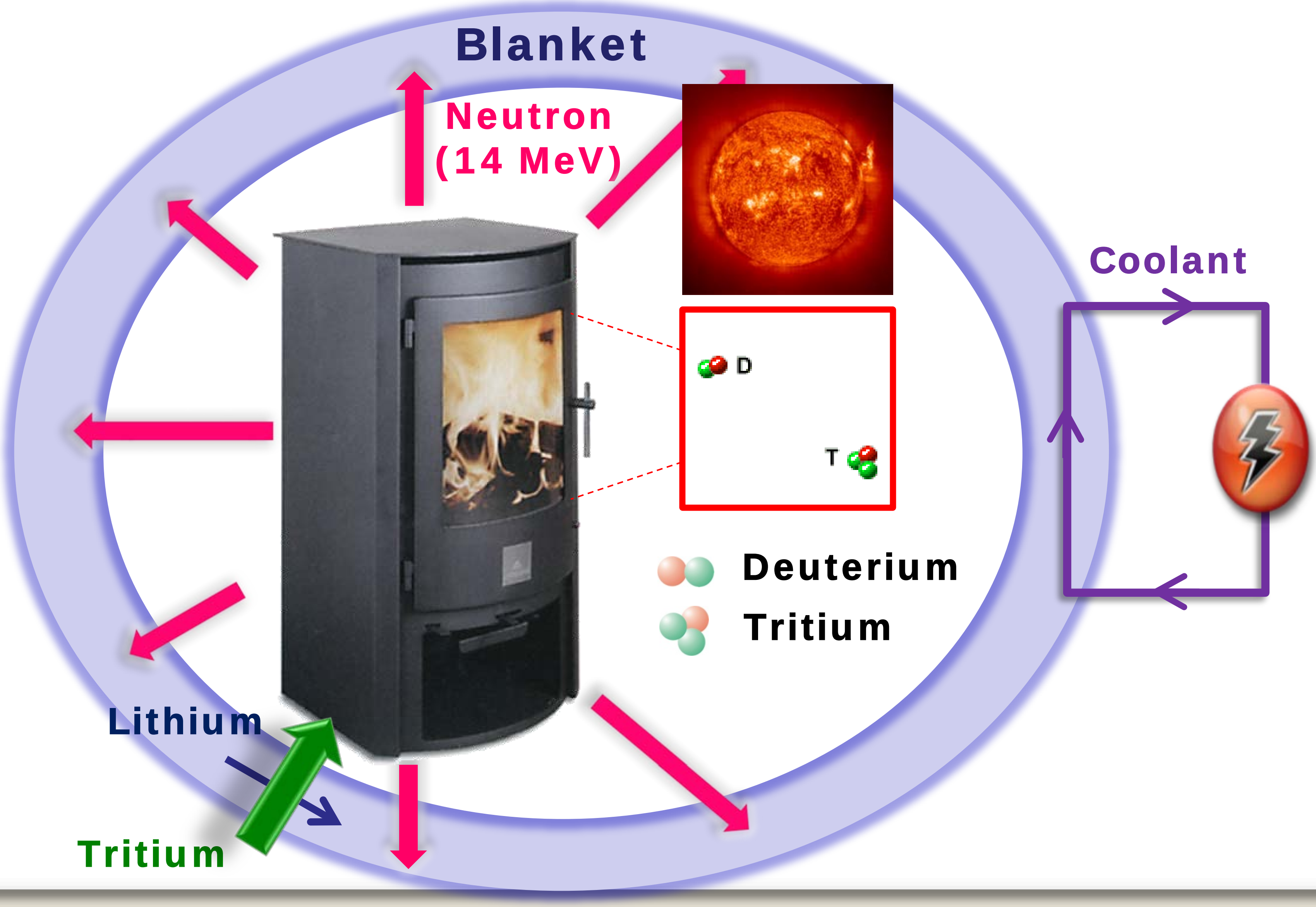
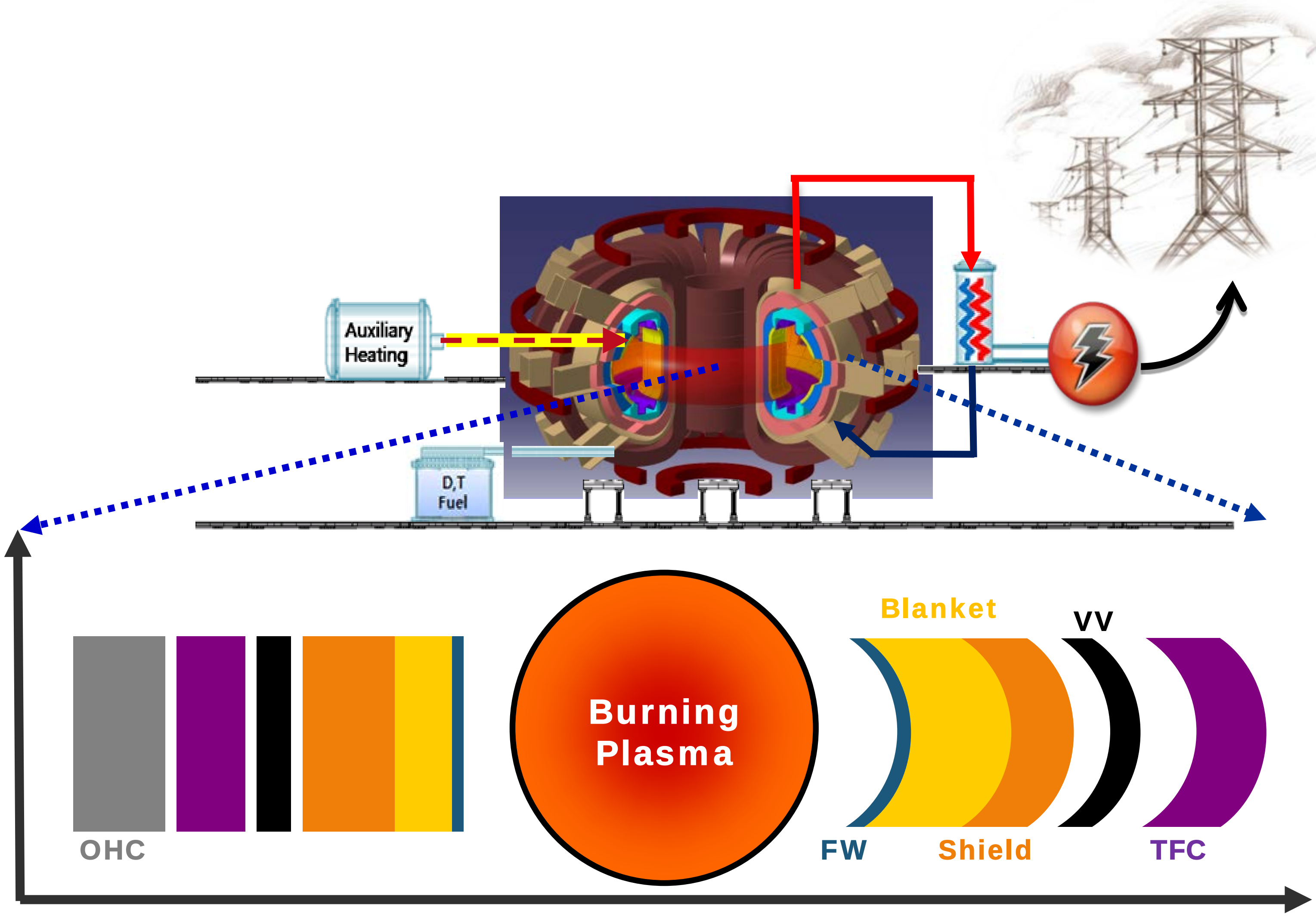
Introduction to Nuclear Fusion

