Nuclear fuel processing using fast fusion neutrons produced in a spherical tokamak.

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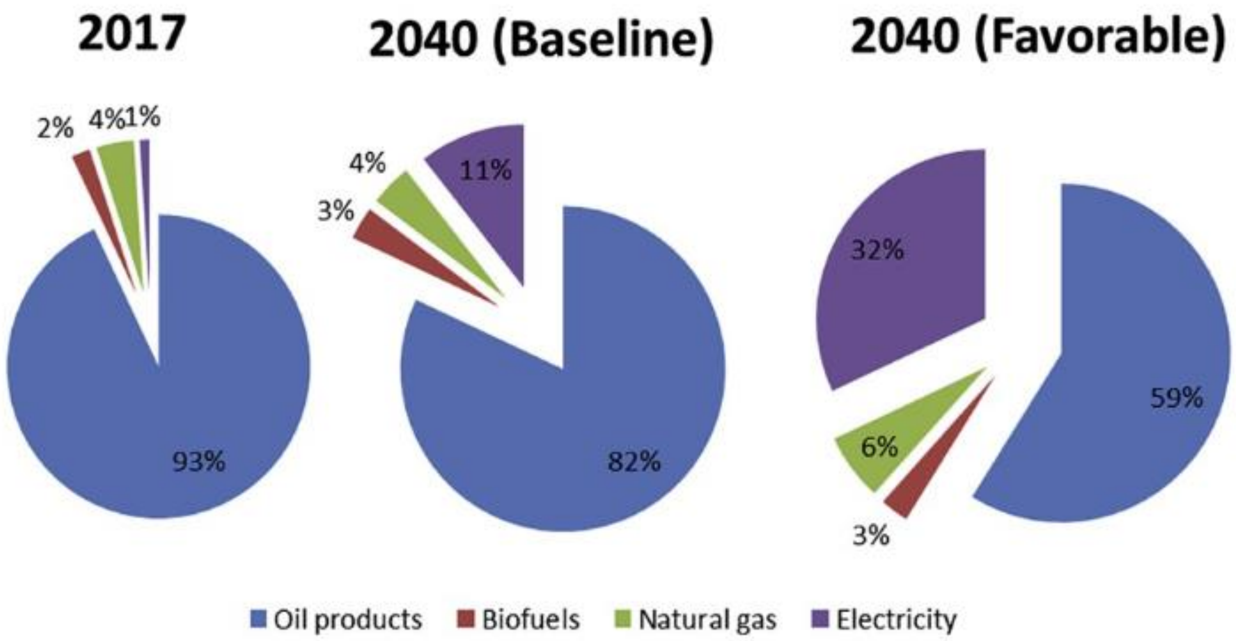
Nuclear electricity is more important than ever!

Energy use in the transportation sector

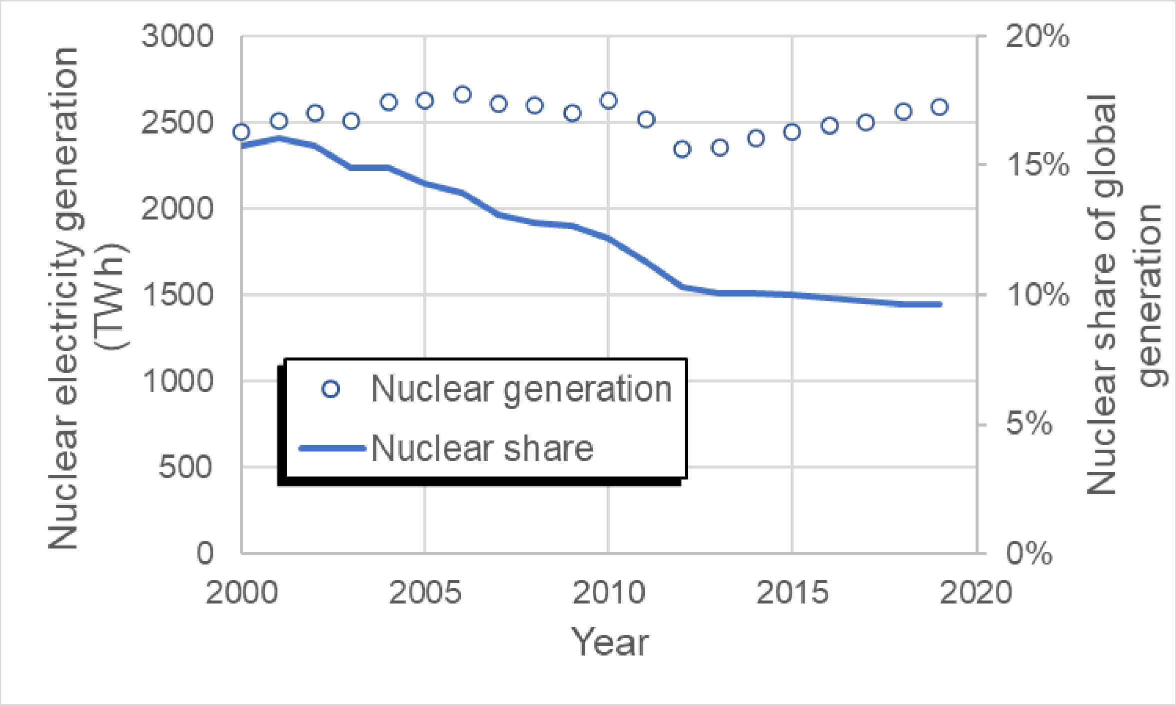


N.O. Kapustin. *Energy Policy* **137**, 1103 (2020)

- The expansion of the electric automobile fleet will require a significant growth of electricity demand.
- Electricity usage patterns will be modified as well. The increased peak loads produced by EV charging are a challenge for grid stability.
- To top it off, the plan is to cover this erratic demand with irregular generation of renewable energy.
- Irregularity on both supply and demand is a recipe for disaster.
- This issue does is not apparent or pressing now due the current modest size of both the electric fleet and RES generation.

Nuclear power today

- 443 nuclear power reactors were operational, with a total net installed power capacity of 392 GW(e).
- 54 reactors (57 GWe) were under construction.
- 6 new nuclear power reactors (5.2 GWe) were connected to the grid in 2019.
- 13 reactors (10.2 GWe) were retired last year.
- 5 new reactors (6 GWe) broke ground in 2019.
- Electricity production from nuclear power reactors increased about 4% with respect to 2018, reaching 2 657 TW·h.
- Nuclear power accounted for 10.4% of total electricity production in 2019.



Fuel availability

Source:)

Table 1.1. **Changes in identified resources (recoverable) 2015-2017**

Resource category	2015	2017	Change (1 000 tU)[a]	% change
Identified (total)				
<USD 260/kgU	7 641.6	7 988.6	347.0	4.5
<USD 130/kgU	5 718.4	6 142.2	423.8	7.4
<USD 80/kgU	2 124.7	2 079.5	-45.2	-2.1
<USD 40/kgU[b]	646.9	1 057.7	410.8	63.5
RAR				
<USD 260/kgU	4 386.4	4 815.0	428.6	9.8
<USD 130/kgU	3 458.4	3 865.0	406.6	11.8
<USD 80/kgU	1 223.6	1 279.9	56.3	4.6
<USD 40/kgU[b]	478.5	713.4	234.9	49.1
Inferred resources				
<USD 260/kgU	3 255.1	3 173.0	-82.1	-2.5
<USD 130/kgU	2 260.1	2 277.0	16.9	0.7
<USD 80/kgU	901.1	799.9	-101.2	-11.2
<USD 40/kgU[b]	168.4	344.4	176.0	104.5

