Analysis of hybrid reactors international activities and proliferation risks

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REFERENCES

Orlov et al. “Nuclear problems of thermonuclear power generation” Atomic Energy 124 2018
Kuteev et al. "Fusion-fission hybrid systems: yesterday, today, and tomorrow", FST 2020
Velikhov et al. "Nuclear power system based on fission and fusion reactions is the strategic line of nuclear power industry development" PAN 2018
Sakharov, Collected Scientific Works (Publ. Marcel Dekkes, Inc., New York, N.Y., 1982)
Martin and R.Gatto “Overview of thermonuclear fusion proliferation risks” IAEA-FEC (2023); Various Sapienza Master theses (from 2021)
Glaser and Goldston, “Proliferation Risks of Magnetic Fusion Energy,” Nuclear Fusion, 52, 2012
Velikhov et al. “Some thoughts on the future of the nuclear energy industry” Phys. at. Nuclei 83 2020
Weston, “A strategic opportunity for magnetic fusion energy development” J Fusion Energ 35 2016
Shmelev et al. “Hybrid fusion-fission reactor with a thorium blanket: its potential in the fuel cycle of nuclear reactors” Phys. Atom. Nuclei 78 2015
Wang “Overview and prospects for fusion fission hybrid system development in China” Technical Meeting on Synergies in Technology Development between Nuclear Fission and Fusion for Energy Production” 2022
Stacey “Solving the spent nuclear fuel problem by fissioning transuranics in subcritical advanced burner reactors driven by tokamak fusion neutron Sources” Nucl. Technology 200 2017
Brown and al. “Thorium fuel cycles with externally driven systems” Nucl. Technolgy 194 2016
Moir et al. “Mirror-based hybrids of recent design” Fusion for neutrons and subcritical nuclear fission” AIP Conf. Proc. 2012
Greenspan “Personal views on hybrid reactors” 4 Sept. 2009.

OUTLINE

- Status of ***present nuclear energy system*** and ***motivations for FF hybrids***:
  (i) problematic issues in the present nuclear energy system
  (ii) problematic issues with fusion energy
  (iii) Potential role of FF hybrids

- Overview of ***international FF hybrid research programs and objectives:***
  - ➔ Russian Federation
  - ➔ China
  - ➔ United States

- ***Proliferation risks***

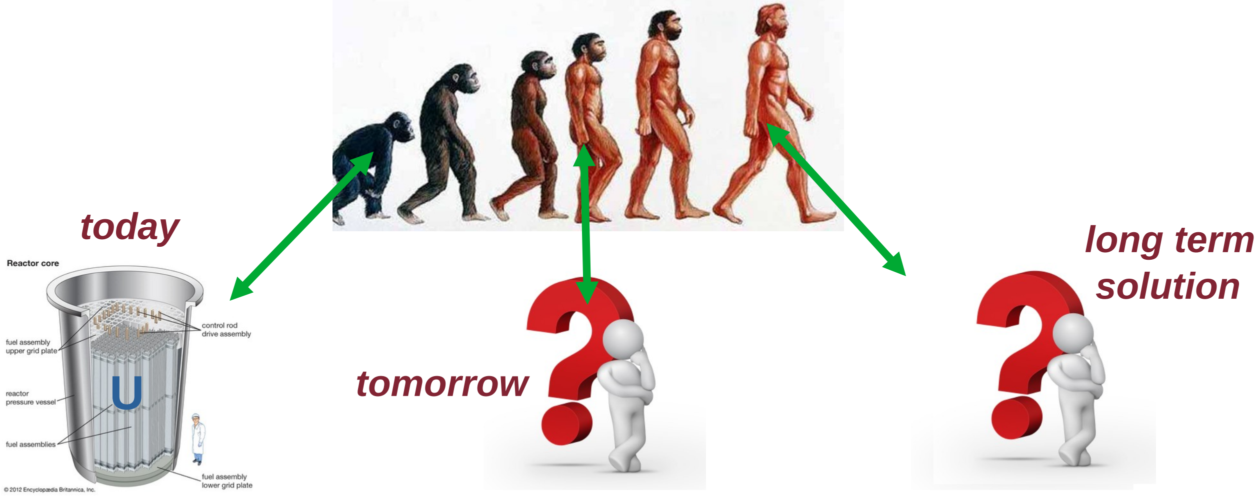
- ***Conclusions***

STATUS OF PRESENT NUCLEAR ENERGY SYSTEM AND MOTIVATIONS FOR FUSION FISSION HYBRID SYSTEMS (FFHSs)

Why are we here today to talk about FFHSs?

Is it only an ***academic exercise*** put forward by nuclear energy physicists and engineers, intrigued by the complexities of the synergy between fission and fusion energy production?

Or is an issue born out from the ***shared awareness*** that the present system of nuclear energy production, based on thermal fission reactors using Uranium as a fuel, is only ***the first step*** into the exploitation of nuclear energy, and that the evolution toward a system that is truly ***sustainable*** might lead to ***a very different solution from the present one***



today

tomorrow

long term solution

STATUS OF PRESENT NUCLEAR ENERGY SYSTEM AND MOTIVATIONS FOR FUSION FISSION HYBRID SYSTEMS (FFHSs)

Fission energy: closing the fuel cycle, and more

- The word **SUSTAINABILITY** is the key word of our time.
  In the present context of nuclear energy production based on fission reactors it means, among other things: (1) energy generation with an ***equilibrium amount of Pu and MA***, therefore burning them efficiently
  (2) extension of ***fuel reserves*** by using 100% of the Uranium/Thorium energy content as well as breeding new fuel
  (3) ***safety***
  (4) ***non-proliferation***

- The ***dual system of thermal and fast fission reactors*** solution: energy produced mainly by the thermal fleet but closing the fuel cycle using a smaller fleet of fast reactors, where MAs are eliminated by fissioning, producing at the same time energy - ***closed fuel cycle***

- However, despite Fermi’s fast spectrum reactor suggestion in 1944, the ***history of fast reactors to date has not been very successful*** (e.g. Super-Phenix), and in any case even in the best expectations the transition to an equilibrium closed fuel cycle ***takes a long time***, perhaps 100 or 200 years. How many things can happen in this time frame? E.g. ***fusion ...***

STATUS OF PRESENT NUCLEAR ENERGY SYSTEM AND MOTIVATIONS FOR FUSION FISSION HYBRID SYSTEMS (FFHSs)

Fusion energy: are we there?

- Many private companies are claiming that a ***fusion reactor*** can be realized within a short period of time (10-20 years or so). However, considering the most successful approach to date – the ***tokamak*** based on D-T fuel - we point out several still unresolved ***issues***:

- First proposal of thermonuclear fusion based on magnetic confinement in ***1950*** (Sakharov) – at today thermonuclear fusion has not been realized on Earth for longer that ***5 sec*** (JET), and ITER's discharges should extend up to 400 sec ...
  Challenging physics and technological problems must still be solved satisfactorily (e.g., still need to explore ***plasma operational regimes with high rate of fusion reactions***!).

- The ***tritium problem***:
  (i) a ***1 GWe fusion power plant requires 180 kg tritium/year***, and "wastes" 1.15 x 10^{21} n/sec for tritium production in its blanket – self-sufficient tritium production in situ ***not demonstrated yet***
  (ii) in any case tritium is a ***dangerous radioactive element***: an accidental release of few grams of tritium (the amount foreseen in the plasma of a fusion reactor during operation) in the atmosphere can lead to serious environmental consequences

STATUS OF PRESENT NUCLEAR ENERGY SYSTEM AND MOTIVATIONS FOR FUSION FISSION HYBRID SYSTEMS (FFHSs)

Fusion energy: are we there?

- Moreover, transforming fusion kinetic energy directly in to heat (pure fusion) doesn’t seem to be the most reasonable method of using D-T fusion neutrons: one neutron deposits 14.1 MeV in a fusion blanket, while one neutron release 200 MeV after fission (14 times greater energy value): in terms of energy production efficiency, ***a pure fusion reactor is worse that a fission reactor***.