Prof. Dr. Yong-Su Na

Fusion Reactor



Radial Build in a Tokamak Fusion Reactor



What is a blanket?

Blanket Functions

- **Power Extraction**

  To recover energy from the emitted radiation and reaction products

  - Convert kinetic energy of neutrons and secondary gamma rays into heat
  - Absorbing plasma radiation on the first wall
  - Extracting the heat (at high temperature, for energy conversion)

- **Tritium Breeding**

  To breed tritium required in the D-T reactor core

  - Tritium breeding, extraction, and control
  - Having lithium in some form for tritium breeding

$$n + {}^{6}Li \rightarrow t + {}^{4}He + 4.78\ \mathrm{MeV}$$

$$n + {}^{7}Li \rightarrow t + {}^{4}He + n' - 2.47\ \mathrm{MeV}$$

Blanket Functions

- **Physical Boundary for the Plasma**

  To sustain a sufficiently clean plasma domain

  - Physical boundary surrounding the plasma, inside the vacuum vessel
  - Providing access for plasma heating, fueling
  - Must be compatible with plasma operation
  - Innovative blanket concepts can improve plasma stability and confinement.

- **Radiation Shielding of the Vacuum Vessel**

  - To shield the surrounding structures and personnel

Blanket Concepts

- **Solid Breeder: Lithium in a solid form**
- **Liquid Breeder: Lithium in a liquid form**

Blanket Concepts

- **Solid Breeder Concepts**

  - Solid breeder: Lithium ceramic (Li_2O, Li_4SiO_4, Li_2TiO_3, Li_2ZrO_3)
  - Always separately cooled
  - Coolant: Helium or Water

Blanket Concepts

- **Liquid Breeder Concepts**

- Liquid breeder can be

a) Liquid metal (high conductivity, low Pr): Li, or $Li_{17}Pb_{83}$

b) Molten salt (low conductivity, high Pr): Flibe ($(LiF)_n \cdot (BeF_2)$), Flinabe (LiF-BeF_2-NaF)

1. Self-Cooled

   Circulating at high enough speed to also serve as coolant

2. Separately Cooled

   Circulating only at low speed for tritium extraction

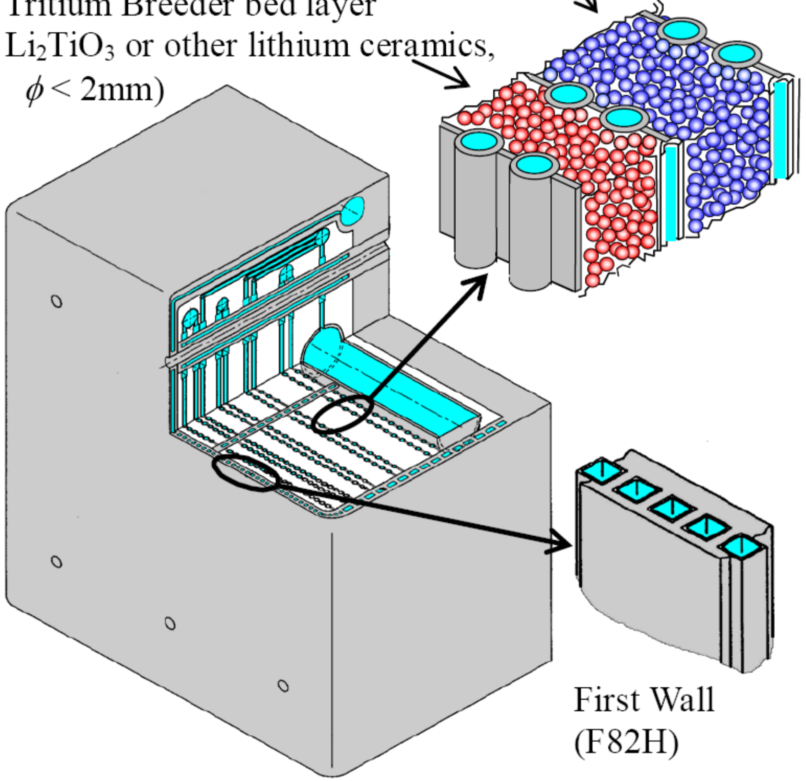
   Using a separate coolant (e.g., He)

