Safety and Environment – Tritium Cycle

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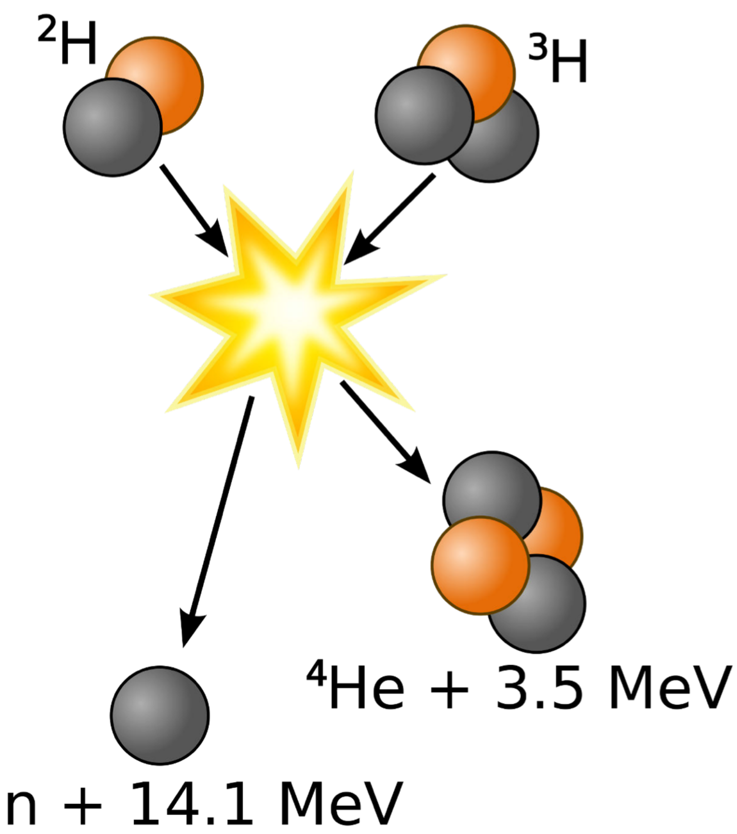
Outline

- **What are the tritium issues?**
- **What are the other environmental impacts of fusion reactors?**
- **Are there sufficient materials to build fusion reactors?**

Deuterium-tritium reaction is favored since it has the highest reaction rate at the lowest temperature



- $\Delta E_{D\text{-}T \rightarrow 4He}$ = 17.6 MeV
- Energy in neutrons (~80%, 14.1 MeV) for energy production (e.g., heating of blanket, also tritium production)
- ^{4}He (fast α particles) for internal, self-sustained heating of the fusion process

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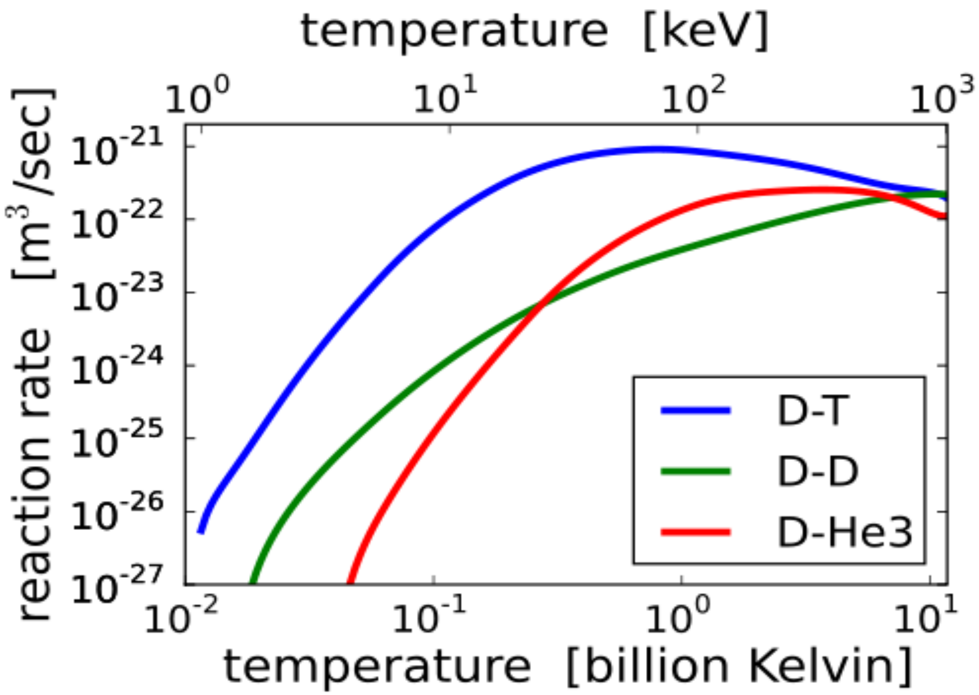


http://en.wikipedia.org

- **Reactant nuclei have to overcome electrostatic repulsion ⇒ heating to increase thermal velocity**
- **Reaction rates have a maximum, depending on reactants**
- **At (engineering feasible) 10 keV, D-T reaction three orders of magnitude higher than D-D**

