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ORIGINAL RESEARCH

A Strategic Opportunity for Magnetic Fusion Energy Development

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Abstract The realities of energy development and the perception of and support for magnetic fusion in the US are briefly summarized as background for proposing a strategic opportunity for magnet fusion energy development as fusion neutron sources for subcritical advanced burner (transmutation) reactors for the destruction of long-lived transuranics in spent nuclear fuel.

Keywords Subcritical advanced burner reactor · Transmutation reactor · Fusion–fission hybrid

Realities of the Energy Development Debate

The facts regarding energy resources, as we know them, make a convincing case that fusion must be the ultimate energy source for mankind, and the facts, again as we know them, about the negative environmental impact of fossil energy conversion processes (e.g. Ref. [1]) make a convincing case that an environmentally benign energy source, such as fusion, capable of meeting projected energy demands with a minimum of collateral impacts should be developed as soon as possible. However, very few people or decision-makers are aware of or interested in these facts. Rather, government energy development policy, such as it is, is dominated by the strong economic interests in continuing the use of fossil fuels and by the idealistic but misguided "feel-good" emotional interest in developing "green energy" sources of limited practicality and capability. This situation is not helped by "policy-type" studies of energy development which do not take into account the technical credibility of the input performance assumptions nor the collateral impacts of the technology. Such studies provide misleading guidance to the decision-making process. The result of all of this is politically motivated government support of burning more fossil fuels and building windmill and solar farms to placate the greens, while the development of nuclear fission and fusion energy is held back by government subsidy of competing fossil fuels[1] and by inadequate R&D resources, respectively.

The country would be well-served by a technically-guided National Energy Development study that emphasized technical scrutiny of both input performance parameters and collateral impacts on environment, land usage, electricity distribution systems, etc. Such a study would best be carried out by NAS/NAE or a joint task force sponsored by APS, ANS and other technical professional societies. Such a study should also address the criteria used to evaluate public safety and environmental impact.

Perception of Magnetic Fusion by the Larger Scientific/Technical Community

"Fusion is the energy of the future, and always will be" and "Fusion is 35 years off, and always will be" are familiar cracks from members of other scientific and technical communities. These comments detract from an appreciation of the significant progress being made in

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[1] Oil, natural gas and coal have received more than $500B in US federal subsidies over the period 1950–2006, most of it in the form of tax breaks [1]. Furthermore, the actual (not environmental) costs of the pollution (The NAS estimates the cost due to coal pollution alone to be $62B per year [1]) are paid for by the public tax funds rather than included in the cost of fossil generated electricity.

fusion research.[2] Such cracks are based on previous plans to build an experimental power reactor within 30–35 years which were put forward a few times during the second half of the twentieth century. These plans went unfulfilled because funding for the required R&D and engineering design was never forthcoming before ITER [2] (which will be operating within about 35 years of project formation in 1988, despite the delays associated with a lengthy site selection process).

Perspectives Within the US Magnetic Fusion Community

The US Magnetic Fusion Community consists of many people with different professional interests. There are plasma physicists whose professional home is the American Physical Society's Division of Plasma Physics (APS-DPP), nuclear engineers whose professional home is the American Nuclear Society's Division of Fusion Energy (ANS-FED), electrical engineers whose professional home is the Institute of Electrical and Electronics Engineers (IEEE), computational physicists and assorted other scientists and engineers. For many, perhaps most, of these people it is the quest for fusion energy that motivates their work, but for many physicists it is the development of plasma physics as a basic scientific discipline that provides such motivation.

