PRINCIPLES AND RATIONALE OF THE FISSION-FUSION HYBRID BURNER REACTOR

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The Fusion-Fission Hybrid

- *What is it?*

  A Fusion-Fission Hybrid (FFH) is a sub-critical fission reactor with a variable strength fusion neutron source.

- *Mission?*

  Supporting the sustainable expansion of nuclear power worldwide by helping to close the nuclear fuel cycle.

SUSTAINABLE EXPANSION OF NUCLEAR POWER

- TECHNICAL IMPEDIMENTS—*CLOSING FUEL CYCLE*

  i) *immediate*--accumulation of spent nuclear fuel (SNF).

  ii) *50 years*---uranium fuel shortage by end of century
  (present 'once-through' fuel cycle utilizes <1% of uranium energy content).
- TECHNICAL SOLUTIONS

  i) *immediate*--separate long-lived transuranics in SNF and fission it in *fast burner reactors*.

  ii) *50 years*---transmute non-fissionable uranium (>99%) into fissionable transuranics in *fast breeder reactors*.
- SUBCRITICAL OPERATION (FFH) COULD GREATLY FACILITATE THE *FAST BURNER REACTOR* TECHNICAL SOLUTION TO THE IMMEDIATE TECHNICAL IMPEDIMENT TO A SUSTAINABLE EXPANSION OF NUCLEAR POWER.

Rationale for FFH Fast Burner Reactors

- Fast Burner Reactors could dramatically *reduce* the required number of high-level waste *repositories* by fissioning the transuranics in LWR SNF.

- The potential advantages of FFH burner reactors over critical burner reactors are:

  1) *fewer reprocessing steps*, hence *fewer reprocessing facilities and HLWR repositories*[a] *would be needed*---no criticality constraint, so the TRU fuel can remain in the FFH for deeper burnup to the radiation damage limit.

  2) *larger LWR support ratio*---FFH can be fueled with 100% TRU, since sub-criticality provides a large reactivity safety margin to prompt critical, so *fewer burner reactors would be needed*.

[a] separation of transuranics from fission products is not perfect, and a small fraction of the TRU will go with the fission products to the HLWR *on each reprocessing*.

Relation Between Fusion and Fission Power

$$N_{fis} = \frac{S}{\upsilon \Sigma_{rem} \left(1-k\right)}, \; S = \frac{P_{fus}}{E_{fus}}, \; k = \frac{\nu \Sigma_{fis}}{\Sigma_{rem}}$$

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

Sub-critical operation increases fuel residence time in Burner Reactor before reprocessing is necessary

As *k* decreases due to fuel burnup, Pfus can be increased to compensate and maintain Pfis constant.

Thus, sub-critical operation enables fuel burnup to the radiation damage limit before it must be removed from the reactor for reprocessing.

Sub-critical operation provides FFH a much larger margin of safety against accidental prompt critical power excursions, allowing use of 100% transuranic fuel in FFH, but requiring a mixture of U and TRU fuel in critical reactor.

Neutron density in critical reactor satisfies

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

$$\Lambda \approx 10^{-6}\,s \;\; for \;\; fast\ reactors, \;\; \lambda^{-1} \approx 0.1 - 10\,s$$

$$For\ \rho \equiv (k-1)/k > \beta, the\ first\ term\ increases\ \exp onentially\ on\ 10^{-4} - 10^{-5}\,s\ period.$$

$$Thus, \rho_{safe}^{\max} = \beta\ is\ reactivity\ m\arg in\ of\ safety\ for\ critical\ reactor.$$

$$\beta_{TRU} << \beta_U : \;\; \beta_U \sim 0.007\ for\ U\ fuel, \;\; \beta_{TRU} \sim 0.002 - 0.003\ for\ TRU\ fuel$$

In sub-critical FFH reactor

$$(\rho_{safe}^{\max})_{FFH} = (k_{sub}-1)/k_{sub} + \beta >> \beta \quad with\ k_{sub} < 0.95$$