3. Dual Coolant

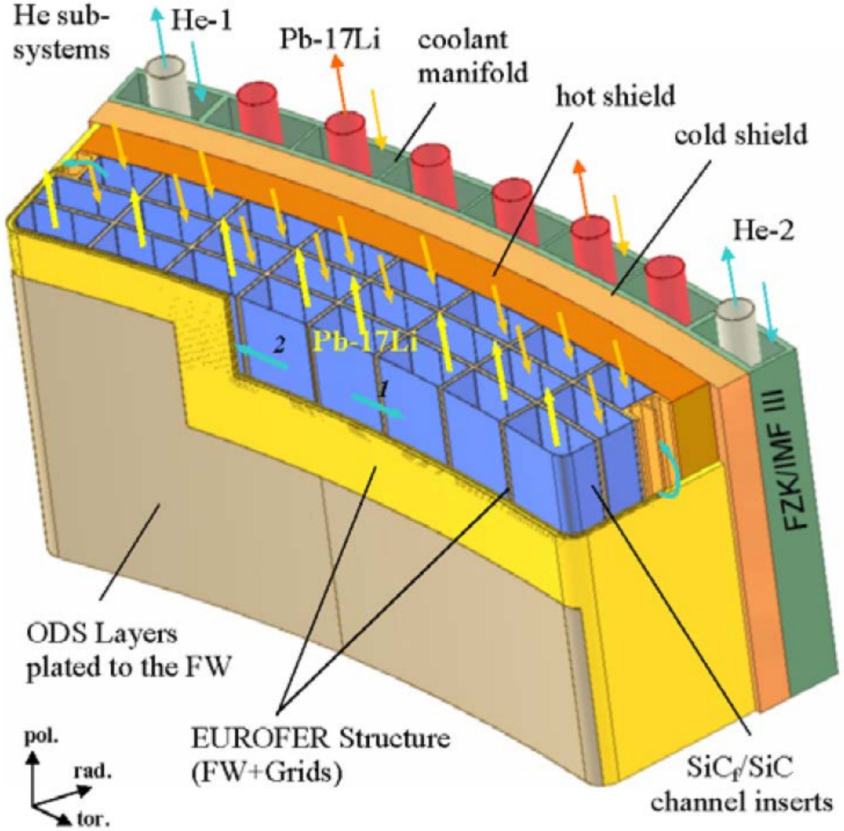
   Breeding zone: self-cooled

   FW and structure: cooled with separate coolant (e.g., He)

Blanket Structure



Japan DEMO 2001
solid blanket concept



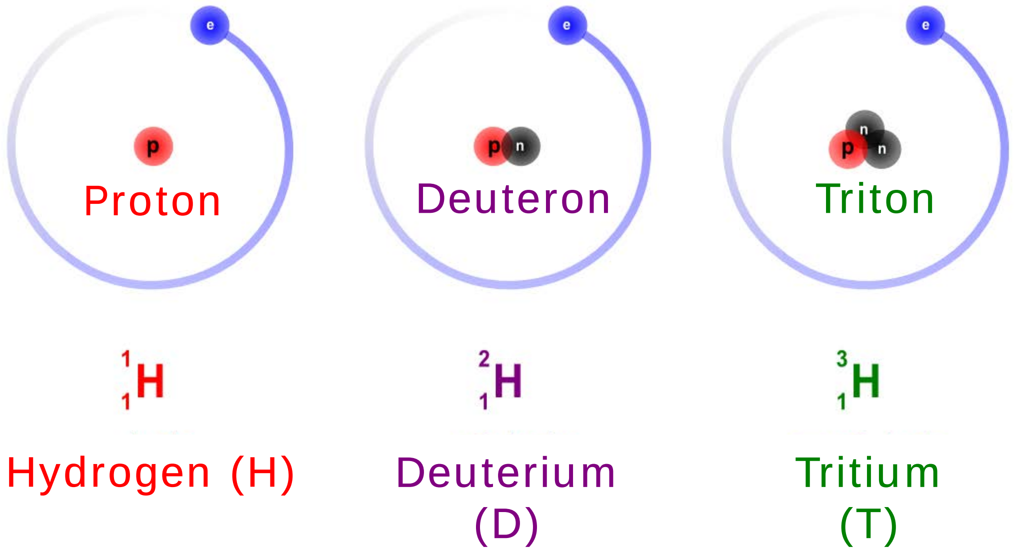
EU PPCS Model C
dual-coolant blanket concept

http://ec.europa.eu/research/energy/print.cfm?file=/comm/research/energy/fu/fu_rt/fu_rt_tec/article_1233_en.htm

Tritium breeding in a blanket

Tritium Breeding

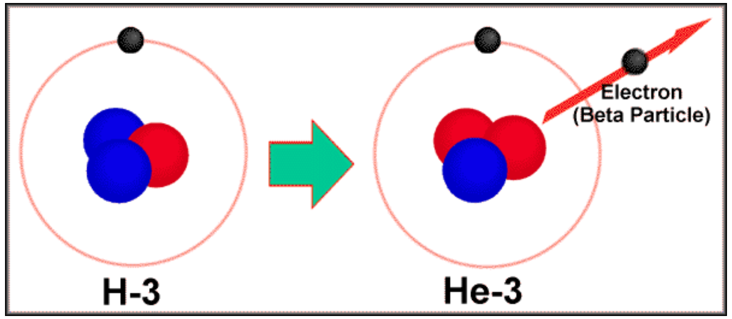
- **Tritium**
  - The name is formed from the Greek word "tritos“ meaning "third".

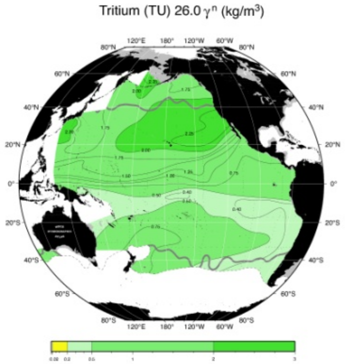


http://lhs2.lps.org/staff/sputnam/chem_notes/UnitII_Radioactivity.htm http://www-pord.ucsd.edu/whp_atlas/pacific/maps/tritum/pac2600_tritium_final.jpg

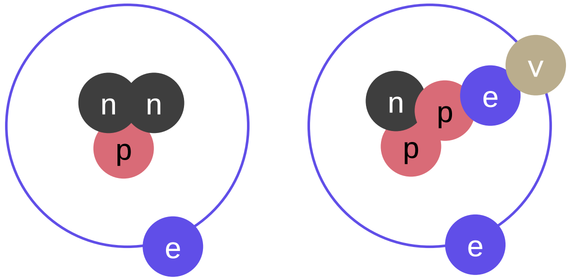
Tritium Breeding

- **Tritium**
  - The name is formed from the Greek word "tritos" meaning "third".
  - Total steady state atmospheric and oceanic quantity produced by cosmic radiation ~ 50 kg





$${}^{3}_{1}T \rightarrow {}^{3}_{1}He^{1+} + e^{-} + \nu$$



$$n \rightarrow p^{+} + e^{-} + \nu$$

Neutrino:

First postulated in 1930 by Wolfgang Pauli to preserve conservation laws in beta decay

http://lhs2.lps.org/staff/sputnam/chem_notes/UnitII_Radioactivity.htm

http://www-pord.ucsd.edu/whp_atlas/pacific/maps/tritum/pac2600_tritium_final.jpg

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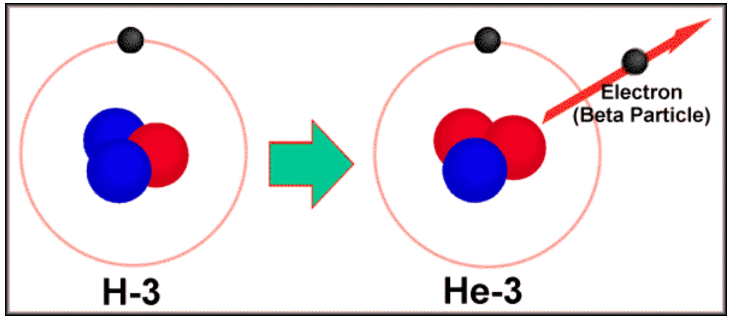
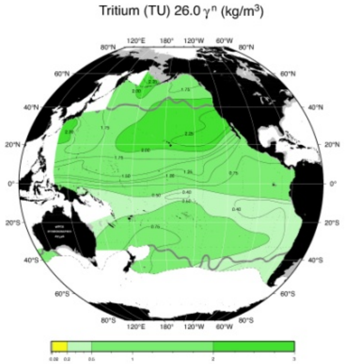




- **Tritium production by heavy water reactors (HWR)**

  - extracted from the coolant and moderator of HWR $n + {}_1^2H \rightarrow {}_1^3H$
  - Tritium could also be produced by placing lithium into control and shim rods of fission reactors.

http://lhs2.lps.org/staff/sputnam/chem_notes/UnitII_Radioactivity.htm http://www-pord.ucsd.edu/whp_atlas/pacific/maps/tritum/pac2600_tritium_final.jpg

Tritium Breeding

- **Tritium**
  - Half life of 12.32 years with decay rate of $1.78 \times 10^{-9}\ s^{-1}$
  - Releasing 18.6 keV of energy with 5.7 keV of an average kinetic energy of electrons
  - Nuclear activity (decay rate of 1 kg of tritium)

$$ {}^{3}_{1}T \rightarrow {}^{3}_{1}He^{1+} + e^{-} + \nu $$

$$ Act = \left| \frac{dn_t}{dt} \right| = \lambda_t n_t = \frac{\lambda_t M_t}{m_t} = \frac{1.78 \times 10^{-9} s^{-1} \times 1kg}{5 \times 10^{-27} kg} $$

$$ = 3.56 \times 10^{17}\ Bq $$

$$ = \frac{3.56 \times 10^{17}}{3.7 \times 10^{10}} Ci $$

$$ \approx 10^{7}\ Ci $$

1 Bq (becquerel): unit of radioacitivity (SI unit).
activity of a quantity of radioactive material in which one nucleus decays per second

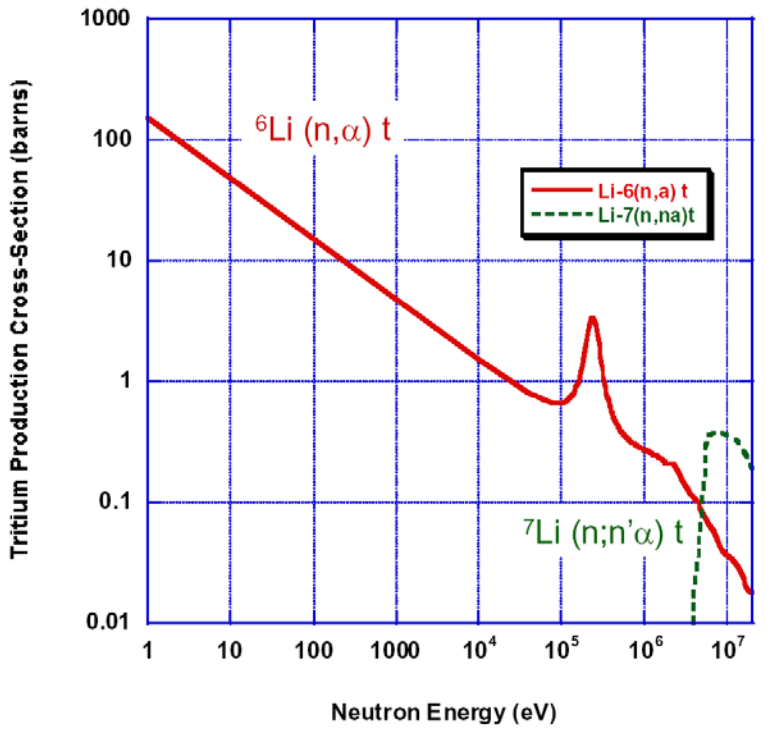
1 Ci (curie): 3.7×10^{10} decays per second (Bq)
~ activity of 1g of the radium isotope ^{226}Ra studied by the Curies

Tritium Breeding

- **Tritium production by neutron-induced reactions with natural lithium (^6Li:^7Li=7.5:92.5)**

$$n + {}^6Li \rightarrow t + {}^4He + 4.78\,\mathrm{MeV}$$: thermal and epithermal neutron energy range

$$n + {}^7Li \rightarrow t + {}^4He + n' - 2.47\,\mathrm{MeV}$$: fast neutron energy range



- The ^{7}Li(n,n'α)t reaction is a threshold reaction and requires an incident neutron energy in excess of 2.8 MeV.

$$d + t \rightarrow n + \alpha + 17.6\,\mathrm{MeV}$$

Tritium Breeding

- **TBR (Tritium Breeding Ratio)**
  - Ratio of total tritium production rate in blanket and tritium destruction rate in core
  - Needed to be higher than 1.08 to compensate for tritium transport losses during extraction and transfer as well as for its decay before injection into the core and to consider the construction rate of the fusion reactor

$$C_t = \frac{\int_{V_b}\int_{v_n} \sigma_{n6}(v_n) N_6 N_n(v_n) v_n dv_n d^3r + \int_{V_b}\int_{v_n} \sigma_{n7}(v_n) N_7 N_n(v_n) v_n dv_n d^3r}{\int_{V_c} N_d N_t < \sigma v >_{dt} \; d^3r}$$

N_6, N_7: ^{6}Li and ^{7}Li atom densities in the blanket volume V_b
σ_{n6}, σ_{n7}: corresponding microscopic neutron absorption cross sections
N_n: speed dependent neutron density
v_n: neutron speed
V_c: fusion core volume

