Chapter 7. Safety, Tritium & Environmental Impacts

Reading assignments: Dolan, *Chap.* 28, Harms *Chap. 14*; Stacey *Chap. 11*

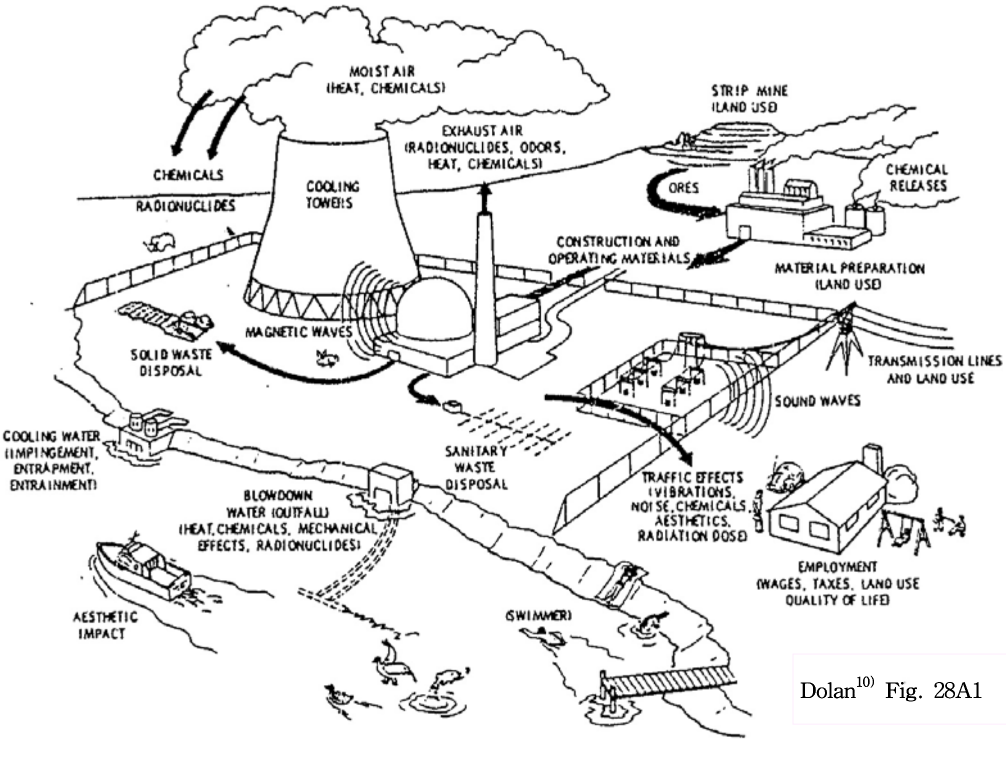
1. Safety and environmental considerations

A. Safety & environmental goals of fusion reactor

- Protection of workers and general public from accidents, radioactivity and toxic materials
- Protection of environments from pollutants and waste
- Minimization of investment for power plant construction

B. Potential hazards of fusion reactors

- Routine release of tritium
- Accidental releases or disposals of radioactivity (T, activated structures)
- Discharges of chemical and toxic materials
- Thermal discharge to water and air
- Stored energy release (radioactive afterheat, liquid metal fire, hydrogen explosion, stray magnetc fields, ...)
- Accidents associated with high vacuum, high pressure, cryogenic fluids, high voltage & current, heavy masses, ...)
- Plant decommissioning
- Proximity to popuilation centers, industry, transportation facilities
- Effects on local economic and social conditions

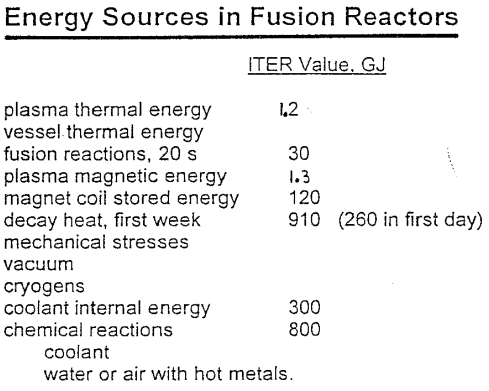


Dolan10) Fig. 28A1

2. Safety of fusion power plantss

A. Types of accidents

- Reactor core plasma events (fusion overpower, disruptions, delayed shutdown)
- Loss of coolant accident (LOCA)
- Loss of flow accident (LOFA)
- Loss of vacuum accident (LOVA)
- Loss of cryogen
- Magnet events
- Tritium plant events
- Auxiliary system events