Choice of Fission Technologies for FFH Fast Burner Reactor

- Sodium-cooled fast reactor is the *most developed* burner reactor *technology*, and most of the world-wide fast reactor R&D is being devoted to it (deploy 15-20yr).
  1. The metal-fuel fast reactor (IFR) and associated pyroprocessing separation and actinide fuel fabrication technologies are the most highly developed in the USA. The IFR is <u>*passively safe*</u> against LOCA & LOHSA . The IFR fuel cycle is <u>*proliferation resistant*</u>.
  2. The sodium-cooled, oxide fuel FR and aqueous separation technologies are highly developed in France and Russia, and also in Japan and the USA.
- Gas-cooled fast reactor is a much less developed backup technology.
  1. With oxide fuel and aqueous reprocessing.
  2. With TRISO fuel (burn and bury). Radiation damage would limit TRISO in fast flux, and it is probably not possible to reprocess.
- Other liquid metal coolants, Pb, Pb-Bi, Pb-Li, Li.
- Molten salt fuel would simplify refueling, but there are issues. (Molten salt coolant only?)

Choice of Fusion Technologies for the FFH Fast Burner Reactor

- *<u>The tokamak is the most developed fusion neutron source technology</u>*, most of the world-wide fusion physics and technology R&D is being devoted to it, and ITER will demonstrate much of the physics and technology performance needed for a FFH (deploy 20-25 yr).

- Other magnetic confinement concepts promise some advantages relative to the tokamak, but their choice for a FFH would require a massive redirection of the fusion R&D program (not presently justified by their performance).
  1. Stellarator, spherical torus, etc. are at least 25 years behind the tokamak in physics and technology (deploy 40-50 yr).
  2. Small Mirror (GDT) could probably be deployed in 20-25 years, but would require redirection of the fusion R&D program into a dead-end technology that would not lead to a fusion power reactor.

Subcritical Advanced Burner Reactor (SABR)
Design Concept

SABR FFH DESIGN APPROACH

- Use physics, technologies, designs and design criteria that have been developed for IFR and ITER, as much as possible, so that operation of an IFR and of ITER will prototype FFH.
- Be conservative to allow for uncertainties

  i) modest plasma parameters, power density, etc.

  ii) 99% transuranic-fission product separation efficiency (99.9% achieved in lab).

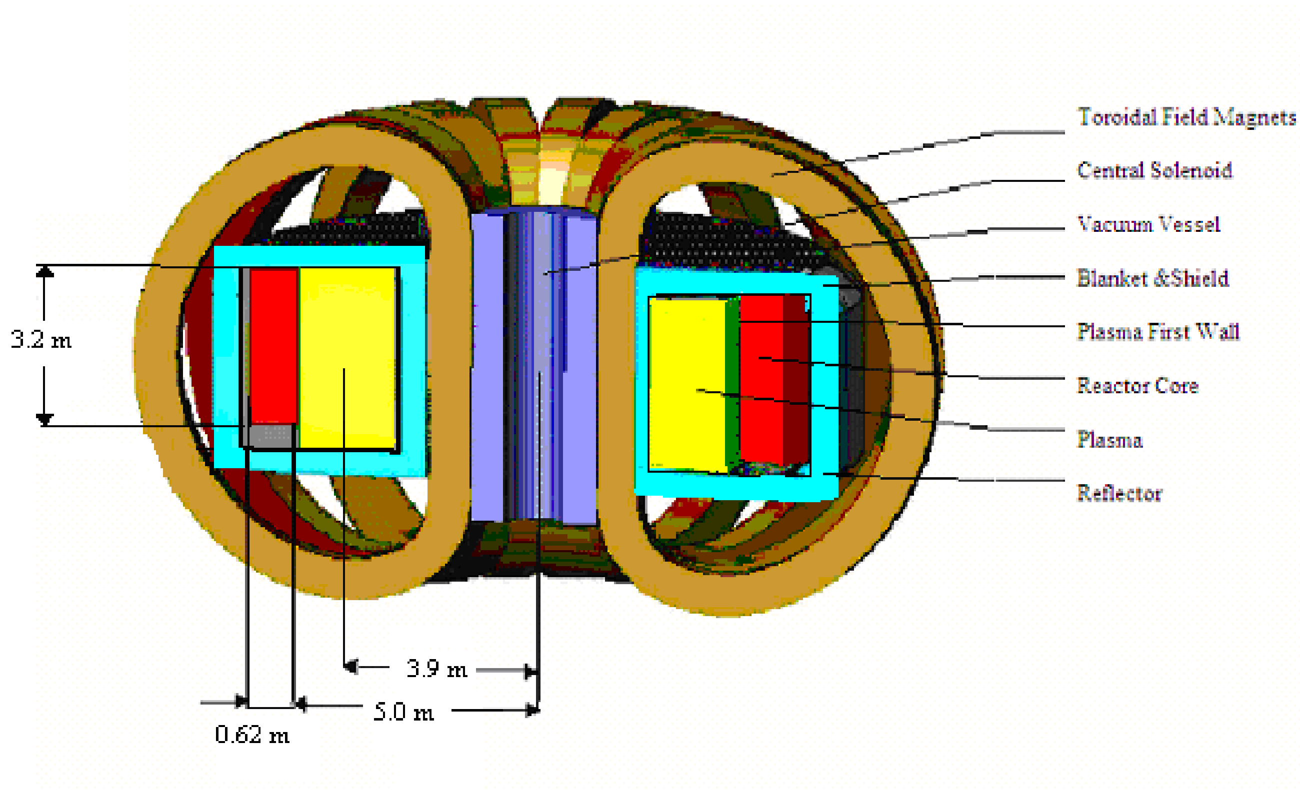
SUB-CRITICAL ADVANCED BURNER REACTOR (SABR)