- Numerous other technological problems to be solved:
  - (i) ***material damage*** by intense neutron and particle bombardment
  - (ii) ***plasma heat exhaust*** on the first wall (divertor/limiter)
  - (iii) ***remote maintenance***
  - (iv) ***economic acceptability.***

STATUS OF PRESENT NUCLEAR ENERGY SYSTEM AND MOTIVATIONS FOR FUSION FISSION HYBRID SYSTEMS (FFHSs)

FF hybrids: a potential candidate system for the medium-term development of the nuclear energy system in the path of sustainability

In his 1950's paper on FF hybrids Sakharov himself proposed fusion neutrons be used to ***breed fissile isotopes to be subsequently used in fission reactors***

F-F hybrid machines are not simply the juxtaposition of two technologies that in coupled operation retain their conventional characteristics, but on the contrary are machines with ***fundamentally new features and parameters***

The reason resides in the coupling of an ***intense source of high energy neutrons*** (14 MeV vs the 2 MeV of fission neutrons) with a ***highly multiplying medium*** composed of heavy nuclei

STATUS OF PRESENT NUCLEAR ENERGY SYSTEM AND MOTIVATIONS FOR FUSION FISSION HYBRID SYSTEMS (FFHSs)

These ***new nuclear systems*** turns out to have the following beneficial characteristics to overcome the difficulties of the present nuclear energy system and ***contribute to its medium-term development in the path of sustainability***:

- In a blanket comprises of ^{238}U or ^{232}Th (fertile nuclei) and ^{6}Li surrounding the source of fusion neutrons: one 14.1 MeV neutron can produce ~1 T nucleus, ~1 fission reaction, ~3 ^{239}Pu nuclei or ~1.3 ^{233}U nuclei, ending up with an energy generated in the blanket ~ 10 times greater that the fusion energy of 17.6 MeV (even considering that one neutrons must be expended in producing one T atom)

- Higher neutron spectrum leads to a more efficient breeding (wrt critical fission reactors) of ^{239}Pu or ^{233}U to be used in thermal reactors

- Higher neutron spectrum leads to a more efficient fission (burning) of MA

STATUS OF PRESENT NUCLEAR ENERGY SYSTEM AND MOTIVATIONS FOR FUSION FISSION HYBRID SYSTEMS (FFHSs)

- Access to endo-thermal multiplication reactions (n,2n) and (n,3n) on heavy isotopes contribute to the neutron economy, and opens up ***new routes of burn-up***
- Better apt to ***produce tritium***
- ***Safe to operate*** due to the subcritical status of the fission blanket
- ***Control is facilitated*** by the independence of the primary fusion source on fission blanket neutron fluxes
- Being subcritical a FFHS lends itself naturally to adopt the ***thorium cycle***
- Plasma can be much less performing that in a pure fusion reactor: Q ~ 1 is sufficient (as in present tokamak experiments): ***acceleration of the exploitation of fusion energy***
- Provide a diffuse high energy neutron source for ***testing nuclear materials*** and ***other applications***

OVERVIEW OF WORLDWIDE FFHS RESEARCH PROGRAMS AND OBJECTIVES

Overview

- Most nuclear countries have ***ongoing programs on FFHS*** supported mainly by ***Governmental funds***, which demonstrates their awareness of the important contribution these systems can make to the sustainable development of nuclear energy

- Differently from fission and pure fusion systems, ***no private funds*** have been directed into FFHS activities (very few exceptions)

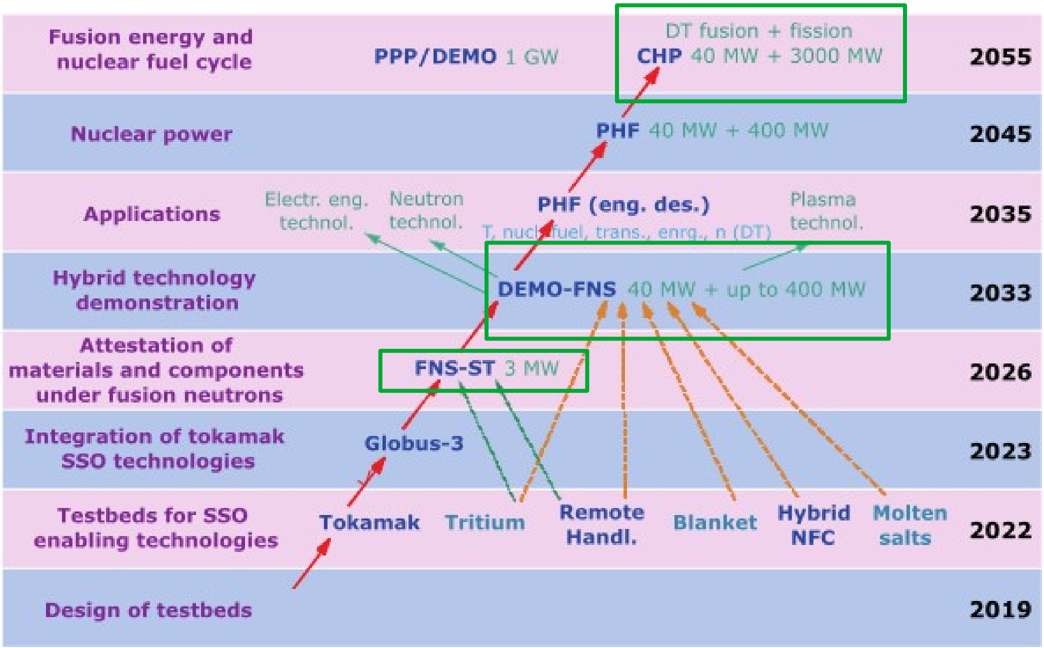
- Europe has a weak research programs on FFHS, Italy is not exception

I will come back to these observations in my afternoon talk

OVERVIEW OF WORLDWIDE FFHS RESEARCH PROGRAMS AND OBJECTIVES

RUSSIAN FEDERATION: Roadmap for FFHS development

At present, Russia’s nuclear industry considers ***FFHS a key element in the in shifting AE system to the closed fuel cycle.*** Hybris systems are included in the Federal project “Development of Fusion and Innovative Plasma Technolgies”, recommending to start ***design and construction of fusion neutron devices as soon as possible,*** beginning with steady-sate D-D fusion devices taking advantage of non-Maxwellian beam-plasma fusion

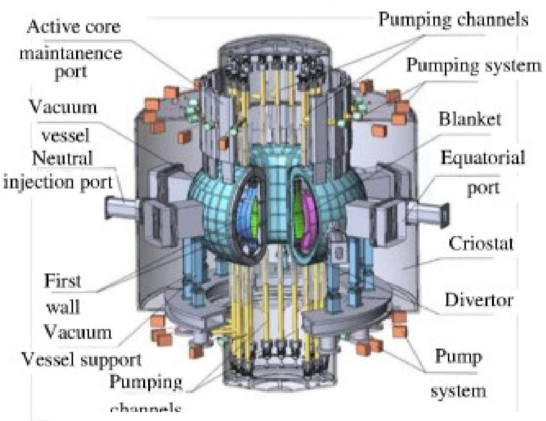


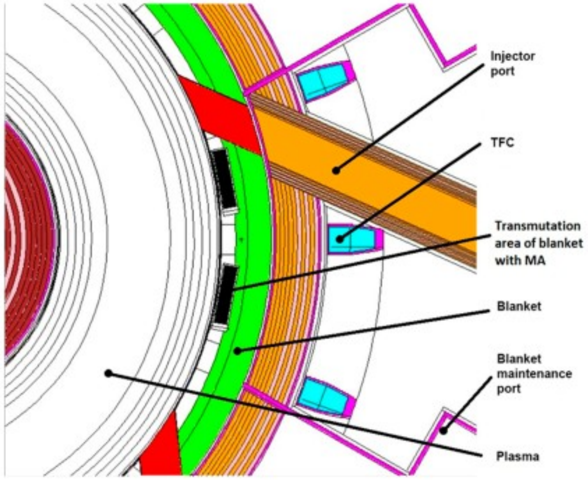
Fusion energy and nuclear fuel cycle	**PPP/DEMO** 1 GW DT fusion + fission **CHP** 40 MW + 3000 MW	**2055**
Nuclear power	**PHF** 40 MW + 400 MW	**2045**
Applications	Electr. eng. technol. Neutron technol. **PHF (eng. des.)** T, nucl. fuel, trans., enrg., n (DT) Plasma technol.	**2035**
Hybrid technology demonstration	**DEMO-FNS** 40 MW + up to 400 MW	**2033**
Attestation of materials and components under fusion neutrons	**FNS-ST** 3 MW	**2026**
Integration of tokamak SSO technologies	**Globus-3**	**2023**
Testbeds for SSO enabling technologies	**Tokamak** **Tritium** **Remote Handl.** **Blanket** **Hybrid NFC** **Molten salts**	**2022**
Design of testbeds		**2019**

