TRANSMUTATION MISSIONS FOR FUSION NEUTRON SOURCES

W. M. Stacey
Fusion Research Center
Georgia Institute of Technology
Atlanta, GA, USA

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ABSTRACT

There are a number of potential neutron transmutation missions (destruction of long-lived radioisotopes in spent nuclear fuel, 'disposal' of surplus weapons grade plutonium, 'breeding' of fissile nuclear fuel) that perhaps best can be performed in sub-critical nuclear reactors driven by a neutron source. The requirements on a tokamak fusion neutron source for such transmutation missions are significantly less demanding than for commercial electrical power production. A tokamak fusion neutron source based on the current physics and technology database (ITER design base) would meet the needs of the spent nuclear fuel transmutation mission; the technical issue would be achieving $\geq$ 50% availability, which would require advances in component reliability and in steady-state physics operation.

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I. INTRODUCTION

For many years there has been a substantial R&D activity devoted to the nuclear fuel cycle. Over the decade of the 1990s and into the early years of this century this activity focused on the technical evaluation of the possibility of reducing the requirements for long-term geological high-level waste repositories (HLWR) for the storage of spent nuclear fuel (SNF) by transmutation of the plutonium and higher transuranics in the spent fuel discharged from fission power reactors[1-8]. Repeated recycling of this SNF in thermal spectrum fission power reactors, the most obvious option, was found to not significantly reduce the HLWR requirements[1,2], because the destruction of transuranics (by neutron fission) would be offset by the production of more transuranics by transmutation (by neutron capture) in the isotope ^{238}U that constitutes about 95% of thermal reactor fuel. Repeated recycling of the SNF in special purpose fast spectrum reactors was found to be more effective, but with the net destruction rate of transuranics still limited by the requirement for ^{238}U to provide a negative reactivity coefficient for safety and with a safety-related limit on the transuranics loading. In principle, these two safety-related limits can be relaxed if the reactor is operated sub-critical, with a neutron source making up the sub-criticality neutron deficit to maintain the neutron chain reaction. A general consensus emerged from these studies that significantly higher net transuranics destruction rates could be achieved in sub-critical reactors[1,2]. Almost all of the studies of sub-critical transmutation reactors have been based on the use of an accelerator-spallation neutron source[1-8], although there have been a few studies based on the use of a D-T fusion neutron source[9-18].

More recently the focus of the nuclear fuel cycle studies, at least in the US, has shifted to the development of one or more advanced fuel cycles for the fourth generation of nuclear reactors, the so-called Generation IV (GEN-IV) studies[20]. Reduction of HLWR requirements by destruction of the transuranics produced in nuclear fuel by transmutation of ^{238}U remains an important objective of these studies.

The purpose of this paper is to present an initial evaluation of the possibility and requirements of a transmutation mission for fusion along the path to the ultimate mission of electrical power production. Possible transmutation missions are described in section II. The technical requirements for a tokamak fusion neutron source that could fulfill the transmutation mission and a design concept for a fusion-driven sub-critical transmutation reactor are identified in section III. The time-frame of the transmutation mission is discussed in section IV, and a fusion-driven sub-critical transmutation reactor is compared with the competition in section V. Incorporation of a transmission mission into the fusion development program is discussed in section VI, and a summary is presented in section VII.

II. TRANSMUTATION MISSIONS

There are several possible transmutation missions that could employ fusion neutron sources to drive sub-critical reactors, corresponding to the several scenarios for the future of nuclear energy that are presently under discussion. Transmutation (by neutron fission) of the plutonium and higher transuranics in SNF, primarily to reduce capacity requirements for high-level waste repositories (HLWRs) but also to extract the remaining energy content from the SNF and to 'dispose of' reactor-grade plutonium, is a potential mission in all scenarios for the future of nuclear energy. The 'disposition' of surplus weapons-grade plutonium by using it as fuel in a sub-critical reactor is another possible mission similar to the SNF transmutation mission. In scenarios which foresee an increasing use of nuclear energy in the next half-century, the use of reactors fueled with the Pu and higher transuranics from SNF for the transmutation (by neutron capture) of fertile ^{238}U into fissile Pu for fueling light water reactors (LWRs) is foreseen as a necessity. The SNF transmutation and weapons-grade Pu disposal missions are less demanding in terms of fusion power (neutron source) level than is the Pu breeding mission, because of the lower multiplication factor of a plutonium breeding reactor, but the other requirements on the fusion neutron source are similar.

