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Mirror-based hybrids of recent design

R. W. Moir[a], N. N. Martovetsky[a], A. W. Molvik[a], D. D. Ryutov[a], T. C. Simonen[b]

[a]*Lawrence Livermore National Laboratory, Livermore, CA USA,* ralph@ralphmoir.com, martovetskyn@ornl.gov, AWMolvik@lbl.gov, ryutov1@llnl.gov
[b]*University of California, Berkeley, CA USA,* simonen42@yahoo.com

Abstract. Early application of the simple axisymmetric mirror, requiring intermediate performance between a neutron source for materials testing $Q=P_{\mathrm{fusion}}/P_{\mathrm{input}}$ ~0.05 and pure fusion Q>10, are the hybrid applications. The Axisymmetric Mirror has attractive features as a driver for a fusion-fission hybrid system: geometrical simplicity, as well as the typical mirror features of inherently steady-state operation, and natural divertors in the form of end tanks. Operation at Q~0.7 allows for relatively low electron temperatures, in the range of 3 keV, for the DT injection energy ~ 80 keV from existing positive ion neutral beams designed for steady state. This level of physics performance has the virtue of being low risk with only modest R&D needed; and its simplicity promises economy advantages. A simple mirror with the plasma diameter of 1 m and mirror-to-mirror 2.5 T solenoid length of 40 m is discussed. Simple circular steady state superconducting coils at each end are based on 15 T technology development of the ITER central solenoid. Hybrids obtain important revenues from the sale of both electricity and fuel production or waste burning. Burning fission reactor wastes by fissioning transuranics in the hybrid will multiply fusion's neutron energy by a factor of ~10 or more and diminish the Q needed to overcome the cost of recirculating power for good economics to less than 2 and for minor actinides with multiplication over 50 to Q~0.2. Hybrids that produce fissile fuel with fissioning blankets might need Q<2 while suppressing fissioning might be the most economical application of fusion but will require Q>4.

Keywords: Fusion-fission hybrid, magnetic mirror fusion, fusion breeder
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I. INTRODUCTION

Mirrors have a number of attractive features as future fusion devices: they have simple linear geometry to ease construction and maintenance, are inherently steady state, operate at high beta, have no externally driven currents, and have natural divertors to handle heat loads external to the magnet system that also reduces first wall heat loads.

Over the past decades, largely after the termination of the mirror program in the US, several techniques have been suggested and, in some cases, tested experimentally, for making mirrors stable in axisymmetric geometry. The confidence in the practicality of axisymmetric MHD-stable mirrors has increased significantly after a set of experiments conducted in 2005-2010 on the upgraded axisymmetric Gas Dynamic

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Trap (GDT) mirror machine at Novosibirsk [1]. It routinely operates at a plasma beta equal to 0.6 and average ion energy of a few keV, with the plasma axial losses being in a good agreement with the classical predictions. Its important feature is being fully axisymmetric and, at the same time MHD–stable. A significant role in making this device MHD stable is played by the out flowing plasma, which, on the one hand, provides a favorable contribution to the stability integral [2] and, on the other hand, provides an electric contact with the conducting end wall. Applying a potential to the segmented limiter transfers to the confinement zone along the field lines a radial potential that may further improve stability [3,4]. This technique can be used in a fusion neutron source for materials and subcomponent testing with no (or with a minor) extrapolation of the plasma parameters from the existing experiment [1], which will operate at plasma Q of order of a few percent [5].

The attractive features of mirrors are tremendously amplified in the case of axial symmetry. In particular, neoclassical and resonant transport are completely eliminated; engineering simplicity and general flexibility of the device increase significantly; much higher magnetic fields become available for mirror throats, etc. Axisymmetry is thus a game-changer in mirror systems!

In this paper, we concentrate on the use of an axisymmetric mirror as a driver for a fusion-fission hybrid [6]. In order to have a meaningful power balance of this system, the fusion driver has to have a much higher value of Q than the neutron source. A physics background for this more challenging application has been assessed in [7], where plausible stabilization techniques have been identified and other plasma physics issues affecting the driver performance have been analyzed. The result was a simple, single cell mirror device with large expansion tanks at the ends.

Fusion-fission hybrids can potentially be used to produce energy, to breed fuel for fission reactors, to "burn" the most hazardous waste of fission reactors, or perform some combination of these functions [8]. We do not try to be very specific with regard to a possible best application of a mirror driver. We show that it is compatible with a broad variety of blankets and can perform any of the aforementioned functions. We discuss the requirements for the main systems of the facility: neutral beam injection system, gas feed and vacuum systems, magnetic system, tritium breeding and, of course, blanket and shield. We identify areas where the required technologies and components are available today and where some further development is needed [9,10].