ANNULAR FAST REACTOR (3000 MWth)

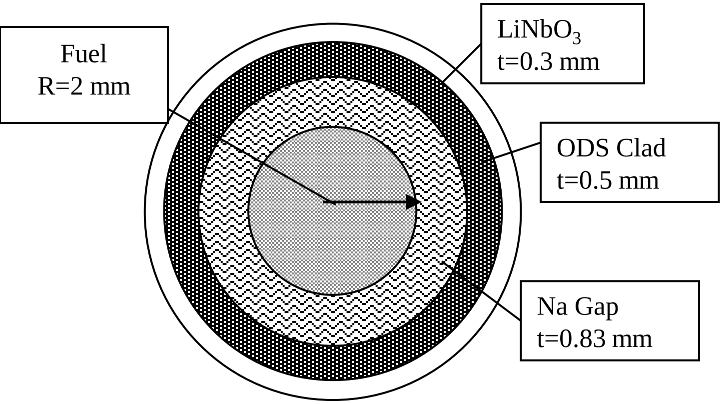
- Fuel—TRU from spent nuclear fuel. TRU-Zr metal being developed by ANL.
- Sodium cooled, loop-type fast reactor.
- Based on fast reactor designs being developed by ANL in Nuclear Program.

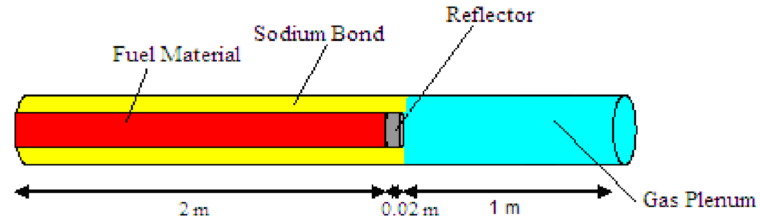
TOKAMAK D-T FUSION NEUTRON SOURCE (200-500 MWth)