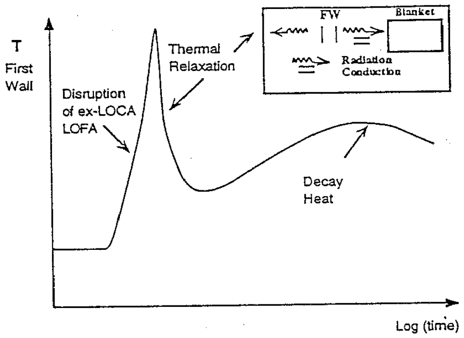


Energy Sources in Fusion Reactors

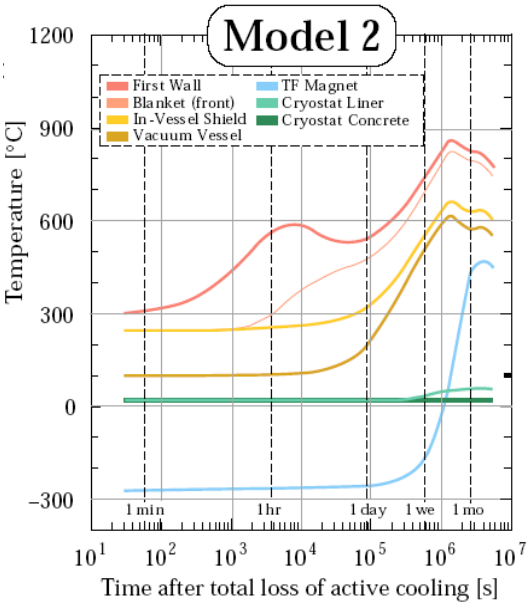
	ITER Value, GJ	
plasma thermal energy	1.2	
vessel thermal energy		
fusion reactions, 20 s	30	
plasma magnetic energy	1.3	
magnet coil stored energy	120	
decay heat, first week	910	(260 in first day)
mechanical stresses		
vacuum		
cryogens		
coolant internal energy	300	
chemical reactions	800	
coolant		
water or air with hot metals.		

First Wall Temperature vs. Time after Disruption or LOCA

From Dolan 7/23/95

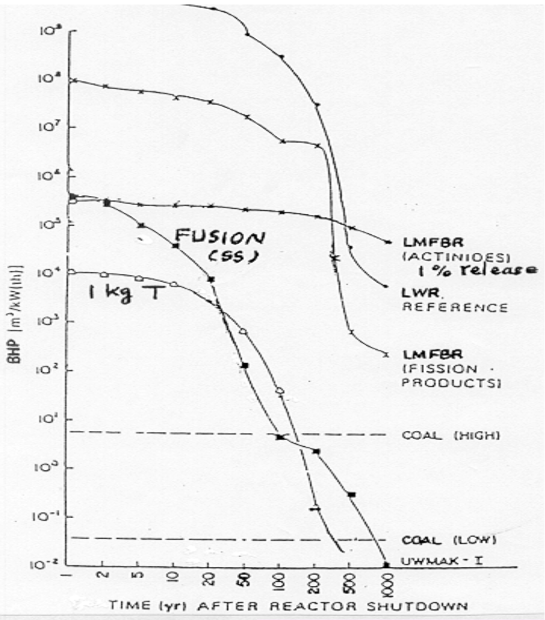


Temperature Variation of reactor materials after LOCA (Model2 fusion reactor: SS 1st wall, LiPb breeder, water coolant)



(From H.-S. Bosch, MP-IPP Summer Univ. (1999))

