Tutorial
Principles and Rationale of the Fusion-Fission Hybrid Burner Reactor

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Abstract. The potential advantages of Fusion-Fission Hybrid (FFH) reactors (relative to critical fast reactors) for closing the back end of the nuclear fuel cycle are discussed. The choices of fission and fusion technologies for FFH burner reactors that would fission the transuranics remaining in spent fuel discharged from nuclear power reactors are summarized. The conceptual design and fuel cycle performance of the SABR FFH burner reactor are presented, and a fusion power development schedule with a symbiotic dual FFH path is outlined.

Keywords: Fusion-Fission Hybrid, Subcritical Burner Reactor, Transmutation Reactor, SABR.
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I. Introduction

The idea of sustaining a fission neutron chain reaction by providing a source of D-T fusion-produced neutrons has been investigated for various purposes over the past 30-40 years or longer. The motivations for these studies have included enhancing the energy output of a fusion reactor, "breeding" fissile Pu-239 or U-233 (by neutron transmutation of U-238 or Th-232, respectively) for fueling nuclear power reactors, and destroying the long-lived fissionable transuranics remaining in spent nuclear fuel discharged from nuclear power reactors. Fission-enhanced fusion power does not appear to be economically viable compared to fission power, and the slowdown in the growth of nuclear power in the last decades of the 20th century reduced the perceived need for breeding fissile fuel from U-238 or Th-232, leading to a reduced interest in using fusion neutrons to sustain the fission neutron chain reaction.

However, a growing awareness of the adverse environmental consequences of continuing to burn carbon-based fuels has recently led to increasing recognition of the need to significantly expand the nuclear contribution to worldwide power production. While the recent tsunami damage to Japanese nuclear power plants has triggered a reaction against nuclear power in some countries, this is probably only temporary, and most of the world is moving forward towards an expansion of nuclear power.

There are two technical impediments to a sustainable world-wide expansion of nuclear power---the accumulation of increasing inventories of radioactive spent nuclear fuel and, by later in the century, the availability of sufficient nuclear fuel. The immediate impediment to a significant expansion of nuclear power is the accumulation of long-lived radioactive spent nuclear fuel. While burying the spent nuclear fuel in-toto in high level waste repositories (HLWRs) is a technically feasible solution, a large number of HLWRs would be needed to support a significant expansion of nuclear power, which may not be politically feasible in some countries. In any case, burial in-toto would waste fissionable material that will be needed as fuel for a significant expansion of nuclear power. A different technical solution to the spent nuclear fuel problem is to partition the relatively short-lived (for the most part) radioactive fission products from the long-lived transuranics, send only the former to HLWRs and use the latter to fuel special purpose "burner" nuclear power reactors. Since all of the transuranics have a significant fission cross section for fast neutrons, these reactors would likely be "Fast Burner Reactors".

There are technical reasons that these fast burner reactors could be more effective in reducing the number of HLWRs that are needed if the fission neutron chain reaction was sustained by D-T fusion neutrons---i.e. if they were Fusion-Fission Hybrid (FFH) burner reactors. These technical advantages are one reason for the renewed interest in FFHs.

Another reason for the renewed interest is that the ITER tokamak experiment presently under construction will achieve many of the physics and technology operational parameters that would be needed for a fusion neutron source for a FFH; i.e. the FFH option is becoming realistic to think about for the near-term.

II. Technical Rationale for Fusion-Fission Hybrid Fast Burner Reactors

A Fusion-Fission Hybrid reactor is basically a nuclear reactor operated sub-critical with a D-T fusion neutron source to sustain the fission neutron chain reaction. Such a sub-critical FFH reactor would be more complex and more expensive than an equivalent reactor operated critical (a "critical" reactor is one in which the fission neutron chain reaction is sustained by fission neutrons alone). We designate a critical fast reactor as a CFR. Thus, a FFH would be used for the destruction of nuclear waste (i.e. the fissioning of the transuranics remaining in spent nuclear fuel) only if the overall cost of the transuranics—fission product separation facilities, the fuel fabrication facilities, the HLWRs, and the fast burner reactors was less with FFH burner reactors than with CFR burner reactors, or if the task could not be carried out to a sufficient extent with CFR burner reactors alone. We believe that the use of FFH burner reactors could result in the need for fewer burner reactors, fewer separations facilities, fewer fuel fabrication facilities and fewer HLWRs than would be possible with CFR burner reactors. The rationale for this belief is discussed qualitatively in this section, although it remains to carry out the extensive calculations necessary to make the quantitative determination.