Even among those motivated by the development of fusion energy there is a division of opinion between those who favor pushing to extend the physics limitations of the most highly developed tokamak concept and those who favor investigating much less developed confinement concepts that do not seem to have these particular limitations. The majority of the US experimental research and associated theory is now focused on tokamaks in three major programs at DIII-D, a moderate size experiment (which is almost 40 years old) at General Atomics, NSTX (a new tokamak-like experiment) at Princeton, and the small C-Mod experiment at MIT (which is being shut down), and in a number of small university groups. For the most part, further development of the tokamak concept must be performed at the large tokamak laboratories (at GA and PPPL in the US), which threatens the economic and professional interests of many plasma physicists in university and smaller laboratory research. This process of concentration has led in recent decades to the shutdown of major alternative confinement experiments at LANL (pinch) and LLNL (mirror), and the demise of the stellarator programs at ORNL and PPPL. This situation has been exacerbated recently by DOE taking money from the domestic fusion research program to pay for the US contribution of components for ITER.

Near-Term Research Priorities for Magnetic Fusion Energy Development

The fusion energy science development mission and the overriding importance of successful ITER operation dictate the appropriate near term research priorities for the DOE Fusion Energy Science Program: (1) design, construction and operation of ITER; (2) plasma theory, experiments and analyses supporting successful plasma performance in ITER; (3) technology development supporting successful operation of ITER; (4) development of fusion nuclear science; (5) preparation for experimental utilization of ITER; (6) experiments to improve tokamak plasma performance beyond the ITER level; (7) development of fusion nuclear materials; (8) development of "game-changing" advanced plasma support technologies (e.g. high temperature superconducting magnets); (9) investigation of promising alternative plasma magnetic confinement concepts and (10) basic plasma science.

A Strategic Opportunity for Magnetic Fusion Energy Development

The long-term objective of fusion energy development is clear—electric power production from D–T (and ultimately D–D) fusion that is competitive with other sources of electricity. The question is how to get there? A realistic strategy must take into account the realities of the overall energy development situation and the level of support for fusion in the US. Fusion will not be taken seriously as a potential electrical energy source until ITER [2] meets its performance objectives in the 2030s. Even then fusion will not be capable of producing electricity that is economically competitive with electricity produced by fossil fuels and nuclear. If the realization that we must stop burning fossil fuels [1] has been widely accepted by then, and if we have realized that solar and wind are intermittent in nature and only practical for niche applications (as is expected [1]), then the only available option for displacing fossil fuel produced electricity on a large scale in the first half of this century will be nuclear power [1].

However, nuclear power has an unresolved problem that fusion can help solve—the disposal of spent nuclear fuel containing radioactive transuranic elements with extremely long half-lives of 100,000 years or more. While disposal of this spent fuel by burial in secured repositories is technically feasible and not excessively expensive, this solution

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[2] The principal fusion performance parameter ($nT\tau_E$) has increased faster than Moore's law over the past half century.

has been rejected in the US (at least temporarily) for political reasons. The burial solution also wastes the substantial energy source in the transuranics in the spent fuel. A better, but technically more difficult, solution is to separate the long-lived transuranics in spent nuclear fuel, which are fissionable, and use them as fuel in special purpose "fast burner" or "transmutation" reactors [3], thus destroying the long half-life radioactive material, while extracting additional energy.

There are technical reasons why such transmutation reactors would work better if operated subcritical with a neutron source rather than operated critical [4]. (In a critical reactor the neutron fission chain reaction is maintained entirely by the neutrons produced in fission, while in a subcritical reactor the neutrons produced by fission must be supplemented by source neutrons in order to maintain the neutron fission chain reaction.) One advantage of subcritical operation is that the neutron source strength can be increased to maintain the neutron fission chain reaction (power) level as the fissionable material is destroyed, allowing a longer fuel residence time in the reactor and more transuranic destruction before reprocessing. Another advantage of subcritical operation is that the margin of reactivity error to a runaway power excursion is much larger in a subcritical reactor than in a critical reactor where it is related to the small fraction of delayed fission neutrons which are not emitted instantaneously. Since this delayed neutron fraction is much smaller for the transuranics than for uranium, prudence dictates that only a fraction (about 20 %) of the fuel in a critical reactor be transuranics. The much larger margin of reactivity error with subcritical operation would allow the subcritical transmutation reactor to be completely fueled with transuranics, resulting in 5 times fewer subcritical than critical transmutation reactors being needed to "burn" a given amount of transuranics.