Our main conclusion is that the hybrid driver in the form of axisymmetric mirrors can be built based mostly on either existing technologies or technologies that will be needed in any of the fusion energy systems (e.g., tritium breeding and neutral beam injection). Further, the axisymmetric mirror hybrid can accommodate blankets designed for any other confinement system.

II. A GENERAL SCHEME AND A SUMMARY OF THE PHYSICS PARAMETERS

A schematic of the system is presented in Fig. 1 and its parameters are summarized in Table 1. Atomic beams are injected normally to the magnetic axis near the ends of the confinement region where the magnetic field is ~ 2 times higher than in the uniform part of the facility. The maximum magnetic field (in the mirror throat) will be 3-4 times higher than that in the injection point, this means the injected ions are well confined. In this uniform section the ions will have a "sloshing" distribution, with the average pitch-angle of 45°. Such a distribution was proven to possess good micro-stability [13]. The sloshing distribution is compatible only with relatively cold electrons, so that the slowing-down time is shorter than the ion scattering time. To hold the electron temperature low, at the level of 3 keV, we envisage injection of cold atomic streams in the zone between the mirrors and the ion turning points as shown in Fig. 1. The distance to the ion turning point has to be large-enough to minimize penetration of atoms to the zone with significant hot ion population, in order to minimize charge exchange losses.

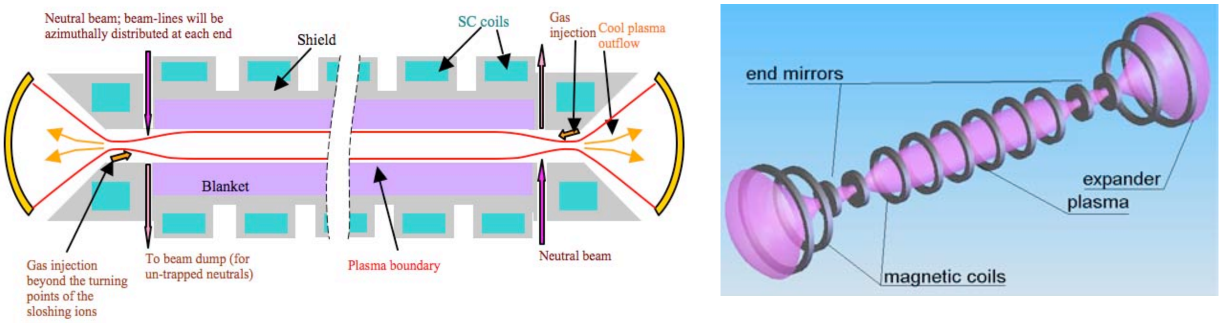


FIGURE 1. Schematic of a simple axisymmetric mirror as a driver for fusion-fission hybrid is shown on the left. The figure on the right has one extra end cell on each end (Kelley mode) to enhance Q.

TABLE 1. Characteristic parameters of a mirror driver

Plasma radius[a], m	0.5
Mirror-to-mirror length, m	40
Length of a reacting plasma[2], m	35
Volume of a reacting plasma[2], m^3	25
Plasma surface area[b], m^2	100
Injected ion energy[c], keV	80
Average ion energy[c], keV	40
Average ion density, m^{-3}	10^{20}
Electron temperature, keV	3
Peak ion density, m^{-3}	1.3×10^{20}
Z_{eff}[d]	1.2
Magnetic field, T	2.5
Mirror field, T	15
Volume-averaged beta	0.25
s = plasma radius/ average ion gyroradius	30
NBI trapped power, MW	65
Plasma Q	0.7
Fusion power, MW	45
Neutron power, MW	36
Neutron wall load, MW/m^2 @ 0.6 m	0.27
Power to end tanks, MW	75

[a] In the midplane
[b] Between the turning points of the sloshing ions
[c] Ignoring ½ and 1/3 energies
[d] Based on the experience with large-scale mirror facilities and composition of the injected particle beams [14].

Injected gas, after having been ionized, flows out of the facility to the end tanks and establishes an electrical contact between the confinement zone and the conducting wall. This provides conditions for suppression of the large-scale flute perturbations via partial line-tying. The growth rate of instabilities decrease by an order of magnitude compared to their un-inhibited value. Residual slow instability can be stabilized by other techniques, like feedback stabilization.

The flaring of the magnetic field in the end tank allows one to reduce the heat flux on the plasma absorbers to a manageable level of 1 MW/m^2. For the parameters of Table 1, this requires the surface area of each of the absorbers to be ~ 40 m^2, meaning that the magnetic field at the end surface will be ~ 0.05 T. Strong flaring leads to a formation of the ambipolar potential between the mirror throat and the end-wall; this potential barrier repels most of the electrons back to the mirror and reduces the electron heat loss to a small level. More detailed description of the physics processes can be found in Ref. [7], together with further references.