Conjecture #1: Fewer separations steps, hence fewer separations facilities, fewer fuel fabrication facilities and fewer HLWRs would be needed with FFH than CFR burner reactors.

The fission power level, hence the transuranic destruction rate, can be maintained in a subcritical FFH by increasing the neutron source strength to compensate the reduction of fission neutrons caused by depletion of the transuranic fuel and buildup of neutron absorbing fission products. This can be seen by considering[1] the number of fission neutrons

$N_{fis} = S / \upsilon \Sigma_{rem} (1-k)$ that will be present in a sub-critical system with neutron multiplication constant $k = \nu \Sigma_{fis} / \Sigma_{rem}$, where Σ_{fis} and Σ_{rem} are the fission and absorption plus leakage cross sections, both appropriately averaged over the assembly, and ν is the number of neutrons produced per fission, υ is the appropriately averaged neutron speed and S is the neutron source. With a fusion neutron source $S = P_{fus} / E_{fus}$, so that the fusion power level needed to maintain a given fission power level is given by

$$P_{fis} = \upsilon N_{fis} \Sigma_{fis} E_{fis} = \frac{E_{fis}}{E_{fus}} \frac{k}{\nu (1-k)} P_{fus} \tag{1}$$

where $E_{fus} = 17.6 MeV$ and $E_{fis} \simeq 190 MeV$. The decrease in *k* due to the decrease in fissionable material and the increase in neutron absorbing fission products can be compensated by an increase in fusion power.

Thus, fuel can remain in a FFH burner reactor until it reaches the radiation damage failure limit. In the CFR burner reactor, compensating material changes must be made to maintain $k = \nu \Sigma_{fis} / \Sigma_{rem} \equiv 1$, which would almost surely require removal of the fuel before the radiation damage limit is reached, or production of transuranics from U-238 to increase k, which would reduce the net transuranics destruction rate.

The longer fuel residence time in a FFH burner reactor than in an equivalent CFR burner reactor means that fewer separation steps are required to burn a given quantity of TRU to a given burnup level. Thus fewer separation facilities and fewer fuel fabrication facilities would be needed with FFHs than with CFRs.

Since the separation process is imperfect, some percentage of the TRU goes with the fission products to the HLWR on every reprocessing step, and since the HLWR capacity is determined by the transuranics in the long term, fewer separations steps would therefore result in fewer HLWRs being needed for FFH burner reactors than for CFR burner reactors.

Conjecture #2: Fewer FFH burner reactors, which can be loaded with 100% transuranic fuel, will be needed than CFR burner reactors, which would be loaded with mixed uranium and transuranic fuel to achieve an adequate reactivity margin of safety to prompt critical.

The neutron density *n* in a CFR satisfies[2]

$$n(t) = n_0 \left[\frac{\rho}{\rho - \beta} \exp\left(\frac{\rho - \beta}{\Lambda} t \right) - \frac{\beta}{\rho - \beta} \exp\left(\frac{-\lambda \rho}{\rho - \beta} t \right) \right] \tag{2}$$

where $\Lambda \approx 10^{-6} s \; for\ fast\ reactors, \; \lambda^{-1} \approx 1\,s, \rho = ((k-1)/k)$
$\beta \simeq 0.007 \; for\ U\ fuel, \; \beta \simeq 0.002 - 0.003 \; for\ TRU\ fuel$

