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Georgia Tech Studies of Sub-Critical Advanced Burner Reactors with a D-T Fusion Tokamak Neutron Source for the Transmutation of Spent Nuclear Fuel

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Abstract The possibility that a tokamak D-T fusion neutron source, based on ITER physics and technology, could be used to drive sub-critical, fast-spectrum nuclear reactors fueled with the transuranics (TRU) in spent nuclear fuel discharged from conventional nuclear reactors has been investigated at Georgia Tech in a series of studies which are summarized in this paper. It is found that sub-critical operation of such fast transmutation reactors is advantageous in allowing longer fuel residence time, hence greater TRU burnup between fuel reprocessing stages, and in allowing higher TRU loading without compromising safety, relative to what could be achieved in a similar critical transmutation reactor. The required plasma and fusion technology operating parameter range of the fusion neutron source is generally within the anticipated operational range of ITER. The implications of these results for fusion development policy, if they hold up under more extensive and detailed analysis, is that a D-T fusion tokamak neutron source for a sub-critical transmutation reactor, built on the basis of the ITER operating experience, could possibly be a logical next step after ITER on the path to fusion electrical power reactors. At the same time, such an application would allow fusion to contribute to meeting the nation's energy needs at an earlier stage by helping to close the fission reactor nuclear fuel cycle.

Keywords Neutron source · Fusion–fission hybrid · Transmutation reactor

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Introduction

The neutron transmutation (fission) of the long-lived actinide isotopes in spent nuclear fuel (SNF) with decay times on the order of millennia into fission products with decay times of a few hundreds years would profoundly impact the problem of storing SNF that confronts the expansion of nuclear power. Interest in this aspect of closing the nuclear fuel cycle, for the purpose of reducing high level radioactive waste (HLW) storage requirements and proliferation risk, increased significantly during the 1990s [1–4], giving rise to the concept of 'transmutation', or 'advanced burner', reactors fueled with the transuranics (TRU) from SNF. Such reactors could greatly reduce the growing SNF stockpile, while producing power by fissioning the transuranics in SNF discharged from commercial nuclear reactors.

It was recognized in the 1990s studies [1–4] that sub-critical operation of fast reactors with an external neutron source would have some advantages (and may even be necessary) in achieving the 'deep burnup' of the TRU fuel necessary to truly reduce repository requirements. In particular, fissioning of the 'minor actinides' above plutonium might require sub-critical operation. Sub-critical operation may well also ameliorate some safety issues which would arise in reactors fueled purely or largely with TRU.

A number of design concepts were developed [1–4] in the 1990s for sub-critical fast reactors 'driven' by accelerator-spallation neutron sources [ADS]. More recently, a series of conceptual design, fuel cycle and dynamic safety studies of sub-critical fast reactors driven by tokamak D-T fusion neutron sources [FDS] of the ITER type were performed at Georgia Tech [5–25]. The most recent of these design concepts [23] was for a 3,000 MWth sodium cooled, TRU fueled, sub-critical advanced burner reactor (SABR). Because such a reactor concept is based on nuclear and reprocessing technology being developed in the DoE Nuclear Energy Program and because the neutron source is based on physics and technology that is the design basis for and that will be tested in ITER, such a SABR could potentially become operational within 25–30 years.

Since a sub-critical reactor with a fusion neutron source will be more complex and more expensive than a critical reactor, the compensating advantages of a sub-critical reactor must be compelling in order to justify its development and implementation. We believe they could be, and the work described herein is a first step towards evaluating and quantifying the potential technical advantages of sub-critical operation of ABRs with a tokamak fusion neutron source. This work [23] indicates that the variable strength fusion neutron source can provide more flexible fuel cycles with substantially fewer complex and expensive fuel reprocessing/refabricating/recycling steps than would be required with a critical reactor to obtain comparable fissioning of the TRU actinides in the SNF. This advantage results in part because subcritical operation relaxes the criticality constraint on fuel residence time imposed by critical operation. The substantially larger reactivity safety margin to prompt critical inherent to subcritical operation also allows the use of pure TRU fuel to achieve a larger net TRU burnup in a given fuel residence time without compromising safety.