A wide range of reactants may be used besides hydrogen isotopes, at the cost of higher plasma temperatures

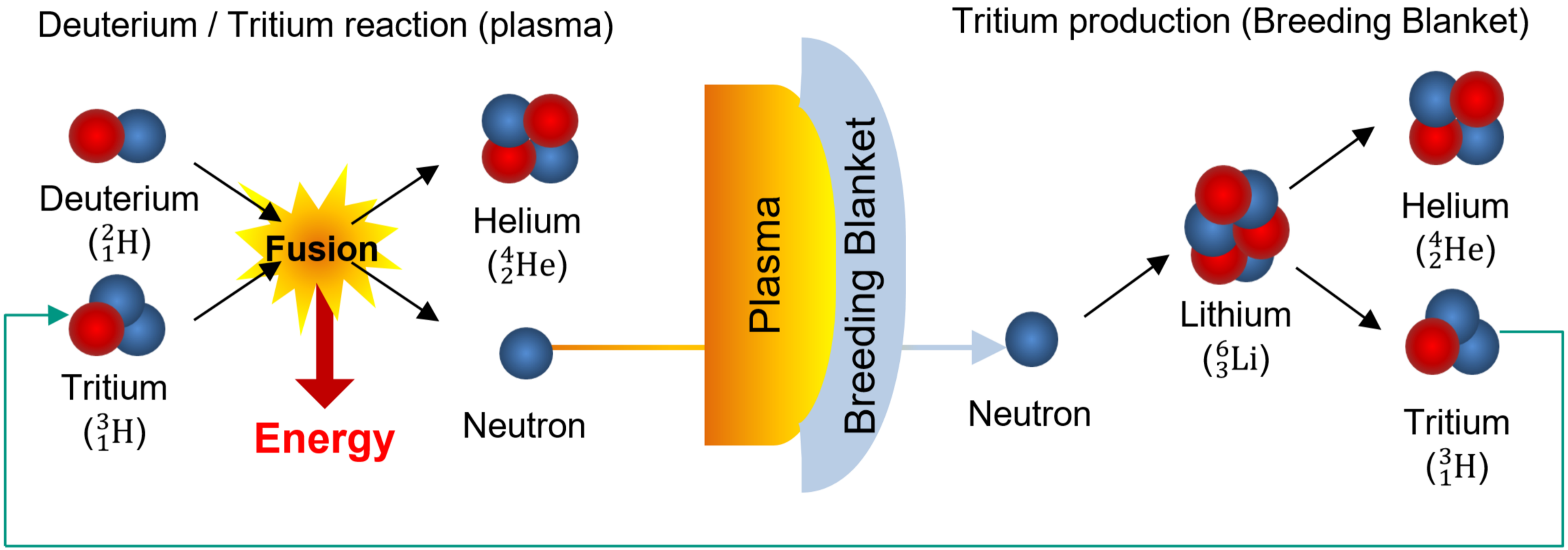
D+T	^{4}He (3.5 MeV) + n (14.1 MeV)
D+D	50%: T (1.01 MeV) + p (3.02 MeV)
	50%: ^{3}He (0.82 MeV) + n (2.45 MeV)
D+^{3}He	^{4}He (3.6 MeV) + p (14.7 MeV)
T+T	^{4}He + 2n + 11.3 MeV
^{3}He+^{3}He	^{4}He + 2p
^{3}He+T	51%: ^{4}He + p + n + 12.1 MeV
	43%: ^{4}He (4.8 MeV) + D (9.5 MeV)
	6%: ^{4}He (0.5 MeV) + n (1.9 MeV) + p (11.9 MeV)
D+^{6}Li	^{4}He (1.7 MeV) + ^{3}He (2.3 MeV)
^{3}He+^{6}Li	2 ^{4}He + p + 16.9 MeV
p+^{11}B	3 ^{4}He (1.7 MeV) + 8.7 MeV