Transmutation Mission—Spent Nuclear Fuel &Weapons Pu

Because it could be an important national mission under a range of scenarios for the future of nuclear energy in the USA, the transmutation of SNF is chosen as a representative transmutation mission for a sub-critical reactor driven by a fusion neutron source. The SNF inventory is usually given in terms of the metric tonnes of uranium (MTU) that was initially used to fabricate the fresh fuel. In the USA, the SNF inventory is estimated to be 47,000 MTU as of the end of 2002, and the current rate of production of the approximately 100 electric power reactors operating in the USA is > 2,000 MTU/year. The Yucca Mountain HLWR has a statutory limit of 70,000 metric tonnes of heavy metal, which includes 63,000 MTU of SNF. If the present level of nuclear power production continues into the near future, which seems likely, a new HLWR of the Yucca Mountain capacity will be needed in 6 years and every 30 years thereafter.

The capacity of a HLWR is set by the decay heat removal capability. During the first 100 or so years after irradiation the decay heat of SNF is dominated by fission products, after which it is dominated by the decay of plutonium and the higher transuranics. If the HLWR is not sealed for 100 or so years after the SNF is removed from a reactor, the Pu and higher transuranics decay heat will determine the capacity of the HLWR.

Reprocessing of SNF from LWRs to separate: 1) the uranium that can be sent to a low level waste repository; 2) the Pu and higher transuranics that can be made into fuel for recycling in 'transmutation' reactors; and 3) the fission products that can be sent to a HLWR would greatly reduce the amount of material sent to the HLWR. In principle, with repeated recycling and reprocessing steps 2 and 3, all of the plutonium and higher actinides can ultimately be fissioned, and only fission products will be sent to the HLWR. However, a practical limit is set by the efficiency with which the Pu and higher transuranics can be separated from the fission products that are sent to the HLWR in each processing step. Separation efficiencies well above 99% are projected for both aqueous and pyrometallurgical separation processes, leading to detailed fuel cycle calculations (e.g. Ref. 21) that predict that (with repeated recycling) in excess of 99% of the Pu and higher transuranics in SNF can be fissioned, which would reduce HLWR capacity requirements a hundred-fold. Even a 90% separation efficiency would lead to a ten-fold reduction in HLWR capacity requirement; i.e. a new HLWR every 300 years instead of every 30 years, at the present level of nuclear power production. Moreover, by repeated recycling of the Pu and higher actinides in transmutation reactors, the energy extracted from the original LWR fuel can be increased by about 30% relative to the energy extracted in the 'once-through' cycle of the original fuel in a LWR.

If weapons-grade plutonium is blended in with the SNF plutonium and higher transuranics and recycled repeatedly, the 'plutonium disposition' mission can be carried out as part of the 'transmutation' mission. This mission can also be carried out by blending the weapons-grade plutonium in LWR fuel.

Transmutation Mission--Fissile Breeding

The 'fissile breeding' mission could be carried out as a variant of the recycling/reprocessing scenario described above. If the uranium separated from the SNF and the 'depleted' (in fissile U-235) uranium from the original fuel enrichment are recycled back as part of the transmutation reactor fuel, the transmutation of U-238 by neutron capture will produce fissile plutonium which can be used as LWR fuel, in which case the 'transmutation' reactor would become a 'breeder' reactor. Of the potential energy content of the original uranium ore, 16.5% remains in the uranium in the discharged SNF and 82.7% remains in the depleted uranium residue from the original fuel enrichment, 0.2% remains in the plutonium and higher transuranics in the discharged SNF, and 0.6% has been extracted by fission in one cycle of the fuel in a LWR. Recovering some significant fraction of this remaining 99+% of the potential energy content of the uranium ore is the motivation for the 'fissile breeding' mission.