Biological Hazard Potential (안전농도희석량) for cooling the afterheat

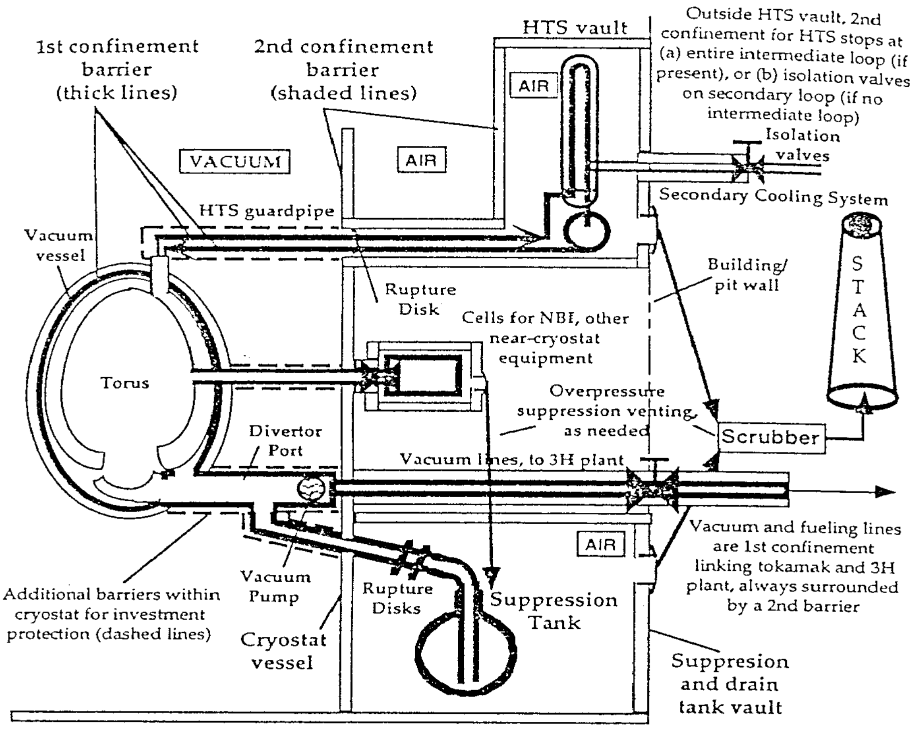


From Dolan[10)] Fig. 28C5

B. Safety philosophy of fusion reactor

- Passive multiple barriers
  (vacuum vessel + cryostat + containment building)
- Design for reliability (redundancy of components, diversity, independence, simplicity, surveillance & testing)
- Consideration of human factors
- Fail-safe design
- Remote maintenance
- Safety culture in worker attitudes
- Quality assurance (codes & standards, verification & validation, safety analysis)
- Operational controls (parameter limits, fault detection, automatic corrective response)
- Safety and protective systems
- Accident preparedness & management
- Emergency planning

Illustration of Confinement Strategy for the Tokamak Building



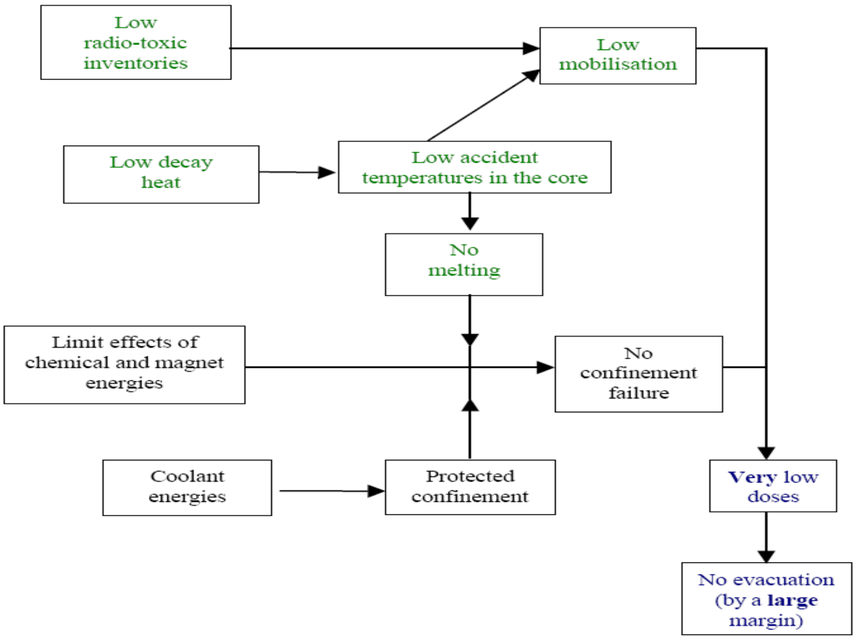
Not shown: fueling lines (similar to vacuum lines), divertor HTS lines (similar to the HTS that are shown), and ECRF/ICRF lines (which extend outside the tokamak building)

