The SABR TRU-Zr Fuel, Modular Sodium-Pool Transmutation Reactor Concept

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Abstract. The updated Georgia Tech design of the SABR fusion-fission hybrid spent nuclear fuel transmutation reactor and supporting analyses are summarized. SABR is based on tokamak fusion physics and technology that will be prototyped in ITER and the fast reactor physics and technology proposed for the Integral Fast Reactor and the PRISM Reactor, which has been prototyped in EBR-II. Introduction of SABRs in a 1-to-3 power ratio with LWRs would reduce the spent nuclear fuel HLWR capacity requirement by a factor of 10 to 100.

I. INTRODUCTION

The fusion group at Georgia Tech has worked (over the past two decades) to identify a practical, near-term application of a D-T fusion neutron source based on the fusion plasma physics and technology that will be demonstrated by the operation of ITER[1]. A D-T plasma producing the ITER design objective 500 MWth of fusion power will produce $S_{fus}^{500} = 2.1x10^{20} n/s$ 14 Mev neutron/s. If this fusion neutron source is surrounded by fissionable material in an assembly with multiplication constant k the total neutron transmutation (fission) rate will be[2] $TR_{fis} = kS_{fus}/(1-k)$ fis/s, provided $k<1$. Thus, a constant transmutation (power production) rate can be maintained as k varies with fuel burnup by varying the fusion source level. The characteristics and performance capability of nuclear facilities driven by a tokamak fusion neutron source operating with essentially ITER-level physics and technology (but improved availability) have been characterized[2-6] and design concepts have been developed for different nuclear applications (transmutation of weapons-grade plutonium[7], tritium production[8], transmutation of transuranics (TRU) in spent nuclear fuel[9-18] and breeding of fissile material[19]) operating with such tokamak D-T fusion neutron sources. The fuel cycle performance[20-27] and dynamic safety[28] of the fission-fusion hybrid TRU transmutation reactors have been investigated, and the work has been summarized in Refs 29-31.

It would appear that the transmutation (destruction by fission) of TRU in spent nuclear fuel provides the most promising opportunity for fusion to contribute to nuclear energy in the first half of the present century. The realization that we must decrease burning of fossil fuels[32] is becoming widely accepted, and the dream of large-scale replacement of fossil fuel power with reliable baseline solar and wind power is slowly being confronted by the reality that these sources are environmentally problematical in other ways and inherently intermittent in nature, with only niche practical applications[32]. This leaves nuclear power as the only available option for displacing fossil fuel produced electricity on a large scale in the first half of this century[32].

However, nuclear power has an unresolved problem that fusion can help solve—the disposal of spent nuclear fuel containing radioactive TRU 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 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 in fast reactors, and use them as TRU fuel in special purpose "fast burner" or "transmutation" reactors, thus destroying the long half-life radioactive material, while extracting additional energy from the uranium fuel resource.

There are technical reasons why such transmutation reactors would work better if operated subcritical with a neutron source rather than operated critical. (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 $(\beta \approx 0.002)$ than for uranium $(\beta \approx 0.006)$, 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 $(\delta k_{sub} \approx 0.003)$ 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.

II. THE SABR TRU TRANSMUTATION REACTOR DESIGN CONCEPT

There has been a substantial technical investigation[9-12,16-18,20,22-31] of fission-fusion transmutation reactors based on tokamak and sodium-cooled/metal-fuel fast reactor technologies. The reason that these technologies were chosen is that they are the most highly developed fusion and fission transmutation-applicable 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)[16,18] is based on ITER[1] fusion technology and physics, so in a sense ITER will be the prototype for the fusion neutron source for SABR. The fission reactor physics and technology for SABR is based on the Integral Fast Reactor (IFR)[33,34] and the GE PRISM[35] designs, so the successful operation of EBR-II and its associated pyro-processing system[34,36] were the prototype for the fission system.

It has been calculated that the ITER[1] 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 to maintain a 3000 MWth annular fast burner reactor surrounding the plasma[4,16] over an operating period of 2800 full power days in a 4-batch fuel cycle that would accumulate 200 dpa in the discharged fuel cladding, the design limit on the ODS steel fuel cladding. The SABR fusion neutron source is described in Fig.1 and Table 1.