There has been a substantial technical investigation [5, 6, 9] of fission–fusion transmutation reactors based on tokamak and sodium-cooled fast reactor technologies. The reason that these technologies were chosen is that they are the most highly developed fusion and fission transmutation technologies, about which we know enough to make a realistic assessment of something that could be built in the next 25–30 years. The Subcritical Advanced Burner Reactor (SABR) [5, 6] is based on ITER [2] fusion technology and physics, so in a sense ITER will be the prototype. EBR-II and its associated pyro-processing system were the prototype for the fission system [3, 7] (GE will sell you a PRISM reactor [8] based on this technology). It has been shown that the ITER [2] tokamak magnetic and plasma support technology configuration, with a slightly smaller plasma operating with somewhat lesser performance parameters but with higher availability, could provide an adequate D–T fusion neutron source for a 3000 MWth annular fast burner reactor surrounding the plasma [5, 6].

Such a SABR, based on the sodium cooled, metal fuel technology developed at ANL [7] and proposed in the GE PRISM reactor [8], operating at 75 % availability could destroy annually all the transuranics produced by three 3000 MWth LWRs [9]. Thus, an equilibrium nuclear fleet could be envisioned in which 75 % of the power is produced by advanced versions of the present LWRs and 25 % is produced by SABRs burning the transuranics produced in the LWRs. In an alternative fuel cycle intended to phase out LWRs in favor of conventional fast reactors, the Pu could be separated from the transuranics in spent fuel and used to fuel critical fast reactors, while the remaining "minor actinide" transuranics were used to fuel SABRs. One 3000 MWth SABR could destroy annually all the minor actinides produced in 25 3000 MWth LWRs [9].

With such SABR fleets, the relatively short-lived fission products (most with less than a few hundred year half-life), the few longer-lived fission products and trace amounts of transuranics would still need to be buried in secure repositories, but an order of magnitude fewer of them would be needed.

There are, of course, other fission and fusion technologies that could be considered for later SABRs, if they prove to be technically feasible. In general, the requirement is a fission technology which produces a fast neutron spectrum, which maximizes the neutron fission-to-capture ratio. For fusion technologies the requirement is for reliable plasma performance at the level expected in ITER. In the near-term (i.e. the next 25 years), only the tokamak fusion technology being proven on ITER and the sodium-cooled fast reactor technology demonstrated on EBR-II and other fast reactors are sufficiently developed to be used for a SABR to operate before mid-century.

The fusion development program needed to support a SABR nuclear mission would build directly on the ITER fusion physics and technology development program and be identical to the R&D program needed to develop fusion electrical power reactors—development of advanced tokamak physics, fusion nuclear science, fusion nuclear materials, advanced plasma support technology, etc. The nuclear fission development program to support a SABR would likewise be identical to the program needed to support Advanced (critical) Burner Reactor development. However, the integration of the fission and fusion technologies in the same device would undoubtedly require additional R&D [6].

The idea of a fusion–fission hybrid has been around for some time (e.g. Ref. [10]), but there has been renewed interest recently (e.g. Ref [11]). In addition to using fusion neutrons to destroy the transuranics in spent fuel (a burner reactor) it is also possible to use fusion neutrons to breed fissionable Pu from U238 (a breeder reactor) to fuel other nuclear reactors. It was recently announced [12] that Russia will construct a protype molten salt fueled 500 MWth subcritical advanced breeder reactor driven by a tokamak producing 100 MWth D–T fusion power by 2030, and will begin (?) construction of a 3000 MWth Industrial Hybrid plant driven by 500 MW of D–T fusion power by 2040. These Industrial Hybrid parameters are essentially identical with those of SABR [6], which could also function as a Subcritical Advanced *Breeder* Reactor [13] (SABrR). China has even more recently announced [14] plans for a fission–fusion hybrid transmutation reactor to be built by 2030.