(From ITER Design Report (July, 1995), Fig. 2.6-1)

C. Intrinsic passive safety of fusion reactor

Intrinsically no core melt-down accident in the fusion reactor

- No chain reactions by neutrons
- Continuous fuel supply of few g into a reactor of few hundred m^3
  (cf) ~50 tons of fuel in a fission reactor
- Automatic shutdown and rapid cooling in case of control failures
- Low decay heats after the shutdown of reactor operation
- No evacuation of residents in case of severe accidents
- Public acceptance from the aspect of safety



Passive Safety Features

	Typical failure rates*
♦ Multiple barriers	
– vessels & ducts	10^{-4}-10^{-5} / y for strong vessels
– shell	10^{-1}-10^{-2} / demand, weak barriers
– building	10^{-1}/ demand
♦ Lithium drains to tanks	10^{-1}-10^{-2} / demand
♦ Concrete liner	10^{-3} / demand
♦ Inert cover gas	10^{-1}/ demand
♦ Stack structure	10^{-4}-10^{-5} / y for earthquakes
♦ Aerosol plate-out	~0.01-10 % releasable

Active Safety Features

♦ Active safety systems	Typical failure rates*
– Stack exhaust	10^{-4}-10^{-5}/ h fan failure
– Li fire suppression system	10^{-2}-10^{-3} / demand
– Air filtration	10^{-5} / hour failure of filter fibers

♦ Design Features
- No water in building
- Low pressure coolant
- Natural convection cooling of decay heat

* Provided by Lee Cadwallader, INEL.

ITER Mobilizable Tritium Inventory Estimates

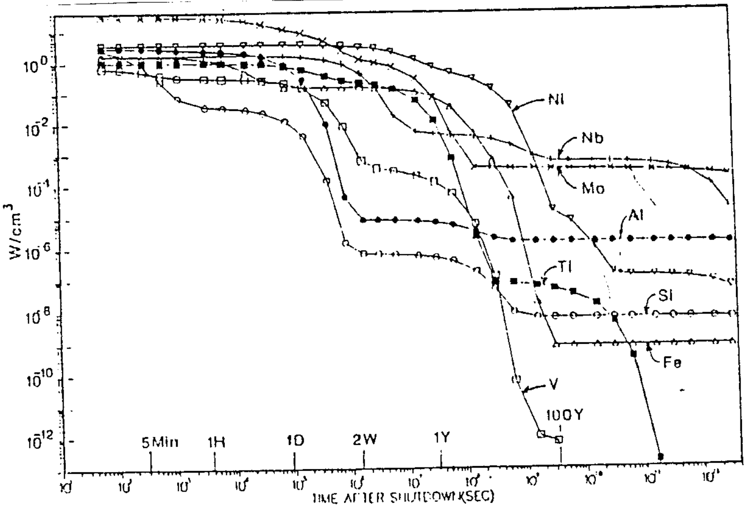
(ESECS, 1995)	grams Tritium
Plasma, vessel, vacuum system	700 - 2000
Fueling cell	140
Exhaust processing	80-160
Baking system	0-100
Divertor coolant	150
FW/B/S coolant	80
Baffle & limiter coolant	150
Vacuum vessel coolant	5
On-line storage	600
Long-term secure storage	1000
In waste & hot cells	500-1000

ITER mobilizable radioactive materials inventory

	kg
Tokamak dust	20-100
Vaporized Be or W per disruption	1-60
Divertor corrosion products	< 10 loop
FW/baffle/limiter corrosion products	1-10 per loop
Blanket/shield corrosion products	1-10 per loop
Mobile in-vessel corrosion products	~ 0.01
Volatile oxides, 773 K	SS: 20-230 g/h Cu: 0.1 - 8 g/h W: 80-200 g/h
Volatile oxides, 1073 K	SS: 24-240 g/h Cu: 80-800 g/h W: 600-6000 g/h.