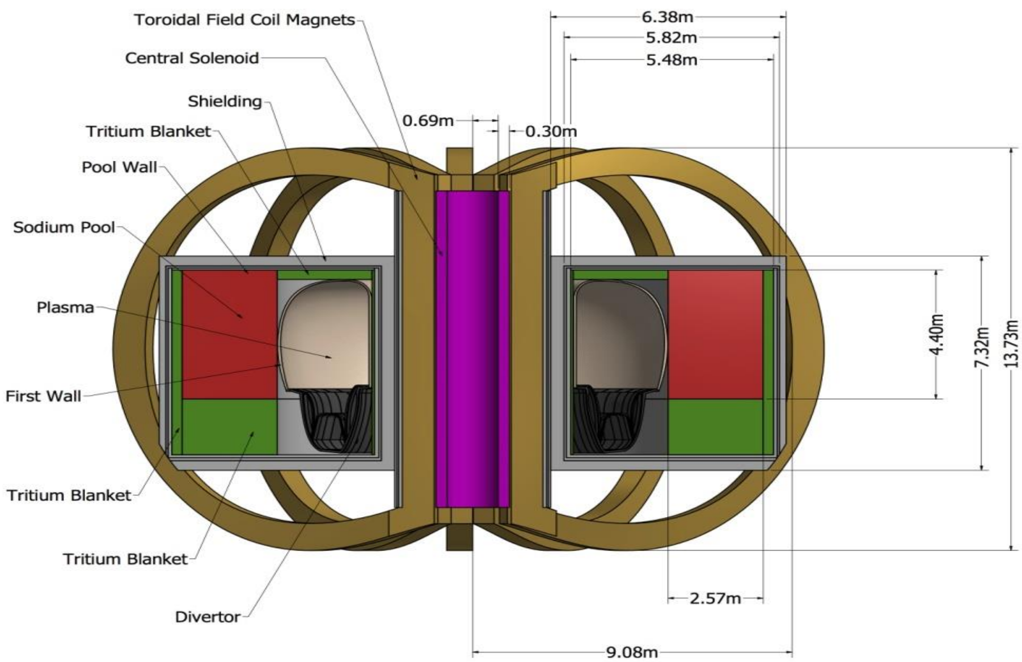


Figure 1 SABR configuration

Table 1 SABR plasma physic parameters

Plasma	
Major radius	4.0m
Plasma radius	1.2m
Elongation	1.5
Toroidal magnetic field (on axis)	5.6T
Plasma current	10 MA
Inductive current startup	6.0 MA
Non-inductive current drive	4.5 MA
Bootstrap current fraction	0.55
Heating & current-drive power	110 MW (70 EC, 40LH)
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 MW and 233 MW
Max. fusion neutron source strength	$1.8x10^{20}$n/s
Fusion gain ($Q_p=P_{fusion}/P_{extheat}$)	4.6

The ITER magnetic, first-wall and divertor systems (the latter two converted to Na coolant) were used with minimal alteration, and the heating-current drive system was adapted from that of ITER

The TRU-Zr fuel is clad with ODS steel in 0.54 cm OD fuel pins, 469 of which are contained in each of the 80 fuel assemblies, 13.9 cm across flats, in each of the 10 Na-pools. Each pool also contains an intermediate heat exchanger, as depicted in Fig. 2. A 3 mm thick SiC flow channel insert is placed within each assembly to prevent current loops connecting through the duct wall, which would increase the MHD pressure drop.

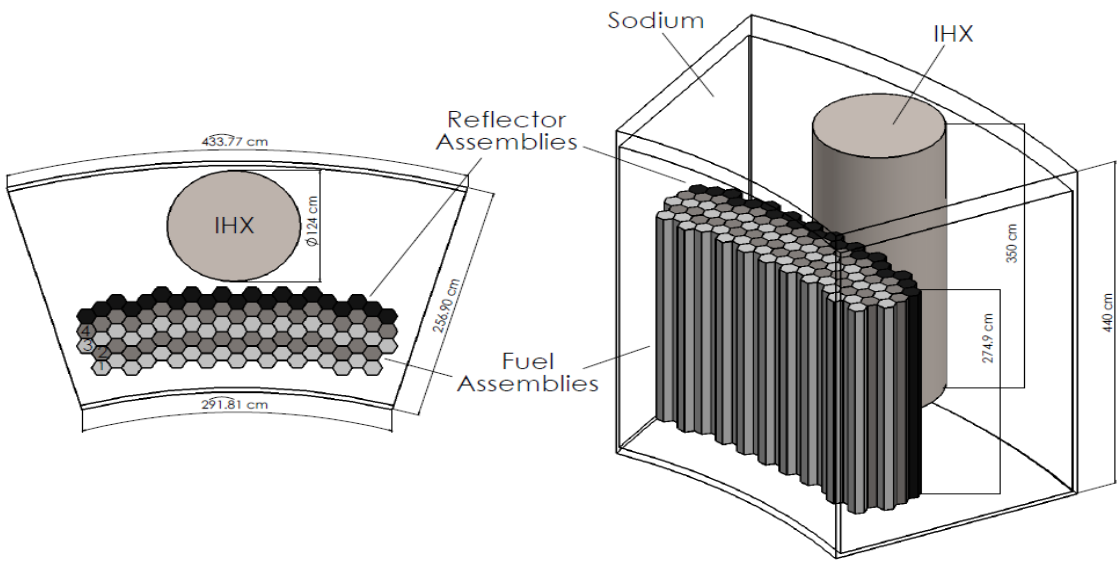


Figure 2. SABR modular sodium pool with reactor and intermediate heat exchanger.

