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A 14 MeV fusion neutron source for material and blanket development and fission fuel production

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Abstract
Fusion development will require materials capable of withstanding extensive harsh bombardment by energetic neutrons and plasma. The plasma-based gas dynamic trap neutron source concept is capable of testing and qualifying materials and fusion blanket sub-modules for eventual deployment in fusion energy systems. In this paper we describe the suitability of this source to assess thermal fatigue in fusion blanket components caused by the small normal variability of neutron flux inherent in fusion energy concepts. A second part of the paper considers the requirements for a fusion–fission hybrid suitable for producing fissile fuel. Both solid and molten salt fuel from blanket designs are described which emphasize non-proliferation and passive safety.

(Some figures may appear in colour only in the online journal)

1. Introduction: the gas dynamic trap concept

Economical fusion energy deployment will require materials that withstand intense bombardment by 14 MeV neutrons for many years. Qualifying materials and components will require testing in such a neutron environment. The gas dynamic trap (GDT) concept has been shown to have this potential [1–6]. This concept, invented and developed in Novosibirsk Russia [1, 3], is a 14 MeV plasma neutron source. In contrast to earlier magnetic mirror concepts it operates collision-dominated, rather than collision-less. Consequently it avoids micro-instability issues and operates with low electron temperature. It utilizes simple high-field axisymmetric magnets as illustrated in figure 1. The existing GDT device at Novosibirsk utilizes 10 T circular magnets to mirror confine a 7 m long plasma column powered by 5 MW of 20 keV neutral beam power. GDT plasma achieves a high plasma beta of 60%, ion energy of 10 keV and electron temperature of 0.2 keV. Ions are injected at 45° to the mid-plane magnetic field. These sloshing ions are reflected at a magnetic field twice that at the mid-plane to produce density peaks creating two regions of intense neutron production [2].

The neutron source concept considered here is based on these GDT results. Dimensionless parameters such as beta and T_e/T_i are identical while the magnetic field, neutral beam energy and power are increased by a factor of four [5]. In this case the neutron flux is 2 MW m^{-2} and meets the material science community's spatial uniformity and environmental requirements. The GDT-type source would produce a much larger test zone than accelerator-based sources but considerably smaller than tokamak systems so tritium consumption is small (∼100 g/yr), alleviating the need to breed tritium. This paper evaluates methods to control temporal variations of neutron flux output and also describes breeding blanket concepts that could be employed to utilize the GDT concept for fissile fuel production.

Extrapolation of the GDT database to the fuel production mission requires demonstrating MHD stability with lower end losses with axisymmetric end plugs [6] and showing that the electron temperature can significantly exceed 1% of the ion energy. Initial feasibility tests of these issues can be performed with modifications to GDT.

2. Modulating the neutron flux to investigate thermal fatigue

Burning fusion plasmas will have small fluctuations in neutron output associated with normal variation of plasma properties arising from various plasma relaxation and control phenomena. There are many sources of this variability with a broad range of time-scales, such as burning plasma thermal variations

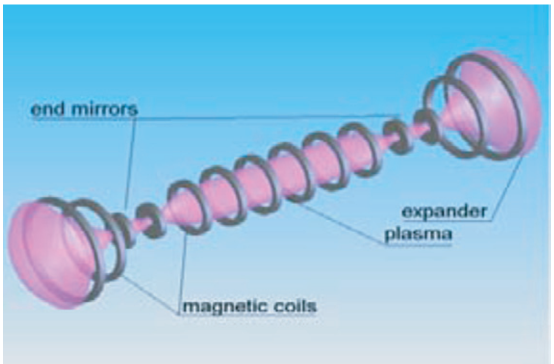

Figure 1. The GDT magnet configuration.

associated with plasma shape, position, heating and fuelling systems as well as variations due to numerous plasma equilibrium relaxation phenomena.