Likelihood of a Transmutation Mission

The likelihood that a transmutation mission will be viewed as necessary to solve a "national problem" is different for the three possible missions discussed above. The surplus weapons Pu disposition mission is widely recognized as a national problem and is funded as such by the government, but this can and is being done in critical reactors, and the opportunity for fusion to contribute is small because of the immediate time scale. The SNF transmutation mission, which may be viewed as a reactor grade plutonium disposal mission as well as a high-level waste repository requirements reduction mission, is widely recognized as being worth examining, and there is substantial R&D support for this mission. However, the urgency felt by governments to implement a SNF transmutation solution is not as great as for the weapons Pu disposal mission. The SNF transmutation mission is longer term and continuing, and there appear to be some advantages to using sub-critical reactors, which would provide an opportunity for a fusion contribution. The fissile breeding mission will become urgent only if the need to rely on nuclear power for expanded electrical power production is recognized as national policy, which is not yet the case.

III. TECHNICAL REQUIREMENTS

Fusion Neutron Source

Since most of the neutrons in a sub-critical transmutation reactor would be created by the fission process in the reactor, and the role of the fusion neutron source would be to provide a modest number of neutrons to maintain the neutron fission chain reaction, the requirements on fusion power level, power density and neutron and thermal wall loads is less demanding than for a pure fusion electric power reactor. This is more the case for the transmutation of SNF and weapons-grade plutonium than for transmutation of ^{238}U into fissile isotopes.

Tokamak Neutron Source Requirements

A series of systems studies has been performed[16-20] to examine whether a tokamak neutron source for a sub-critical transmutation reactor could be designed using the existing physics and fusion technology databases. Such a tokamak neutron source would be based on the ITER physics design basis and on the ITER first-wall, divertor, heating-current drive, tritium, etc. systems, but would likely use a liquid metal or He coolant for compatibility with the transmutation reactor and a ferritic steel structural material of the type being developed for nuclear applications. Two variants of a liquid metal cooled system were examined—the FTWR (fusion transmutation of waste reactor) with copper magnet systems and the FTWR-SC with essentially the ITER superconducting magnet systems. A third liquid metal cooled variant based on advanced tokamak (AT) physics and the ITER superconducting magnet system—the FTWR-AT—was also examined. Two variants of He cooled system GCFTR (gas-cooled, fast transmutation reactor) were also developed. The principal parameters of such tokamak neutron sources are given in Table 1. The fusion powers shown in Table 1 correspond to the indicated value of β_N and the plasma volume; smaller values would result from operating at lower β_N.

Table 1 Tokamak Neutron Source Parameters for Transmutation Reactors

Parameter	FTWR[a]	FTWR-SC[b]	FTWR-AT[c]	GCFTR[d]	GCFTR-2[e]	ITER[f]
Fusion power, P_{fus} (MW)	≤ 150	≤ 225	≤ 500	≤ 180	≤ 180	410
Neutron source, S_{fus}(10^{19} #/s)	≤ 5.3	≤ 8.0	≤ 17.6	≤ 6.5	≤ 6.5	14.4
Major radius, R (m)	3.1	4.5	3.9	4.3	3.7	6.2
Minor radius, a (m)	0.9	0.9	1.1	1.1	1.1	2.0
Elongation, κ	1.7	1.8	1.7	1.7	1.7	1.8
Current, I (MA)	7.0	6.0	8.0	7.1	8.3	15.0
Magnetic field, B (T)	6.1	7.5	5.7	5.7	5.7	5.3
Confinement, H(y,2)	1.1	1.0	1.5	1.0	1.0	1.0
Normalized beta, β_N	≤ 2.5	≤ 2.5	4.0	≤ 2.0	≤ 2.0	1.8
Plasma Power Mult., Q_p	≤ 2.0	≤ 2.0	4.0	2.9	3.1	10
Electric Power Mult, Q_e	1	5		3.3	3.2	
Current-drive effic. η_{cd}	0.03	0.024	0.05			
" , γ_{cd} (10^{-20} A/Wm^2)	0.19	0.20	0.28	0.64	0.61	
Bootstrap I fraction, f_{bs}	0.67(0.38)[g]	0.56(0.24)	0.25	0.30	0.31	
Neut. flux, Γ_n (MW/m^2)	≤ 0.8	≤ 1.0	≤ 1.7	≤ 0.6	≤ 0.6	0.5
Heat flux, q_{fw} MW/m^2)	≤ 0.4	≤ 0.3	≤ 0.5	≤ 0.23	≤ 0.23	0.15
Availability (%)	≥ 50	≥ 50	≥ 50	≥ 50	≥ 50	