The fuel pin design is depicted in Fig. 3. The pin is about 2 m in height, with the TRU fuel in the lower third and a fission gas plenum in the upper two-thirds.

The fuel assembly consists of 469 of these pins, arranged as indicated in Fig. 4. Note the SiC liner separating the fuels pins and sodium within the assembly from ODS steel duct in order to prevent current loops that would cause MHD pressure drops.

Fuel assembly calculations were made in 1968 groups P_1 transport theory to homogenize the fuel assemblies for a 2D, S_8, 33-group ERANOS neutronics calculation, and RELAP-5 thermal-hydraulic calculations were made to obtain the parameters given in Table 2.

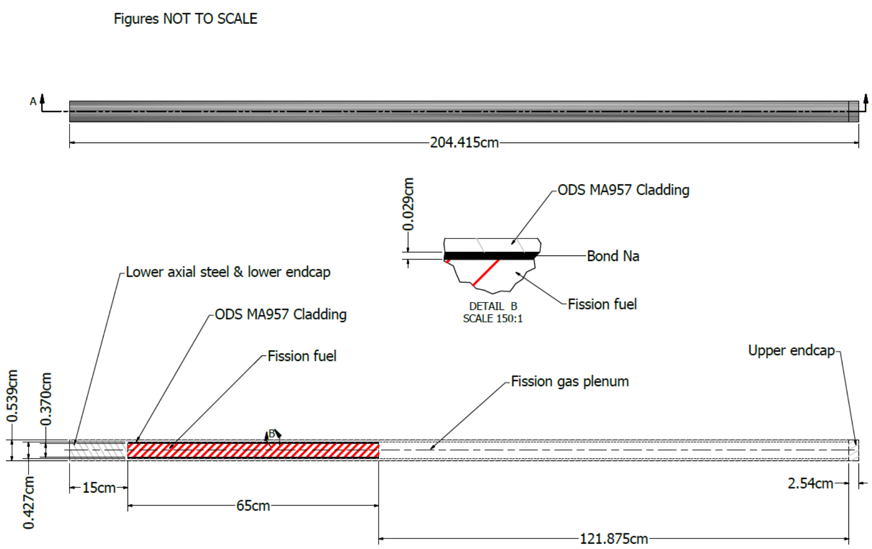


Figure 3. TRU fuel pin configuration.

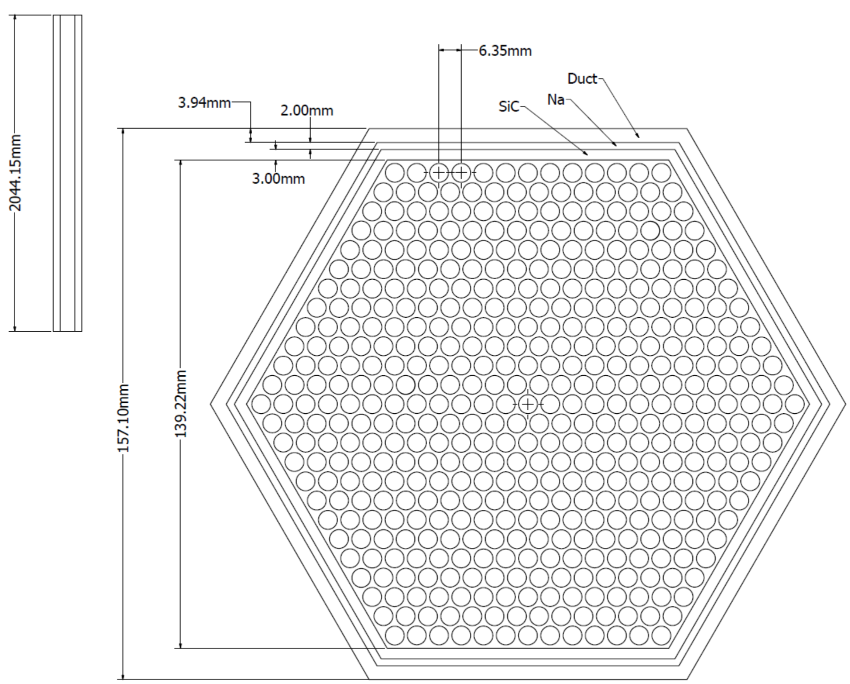


Figure 4. TRU fuel assembly configuration.