The entire blanket structure will immediately feel these temporal variations through the change in volumetric neutron heating. The heating is necessarily non-uniform and leads to the appearance of mechanical stresses driven by thermal expansion and contraction. Estimates [7] for typical designs of fusion blankets with 10% flux variations at ∼1 Hz will experience temperature excursions as high as 10 °C. In the mechanically complex structure of the blanket, 30 million cycles per year may lead to unanticipated early failure.

In this paper we illustrate that the GDT-type neutron source is capable of producing controlled temporal variations of neutron flux in order to address the effects on material structural properties. Four methods [8] of modulating the neutron output of the GDT-type neutron source are evaluated.

2.1. Neutral beam energy and/or current modulation

The simplest method would be to modulate the neutral beam injection system [8]. This would vary the neutron output via the DT reactivity and/or the energetic ion density. Modulation of the neutral beam power below 100 Hz could produce neutron flux variations exceeding 10%. Neutral beam injector system longevity is uncertain because of cyclic thermal stresses and sputtering of the injectors delicate accelerating grids. Injector neutron damage is minimized by 45° injection at the mid-plane where the neutron production is less intense.

2.2. Ballistic ion bunching

Reference [9] evaluates the possibility of periodically sweeping the neutral beam injection energy to produce periodic bunching of energetic ions thereby modulated neutron output. A modulation frequency as high as a few tens of kHz is possible. Again the injector lifetime is an issue.

2.3. Magnetic field modulation

The neutron output can also be varied by modulation of the magnetic field with coils beyond the energetic ion turning points, thus beyond the location of intense neutron flux. Alternatively, one could modulate the magnetic field near the beam injection location where the field and neutron flux is modest. A few per cent neutron flux variation can be produced up to 1 kHz, much faster than necessary.

2.4. Electron temperature modulation

Periodic gas fuelling, pellet fuelling or electron cyclotron heating will also modulate the electron temperature and in turn the density of neutron producing energetic ions. The electron temperature sets the ambipolar plasma potential which will affect the position of the ion turning points and thus the local neutron output. This technique does not require additional magnetic field coils nor stress the neutral beam injectors.

3. Mirror-based hybrid for fission fuel production

Beyond the application of the GDT concept for fusion material development we have considered the potential and requirements for commercial applications [10–13]. We focus on a molten salt (MS) fission-suppressed fusion breeder of ^{233}U on the thorium cycle. This design aids non-proliferation of nuclear weapons by also producing the gamma emitting ^{232}U and incorporates passive safety by emergency draining to passively cooled storage tanks. Using a power flow analysis we determine that economic feasibility requires Q above 4 to keep the recirculation power fraction below 40%. This hybrid mission requires plasma performance above that achievable with a conventional GDT operating mode so we envision employing simple tandem mirror end plugs [6] without thermal barriers. Also needed for this hybrid mission is an increased demand for fuel to feed the construction of fission power plants possibly to a capacity in the range of 10 TWe over the next century from today's 0.4 TWe, beyond the known uranium resource to supply fuel for today's fission reactors. Thorium MS reactors could seamlessly use this hybrid generated fuel and once fuelled would be wholly or largely fuel self-sustaining.

3.1. Fission-suppressed fuel producing blanket designs

Fission-suppressed fuel producing hybrids maximize safety and the amount of fuel production per unit of nuclear power. Safety is enhanced by fission being suppressed; therefore, fewer fission products and in the event of a failure, the MS can be passively drained to passively cooled storage tanks.

Two designs are considered. Both use MS to carry the thorium that breeds ^{233}U. Figure 2 (called Li/MS) uses lithium-7 to multiply neutrons while it also makes tritium. Figure 3 (called Be/MS) uses beryllium to multiply neutrons. The two flowing liquids cool the Li/MS design. The Be/MS design uses helium cooling of beryllium pebbles to multiply neutrons and MS flowing through the tubes breed both tritium and ^{233}U.

