

NUCLEAR MISSIONS FOR FUSION (TRANSMUTATION, FISSILE BREEDING & Pu DISPOSITION)

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SUMMARY

There are potential applications of fusion neutron sources to ‘drive’ sub-critical fission reactors to perform one or more possible ‘nuclear’ 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 $P_{\text{fus}} \leq 250$ MW, fusion power density $\beta_N \leq 2.5$, 14 MeV neutron wall load $\Gamma_n < 1$ MW/m² and power amplification $Q_p \leq 2$). 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 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.

NUCLEAR MISSIONS

General

There are several possible nuclear missions that could employ fusion neutron sources to drive sub-critical reactors, corresponding to the several scenarios for the future of nuclear energy being discussed within the nuclear community and the government. The transmutation (by neutron fission) of the plutonium and higher actinides in spent nuclear fuel (SNF) to reduce capacity requirements for high-level waste repositories (HLWRs) and, secondarily, to extract the remaining energy content from the SNF and ‘dispose of’ reactor-grade plutonium is a potential mission in all scenarios for the future of nuclear energy. 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 actinides from SNF for the transmutation (by neutron capture) of fertile U-238 into fissile Pu for fueling light water reactors (LWRs) is foreseen as a necessity. The SNF transmutation mission is less demanding in terms of fusion power (neutron source) level than is the Pu breeding mission, because of the lower multiplication factor of an optimized plutonium breeding reactor, but the other requirements on the fusion neutron source are similar. The ‘disposition’ of surplus weapons-grade plutonium by using it as reactor fuel provides an additional mission similar to the SNF transmutation mission.

Transmutation Mission¹⁻⁶

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 representative of the possible nuclear missions 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 by 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 8 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 actinides. If the HLWR is not sealed for 100 or so years after the SNF is removed from a reactor, the Pu and actinide 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 actinides 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 actinides 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 that predict that (with repeated recycling) in excess of 99% of the Pu and higher actinides 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; e.g. 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.

Fissile Breeding and Plutonium Disposition Missions

The 'fissile breeding' and 'plutonium disposition' missions could be carried out as variants of the recycling/reprocessing scenario described above for the 'transmutation' mission. 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 actinides 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 potential energy content of the uranium ore is the motivation for the 'fissile breeding' mission.

If weapons-grade plutonium is blended in with the SNF plutonium and higher actinides 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.

TECHNICAL REQUIREMENTS

Requirements for a 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. Recent studies⁷⁻¹⁵ provide some indication of these requirements.

Tokamak Neutron Source Requirements

A tokamak neutron source for a sub-critical transmutation reactor could be designed using the existing physics and fusion technology databases that were used as the basis of the ITER design¹³⁻¹⁵, with a few exceptions. Such a tokamak would be based on the ITER superconducting magnet, first-wall, divertor, heating-current drive, tritium, etc. systems, but would likely use a liquid metal coolant for compatibility with the transmutation reactor and a ferritic steel structural material of the type being developed for nuclear applications. The parameters of such a tokamak recently have been calculated to be about ($R = 4.5\text{m}$, $a = 0.9\text{m}$, $\kappa = 1.8$, $I = 6\text{ MA}$, $B_0 = 7.5\text{ T}$, $H(y,2) = 1.0$, $\beta_N \leq 2.5$, $\eta_{cd} = 0.03\text{-}0.04$, $f_{bs} = 0.2\text{-}0.4$, $\gamma_{cd} = 0.35\text{ Amp}/(\text{Wm}^2)\times 10^{-20}$, $Q_p \leq 2$, $P_{\text{fusion}} \leq 225\text{ MW}$, $\Gamma_n < 1\text{ MW/m}^2$, $q_{FW} < 0.3\text{ MW/m}^2$). If the superconducting magnet system is replaced by a liquid nitrogen cooled copper magnet system, the major radius and the fusion power are reduced to $R \approx 3.0\text{ m}$ and $P_{\text{fusion}} \leq 150\text{ MW}$ in a device with the same Q_p , but the electrical power amplification factor drops from $Q_e = 5$ to 1. A recent Russian study of a low aspect