Refueling (removal and replacement) of the fuel assemblies located within the TF coil configuration is a challenging design issue that was addressed as illustrated in Fig. 5. Transport casks for removal of an individual Na pool to a hot bay are located between TF coils on the outboard at the locations of pools 1 and 6 in Fig. 5. The pools in these locations are removed radially, first, then the other pools are individually rotated to a port and removed. The secondary coolant system must be disconnected for the individual pool during its removal. The thermal capacity of the pool must absorb the decay heat during the removal to prevent clad damage, which places an upper limit on the allowed decay heating for a given decay heat fraction. We estimate the procedure will work for 1 h removal time and decay heat equal 1% of operating power, which it will reach about 3 h after shutdown.

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 MWth
Power Peaking	1.27
Mass flow rate per pool	1669 kg/s
Number of pumps per pool	2
Pumping power per pool (EM pumps)	20 MW
Core Inlet/Outlet temperatures	628 K/769 K
Fuel Max Temp/Max Allowable Temp	1014 K/1200 K
Clab Max Temp/Max Allowable Temp	814 K/973 K
Coolant Max Temp/Max Allowable Temp	787 K/1156K

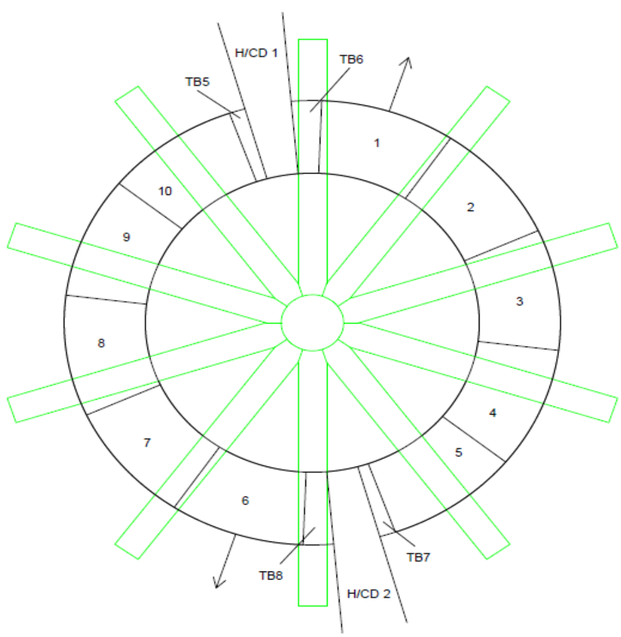


Figure 5. Removal of Na-pools from modular pool configuration.

III.   FUEL CYCLE

Several fuel cycles based on pyroprocessing the fuel removed from SABR to separate the remaining transuranics in aggregate from the fission products and recycling of the TRU have been investigated[22-27]. The maximum fuel residence time in the reactor is limited to 700 days by the 200 dpa radiation damage limit on the fuel cladding. A 4-batch fuel cycle is indicated in Fig. 6. The maximum effective multiplication constant was $k_{eff}^{BOL} \leq 0.97$ at BOL and the maximum fusion power required to maintain the 3000MWth fission rate was < 500 MW.

A SABR, based on the sodium cooled, metal fuel technology developed at ANL[33,34] and proposed in the ANL IFR[35] and the GE PRISM reactor[36], operating at 75% availability with a 4-batch out-to-in fuel cycle (with total fuel residence time limited by 200 dpa radiation damage in the clad) could destroy annually all the transuranics produced annually by three 3000MWth LWRs[22,23,25]. 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 in which the LWRs are phased out in favor of critical 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 3000MWth SABR could destroy annually all the minor actinides produced annually in 25 3000MWth LWRs. 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 than for the direct burial of LWR spent fuel.