A project is underway in Russia to develop a fusion-fission hybrid facility based on the ***DEMO-FNS Superconducting Tokamak (40 MW fusion + 400 MW fission power)***

OVERVIEW OF WORLDWIDE FFHS RESEARCH PROGRAMS AND OBJECTIVES

RUSSIAN FEDERATION: DEMO-FNS



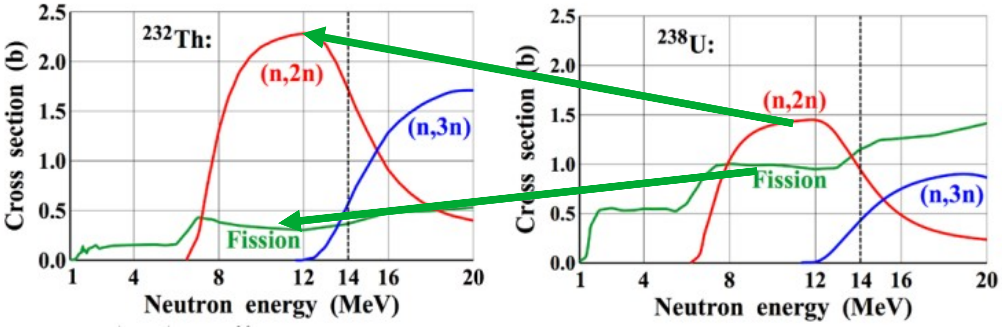


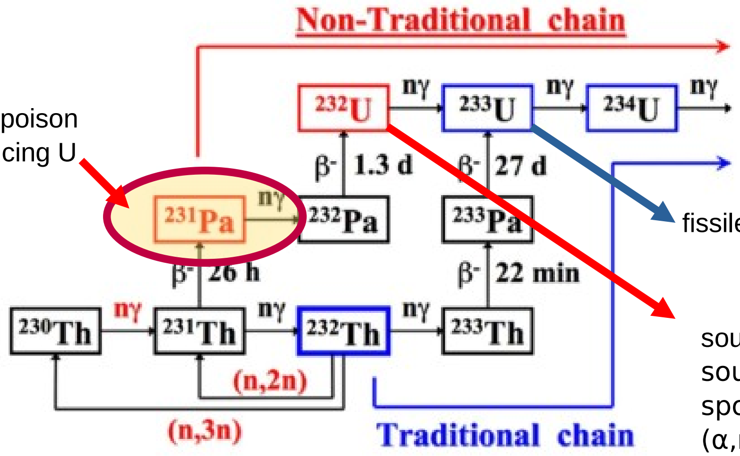
Technical Parameters Characterizing Major Existing and Prospective Fusion Facilities

Facility	n_{20}, $(10^{20}\ \mathrm{m}^{-3})$	T (keV)	τ_E (s)	k_g (g/day)	t_{SS} (yr)	C	Q	K_g
JET	1	10	0.3	0.35	3.5×10^{-7}	0.1	1	4×10^{-8}
NIF	10^{12}	0.2	2×10^{-11}	10^{-8}	10^{-6}	0.1	0.015	4×10^{-15}
ITER	1	10	3.5	25	10^{-4}	0.25	10	2×10^{-2}
FNS-ST	1	2	0.05	0.2	1	0.3	0.2	6×10^{-3}
DEMO-FNS	1	4	0.3	2	1	0.3	1	7×10^{-1}
DEMO	1	15	5	50	1	0.5	25	2×10^{3}
PROTO	1	15	6	150	1	0.8	30	1×10^{4}

OVERVIEW OF WORLDWIDE FFHS RESEARCH PROGRAMS AND OBJECTIVES

RUSSIAN FEDERATION: Fuel generation from Th cycle with high burnup

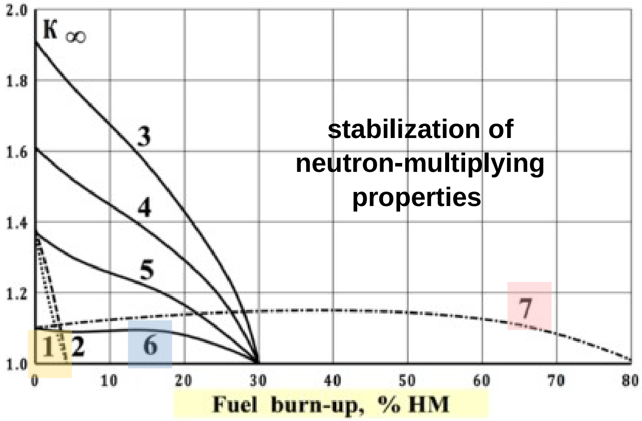




burnable poison
but producing U

fissile

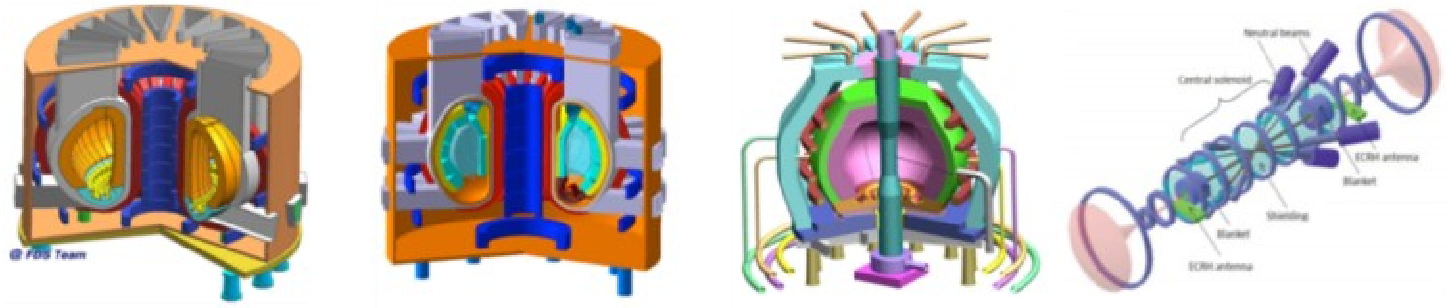
source of α
source of heat
spontaneous fission n
(α,n) n
proliferation resistance



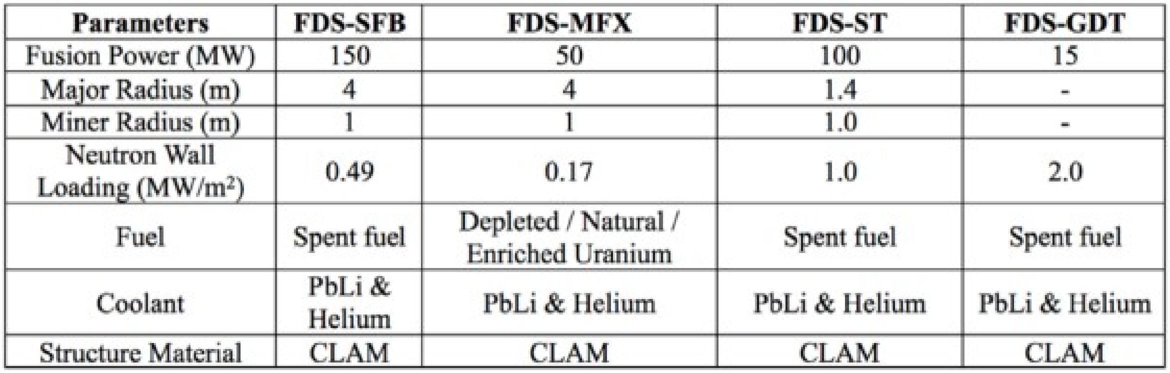
stabilization of neutron-multiplying properties

1 - (4.4%235U+95.6%238U)O2,
2 - (5.33%233U+94.67%232Th)N,
3 - (0%231Pa+31%233U+69%232Th)N,
4 - (5%231Pa+26%233U+69%232Th)N,
5 - (10%231Pa+21%233U+69%232Th)N,
6 - (15%231Pa+16%233U+69%232Th)N,
7 - (61%231Pa+39%233U+ 0%232Th)N.