Tritium Breeding

- **Neutron Multiplication**

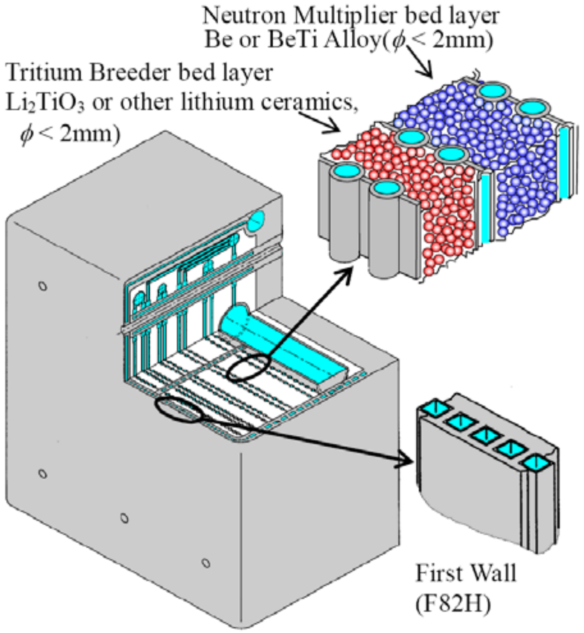
  - Adequate tritium breeding may be obtained if a neutron multiplier such as ^{9}Be or Pb is added.

$$^{9}Be + n \rightarrow 2n + 2He - 2.5\ MeV$$

$$^{A}Pb + n \rightarrow 2n + {}^{A-1}Pb - 7\ MeV$$

Material	Estimated Upper Limit Breeding Ratio, C_T
^{6}Li	1.1
Natural Li	0.9
^{9}Be + ^{6}Li (5%)	2.7
Pb + ^{6}Li (5%)	1.7

Assuming materials encompassing the entire fusion core



Japan DEMO 2001
solid blanket concept

Tritium Breeding

Material	Calculated Tritium Breeding Ratio, C_T
$Li_{17}Pb_{83}$	1.6
LiPb	1.4
FLIBE	1.1
$LiAlO_2$	0.9
Li_2O	1.3
Li_2SiO_4	0.9
Li_2ZrO_3	1.0

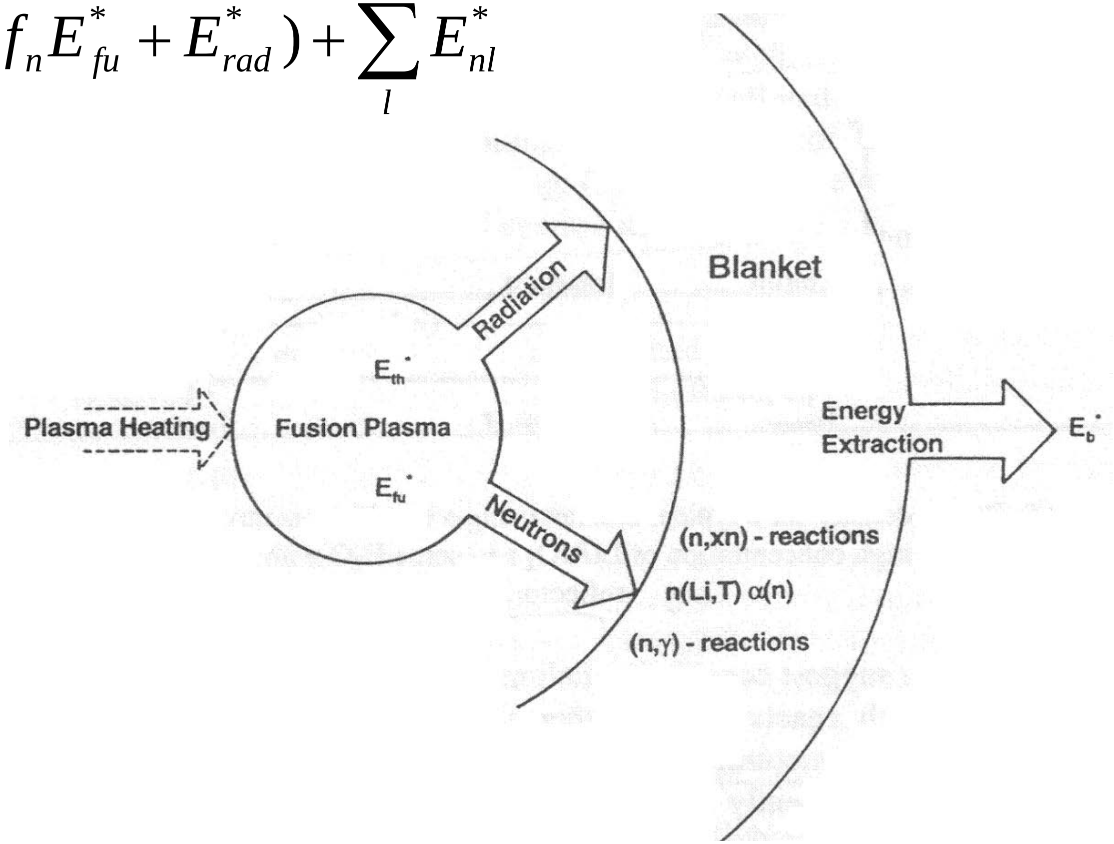
- In a “typical” blanket 1 cm thick with 10% volume fraction of 316 SS, preceded by a 1 cm steel front-wall and backed by a 100 cm thick shield: Use of the various solid breeders generally requires an added neutron multiplier

Power extraction in a blanket

Power Extraction

- **Energy Removable from the Blanket**

$$E_b^* = b(f_n E_{fu}^* + E_{rad}^*) + \sum_l E_{nl}^*$$



b: blanket coverage factor depending on the specific blanket geometry

E^*_{nl}: total energy released by an *l*-type neutron-induced reaction

Energy flows into and from a fusion reactor blanket

Power Extraction

- **Blanket Multiplication Factor**

  - Generalising energy enhancement in blankets
  - M_b = 1.3-1.8

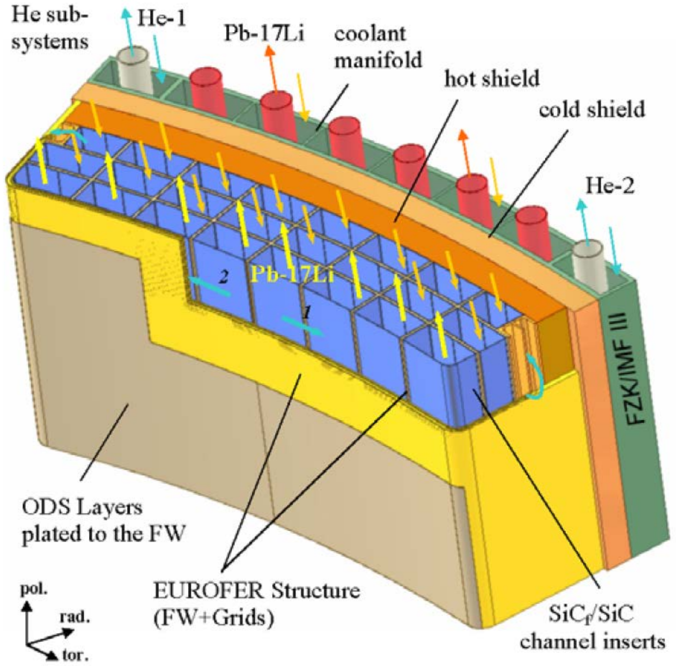
$$M_b = \frac{bf_n E^*_{fu} + \sum_l E^*_{nl}}{f_n E^*_{fu}} = b + \frac{\sum_l \int_{V_b} R_{nl} Q_{nl} d^3 r}{f_n \int_{V_c} R_{fu} Q_{fu} d^3 r}$$