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



FUEL



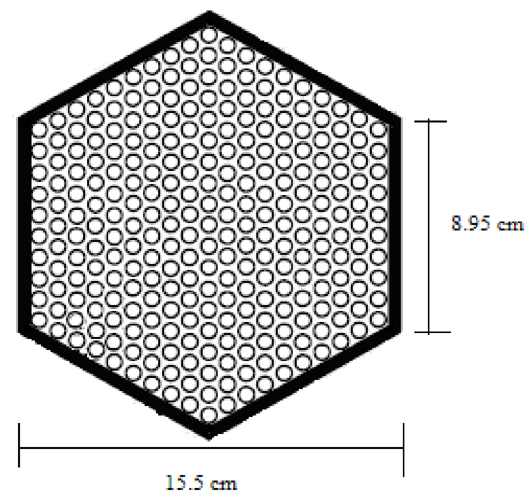


Axial View of Fuel Pin

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

SABR FUSION NEUTRON SOURCE

- ITER SC magnet system scaled down, observing same stress limits, structural fractions, etc.
- ITER FW and divertor designs adapted for Na cooling and slightly higher q”. Confirmed by FLUENT heat removal calculations.
- ITER LHCD system used directly.
- Li_4SiO blanket operates 420<T<640 C to achieve tritium self-sufficiency (TBR=1.16).
- Most physics operating parameters within ITER range.

SABR Neutron Source Design Parameters

Parameter	SABR Low power	SABR High power	ITER	Pure Fusion Electric ARIES-AT
Current, I (MA)	8.3	10.0	15.0	13.0
P_{fus} (MW)/S_{neut}(10^{20}/s)	180/1.4	500/1.8	500/1.8	3000/10.5
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
Htg&CD Power, MW	100	100	110	35
Neutron Γ_n (MW/m^2)	0.6	1.8	0.6	4.9
LHCD ηcd/fbs	.61/.31	.58/.26		/.91
Availability (%)	75	75	25(4)	>90

SABR MAJOR TECHNICAL ISSUES

1. Fusion Physics
   - Current drive efficiency and bootstrap current. Plasma heating with LHR.
   - Disruption avoidance/mitigation.
2. Fusion Technology
   - Tritium retention.
   - Tritium breeding and recovery.
   - A 100-200 dpa structural material (ODS).
3. Fission Technology
   - MHD effects on Na flow in magnetic field. (molten salt coolant backup?)
   - Refueling in tokamak geometry.(new fuel assy design?)

2 BURNER FUEL CYCLES

1. LWR fleet supported by SABRs---TRU BURNER Fuel Cycle—all TRU from LWR SNF (ANL 65.8%Pu & 34.2% MA) fabricated into fast burner reactor fuel.

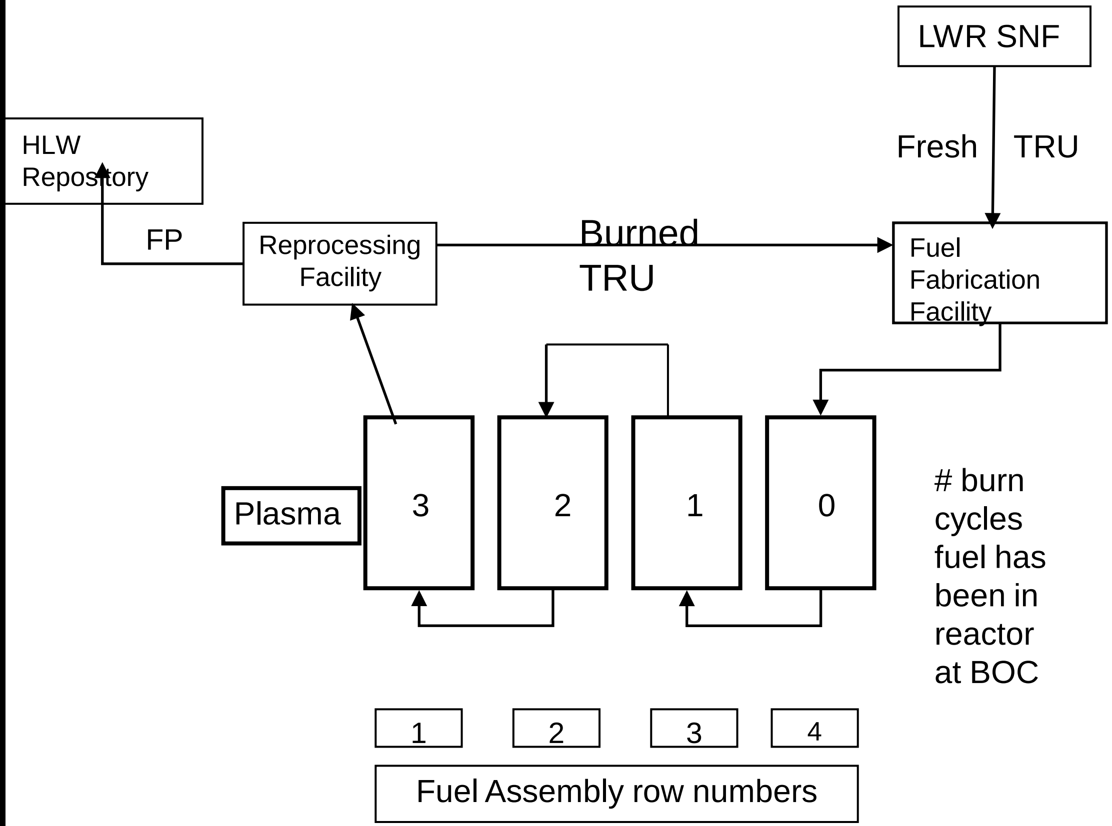
2. LWR fleet transitioning to FR fleet supported by SABRs---MA BURNER Fuel Cycle---some Pu set aside, and remaining MA-rich TRU (EU 45.7%Pu & 54.3%MA) fabricated into fast burner reactor fuel.