If $\rho > \beta$, the large exponent in the first term becomes positive, causing the neutron density to rise exponentially on the microsecond-to-millisecond time scale, so $\rho_{safe} = \beta$ is a measure of the accidental reactivity insertion that could be tolerated in a CFR without an exponential power excursion taking place, i.e. $\rho_{safe} = \beta$ is a “reactivity margin of safety”. The value of β with transuranic fuel is only a fraction of the value with uranium fuel. Furthermore, the presence of U-238 in uranium fuel makes a negative “Doppler” contribution $(\Delta\rho/\Delta T)_{238}\Delta T < 0$ that is absent with transuranic fuel. This would probably mean that a CFR burner reactor would contain only about 20% transuranic fuel, with the remainder being uranium fuel.

A FFH burner reactor, by contrast, has a reactivity safety margin $((1-k_{sub})/k_{sub}) + \beta \gg \beta$ for $k_{sub} \leq 0.95$ and could safely be fueled with 100% transuranic fuel. Thus, a CFR burner reactor would probably destroy (fission) only about 20% as much transuranics as a FFH burner reactor operating at the same fission power level. Put another way, the support ratio for a FFH would be about 5 times that of a CFR burner reactor.

III. Choice of Technologies for a FFH Burner Reactor

Fission Technologies

The most developed burner reactor technology is the sodium-cooled fast reactor, with its associated transuranics separation and fuel fabrication technologies. Most of the worldwide fast reactor technology development is based on this technology. It should be possible to deploy a sodium-cooled fast burner reactor in 15-20 years.

The metal fueled fast reactor known as the Integral Fast Reactor[3] (IFR) is the most highly developed in the USA. This technology has been demonstrated to be passively safe against loss-of-coolant and loss-of-heat-sink accidents. Because the associated pyroprocessing technique for separation of the transuranics from the fission products does not separate the plutonium isotopes from the higher actinides, this technology is proliferation resistant.

Oxide fuel fast reactor technology and the associated aqueous separation technology are highly developed in France and Russia, and to a lesser extent in the USA and Japan.

Gas-cooled fast reactor technology is being developed as a backup burner reactor technology. The oxide fuel and aqueous separation technology is the leading candidate. The TRISO fuel option, which would in principle allow the transuranic fuel to be burned up to a high degree and then placed in a HLWR, without any intermediate separation steps (burn and bury), does not at present seem feasible in a fast neutron spectrum because of radiation damage.

Other liquid metal (e.g. Pb, Pb-Bi, Pb-Li, Li) and molten salt coolants are secondary backup options.

Fusion Technologies

The tokamak is the most developed magnetic fusion technology that could be used as the neutron source for a FFH. Most of of the world-wide fusion physics and technology R&D is devoted to the tokamak, and ITER[4] (2020-35) will serve as a prototype for much of the physics and technology performance that is needed for a FFH. It should be possible to deploy a tokamak fusion neutron source for a FFH in 20-25 years.

Other magnetic confinement concepts which promise some advantages relative to the tokamak (e.g. stellarator, spherical torus, etc.) would require at least 25 years to reach the present stage of the tokamak. A massive redirection of worldwide fusion R&D (which is not justified by performance to date) would be required to deploy a stellarator, spherical torus, etc. FFH neutron source in 40-50 years. A mirror (gas dynamic trap) could probably be deployed as a small FFH neutron source in 20-25 years, but this would also require a massive redirection of fusion R&D into a dead-end technology that will not lead to a fusion power reactor.

IV. The SABR FFH Burner Reactor Design Concept[5]

The Subcritical Advanced Burner Reactor (SABR) concept is based, insofar as possible, on the physics, technologies, and component designs that have been developed for the leading Integral Fast Reactor (IFR) and International Thermonuclear Experimental Reactor (ITER). Conservative choices of operating parameters were made to provide margins for uncertainty. The successful operation of an IFR prototype and associated fuel separations and fabrication facilities, and the successful operation of ITER and its blanket test program, would serve as a prototype for SABR.

