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Fusion–Fission Transmutation Scheme—Efficient destruction of nuclear waste

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ABSTRACT

A fusion-assisted transmutation system for the destruction of transuranic nuclear waste is developed by combining a subcritical fusion–fission hybrid assembly uniquely equipped to burn the worst thermal nonfissile transuranic isotopes with a new fuel cycle that uses cheaper light water reactors for most of the transmutation. The center piece of this fuel cycle, the high power density compact fusion neutron source (100 MW, outer radius <3 m), is made possible by a new divertor with a heat-handling capacity five times that of the standard alternative. The number of hybrids needed to destroy a given amount of waste is an order of magnitude below the corresponding number of critical fast-spectrum reactors (FRs) as the latter cannot fully exploit the new fuel cycle. Also, the time needed for 99% transuranic waste destruction reduces from centuries (with FR) to decades.

1. Introduction

Given the long ramp-up time for any large-scale energy technology, a non-intermittent and presently mature technology like nuclear fission seems well suited, along with renewables, to provide the appropriate low-carbon energy mix needed to prevent the dangerous consequences of anthropogenic climate interference [1]. Invention of affordable and timely technical solutions to nuclear waste disposal and proliferation is crucial to any such rapid expansion of nuclear fission energy.

We propose here a waste destruction strategy – a Fusion–fission Transmutation System (FFTS) – that we will show to be considerably less costly than known alternatives. It is based on the fusion–fission hybrid reactor (Hybrid) in which fast neutrons, generated in a high density compact fusion neutron source (CFNS), strongly augment the rate of nuclear reactions in a surrounding subcritical fission blanket fuelled by transuranics (Fig. 1).

The generic Hybrid, combining neutron-rich fusion with energy-rich fission, was first conceptualized several decades ago [2–8]. However, it is only now that accumulated advances in fusion science and technology allow designing a neutron source like CFNS that is simultaneously compact and high power density. The former is essential for efficient coupling to the fission blanket, and the latter is key to efficient neutron production necessary to yield high neutron fluxes needed for effective transmutation. The recent invention of the SuperX-Divertor (SXD) [9], a new magnetic configuration that allows the system to safely exhaust large heat and particle fluxes peculiar to CFNS-like devices [10], is a crucial addition to the underlying knowledge base.

Creating a source of fast neutrons is scientifically a much more modest goal than creating an economical pure fusion reactor. Following the “neutron route” to destroy fission waste (and thereby promote fission energy) is by far the least technically demanding option through which fusion can make a significant contribution to the energy scene in the near term.

Since many of the long-lived biologically hazardous transuranics do not readily fission in the thermal neutron spectrum of the standard utility light water reactor (LWR) [11], all waste destruction schemes use either fast-spectrum reactors (critical FRs) or external-neutron-driven subcritical assemblies. Both FFTS and accelerator-driven systems (ADS) belong to the latter category. Since CFNS neutrons are expected to be an order of magnitude

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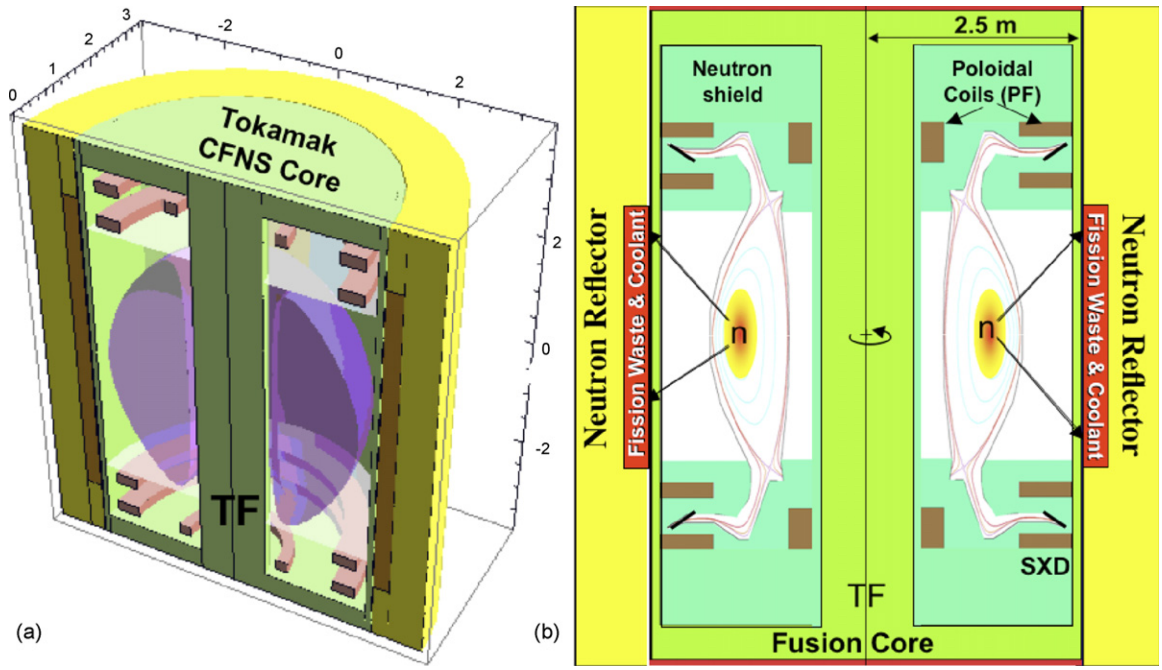