CHINA: Roadmap for Fusion Driven Subcritical series

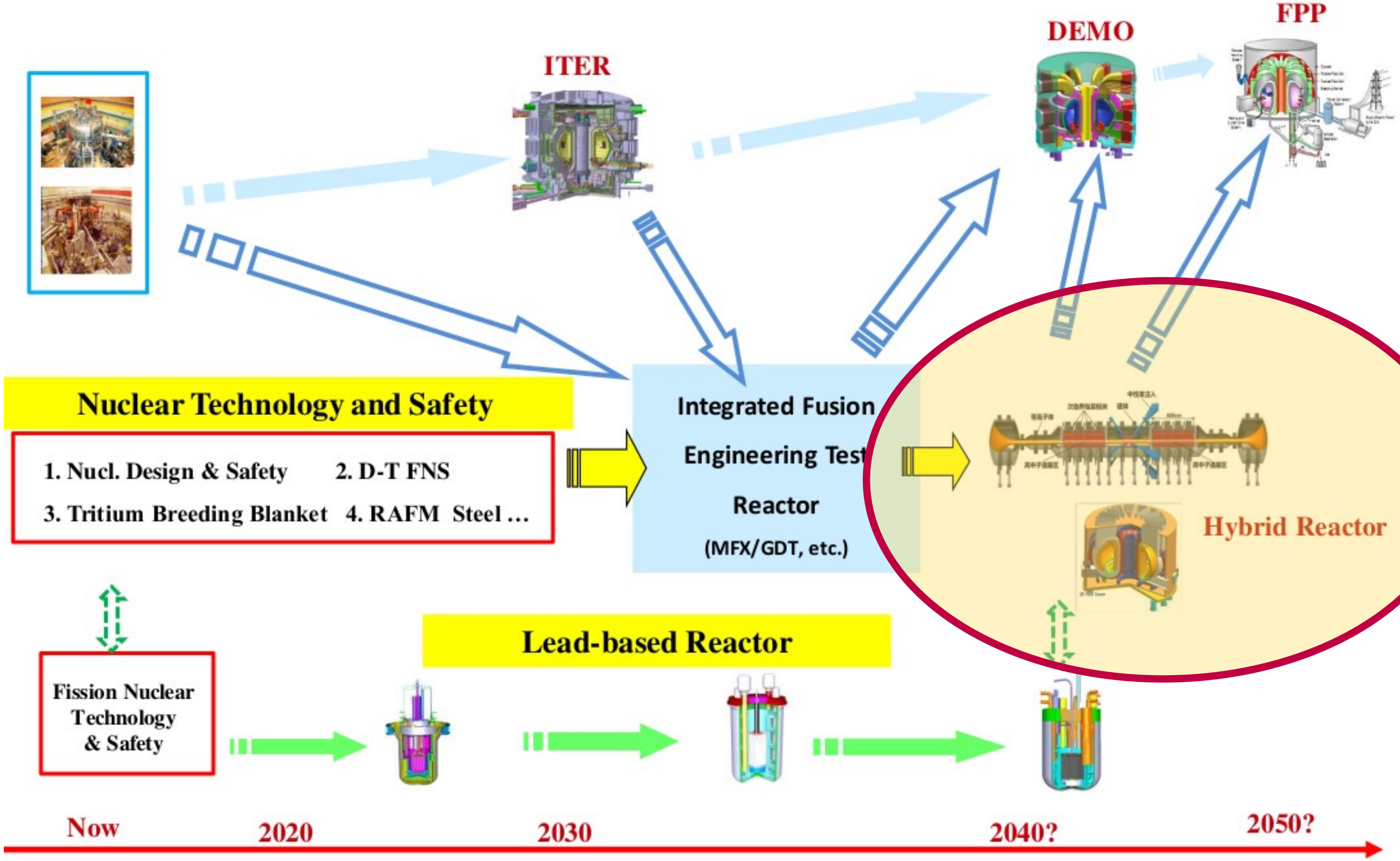


(a) FDS-I/SFB (b) FDS-MFX (c) FDS-ST (d) FDS-GDT



Parameters	FDS-SFB	FDS-MFX	FDS-ST	FDS-GDT
Fusion Power (MW)	150	50	100	15
Major Radius (m)	4	4	1.4	-
Miner Radius (m)	1	1	1.0	-
Neutron Wall Loading (MW/m^2)	0.49	0.17	1.0	2.0
Fuel	Spent fuel	Depleted / Natural / Enriched Uranium	Spent fuel	Spent fuel
Coolant	PbLi & Helium	PbLi & Helium	PbLi & Helium	PbLi & Helium
Structure Material	CLAM	CLAM	CLAM	CLAM

CHINA: ROADMAP for FFHS



ITER

DEMO

FPP

Nuclear Technology and Safety

1. Nucl. Design & Safety
2. D-T FNS
3. Tritium Breeding Blanket
4. RAFM Steel …

Integrated Fusion Engineering Test Reactor
(MFX/GDT, etc.)

Hybrid Reactor

Lead-based Reactor

Fission Nuclear Technology & Safety

Now — 2020 — 2030 — 2040? — 2050?

CHINA: FDS-I/-SFB

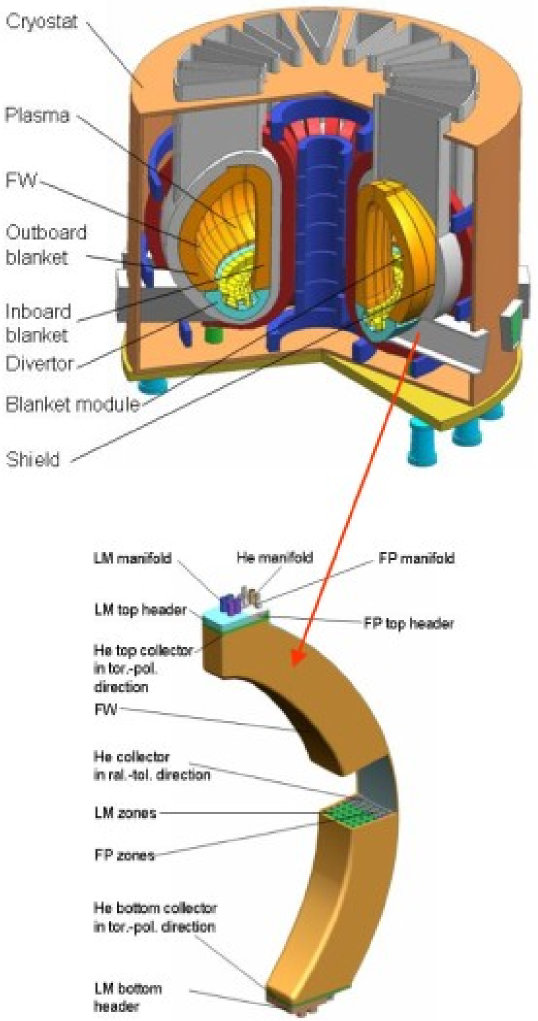
Fusion Driver Subcritical for Spent Fuel Burning based on conventional tokamak design

Configuration:

● D-T fusion power	150 MW
● Neutron wall loading	0.5 MW/m^2
● Neutron source intensity	5.334 x 10^{19} n/sec
● Major radius	4 m
● Minor radius	1 m
● Elongation	1.7

Main functions:

- Transmute long-lived nuclear wastes from fission power plants
- Breed fissile fuel for fission power plants
- Generate energy
- Self-sustain tritium for fusion core



CHINA: FDS-ST

Fusion Driver Subcritical based on Spherical Tokamak-Based System

Plasma core:

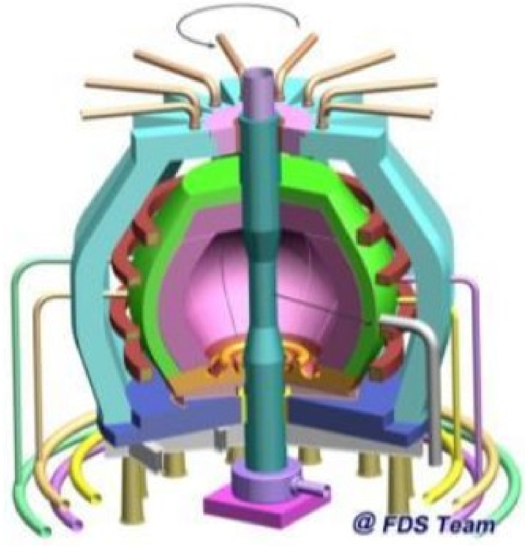
- Fusion power: 100-200 MW
- Power gain ~ 5
- Neutron wall loading 0.5-1 MW/m^2
- Innovative liquid metal Center Conductor Post to prolong lifetime and to increase tritium breeding

Blanket

- Sub-critical outboard with high energy multiplication (to compensate the large fraction of re-circulating power)

Main functions:

- Exploit and assess innovative approach of fusion energy



CHINA: FDS-GDT

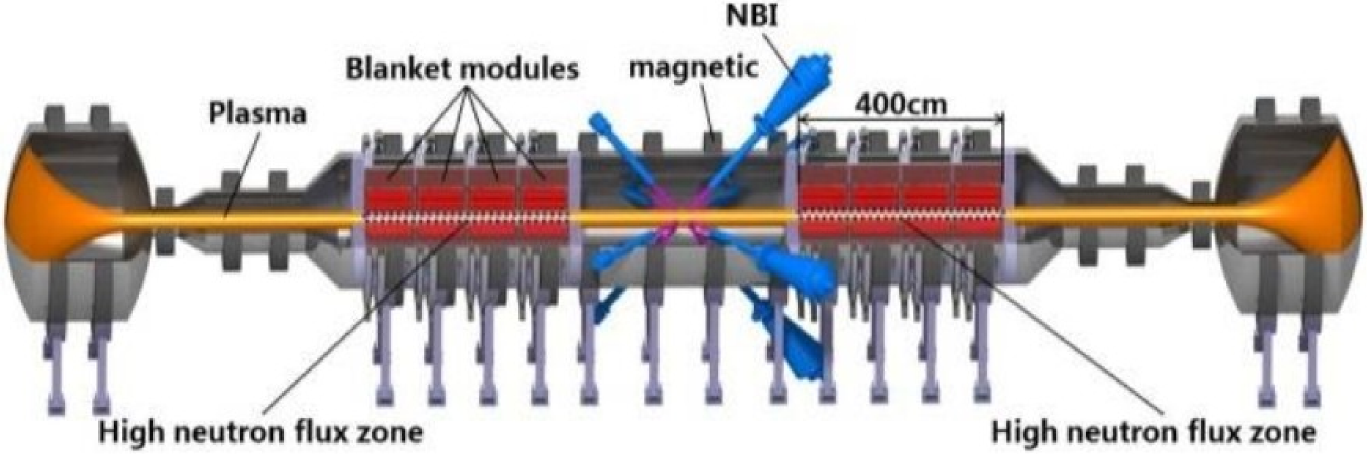
Fusion Driver Subcritical Gas-Dynamic Trap

Parameters:

Fusion power	~ 15 MW
System power	~ 500 MWt
keff	0.95-0.97
Fuel	UZr
Coolant	PbLi

Goals:

- Adopt simple structure, compact and economical driven system
- Use gas dynamic trap to drive subcritical traveling wave blanket
- Minimum generation of nuclear waste
- Maximum fuel utilization efficiency

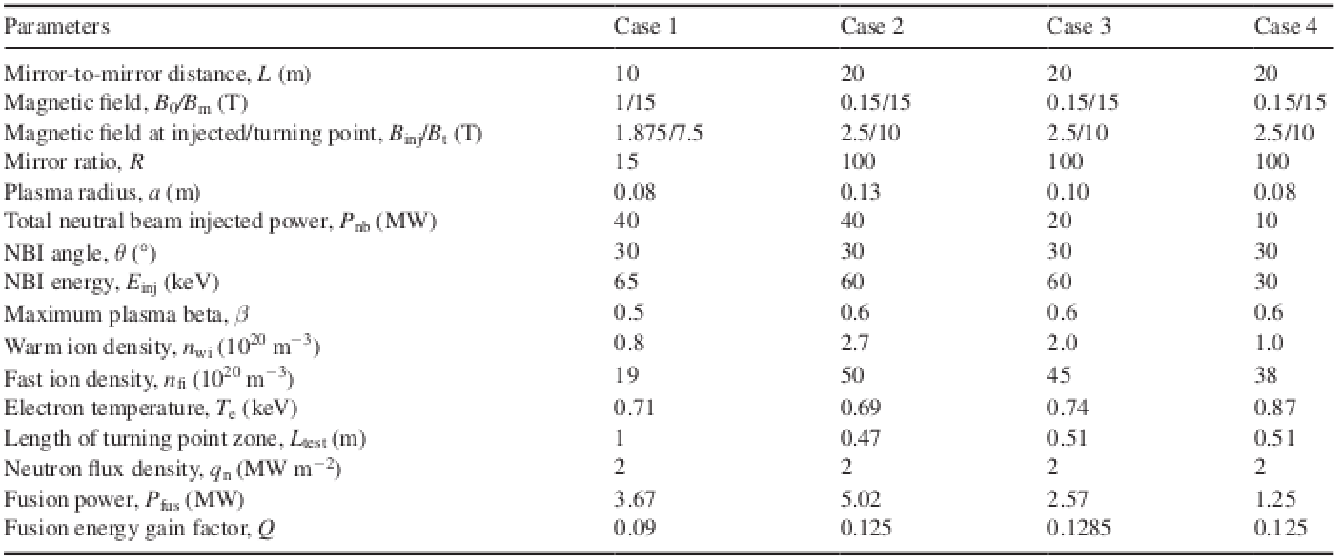


CHINA: FDS-GDT

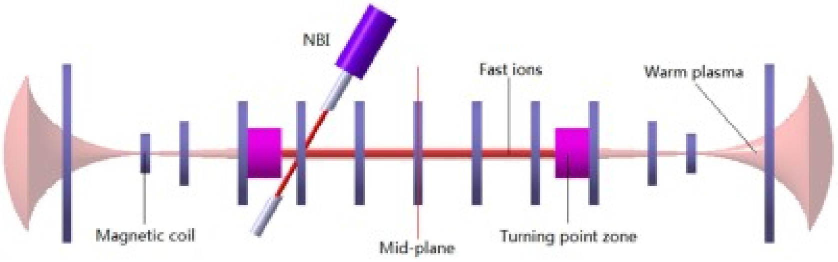
Fusion Driver Subcritical Gas-Dynamic Trap

Axisymmetric magnetic mirror with high mirror ratio (R>10) and long mirror length exceeding the effective mean free path of warm ions:

- oblique injection of high energy D and T neutron beam to produce fast ions
- due to the small spread angle, fast ions concentrate in two zones of turning points where fusion reactions occurs