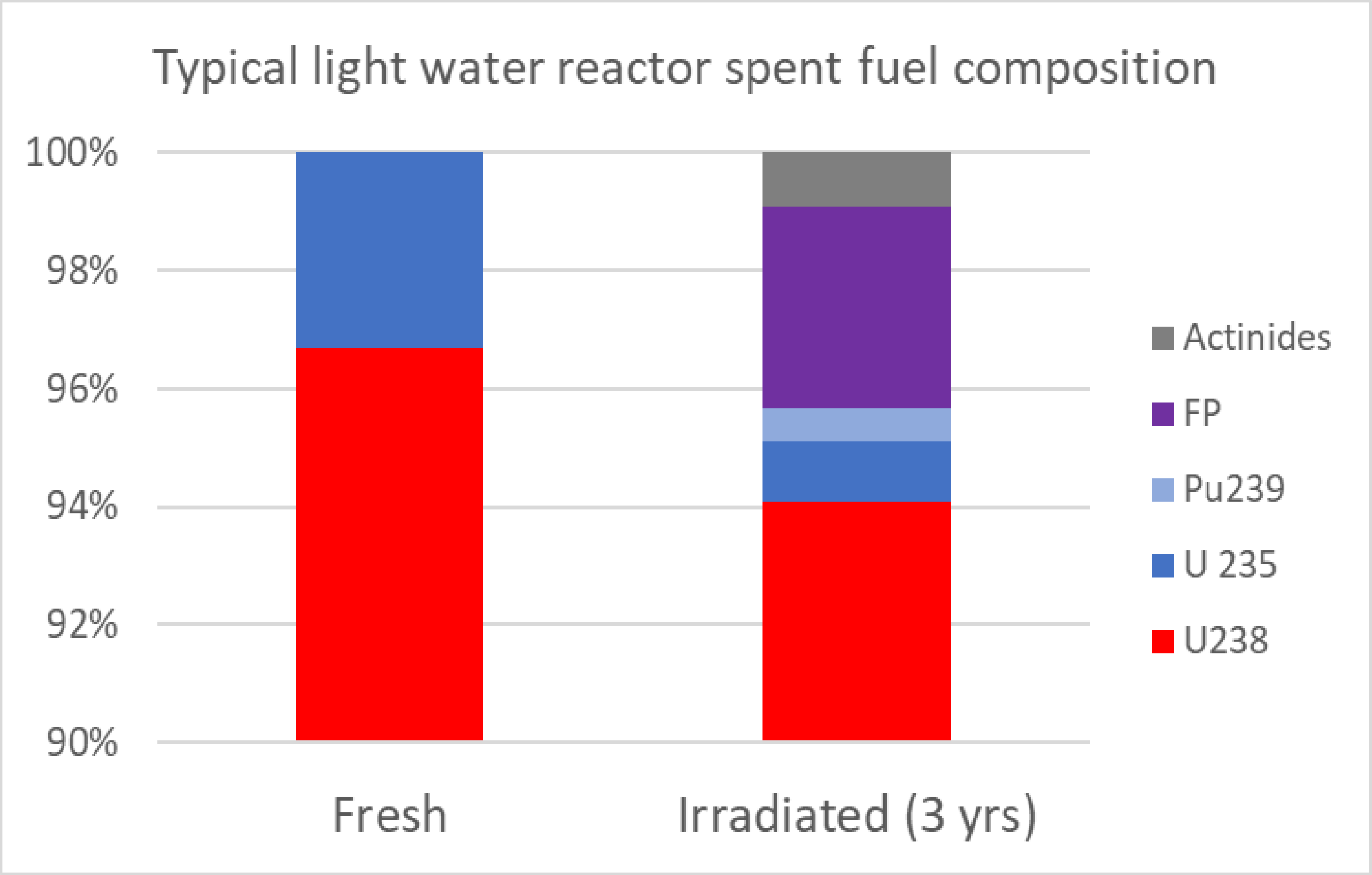
(a) Changes might not equal differences between 2015 and 2017 because of independent rounding.

(b) Resources in the cost category of <USD 40/kgU are likely higher than reported because some countries have indicated that detailed estimates are not available, or the data are confidential.

OECD Uranium 2018 Report

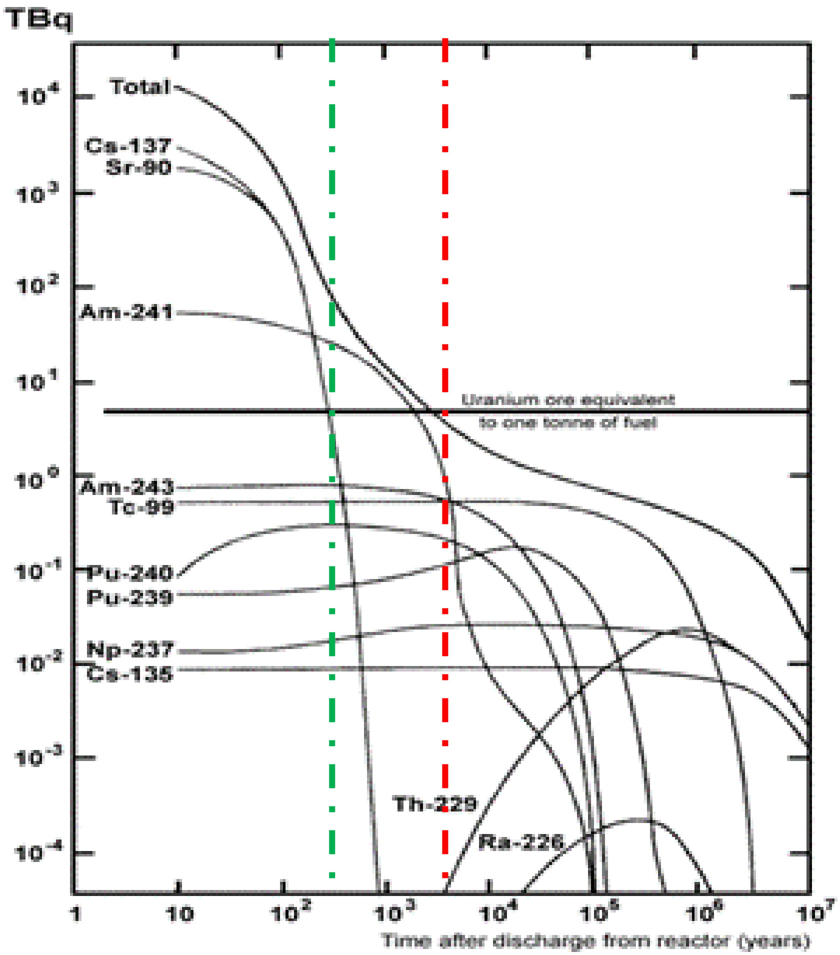
- Current natural U consumption for the nuclear reactor fleet is on the order of 60000 tons/yr
- Considering reserves with 130 USD/kg, they will last about 100 years (6000 Gg/60 Gg/yr)
- Any increase in reactor fleet will reduce this number
- Going to 1 TW of nuclear electrical power (25% share) will make reserves last only 40 years.

Nuclear Spent fuel



- For every GWe, around 30 tons/yr of spent fuel are generated
- That gives 12,000 tons generated each year
- About 1/3 of the U-235 remains in the spent fuel
- Other fissile material is present (Pu-239)
- 94% of the waste mass is inert U-238
- This material should not be called "waste"

Spent fuel radiotoxicity



Activity of high-level waste from one tonne of spent fuel

Elimination of minor actinides (less than 1% of the spent fuel mass) reduces the radiotoxicity of the spent fuel.

The time it takes to decay to reach the activity of natural uranium is reduced by a factor of 10 - 20.

Nuclear fuel irradiation with fast neutrons

- Exposure of nuclear fuel assemblies to a flux of high energy neutrons can:
  - Convert some fertile material to fissile material
  - Destroy minor actinides by neutron absorption or fission
- The neutron energy will determine the balance between breeding and burning.
- For breeding, neutron energy below 1 MeV is desirable
- For actinide destruction, neutron energy above 1 MeV is desirable

Why a hybrid?

- Fusion systems produce fast neutrons (14 MeV), completely decoupled from the fission process.
- Alternate technology for fissile material breeding.
- Possibility of burning minor actinides.
- Build operational experience on fusion technology under nuclear conditions.
  - Tritium breeding/recovery technologies.
  - Long term exposure of components to neutron fluence.
- Insertion of fusion technology in an active economic cycle (nuclear fuel industry).

The need to multiply neutrons

- Fusion reactions between deuterium and tritium produce 14.5 MeV neutrons:

$${}_{1}^{2}H + {}_{1}^{3}H \longrightarrow {}_{2}^{4}He + {}_{0}^{1}n$$

- Each tritium consumed generates a neutron.
- The neutron can be used to produce a tritium by reaction with Li-6:

$${}_{0}^{1}n + {}_{3}^{6}Li \longrightarrow {}_{1}^{3}H + {}_{2}^{4}He$$

- But if each neutron is used to replenish a tritium, there are no leftover neutrons that can irradiate nuclear fuel in a hybrid!
- Thus, materials that can multiply neutrons need to be introduced in the system.

Lidsky* nuclear hybrids taxonomy.