From Dolan 7/23/95

* Li 자체냉각 블랑켓의 1벽 구조재의 운전정지 후 붕괴 잔열 (5 MW/m^2 벽부하로 4년간 가동)



3. Radioactive materials

A. Radioactivity in fusion reactors

1) Radioactivity sources and reduction strategy

a. Radioactivity sources

- Intrinsic radioactivity : Tritium(T) fuel (β decay, Haf-life 12.3 years)
- Induced radioactivity: 14.1-MeV neutron activation of reactor materials (PFC, structure, blanket, shield, coolant, magnet, ...)

b. Strategy for reducing radioactivity

- Reactor design for low inventory and minimum release of T
- Development of low activation materials

2) Radiological aspects of tritium

- β decay : $T \rightarrow {}^3He + \beta + \nu + 18.5$ keV
- Half-life : 12.3 years
- Biological half-life : 10 days
- Activity : ~ 10 MCi/kg ≃ 3.7×10^{17} Bq/kg
- Dose from ingestion : ~ 70 mrem/Ci
- Inventory of a 1-GWe D-T reactor : 10~100 MCi (1~10kg)
- Release limit from a reactor : 10~100 Ci/day
- Release form : gaseous - TH, T_2, TD (rapid dispersion, skin)
  aqueous - THO, T_2O, TDO (intrusion into tissues & organs)
- Routine release : vacuum pump, coolant, blanket, recovery system, permeation
  4 MCi/year from 1000 plants
- Maximum Permissible Concentration (THO 또는 T_2O) : 0.2 μCi/m^3 (air)
  3 mCi/m^3 (water)
- Biological Hazard Potential : 5×10^{14} m^3 (air)
  ≡Inventory/MPC 3×10^{10} m^3 (water)
  (cf) LWR ^{131}I의 BHP : 6×10^{20} m^3 (air)
  LMFBR Pu의 BHP : 2×10^{19} m^3 (air)

* *Advantages of low T inventory*

- Low initial cost of tritium fuel (about 1~2 M$/kg)
- Prevention of structure from embrittlement ($n_T \geq 100$ appm)
- Low release to the environment ($n_T <$ 1-10 appm)

3) Neutron activation of materials

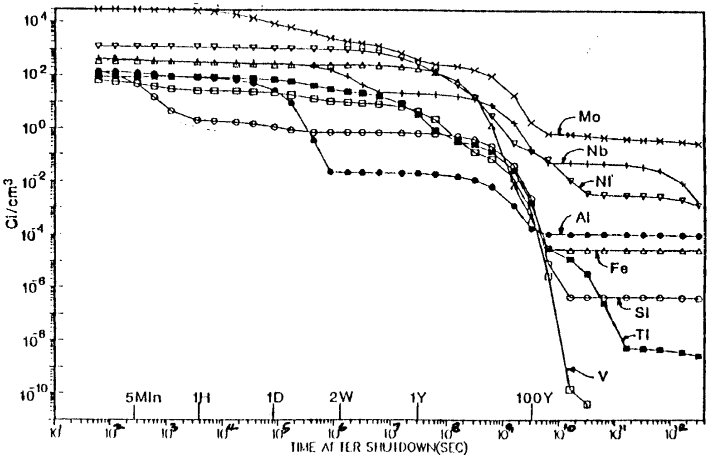
a. Neutron fluxes from reactor core

- Flux : 2~5 × 10^{14}/cm^2.sec at 1 MW/m^2 wall loading
- Biological dose rate : ~ 10^{10} rem/h

b. Induced radioactivity of structural elements after shutdown

(For FW of a Li self-cooled blanket after four-year operation
at 5 MW/m^2 neutron wall loading)