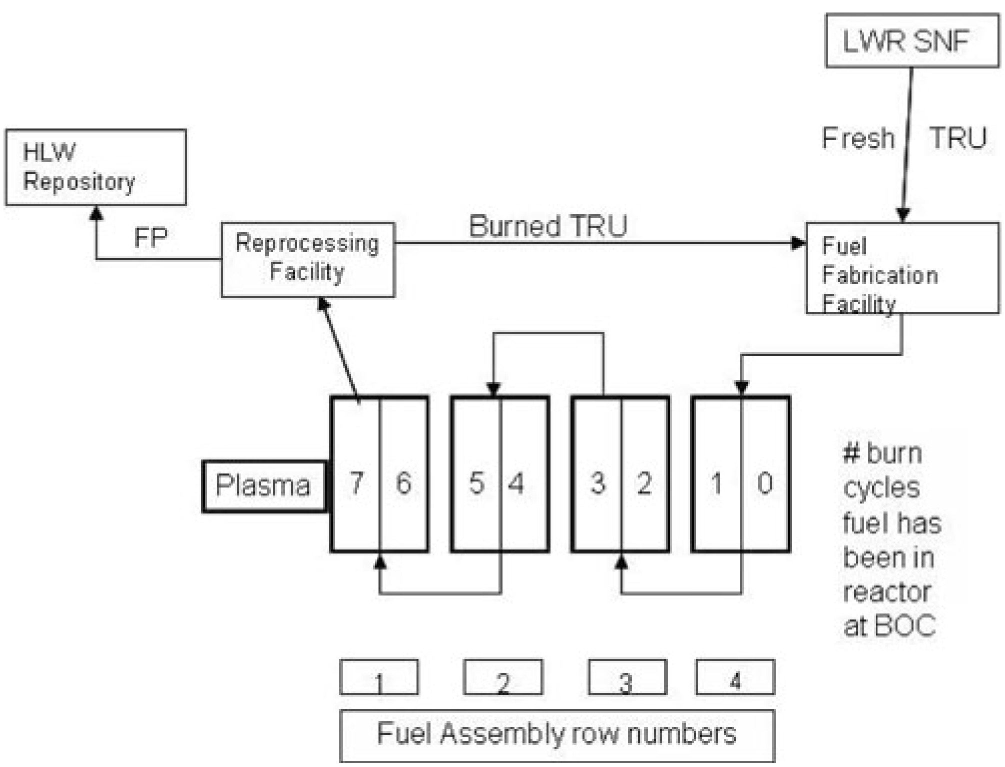


Figure 6 The SABR 4-batch out-to-in fuel cycle.

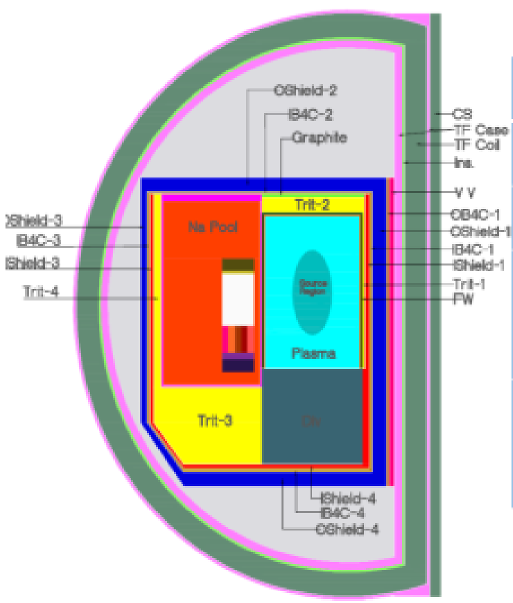
IV. TRITIUM SELF-SUFFICIENCY

Modular sodium-cooled Li_4SiO_4 blankets are located i) above the plasma, ii) below the sodium pools, iii) outboard of the sodium pools and iv) in two locations 180 ^{o} apart in the ring of sodium pools shown in Fig. 3 (TB5, TB6, TB7, TB8). This tritium must migrate through the blanket to helium purge channels, which requires a blanket temperature in the range 325 C < T < 925 C. Thermal-hydraulics calculations indicate that the nuclear heating can readily be removed to maintain temperatures in the blanket within this temperature window. Neutron transport calculations (R-Z, S_8, 33-grp) indicate that this configuration produces an average TBR = 1.12. A time-dependent calculation of the tritium inventory in the Li_4SiO_4 blankets, the tritium processing system, the tritium storage system and plasma demonstrated tritium self-sufficiency for an operational cycle based on one year of burn at 75% availability, followed by 90 days of downtime for the refueling operation. SABR consumes about 15 kg/yr of tritium.

V. SHIELDING

The SABR shield design is indicated in Fig. 7. A 2D, R-Z MCNP-B Monte Carlo calculation confirmed that this shield design reduced the radiation damage to the TF Coils below the design limits shown in Table 3 for a 40 yr operational lifetime at 75% availability.