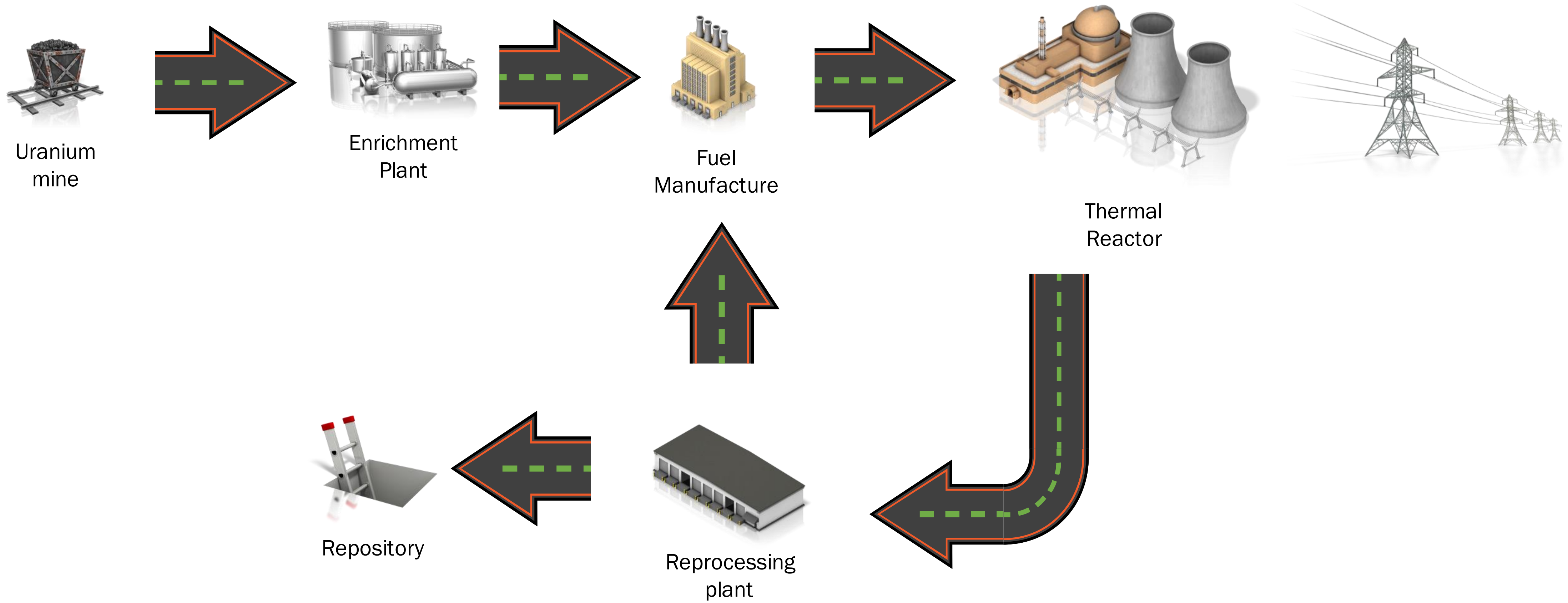
- **Symbiotic**: systems in which fuel is produced for consumption in physically separate fission reactors, with fission reactions suppressed (fuel breeder, relevant to front end).
- **Augean:** systems in which fission reactor waste products are transmuted to less toxic form (minor actinide burner, relevant to back end).
- **True Hybrid:** systems in which an energy-multiplying fission blanket surrounds an idealized fusion reactor (fusion-driven fast reactor).

Short term

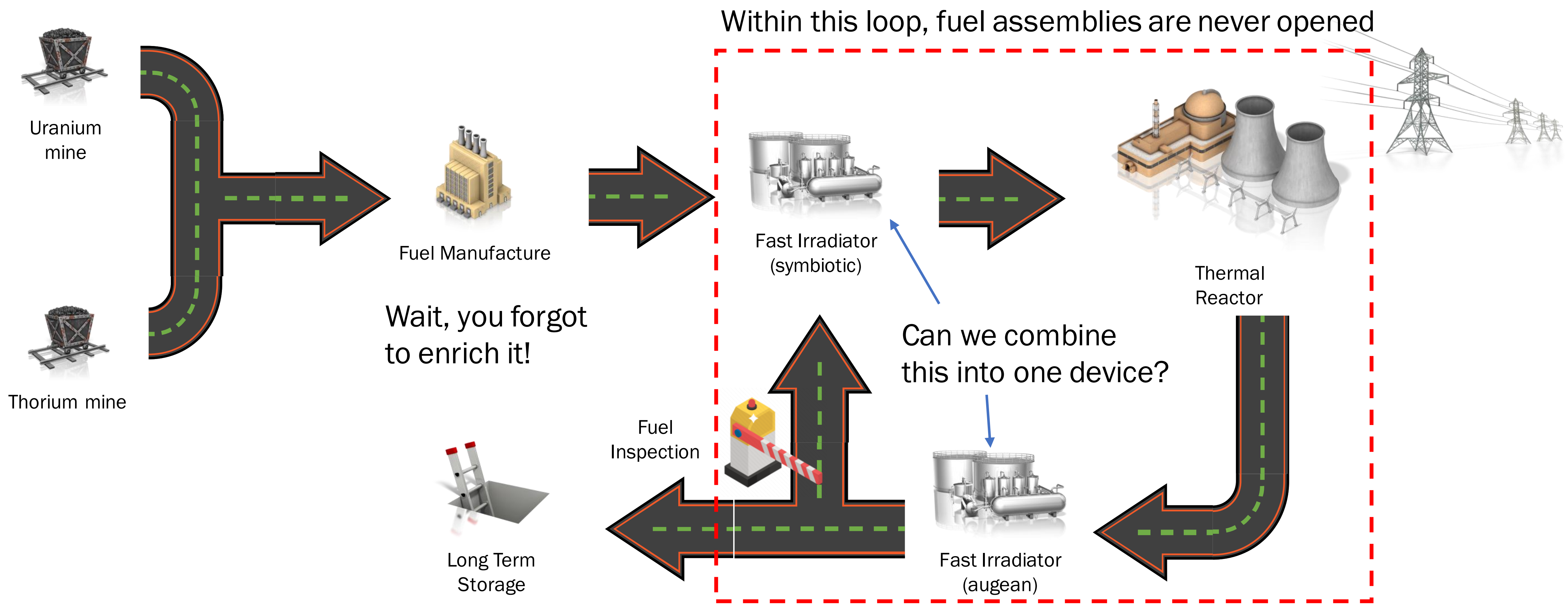
Long term

*L. M. Lidsky. *Nuc. Fus.* **15**, pp. 151-173 (1975)

Conventional closed nuclear fuel cycle



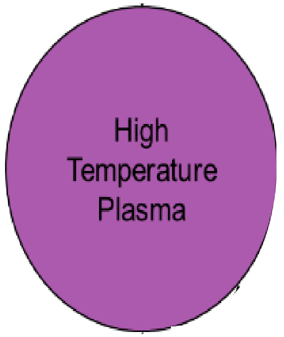
Nuclear fuel cycle incorporating fusion-based neutron irradiators



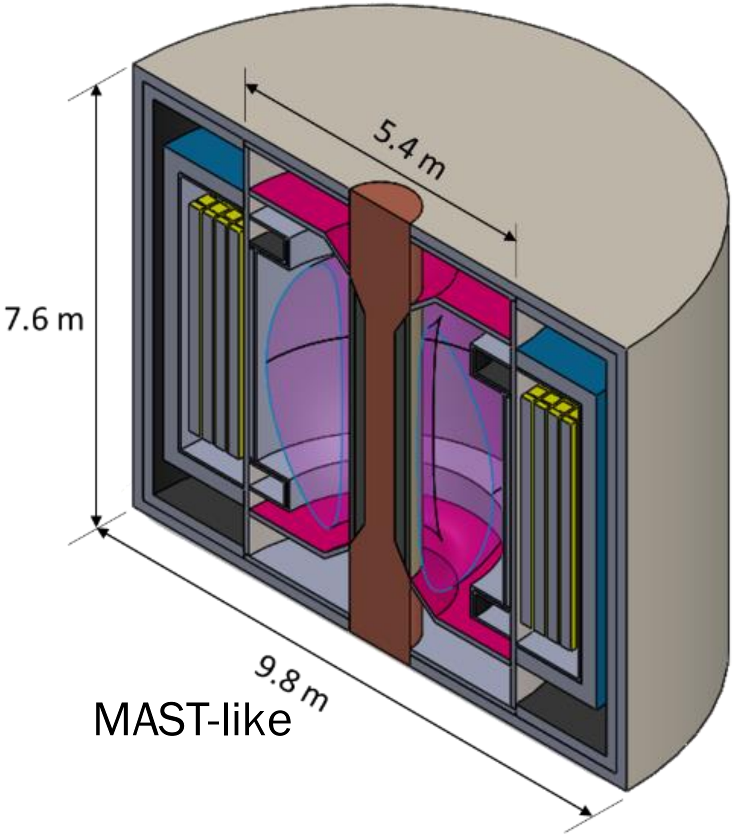
The big question…

- How does this fast irradiator look like?
- A suitable irradiator can be designed based around **any** fusion technology alternative, from plasma focus to stellarators.
- The key is that it must provide sufficient neutrons to do homogeneous fuel processing in a reasonable amount of time.
- For this particular study, we decide to look at a spherical tokamak configuration.