The performance of the Li/MS blanket shown in figure 2 is $M = 1.4$ and $F = 0.5$ ^{233}U atoms are produced for each fusion event and M is the energy produced in the blanket divided by 14 MeV. For the Be/MS blanket shown in figure 3 $M = 2.1$ and $F = 0.6$ ^{233}U atoms are produced for each fusion event. The fuel production from the fission-suppressed Be/MS fusion breeder is 2.60 kg/MW$_{\text{fusion}}$ yr and for the fission-suppressed Li/MS fusion breeder is 2.17 kg/MW$_{\text{fusion}}$ yr. The ratio of nuclear power to fusion power is (0.2+0.8M) 1.88 for Be/MS and 1.32 for the Li/MS, so the production becomes 1.38 kg/MW$_{\text{nuclear}}$ yr for Be/MS and 1.64 kg/MW$_{\text{nuclear}}$ yr for

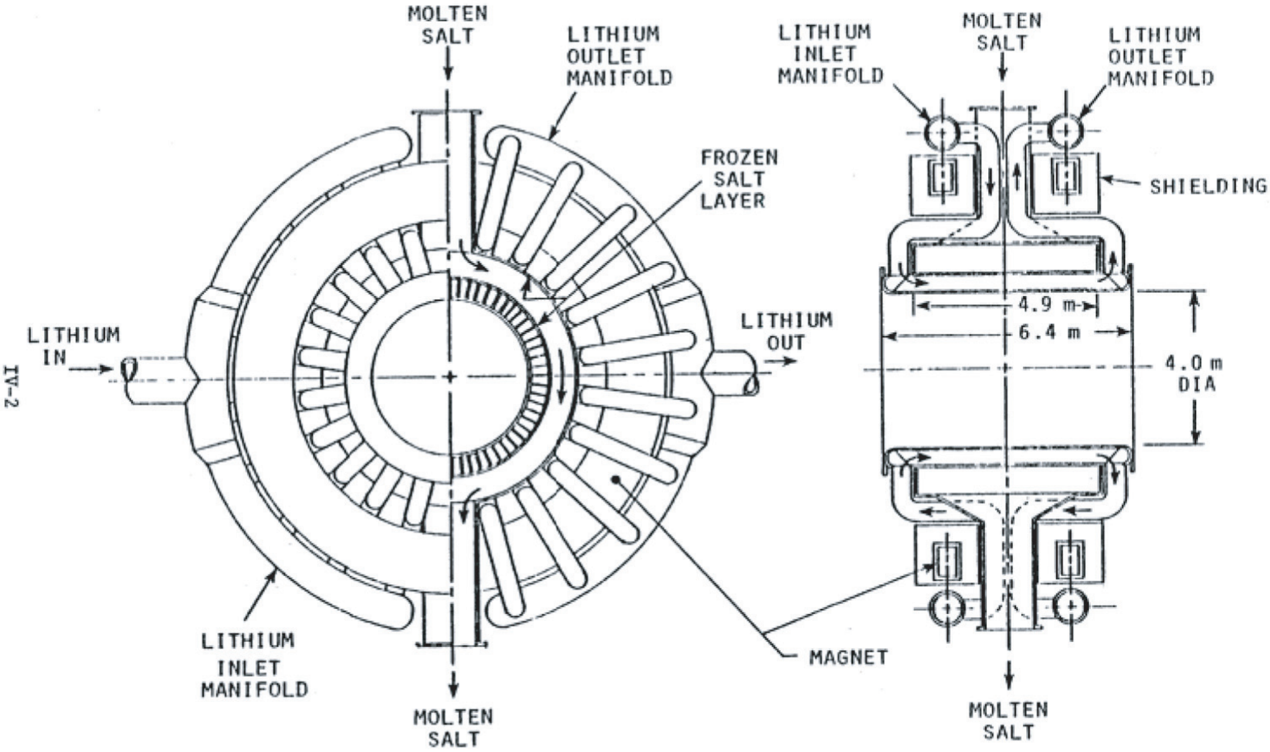

Figure 2. Two-zone Li neutron multiplier blanket with a MS zone for breeding media (Li/MS) [14].