- Activity



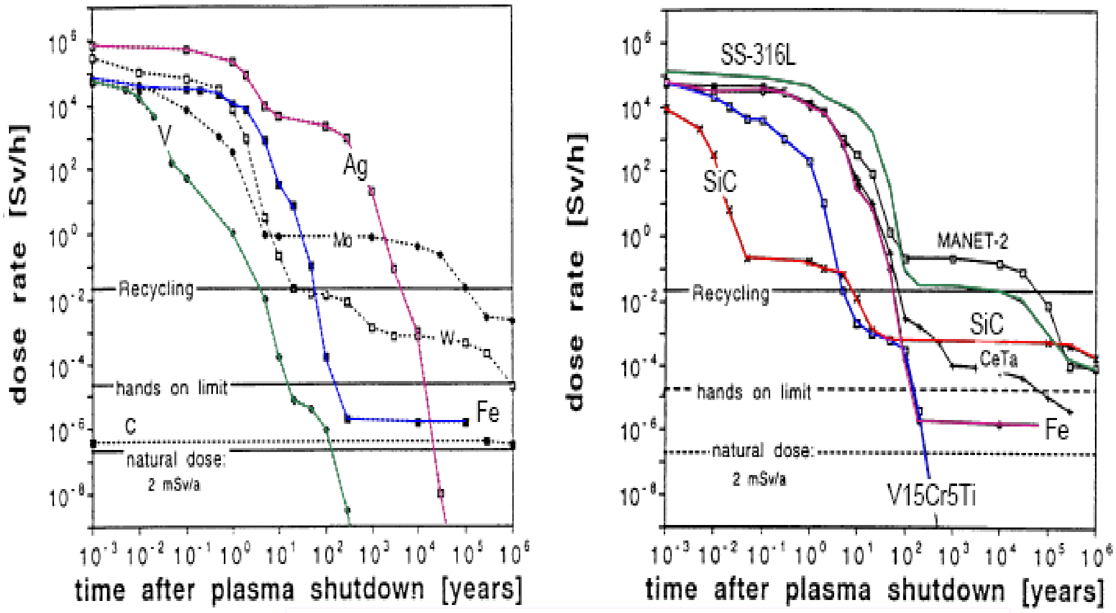
- Induced raioactive nuclides

	elapsed time after shutdown				
원소	*1 hour*	*1 day*	*1 year*	*10 years*	*1000 years*
Be	T(12,3y)	→	→	→	^{10}Be(1.6×10^6y)
C	T	→	→	→	^{14}C(5730y), ^{10}Be
O	T	→	→	→	^{14}C
F	^{18}F(1.83h)	T	→	→	^{14}C
Al	^{24}Na(15h)	→	T, ^{24}Na(2.6y)	T	^{26}Al(7.2×10^5y)
Si	^{24}Na, T	→	T	→	^{26}Al
Ti	^{46,47,48}Sc, ^{45}Ca	→	^{45}Ca, T	T	^{39}Ar(269y)
V	^{47,48}Sc, ^{49}V(330d)	→	^{49}V, T	T	^{39}Ar
Fe	^{55}Fe, ^{54,56}Mn	→	^{55}Fe, ^{54}Mn	^{55}Fe, T	^{53}Mn(3.7×10^6y)
Ni	^{57,58}Co, ^{55}Fe	→	^{57,60}Co, ^{55}Fe	^{55}Fe, ^{60}Co, T	^{59}Ni(7.5×10^4y)
Nb	^{92m}Nb(10.2d)	→	^{92m}Nb(13.6y)	→, T	^{94}Nb(2×10^4y)
Mo	^{99m}Tc, ^{97}Ru	^{97}Ru,^{97m}Tc	^{97m}Tc, T	T	^{99}Tc(2.1×10^5y) ^{91}Nb(700y), ^{94}Nb ^{93}Mo(3.5×10^3y) ^{97}Tc(2.6 ×10^6y) ^{98}Tc(4.2 ×10^6y)

c. Classification of structural elements

activity	*elements*	*structural candidates*	*environmental regul..*
lowest(decay < 2 weeks)	Li,Be,B,C,O,Si,Mg	SiC, C composites	hand maintenance
low (1 mo~5 years)	Ti,V,Cr,W	V alloy	low-level waste disposal
medium (10~30 years)	Mn,Fe,Zn	Fe-Cr alloy	medium-level waste disposal
high (> 100 years)	Co,Ni,Nb,Mo,Mn		