Although there has been some evaluation of the technical pro's and con's of sub-critical versus critical reactors for accelerator-driven sub-critical reactors [1–4] in Europe, Russia and Japan, there has not yet been a systematic comparison of the fuel cycle and dynamic safety issues of the sub-critical, fusion-driven and critical advanced burner reactors (ABRs).

Georgia Tech Advanced Burner Reactor Studies

Subcritical Advanced Burner Reactor

A point design concept for a Subcritical Advanced Burner Reactor (SABR) that would be fueled with pure TRU fuel to maximize net TRU burnup and that would operate far subcritical with a variable neutron source to achieve deep TRU burnup has been developed. SABR is a loop type sodium-cooled fast reactor fueled with transuranics (TRUs) cast into a TRU-Zr metal fuel pin. The annular SABR core is adapted from previous ANL fast reactor designs and consists of four concentric rings made up of 918 hexagonal fuel assemblies. Each assembly is 15.5 cm across flats and contains 271 wire-wrapped fuel pins of radius 3.63 mm clad in ODS steel. The "fresh" TRU fuel is the 40Zr-10Am-10Np-40Pu being developed at ANL (Argonne National Laboratory). The initial loading is 36 MT, which achieves $k_{\mathrm{eff}} \approx 0.95$ for all fresh TRU fuel. The 4-ring annular core wraps around a tokamak D-T fusion neutron source with an inner core radius of 5.0 m, a thickness of 0.62 m and an active fuel height of 2 m (plus a 1 m upper fission gas plenum). See Fig. 1.

The core produces 3,000 MWth, with a specific power of 83.3 kWth/kg TRU, an average power density of 72.5 MW/m^3 and an average fuel pin linear power of 6 kW/m, which is removed by sodium with mass flow rate 8,700 kg/s. The core operates with $k_{\mathrm{eff}} \leq 0.95$, driven by a variable strength neutron source capable of maintaining 3,000 MWth fission power output for k_{eff} down to about 0.62 to facilitate very deep fuel TRU burnup. The 'leaky' annular core configuration achieves a relatively small, but still positive, sodium voiding reactivity coefficient of $\rho = 2.1 \times 10^{-5}$/°K, and the presence of Zr in the fuel provides a small negative fuel Doppler coefficient of reactivity of $\rho = -2.2 \times 10^{-7}$/°K. Tritium self-sufficiency is obtained by a Li_4SiO_4 tritium

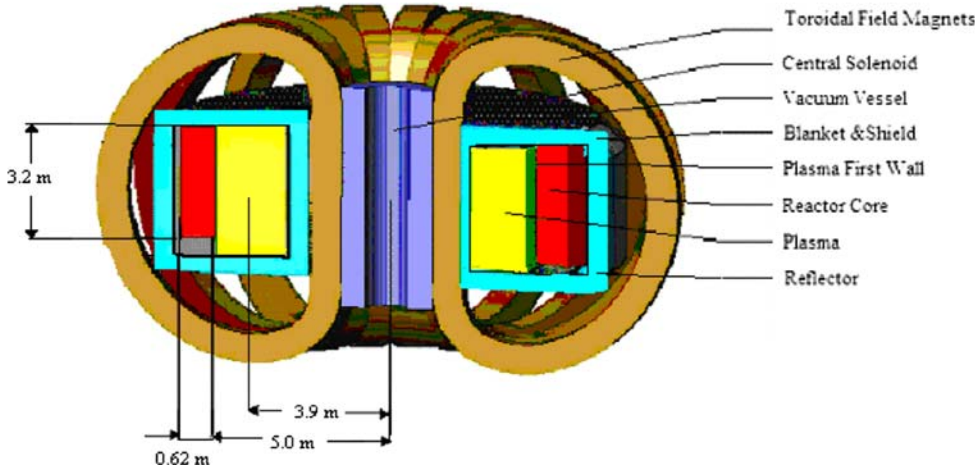

Fig. 1 Configuration of the SABR

breeding blanket surrounding the fission core and plasma chamber.