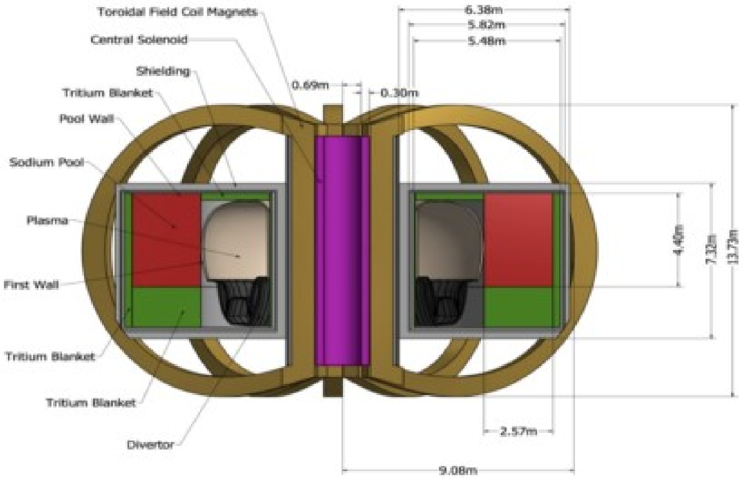
Parameters	Case 1	Case 2	Case 3	Case 4
Mirror-to-mirror distance, L (m)	10	20	20	20
Magnetic field, B_0/B_m (T)	1/15	0.15/15	0.15/15	0.15/15
Magnetic field at injected/turning point, B_{inj}/B_t (T)	1.875/7.5	2.5/10	2.5/10	2.5/10
Mirror ratio, R	15	100	100	100
Plasma radius, a (m)	0.08	0.13	0.10	0.08
Total neutral beam injected power, P_{nb} (MW)	40	40	20	10
NBI angle, θ (°)	30	30	30	30
NBI energy, E_{inj} (keV)	65	60	60	30
Maximum plasma beta, β	0.5	0.6	0.6	0.6
Warm ion density, n_{wi} (10^{20} m^{-3})	0.8	2.7	2.0	1.0
Fast ion density, n_{fi} (10^{20} m^{-3})	19	50	45	38
Electron temperature, T_e (keV)	0.71	0.69	0.74	0.87
Length of turning point zone, L_{test} (m)	1	0.47	0.51	0.51
Neutron flux density, q_n (MW m^{-2})	2	2	2	2
Fusion power, P_{fus} (MW)	3.67	5.02	2.57	1.25
Fusion energy gain factor, Q	0.09	0.125	0.1285	0.125



USA: SABR

Subcritical Advanced Burner Reactor (SABR) spent fuel transmutation reactor, based on:
(I) fast reactor physics and technology of EBR-II: Na-cooled, metal-fuel fast reactor
(ii) fusion neutron source physics and technology of ITER: D-T tokamak

These are the most highly developed fusion and fission transmutation-applicable technologies → could be built in 25-30 years



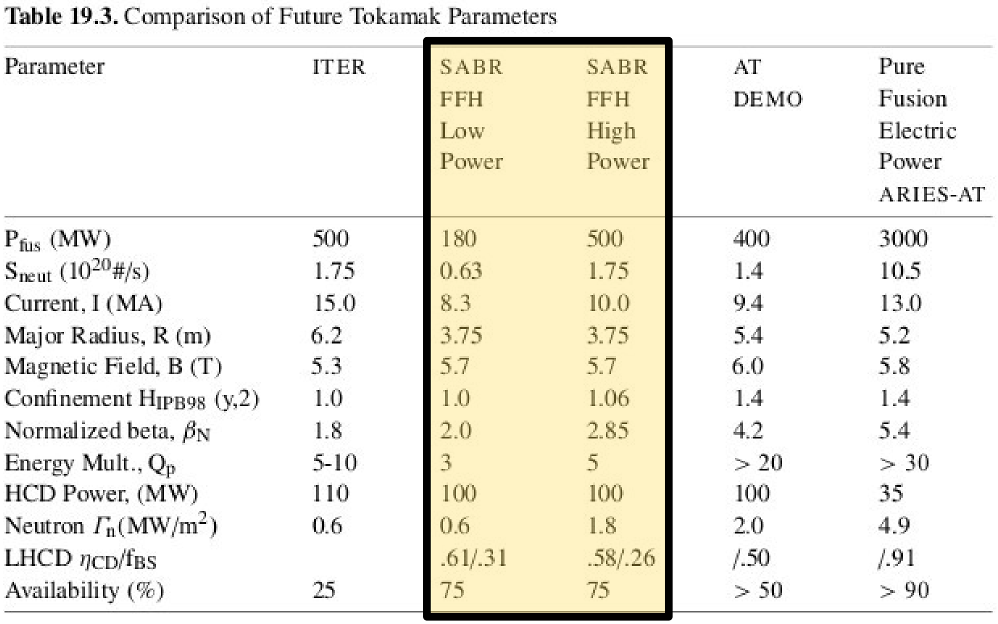
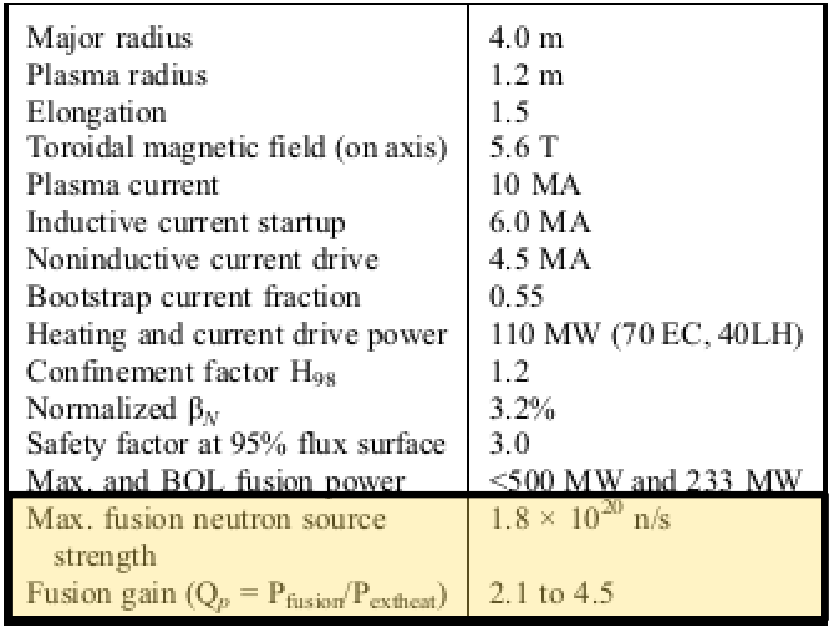


Table 19.3. Comparison of Future Tokamak Parameters

Parameter	ITER	SABR FFH Low Power	SABR FFH High Power	AT DEMO	Pure Fusion Electric Power ARIES-AT
P_{fus} (MW)	500	180	500	400	3000
S_{neut} (10^{20}#/s)	1.75	0.63	1.75	1.4	10.5
Current, I (MA)	15.0	8.3	10.0	9.4	13.0
Major Radius, R (m)	6.2	3.75	3.75	5.4	5.2
Magnetic Field, B (T)	5.3	5.7	5.7	6.0	5.8
Confinement H_{IPB98} (y,2)	1.0	1.0	1.06	1.4	1.4
Normalized beta, β_N	1.8	2.0	2.85	4.2	5.4
Energy Mult., Q_p	5-10	3	5	> 20	> 30
HCD Power, (MW)	110	100	100	100	35
Neutron Γ_n(MW/m^2)	0.6	0.6	1.8	2.0	4.9
LHCD η_{CD}/f_{BS}		.61/.31	.58/.26	/.50	/.91
Availability (%)	25	75	75	> 50	> 90