Magnetic system

The magnet system consists of two subsystems – a 40-m long solenoid with 2.5 T central field and mirror solenoids at the end with a high field of 15 T. The long solenoid is quite feasible with NbTi superconductor [9]. The 15 T mirror solenoid is feasible but at the state-of-the-art level with the today's technology. A close to the required parameters is the 13 T peak field Central Solenoid Model Coil (CSMC) [15] built by ITER collaboration in 1999. There has been a significant progress in superconducting materials since 1999, although structural materials, that occupy most of the winding pack, did not improve that much since then. The magnet system feasibility for the hybrid is discussed in [9] in more details.

Plasma Sustainment and Exhaust

In order to provide some insight into the technical readiness of various systems needed for the construction of the fusion 'core', we briefly outline a possible overall design. We expect a facility like this to be preceded by a neutron source that will develop steady-state neutral beams (likely with direct conversion of the unneutralized ion beam), cryopanels with regeneration, tritium-generating lithium blankets, and fusion-fission hybrid blankets.

The power density to the end-wall is not the serious problem in mirror machines as it is to divertor strike surfaces in tokamaks, because we are free to expand the plasma cross section to a large area, to reduce the power density below any reasonable threshold desired. To keep end-wall sputtering to ≤560 μm/yr, we expand the plasma radius from 0.2 m at the mirror to 3.5 m at the end wall.

We find that end-cell pumping is an issue with too much charge exchange so direct converter efficiency is low for this fusion-fission hybrid because we have a fusion gain of not quite unity, $Q \leq 1$. This means that end losses are large. Although we chose 80 keV as the injection energy, raising it to about 100 keV would lower the charge exchange cross section and decrease the end loss. For pure fusion, where Q needs to be >10, this ceases to be an issue, because the end-loss currents decrease nearly as Q^{-1}.

Gas injection will be located beyond the turning point of energetic beam-injected ions, and near the peak magnetic field at the mirror as shown in Fig. 1. The exact location will be optimized to minimize hot-ion loss through charge-exchange on injected gas by moving the injection away from the neutral beam injection location and towards the mirror or even outside of it.

Separation of tritium from deuterium, hydrogen, and other impurities has been demonstrated at Los Alamos on the Tritium Systems Test Assembly (TSTA) [16]. This is a known technology, but is quite expensive for the large flow rates envisioned for a fusion-fission hybrid. We therefore propose to use a near 50:50 mixture of deuterium and tritium, thereby minimizing the amount of isotope separation needed, however, with separation tritium could be injected at higher energy thus increasing Q and lowering charge exchange losses. The flow rate of tritium circulating in the system is ~0.6 kg/hr, ~0.22 kg/hr to the end tank pumps, and ~0.34 kg/hr to the neutral beam line pumps. This is about 33% of the ITER tritium flow rate of 1.8 kg/hr [17, p 145].

Long-pulse neutral beam accelerators on TFTR (120 keV), and DIIID (80 keV) [18,19,20] have demonstrated reliable operation at durations of a few seconds, these durations exceed ten thermal time constants of the accelerator electrodes, and so they are effectively steady state cooled. Development to minimize grid erosion will be needed to extend the life to ~1 yr. Direct conversion of the power in the unneutralized portion of the beam was demonstrated on 0.5 s pulsed neutral beams [21]. As we show in the next section, increases in beam efficiency have a particularly large-favorable effect on the efficiency and economics of operation near Q~1; so we suggest completing the development of steady-state direct convertors as part of the neutral-beam line.

Minimizing streaming neutrons is essential to minimize the neutron heat load to cryopanels, and to maximize the lifetime of beam line components, especially the insulators, against degradation by neutrons [22,23,24].

Linear, axisymmetric systems like magnetic mirrors provide attractive options for maintenance. Cylindrical symmetry is convenient because all sides of the system are accessible, with no need to squeeze components into the donut hole of a torus. If we locate the vacuum seals outside of the blankets and neutron shields where it is protected from neutrons for a long-reliable life, then access to the blankets can be obtained by rolling the ends of the facility outwards on rails or alternatively, move perpendicularly to the magnetic axis. The perpendicular movement allows replacing of one blanket module without disturbing the other modules. Vacuum seals can be bolted hard seals, or edge-seam-welded sheet metal. The latter can be opened by grinding off the weld; then rewelded after closing up, as is done daily on some industrial ovens.