A simplified representation of the SABR design concept is shown in Fig. 1. (The design concept also includes a lower single-null divertor not shown in Fig. 1.)

The toroidal tokamak plasma is surrounded by an annular fast reactor core consisting of four rings of hexagonal fuel assemblies, as shown in Fig. 2.

The fission core and tokamak plasma are surrounded by a 15 cm Li_4SiO_4 tritium breeding blanket capable of providing tritium self-sufficiency, then by a reflector and a multi-layered shield to protect the superconducting magnets for a 40 year operating lifetime at 75% availability. The core design concept was confirmed by ERANOS neutronics calculations and FLUENT sodium heat removal calculations.

The SABR fusion neutron source[6] was scaled down from the ITER design. The ITER first-wall and divertor system were based directly on the ITER design, but using Na coolant. All coolant channels were coated with an electrical insulator to minimize MHD pressure drops. The heat removal capability was confirmed with FLUENT calculations. The superconducting magnet systems were scaled down from the ITER design preserving structure fractions and monitoring stress limits vis-à-vis ITER values. The ITER LHR current drive/heating system design was used directly. The neutron source design parameters are compared with ITER and with the ARIES-AT commercial tokamak reactor design parameters in Table 1.

ANNULAR FAST REACTOR (3000 MWth)

- Fuel—TRU from spent nuclear fuel. TRU-Zr metal being developed by ANL.
- Sodium cooled, loop-type fast reactor.
- Based on fast reactor designs being developed by ANL in Nuclear Program.

TOKAMAK D-T FUSION NEUTRON SOURCE (200-500 MWth)

- Based on ITER plasma physics and fusion technology.
- Tritium self-sufficient (Li_4SiO_4).
- Sodium cooled.

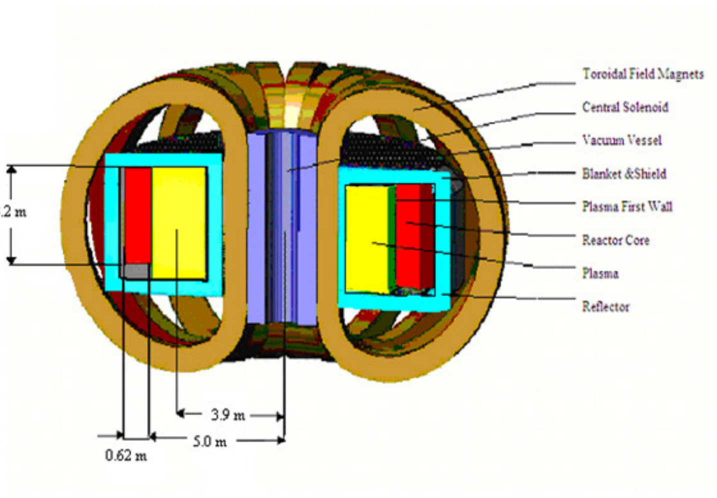
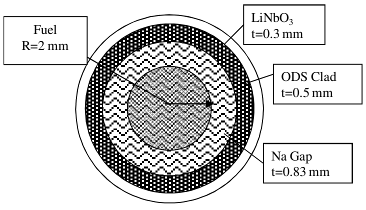
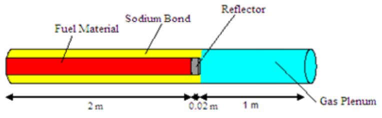


Figure 1. SABR Design Concept



FUEL

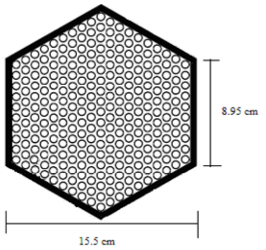


Axial View of Fuel Pin

Composition 40Zr-10Am-10Np-40Pu (w/o)
(Under development at ANL)

