VII. SABR DYNAMIC SAFETY ANALYSIS

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Abstract

A model was developed to simulate the coupled dynamics of a sub-critical fast reactor fueled with transuranics (TRU), a DT tokamak fusion neutron source and the heat removal and secondary systems. Several types of accident initiating events—inadvertent increases in the auxilliary power and fueling sources for the fusion neutron source, inadvertent control rod ejection from the reactor core, loss of flow (LOFA), and loss of heat sink (LOHSA)—were simulated in order to determine the time available to detect accident onset and take corrective action. A more detailed description is presented in Ref. 1.

A. SABR spent nuclear fuel transmutation reactor

SABR[2] is a TRU-metal-fueled, sodium cooled, subcritical fast transmutation reactor driven by a D-T fusion neutron source. Figure 1 shows a simplified three dimensional model of the reactor. An annular fission core contains metallic TRU fuel with initial weight percent composition of 40Zr-10Am-10Np-40Pu and maximum nominal operating temperature of 970 K. The core produces 3000MWth (83.3 kWth/kg TRU), with coolant nominal T_{in} = 650 K and T_{out} = 923 K. Reactivity decrease with fuel burnup is offset by increasing the fusion neutron source strength.

The fusion neutron source is surrounded on the outside by an annular fission core. Surrounding the fission core and the plasma there are tritium breeding blankets and several layers of shielding to protect the superconducting magnets that are used for the confinement of the plasma. The tokamak DT fusion neutron source for SABR is described in Ref. 3.

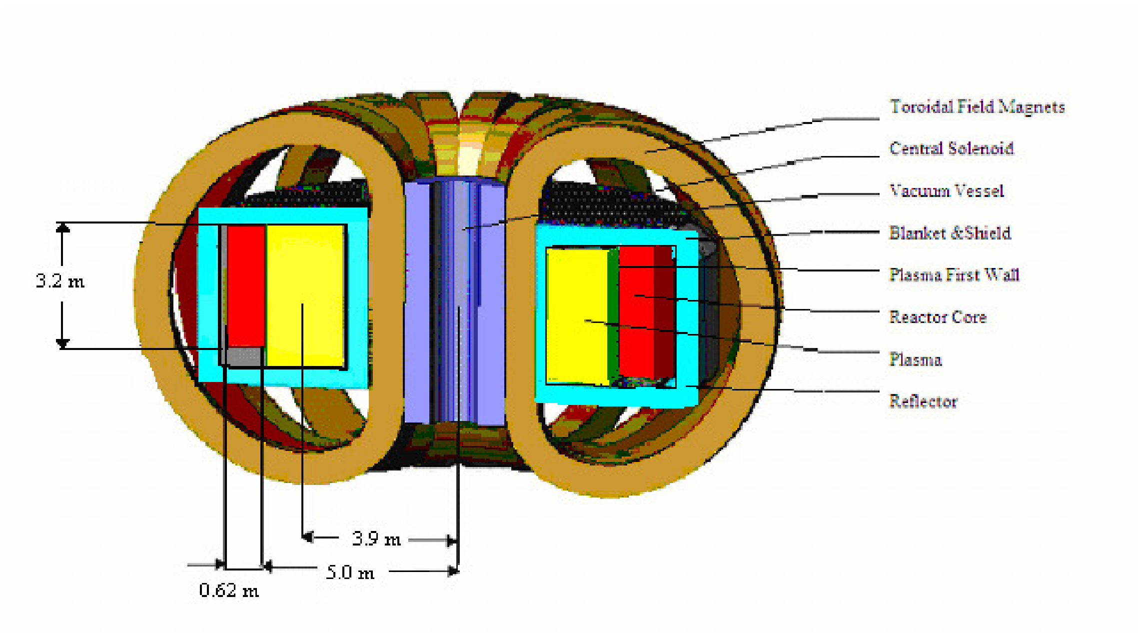

Figure 1: Configuration of SABR

B. Dynamical safety analyses

A Subcritical Advanced Burner Reactor)SABR) 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 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 $\rho+\beta >> \beta$ for SABR. Moreover, the dynamics of a subcritical reactor will differ from those 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, control rod insertion would lead to a lower power operation of the fission reactor, 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 shut down a subcritical reactor.

A model of the coupled dynamics of the fusion neutron source, the fission core, and the heat removal system has been implemented[1], 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 (e.g. fuel melt at 1473 k, sodium boiling at 1156 K). Turning off the auxiliary heating power to the fusion neutron source was found to be an effective "scram" mechanism, shutting 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).

Neutron source excursions

Simulation of neutron source excursions due to inadvertent increases in plasma heating or fueling indicated that the inherent plasma pressure limit (Troyon beta limit or Greenwald density limit) would limit fusion power excursions before fuel melting or sodium boiling occurred in the core, except for one case, as summarized in Tables 1 and 2. (BOL refers to beginning of core life, BOC refers to beginning of equilibrium fuel cycle, and EOC refers to end of equilibrium fuel cycle.). The auxiliary heating power for the fusion neutron source consists of 6 different 20 MW sources. Only when two of these sources are accidently turned on at beginning of core life would there be any core damage if corrective action were not taken.