III. Q REQUIRED FOR FAVORABLE ECONOMICS

As a detailed economical model at present is unavailable, we will base our analysis on a figure of merit, $F_{\text{recirculating}}$= recirculating power to the injector system/gross electrical power. Revenues from the sale of electricity will be important even for fuel production or actinide burning and our figure of merit measures the fraction of power not available for sale. The power flow diagram is shown in Fig. 2. This figure of merit allows us to determine the required fusion performance especially Q (=fusion power/absorbed power) to make any particular system economical even for a fuel producer, actinide burner or power producer only.

We include direct conversion of end loss plasma flow and of unneutralized ions in the neutral beam system.

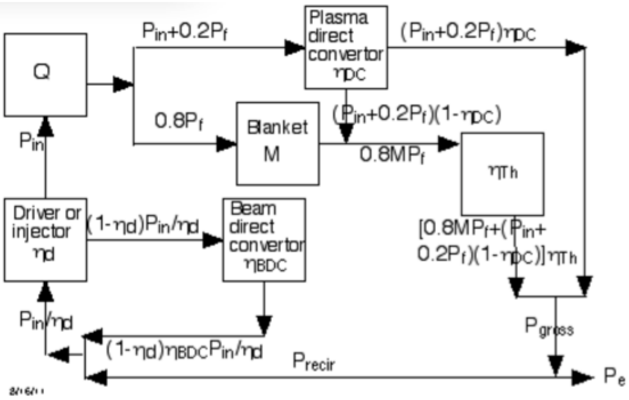


Figure 2. Power flow diagram for mirror hybrid.

η_{Th} =thermal conversion efficiency, typically = 0.4. η_d=efficiency of converting electrical energy into neutral beam power trapped in the plasma = 0.5. η_{BDC} =efficiency of conversion of unneutralized beam, i.e., beam direct conversion =0.5 for our examples. η_{DC}=efficiency of plasma direct conversion of end losses, typically 0.5 for our examples. Our figure of merit, F_{recirc} is plotted in Fig. 5 for values of the blanket energy multiplication by nuclear reactions, M of 1.34, 2.1, 10 and 20 that spans from pure fusion, fission suppressed thorium hybrid, fast-fission hybrids and certain actinide burners all of which are discussed in Sec. IV.

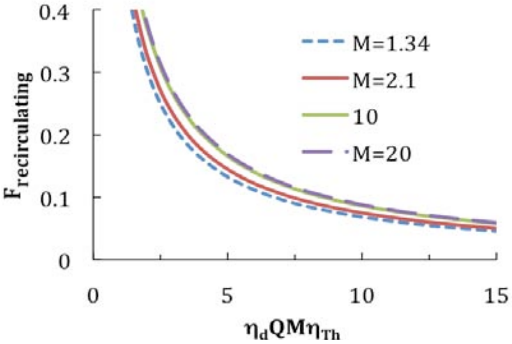


FIGURE. 3. Recirculating power fraction figure of merit versus $\eta_d QM\eta_{th}$.

Based on experience, serious economic loss occurs for $F_{recirc} > 0.2$ and the quantity $\eta_d QM\eta_{th}$ should exceed 3 to 4 or 6 without direct conversion. This means Q should be greater than 8 for the M=2.1 blanket and 2 for the M=10 or 20 blankets. Another way of gauging economics is to look at the annual revenues from the sales of electricity and revenues from fuel sold or actinide destroyed by fission. 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 Fig. 4

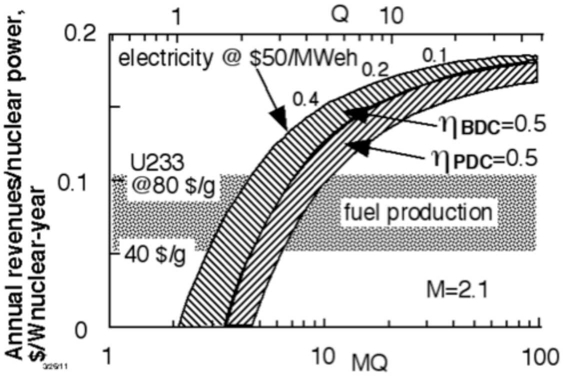


Figure. 4 Annual revenues for both fuel and electricity sales versus Q and QM for the fission suppressed fusion breeder when producing 0.6 fissile atoms per fusion event and M=2.0.

and 5, where the numbers along the top curves are the recirculating power fractions from Fig. 3.