SHIELDING (SABR MEETS 30FPY DESIGN OBJECTIVE)



Radiation Limit	Value	Units
Insulation Dosage	1 x 10^9	rads
Nuclear Heating Rate	1.0 – 5.0	mW/cc
Neutron fluence (>0.1MeV)	1.0 x 10^{19}	n/cm^2
Copper Stabilizer Resistivity	1.2	nΩm

Figure 7: SABR Shield Design Table 3: SABR Shield Design Limits to TF Coils

VI. ONGOING DYNAMIC SAFETY ANALYSIS

A. Feedback Control of Plasma Power Excursions

The SABR must be designed to prevent or suppress any dynamic power surges that may inadvertently occur in the plasma neutron source or in the modular fission cores. The actions of various negative and positive reactivity feedback mechanisms for the fission cores are well-known, and in fact it was demonstrated in EBR-II that metal-fuel, sodium pool technology could be designed to be inherently safe (i.e. negative feedback mechanisms shut the reactor down without damage when pumps in the sodium pool and in the external heat removal system were intentionally shut down to increase the fuel temperatures[33,37,38]).

Earlier work[28] examined the transient response to loss-of-flow, loss-of-heat-sink and loss-of-power events in a single 3000MWth SABR core with a sodium-loop cooling system. The earlier loop-type cooling system has now been replaced by a modular sodium pool design with the intention of capturing the inherent safety features demonstrated by such a system. We are constructing a coupled-core, or nodal, neutron and coolant dynamics model of the 10 fission cores, the fusion neutron source and the associated heat removal systems in order to investigate whether these inherent safety features[33,37,38] can be retained by the SABR modular core design and to investigate if the modular fission core configuration might be subject to spatial power oscillations.

Power excursions in the plasma neutron source, due either to instabilities within the plasma or to the inadvertent turn-on of a modular plasma heating unit or pellet fueling unit or the inadvertent opening of a gas fueling valve, etc. are a concern because they would produce power excursions in the fission cores. We have recently begun an investigation of burn control mechanisms that could limit unanticipated D-T plasma power excursions. We are motivated by the observation that the edge plasma parameters have a strong impact on the core plasma parameters to search for possible burn control mechanisms in the plasma edge. Experimental and theoretical observations encourage us that it may be possible to use fueling of deuterium or a seeded impurity gas in such a way that the plasma would respond to an increase in edge temperature by momentarily dropping into the L-mode confinement regime and thereby to terminate or at least limit any plasma power excursion.

We are presently assembling a dynamic plasma-impurities-neutrals edge transport code coupled to a global plasma dynamics code, a wall recycling model and a 2-pt divertor model for the purpose of investigating the ability of modulated gas puffing (D) or impurity seeding (Ne, Ar, Xe) to create edge conditions in which an increase in edge temperature causes a momentary H-L transition to suppress the power excursion. For example, impurities seeded into a plasma edge that was somewhat cooler than the temperature for which the impurity radiation is maximum would respond to an increase in temperature with an increase in radiative power, hence a decrease in non-radiative power across the separatrix below the threshold $P_{\min}^{H-L}$, causing the plasma to drop momentarily into L-mode in response to a positive edge temperature excursion and thus serving as a burn control mechanism. Another possibility that will be investigated is that an increase in edge temperature would produce an increase in ion orbit loss of energy that would terminate a power excursion.

B. Nodal Neutron Dynamics Model

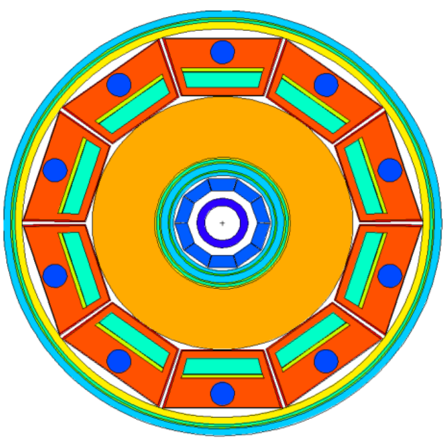
We are developing a coupled nodal neutron dynamics model for the neutron population in the different sodium pools. A node is defined as all of the fuel assemblies and reflector assemblies in a given sodium pool. These nodal kinetics equations will be used to calculate the time-dependent power in each separate core during various accident scenarios such as Loss of Flow Accidents (LOFA) and Loss of Heat

Sink Accidents (LOHSA). The neutron dynamics equations for the neutron density n_j and for the delayed neutron precursor density in group i in each node j, $c_{i,j}$ are