Design Parameters of Fuel Pin and Assembly

Length rods (m)	3.2	Total pins in core	248778
Length of fuel material (m)	2	Diameter_Flats (cm)	15.5
Length of plenum (m)	1	Diameter_Points (cm)	17.9
Length of reflector (m)	0.2	Length of Side (cm)	8.95
Radius of fuel material (mm)	2	Pitch (mm)	9.41
Thickness of clad (mm)	0.5	Pitch-to-Diameter ratio	1.3
Thickness of Na gap (mm)	0.83	Total Assemblies	918
Thickness of $LiNbO_3$ (mm)	0.3	Pins per Assembly	271
Radius Rod w/clad (mm)	3.63	Flow Tube Thickness (mm)	2
Mass of fuel material per rod (g)	241	Wire Wrap Diameter (mm)	2.24
$Volume_{Plenum}$/ $Volume_{fm}$	1	Coolant Flow Area/ assy (cm^2)	75



Cross-Sectional View Fuel Assembly

Figure 2 SABR Fuel Assembly Design Concept

Table 1 SABR Neutron Source Parameters

Parameter	SABR Low Power	SABR High Power	ITER	Pure Fusion Electric Power ARIES-AT
P_{fus}(MW)	180	500	500	3000
S_{neut}(10^{20} #/s)	1.42	1.75	1.75	10.5
Current, I(MA)	8.3	10.0	15.0	13.0
Major Radius, R(m)	3.75	3.75	6.2	5.2
Magnetic Field, B(T)	5.7	5.7	5.3	5.8
Confinement H_{IPB98}(y,2)	1.0	1.06	1.0	1.4
Normalized beta, β_N	2.0	2.85	1.8	5.4
Energy Mult., Q_p	3	5	5-10	>30
HCD Power, (MW)	100	100	110	35
Neutron Γ_n(MW/m^2)	0.6	1.8	0.6	4.9
LHCD η_{CD}/f_{BS}	.61/.31	.58/.26		/.91
Availability (%)	75	75	25(4)	>90

The SABR plasma parameters in Table 1 are generally within the range that have already been achieved and that are part of the ITER design database $\left(\beta_N < 2.5-3.0, H_{IPB98} \simeq 1.0\right)$ or that are expected to be achieved on ITER $\left(Q_p \simeq 5-10, \Gamma_n \simeq 0.5\right)$, and are much less demanding than the parameters $\left(\beta_N \simeq 5.4, H_{IPB98} >> 1.0, Q_p > 30, \Gamma_n \simeq 5\right)$ that would be needed for fusion electric power reactor. The magnetic field at the coils in SABR is the same as will be achieved in ITER. The major advance over ITER needed for SABR is availability; ITER is scheduled to achieve 25% over a limited time, whereas the SABR fuel cycle performance is predicated on achieving 75%.

Although the ITER and IFR designs were adapted, and conservative parameter choices were made, there are some technical issues in the SABR design that require resolution before such a FFH could be built. The major issues of fusion physics are achieving the necessary current drive and plasma heating with LHR and disruption avoidance/mitigation. The major issues with fusion technology are tritium retention, tritium breeding and recovery, and the development of a structural material with a radiation damage limit of 200 dpa. There are also some fusion-fission technology integration issues, such as MHD effects with liquid Na flowing in a magnetic field and refueling in tokamak geometry, that must be resolved.