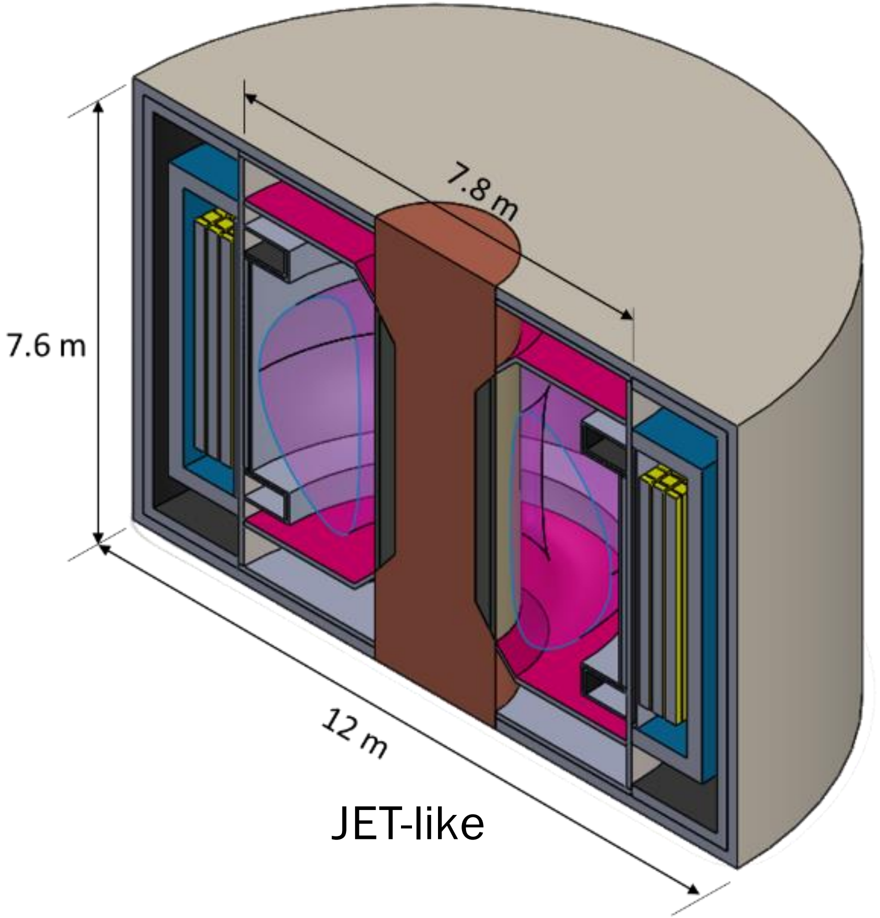
Overall scheme of a fusion fast neutron irradiator



A clear advantage of a spherical tokamak



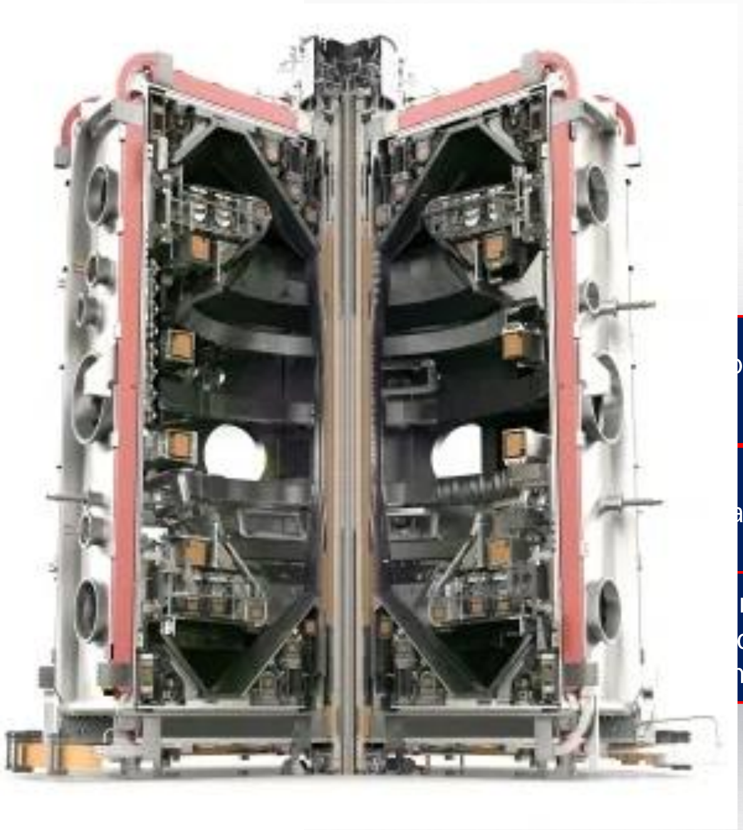
MAST-like

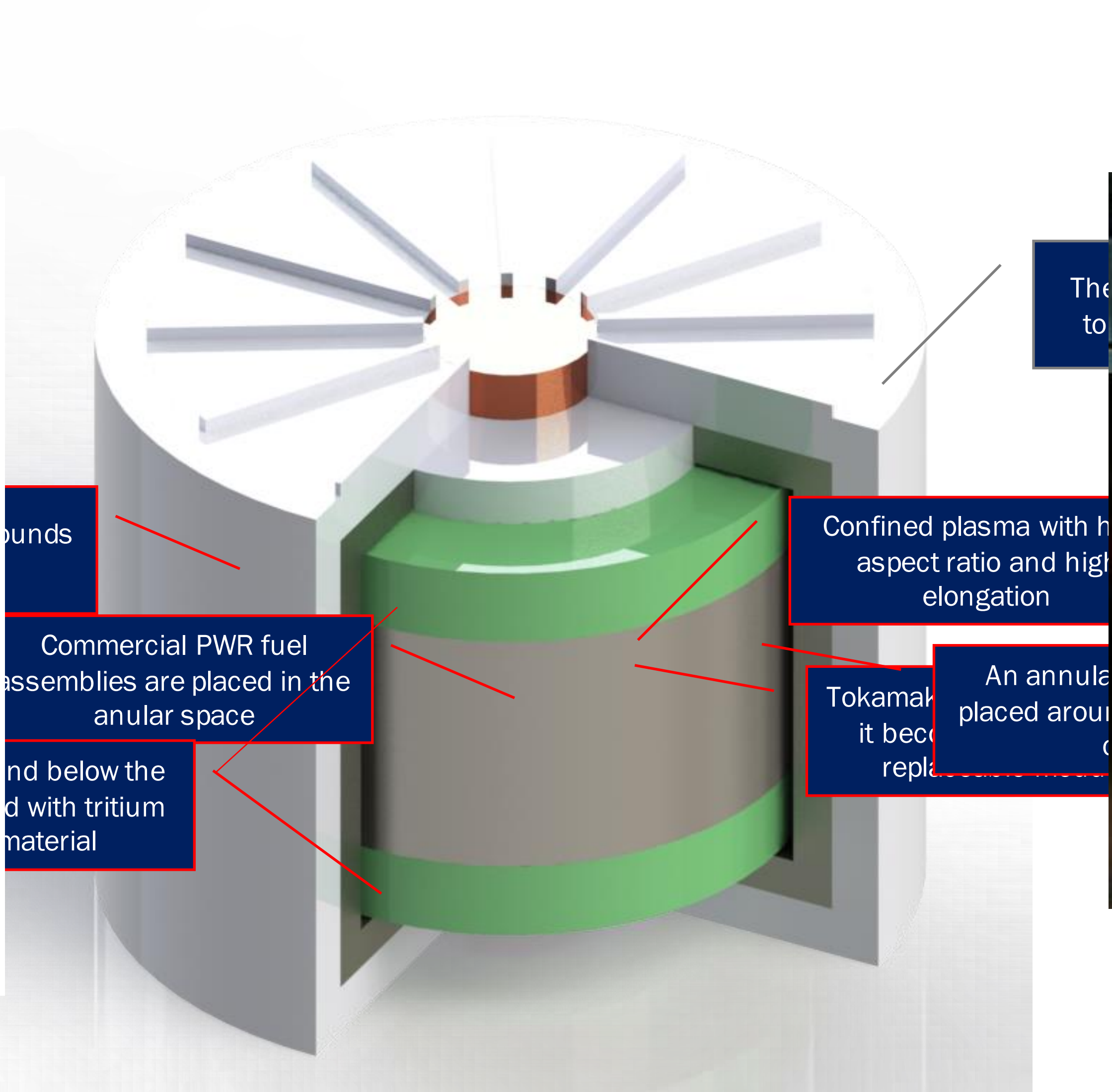


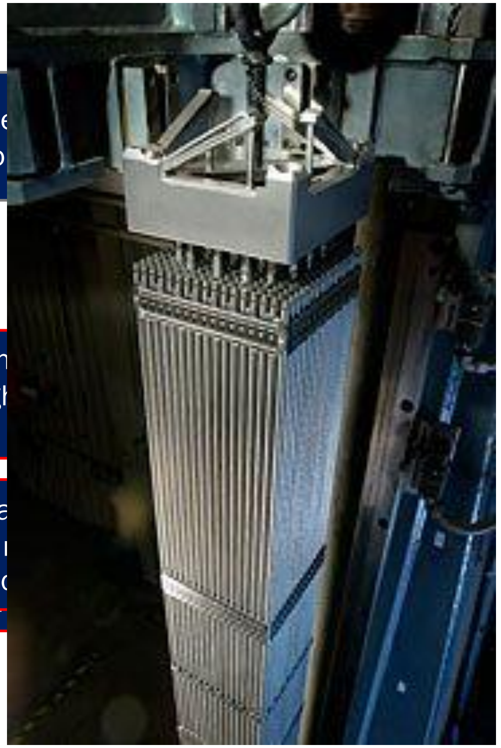
JET-like

For a given neutron power, which configuration gives larger neutron flux to the fuel assemblies?