Tokamak Neutron Source Plasma Physics

Conservative ITER-like physics has been adopted for the design of the SABR tokamak neutron source. A reference normalized beta $\beta_N = 2.0\%$ was chosen, although operation at β_N values up to 2.5% could be justified on the basis of present experience. A confinement multiplier $H = 1.0$ relative to the IPB98(y,2) energy confinement scaling was adopted. The line average electron density was fixed at 75% of the Greenwald density limit to avoid confinement degradation at higher densities. An edge safety factor $q_{95} = 3$ was specified to avoid MHD kink instabilities.

Standard aspect ratio–current ($I_p - A$) analysis was employed to determine the major design parameters of the neutron source. In this approach, the major geometric and operational parameters are expressed in terms of the aspect ratio A and plasma current I_p, taking into account the various physics and engineering constraints as well as the radial build constraint.

The requirements on β_N and confinement are within the range routinely achieved in present experiments, and the requirements on β_N, confinement, energy amplification $\mathrm{Q_p}$, and fusion power level are at or below the ITER level. The requirement on the current-drive efficiency, after calculation of bootstrap current fraction using ITER scaling, is only somewhat beyond what has been achieved to date ($\gamma_\mathrm{CD} = 0.45$ in JET and 0.35 in JT60-U). The ongoing worldwide tokamak program is addressing the current-drive/bootstrap current/steady-state physics issue. The current-drive efficiency/bootstrap fraction needed for SABR is certainly within the range envisioned for Advanced Tokamak operation and may be achieved in ITER.

The required fusion neutron source strength, measured in terms of the fusion power output, is related to the desired power output, $P_\mathrm{fission} = 3{,}000$ MWth, and the neutron multiplication constant, k_m, of the fission reactor by $P_\mathrm{fusion} \approx \frac{E_\mathrm{fusion}}{E_\mathrm{fission}} v \cdot \frac{(1-k_m)}{k_m} P_\mathrm{fission}$, where $v \approx 2.8$ is the number of neutrons per fission and the E_x are the energy released per fission ($\approx$195 MeV) or fusion (17.6 MeV). The SABR neutron source was designed to produce $P_\mathrm{fusion} \approx 500$ MWth, which would allow operation of SABR at $P_\mathrm{fission} = 3{,}000$ MWth for $k_m > 0.62$. As discussed below, the actual operational requirements are only for $P_\mathrm{fusion} < 250$ MWth.

There is of course a broad range of values for these various parameters over which the design objectives can be met, as depicted in the operating space plots of Figs. 2 and 3 for the SABR design.