[a] ITER physics, liquid nitrogen cooled copper magnets.(Ref. 16)
[b] ITER physics, superconducting magnets. (Ref. 17)
[c] AT physics, superconducting magnets. (Ref. 18)
[d] ITER physics, " " (Ref. 19)
[e] ITER physics, " " (Ref. 20)
[f] ITER design parameters. (Ref. 21)
[g] required (estimated from present database)

For the FTWR, FTWR-SC, and both GCFTRs the requirements on β_N and confinement are within the present experimental range, and the requirements on β_N, confinement, energy amplification Q_p, and fusion power level are at or below the ITER level. The requirement on the combination of current-drive efficiency and bootstrap current fraction is beyond what has been achieved to date, but is certainly within the range envisioned for AT operation and may be achieved in ITER. Actually, the advanced current drive capability is the only AT operating capability that is needed or that can be taken advantage of for a fusion neutron source for the transmutation mission.

The configuration of the three FTWR concepts is depicted in Fig. 1. The sub-critical reactor is in the form of an annulus 40 cm thick by 228 cm high that wraps about the outboard side of the plasma chamber. This reactor is composed of fast reactor fuel assemblies containing 0.6 cm pins of a zirconium alloy containing transuranics from the SNF dispersed in a zirconium matrix. The reactor coolant is a lithium-lead eutectic enriched in ^{6}Li to achieve tritium self-sufficiency. A reflector and shield are located inboard of, above, and below the plasma chamber and above, below and outboard of the reactor to protect the magnets from radiation damage and to reflect neutrons towards the reactor. The magnet systems for the FTWR used oxygen-free high conductivity copper conductor and liquid nitrogen coolant, and the magnet systems for the FTWR-SC and FTWR-AT used Nb_3Sn and NbTi conductor cooled by supercritical helium.

The configuration of the two He-cooled GCFTR concepts is similar, but with annular cores 1 m wide and 3 m high. The cores are composed of TRISO coated fuel particles in a SiC matrix in fuel pins of 1.34 cm diameter.