Once the technical specifications of a SABR and the associated fuel separation and re-fabrication plants have been defined in some detail, it will be possible to make an economic cost-benefit analysis of transmuting spent nuclear fuel to reduce HLWR requirements versus directly burying the spent fuel in HLWRs. However, this can only be done after we have a better idea of the various reactor and reprocessing systems involved so that their costs can be compared with the savings in HLWR costs, taking into account the value of the electricity production by the transmutation reactors.

Glossary

ANL	Argonne National Laboratory
ANS	American Nuclear Society
APS	American Physical Society
C-MOD	Tokamak experiment at MIT
DOE	Department of Energy
DIII-D	Tokamak experiment at General Atomics
GA	General Atomics
GE	General Electric
IEEE	Institute of Electrical and Electronics Engineers
ITER	International Tokamak Experimental Reactor Project
LANL	Los Alamos National Laboratory
LWR	Light Water Reactor
MIT	Massachusetts Institute of Technology
NAE	National Academy of Engineering
NAS	National Academy of Science
NSTX	National Spherical Torus Experiment
ORNL	Oak Ridge National Laboratory
PPPL	Princeton Plasma Physics Laboratory
SABR	Subcritical Advanced Burner Reactor
SABrR	Subcritical Advanced Breeder Reactor

APPENDIX: SABR Design

The SABR design has recently been re-examined [6] to address several issues related to the compatibility of fusion and fission technologies in the same device—e.g. the effects of the magnetic field on flowing sodium, re-fueling the fission reactor located within the magnetic field coils of the tokamak. There do not seem to be any “no-go” issues.

The configuration of the SABR [6] fusion–fission hybrid burner reactor concept (based on ITER [2] fusion physics and technology and Integral Fast Reactor fission physics and technology [7]) is depicted in Figs. 1 and 2 and Tables 1 and 2. The annular subcritical reactor consists of 10 modular sodium pools located within the toroidal magnet system which can be rotated to one of two transport ports and removed for refueling.