Tritium is a radioactive isotope of hydrogen with a half-life of 12.3 years

- **T → He + e$^-$ (β) + ν_e (antineutrino)**
- **No natural tritium available:** trace amounts due cosmic rays (g to kg per year), and 10s of kg due to atmospheric nuclear testing between 1945-80
- **1 GW fusion power reactor predicted to require about 56 kg tritium / year, some sources say 100-200 kg T / year**
  - Due to low power and duty cycle, ITER startup 3 kg, JET 20 g
- **Tritium is produced in Canadian CANDU reactors by neutron absorption in deuterium:** in 2003, 1.5 kg tritium / year recovered from all CANDUs ⇒ total inventory 19 kg
  - Cost of tritium: 2004 Canada – 30 M$/kg, US – 100 M$/kg*

*Willms LANL Report LA-UR-05-1711 (2004)

In fusion reactors tritium is planned to be bred by using 14.1 MeV fusion neutrons



- **n + ^{6}Li → ^{4}He (2.05 MeV) + ^{3}H (2.75 MeV) (exothermic reaction)**
- **n + ^{7}Li → ^{4}He + ^{3}H + n (endothermic react.: -2.5 MeV)**
- Neutron multiplication in beryllium or lead ⇒ pebbles consisting of lithium bearing ceramics including Li_2TiO_3 and Li_4SiO_4

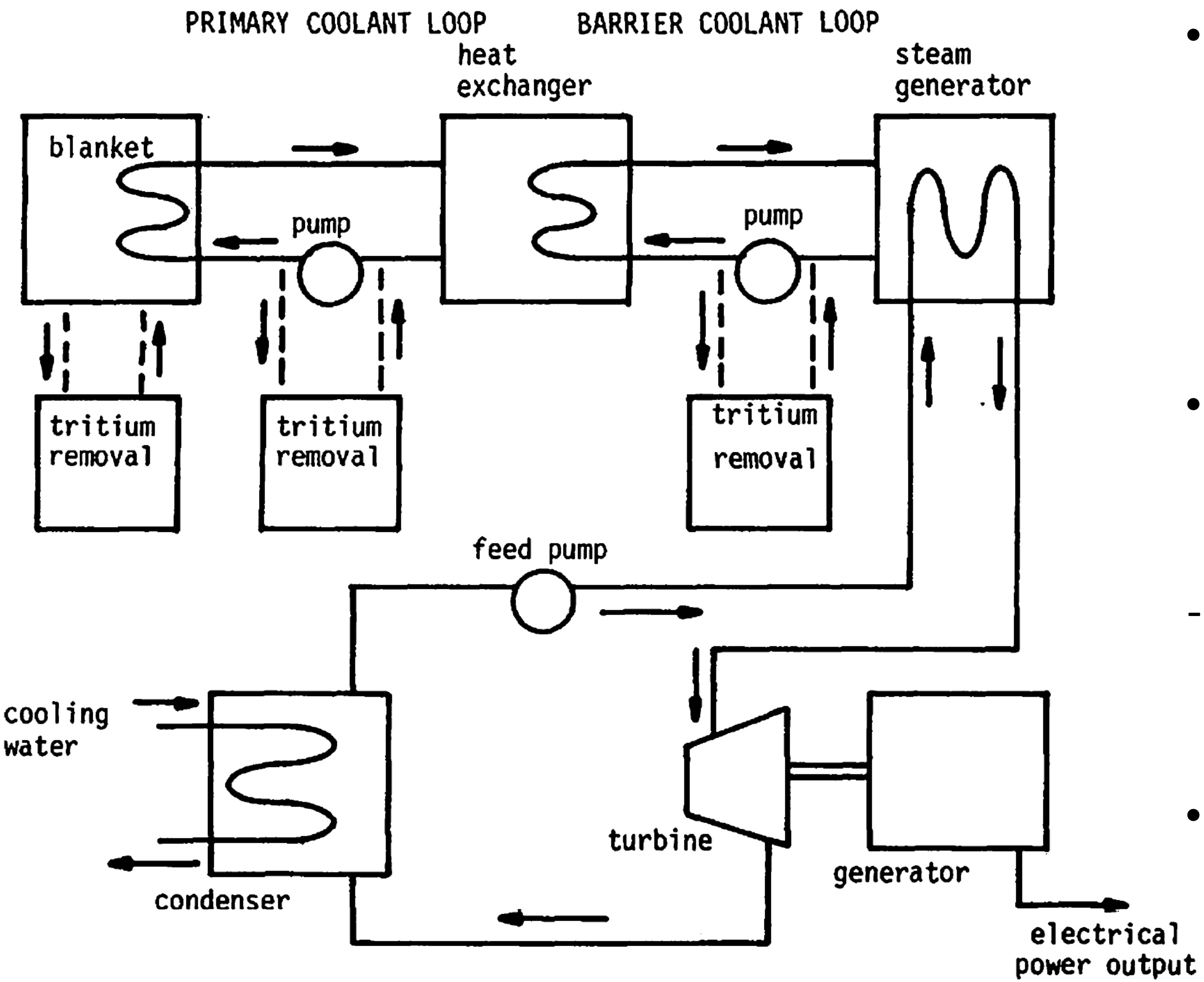
www.euro-fusion.org: picture KIT-ITeP-TLK