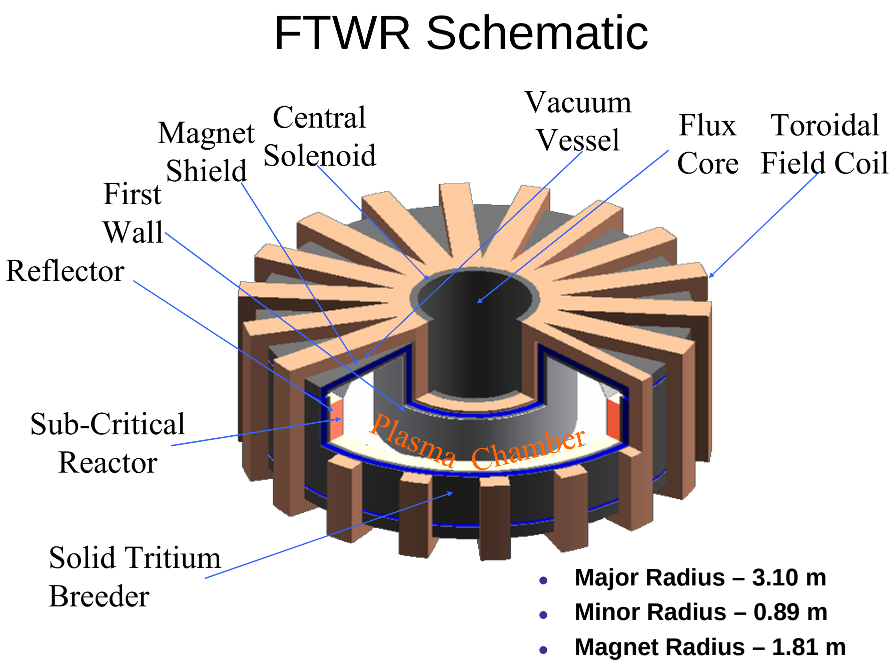

Figure 1 **Tokamak Fusion Transmutation of Waste Reactor**

The rationale for operating a transmutation reactor sub-critical is to relax certain safety-related constraints that otherwise would act to limit the net actinide transmutation rate. On the other hand, the purpose of a transmutation reactor is to fission transuranics, which capability is enhanced greatly by operating as close to critical as possible. We chose to specify a maximum beginning-of-life multiplication factor of $k_{eff} = 0.95$, which leads to a multiplication of the fusion source neutrons reaching the transmutation reactor by a factor of 20.

Availability determines the annual transmutation rate of a given reactor, hence the number of transmutation reactors needed to service the LWR fleet and their total cost. The projected SNF transmutation rates are 100A, 150A, 333A and 99A MTU per year for the FTWR, FTWR-SC, FTWR-AT, and GCFTRs, respectively, where A is the availability. Recalling that at the present level of nuclear power production in the US, about 100 LWRs produce about 2000 MTU of SNF per year, we see that 20/A, 13/A and 6/A transmutation reactors would be needed to handle the annual SNF production, assuming the present level of nuclear power continues indefinitely. If there are other viable options for transmutation, then high availability will be important for economic competitiveness. On the other hand, if it turns out that sub-critical reactors are necessary to effectively accomplish the transmutation mission, then the technical feasibility of a neutron source with good enough availability to eliminate the need for building any further HLWR repositories after Yucca Mountain would be the paramount consideration. Operating at 50% availability, about 25-40 sub-critical reactors driven by tokamak fusion neutron sources based on ITER physics and technology would accomplish this transmutation mission. At 75% availability, only 15-25 would be needed.

R&D Program for a Tokamak Neutron Source

The ongoing worldwide tokamak program is addressing the current-drive/bootstrap current/steady-state physics issue. Since the physics and technology design bases of a tokamak neutron source would be almost identical to those of ITER, the operation of ITER will provide the prototype test for a tokamak fusion neutron source. Issues related to disruptions and ELMS would be less severe for the neutron source than for ITER and presumably would be resolved by the time of ITER operation. In addition to ITER, a set of technology test facilities would be needed for the high performance testing required to develop the highly reliable components (magnets, first-wall, divertor, heating and current-drive, etc.) needed to obtain high availability operation of a tokamak neutron source; such facilities are also required before the construction of a fusion electric power DEMO. Thus, the required R&D for a tokamak fusion neutron source is directly on the development path for fusion power. Moreover, the operation of a fusion-driven sub-critical reactor could serve most, if not all, the purposes presently envisioned for a 'volume neutron source', thus serving also as one of the facilities presently envisioned to be needed for the development of fusion power.

Other Possible Fusion Neutron Sources

Although the tokamak is the only confinement concept for which the physics database is sufficiently advanced that it can be considered for a neutron source application at the present time, other confinement concepts (e.g. stellarator, spherical torus) are being developed which might have certain advantages relative to the tokamak as a fusion neutron source for the transmutation mission at some point in the future. The absence of disruptions and the natural steady-state operation characteristic of the stellarator and the higher power density and more compact geometry of the spherical torus are features that might ultimately make these concepts superior to the tokamak as a neutron source. However, since in terms of performance these concepts are presently at the stage reached by tokamaks 15-20 years ago, they should be considered as possibilities for a second generation of fusion neutron sources.

Reactor Technologies

In principle, the reactor (nuclear, materials, coolant, separation and processing) technologies that are being developed worldwide for use with critical reactors and with accelerator-driven sub-critical reactors also can be used with fusion-driven sub-critical reactors, with the additional requirement to include a lithium-containing material in or near the reactor for tritium breeding. The transmutation reactor technology that has received the most attention in the US nuclear community is a fast spectrum reactor with metal fuel, liquid metal coolant, ferritic steel structural material and pyrometallurgical separation and processing, although other reactor technologies are now being examined in the GEN-IV studies[22]. A recent study[23] indicates that this technology can be adapted for a sub-critical reactor driven by a fusion neutron source either by including some solid lithium-containing material in the reactor or by using a PbLi coolant in order to breed tritium. The additional development of solid lithium-containing tritium breeding elements and/or of PbLi coolant should be accomplished as part of the ITER blanket test program, is directly on the path to the development of fusion power, and is needed before the construction of an electric power DEMO.