Fig. 1. (a) 3D and (b) 2D schematics of a CFNS-based Fusion–Fission Hybrid shown with actual dimensions used in MCNPX [27] calculations.

cheaper than those from ADS, we will not pursue ADS any further. A National Academy Study [12] found it to be not only expensive but also unreliable for steady-state operation.

The subcritical FFTS acquires a definite advantage over the critical FR approach because of Hybrid's ability to support an innovative fuel cycle that makes the cheaper LWR do the bulk (75%) of the transuranic transmutation (for thermally fissile isotopes like Pu239). This cycle is not accessible to the critical FR approach because the remaining 25% marginally fissionable long-term radiotoxic and biohazardous transuranic "sludge" is a poor reactor fuel that defies destruction in stable operations. It requires the powerful boost of CFNS neutrons – an order of magnitude stronger than that obtained from an ADS – to fully burn this "sludge". The cost cutting and time saving synergy between the fuel cycle and the subcritical Hybrid assembly will be established later.

The fission part of the Hybrid consists of standard FR components; the real challenge of the Hybrid lies in the creation of the CFNS, expected to be a relatively inexpensive fusion neutron source of sufficiently high flux that couples efficiently to the fission blanket.

2. Fusion—CFNS

The building of a Component Test Facility (CTF) [13–16] for the purpose of developing and testing components with acceptable lifetime in a fusion neutron environment has been an objective of fusion research. Incorporating Super-X-Divertor (SXD) geometry (for high power exhaust) in the design of a generic CTF would yield a device slightly more ambitious than the envisaged CFNS. Since CTF's epitomize engineering developments necessary for a pure fusion power reactor, successful implementation of the CFNS-Hybrid will be a milestone in fusion engineering; the near-term Hybrid era may prove to be a critical stepping stone to pure fusion power.

Drawing from the knowledge base of fusion research and respecting technological constraints, we conceptualize a reference CFNS small enough to fit inside a fission blanket but powerful enough to supply sufficient neutrons to meet the transmutation goals. It is a tokamak with operational parameters (Table 1) lying conservatively within the bounds set by experimental demonstrations on current tokamaks. Future optimizations will cover a significant range of alternative parameter choices to explore.

The three most important dimensionless physics parameters [17,18], determining the scientific feasibility of the reference CFNS are

(1) Plasma $\beta = P/B^2$, the ratio of the core plasma pressure P to the magnetic field pressure. Since fusion power density is roughly proportional to P^2, high P or β (for a given B) holds the key to high power density.
(2) Beta normal $\beta_N = \beta/I_N$, the ratio of plasma beta to the normalized plasma current $I_N = I/(aB)$ (the original Troyon definition is used here, since it has the greatest generality [18]), is a physics indicator of plasma pressure. Considerations of magnetohydrodynamic (MHD) stability constrain attainable β_N. Pushing β_N, i.e., searching for equilibria (by wall stabilization, magnetic field shaping, the profiles of current, density, temperature, etc.) that remain MHD-stable for larger and larger values of β_N, is a hotly pursued research goal. Since β is proportional to β_N, a higher power density CFNS will require higher β_N. For a given β_N, β (power density) may be increased by increasing I_N.
(3) The factor H that measures the confinement time of the given discharge in terms of the average H-mode confinement time [17]. Both β_N and H are figures of merit; the higher they are, the

Table 1
Parameters for the reference compact fusion neutron source (CFNS).