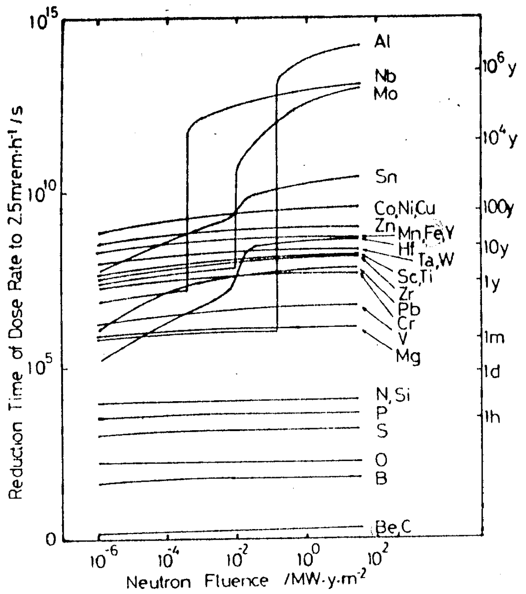
Dose rate after neutron irradiation (12 MWa/m^2)



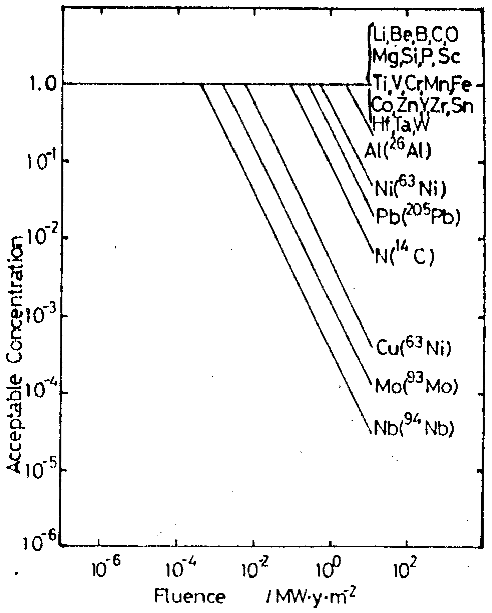
(H.-W. Bartels, MP-IPP Summer Univ. (2005)), Figs. 17.3 & 17.5)

d. Environmental requirements

Reduction time of dose rate to acceptable exposure rate

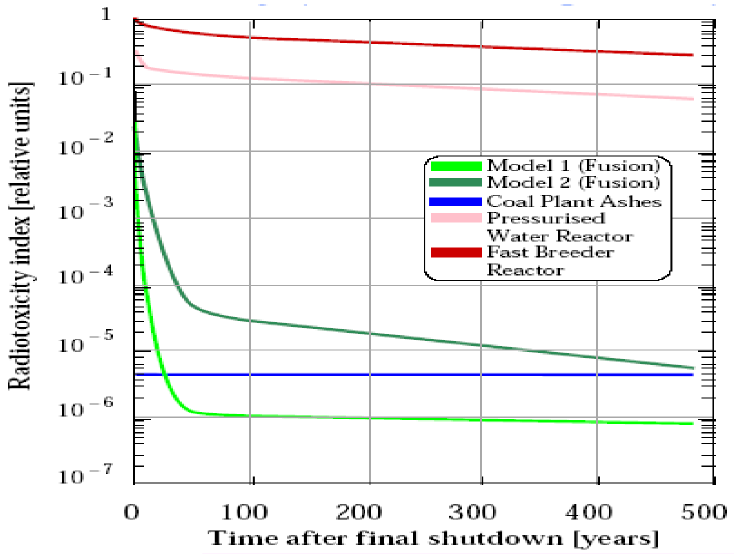


Acceptable concentration for shallow disposal (10CFR61, Class C)



d. Possible low activation materials (From EC SEAFP (1999))

발전소모델	구조재	T 증식재	n 증배재	냉각재
Model 1	V 합금	Li_2O ceramic pebble bed	없음	He
Model 2	저방사화 SS	액체 $Li_{17}Pb_{83}$	$Li_{17}Pb_{83}$	경수
Model 3	저방사화 SS	Li_4 SiO_4 ceramic pebble bed	Be	He
Model 4	SiC	액체 $Li_{17}Pb_{83}$	$Li_{17}Pb_{83}$	액체 $Li_{17}Pb_{83}$
Model 5	저방사화 SS	액체 $Li_{17}Pb_{83}$	$Li_{17}Pb_{83}$	He, 액체 $Li_{17}Pb_{83}$
Model 6	SiC	Li_4 SiO_4 ceramic pebble bed	Be	He



(From H.-S. Bosch, MP-IPP Summer Univ. (1999))