The use of molten salt reactor technology with a fusion neutron source also has received recent attention. Molten salt fuel offers the possibility of on-line reprocessing to remove fission products and to recycle 'fresh' transuranics, which would reduce or eliminate the decrease in multiplication constant over the fuel cycle found in solid fuel reactors. Experience with an experimental molten salt power reactor was obtained in the 1960s, and R&D has been initiated recently in the nuclear energy and accelerator applications programs for transmutation applications and in the fusion program for fusion electrical power applications. The critical issues with using molten salts are solubility of transuranics in the fluoride salts, separation of fission products from transuranics, and corrosion control of molten salt with ferritic steels.

The use of TRISO coated fuel pellets with high radiation resistance in gas-cooled reactors is another technology that is receiving increased attention, and that was examined in the GCFTR studies[19,20].

IV. INITIATION AND DURATION OF THE TRANSMUTATION MISSION

The Generation IV nuclear reactor planning activity[22] envisions that the development of the processing technology should be sufficiently advanced by about 2020 that the detailed design of a critical fast transmutation or fissile breeder reactor and the associated processing/separation facility could be started, which would bring the system online in about 2030. The roadmap[6] for developing sub-critical transmutation reactors driven by accelerator-spallation neutron sources also envisions such a reactor coming on line in about 2030. Thus, the implementation of a system of transmutation reactors and processing facilities could be initiated as early as about 2030.

The pacing items in bringing online a tokamak neutron source to drive a sub-critical transmutation reactor are the operation of ITER as a prototype and the operation of a set of technology test facilities required in order to develop component reliability. ITER is scheduled to operate from 2015 to 2035. Component test facilities could be upgraded (existing ITER R&D facilities?) or constructed to operate before and in parallel with ITER, so it would be plausible to begin detailed design of a tokamak neutron source in about 2025. Construction of a sub-critical reactor using the same fast reactor technology developed for critical reactors and construction of a tokamak fusion neutron source could then begin as early as about 2030, leading to initial operation in about 2040.

The scenario for implementation of a system of transmutation reactors depends on the scenario for the future growth of nuclear power. Enough transmutation reactors would be built to fission the backlog of SNF residing in temporary storage and then to transmute SNF as it is discharged from LWRs. The initial transmutation reactors might be critical, and then sub-critical accelerator- and/or fusion-driven reactors might be phased in a decade or so later. These transmutation reactors also would produce a significant fraction of the electric power coming from the nuclear fleet of LWRs plus transmutation reactors (in a roughly 3-5/1 ratio of LWR to transmutation reactor powers). For example, in a recent study[17] of a sub-critical ($k \leq 0.95$) fast reactor driven by the superconducting tokamak neutron source (FTWR-SC), the transmutation reactor produced a net 1800 MWe ($Q_e = 5.0$) and would support (transmute the SNF discharged from) several LWRs that produced a total power of 4.5 times that amount of electricity.

The duration of the transmutation mission will depend on the future of nuclear power. In the unlikely event that nuclear power is phased out when the present reactors end their lives, which are presently being extended many years by re-licensing, then the transmutation mission would be completed over roughly the last two-thirds of this century. In the more likely case that nuclear power production continues at the present level or increases over the century, the transmutation mission will continue indefinitely, in parallel with the anticipated introduction of purely fusion power plants in the latter half of the century.

V. COMPARISON OF FUSION WITH THE COMPETITION

The competition of fusion-driven, sub-critical reactors for the transmutation mission are 1) critical fast and thermal spectrum nuclear reactors and 2) accelerator-driven sub-critical fast-spectrum reactors, both of which have been studied extensively for the transmutation mission.

