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# Reprocessing free nuclear fuel production via fusion fission hybrids

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ABSTRACT

Fusion fission hybrids, driven by a copious source of fusion neutrons can open qualitatively "new" cycles for transmuting nuclear fertile material into fissile fuel. A totally reprocessing-free (ReFree) $Th^{232}$–$U^{233}$ conversion fuel cycle is presented. Virgin fertile fuel rods are exposed to neutrons in the hybrid, and burned in a traditional light water reactor, without ever violating the integrity of the fuel rods. Throughout this cycle (during breeding in the hybrid, transport, as well as burning of the fissile fuel in a water reactor) the fissile fuel remains a part of a bulky, countable, $ThO_2$ matrix in cladding, protected by the radiation field of all fission products. This highly proliferation-resistant mode of fuel production, as distinct from a reprocessing dominated path via fast breeder reactors (FBR), can bring great acceptability to the enterprise of nuclear fuel production, and insure that scarcity of naturally available $U^{235}$ fuel does not throttle expansion of nuclear energy. It also provides a reprocessing free path to energy security for many countries. Ideas and innovations responsible for the creation of a high intensity neutron source are also presented.

## 1. Preamble and introduction

A fusion fission hybrid (Hybrid) harnesses fusion-generated neutrons to greatly augment fission reactions [1], and thus, allows the implementation of nuclear fuel cycles that may not be readily accessible to fission-only systems. This paper has two main objectives; (1) an exposition of scientific explorations of ideas and innovations that may lead to a near term technically feasible hybrid, and (2) a discussion of the more significant and unique applications of the hybrid, in particular, in the arena of nuclear fuel breeding – that is breeding fissile fuel ($Pu^{239}$ and $U^{233}$) from the naturally occurring fertile materials ($U^{238}$ and $Th^{232}$) to feed the standard nuclear reactors (for example the light water reactors (LWR)).

Amongst the breeding cycles that we have investigated, a particular Thorium based fuel cycle that avoids reprocessing altogether (to be referred as Reprocessing-Free = ReFree), will be emphasized here. The ReFree cycle may be not only the most proliferation resistant of the known fuel producing schemes (including alternative fuel production via FBRs [2] and enrichment via centrifuges [3]), it is also found to be very efficient in the sense that a single hybrid would suffice to fuel ~3.5–4 LWRs of the same thermal power; such a high support ratio will translate into good economics.

Today, nuclear energy offers, perhaps, the most mature, tried and tested option available for supplying base-load carbon-free electricity. Driven by a variety of considerations, many countries are building, or are planning to build a large numbers of nuclear power plants. The primary reason for this activity may be simply to cope with the rapidly growing energy needs but the fact that nuclear power plants can directly replace base load coal power plants (whereas intermittent renewables cannot readily do so in the foreseeable future) may also have played a decisive role. In addition, several countries pursue nuclear energy as a means to become energy self-sufficient through nuclear fuel breeding.

Most commercial nuclear plants, likely to be built in the next several decades, will be predominantly [4] Light Water Reactors (LWRs) that are cooled and moderated by ordinary water and use enriched Uranium as a fuel. Since the percentage of the fissile isotope $U^{235}$ is only ~0.7% of the natural occurring Uranium (most of it is $U^{238}$ that is not fissile in the thermal neutron spectrum), the standard mode of nuclear power production extracts less than a percent of the total energy stored in Uranium [5].

Because of the scarcity of $U^{235}$ (the only naturally occurring fissile isotope), the nuclear economy may, eventually, face fuel shortages, particularly, if nuclear energy were to substantially replace base load coal power over the next thirty to forty years. In addition, since a typical modern LWR is designed, and is being licensed for over 60 years of operation, (ultimate lifetimes could well be 80 or even 100 years for some designs), the resurgence and sustenance of nuclear economy in the next several decades will demand a guaranteed supply of fuel up to, and extending past 2100 – manufacturers would not build and utilities would not buy unless they are sure that adequate fuel will be available for the expected life time of the reactor. Fueling requirements for the

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lifetime of this new generation of reactors (past 2100), therefore, could become a serious issue in the much nearer term.

The fuel supply problem, in principle, is technically solvable within the realm of nuclear fission. There can be two straightforward approaches towards this end:

(1) The first approach will directly use the much more abundant $U^{238}$. Although the isotope $U^{238}$ cannot fuel the typical LWR (because of its negligible fission cross section in the LWR neutron spectrum), it can be used as fuel in reactors in which the fission neutrons are not moderated (and cooled). Such fast spectrum reactors (FRs), that can directly utilize $U^{238}$, have been investigated for a long time in several countries. Commercial experience with FRs is limited but not zero. Unfortunately, to date, most commercial FRs have had serious problems with reliability, and economics; they have also been prone to accidents. One must appreciate, however, that even if conversion to FRs were possible at some future date, it will create a totally new parallel FR-based nuclear economy. It will still beg the question of fuel supply needed for the fleet of current and future LWRs built to satisfy the need for near term de carbonization of energy production. One must note that for a long time to come, *almost all of the growth in nuclear energy sector will be based on thermal reactors that will need fissile fuel*.