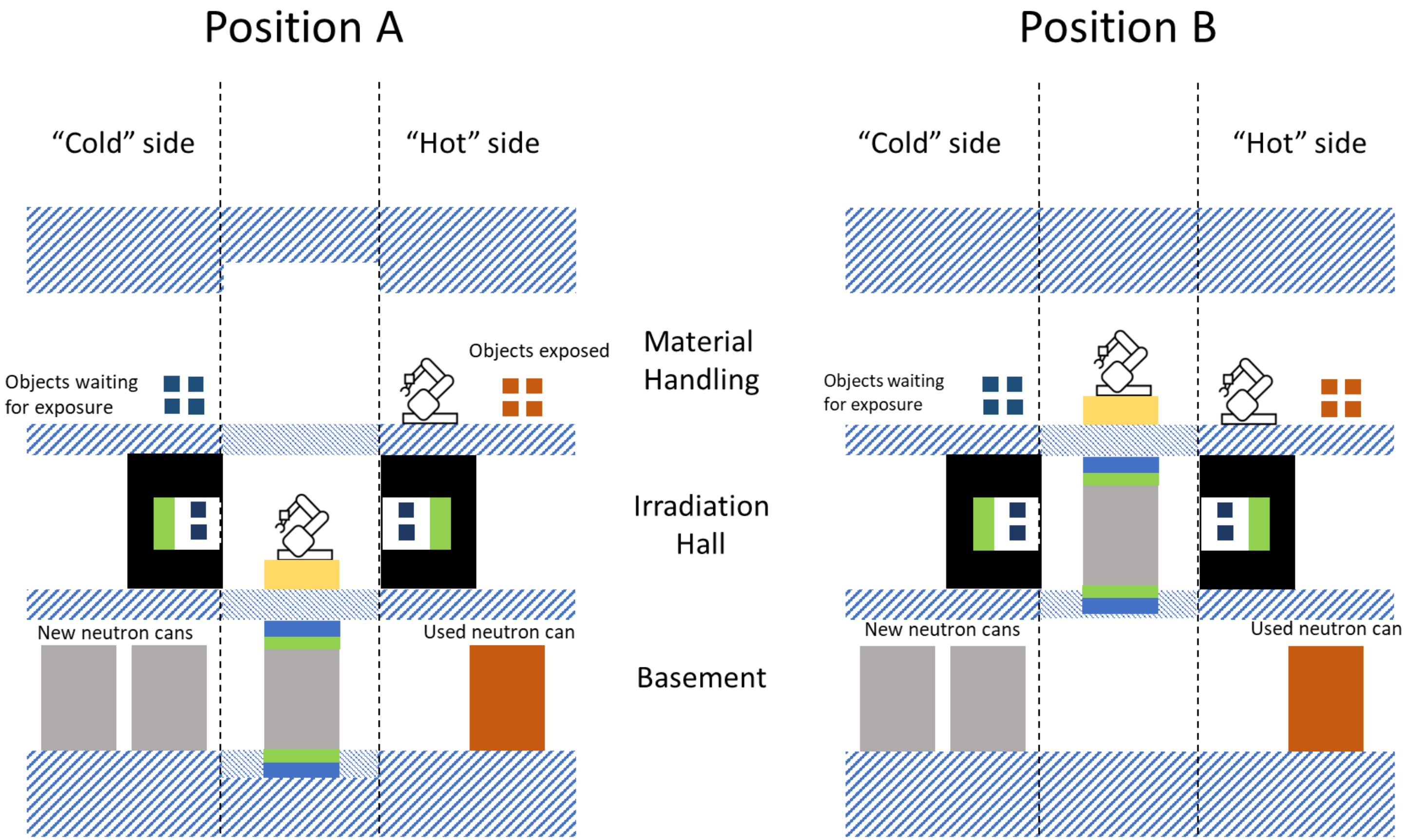
General anatomy of the hybrid system







Conceptual use case



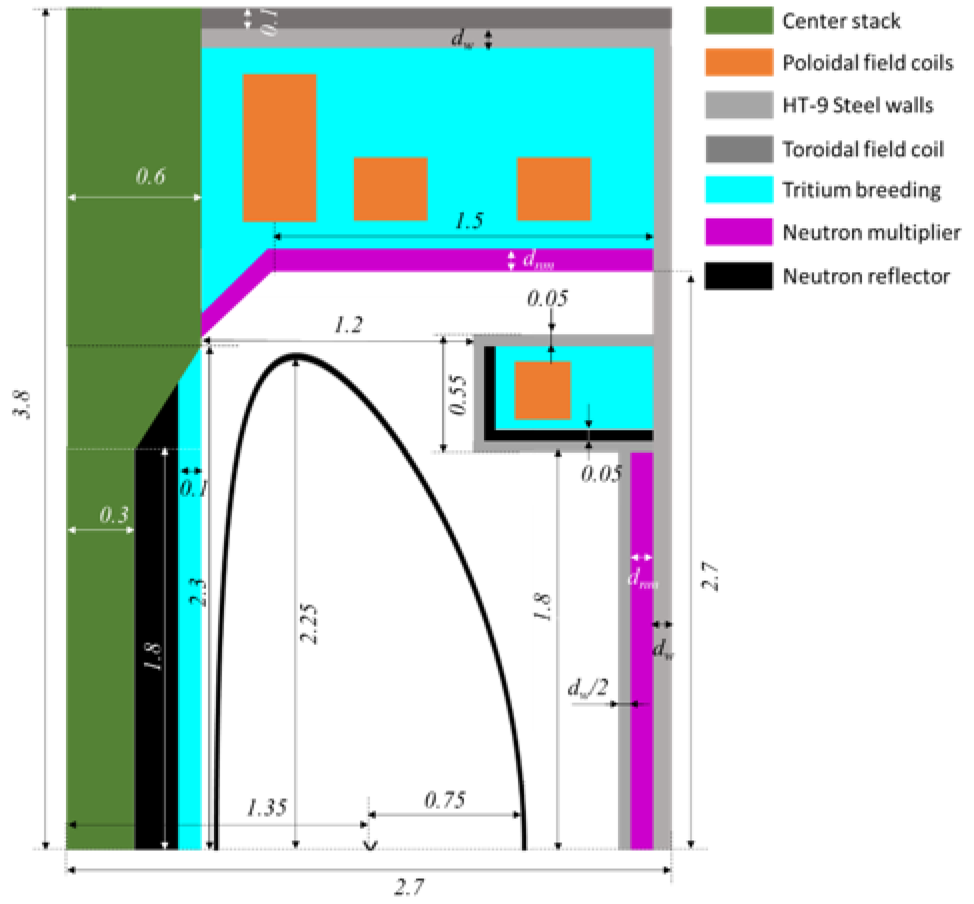
Critical issues for viability

- The system should be self-sufficient in tritium. Estimation is on the order of 150 kg/GWyr (neutron power).
- For fuel breeder, the system should be able to get the fuel ready to be placed in a thermal reactor in a reasonable amount of time (i.e. refueling cycle, 1.5 years).