Inherent Advantages of Sub-Critical Reactors Relative to Critical Reactors

The fundamental source of any advantage that a sub-critical reactor may have relative to a critical reactor will be associated with its larger reactivity margin of safety. If the neutron multiplication constant, k, exceeds 1+β, where β is the delayed neutron fraction, the neutron population and fission heating would increase exponentially with a period of $T \approx \Lambda/(k-1-\beta)$, where the neutron lifetime is $\Lambda \approx 10^{-5}$ s in a fast spectrum reactor, a condition that must be avoided or terminated immediately. The reactivity margin relative to this condition is $1+\beta-k_n$, where k_n is the multiplication constant under normal conditions. In a critical reactor (k_n =1.000) the reactivity margin is just β. The necessity to design the reactor so that any off-normal condition does not increase k by more than β for more than a few neutron lifetimes (10-100 microseconds) imposes design constraints (e.g. to insure inherent, instantaneous negative reactivity changes in response to a fuel temperature increase) on the reactor, and these design constraints may in turn penalize the net transuranics destruction rate (or Pu breeding rate). Because $\beta \approx 0.0065$ for U-235, 0.0022 for Pu-239, 0.0054 for Pu-241, etc., these design constraints will be more severe for reactors fueled with the Pu and higher transuranics in SNF than for uranium fueled reactors.

When a reactor is operated sub-critical, the reactivity margin is much larger. For example, a SNF fueled reactor operating at $k_n = 0.95$ would have an order of magnitude larger reactivity margin of 0.05+β than the reactivity margin of β for a critical reactor. This larger reactivity margin should allow the use of reactor designs with larger concentrations of Pu and higher transuranics (which would have smaller effective β), as well as other design innovations, that would not be advisable in a critical reactor.

Another advantage of sub-critical operation is the ability to compensate the reactivity decrease that occurs with fuel burnup by increasing the neutron source strength over the fuel cycle. This should reduce the excess beginning-of-cycle reactivity necessary to compensate fuel burnup, thus reducing the magnitude of possible accidental reactivity insertions, and/or allowing longer burnup cycles between refueling intervals.

Disadvantages of Sub-Critical Reactors Relative to Critical Reactors

The principal sources of any disadvantages of a sub-critical reactor relative to a critical reactor will be the added cost and power consumption of the neutron source, the added complexity of the reactor configuration needed to accommodate the neutron source, the introduction of thermal and mechanical transient stresses in the reactor due to beam trips in accelerators or disruptions in tokamaks, and the initial lower reliability, hence availability, of the neutron source than of the reactor. There may also be secondary disadvantages associated with enhanced power peaking at the reactor-source interface, the more complex dynamics and control of the coupled source-reactor system, etc.

Comparison of Fusion and Accelerator-Spallation Neutron Sources

The geometry of a reactor with an accelerator-spallation neutron source consists of a very localized target and a beam port embedded within a more-or-less conventional cylindrical reactor configuration. The localization of the neutron source will lead to very significant problems of heat removal and neutron damage to materials within the target and to a relatively small volume around the target in which the source neutrons are deposited. This last problem can be mitigated by switching the beam among several targets, but the heat removal and neutron damage problems will remain formidable.

In sharp contrast to the accelerator-spallation neutron source, the fusion neutron source is very distributed, and the source neutrons will be deposited over a large volume. Heat removal requirements and radiation damage within the neutron source will be much more modest than for the accelerator-spallation neutron source. On the other hand, the geometry of the fusion neutron source will impose non-conventional reactor geometry.

VI. INCORPORATION OF TRANSMUTATION MISSION INTO THE FUSION DEVELOPMENT PROGRAM

The transmutation mission can be carried out with a tokamak fusion neutron source based on physics (H, β_N, Q_p, etc.) similar to or less demanding than that used for the ITER design, so the R&D program supporting ITER and the electrical power development mission will suffice for a transmutation neutron source in most physics areas. However, the transmutation neutron source would need to achieve a higher bootstrap current fraction and/or higher current drive efficiency and to achieve quasi-steady state operation in order to achieve higher availability than ITER. These issues must be addressed prior to the DEMO in the electrical power development path, but would have a higher relative priority in a physics R&D program for the transmutation mission.

The transmutation fusion neutron source can be constructed with the fusion technology being developed for ITER, for the most part, so the technology R&D supporting ITER will also support the fusion neutron source. However, the fusion neutron source will need to achieve greater availability, hence have greater component reliability, than ITER. The issue of component reliability, which will require various component test facilities, must be addressed prior to the DEMO in the electric power development path, but would have a higher relative priority in a technology development program to support the transmutation mission.