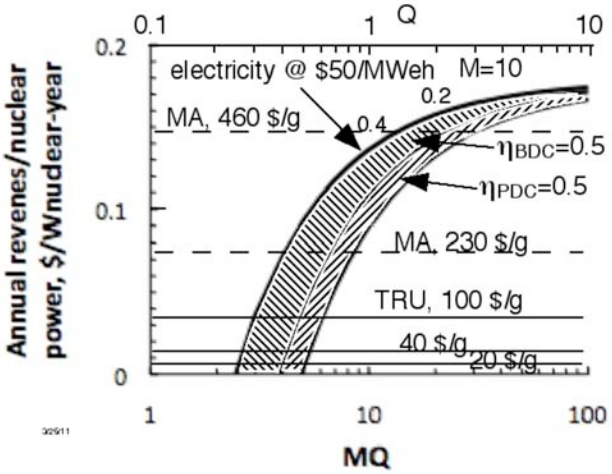


FIGURE. 5. Annual revenues for both actinide burning and electricity sales versus Q and QM for the actinide burning hybrid M=10.

IV. HYBRID BLANKET DESIGNS: ACTINIDE BURNER, FUEL PRODUCER AND POWER PRODUCER

Waste burning of transuranic elements (A>92) by fission in a tokamak has been studied [25] where fuel elements in the form of rods are made up of separated fission reactor wastes and cooled by liquid sodium with M=19. For good economics we require Q>0.5 for F_{recir}<0.4.

Similar studies of minor actinide (transuranics other than plutonium) burning have been carried [26] for fissioning in a normal conducting spherical tokamak also with liquid metal cooling with $K_{eff} \approx 0.99$ and M=50. Good economics requires Q>0.2 for F_{recir}<0.4. Both these blanket designs could be adapted to the axisymmetric mirror with its geometric simplification advantages as well as avoidance of transients. Both these designs require active cooling of afterheat. A transuranic burner using molten salt that allows draining the molten salt to a passive cooled tank for afterheat was studied [27] and is recommended for both these designs. A similar design using molten salt is shown in Fig. 6 and discussed next.

Fission-suppressed fuel producing hybrids maximize safety and the amount of fuel production per unit of nuclear power. Two example designs are shown. One uses lithium-7 to multiply neutrons while it makes tritium shown in Fig. 6 (Li/MS) and the other uses beryllium to multiply neutrons, shown in Fig. 7 (Be/MS). Both use molten salt to carry the thorium that breeds ^{233}U. The two flowing liquids cool the Li/MS design. The Be/MS design uses helium cooling of beryllium pebbles to multiply neutrons and molten salt slowing flowing through tubes to both breed tritium and ^{233}U. Producing ^{233}U from thorium has both proliferation advantages and concerns. ^{232}U that inevitably accompanies ^{233}U production makes the material undesirable but not impossible for use in fission weapons. <u>**Fusion is unique**</u> compared to fission in its role of making ^{232}U. Fusion's 14 MeV neutron being well above the 6 MeV threshold for making ^{232}U can enhance the $^{232}U/^{233}U$ ratio from its usual value in fission reactors of ~0.1% to >>1%. This enhances the generation of both 2.6 MeV gamma rays and decay heat that facilitates detection of stolen material and makes for weapon design problems.