Major radius	1.35 m
Aspect ratio	1.8
Plasma elongation	3
Current drive power	50 MW
Average plasma density	$(1.3–2.0) \times 10^{20}\ \mathrm{m}^{-3}$
Greenwald ratio	0.14–0.3
Minimum plasma safety factor q	2–2.5
Plasma beta	15–18%
Plasma current	10–14 MA
B at plasma center	2.9 T
B at central coil	7 T
Average fusion neutron wall load	$0.9\ \mathrm{MW/m^2}$

Table 2
Parameters for fusion devices. Outer *R* is the major plus minor radius in meters. Rows 1–3 (4–7) show current (next generation) machines.

Device	Outer *R*	Power (MW)	Sustained β_N	*H*	*Q*
NSTX [13,19], MAST [20]	1.6	–	≤4.5	≤1.5	–
DIII-D [21]	2.2	–	≤4.4	≤1.5	–
JET-TFTR [17]	4	10–16	≤3	≤1.5	0.25–1
CFNS [10]	2.1	100	2–3[a]	1–1.2	~2
ST-CTF [14]	2.2	75–280	2.5–4	1.4–1.6	~2–4
CTF-FDF [17]	3.1	100–300	3.7–4	1.3–1.6	~2–4
ITER [22,23]	8.0	400	2–3	1–1.5	~5–10
Low-Cost Reactor [24,25]	6–9	2000–3500	4.0–5.6	1–1.5	>15

[a] Attaining $\beta_N > 3$ is known to add substantial challenges to plasma control and operation.

better the quality of the fusion plasma. If the CFNS plasma is to produce 100 MW of fusion power in a relatively small volume, its β_N and *H* must remain above a certain threshold.

Table 2 shows the size (outer radius), the fusion power level, and the ranges for β_N, *H*, and *Q* for two distinct sets of machines [13–25]. The entries in the first three rows show experimentally demonstrated values, while for the future machines (CFNS onwards), these ranges reflect requirements for their adequate functioning. *Note*:

(1) Regarding β_N, *H*, and *Q*, a CFNS is considerably less demanding (and therefore easier to build) than a pure fusion reactor. In terms of the energy gain factor *Q*, CFNS ($Q = 2$) is much less ambitious than ITER ($Q = 5$–10). Experimentally, affecting even a modest increase in β_N and *H*, in sustained operation, is difficult. Current experiments routinely explore the *H* and β_N ranges relevant to a conservative CFNS, but extrapolation of present experimental results to reliable operations at either $H \sim 1.5$ or β_N in the range 4 and above is much more uncertain.
(2) Because of its relatively modest physics requirements, building a device of CFNS caliber is well within existing fusion expertise as reflected in the impressive ranges of accessed β_N and *H*. The reference CFNS, with similar dimensionless parameters, could be viewed as a higher-B extrapolation of NSTX [19] and MAST [20]. For the same β, higher *B* means higher core pressure *P* implying higher power density, the defining hallmark of CFNS. Naturally future experiments on NSTX/MAST will be of direct relevance to FFTS.

But for the plasma burn duration, we have situated the CFNS physics comfortably within the reach of present experiments. The machines in rows 1–3 of Table 2 have pulse lengths of up to 10 s while the proposed machines, including CFNS, are designed for continuous operation. There are, indeed, current machines like Tore Supra [17] and KSTAR [17] that do have pulse lengths of ~1000 s. It does not appear that physics considerations should limit the pulse length, but some technological advances are required for the extremely long pulses envisaged for a CFNS. In fact the development of longer and longer pulses is likely to be a major part of the R&D effort towards realizing a CFNS. The march towards continuous operation is expected to be steady but challenging. We now summarize the broad features of the tokamak-based CFNS experiment and device (for details see [10,13]):