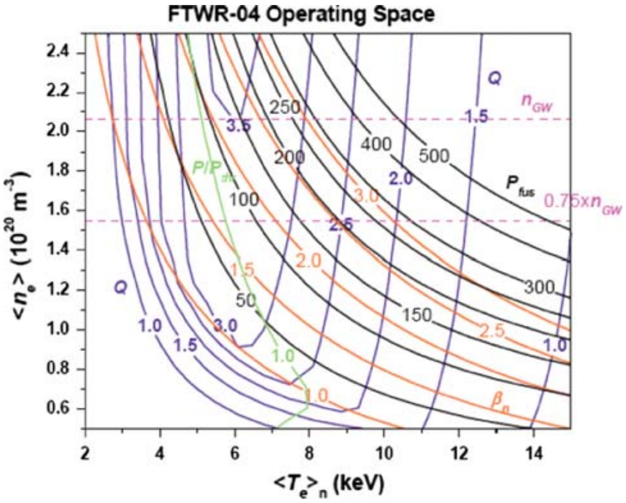

Fig. 2 Operating space of the SABR at 7.2 MA

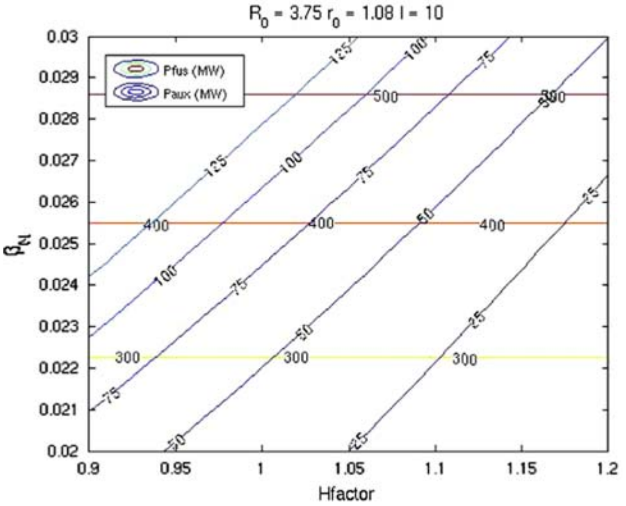

Fig. 3 Operating space of SABR at 10 MA. (Horizontal lines indicate $\mathrm{P_{fus}}$; slanted lines $\mathrm{P_{aux}}$)

Neutron Source Technology for SABR

The ITER lower single null divertor (not shown in Fig. 1) and first wall were adapted for sodium coolant by scaling down to the SABR dimensions with the same coolant channels.

The ITER heating and current drive system was adapted to provide 100 MW of heating and to drive 7.5 MA of plasma current. Lower Hybrid (LH) was chosen as the reference system because of the superior current drive efficiency and the very constrained access requirements.

The TF and CS superconducting magnet systems for SABR were directly adapted from the ITER cable-in-conduit $\mathrm{Nb_3Sn}$ conductor surrounded by an Incoloy 908 jacket and cooled by a central channel carrying super-cooled helium, with maximum fields of 11.8 and 13.5 T, respectively. The dimensions of the CS coil were constrained by the requirement to provide inductive startup and to not exceed a maximum stress of 430 MPa set by matching ITER standards and Incoloy properties. The dimensions of the 16 TF coils were set by conserving tensile stress calculated as for ITER, taking advantage of an Incoloy 908 jacket for support.

Fuel Cycle Analysis for Subcritical SABR

An initial set of fuel cycle analyses for SABR have been carried out [24]. A 4-batch fuel cycle was used in which the fuel resides for one burn cycle (of 750 days) in each of the four annular rings of the core, for a total fuel residence time (equal to 4 burn cycle times) of 3,000 days, limited by the radiation damage to the ODS steel clad and fuel assembly structure corresponding to 200 dpa. A "once-through" fuel cycle (in which "fresh" TRU fuel from SNF is loaded into one of the four rings at the beginning of each burn cycle and fuel which has been in residence for 4 burn cycles is removed and sent to a high level waste repository [HLWR]) achieves about 23% burnup (about 8.3 MT of TRU) before the clad acquires 200 dpa and must be removed.

A maximum $k_{\text{eff}} = 0.95$ occurs at beginning of life with 36 MT fresh TRU fuel in all assemblies ($k_{\text{eff}} \approx k_m$ for these conditions). Once such a fuel cycle reaches equilibrium, the values of k_{eff} at beginning and end of cycle (BOC and EOC) are about 0.90 and 0.85, which requires corresponding neutron source strengths in terms of P_{fusion} of about 180 and 240 MW, respectively, to maintain 3,000 MWth fission power. The integral decay heat of the discharged fuel over 10^6 years is only reduced by a factor of about 2 (relative to the SNF discharged from LWRs) by such a "once-through" fuel cycle, implying a factor of 2 reduction in repository requirements. This fuel cycle provides a baseline of what can be accomplished without further reprocessing and recycling of the TRU fuel.