(2) The fast reactor can be used in another mode, that is, as a breeder of fissile fuel – that is, as a producer of fuel in addition to the amounts it needs to maintain its own criticality. In this incarnation, it is aptly called a fast breeder reactor (FBR), and development of FBRs is very much on the agenda of many countries. From the two naturally occurring fertile isotopes – Uranium ($U^{238}$) and Thorium ($Th^{232}$), one may breed excess fissile fuels – Plutonium (mainly $Pu^{239}$) and $U^{233}$ respectively – and keep any LWR fleet running almost endlessly. However an FBR based nuclear economy has excited much controversy; more pertinent objections may be summarized as: (1) in order to extract the fissile fuel to be sent to an LWR, copious amount of reprocessing and handling of $Pu^{239}/U^{233}$ is required creating serious problems on the nuclear weapon proliferation front, (2) FBRs are not efficient as producers of excess fissile fuel; an FBR cannot even supply enough excess fuel for a single LWR of comparable power, (3) the time required to build and fuel a large number of FBRs (they require a large amount of initial fissile loading) could be long, possibly too long to meet the challenge of future growing energy needs or evolving shortfalls of natural fissile fuel for a fleet of LWRs and other thermal reactors, and finally (4) FBRs, especially with fuel reprocessing, have not been found to be commercially competitive with LWRs, at least so far.

One is thus forced to conclude that the FR (FBR) path may not be a very attractive solution for assuring a dependable and economic fuel supply for the steadily growing nuclear industry firmly based on thermal spectrum reactors. It is, then, prudent to explore other options – including the ones not wholly within fission – lest the fuel scarcity becomes the Achilee's heel of nuclear power sorely needed as a near time, low carbon replacement for coal. Demonstrating the workability of just such an alternative – fuel production using fusion fission hybrids – provided the theme as well as the prime motivation for this work.

The basic idea of a Hybrid is as old as nuclear reactors [1]. All these years, one could not quite marshal it to help fission because the intense fusion neutron sources, required for effective breeding, were not on the horizon. Recent advances in fusion research, strengthened by several new ideas and innovations spanning fusion, fission (and their coupling), however, have set the stage for the conceptual design of a technically credible Hybrid driven by a compact fusion neutron source (CFNS). Although the main purpose of this paper is to present a critique of the Hybrid as a fuel-breeder, some description of the CFNS-Hybrid will also be given.

It may be some interest to make a small digression here. A Hybrid, just like an FR, does have another incarnation; instead of being an excess fuel breeder, it can function as a direct fission reactor. What is different and important is that unlike a standard fission reactor (LWR or FR), the Hybrid can safely operate with very bad fuel. The fusion neutrons can provide the extra neutrons needed to burn the "difficult to fission" isotopes like the minor actinides. Since these minor actinides comprise most of the very long lived radio toxicity in the spent nuclear fuel (the so-called nuclear waste) coming out of a thermal-spectrum reactor, the Hybrid has unique capabilities as a waste destroyer. Once in action, the Hybrid can help rid the nuclear industry of the three cardinal drawbacks associated with nuclear power – the accumulation of very long lived hazardous waste, proliferation concerns and future fuel scarcity.

Fusion fission hybrids are highly complex systems in which a fusion neutron source and a fission blanket must be optimally coupled to produce the best results. In order to investigate the efficiency and efficacy of the Hybrid (working, for instance, as a fuel maker), we have done detailed neutronic calculations in a system that incorporates realistic geometries of the fusion and fission parts. Distinguishing qualitative features of our reference ReFree cycle may be summarized as:

(1) Because the ReFree cycle requires no fuel reprocessing, it has major proliferation advantages. Fuel rods of the fertile $Th^{232}$ are exposed to neutrons in the hybrid to produce an appropriate small percentage of the fissile material. *These fuel rods are then taken, with no further modification, to an LWR and used as fuel*. In the thermal spectrum of water-moderated reactors (LWRs), this small percentage of $U^{233}$ is quite sufficient for criticality, though in the faster spectrum of the hybrid breeder, the rods are strongly sub-critical. In fact the Hybrid is always run in a safe highly subcritical mode. Note that the fissile material is protected, at all times, by a strong radiation field from *all* fission products generated by fission reactions occurring in the hybrid during the breeding phase. In these "charged" rods, the fissile material is highly diluted and embedded in a very bulky matrix (many discrete, easily countable fuel rods) of fertile material. *The ReFree mode of fuel production is qualitatively different from the advertized FBR fuel cycle; the proliferation problems characteristic of the FBR cycle*[2] *are completely absent*. In fact, this method of fuel production, in several respects, has substantial proliferation advantages over the gas centrifuge enrichment technology that is used to make the enriched $U^{235}$ fuel of today[3]. The fuel cycle components that have historically lead to proliferation – enrichment and reprocessing – are absent.

(2) A Hybrid, supplied with fusion neutrons, is far more efficient as a fuel breeder. A single Hybrid in the ReFree mode can support at least 6 times more LWRs than a comparable thermal power FBR, so relatively few hybrids would be required to sustain commercially proven thermal reactors. Two crucial advantages result from high support ratio: (1) the cost of fuel production is considerably reduced, and (2) the Hybrid does not fundamentally change the nature of the current, successful nuclear economy that will remain predominantly based on LWRs, and in the future may use thermal reactors on the drawing board that are cheaper and safer. The (advanced reactor) Hybrid, unlike the (fission only) advanced reactor FBR is only a perturbation (though with crucial impact) on the entire energy production system. Both the Hybrid and the FR have uncertain costs, but cost of the overall nuclear energy system is much less sensitive to the cost of a Hybrid.