(1) Constraints of compactness and high power density dictate the parameter choice (Table 1). Operating at $Q \sim 1$–2, the CFNS will use normal copper (rather than super conducting) coils. The choice of aspect ratio 1.8 (versus 1.5 for the ST-CTF) was, in part, motivated to allow for the possible need for neutron shielding to extend the life of the center post.
(2) Steady-state maintenance of plasma current precludes a purely inductive drive. External power applied to drive the steady-state currents heats the plasma, assists in maintaining thermonuclear temperatures, and allows external control of the plasma. The fraction of driven current required for increasing stability and confinement is assumed to be in the experimentally warranted range between 0.5 and 0.6 (experimentally observed and anticipated in ITER steady-state operations [23]). Assuming an efficiency of 2–$3 \times 10^{19}(\langle T_e \rangle / 10\,\mathrm{kev})\mathrm{A/Wm}^2$ [10,22,24], some optimal mix of current drive schemes with ~50 MW power will be needed.
(3) For a given β_N, various known mechanisms for boosting β and core plasma pressure *P* will be invoked including strong shaping via lower aspect ratio ($A = 1.8$), higher elongation $\kappa = 3$ (consistent with vertical stability) and triangularity δ. Recent experimental and theoretical advances show that much higher plasma pressure is possible in low-aspect-ratio machines with strong shaping [18–20].
(4) The CFNS can be run in the so-called “plasma-hybrid” mode of confinement [22]. Experiments have already achieved $H \sim 1.2$ in such modes, though values of *H* up to ~1.5 have been obtained in discharges with reverse central shear. To produce 100 MW of power, a CFNS in a hybrid mode with $\beta_N = 2$–3 would require an *H* factor of ~1, and a current drive power of ~ 50 MW [3].
(5) To address the critical problem of safely exhausting the large heat and particle flux from a compact CFNS, the SuperX-Divertor (SXD) will be employed [9,10]. By restructuring the edge region–placing the divertor plate at a radius 2–3 times the radius at the main X-point, and increasing the magnetic distance between the plate and the plasma by ~4 times—the thermal capacity of SXD becomes approximately five times that of the corresponding ITER-like standard divertor. Such enhanced SXD capacity is essential for CFNS operation. Even after great developmental efforts, no alternatives exist within the ITER engineering envelope. Also, if one tried, for example, to dissipate heat via extra radiation from the core, the demands on required *H*, to maintain confinement, could become much higher [26].
(6) The SXD geometry also allows a substantial shielding of the divertor components from neutron damage. MCNPX [27] and ORIGEN-2 [28] calculations indicate that the neutron damage to the divertor plate can be reduced by over an order of magnitude. Consequently, substantial divertor technology developed for ITER could be transferred to CFNS despite the fact that the anticipated CFNS fusion neutron fluence will be an order of magnitude higher.
(7) Since SXD can handle more than 50% of the total heat, the surface heat loads on the main chamber can be kept below the most stringent (0.2–0.6 MW/m^2) suggested engineering limit [29]. With fusion neutron power fluence also limited to 1–2 MWyr/m^2, the engineering requirements on a CFNS are far less stringent than for pure fusion reactors (~10 MWyr/m^2).

Thus, most of the physics and large parts of the technology already exist to warrant an engineering design of a CFNS. Several important issues, however, could be addressed only by a prototype CFNS with a mission strongly overlapping that of a CTF. These include developing and testing solutions for (a) materials tolerant of high neutron fluences, (b) device availability growth, (c) tritium retention in plasma-facing materials, and d) tritium breeding and handling at high throughputs. Though similar, the CFNS mission is less demanding than the CTF mission, which requires solutions adequate for a pure fusion DEMO [16]. We believe that ongoing and future fusion research will expand the knowledge base required for building a prototype CFNS in the near-term. Although our reference CFNS is 100 MW, an even less demanding 50 MW neutron source may prove to be adequate if the fission blanket were to be appropriately optimized.

Preliminary calculations show that a tritium breeding ratio (TBR) over 1.1 is obtainable by adding, to the hybrid assembly, a Lithium Titanate blanket with homogenized density of 1.9 g/cm^3. Most of the tritium is produced in a blanket outside the fission lead shield. Calculations are in progress to determine optimized blanket positioning to utilize neutrons that are lost in regions other than the fission blanket, and indications are that a TBR over 1.3 will be possible without degrading fission performance.