For D-T fusion and assuming lithium as the only neutron reactive substance in the blanket

$$= b + \frac{Q_{n6} \int_{V_b} \int_{v_n} \sigma_{n6} N_6 N_n(v_n) v_n dv_n d^3 r + Q_{n7} \int_{V_b} \int_{v_n} \sigma_{n7} N_7 N_n(v_n) v_n dv_n d^3 r}{f_{n,dt} Q_{dt} \int_{V_c} N_d N_t < \sigma v >_{dt} d^3 r}$$

f_n: fraction of the fusion energy carried by the neutrons

Radioactivation and selection of material in a blanket



Radioactivation

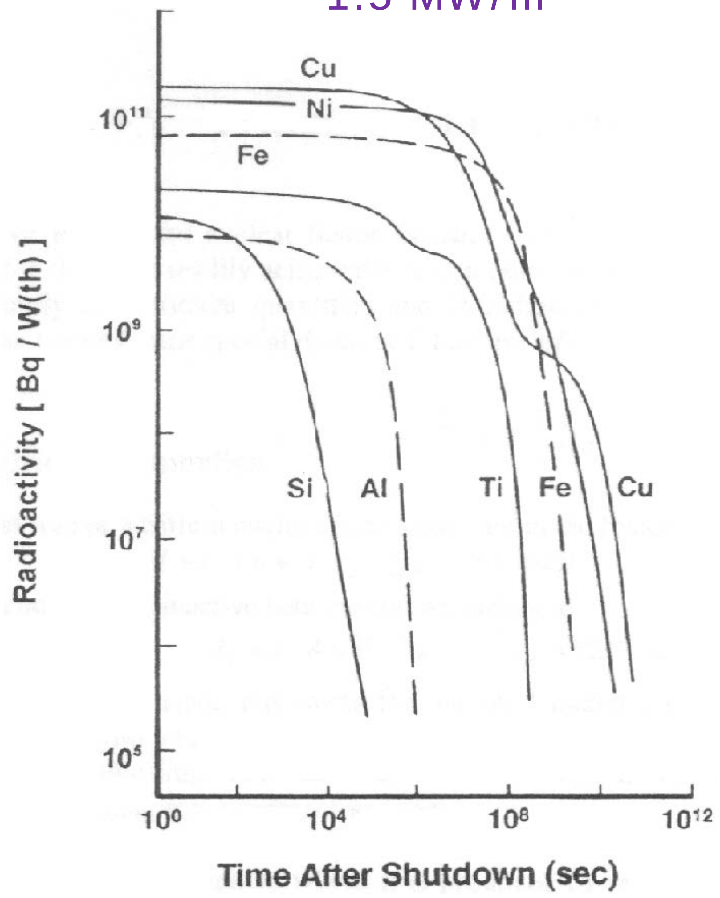
- Radiation damage occurs by atom displacement and by nuclear transmutation involving primarily those producing ^4He.
- Typical atomic displacement and gas production for 1 MW/m^2 neutron wall loading (typical on FW): displacement rate not strongly dependent on the type of material whereas the gas production rate sensitive to material choices.
- Lithium possess a significant gas production gas-production capacity but if this occurs in the liquid, pressure buildup and swelling are not a problem as it can be in solids.

Material	Displaced atoms (10^7 atoms/s)	He production (10^7 atoms/s)	H production (10^7 atoms/s)
Fe	3.6	35	150
Ni	3.9	130	400
Mn	3.6	27	100
Nb	2.3	9	30
Ti	5.0	34	50
Cu	4.9	32	170
^6Li		3100	3100
^7Li		360	370

Radioactivation

- Neutron-induced transmutations in blanket materials also result in radioactivation – most important with respect to reactor maintenance, storage of reactor components.

The residual radioactivity of selected elements irradiated for 2 years in a typical first wall flux of 1.5 MW/m^2



1 year (365 days) = 31,536,000 s

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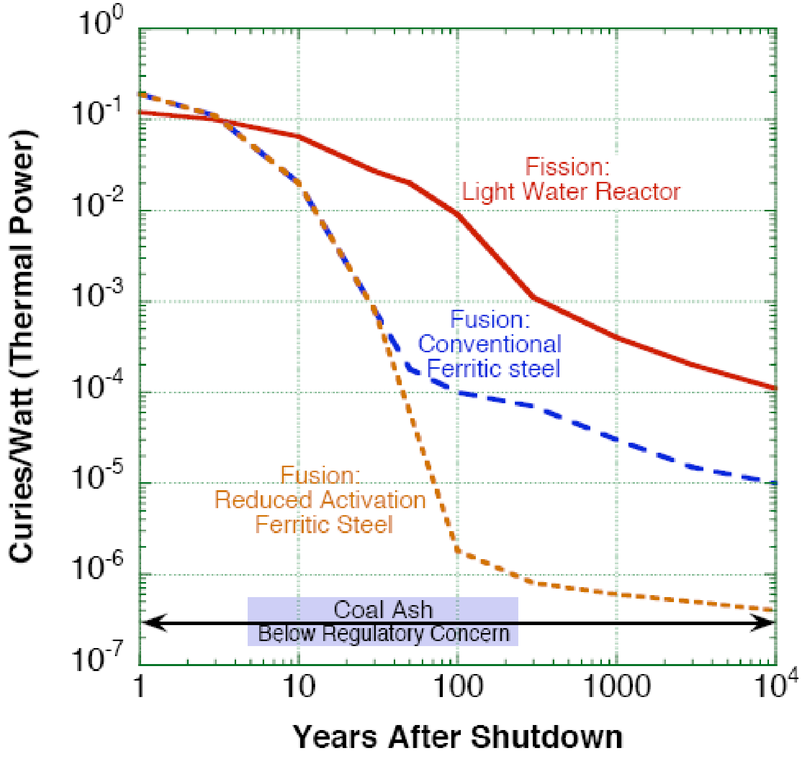
Comparison of Fission and Fusion Radioactivity after Shutdown