Fig. 1 The SABR configuration

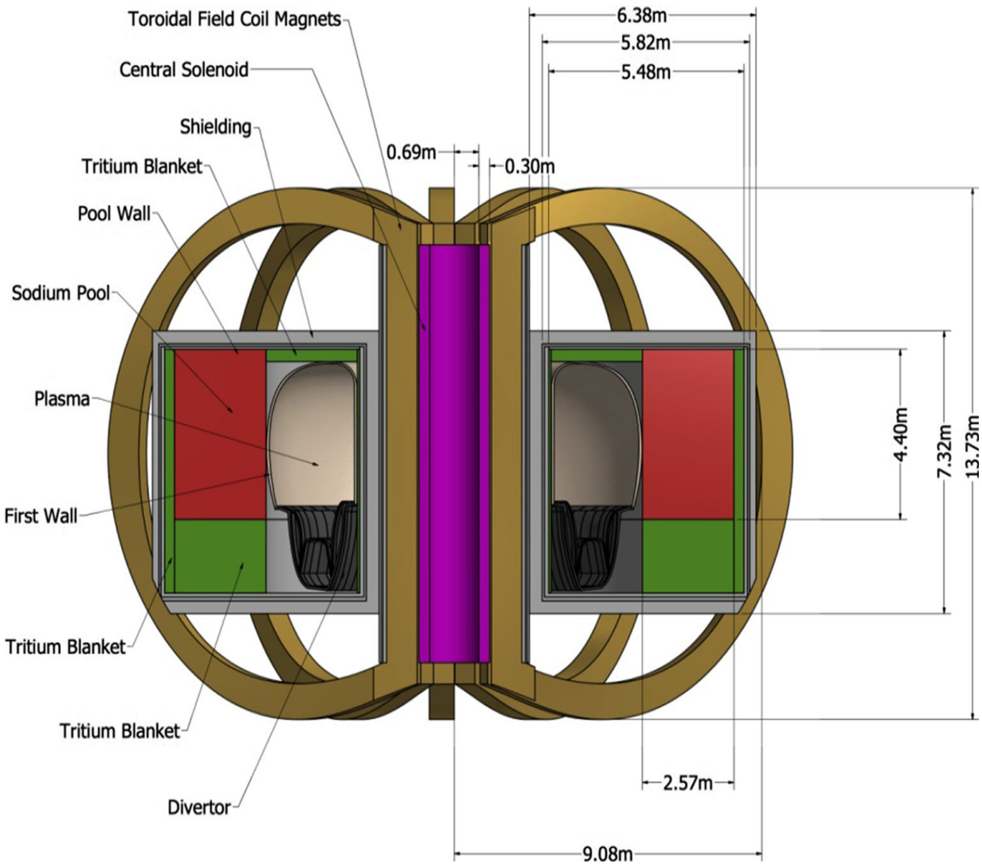

Fig. 2 SABR modular sodium pool with reactor and intermediate heat exchanger

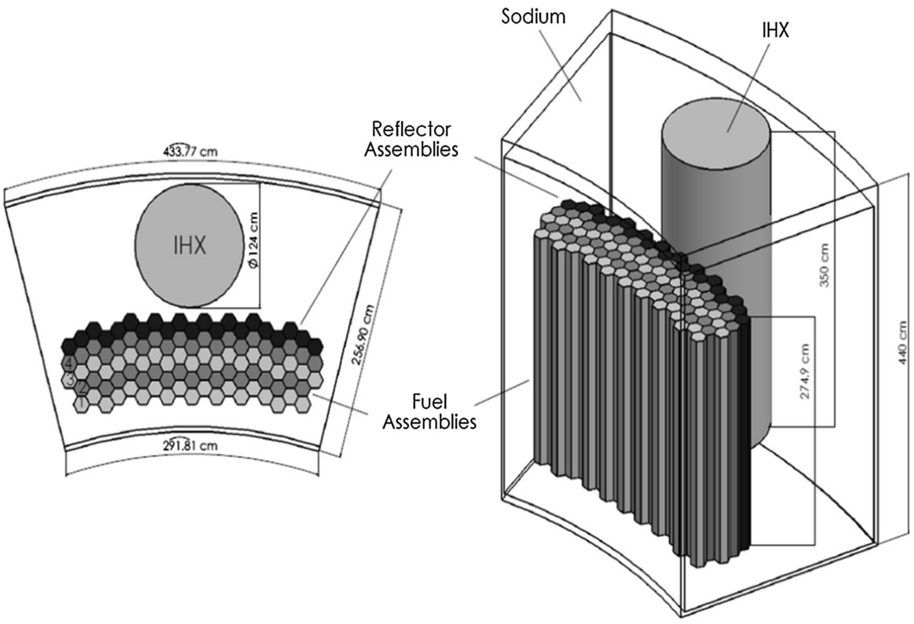

Table 1 SABR plasma physic parameters

Plasma	
Major radius	4.0 m
Plasma radius	1.2 m
Elongation	1.5
Toroidal magnetic field (on axis)	5.6 T
Plasma current	10 MA
Inductive current startup	6.0 MA
Non-inductive current drive	4.5 MA
Bootstrap current fraction	0.55
Heating and current-drive power	110 MW (70 EC, 40 LH)
Confinement factor H_{98}	1.2
Normalized β_N	3.2 %
Safety factor at 95 % flux surface	3.0
Max. and BOL fusion power	500 and 233 MW
Max. fusion neutron source strength	1.8×10^{20} n/s
Fusion gain ($Q_p = P_{fusion}/P_{extheat}$)	4.6

Table 2 SABR modular sodium pool parameters

Sodium pool	
Number of modular pools	10
Mass of fuel per pool	1510.4 kg
Mass of Na per pool	22,067 kg
Power per pool	300 MW
Mass flow rate per pool	1669 kg/s
Number of pumps per pool	2
Pumping power per pool	20 MW

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