ratio tokamak neutron source with copper magnets has the parameters ($R = 2\text{m}$, $a = 1\text{m}$, $\kappa = 1.7$, $I = 5.85\text{--}6.65\text{ MA}$, $B_0 = 3.9\text{ T}$, $H(y,2) = 1.4$, $\beta_N = 3\text{--}3.55$, $\eta_{cd} = 0.05\text{--}0.1$, $f_{bs} = 0.52\text{--}0.71$, $Q_p = 2.4$, $P_{\text{fusion}} = 72\text{--}80\text{ MW}$, $\Gamma_n = 0.4\text{--}0.44\text{ MW/m}^2$, $q_{fw} = 0.31\text{--}0.34\text{ MW/m}^2$). The principal advancement needed in the present physics database to realize such tokamak neutron sources is in the area of non-inductive current drive efficiency and/or bootstrap current enhancement to achieve quasi-steady state operation.

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 will 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, all of this R&D 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. Recent studies have shown 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 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' actinides, 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 actinides in the fluoride salts, separation of fission products from actinides, and corrosion control of molten salt with ferritic steels.

The use of long-lived silicon carbide fuel pellets in gas-cooled reactors is another technology that is receiving increased attention.

*Fusion Proton Transmutation of Fission Products*¹⁶

Some of the most radiologically troublesome fission products have small neutron cross sections, particularly for fast neutrons, which makes their transmutation into stable isotopes by neutron transmutation more problematical than for the actinides. The possibility of irradiating such fission products with the 15 MeV protons that are produced in D-³He fusion has been investigated. Long-lived isotopes can be transmuted into much shorter lived isotopes by high energy proton capture: e.g. ¹²⁹I ($t_{1/2} > 10^7$ y) into ¹²⁹Xe ($t_{1/2} < 10^{-1}$ y); ¹³⁵Cs ($t_{1/2} > 10^6$ y) into ¹³⁵Ba ($t_{1/2} < 10^{-2}$ y); ⁹³Zr ($t_{1/2} > 10^6$ y) into ⁹³Nb ($t_{1/2} < 10^2$ y); ⁹⁹Tc ($t_{1/2} > 10^5$ y) into ⁹⁹Ru ($t_{1/2} < 10^{-3}$ y). Although the cross sections, hence the transmutation rates, are uncertain, fusion proton transmutation might offer a promising option for disposing of long-lived fission products.

INITIATION AND DURATION OF THE TRANSMUTATION MISSION

The Generation IV nuclear reactor planning activity 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 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 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 3/1 ratio). For example, in a recent study of a sub-critical ($k \leq 0.95$) fast reactor driven by the superconducting tokamak neutron source described above, the transmutation reactor produced a net 1800 MWe ($Q_e = 5.0$) and would support (transmute the SNF discharged from) several LWRs producing a total power of 4500 MWe.

The duration of the transmutation mission will depend on the future of nuclear power. If nuclear power is phased out when the present reactors end their life, which is currently 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 introduction of purely fusion power plants in the latter half of the century.

COMPARISON OF FUSION WITH THE COMPETITION

The competition of fusion-driven sub-critical reactors for the transmutation mission are 1) critical fast 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. When the neutron multiplication constant, k , exceeds $1+\beta$, where β is the delayed neutron fraction, the neutron population and fission

heating will increase exponentially with a period of $T \approx \Lambda / (k - 1 - \beta)$, where the neutron lifetime is $\Lambda \approx 10^{-6}$ s in a fast spectrum reactor, a condition to 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 periods (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 actinide 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 actinides 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 $0.05 + \beta$ than the reactivity margin of β for a critical reactor. This larger reactivity margin would allow the use of reactor designs with larger concentrations of Pu and minor actinides (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 severity of possible reactivity insertion accidents, and/or allow 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 stress transients 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 one or more very localized targets and beam ports 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 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 a non-conventional reactor geometry.

EVALUATION CRITERIA

1. *Will the application be viewed as necessary to solve a “national problem” or will the application be viewed as a solution by the funding entity?* The 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 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 worldwide as solving a “national problem” and there is substantial R&D support for this mission, but the urgency felt by governments to implement a transmutation solution is not so great as for the weapons Pu disposal mission. The transmutation mission is longer term and continuing, and there appear to be some advantages to using sub-critical reactors, which would provide an opening for a fusion contribution. The plutonium 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.