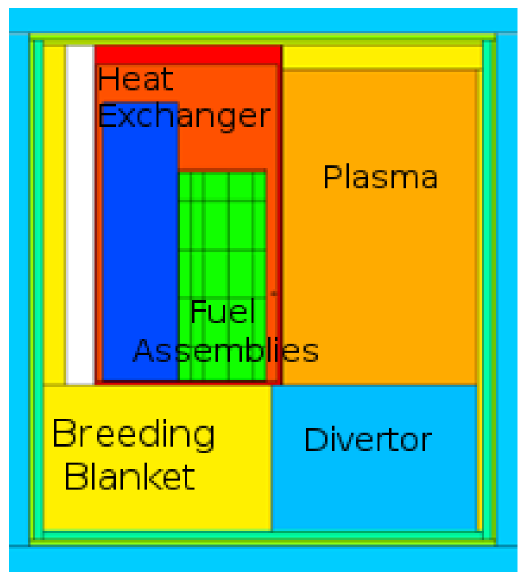
$$\frac{dn_j(t)}{dt} = \frac{(1-\beta_j)}{\Lambda_j} n_j(t) + \sum_{i=1}^{6} \lambda_{i,j} c_{i,j(t)} + \frac{n_j(t)}{\tau_j} + \mathrm{S_{fus,j}} + \sum_{k=1}^{10} \frac{\alpha_{k,j} n_k(t)}{l_{e,k}} - \frac{n_j(t)}{l_{e,j}} - \frac{n_j(t)}{l_{a,j}}$$

$$\frac{dc_{i,j}}{dt} = \frac{\beta_{i,j}}{\Lambda_j} n_j(t) - \lambda_{i,j} c_{i,j}$$

Λ is the fission generation time, τ is the n-2n generation time, l_a is the absorption lifetime, l_e is the escape lifetime, $S_{fus,j}$ is the rate at which fusion neutrons from the plasma enter node j, and $\alpha_{k,j}$ is the nodal coupling coefficient (i.e. the probability that a neutron leaking from node k will enter node j before entering another node). These kinetics terms are calculated using MCNP6[39] in a 3D geometry shown in Fig.8. We also include in the model a calculation of how these kinetics parameters change during various perturbations such as fuel Doppler broadening, sodium voiding, fuel rod axial expansion, core grid plate expansion, and fuel bowing.



Top down view sodium pools in MCNP model



Side view of sodium pools in MCNP model

Figure 8 3D Geometry of Nodal Neutron Dynamics Model

The power is calculated in MATLAB by numerically solving the kinetics equations. This MATLAB model is coupled to COMSOL Multiphysics[40] which in turn solves all of the thermal and fluid calculations required for each accident scenario. For each of the 10 nodes, there is one neutron density equation and 6 precursor equations.

IV. ECONOMICS

Over the past two years, the SABR research group has collaborated with Georgia Tech's Scheller College of Business and the law school at Emory University to investigate the economic viability of the SABR concept and explore potential commercialization strategies[41].

This investigation initially focused on the United States as a target market for SABR, however the team later expanded to consider other markets (countries) around the world. The primary attributes for any suitable SABR market are: (1) a dependency on nuclear energy generation; (2) the existence of a "commercial" reprocessing program; (3) a favorable regulatory environment and public opinion; and (4) status as an ITER Party. Reprocessing, which is a method that separates the transuranic waste components of spent nuclear fuel, is a critical technology for any suitable SABR market.

There are significant challenges in assessing the economic viability of a potential SABR implementation, not the least of which is the significant amount of uncertainty in the construction cost of a SABR. The determination of whether a SABR scenario could be economically viable vis-à-vis direct burial of SNF in HLWRs cannot be based on a simple cost comparison because, unlike geological repositories, SABRs would produce electricity, change the number of traditional nuclear reactors in operation, and even affect the cost of fuel for those traditional nuclear reactors.

To reduce these complex considerations to a single number, the energy industry uses the Levelized Cost of Electricity (LCOE). The LCOE can be thought of as the current price of electricity per kilowatt-hour from a power plant which, when adjusted for inflation throughout the lifetime of the plant, would result in the plant meeting all debt obligations incurred in constructing the plant and providing a reasonable return to equity investors. Calculations of the LCOE for nuclear power, such as that done by MIT in the 2003 report "The Future of Nuclear Power", typically stop short of accounting for the true societal cost of the SNF. Instead, they use the waste fee that nuclear plants are required to pay to the federal government. The team modified the calculation to compute a true, post-waste LCOE, which is better suited to evaluating the effects of a SABR program on the complex nuclear industry.

It is not feasible at this time to estimate the cost of a SABR and its prorated share of the associated fuel processing and re-fabrication facilities—a *SABR+* cost. Instead, we are taking the approach of determining a "break-even" *SABR+* cost with respect to direct burial of SNF in HLWRs. We will first determine the true LCOE of nuclear power with direct burial of SNF in HLWRs that can be secured indefinitely into the future. We will then determine the "break-even *SABR+"* cost for each SABR and its prorated share of the associated reprocessing and fuel fabrication facilities for which the electricity revenue and cost savings resulting from avoiding the construction of the majority of the repositories will result in a similar overall LCOE for nuclear energy, compared to the direct SNF burial in HLWRs (i.e. Yucca Mountains) scenario. A lower than "break-even" construction cost for a SABR and its prorated associated reprocessing and fuel re-fabrication facilities would result in a lower LCOE for nuclear power with SABRs than with HLWRs. If plutonium is separated during the reprocessing stage and used as fuel in critical fast reactors to produce additional electricity, the LCOE for the SABR scenario can be reduced; however this would mitigate the non-proliferation aspect of the reference SABR fuel cycle in which the transuranics and the plutonium are processed as an aggregate metal.