SABR TRU Burner Fuel Cycle in Support of LWRs

The reference SABR fuel cycle[7] is indicated in Fig. 3. The fuel assemblies are first loaded in the outermost ring 4, burned for one burn cycle, then moved inward to ring 3, burned for one burn cycle, etc. until they have been burned for four burn cycles, at which point they are removed from the innermost ring 1 and sent to the reprocessing facility for separation of the remaining transuranics from the fission products. The separated transuranics (plus 1% of the fission products) are then sent back to the fuel fabrication facility where they are mixed with "fresh" transuranics (TRU) taken directly from LWR spent fuel and recycled back through the burner reactor again. At the beginning of operation (BOL) the fuel in all four rings has the composition of the spent nuclear fuel removed from LWRs, but after a few such cycles the composition of the fuel entering ring 4 at beginning of cycle (BOC) and the composition of the fuel removed from ring 1 at end of cycle (EOC) and sent for reprocessing both reach an equilibrium composition. The fuel residence time of 2800 full power days (fpd) in SABR is set by the 200 dpa clad radiation damage limit, and each burn cycle is one-fourth of this residence time, or 700 fpd. With this type of repeated reprocessing of the burner reactor discharge fuel, all of the transuranics are eventually destroyed, except for the 1% that go to the HLWR with the fission products on each reprocessing step because of separation inefficiency. The decay heat in the HLWR at 100,000 years is reduced to 3.5% of the value that would be present if the spent nuclear fuel from LWRs was placed directly in the HLWR, indicating about a 30-fold reduction in the required HLWR capacity relative to direct burial of the discharged LWR spent fuel.

SABR TRU BURNER Fuel Cycle

ANL Fuel Composition

	Mass Percent	Mass Percent
Isotope	BOL	BOC
Np^{237}	17.0	8.53
Pu^{238}	1.4	12.62
Pu^{239}	38.8	21.71
Pu^{240}	17.3	26.83
Pu^{241}	6.5	6.22
Pu^{242}	2.6	6.95
Am^{241}	13.6	8.32
Am^{242}	0.0	0.54
Am^{243}	2.8	2.96
Cm^{242}	0.0	0.40
Cm^{243}	0.0	0.08
Cm^{244}	0.0	2.25
Cm^{245}	0.0	0.57

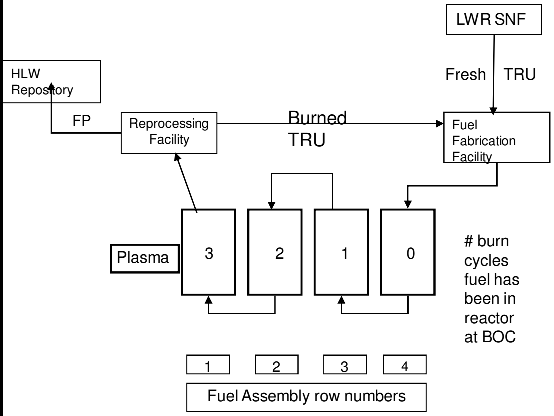


Figure 3. SABR 4-Batch Fuel Cycle with Out-to-In Fuel Shuffling

With the initial BOL composition containing 30.3 MT of TRU, k_{eff} = 0.945 and P_{fus} = 172 MWth is needed to provide enough fusion neutrons to produce 3000MWth power in the fission reactor core (from fission, exoergic reactions and the slowing down of fusion neutrons). Once the equilibrium fuel cycle is reached, at BOC k_{eff} =0.878, P_{fus}= 312 MW, TRU=28.8MT, and at EOC k_{eff}=0.831, P_{fus}=409 MW, TRU= 26.8MT. In the equilibrium fuel cycle, 1.06 MT of TRU is fissioned every full-power year (fpy).

Since a 1000 MWe LWR also produces about 3000MWth power and 0.25 MT/y TRU, the support ratio for SABR is 3.2 at 75% availability (4.2 at 100% availability). Thus, one could envision a reactor fleet of LWRs producing 75% of the power and SABRs producing 25% of the power by burning all the TRU produced in the LWRs.

SABR Minor Actinide Burner Fuel Cycle in Support of a Transition to a Fast Reactor Fleet

If some of the plutonium is separated from the TRU discharged from LWRs to use to start up fast reactors at a later date, this leaves a minor actinide (MA) rich composition of transuranics to be fissioned in fast burner reactors. We have investigated a similar 4-batch burner reactor fuel cycle based on the BOL fuel composition which is used in European studies of this situation. The MA-rich TRU-oxide fuel (with some Pu removed) is less reactive than the TRU fuel shown above, and it was necessary to slightly redesign the SABR fuel assemblies to accommodate this fuel while remaining within the same general range of k_{eff} and P_{fus} discussed above.