- Energy expenditure for enriching should be smaller than the energy of enriched material (how small?).
- Cost should be competitive with open cycle (new fuel + disposal) and reprocessing (exchanging used fuel for new fuel)

Criteria

- As simple as possible (i.e. no NBI, no cryogenics).
- Small surface to volume ratio (maximizes flux per unit power).
- Replaceable as a module.
- Able to process existing fuel to support existing LWRs.
- Geometry fixed to CFNS design*

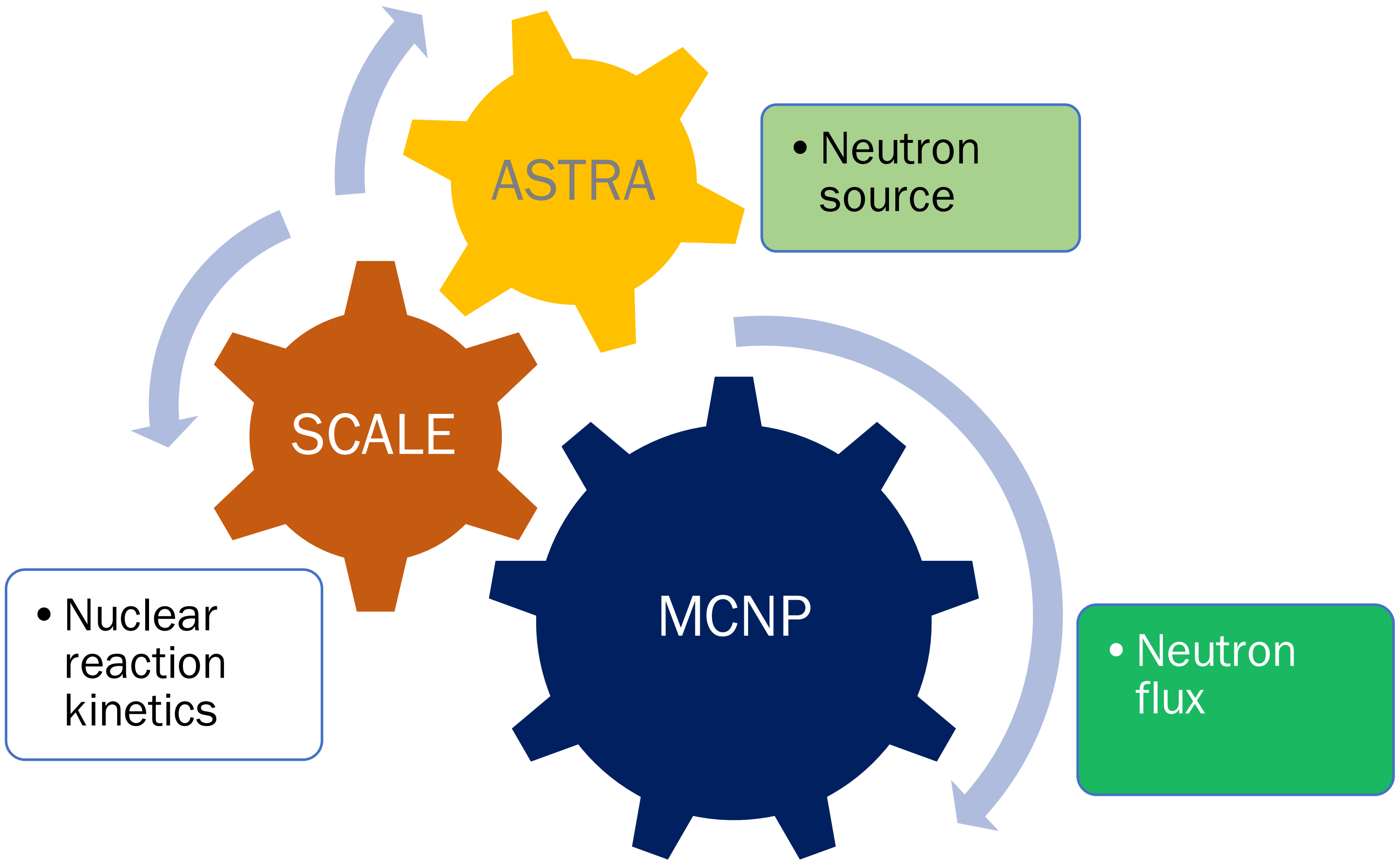


*M. Kotschenteuther. *Nuc. Fus.* **50**, 035003 (2010)

The three things we need to know

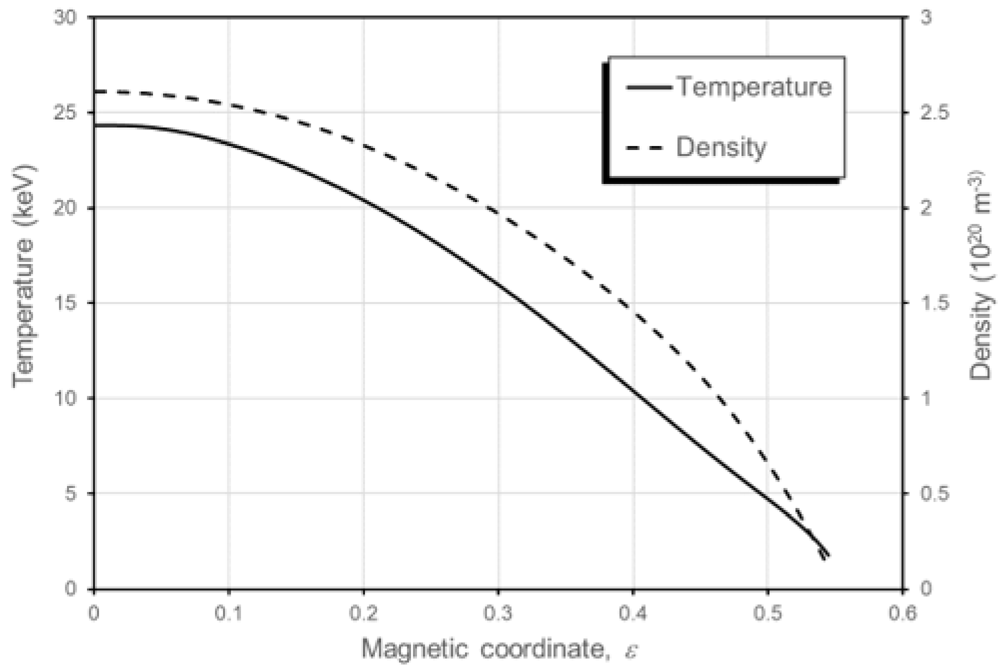
- How many neutrons are we producing externally and where are they produced?
- What is the value of the neutron flux at each location within the system?
- At what rates species are being produced/consumed due to the neutron bombardment?

Simulation scheme.



Neutron source parameters

Parameter	Value
Neutron wall load (MW/m^2)	1
Major radius (m)	1.35
Minor radius (m)	0.75
Plasma current (MA)	10 - 14
Central field (T)	2.9
Average density (10^{20} m^{-3})	1.3 - 2
Average temperature (keV)	15
Plasma volume (m^3)	42



Density and temperature profiles obtained from ASTRA using ST transport models*

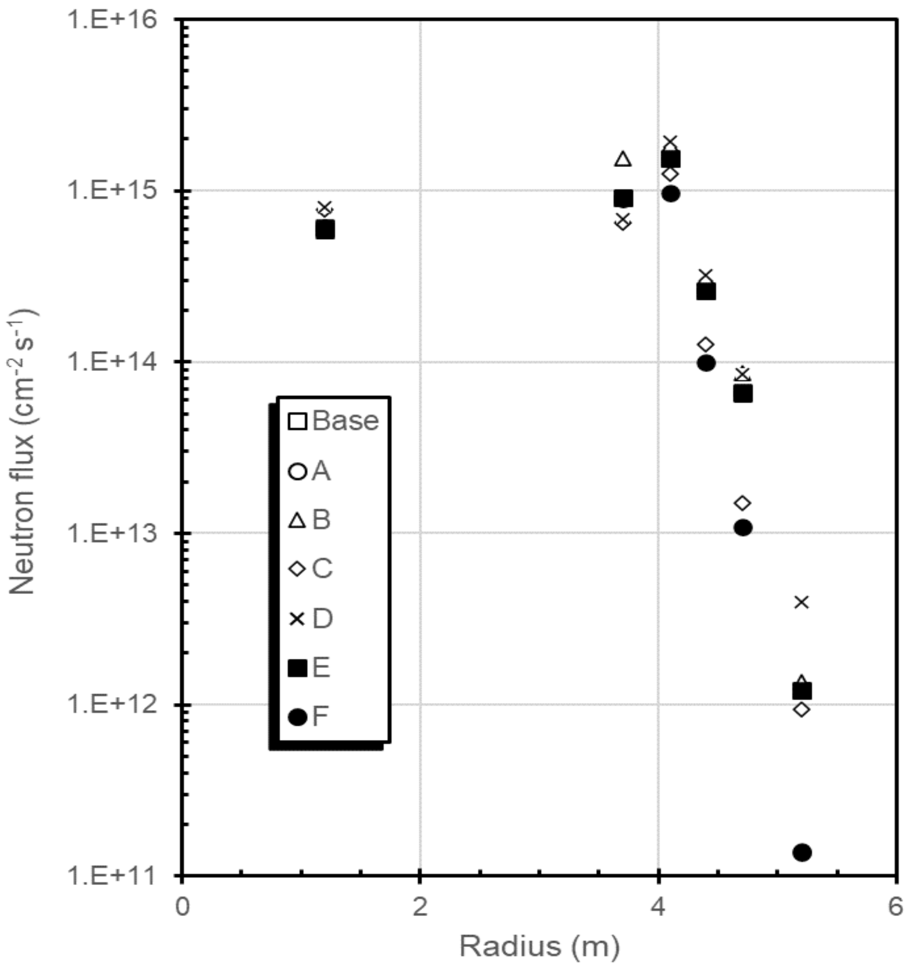
*A. E. Costley. *Plasma Pys. Cont. Fus.* **63**, 035005 (2021)

