edu

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