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Table 1: Summary of Accidental Plasma Auxiliary Heating Increases

(fuel melts @ 1473 K, sodium boils @ 1156 K)

	BOL	BOC	EOC
Max. Coolant Temperature for 20 MW increase in P_{aux} (K)	1,079	968	952
Max. Fuel Temperature for 20 MW increase in P_{aux} (K)	1,142	1,020	1,002
Max. Coolant Temperature for 40 MW increase in P_{aux} (K)	1,184*	1,003	976
Max. Fuel Temperature for 40 MW increase in P_{aux} (K)	1,259	1,058	1,028

The accidental increase in plasma fueling rate which would produce an increase in the plasma ion density and hence the fusion neutron production rate was simulated…In all cases the Troyon beta limit would be exceeded before the ion density increased enough to cause fuel melting or coolant boiling. Even if the density exceeding the Troyon beta limit did not limit the fusion neutron source excursion, the time between the initiation of the accident and coolant boilng or fuel melting was sufficiently long to enable the accident to be detected and corrective action to be taken.

Table 2: Summary of Accidental Plasma Ion Density Increases

	BOL	BOC	EOC
Allowable Plasma Ion Density Increase Before Coolant Boiling	12%	17%	19%
Time Until Coolant Boiling (seconds)	46	29	27
Allowable Plasma Ion Density Increase Before Fuel Melting	19%	29%	32%
Time Until Fuel Melting (seconds)	14	13	16
Maximum Plasma Ion Density Increase Before Troyon Beta Limit Exceeded	11%	1%	2%

Control rod ejection

Simulation of accidental control rod injection (+9$) in the most reactive condition resulted only in increase in fission power to a new equilibrium, with core temperatures remaining below levels at which either fuel melting or core boiling would occur.

Loss-of-flow-accidents (LOFAs)

Simulation of LOFAs 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 seconds to shut off the neutron source before fuel melting occurs. The fuel and coolant maximum temperatures are plotted for 50, 65 and 80% loss-of-flow accidents in Figs. 2 and 3.

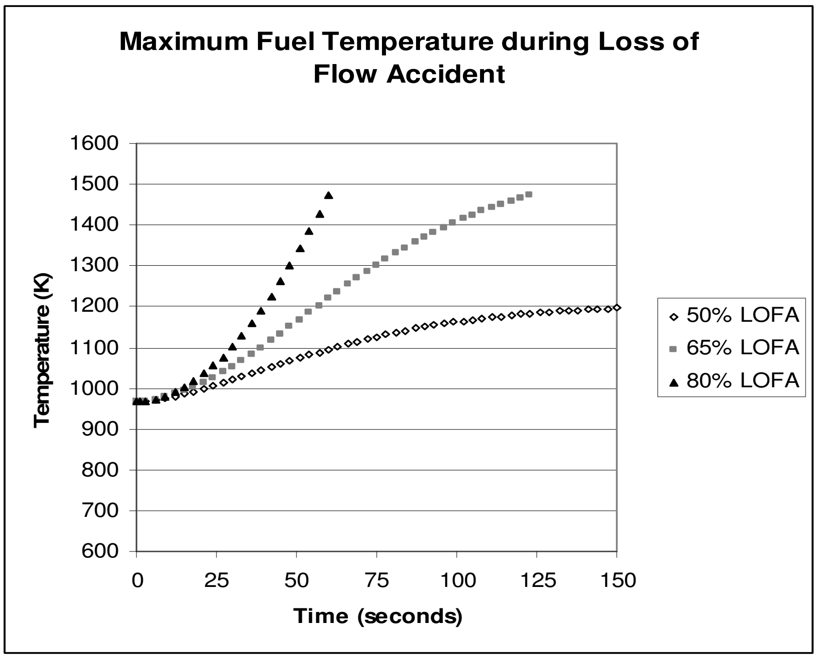

Figure 2: Maximum Fuel Temperature during Loss of Flow Accident at BOL (Fuel melting at 1473 K)