3. The Fusion–Fission System

Department of Energy (DOE) sponsored programs (the Advanced Fuel Cycle Initiative (AFCI) [30] and Global Nuclear Energy Partnership (GNEP) [31]) have put forth a number of conceptual fuel cycles involving synergistic mixes of thermal and fast-spectrum fission reactors (FR) that lead to near-zero net production of the hazardous, hard-to-dispose transuranics.

The search for new fuel cycles is prompted by the fact that since metal-cooled fast-spectrum reactors are more expensive to build and operate than LWRs [32], it is economically advantageous to complete as much transmutation as feasible in cheaper LWRs. The most promising such path, offering up to 75% burnup of transuranics, involves a single recycle in an inert matrix, fertile-free fuel form (IMF). However for the overall fuel cycle to adopt the IMF-LWR burnup, the advanced FR must have the ability to safely fission the residual “sludge” consisting mainly of thermal nonfissile species: Pu242, Am243, Cm244 and Cm246 [11]. Though constituting only 25% of the original mass, these isotopes contain almost all the long-term radiotoxicity of the original transuranics.

The transuranic “sludge” is extremely unfavorable as a fuel for any critical system. It has poor criticality characteristics: a low delayed neutron fraction leading to problems of control and a strongly positive coolant void reactivity coefficient (because the fuel is composed almost entirely of threshold fissioners). Thus a critical FR-based waste destruction strategy cannot fully exploit the advantages inherent in the IMF-LWR option; the leftover toxic residue just cannot be safely burnt in critical reactors.

Although a subcritical assembly like the Fusion–Fission Hybrid [2–8] would appear to be ideally suited for incorporating fuel cycles with the IMF-LWR phase, earlier attempts at achieving complete burnup of thermal nonfissile transuranic “sludge” (mainly Pu242, Cm244 and Am243) were not successful. The situation, however, changes with the current proposal, where the Hybrid assembly is powered by a strong source ∼3.6 × 10^{19} [n/s] of fast neutrons from a CFNS producing a total of 100 MegaWatt of DT fusion power. This source lets the Hybrid run in a deep subcritical mode allowing a great deal of latitude in k_{eff}, the multiplication factor in the fission blanket ($k_{\text{eff}} = 1$ is the criticality condition). With strongly boosted subcritical multiplication, the Hybrid, operating stably and safely, can rapidly and comprehensively burn the transuranic “sludge” while producing considerable fission power.

Fig. 2 depicts the fuel cycle of the FFTS strategy, comprising both the thermal and the fast Hybrid components. Since the IMF-LWR incineration removes the more transmutation-friendly species, the total number of advanced (and more expensive) Hybrids required to consume the residue (25%) is drastically reduced. The FFTS, unlike the strategies outlined under the GNEP and AFCI programs, fully exploits the transmutation potential of the IMF concept that lies at the heart of the new fuel cycle.

Fig. 1 displays 3D and 2D schematics of the CFNS-fed Hybrid. The fusion neutron source is surrounded by a 25-cm thick, 300 cm high, liquid sodium cooled annular fission blanket comprising a lattice of HT-9-clad metallic TRU/Zr cylindrical fuel elements. For this study, we have relied mostly on existing technologies, designs and materials. The fuel element geometries and lattice pitch are taken directly from existing advanced conceptual fast reactor designs [33]. The composition of the transuranics discharged from the IMF was taken from [11]; a general discussion of the feasibility of loading LWR cores with IMF fuel assemblies can be found in [34]. The IMF attains a burnup of 700 MWd/kg (MWd = MW days); 75% of the transuranics are fissioned during this step of the fuel cycle. The remaining “sludge”, mainly three species (Pu242 (44% by mass), Cm244 (23%) and Am243 (13%)) must be burnt in the Hybrid assembly.