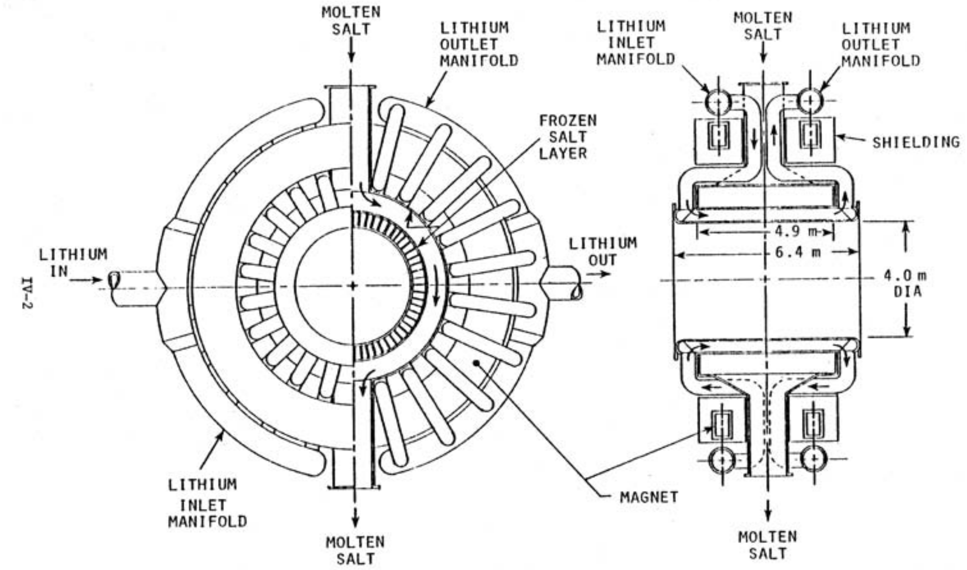
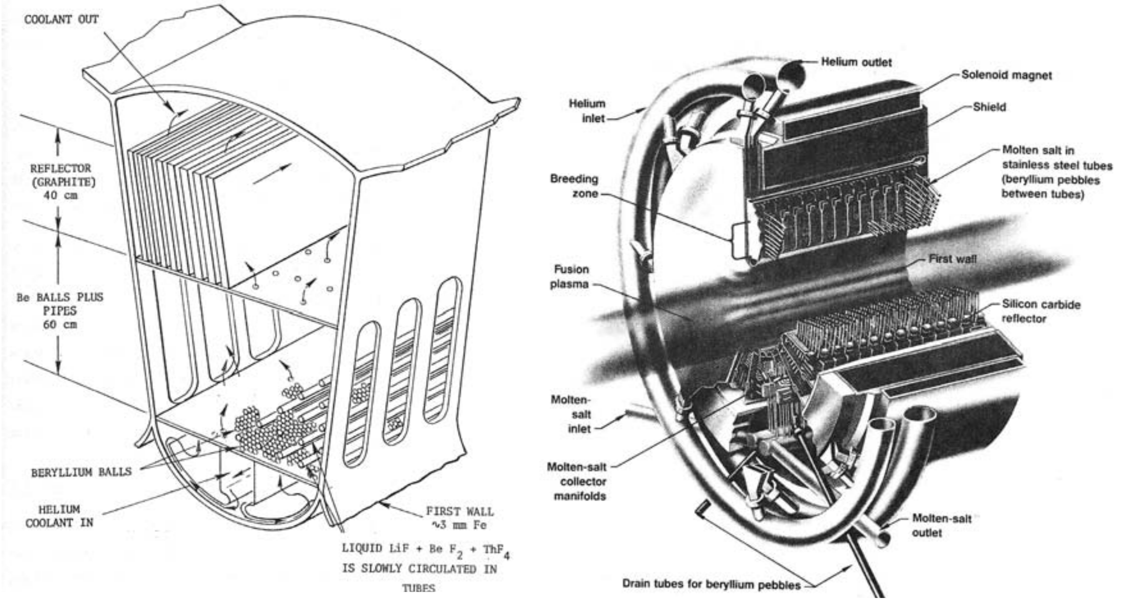


FIGURE. 6. Two zone lithium neutron multiplier blanket with a molten salt second zone for the breeding media (Li/MS) [28].



(a) (b)

FIGURE. 7. Blanket submodule (a) designed both for a tandem mirror [29] and a tokamak [30] with pebbles and helium cooling, adapted to mirror geometry (b) making an integrated package of first wall, blanket, shield and solenoidal magnet.

The performance of the Li/MS blanket shown in Fig. 6 is M=1.4 and 0.5 ^{233}U atoms are produced for each fusion event and for the Be/MS blanket shown in Fig. 7 M=2.1 and 0.6 ^{233}U atoms are produced for each fusion event. Safety is enhanced by fission being suppressed, therefore fewer fission products and in the event of a failure, the molten salt can be passively drained to safe passively cooled storage tanks. As mentioned in the previous section the Q should be >8 for a first approximation of economics but perhaps for 40% recirculating power, Q>4 might be allowed.

V. SUMMARY AND DISCUSSION

The Q required for several different hybrid blankets designed for different purposes are given in Table 3. Actinide waste incineration or burning by fissioning can be accomplished with fusion neutrons. Blankets can use solid fuel forms or molten salt fuel form. With solid fuel forms, cooling of after-heat requires active or engineered safety systems. By comparison, with molten salt fuel forms, the fuel can be drained passively during off-normal conditions to passively cooled dump or storage tanks. The recent Fukushima accidents remind us again of the desirability of "walk away" or passive safety of nuclear systems.

TABLE 3. Require Q for various versions of the hybrid for the recirculating power fraction = 0.2, $P_{nuclear}$=3000MW

Actinide burner			
Blanket multiplication, M	Minimum Q required	P_{fusion}, MW	Comments
Transuranics, M=19	1	200	solid fuel, engineered or active safety
Minor actinides, M=38 to 150	0.1 to 0.5 0.2 av.	25 to 100 50 av.	"
Transuranics, Molten salt, M=13	1.5	280	passive safety
Fuel producer			
Fission-suppressed, M=2.1, ^{233}U	8	1600	passive safety
Fast-fission, M=10, ^{239}Pu	2	370	engineered safety
Power producer			
M=10	2	370	molten salt passive safety solid fuel engineered safety
Pure fusion			
M=1.34	11	2300	passive safety

The condition of recirculating power fraction no more than 20% is restrictive resulting in the require Q values given above. If the recirculating power fraction could be allowed as high as 40%, the required Q values given above would drop approximately in half. A more detailed economic model that fully includes the value of the dual product of both electricity and fuel production or waste burning will result in a higher value of the combined products and therefore a lower required Q. Such a model would include the fleet of fission reactors whose fuel is supplied by the hybrid or the fleet of fission reactors whose wastes are incinerated by fissioning in the hybrid. The fusion performance measured by Q for various operating modes of the mirror confinement is shown in Fig. 8. Also shown is the minimum Q required for the various hybrid applications from Table 3.