Materials choices for the hybrid

- Critical materials are:
  - The tritium breeder (a compound containing Li-6 isotope)
  - The neutron multiplier (containing Be, Zr or Pb)
  - The neutron shield (Pb, Pb-Li, Pb-Bi)
  - The blanket coolant (helium, CO_2, liquid metals)

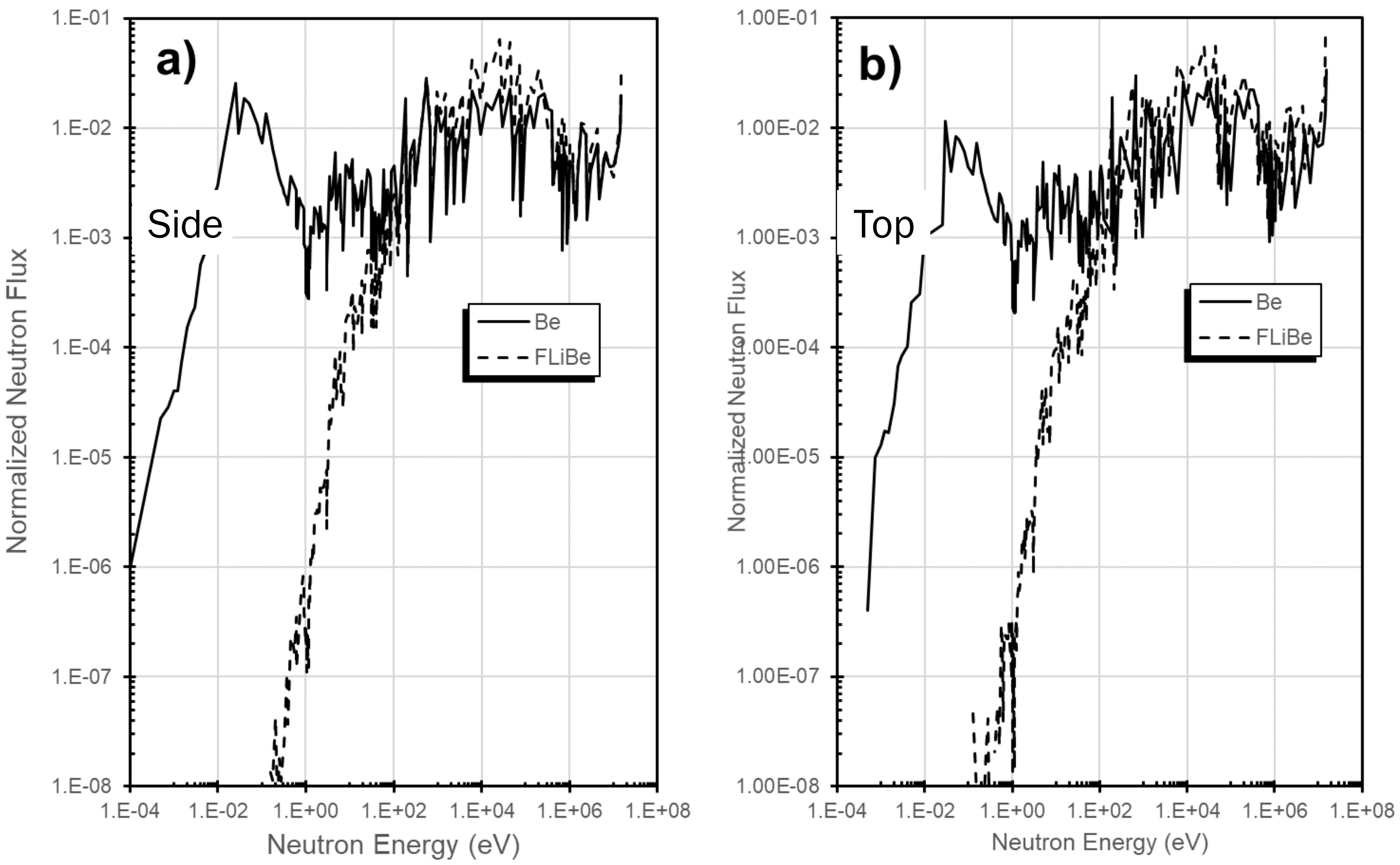
Case	Neutron Multiplier	Tritium breeder	Blanket Coolant	Shields
Base	Be	Li_2O	He	Pb
A	Be	Li_2O	He	Pb-Bi
B	FLiBe	Li_2O	He	Pb
C	FLiBe	Li	Li	Pb-Li
D	FLiBe	Li	He	Pb
E	Be	Li_2O	He	Pb-Li
F	Be	Li_2O	Li	Pb