Tritium release to the environment is one incentive to keep the plant tritium inventory as low as possible

- **Initial cost of tritium and material embrittlement of structures are the other two primary reasons**
- **Fusion power plants would need to reduce initial 10-20 kg to 1-2 kg**
- **Radiological impact on humans, in particular through tritiated water (T_2O, THO, TDO), is significant to require containment / control**
  - Annual personal dose of the order 1-2 mSv (natural background, medical x-rays, inhalation of radioactive mater.)

  ⇔ Dose from ingestion of 1 mg of tritium 15 Sv
- **Tritium is may leave reactor through vacuum pumping system, coolant system, blanket tritium removal system, material permeation, outgassing from removed components ⇒ stringent containment:** tritium release to air at site boundary approx. 50 μSv / year

Tritium can be removed from vacuum system by cryogenic distillation or diffusion through membranes



- **Removal from blanket and coolant challenging, requires very low T pressure**
- **ITER will use electrolysis and catalysis:**
  - HT (gas) + $H_2$0 (liquid) → HTO (l) + H_2 (g)
- **Another technique permeation into PbLi**

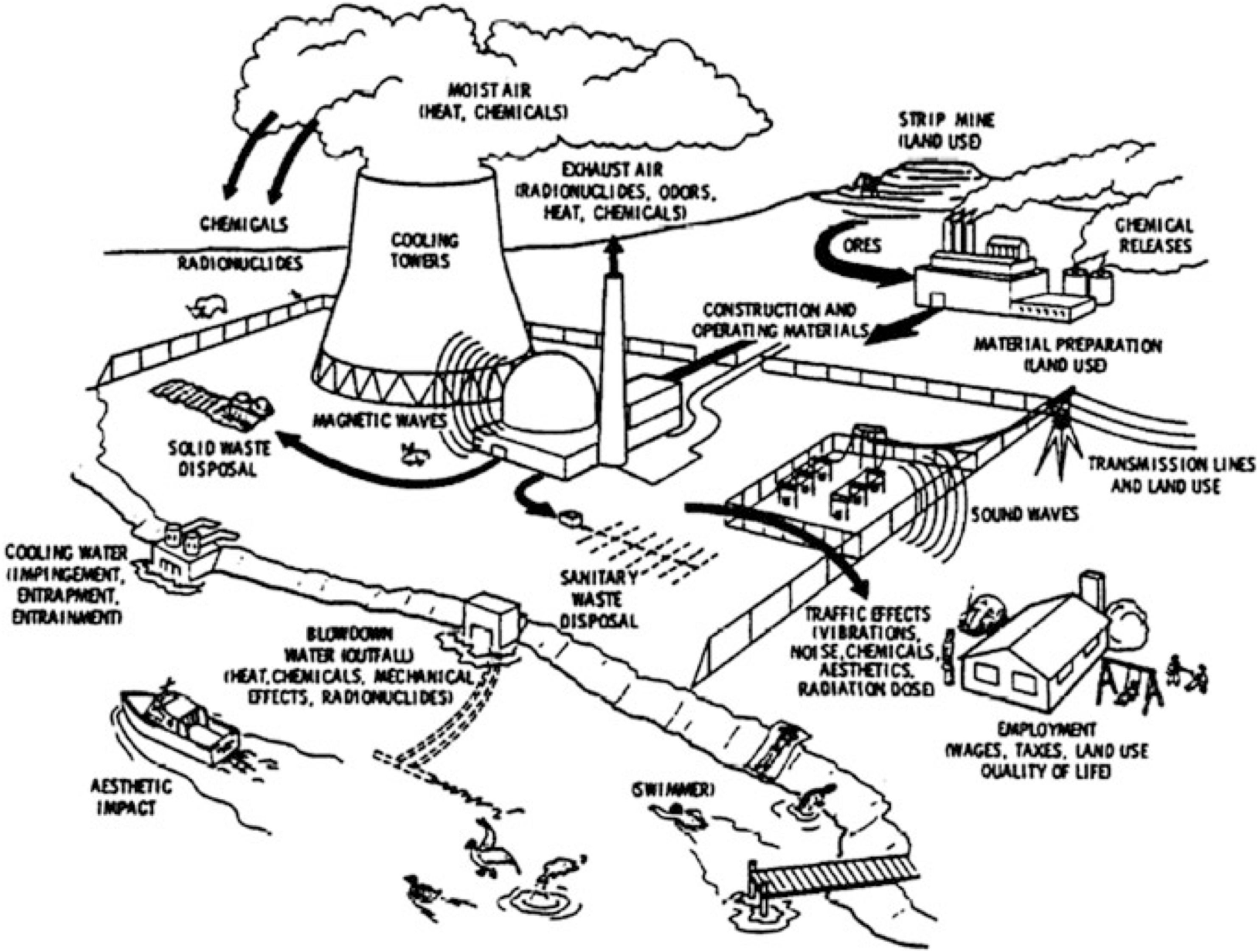
Radioisotopes are generated in any areas of significant neutron fluxes