Radioactivation

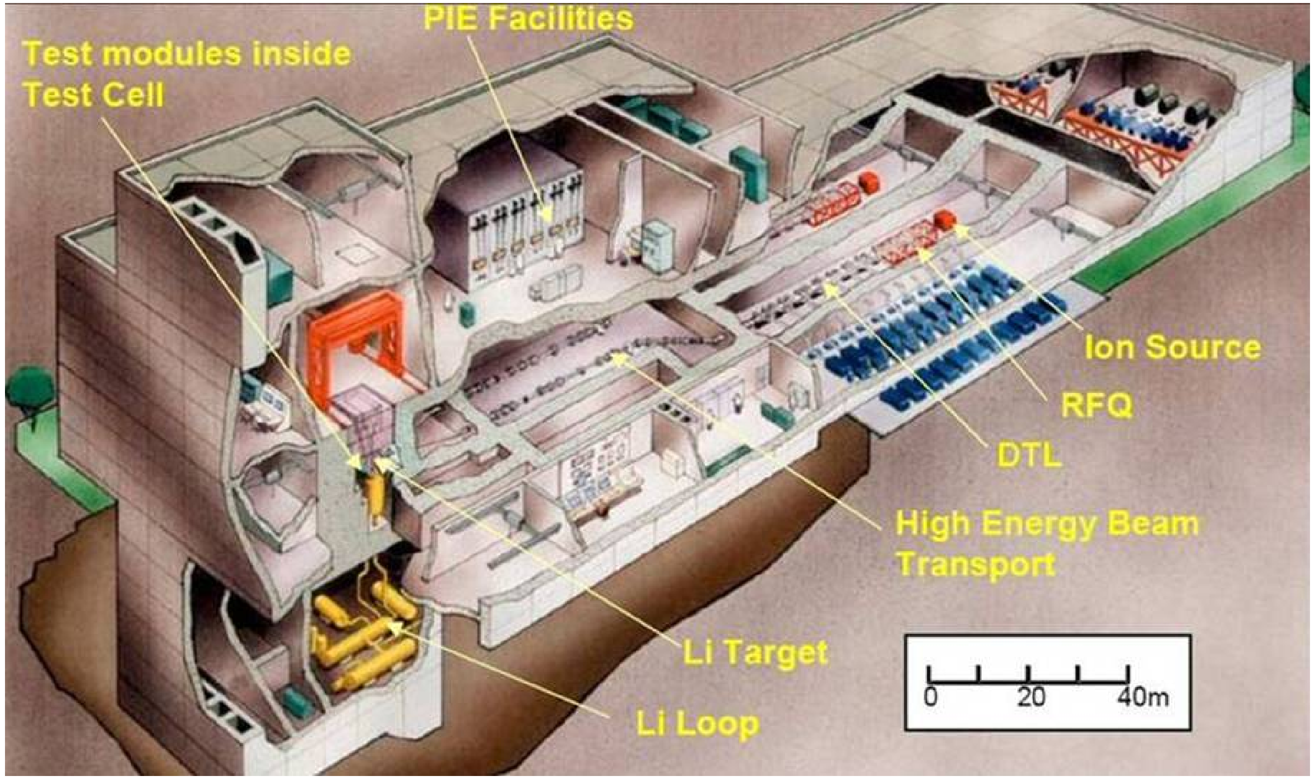
- Neutron-induced transmutations in blanket materials also result in radioactivation – most important with respect to reactor maintenance, storage of reactor components.

- The level of radioactivation, along with other radioactivity aspects such as the T inventory will be a key factor in determining the environmental impact of fusion reactors.

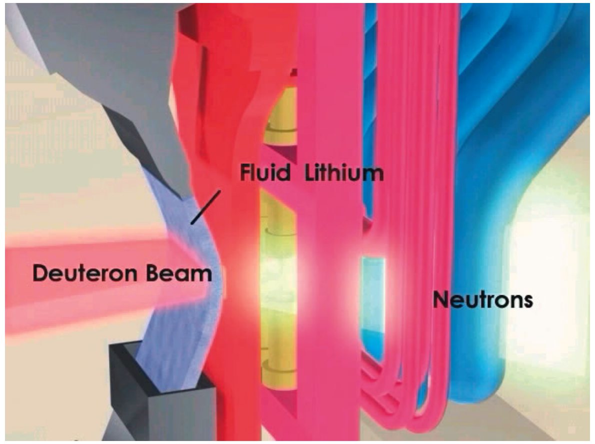
	Eurofer (Europe)	F82H (Japan)
An element	Composition (wt%)	Composition (wt%)
Fe	89.04	89.924
C	0.11	0.09
Cr	9.0	7.7
W	1.1	1.94
Mn	0.40	0.16
V	0.20	0.16
Ta	0.12	0.02
N2	0.03	0.006
Total	100	100

RAFS (RAFM):
Reduced Activation Ferritic (Martensitic) Steel

International Fusion Materials Irradiation Facility (IFMIF)