The fuel cycle[7] was similar to that depicted in Fig. 3, except for Pu being removed from the LWR SNF. At beginning of operation (BOL) k_{eff}=0.889, P_{fus}=470 MW, TRU = 50.0MT, while at the beginning of equilibrium cycle (BOC) k_{eff}=0.949, P_{fus}=195 MW, TRU = 48.5MT and at the end of equilibrium cycle k_{eff}=0.932, P_{fus}=289 MW, TRU = 46.5MT. In the equilibrium fuel cycle 1.08 MT/fpy of TRU (0.85 MT/fpy of MA) is fissioned. Since a 1000MWe LWR produces 0.025 MT/y of MA, the support ratio for SABR at 75% availability is 25.5 in this fuel cycle. Thus, a nuclear power fleet of 96% LWRs supported by 4% SABRs to burn the minor actinides would be envisioned in this "transition to fast reactors" scenario. The decay heat in the HLWR at 100,000 years is reduced to 11% of the value that would be present if the spent nuclear fuel from LWRs was placed directly in the HLWR after some plutonium was removed to be saved for fast reactor startup, indicating a 10-fold reduction in the required HLWR capacity.

V. Impact of FFH Burner Reactor Development on Fusion Power Development Programs

Fusion R&D for a SABR FFH Burner Reactor is on the Path to Fusion Power

The tokamak plasma physics and fusion technology R&D needed for a SABR FFH Burner Reactor is all also needed for the development of fusion electrical power reactors (and the fast reactor fission physics and technology R&D needed for the SABR FFH Burner Reactor is all also needed for the development of CFR burner reactors). Additional R&D is needed for a FFH Burner Reactor related to integration of some of these fusion and fission technologies.

The tokamak plasma physics R&D that is required for a FFH Burner Reactor falls into the following generic categories: i) control of instabilities; ii) achievement of reliable, very-long-pulse plasma operation; iii) avoidance and/or mitigation of disruptions; and iv) control of burning plasmas. Fusion electric power requires this same R&D and also R&D on v) achievement of advances in plasma operational limits (β, τ_E).

Fusion technology R&D required for a FFH Burner Reactor falls into the following generic categories: i) improved reliability of plasma support technologies (magnets, heating, vacuum, etc.); ii) improved heat removal technology; iii) fusion nuclear (i.e.tritium breeding and recovery) technology; iv) structural materials with high radiation damage limits; and v) remote assembly and maintenance technology. Fusion electric power requires this same R&D and also R&D: vi) to develop high radiation damage limit structural materials that operate at high temperatures and high neutron and heat fluxes; and vii) to develop heat removal technology for high heat fluxes.

Symbiotic Electric Power and FFH Burner Reactor Development Paths for Fusion

The general fusion development plan that most fusion scientists and involved governments have had in mind for the past 35 years envisions an experimental power reactor (EPR) followed by national demonstration reactors (DEMOs) leading to economically competitive "commercial" power reactors. ITER, presently under construction for operation over 2020-2035, has significantly lower neutron wall load, fluence and availability objectives than were envisioned when this "plan" was first formulated, which probably means that the DEMOs that would follow it would also have reduced performance objectives vis-à-vis those originally envisioned. However, the requirements for an economically competitive commercial power reactor have actually increased (nuclear reactors are producing electricity at about 2 cents per kilowatt-hr with > 90% average availability). This would seem to imply the need for an additional "prototype" reactor between the DEMO and commercial reactors, which would push the timescale for fusion power reactors towards the end of the century .