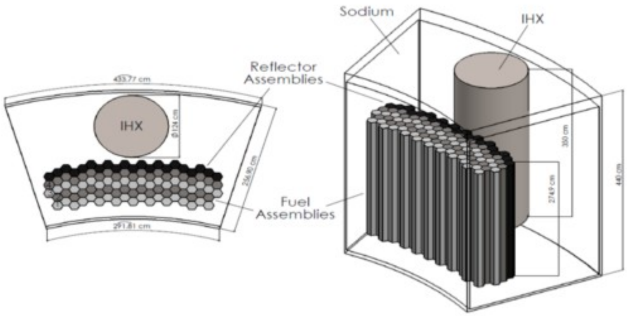
USA: Georgia Tech prof. Stacey

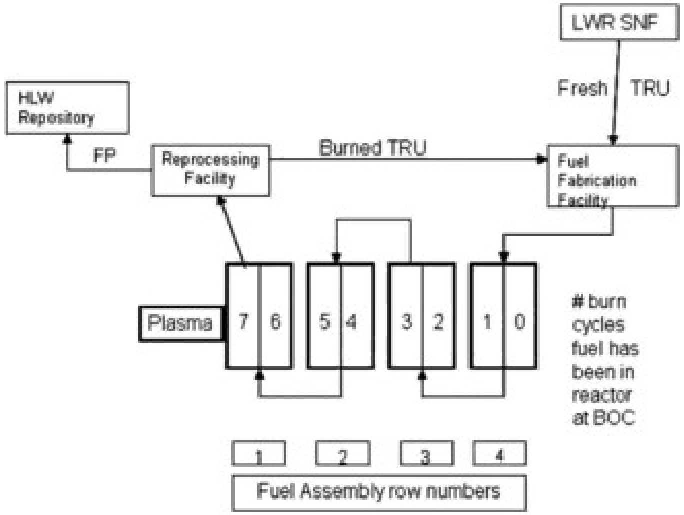
Plasma physics parameters



Major radius	4.0 m
Plasma radius	1.2 m
Elongation	1.5
Toroidal magnetic field (on axis)	5.6 T
Plasma current	10 MA
Inductive current startup	6.0 MA
Noninductive current drive	4.5 MA
Bootstrap current fraction	0.55
Heating and current drive power	110 MW (70 EC, 40LH)
Confinement factor H_{98}	1.2
Normalized β_N	3.2%
Safety factor at 95% flux surface	3.0
Max. and BOL fusion power	<500 MW and 233 MW
Max. fusion neutron source strength	1.8×10^{20} n/s
Fusion gain ($Q_p = P_{fusion}/P_{extheat}$)	2.1 to 4.5

Four-batch out-to-in fuel cycle





USA: Georgia Tech prof. Stacey

Characteristics:

- ***fast spectrum***: $\alpha=\sigma_c/\sigma_f$ for all TRU increases with energy; ν increases with energy
- ***metal fuel*** leads to harder spectrum and greater TRU fission rate
- all TRU are processed as an aggregate (***no Pu separation***)
- some TRU have spontaneous fission rates - non-proliferation

Conclusion:

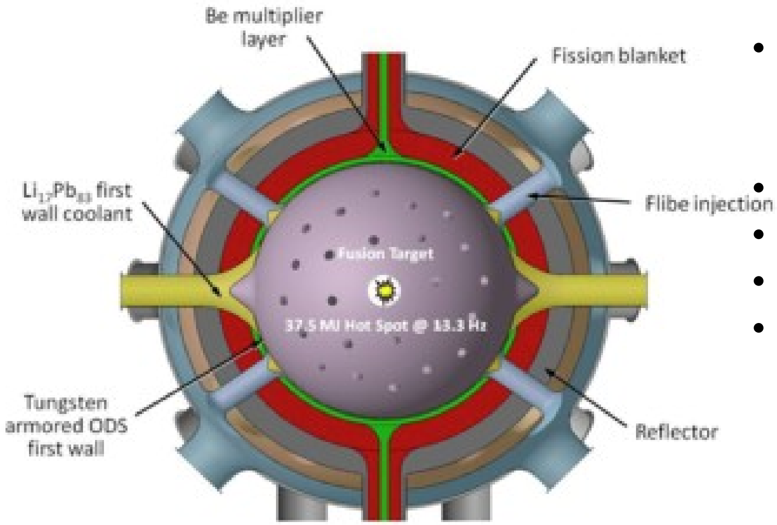
- sub-criticality would enable a proliferation-resistant fuel reprocessing cycle that safely accommodates fuel with ***up to 100% TRU content***
- introduction of SABRs in a ***1-to-3 power ratio with LWRs*** would reduce the required SNF high-level waste repository capacity (based on decay heat) by a factor of 10 to 100
- SABR shut-down to decay heat level ***by turning off the plasma heating power*** with no core damage

USA: EDS with thorium

- ***Externally driven systems (EDS)*** are closely associated with ***thorium*** (no naturally occurring fissile isotopes)
- Fuel cycles with ***natural thorium and no enrichment*** – three variants:
  (1) once-through ***breed-and-burn*** fuel cycle thermal or fast spectrum
  (2) fissile breeder (^{233}U) to support a fleet of critical reactors
  Fuel cycle with ***enriched uranium in addition to thorium***:
  (3) burn Plutonium and MAs
- Each of this fuel presents ***significant potential benefits*** per unit energy generation (waste management, resource utilization, etc.) compared to the present once-through uranium fuel cycle
- Fusion-fission hybrid systems perform ***better than ADSs*** in some missions due to a higher neutron source relative to the energy required to produce it
- EDSs face ***significant development and deployment challenges***. also associated with the use of thorium fuel and with the transition from a uranium-based fuel cycle to a thorium-based fuel cycle

USA: EDS with thorium

Consider the option (1): ***breed-and-burn FFHS, with ICF system*** based on a National Ignition Facility at Lawrence Livermore National Laboratory (“LIFE engine”))



- natural thorium is initially loaded (TRISO particles in carbon pebbles) and fissile material is generated and burned in situ until operational limits are achieved
- liquid LiPb as FW coolant, FLiBe as blanket coolant
- ^{6}Li to breed tritium
- Be multiplier (metallic pebbles)
- reflector

Total power = 2000 MWt [blanket gain (th. fusion power/tot system power) = 4], burn-up of 729 GWd per MTHM could be achieved in 53.2 effective full-power years

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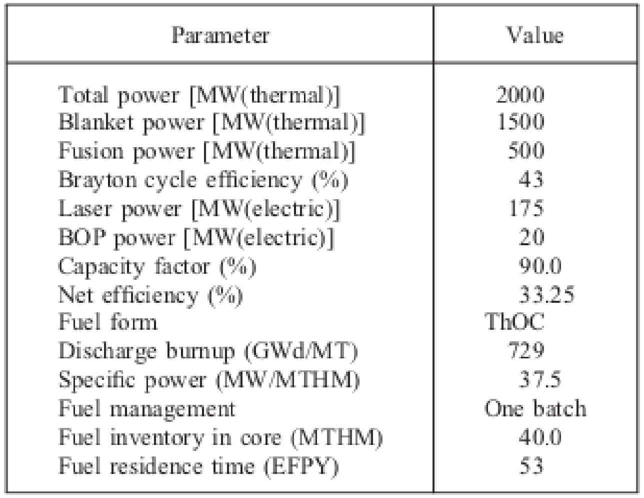
Breed & burn concept:

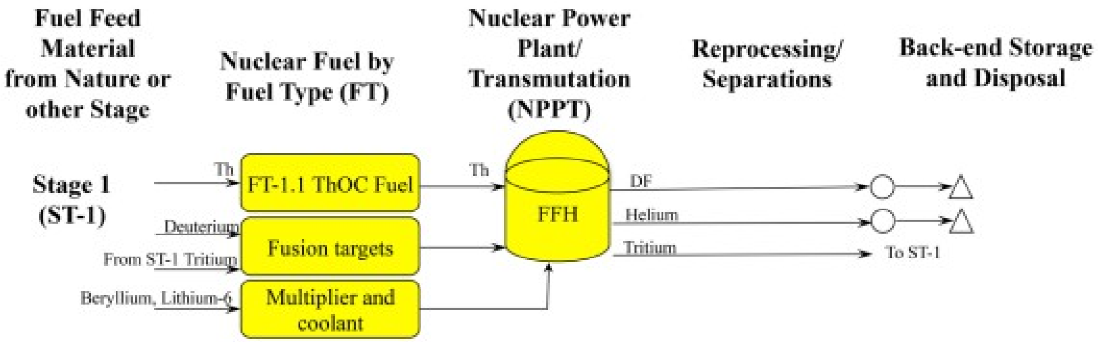
- FFHS initially operates below nominal power - ***ramp-up time***
- After this point nominal ***power is kept constant controlling the level of ^{6}Li enrichment*** in the blanket coolant