When the same 4-batch, 3,000 day residence time fuel cycle is used but the fuel removed after four burn cycles is reprocessed and the TRU is recycled (together with "fresh" TRU from SNF), only the fission products and a small fraction of the actinides (0.15% Pu and Np, 0.03% Am) are sent to the high-level waste repository (HLWR) after each reprocessing step. For such a "reprocessing" fuel cycle, the values of k_{eff} and P_{fusion} at BOC and EOC are about the same and the TRU burnup rates are slightly larger than given above. The integral decay heat of material placed in a HLWR in such a reprocessing transmutation fuel cycle would be reduced to less than 1% of the integral decay heat of the original SNF; i.e. the repository requirement is reduced by a factor of more than 100. SABR operating with 80% availability could support (i.e. burn the TRU in the annual discharged SNF of) four 1,000 MWe LWRs.

If the 200 dpa radiation damage limit on fuel residence time could be relaxed, then greater TRU burnup could be achieved in a single residence time. A "once-though" fuel cycle as described in the first paragraph, but now with four 3,000 day burn cycles and a fuel residence time of 12,000 days (24.65 years) was found to burn 91.2% of the TRU fuel. Once such a fuel cycle reaches equilibrium, the values of k_{eff} at BOC and EOC are about 0.68 and 0.48, which require corresponding neutron source strengths in terms of P_{fusion} of about 433 and 663 MW, respectively, to maintain 3,000 MWth fission power. It is feasible to modify the SABR neutron source to produce more than the present $P_{\text{fusion}} = 500$ MW design limit. However, the integral decay heat of the remaining 8.8% of the TRU and the fission products (hence the HLWR requirement) is only reduced by a factor of about 3 relative to SNF discharged from LWRs, and the power was so strongly peaked near the neutron source in such a far subcritical reactor as to make the practical design of a reactor with such a fuel cycle unlikely. Thus, the 3,000 day, 4-batch, recycling fuel cycle of the previous paragraph is the reference fuel cycle for SABR.

Dynamical Safety Analysis of Subcritical SABR

An Advanced Burner Reactor fueled with pure TRU (in order to maximize net TRU burnup) presents some safety issues relative to a similar reactor fueled with uranium. The delayed neutron fraction β is smaller for TRU than for U-235, meaning that the reactivity margin to prompt critical is smaller for TRU fueled reactors. The absence of U-238 in pure TRU fuel removes the large negative fuel Doppler reactivity coefficient which limits inadvertent power excursions. Operating subcritical by an amount ρ increases the reactivity margin to prompt critical from β to $\rho + \beta \gg \beta$ for SABR, compensating at least in part for the compromise of safety with pure TRU fuel relative to uranium fuel.

However, the dynamics of a subcritical reactor will differ from that of a critical reactor in several ways; e.g. there does not seem to be an inherent feedback mechanism that would shut off the neutron source if a fission power excursion started, and control rod insertion would lead to a lower power operation of the fission reactor, but not to complete shutdown, if the neutron source remained on. On the other hand, turning off the neutron source is a very effective way to rapidly shut down a subcritical reactor.

An initial model of the coupled dynamics of the fusion neutron source, the fission core, and the heat removal system has been implemented, and some initial simulations of reactor shutdown and of accidents in SABR have been simulated to determine how much time is available to detect an accident and shut down the neutron source before damage would occur [25] (e.g. fuel melt, sodium boil). Turning off the auxiliary heating power to the fusion neutron source was found to shut down the fission reactor within a few plasma energy confinement times, which is about a second. There are inherent "soft" plasma pressure and density limits that will inhibit any inadvertent plasma power excursion (hence neutron source excursion) by spoiling the plasma confinement and thus reducing the plasma power (hence neutron source).

Simulation of neutron source excursions due to inadvertent increases in plasma heating or fueling indicated that the inherent plasma pressure limit would limit fission power excursions before fuel damage occurred. Simulation of accidental control rod ejection (+9\$) in the most reactive condition resulted only in an increase in fission power to a new equilibrium, with core temperatures remaining below levels at which damage would occur. Simulation of LOFAs (loss of flow accidents) indicate that a flow reduction of about 50% can be tolerated in SABR without turning off the neutron source, and that even with an unrealistic 100% loss of flow in the core there is about 24 s to shut off the neutron source before fuel failure occurs. Simulation of LOHSAs (loss of heat sink accidents) indicate that up to about 33% loss of sodium heat transfer to the heat exchanger can be tolerated before boiling occurs and that even then about a minute is available to detect this accident and turn off the neutron source; as long as heat transfer to the heat exchanger remains above 30% of nominal the decay heat can be removed without damage to the fuel. In a LOPA (loss of power accident), the neutron source would be shut down with a loss of power, and the only concern in a subcritical system would be the decay heat.