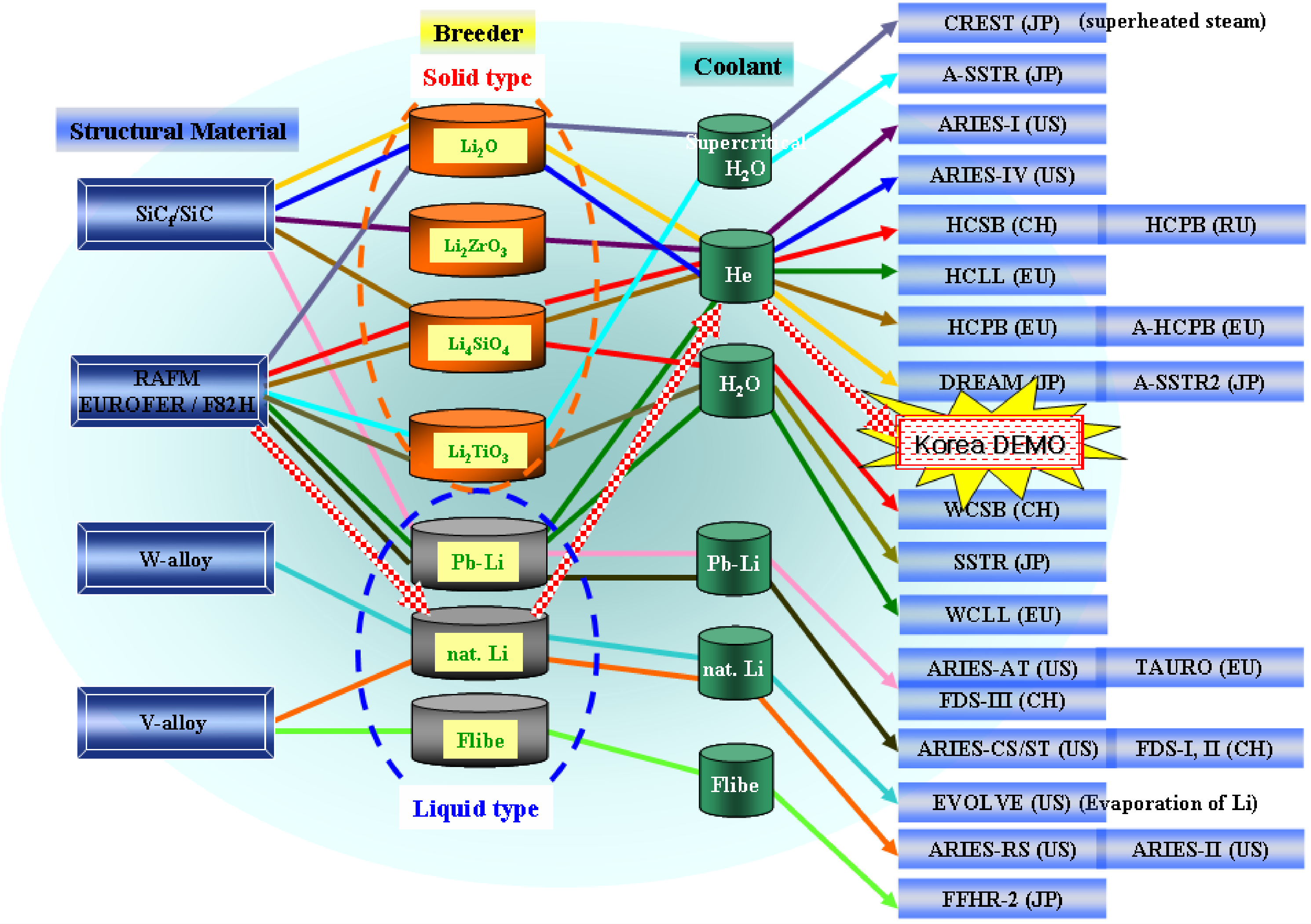
PIE: Post Irradiation Examination
RFQ: Radio Frequency Quadrupole
DTL: Drift Tube Linac



Typical Reactions	$^{7}Li(d,2n)^{7}Be$	$^{6}Li(d,n)^{7}Be$	$^{6}Li(n,T)^{4}He$
Deuterons	30-40 MeV	2x125 mA	Beam footprint 5x20 cm^2

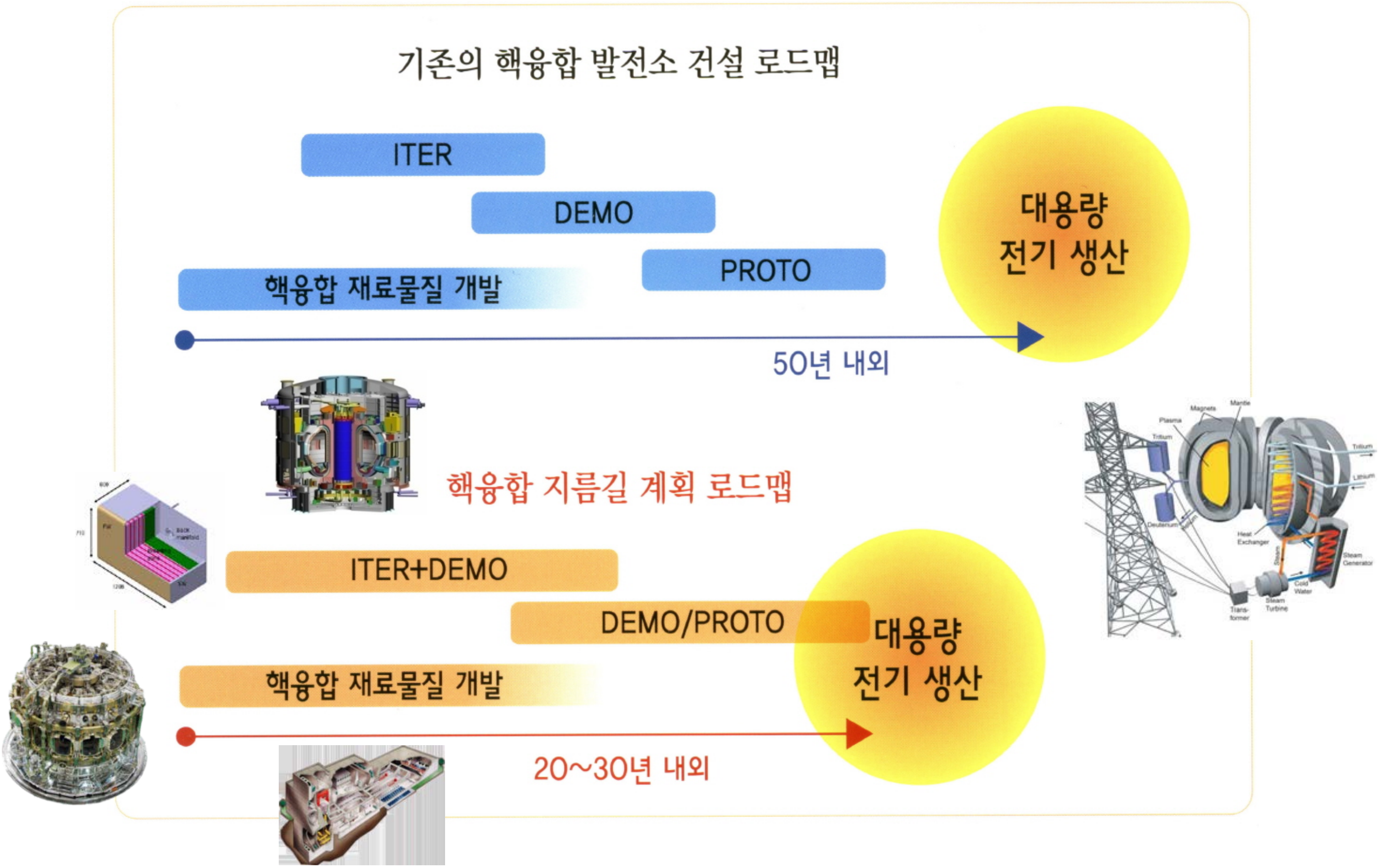
http://www-sen.upc.es/fusion/angles/activities00.htm

Blanket Types



Fusion Energy Development Roadmap

- **The Fast Track Approach**



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