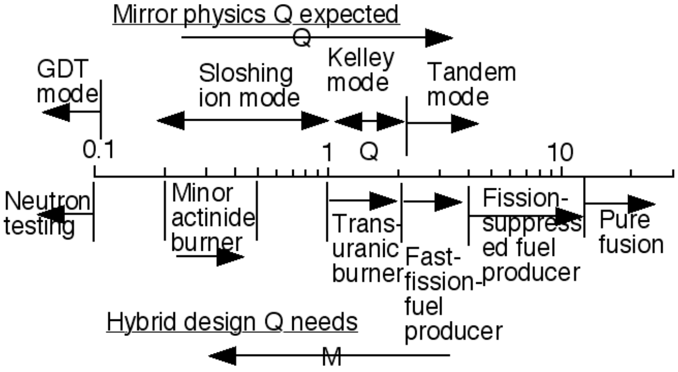


Figure. 8. Hybrid options and corresponding mirror operating regimes show the required Q and M tradeoffs.

VI. CONCLUSIONS

A fusion neutron source can be based on an all axisymmetric set of magnets employing existing neutral beams at 80 keV to achieve plasma conditions modestly extended from those already achieved. The predicted Q of ~0.7 would be sufficient for applications to burn minor actinide wastes (elements beyond Pu) in the sloshing ion mode. Blanket designs proposed for other fusion concepts could be accommodated even more easily in the axisymmetric mirror owing to its simple geometry. The system would be steady state requiring neutral beam technology development to extend lifetime to about a year. The heat load is spread over as much area as needed in end tanks and therefore is within the state-of-the-art. Pumping would be by well known condensation pumping that would need to be made steady by proposed techniques of cycling a portion of the pumps for outgassing at any one time. The solenoidal magnets at 2.5 T are common and even the 15 T mirror magnets are similar to those tested for ITER. With an extra mirror end cell added to each end in the Kelley mention earlier mode, the Q might be raised to about 1 to permit burning all actinides or in the tandem mode to >4 to allow fuel production in the fission suppressed mode. Fusion applications such as a materials-testing neutron source and other fusion technology will likely be developed independently and can be used by this hybrid application.

VII. ACKNOWLEDGMENTS

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VIII. REFERENCES

1. A. A. IVANOV, A. D. BEKLEMISHEV, E. P. KRUGLYAKOV, P. A. BAGRYANSKY, A. A. LIZUNOV, V. V. MAXIMOV, S. B. MURAKHTIN, V. V. PRIKHODKO, "Results of Recent experiments on GDT Device after upgrade of heating neutral beams," *Fusion Sci. Technol.*, **57**, 320-325 (2010).
2. M.N. ROSENBLUTH, C.L. LONGMIRE, "Stability of plasmas confined by magnetic fields," *Annals of Physics,* **1**, 120 (1957).
3. P.A. BAGRYANSKY, A.A. LIZUNOV, A.A. ZUEV, E. YU. KOLESNIKOV, A.L. SOLOMACHIN. "Experiments with Controllable Application of Radial Electroc Fields in GDT Central Cell." *Fusion Sci. and Technology* **43**, 152 (2003)
4. P.A. BAGRYANSKY, A.D. BEKLEMISHEV, E.I. SOLDATKINA. "Influence of radial electric field on high-beta plasma confinement in the Gas-Dynamic Trap." *Fusion Sci. Technol*. **51**, 340 (2007).

5 D.D. RYUTOV, "Mirror type neutron source," *Plasma Physics and Contr. Fusion*, **32**, 999 (1990).

6. L. M. LIDSKY, "Fission-fusion systems: hybrid, symbiotic and augean", *Nuclear Fusion* 15, 151-173 (1975).
7. D.D. RYUTOV, A.W. MOLVIK, T.C. SIMONEN. "Axisymmetric Mirror as a Driver for a Fusion-Fission Hybrid: Physics Issues," *J. Fusion Energy*, **29** (2010).
8. J. FREIDBERG, P. FINCK, C. BOLTON, Eds. Report "Research Needs for Fusion-Fission Hybrid Systems," Report of the Research Needs Workshop (ReNeW) Gaithersburg, Maryland Sept 30-Oct 2, 2009. MIT, January 2010.
9. R. W. MOIR, N. N. MARTOVETSKY, A. W. MOLVIK, D. D. RYUTOV, T. C. SIMONEN, "Axisymmetric Magnetic Mirror Fusion-Fission Hybrid," LLNL-TR-484071 (2011).