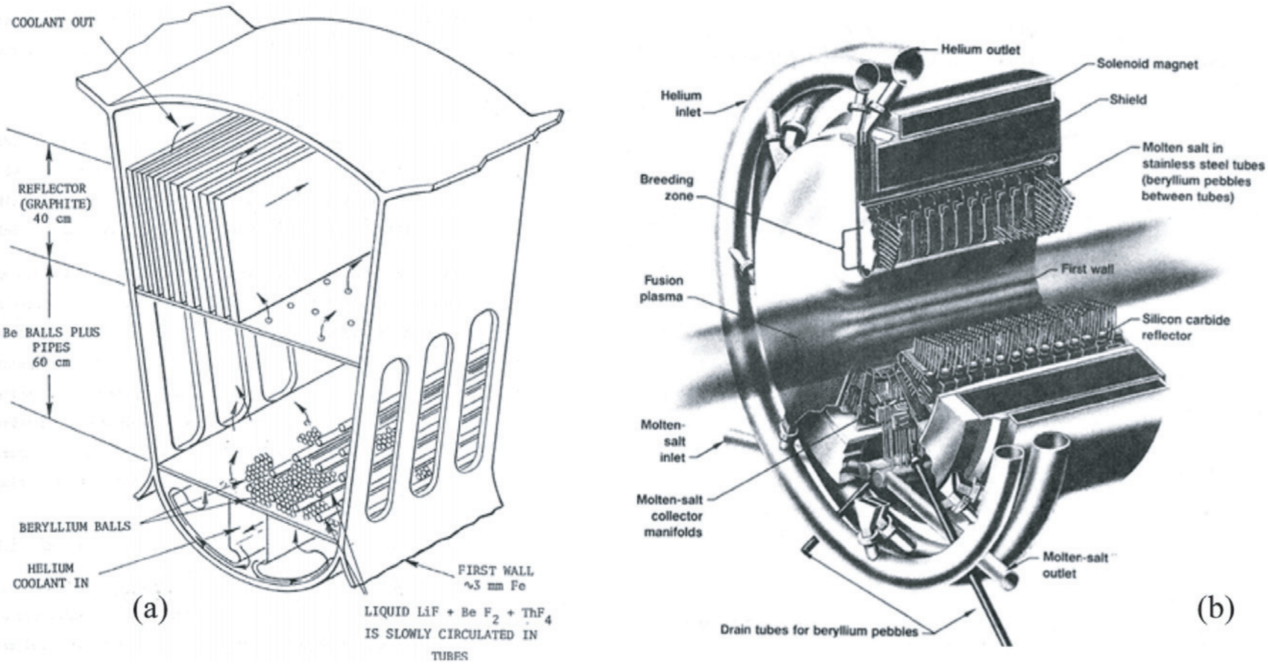

Figure 3. Blanket sub-module (*a*) design for a tandem mirror [15] and a tokamak [16] with pebbles and helium cooling, adapted to mirror geometry (*b*) with integrated first wall, blanket, shield and magnet.

Li/MS. The annual fissile fuel supplied to a molten salt reactor (MSR) is approximately 0.37 kg ^{233}U(1-CR)/MW$_{\mathrm{nuclear}}$ yr. The fusion breeder can supply about 20 MSRs of equal nuclear power with makeup fuel for a conversion ratio, CR = 0.8. With CR = 1 no makeup fuelling is needed once the reactor is started up. The startup inventory of ^{233}U for MSR is typically 0.9 ± 30% kg ^{233}U/MWe depending on design. The fusion breeder could supply the initial fissile inventory each year for 1 to 2 MS reactors of the same nuclear power.