The blanket dimensions and actinide volume fraction in the fuel pins were chosen to match the desired initial k_{eff} and to achieve an average fission power density that allows sustained operation at a system-wide fission power of 3000 MWt (Megawatts thermal). The Monte Carlo particle transport code MCNPX [27] was used to perform the particle transport simulations and material damage rate calculations. Burnup calculations were executed with ORIGEN2.2 [28] libraries using interaction probabilities obtained from transport simulations.

Figs. 3 and 4 display representative results from MCPNX and related calculations, to demonstrate the efficacy of “sludge” destruction in the Hybrid. The red curve in Fig. 3, following the evolution of the fuel multiplication properties with burnup, reveals that k_{eff} first increases at low neutron fluences, reflecting the breeding of readily fissile isotopes such as Cm245 (similar to ADS, accelerator-based transmutation schemes). For this residual fuel, the steadiness of k_{eff} with burnup is even more striking than for the ADS fuels. The blue curve (notice the log scale), showing the fusion power needed to maintain the fission blanket at 3000 MWt, is obtained from the red by factoring in the fusion neutron multiplicity. Even a single-batch fuel management strategy leads to an

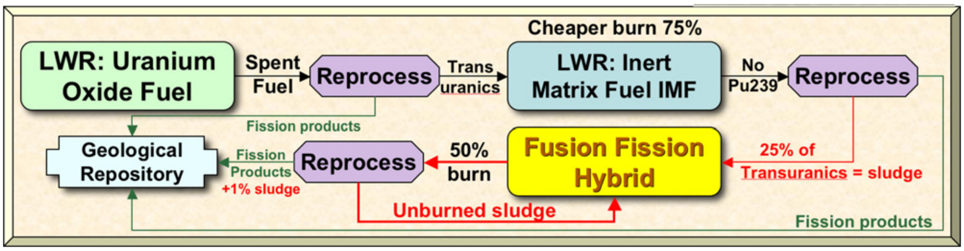

Fig. 2. Zero Net Transuranic Production Fuel Cycle featuring full transuranic burn-down in a Fusion–Fission Hybrid. UOX: uranium oxide fuel, FP: fission products, SF: spent fuel.

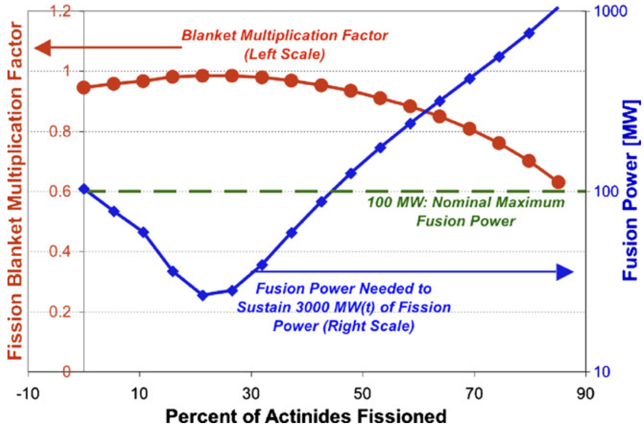

Fig. 3. Fission blanket multiplication factor and fusion power to support fission chain reaction at 3000 MWt vs. burnup, with single-batch fuel management strategy.

exceptionally deep burnup – about 400 MWd/kgIHM – implying fissioning of 45% of the initial loading. A deep burnup decreases the number of recycle "passes" required, and hence the time and cost, to transmute a given quantity of "sludge". As with ADS systems, additional passes allow very high burnups.

Extensive lead shielding (Fig. 1) limits leakage while boosting the strength of the fusion neutron source via 0.60 (n, $2n$) reactions per fusion neutron (MCNPX). The sodium-cooled lattice geometry, shown in red, offers a desirable population of fast-spectrum neutrons. The MCNPX calculations showed that the fresh-core configuration, when coupled to the full 100 MWt fusion neutron source, would produce fission power ∼3000 MWt; the heat removal system of the assembly will be designed to handle a steady-state 3000 MWt. In practice, system operations would call for using some combination of a burnable control absorber and adjustment of the fusion blanket power level. The discharge condition is the point at which the fission power drops below 3000 MWt given no control absorber and the full 100 MWt of fusion power. Given the response of the blanket to the fusion source, this was found to take place when the blanket k_{eff} drops to about 0.93. This figure could be decreased by increasing the multiplicity of fusion neutrons, increasing the transuranic concentration in the metallic fuel, decreasing the aluminum content of the system, or substituting lead for sodium as the coolant.