The reactor technology for the sub-critical reactor driven by the fusion neutron source should logically be adapted from the reactor (nuclear, fuel, cooling, processing, materials) technologies being investigated in the nuclear program (e.g. those being considered in the Generation–IV and other such studies), but these technologies must be modified to provide for the tritium breeding requirement. A fusion nuclear technology program would have to be revived with this goal. There is a need to develop a long-lived structural material, primarily for the fuel assemblies of the sub-critical reactor but also for the first wall of the fusion neutron source, but it may be possible to build the initial transmutation fusion neutron sources with austenitic stainless steel first walls.

The technical requirements for a tokamak fusion neutron source that would fulfill the transmutation mission are significantly less demanding than for an economically competitive tokamak electrical power reactor, as indicated in Table 2. The first such neutron source could be built immediately following ITER, either before or in parallel with a fusion electrical power demonstration reactor (DEMO), which would have more demanding technical requirements on β_N, confinement and Q_p.

A more comprehensive systems/conceptual design investigation of the application of fusion to the transmutation mission is a necessary first step for incorporating the possibility of a transmutation mission into the fusion development program. Evaluation of the competitiveness of sub-critical reactors driven by fusion neutron sources for the transmutation of SNF and of the required R&D would be the objectives of these studies. These investigations should initially be based on the most developed tokamak confinement concept (using the ITER physics and technology databases) and on adaptation of the reactor technology being developed in the nuclear program. Such studies should be coordinated with the GEN-IV nuclear fuel cycle studies.

Table 2 Requirements for a Tokamak Neutron Source for a Transmutation Reactor, for an Economically Competitive Fusion Electric Power Tokamak Reactor and for a Tokamak DEMO

Parameter	Transmutation	Electric Power[a]	DEMO[b]
Confinement H(y,2)	1.0	1.5-2.0	1.5-2.0
Beta β_N	< 2.5	> 5.0	> 4.0
Power Amplification Q_p	< 2	≥ 50	> 10
Bootstrap Current Fraction f_{bs}	0.2-0.4	0.9	0.7
Neutron wall load (MW/m^2)	< 1.0	> 4.0	> 2.0
Fusion Power (MW)	≤ 200	3000	1000
Pulse length/duty factor	long/steady-state	long/steady-state	long/steady-state
Availability (%)	≥ 50	90	≥ 50

[a] ARIES studies (Ref. 25); [b] DEMO studies (Ref. 26)

VII. SUMMARY

There are potential applications of fusion neutron sources to 'drive' sub-critical fission reactors to perform one or more possible transmutation missions. Since only a fraction of the neutrons in these applications would be fusion neutrons, the requirements are modest relative to the requirements for pure fusion electrical power (e.g. for the transmutation mission-- fusion power $P_{fus} \leq 200$ MW, fusion power density $\beta_N \leq 2.0$, confinement $H_{98} = 11$, 14 MeV neutron wall load $\Gamma_n < 1$ MW/m^2 and power amplification $Q_p \leq 3$). A sub-critical, source-driven reactor almost certainly would be more expensive and initially would have lower availability than a conventional critical reactor, because of the additional cost and lower initial availability of the fusion or accelerator neutron source. In order to be competitive with a critical reactor for a given mission, a sub-critical reactor must introduce certain advantages that allow the mission to be carried out more efficiently, and there appear to be such advantages. Making use of ITER physics and technology, using ITER as a prototype, and adopting the reactor and processing technology being developed in the nuclear program could lead to a fusion-driven sub-critical reactor for the transmutation of spent nuclear fuel, fissile breeding or disposition of weapons-grade plutonium being on-line by 2040, as compared to the plans for putting critical and accelerator-driven sub-critical reactors on-line for such missions by 2030. All of the R&D needed to develop the fusion neutron source for such a facility is directly on the path to fusion power (in fact is needed for an electric power DEMO); and the operation of a fusion-driven sub-critical reactor potentially could also serve the purposes envisioned for a 'volume neutron source', thus taking the place of such a device in the development path to fusion power.

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