Implications of Closing the Nuclear Fuel Cycle for Fusion Development Policy

It is clear that closing the nuclear fuel cycle is necessary for the expansion and future of nuclear power. There are two aspect to closing the nuclear fuel cycle: (1) disposal of the SNF annually discharged from conventional nuclear power reactors and (2) recovery of a larger fraction of the potential energy content of the uranium fuel resource. To bury in high-level waste repositories (HLWRs) which must be secured for millennia the SNF discharged from the present fleet of 100 nuclear power reactors operating on the "once-through" fuel cycle in the USA alone would require opening a new Yucca Mountain type facility every 30 years, and the anticipated expansion of nuclear power would require even more HLWRs. The present "once-through" fuel cycle for conventional nuclear power reactors in the USA utilizes <1% of the potential energy content of the uranium fuel and is not sustainable beyond the present century.

Transmutation reactors (critical or sub-critical) and the supporting actinide separation and fuel reprocessing technologies would address the spent fuel disposal aspect of closing the nuclear fuel cycle by providing the capability to reduce the required millennial storage HLWR capacity by a factor of 10–100 by transmuting (fissioning) the long half-life TRU into fission products with half-lives of only hundreds of years. With critical transmutation reactors, the fuel reprocessing step would be the most complex and difficult part of this solution. The work discussed above indicates that sub-critical operation of the transmutation reactors with a variable strength tokamak fusion neutron source is technically feasible and could significantly reduce the number of these complex and expensive fuel reprocessing steps by extending the fuel residence time in the transmutation reactors (hence the TRU burnup) from the limit imposed by remaining critical (several percent TRU burnup) to the limit set by materials damage ($\approx$25% for a 200 dpa damage limit). On the other hand, putting a tokamak fusion neutron source in the middle of a transmutation reactor greatly complicates the transmutation reactor, and certainly would make it more expensive. Evaluation of the tradeoff between the advantage of fewer fuel reprocessing steps and a more complex transmutation reactor requires detailed technical analysis.

Breeder reactors (critical or sub-critical) and the supporting actinide/uranium separation and fuel reprocessing technologies would address the second aspect of closing the nuclear fuel cycle, utilizing a larger fraction of the potential energy content of uranium, by providing the capability to transmute (neutron capture) the non-fissionable (in conventional 'thermal' reactors) 99+% of uranium that is U238 into fissionable Pu239 that could be used to fuel conventional reactors. These breeder reactors could also double as transmutation reactors by using the TRU in SNF discharged from conventional reactors as fuel. Sub-critical operation of such breeder/transmutation reactors with a tokamak fusion neutron source would also seem to offer similar safety and fuel cycle advantages to those discussed above, but the same type of analysis summarized above for transmutation reactors has not been performed for such breeder/transmutation reactors.

The implications of the above results for fusion development policy, if they hold up under more extensive and detailed analysis, is that a D-T fusion tokamak neutron source for a SABR transmutation reactor, built on the basis of the ITER operating experience, could possibly be a logical next step after ITER on the path to fusion electrical power reactors. At the same time, such an application would allow fusion to contribute to meeting the nation's energy needs at an earlier stage by helping to close the fission reactor nuclear fuel cycle. The additional fusion R&D that would be needed for such a neutron source would be virtually the same as would be needed for a tokamak DEMO, except that there would be more emphasis on the achievement of high availability (e.g. on quasi-steady-state plasma operation, component and systems reliability, etc.) and less emphasis on achieving improved plasma parameters (e.g. confinement, Q_p, β_N).

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