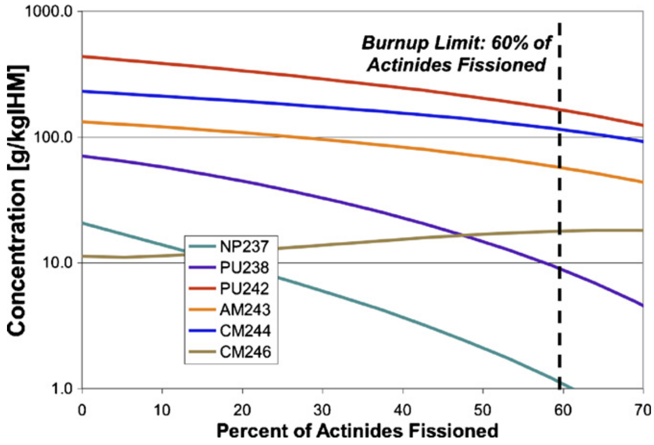

Fig. 4. Evolution of transuranic inventories with burnup (IHM: initial heavy metal).

Using standard techniques of multi-batch fuel management (i.e., only a portion of the used fuel is replaced upon each refueling stoppage, so that there is always a fresh portion of fuel in the system) [35], we find that a three-batch strategy can push the burnup fraction to ∼60% (540 MWd/kg). The evolution of the fuel composition is shown in Fig. 4; 10-fold reductions in Np237 and Pu238 inventories are seen, with substantial reductions in Am and Cm inventories as well. The residue would be recycled and topped up with "sludge" from discharged IMF for the next pass in the Hybrid.

Table 3
Fleet composition, Hybrid system vs. conventional FR transmuter (GWt = GigaWatt-thermal).

	Hybrid system	Conventional FR system
LWR, UOX fuel (GWt)	246	300
LWR, IMF fuel (GWt)	54	0
Hybrid or Gen-IV SFR [37] (GWt)	16.7	163
Number of reactors needed	6	54

Per-pass burnups approaching 90% are possible if one lets the fission power fall, for instance, to 1000 MWt (below the reference 3000 MWt). While this approach would reduce the ability of the system to cover costs by sale of electricity, it would decrease the number of refuel-and-reprocess "passes" needed to consume residual transuranics.

4. Discussion and conclusions

To summarize:

(1) There can be more than one path to "complete" (∼99%) destruction of the transuranic waste. The optimum mix of per-pass burn up and corresponding number of reprocessing passes will be determined by future analysis.
(2) The basic FFTS strategy is continual recycle of "sludge" in the Hybrid and removal of fission products to a geological repository. Since long-lived FPs from "complete" destruction have about 1% of the biohazard of the original transuranics, and the reprocessing losses of transuranics to the FP waste stream from commercially viable reprocessing is estimated to be some fraction of 1%, about 1% of transuranics will end up in the waste stream.
(3) The FFTS drastically reduces the footprint of waste in a geological repository per unit energy produced, and hence, the environmental cost of the fission aftermath [36,37].

We conclude by comparing FFTS (UOX-IMF-Hybrid) performance with that of the more conventional UOX-FR [12] system, in the context of a US-like fission economy of 300 GWt of LWR capacity:

(1) Table 3, displaying the principal result of this paper, shows that by shifting much of the transmutation burden to the cheaper LWR (an option less suitable to FR), the FFTS affects a 10-fold reduction in the number of required expensive fast-spectrum systems.
(2) Another order of magnitude advantage over the critical FR approach is accessible to FFTS in the lowering of transuranic mass that must be recycled through the system. The contributing factors include the IMF-LWR phase, the critical FR dependence on fertile U238 for stability, and differences in burn-up fractions.
(3) Differences in per-pass burn up fractions (FR ∼ 10%, IMF + Hybrid ∼ 60–90%) further imply that 99% transuranic waste destruction can be accomplished in decades (via FFTS) rather than in centuries (FR approach).
(4) Finally, since Pu239 is fully and relatively quickly burnt in the IMF-LWR phase, proliferation risks, current and future, are minimized.

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