Input to Fusion-Fission Hybrid Workshop Bill Stacey July 23, 2009

Rationale for a fusion-fission hybrid reactor

A substantial, immediate and continuing expansion of nuclear power is the “best” electrical energy policy for the USA and the world. “Best” here means most technically realistic, environmentally benign and economical.

This expansion of nuclear power would involve: i) in the near term, deploying improved LWRs immediately, developing advanced fast burner reactors to fission the long half-life transuranics (TRU) in the spent nuclear fuel discharged from LWRs, and perhaps developing other types of improved thermal reactors; ii) in the intermediate term, developing and deploying breeder reactors that can better utilize the uranium fuel resource and developing fusion physics and technology; and iii) in the longer term, developing and deploying fusion power reactors. The principal technical impediments in the near-to-intermediate term to such an expansion of nuclear power are related to closing the nuclear fuel cycle—i) dealing with the TRU in spent nuclear fuel so as to substantially reduce the requirement for multiple high-level-waste storage facilities, and ii) transmuting non-fissionable (in thermal reactors) ^{238}U (>99% of natural uranium) to fissionable plutonium in order to utilize more of the potential energy content of uranium.

Sub-critical operation of these TRU-fueled advanced burner reactors would enable a substantially longer (maybe by 5) fuel residence time, limited by materials damage rather than criticality. This would, in turn, lead to significantly fewer reprocessing steps being required to achieve deep enough TRU burnup to significantly reduce high-level-waste storage requirements. Sub-critical operation would also ameliorate safety constraints related to TRU fuel and thus enable larger TRU throughput rates in advanced burner reactors. Similar advantages of sub-critical operation would be anticipated for fast breeder reactors.

Variable-strength D-T fusion neutron sources sufficient to drive sub-critical advanced burner reactors can be extrapolated from the current magnetic confinement fusion physics and technology database. Such fusion neutron sources could be deployed within 2 decades or so.

Choice of a magnetic fusion neutron source

A tokamak neutron source could be designed and built soon based on the present technology and physics database for ITER, and ITER will serve as a prototype for such a neutron source when it operates. Such a tokamak neutron source would take advantage of the substantial physics and technology R&D program for ITER, as well as the ITER operating experience.

The additional R&D, beyond the present worldwide tokamak program and the ITER project, that would be needed for a tokamak fusion neutron source would also be directly on the path to a fusion DEMO. Since the ITER operating parameters would be sufficient for a neutron source, this additional R&D would emphasize quasi-steady state operation, disruption avoidance, component reliability, materials, etc. as well as selected tokamak physics and technology advances. The development of a radiation damage resistant structural material is a major challenge for both the core and the neutron source of advanced burner reactors. This R&D would be directly relevant to the development of tokamak electric power reactors.

Neutron sources based on other confinement concepts also can be envisioned, but would require substantially more development from their present stage through an ITER-like prototype step, so that they should be considered as candidates for neutron source for a second generation of sub-critical advanced burner reactors. An adequate “alternative concept” development program to qualify any magnetic confinement concept other than the tokamak for a neutron source would dominate the present DoE magnetic fusion program for at least a couple of decades.

Choice of sub-critical advanced burner reactor (hybrid blanket) nuclear technology

Since there probably will be a fleet of advanced burner reactors, some critical and some sub-critical, it makes sense to choose the same nuclear technology for most, if not all, of them. It is generally, but not unanimously, agreed that a fast spectrum nuclear reactor is needed for an advanced burner reactor, and the sodium-cooled fast reactor is the technology with which there is the most experience worldwide. It is tempting to suggest the substitution of lithium or lithium-lead for sodium, but this would involve a large development program that has already been done for sodium. There is also a substantial interest, but no experience, in gas-cooled fast reactors.

Choice of fuel cycle scenario

There are a large number of possible scenarios for recycling the transuranics in LWR spent fuel to fission the TRU—in LWRs, in critical advanced burner reactors, in sub-critical advanced burner reactors, in deep-burn gas-cooled thermal reactors, etc., and in various combinations of the above. This is an important issue, it has been analyzed in detail, and it will be further analyzed. One thing that has come out of these studies is that a sub-critical advanced burner reactor will be needed, at least as a last stage, in order to achieve deep enough burnup of the TRU to significantly impact high-level-waste storage requirements.