2. *What are the technical requirements on fusion imposed by this application with respect to the present state of fusion and to the technical requirements imposed by electricity production?* The requirements on β , confinement, energy amplification Q_p , and fusion power level are at or below the ITER level, which is much less than the level required for commercial fusion electricity production.

The requirements on availability are more difficult to simply quantify. 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. If there are other viable options for transmutation, then high availability will be important for economic competitiveness. However, the transmutation mission is to destroy long-lived HLW in order to eliminate the need to build a new HLWR repository every 30 years (at present level of nuclear power production) or less (at increased level), which would have a great sociological/psychological impact on the acceptance of expanded use of nuclear power. Given this broader impact, the paramount issue may be technical feasibility, not economic competitiveness.

There is general, but not unanimous, agreement among people who have worked on the problem that sub-critical transmutation reactors will be needed to effectively accomplish the transmutation mission, because of safety constraints imposed on critical transmutation reactors by the small delayed neutron fraction of Pu and the higher actinides and by the absence of U-238 resonance absorption. If the fission reactor people are able to develop solutions to these safety issues that do not significantly penalize the net transmutation rate per unit power, then economic competitiveness (which depends on availability) will be the paramount issue regarding the use of fusion-driven sub-critical transmutation reactors. 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. Sub-critical reactors driven by tokamak fusion neutron sources based on ITER physics and technology and achieving about 50% availability would accomplish this transmutation mission.

If accelerator-spallation neutron sources are able to overcome the more demanding heat removal and radiation damage challenges and become technically feasible, then the economic competitiveness of fusion with accelerator neutron sources will become an issue for sub-critical reactors.

In summary, there is a possibility that an availability of about 50% may be acceptable for a fusion neutron source for the first generation of sub-critical transmutation reactors. By comparison, electric power producing fusion reactors must compete economically with existing means of producing electricity which have high availability (e.g. nuclear reactors routinely achieve > 90% availability).

Physics Requirements for a Tokamak Neutron Source for
Transmutation and for an Economically Competitive Fusion
Electric Power Tokamak Reactor

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

What R&D is required to meet these requirements and is it on the path to electricity production?

A tokamak fusion neutron source for the transmutation mission could be designed today using the ITER physics and technology design database, and ITER would serve as a prototype for such a neutron source. Additional physics R&D is required to achieve quasi-steady state operation, and additional technology R&D is required to achieve high component reliability, in order to achieve ~ 50%

availability for the first neutron source. Tritium breeding blanket R&D is required. All of this R&D is exactly the same as would be required for an electrical power fusion DEMO.

3. *What is the competition for this application and what is the likelihood that fusion can beat it?* The principle competition for the transmutation mission (and all nuclear missions) are critical fission reactors. However, a sub-critical reactor may have some safety-related advantages for the transmutation mission, which provides an opportunity for fusion and accelerator neutron sources to contribute. Because the fusion neutron source is distributed, whereas the accelerator neutron source is highly localized, the fusion neutron source may have some advantages with respect to component failure rates due to radiation damage and heat fluxes that must be handled.

INCORPORATION OF TRANSMUTATION (NUCLEAR) MISSION CAPABILITY INTO 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 electrical power development 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 one of 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 re-established with this goal. There is a need to development 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.

Expansion of the small ongoing systems/conceptual design investigation of the application of fusion to the transmutation (nuclear) mission is a necessary first step for incorporating the possibility of a transmutation (nuclear) mission into the OFES 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 investigated/developed in the nuclear program.

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Findings

There are a number of important 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 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 transmutation mission; the technical issue would be achieving high availability, which would require advances in component reliability and quasi steady-state physics operation.

"We recommend that DOE-OFES establish (1) a study at a sufficient level to evaluate the potential application of fusion to the transmutation of spent nuclear fuel, and (2) a 'watching brief' of the current DOE-NE program on nuclear fuel cycle analysis (including spent fuel recycling/transmutation) to guide this study. Evaluation of technical issues for a fusion-driven transmutation reactor design concept, evaluation of the competitiveness of sub-critical reactors driven by fusion neutron sources for the destruction of long-lived radioisotopes in spent nuclear fuel, and identification of the required fusion R&D would be the first objective of this study. 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 and fuel cycles being investigated/developed in the nuclear program."