Effect of material choices on neutron flux

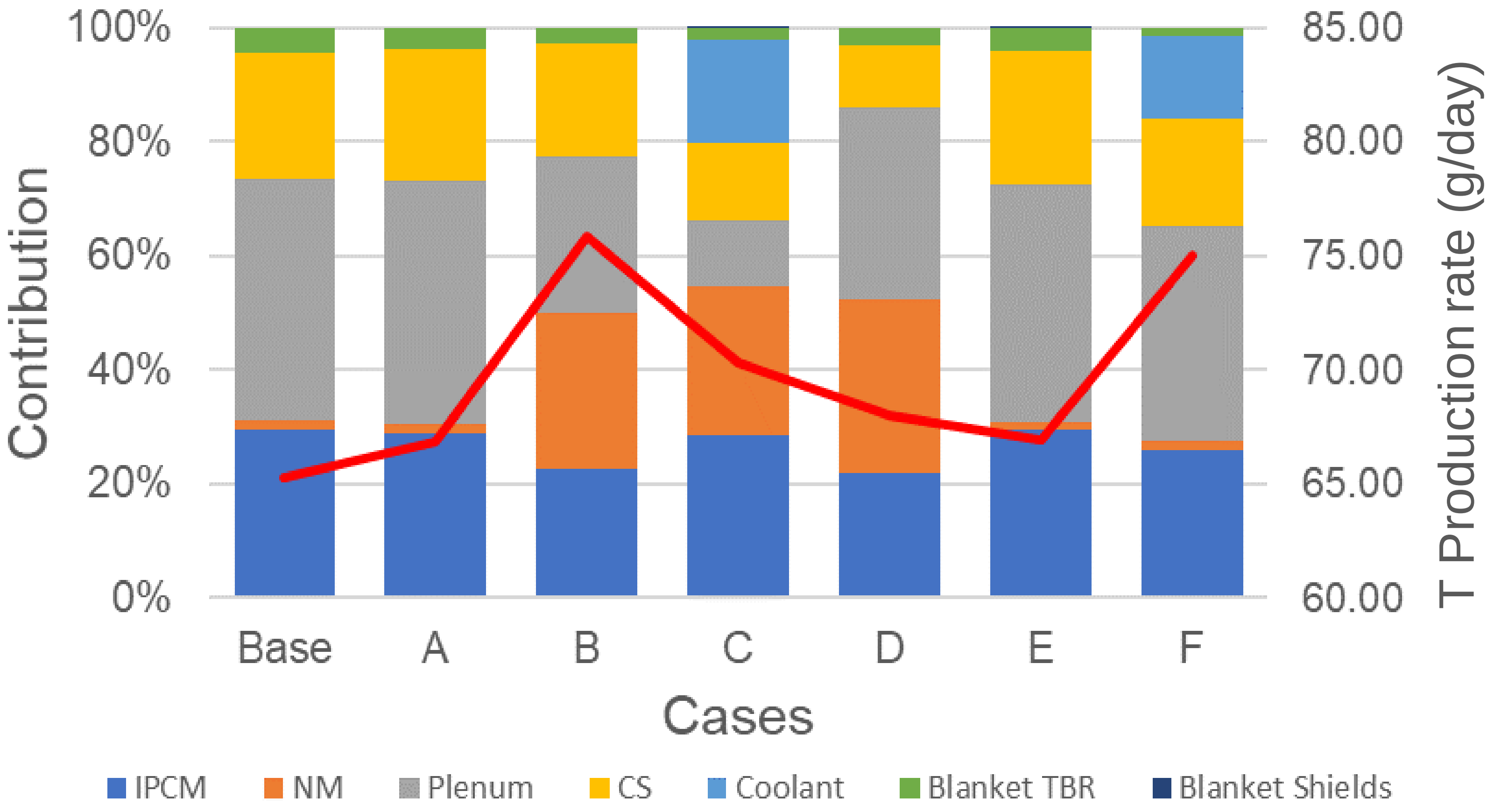


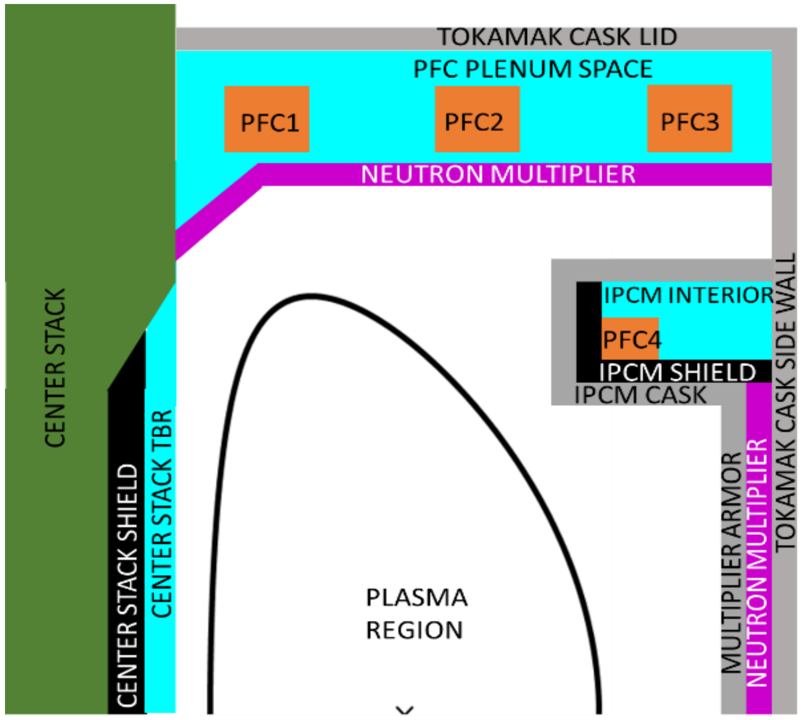
- The most important variation in neutron flux intensity occurs in the radial direction.
- The base case, case **A** and case **E** case are virtually identical, so their symbols overlap. This is an indication that the reflector material choice has very little influence on the performance of the system.
- Cases **C** and **F** stand out because they are consistently lower than the other cases for the blanket region (R > 4 m in the Figure), and those correspond to the cases when Li is used as coolant in the fission blanket
- Case **D**, corresponding to a FLiBe neutron multiplier and a Li breeder, has the opposite behavior, giving the highest flux in the blanket.

Neutron energy distribution on multiplier



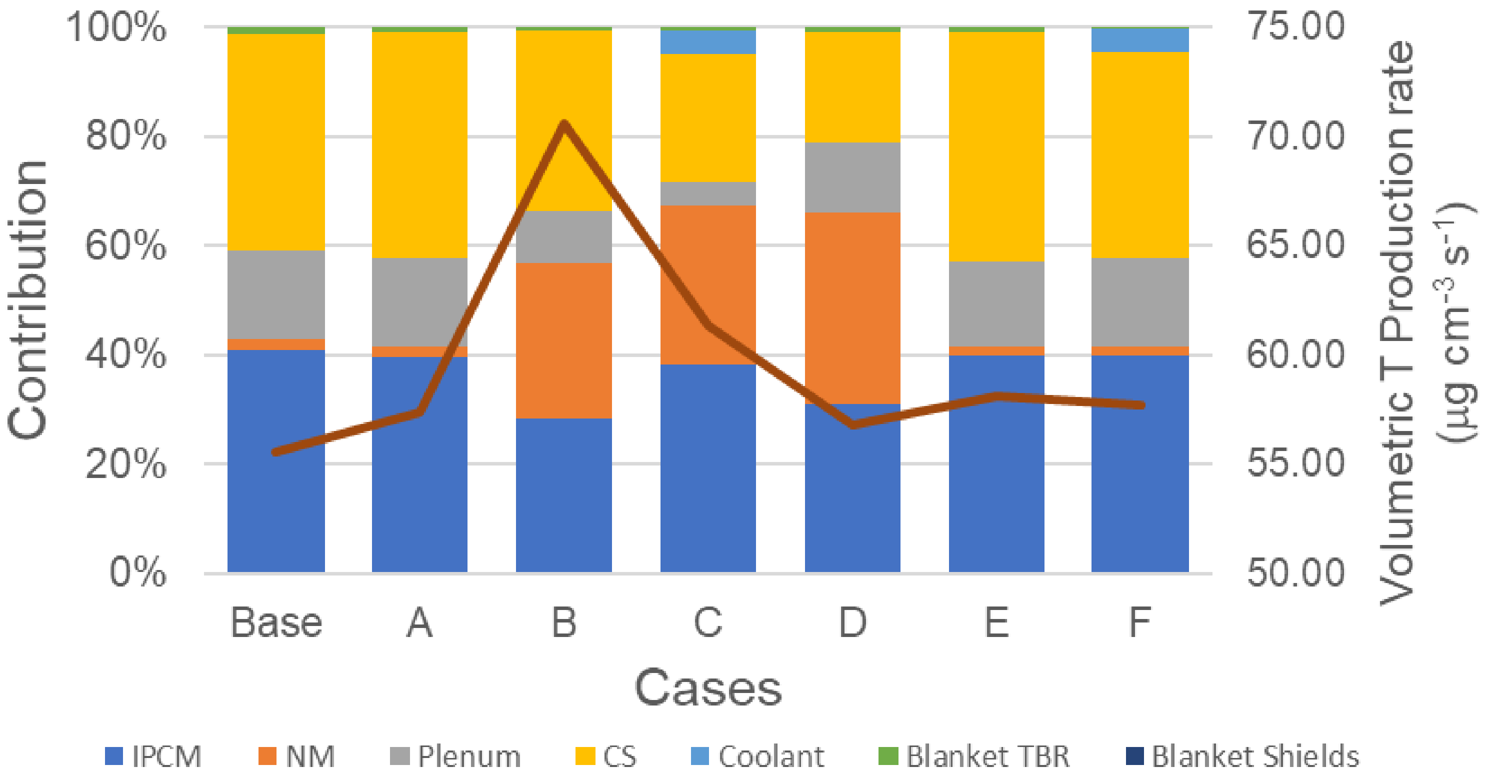
Tritium production





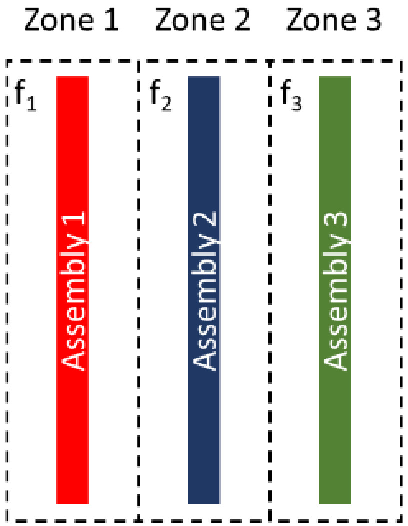
Tritium breeding ratio is between 1.4 and 1.7 for all cases (50 g T/day for 250 MW)

Tritium production per unit volume



Geometrical optimization of the design needs to be done to maximize these numbers.

Time to enrichment calculation



$m_1 = 0$
$m_2 = 0$
$m_3 = 0$

f_i: rate of fissile material production in zone i, in g/day

$$\begin{pmatrix} m_{f,1} \\ m_{f,2} \\ m_{f,2} \end{pmatrix} = \begin{pmatrix} f_1 & f_3 & f_2 \\ f_2 & f_1 & f_3 \\ f_3 & f_2 & f_1 \end{pmatrix} \begin{pmatrix} T_1 \\ T_2 \\ T_3 \end{pmatrix}$$

$$\mathbf{T} = \mathbf{F}^{-1} \cdot \mathbf{m_f}$$

Fissile material generation rate

Case	*^{233}U production rate (g/day)*			*Time to 3% enrichment (months)*
	Zone 1	*Zone 2*	*Zone 3*	
Base	*97.32*	*17.2*	*6.5*	*19*
A	*98.67*	*17.14*	*6.44*	*19*
B	*110.84*	*20.04*	*7.68*	*17*
C	*68.6*	*8.14*	*4.66*	*29*
D	*121.4*	*22.52*	*8.1*	*15*
E	*96.44*	*17.27*	*6.32*	*19*
F	*50.12*	*6.04*	*0.84*	*41*

Final thoughts

- Given the fact that the electric production and consumption landscapes are at the edge of a radical transformation, nuclear electricity should play a role in this new paradigm.
- Fusion neutron sources have the potential to help solve challenges in both the front end and the back end of the current nuclear fuel cycle.
- In that context, a business case can be developed around fusion neutron sources, which will accelerate the maturity of fusion technology and help remove uncertainties around material, fueling and radiological safety issues on fusion devices.
- Our preliminary analysis shows that a 250 MW ST can achieve tritium self sufficiency and enrich 260 PWR fuel assemblies to 3% enrichment within the standard refueling frequency (capable of four 4-loop PWR refuels).
- FLiBe was found to be an attractive neutron multiplier since it gives a high tritium breeding ratio and 15 months to achieve 3% fuel enrichment.
- Lithium oxide was found more efficient than metallic lithium for tritium breeding.