The choice of fuel cycle scenario may have an effect on the choice of advanced burner reactor nuclear technology, but should not have any effect on the choice of fusion neutron source. Put another way, an advanced burner reactor can be designed with a given neutron source to operate under any of a variety of fuel cycle scenarios.

Issues for the Workshop

Need for Sub-Critical Operation of Advanced Burner and Breeder Reactors?

A sub-critical advanced burner reactor (or breeder reactor) with a fusion neutron source (a “fusion-fission hybrid”) will be more complex and expensive than a critical version of the same reactor. A principal advantage of a sub-critical reactor with a variable strength neutron source is that it can achieve deeper TRU fuel burnup (fuel residence time limited by materials damage rather than criticality) and thus require significantly fewer complex and expensive fuel reprocessing/refabrication steps. Since the separation process is imperfect, some transuranics go with the fission products to high level waste storage on each reprocessing step. Moreover, deep burnup of certain “minor actinides” in a critical reactor may require so many reprocessing steps as to simply not be feasible. Certainly the practicality, and possibly the very feasibility, of achieving significant reduction in the requirement for long-term high level waste storage capacity may depend on sub-critical operation of at least some of the advanced burner reactors..

A second advantage of sub-critical operation is that it substantially increases the margin of safety (to prompt critical) for accidental reactivity insertions. This margin is equal to the delayed neutron fraction (which is 2-3 times smaller for TRU than uranium fuel) in a critical reactor, but is increased to the much larger sub-critical reactivity level in a sub-critical reactor.

This ameliorates the design constraint on the TRU fuel fraction that exists for a critical reactor, allowing a much greater TRU throughput in sub-critical reactors completely fueled with TRU.

Development Stage, R&D Requirements, Time-Scale for Deployment and Relevance to Future Development of Fission and Fusion Power?

The various nuclear technologies, materials, fusion confinement concepts, fusion technologies, etc. that have been suggested for hybrids are at vastly different stages of development and have vastly different ongoing R&D programs. These differences translate into differences in the feasibility and credibility of the various concepts. Moreover, the relevance of the development of these various technologies to the future development of fission and fusion power may be quite different. All of this needs to be put into perspective.

Should DoE Undertake a Systematic Evaluation of the Sub-Critical Operation of Advanced Burner and Breeder Reactors with Variable-Strength Fusion Neutron Sources?

This is the question.

The Georgia Tech studies of sub-critical advanced burner reactors

In a number of faculty-student design projects and theses over the last decade, we have developed two concepts for sub-critical advanced burner reactors (summary--J. Fus. Energy 28,328,2009). For both concepts, a tokamak D-T fusion neutron source based on ITER physics and technology (FS&T 52,727,2007) was used. A normal conductor design was found to have excessive resistive heating, and so the ITER superconducting magnets were adapted. We downscaled the ITER design (magnets, first-wall, divertor, etc) and adapted it to He and Na coolants. The physics parameters were similar to those of ITER, the size and power were somewhat less than ITER ($R = 4.0$m, $P_{fus} = 400$-500 MW). We tried to be conservative, so that ITER will really be a prototype for the neutron source.

We developed two nuclear designs. The initial GCFTR design (Nucl Tech. 159,72,2007) was a helium-cooled fast reactor with the TRU fuel in TRISO pellets. We learned that the TRISO pellets would fail quickly in a fast neutron spectrum and were impractical to reprocess, so that another fuel form would be needed. The SABR design (Nucl. Tech. 162,53,2008). was a sodium-cooled, metal fueled (Zr40-TRU) reactor adapted from an Argonne fast reactor design and using a fuel and the pyroprocessing technology being developed at Argonne.

We used a 4-batch reprocessing fuel cycle with fuel residence time in the core limited by 200 dpa in the structure to 3000 days, in which about 25% of the TRU was burned, then the fuel was reprocessed and recycled. Deep burnup (>95%) would be possible without reprocessing if structural materials with large enough radiation damage limits are developed, but such designs may be impractical because of peaked power distributions, etc.. At 3000 MWth fission power, one fast burner reactor operating at 80% availability would fully support 4 1000 MWe LWRs.

A series of dynamic safety analyses (LOCA, LOHSA, source excursion, etc.) were performed for the SABR design. It was found that tens of seconds to minutes would be available to detect such accidents and scram the reactor by turning off the fusion neutron source before sodium boiling or fuel melting occurred.

Papers based on this work may be downloaded from (www.frc.gatech.edu) under the Transmutation Reactors link.