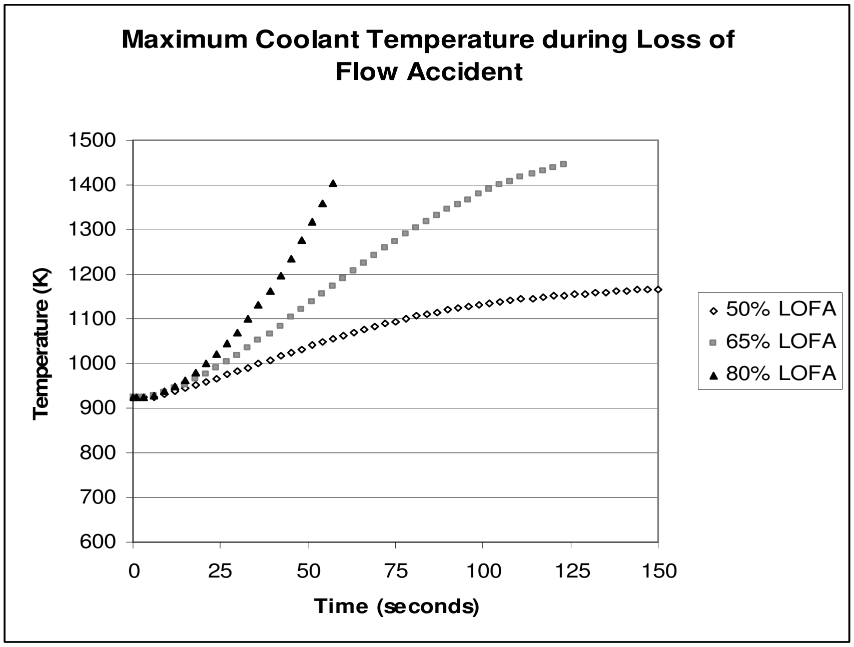

Figure 3: Maximum Coolant Temperature during Loss of Flow Accident at BOL (sodium boiling at 1156 K)

Loss-of-heat-sink-accidents

Simulation of LOHSAs 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. The detailed results of the LOHSAs simulations are summarized in Table 3.

Table 3: Loss of Heat Sink Accident Summary

	BOL	BOC	EOC
Maximum Heat Sink Loss Before Coolant Boiling	33%	36%	36%
Time Until Coolant Boiling (seconds)	65	70	78
Maximum Heat Sink Loss Before Fuel Melting	47%	53%	54%
Time Until Fuel Melting (seconds)	77	87	86
Maximum Heat Sink Loss for which Decay Heat can be Fully Removed.	70%	70%	70%
Time Until Coolant Boiling for 70% LOHSA (seconds)	10	11	11
Time Until Fuel Melting for 70% LOHSA (seconds)	17	21	22

C. Conclusions

Possible transients occurring in SABR can be placed into two different categories. The first category of transients is accidents affecting SABR's neutron population in the fission core. Due to operation very close to the Troyon Beta Limit, SABR is safe against accidental increases in the plasma ion fueling rate and plasma auxiliary heating. SABR is also safe from any accidental control rod ejections due to the large subcriticality.

The second category of transients is those affecting SABR's heat removal systems---Loss of Flow, Heat Sink and Power Accidents. In all of these accidents, there are at least 10 seconds to respond to an initiating event by turning off the plasma auxiliary heating. The 10 second for 100% loss of flow is probably not enough time to react by turning off the plasma auxiliary heating but this accident is the absolute worst case scenario and does not take into account natural circulation or secondary coolant loop flow coast down times. In more realistic accident scenarios, there are many tens of seconds up to a couple minutes for taking corrective measures before the coolant begins to boil and the fuel begins to melt. This required reaction time is implies the need for careful monitoring of the temperature and power levels in the reacto, but it should be sufficient time for reactor operators to take action. After the plasma is shut down, if the coolant flow rate and heat sink capability continue to decrease, back-up pumps and heat exchangers must be turned on to remove the power produced by decay heat.

Because of the large positive sodium voiding and lack of ^{238}U in the TRU fuel, SABR has a positive reactivity feedback. Due to this positive reactivity feedback and decay heat production, SABR will fail in the absence of external counter measures during severe accidents in the heat removal system. The subcritical nature of the reactor, however, provides a considerable margin of safety for dealing with this positive reactivity feedback during transients. The immediate risk that all accidents pose can be diminished if the fusion neutron source is rapidly shut down, leaving only decay heat to deal with. Because back-up and auxiliary pumps and heat exchangers will be responsible for providing sufficient heat removal in extreme cases, SABR requires further design of the primary, intermediate and secondary coolant loops so that a more in depth analysis can determine if the reactor is in fact safe from the worst case accident scenarios. Further work also should include separate systems dedicated to removing decay heat. However, for all accidents suggested in this study, there are viable options for preventing permanent damage to the reactor that make SABR, with additional design, a potential second generation Advanced Burner Reactor for minimizing the amount of Spent Nuclear Fuel that must be stored in High Level Waste Repositories.

References

1. T. S. Sumner, "Dynamical Safety Analysis of SABR", MS Thesis, Georgia Institute of Technology, 2008.
2. W. M. Stacey, et al., "A TRU-Zr Metal Fuel, Sodium Cooled, Fast Subcritical Advanced Burner Reactor", *Nucl. Technol.*, 162, 53 (2008).
3. J. P. Floyd, et al., "Tokamak Fusion Neutron Source for a Fast Transmutation Reactor", Fusion Sci. Technol., 52, 727 (2007).