- Burner reactor fuel TRU separated and recycled. 1% TRU—fission product separation efficiency assumed.
- Fuel residence time limited by 200 dpa radiation damage limit to ODS clad leads to 2800 fpd fuel residence time.
- 4-batch fuel cycles of 700 fpd, out-to-in shuffling.
- Neutronics and fuel burnup calculated with ERANOS, decay heat with ORIGEN.

SABR TRU BURNER Fuel Cycle

ANL Fuel Composition

Isotope	Mass Percent BOL	Mass Percent 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



SABR TRU BURNER PERFORMANCE

- $0.83<k_{eff}<0.95$, $170MW<P_{fus}<410MW$.
- 1 SABR fissions 1.06MT TRU/fpy--- at 75% availability supports > 3 1000MWe LWRs.
- Decay heat of SNF at 10^5 years reduced 30-fold, indicating an order of magnitude reduction in # HLWRs required.

SABR MA BURNER PERFORMANCE

- $0.89<k_{eff}<0.95$, $195MW<P_{fus}<470MW$.
- 1 SABR fissions 0.85MT MA/fpy--- at 75% availability supports > 25 1000MWe LWRs.
- Decay heat of SNF at 10^5 years reduced 9-fold, indicating order of magnitude reduction in # HLWRs required.

FUEL CYCLE IMPLICATIONS SABR FFH BURNER REACTORS

- A SABR TRU-burner reactor would be able to burn all of the TRU from 3 LWRs of the same power. A nuclear fleet of 75% LWRs (% nuclear electric power) and 25% SABR TRU-burner reactors would reduce geological repository requirements by a factor of >10 relative to a nuclear fleet of 100% LWRs.

- A SABR MA-burner reactor would be able to burn all of the MA from 25 LWRs of the same power, while setting aside Pu for future fast reactor fuel. A nuclear fleet of 96% LWRs and 4% SABR MA-burners would reduce HLWR needs by a factor of 10.

FUSION R&D FOR A SABR FFH IS ON THE PATH TO FUSION POWER

FFH PLASMA PHYSICS R&D for FFH or DEMO

1. Control of instabilities.
2. Reliable, very long-pulse operation.
3. Disruption avoidance and mitigation.
4. Control of burning plasmas.