10 R. W. MOIR, N. N. MARTOVETSKY, A. W. MOLVIK, D. D. RYUTOV, T. C. SIMONEN, "Axisymmetric Magnetic Mirror Fusion-Fission Hybrid," to be published in *Fusion Science and Technology* (2011).

13. T.C. SIMONEN, S.L. ALLEN, T.A. CASPER, et al., "Operation of the tandem-mirror plasma-experiment with skew neutral-beam injection," *Phys. Rev. Lett*. **50**, 1668 (1983).
14. A. W. MOLVIK, "Impurity radiation from a beam-plasma neutron source," *Nuclear Fusion* **35**, 1247 (1995).
15. N. MARTOVETSKY, J. MINERVINI, A. RADOVINSKY ET AL., "Test of the ITER Central Solenoid Model Coil and CS Insert", *IEEE Transactions on Applied. Superconductivity v.*12, N 1 March 2002, p. 600-605.
16. R.S. WILLMS, K. KOBAYASHI, Y. IWAI, T. HAYASHI, S. O'HIRA, M. NISHI, D. HYATT AND R.V. CARLSON; "Behavior of tritium in the TSTA test cell combined with operation of the Experimental Tritium Cleanup (ETC) system"; *Fusion Engineering and Design*, 61-62, 575 - 583 (2002).
17. R. HAZELTINE, ET AL., "Research Needs for Magnetic Fusion Energy Sciences," Report of Research Needs Workshop; http://fire.pppl.gov/renew_final_report_2009.pdf
18. M. C. VELLA, W. S. COOPER, P. A. PINCOSY, R. V. PYLE, P. D. WEBER, and R. P. WELLS, "Development testing of the U.S. common long pulse source at 120 keV," *Rev. Sci. Instrum*. **59**, 2357 (1988).
19. J. KIM, R. W. CALLIS, A. P. COLLERAINE, ET AL., Performance of the DIIID neutral beam injection system," *Proc. 12th Symposium on fusion engineering, IEEE* (1987), p. 290.
20. T. STEVENSON, K. SILBER, L. LAGIN, ET AL., "The TFTR Neutral Beam Performance Database," *Fusion Technology* **21**, 1644, Part 2A (1992).
21. W. L. BARR, R. W. MOIR, G. W. HAMILTON, "Experimental results from a beam direct converter at 100 kV," *J. of Fusion Energy* **2**, 131 (1982).
22. E. R. HODGSON, "Challenges for insulating materials in fusion applications," *Nuclear Instrum. and Methods in Physics Research B* **191**, 744 (2002).
23. S. J. ZINKLE, V. A. SKURATOV, AND D. T. HOELZER, "On the conflicting roles of ionizing radiation in ceramics," *Nuclear Instrum. and Methods in Physics Research B* **191**, 758 (2002).

24. M. DECRETON, T. SHIKAMA, E. HODGSON, “Performance of functional materials and components in a fusion reactor: the issue of radiation effects in ceramics and glass materials for diagnostics,” *J. Nuclear Materials* **329-333**, 125 (2004).
25. W.M. STACEY ET AL., “A TRU-Zr metal-fuel sodium-cooled fast subcritical advanced burner reactor,” *Nuclear Technology*, 162, 53, 2008.
26. M. KOTSCHENREUTHER, P.M. VALANJU, S.M. MAHAJAN, E.A. SCHNEIDER, “Fusion-Fission Transmutation Scheme-Efficient Destruction of Nuclear Waste,” *Fusion Engineering and Design* 84 (2009) 83-88.
27. E. T. CHENG, “Performance characteristics of actinide-burning fusion power plants,” *Fusion Science & Technology*, **47**, 1219-1223 (2005).
28. J. D. Lee, et al., "Feasibility Study of a Fission-Suppressed Tandem-Mirror Hybrid Reactor", Lawrence Livermore National Laboratory, Livermore, CA, UCID-19327 (1982), http://ralphmoir.com/media/uCID19327pt1sm.pdf http://ralphmoir.com/media/uCID19327pt2sm.pdf
29. R. W. Moir, et al., “Design of a Helium-Cooled Molten Salt Fusion Breeder”, *Fusion Technology*, **8**, (1985), 465-473.
30. R. W. MOIR, ET AL., “Feasibility Study of a Fission-Suppressed Tokamak Fusion Breeder,” Lawrence Livermore National Laboratory, Livermore, CA, UCID-20154 (1984).