3.2. Non-proliferation features

Producing ^{233}U from thorium has both proliferation advantages and concerns. ^{232}U that inevitably accompanies ^{233}U

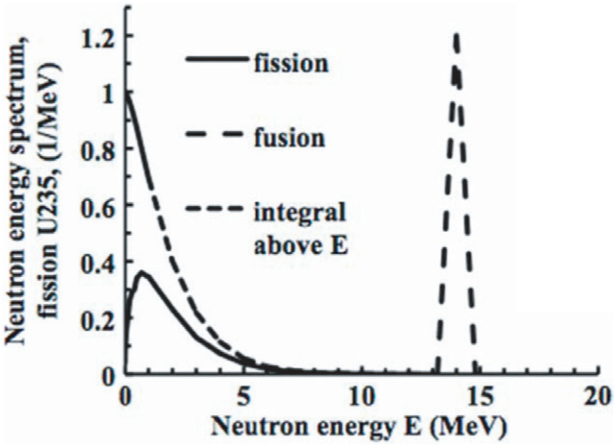

Figure 4. Neutron source spectra for fission (^{233}U and ^{235}U are similar) and fusion where <3% of fission neutrons are above 6 MeV needed to produce ^{232}U. Since fusion neutrons are above 6 MeV the production of ^{232}U is much greater for fusion sources than for fission sources.

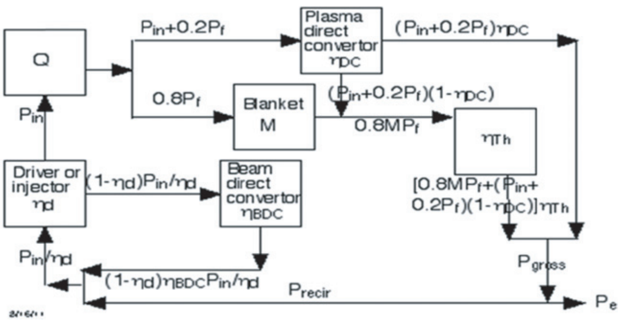

Figure 5. A power flow diagram for a mirror hybrid.

production makes the material highly radioactive and therefore undesirable but not impossible for use in fission weapons. Fusion is unique compared with fission in its role of making ^{232}U. Fusion's 14 MeV neutrons being well above the 6 MeV threshold for producing ^{232}U enhances the ^{232}U/^{233}U ratio from its usual value in fission reactors of ~0.1% to ≈ 5% (see figure 4) [17].

This enhances the generation of both 2.6 MeV gamma rays and decay heat facilitating detection of stolen material and makes for weapon design problems. Non-proliferation is enhanced in typical fission-suppressed designs [17, 18] by generating up to 0.05 ^{232}U atoms for each ^{233}U atom produced from thorium, about twice the IAEA standards of 'reduced protection' or 'self-protection' due to ionizing radiation set at a dose rate of 100 rem/h (1 Sv h^{-1}) 1 m from 5 kg of ^{233}U with 2.4% ^{232}U one year after chemical separation of daughter products [19]. With 2.4% ^{232}U, high explosive material is predicted to degrade owing to ionizing radiation after a little over 1/2 year. The heat rate is 77 W just after separation and climbs to over 600 W ten years later.

The fissile material can be used to fuel mostly any fission reactor but is especially appropriate for MSRs [20] also called liquid fluoride thorium reactors (LFTRs) [21] because the molten fuel does not need hands on fabrication and handling that otherwise would be expensive owing to the 2.6 MeV gamma emission forcing all remote fabrication. Mixing ^{233}U