FFH FUSION TECHNOLOGY R&D for FFH or DEMO

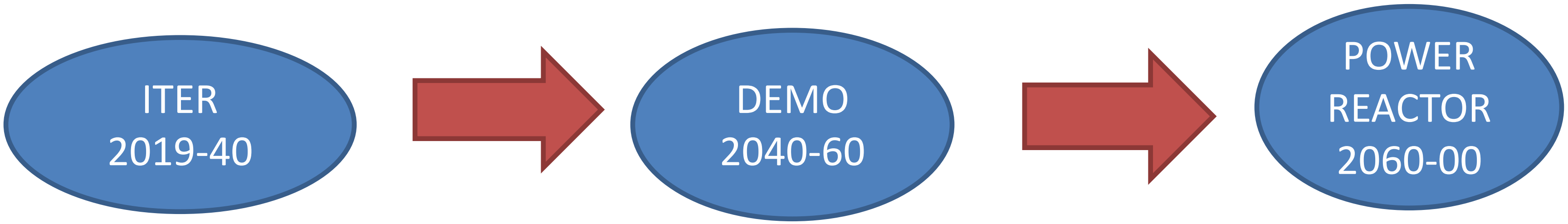
1. Plasma Support Technology (magnets, heating, vacuum,etc.)—improved reliability of the same type components operating at same level as in ITER.
2. Heat Removal Technology (first-wall, divertor)—adapt ITER components to Na coolant and improve reliability.
3. Tritium Breeding Technology—develop reliable, full-scale blanket & tritium processing systems based on technology tested on modular scale in ITER.
4. Advanced Structural (200 dpa) and Other Materials.
5. Configuration for remote assembly & maintenance.

ADDITIONAL FUSION R&D BEYOND FFH FOR TOKAMAK ELECTRIC POWER

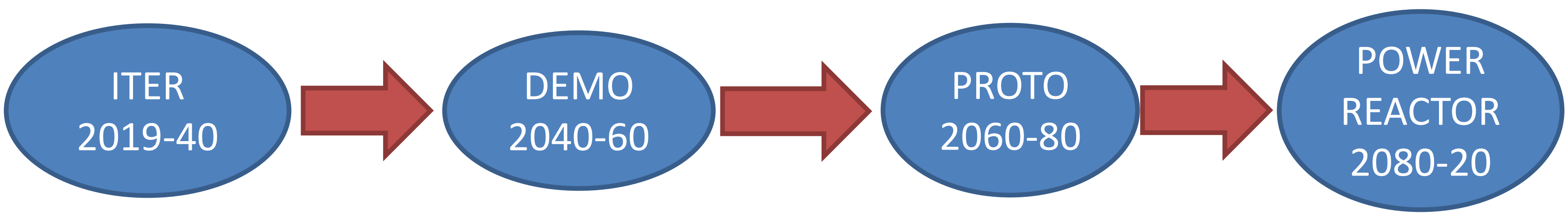
1. Advanced plasma physics operating limits (β,τ) above ITER levels.
2. Improved components and materials operating above ITER levels.