Adding to the present fusion development programs a symbiotic FFH path that focused on a FFH neutron source following ITER that would provide operating experience, which would in turn enable a more ambitious "PROTODEMO", could lead to commercial fusion power reactors in the second half of the century. The major elements of such a "dual-path" fusion development program are indicated if Fig. 4

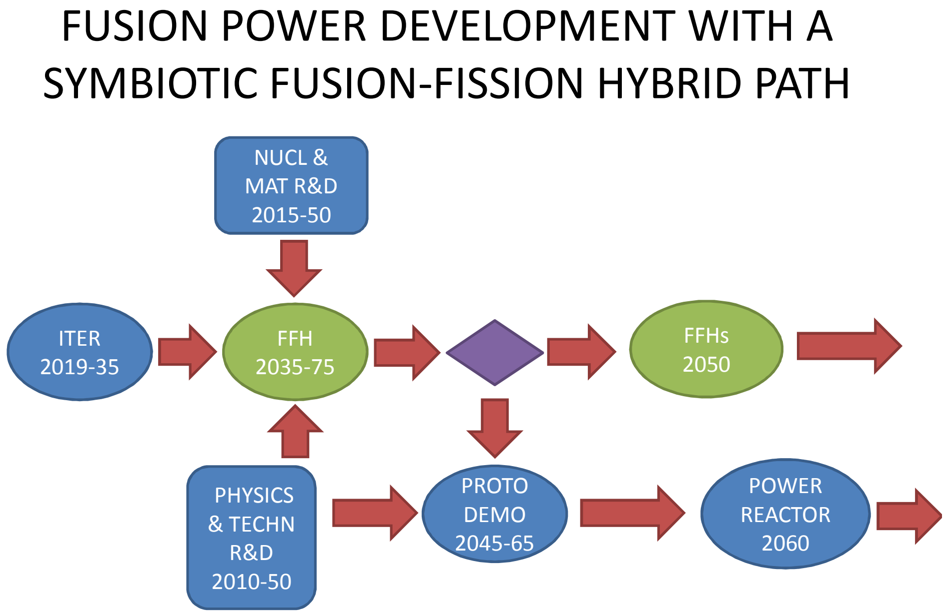


Figure 4 A "Dual-Path" Electric Power and FFH Fusion Development Program

The FFH neutron source must i) achieve highly reliable, very-long-pulse plasma operation with plasma performance parameters $\left(\beta,\tau_E\right)$ similar to those of ITER, and ii) operate with moderately higher surface heat and neutron fluxes than ITER. The PROTODEMO must i) also achieve reliable, very-long-pulse plasma operation but with plasma performance parameters $\left(\beta,\tau_E\right)$ significantly beyond those of ITER, and ii) operate with significantly higher surface heat and neutron fluxes than ITER. Both devices have similar requirements for a structural material with high radiation damage resistance, plasma support systems and fusion nuclear technologies.

VI. Pros and Cons of FFH Burner Reactors

The rationale for the development of FFH Burner Reactors is that they would facilitate (and may even be necessary to enable) the sustainable world-wide expansion of environmentally benign nuclear power. The FFH application also offers the opportunity for fusion to contribute to meeting the world's energy needs at an earlier time than is possible with fusion power reactors. This, in turn, would increase the support for fusion technology development and the operating experience with large scale fusion facilities that are needed to develop economical fusion power reactors.

On the other hand, an FFH Burner Reactor will be more complex and expensive than a CFR Burner Reactor, and the integration of fission and fusion technologies will introduce additional R&D costs. However, a nuclear fleet of LWRs and FFH Burner Reactors should require fewer burner reactors, fewer separation and fuel fabrication facilities, and fewer HLWRs than a nuclear fleet of LWRs and CFR Burner Reactors. Thus, the overall system of burner reactors, separation and fuel fabrication facilities, and HLWRs could be less expensive with FFHs than with CFRs.

VII. Conclusions and Recommendations

Fusion-Fission Hybrid fast burner reactors could by mid-century play a significant, perhaps even essential, role in closing the back end of the nuclear fuel cycle to enable a significant and sustainable expansion of carbon-free nuclear power to meet the world's growing energy demands. This possibility should be investigated in detail by conceptual design studies to establish the technical feasibility of FFHs in the near term, and by comparative fuel cycle, dynamic safety and materials scenario studies to quantify the benefit of FFHs to closing the nuclear fuel cycle.

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