- **Activation of surrounding materials (e.g., vanadium) ⇒ R&D on reduced-activation and martensitic steel**
- **In (potential) molten salt blankets stored heat, generation of chemical toxins (e.g., LiF), and radioisotopes (e.g., ^{18}F, ^{3}H)**
- **Plan for structural radioactivity to decay sufficiently within 100 years ⇒ storage of materials onsite, reprocessing of them afterward**
- **Decommissioning, dissembly and disposition of plant and its radioactive materials ⇒ entombment and/or removal and cleanup of site (like any other power plant)**

Material shortages: elements in short supply also include He, Li, Cu, Cr, Mo, No, Nb, Pb and W

- **Helium is vital, non-renewable resource**
    - Superconducting motors, generator, transmission lines, energy storage systems
- **Lithium:** competing with other sectors, such as Li car batteries, re-use ^{7}Li after usage in fusion reactors
- **Beryllium:** rare material in bertrandite and beryl
    - Beryllium in helium-cooled pebble bed DEMO approx. 120 t, annual burnup 0.2 t / year ⇒ 100 DEMO-type reactor ≈ 12,000 t / year ⇔ 15% of world resources
- **Niobium:** used in steel and superconductors, estimated reserves: 3 Mt
- **Lead:** DEMO-type reactor approx. 4,000 t, annual burnup 3 t / year, estimated reserves: 1.5 Gt
- **Tungsten:** adequate supplies, estimated reserves 3 Mt

Environmental and other hazards for fusion power plants



- **Routine and accidental tritium release**
- **Disposal of activated structures**
- **Chemical and thermal discharges to water or air**
- **Stored energy release**
- **Plant decommission**

Benefits of fusion reactors for environmental impact outweigh those of fission reactors

- **Adverse impact:** increased use of some scarce materials
- **Neutral:** biological effect of long-term exposure to low magnetic fields not an issue outside plant ⇒ oscillating fields in power lines more significant
- **Unchanged:** assured fuel supply, waste water, radioactive structure
- **Positive:**
  - Safety against accidental criticality, prompt criticality, loss-of-coolant accidents
  - (Non)proliferation (in pure-fusion plant): no sources of fissile materials (e.g., uranium, thorium, plutonium)
  - Lower routine chemical releases (e.g., through mining)
  - No high-level radioactive wastes, lower biological hazard
- **Extensive safety analyses for plant operation and accidents performed**

Summary

- **Main hazard of fusion power are tritium (release) and radioactive structures, including dust**
- **Fusion reactors after ITER need adequate in-situ tritium breeding ratios (of > 1.2 T per fusion neutron ⇒ beryllium or lead neutron multiplier)**
- **Shortages of He and Nb may develop, widespread use of Li in batteries potentially increases costs of fusion energy**
- **Extensive safety analyses of fusion plant operation and potential accidents were performed ⇒ plants are designed for public not needed to be evacuated in case of accident**
- **Fusion facilities are nuclear facilities ⇒ nuclear regulations of host countries (and IAEA) apply**