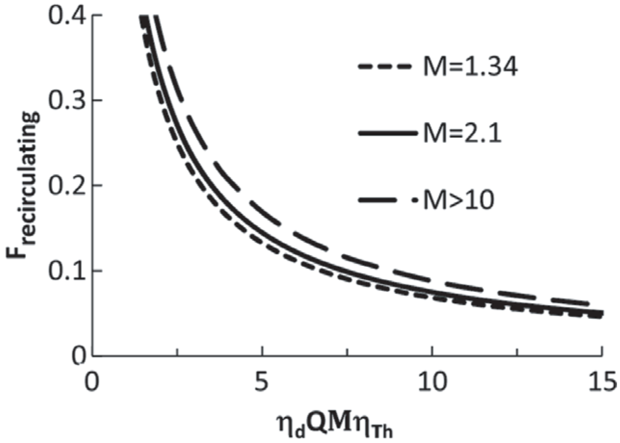

Figure 6. Recirculating power fraction figure of merit versus $\eta_d Q M \eta_{th}$. $F_{recirculating} \approx 1/\eta_d Q M \eta_{th}$.

with ^{238}U called denaturing is another possibility for promoting non-proliferation.

3.3. Required Q for favourable economics

We base our analyses on the tandem mirror GDT version [6]; however, any fusion system could work for the fuel production mission. Since a detailed economical model at present is unavailable, we will base our analysis on a figure of merit, $F_{recirculating}$ that is equal to the recirculating power to the injector system/gross electrical power. Revenues from the sale of electricity will be important even for fuel production and our figure of merit measures the fraction of power not available for sale. The power flow diagram is shown in figure 5. This figure of merit allows us to determine the required fusion performance especially Q (is the fusion power/absorbed power) to make any particular system economical even for a fuel producer.

We include direct conversion of end loss plasma flow and of unneutralized ions in the neutral beam system. η_{Th} is the thermal conversion efficiency, typically 0.4. η_d is the efficiency of converting electrical energy into neutral beam power trapped in the plasma, which is equal to 0.5. η_{BDC} is the conversion efficiency of the unneutralized beam, i.e. beam direct conversion which is 0.5 for our examples. η_{DC} is the efficiency of plasma direct conversion of end losses, typically 0.5 for our examples. Our figure of merit, F_{recirc}, is plotted in figure 6 for values of the blanket energy multiplication by nuclear reactions, M of 1.34, 2.1 and $M > 10$ that spans from pure fusion, fission suppressed thorium hybrid, fast-fission hybrids and certain actinide burners.

Based on experience, serious economic loss occurs for $F_{recirc} > 0.4$ and the quantity $\eta_d Q M \eta_{th}$ should exceed about 2.5. This means Q should be greater than 4 for the $M = 2.1$ blanket. Another way of gauging economics is to look at the annual revenues from the sales of electricity and revenues from fuel sold. For example, if we sell ^{233}U for 50$/g and electricity for 50$/MWeh then we get the revenues plotted against Q shown in figure 7, where the numbers along the top curves are the recirculating power fractions. See [10] for physical characteristics of a mirror hybrid.

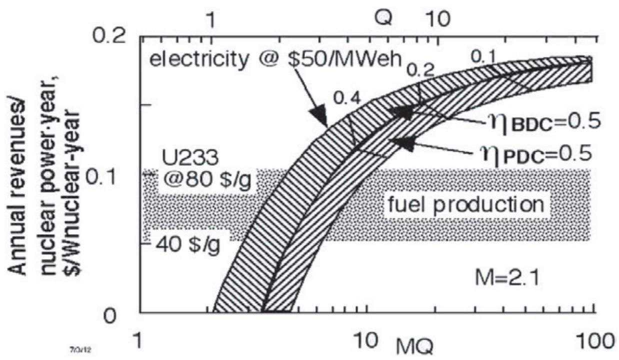

Figure 7. Annual revenues for both fuel and electricity sales versus Q and QM for the fission-suppressed fusion breeder when producing 0.6 fissile atoms per fusion event and $M = 2.0$.

4. Conclusions

We have described applications of the GDT concept to

(1) evaluate thermal cycling of materials to be used in fusion power systems and
(2) produce fission fuel via the fusion–fission hybrid concept.

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