An Unofficial
Fusion Development Schedule

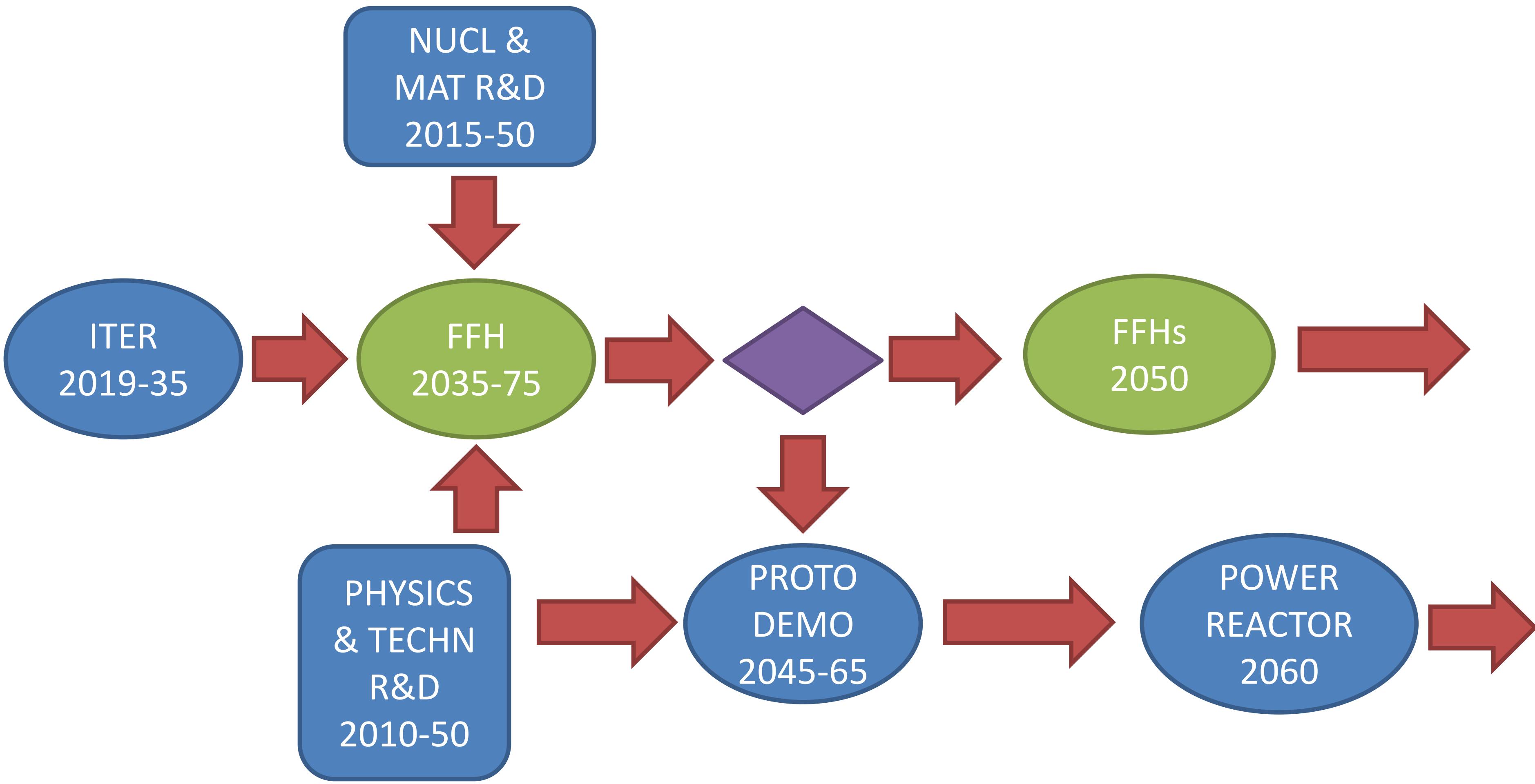
Canonical



More Likely?



FUSION POWER DEVELOPMENT WITH A SYMBIOTIC FUSION-FISSION HYBRID PATH



Plasma Physics
Advances Beyond ITER

- FFH must achieve *highly reliable, very long-pulse plasma operation* with plasma parameters similar to those achieved in ITER.

- PROTODEMO must achieve reliable, long-pulse plasma operation with *plasma parameters* (β,τ) *significantly more advanced* than ITER.

Fusion Technology Advances Beyond ITER

- FFH must operate with moderately higher surface heat and neutron fluxes and with *much higher availability* than ITER.

- PROTODEMO must operate with *significantly higher surface heat and neutron fluxes* and with higher availability than ITER.

- PROTODEMO and FFH would have similar magnetic field, plasma heating, tritium breeding and other fusion technologies.

- PROTODEMO and FFH would have a similar requirement for a radiation-resistant structural material to 200 dpa.

- FFH would require the integration of fusion and fission technologies.

PROs & CONs of Supplemental FFH Path of Fusion Power Development

- Fusion would be used to help meet the world’s energy needs at an earlier date than is possible with ‘pure’ fusion power reactors.

- This, in turn, would increase the technology development and operating experience needed to develop economical fusion power reactors.

- FFHs would support (may be necessary for) the full expansion of sustainable nuclear power in the world.

- An FFH will be more complex and more expensive than either a Fast Reactor (critical) or a Fusion Reactor.

- However, a nuclear fleet with FFHs and LWRs should require fewer Burner Reactors, reprocessing plants and HLWRs than a similar fleet with critical Fast Burner Reactors.

RECOMMENDATIONS

- Detailed conceptual design studies to confirm technical feasibility of FFH burner reactors.
- Comparative fuel cycle, dynamic safety and fuel materials scenario studies of FFH and critical burner reactors.

GEORGIA TECH SABR DESIGN TEAM 2000-11

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