V. SUMMARY

- SABR FISSION PHYSICS & TECHNOLOGY HAS BEEN PROTOTYPED BY EBR-2.
- SABR FUSION PHYSICS & TECHNOLOGY WILL BE PROTOTYPED BY ITER.
- SABR USES THE ITER MAGNET SYSTEM AND THE ITER FIRST-WALL AND DIVERTOR SYSTEMS, THE LATTER MODIFIED FOR NA-COOLANT.

- MODULAR DESIGN ALLOWS REFUELING OF FISSION REACTOR LOCATED WITHIN MAGNET SYSTEM.
- SiC INSERTS IN FUEL ASSEMBLIES REDUCES MHD EFECTS OF NA FLOWING IN B-FIELD.
- SABR IS TRITIUM SELF-SUFFICIENT.
- SABR IS ADEQUATELY SHIELDED TO ACHIEVE 30 FPY.
- SABRS CAN REDUCE THE HLWR CAPACITY NEEDED FOR NUCLEAR POWER BY 10-100.
- 1 SABR CAN BURN THE ANNUAL TRU PRODUCTION OF 3, 1000MWE LWRS, OR THE ANNUAL MA PRODUCTION OF 25, 1000MWE LWRS.
- PASSIVE SAFETY POTENTIAL OF SABR FISSION & FUSION SYSTEMS IS BEING INVESTIGATED.
- THE BREAK-EVEN COST OF SABR + FUEL REPROCESSING/RE-FABRICATION FACILITIES IS BEING EVALUATED BY EQUATING THE *LCOEs* FOR NUCLEAR POWER WITH THE SABR BURN OPTION AND WITH THE DIRECT BURIAL OF SNF IN HLWRs.

APPENDIX: THE RATIONALE FOR A SUBCRITICAL ADVANCED BURNER REACTOR (SABR)

1. Nuclear power is the only technically credible option for carbon-free electric power on the scale needed to impact climate change for at least the first half of the present century.
2. The major technical problem now confronting the widespread expansion of nuclear power is disposal of the extremely long half-life transuranics (TRU) in spent nuclear fuel (SNF) in high-level radioactive waste repositories (HLWRs) that can be secured for 10^5-10^6 yrs .
3. TRU can be fissioned, much more readily in a fast than a thermal neutron spectrum reactor, to yield energy and short half-life fission products (FPs), most which only need to be stored in secured HLWRs for 10-100 years.
4. Reprocessing LWR SNF to separate TRU from the remaining U and FP for use as fuel in advanced fast burner reactors (ABRs) would reduce the required HLWR capacity for nuclear power to that needed to store the long-lived FPs and trace amounts of TRU due to inefficiencies in separation, at least by a factor of 10. (This means e. g. that the present level of nuclear power is the USA would require a new Yucca Mntn. every 300 years instead of every 30 years.)
5. Subcritical operation of ABRs with an external neutron source (e.g. SABR) would have certain advantages:
   a. The reactivity margin of error to a prompt critical power excursion in a critical reactor is the delayed neutron fraction β, which is about 0.002 for TRU, as compared to about 0.006 for U. Prudence would probably dictate that a critical ABR be only partially fueled with TRU (maybe 20%). In a SABR the reactivity margin of error to a prompt critical power excursion is Δk_{sub} > 0.03 >> β, so *a SABR could be fueled 100% with TRU.*
   b. Since the power level (fission transmutation rate) can be maintained constant as the fuel depletes in a SABR by increasing the neutron source *strength, the fuel can remain in the reactor until it reaches the radiation damage limit*, thereby minimizing the number of fuel reprocessing steps and the trace amount of TRU in with the FPs that go to the HLWR. On the other hand, in a critical reactor additional reactivity must be built into the fuel to offset the fuel depletion.
6. The fission physics and technology for a SABR based on: a) a pool-type Na-cooled, TRU-Zr metal fuel has been prototyped by the EBR-2 program in the USA; and b) a Na-cooled oxide fuel has been prototyped in many countries.

7. In the pyro-processing fuel cycle that would be used with the TRU-Zr fuel all the TRU (Pu, Np, Am, Te) is separated from the FPs as an aggregate metal—the Pu is never separated from the other TRU—which greatly reduces any proliferation risk.

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