Fuel cycle performance parameters

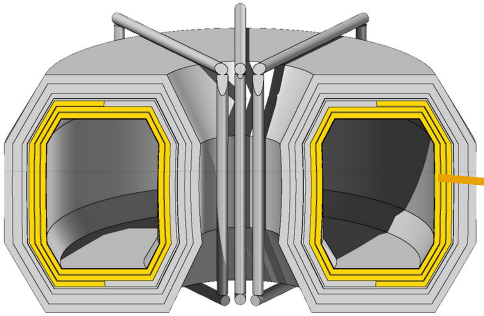


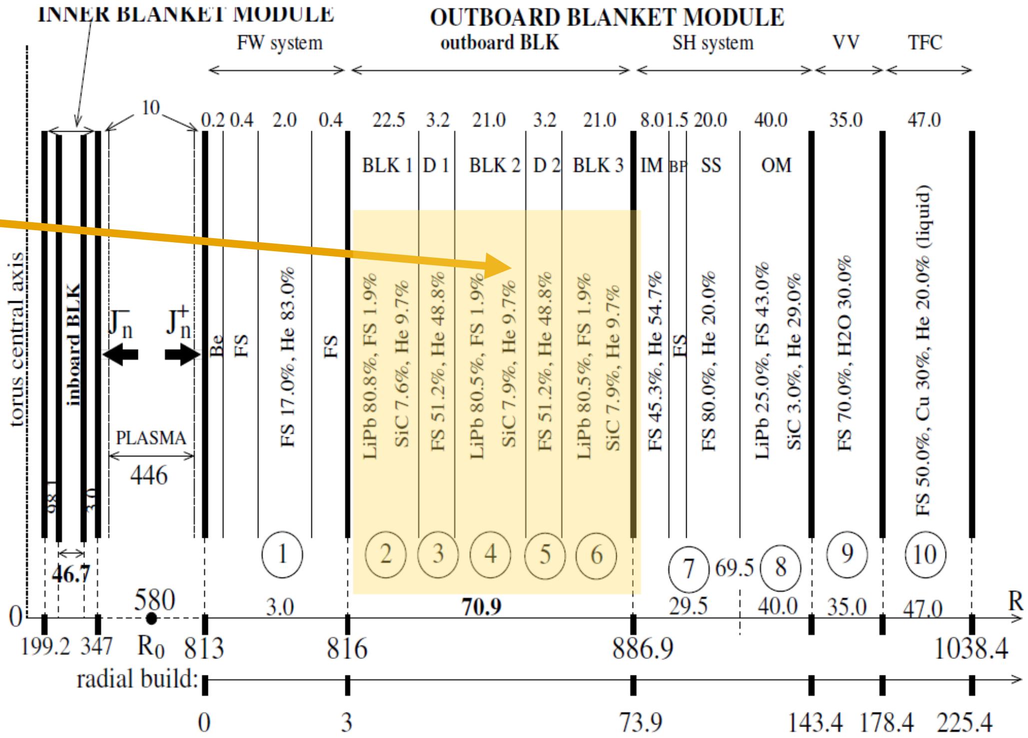
Parameter	Value
Total power [MW(thermal)]	2000
Blanket power [MW(thermal)]	1500
Fusion power [MW(thermal)]	500
Brayton cycle efficiency (%)	43
Laser power [MW(electric)]	175
BOP power [MW(electric)]	20
Capacity factor (%)	90.0
Net efficiency (%)	33.25
Fuel form	ThOC
Discharge burnup (GWd/MT)	729
Specific power (MW/MTHM)	37.5
Fuel management	One batch
Fuel inventory in core (MTHM)	40.0
Fuel residence time (EFPY)	53

Material flow diagram for once-through FFH thorium fuel cycle



PROLIFERATION RISKS

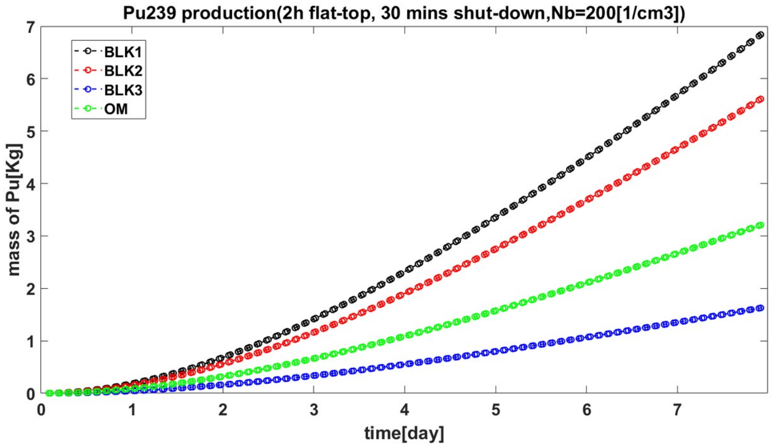




Example of Material composition in the fusion blanket, inspired by the ITER dual coolant LiPb blanket

What is we introduce into blanket ***microspheres containing ^{238}U***?

PROLIFERATION RISKS

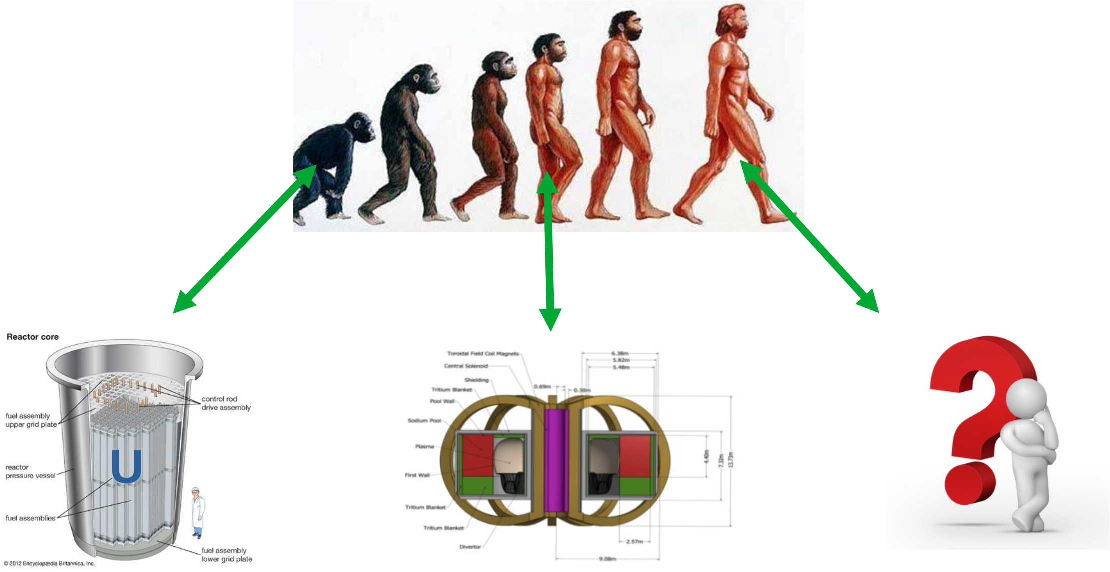


Nb=200 [1/cm^3], UO2					
	BLK1	BLK2	BLK3	OM	Total
Flux [1/cm^2]	1.22E+15	3.96E+14	1.29E+14	7.29E+12	//
Inventory UO2 [tons]	95.6	95.7	69.6	211.21	472
Pu239 [Kg]	6.841	4.613	1.628	3.209	**15.931**
Production compared to total	40.681%	28.956%	10.219%	20.143	//
	13974.565	20745.718	42751.84	65818.011	29627.76

FF hybrid systems with ^{238}U are potentially proliferation devices

Conclusions

- The present status of nuclear energy from thermal reactors ***is not sustainable***
- The ***dual system solution*** (thermal + fast critical reactors) presents criticalities, and requires a log time to be fully implemented
- A ***“pure” fusion reactor***, although it might be the final solution for our energy needs, is still far away
- FFHSs are not simply the juxtaposition of two technologies that in coupled operation retain their conventional characteristics, but on the contrary are ***devices with fundamentally new features and parameters***
- Thanks to their superior efficiency in burning TRU elements, breeding fissile elements, increased safety due to subcritical operation, ***FFHSs can represent an intermediate, if not final, solution*** to nuclear energy generation (less demanding plasma parameters, e.g. $\beta_N \sim 2.5$, $H_{IPB98} \sim 1$, $\Gamma_n \sim 0.5$ MW/m2, $Q_p \sim 1\text{-}5$)
- Governments of all important nuclear Countries are ***investing heavily*** on FF hybrid devices
- At present, ***no private funds*** have been directed toward FF hybrid devices (many profitable applications are possible – medical radioisotope production, material testing, ...)



today

tomorrow