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OCCUPATIONAL RADIATION EXPOSURE at the Experimental Fusion Facilities

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EU Scientific Seminar 2022
Radiological protection considerations for fusion reactors
Luxembourg, 29 November 2022

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- Dose rates and individual doses
- Accidents consequences for workers
- Collective (effective) dose
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The Fusion Road

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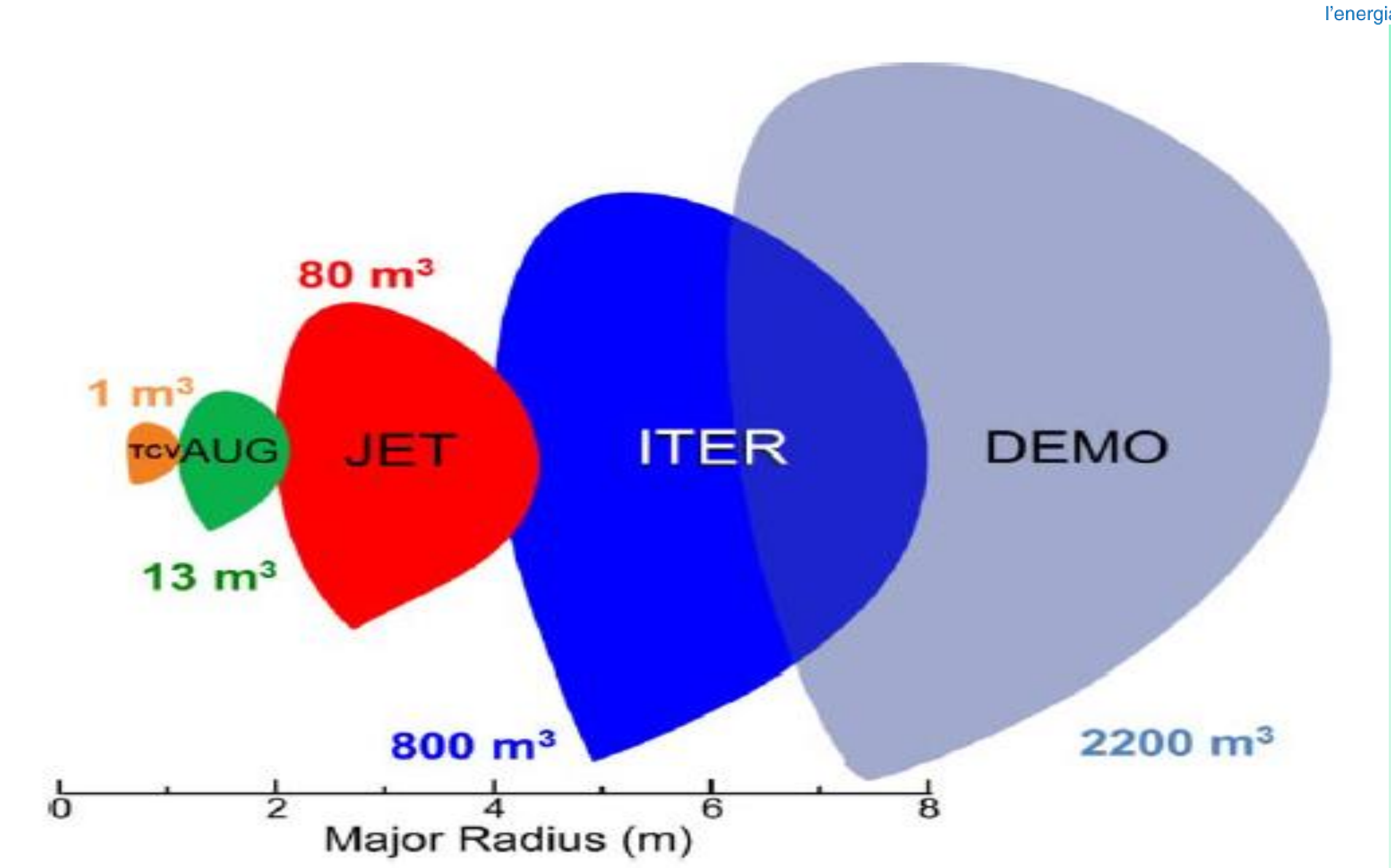

The Joint European Torus

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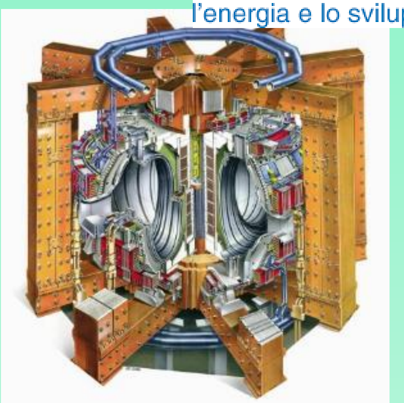
JET, located near Culham, UK, is the largest and most powerful tokamak **in operation** in the world



currently the only machine capable of **operating with the deuterium-tritium fuel** mix of future commercial reactors

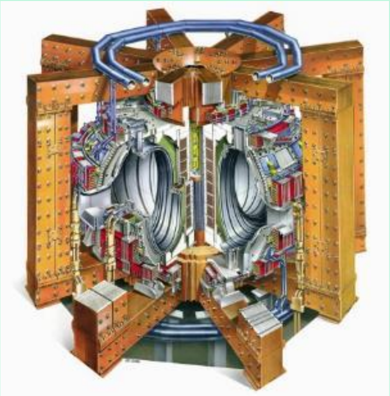
In operation since 1983, as a joint venture, JET is collectively used by more than 40 European laboratories

JET was designed to study plasma behaviour in conditions and dimensions approaching those required in a fusion reactor

Today, its primary task is to support construction and future operation of ITER, acting as a test bed for ITER technologies and plasma operating scenarios

Sharing of dose at JET by workers' group

Group	Average
Administrative support	0.3%
Engineering support	17.9%
Facility support	4.9%
Maintenance	**66.9%**
Operations	2.5%
Safety	1.3%
Scientific support	6.3%
Totals	100.0%



Max tritium dose in one year was significantly less than 10% of the worker dose

JT-60SA, Japan

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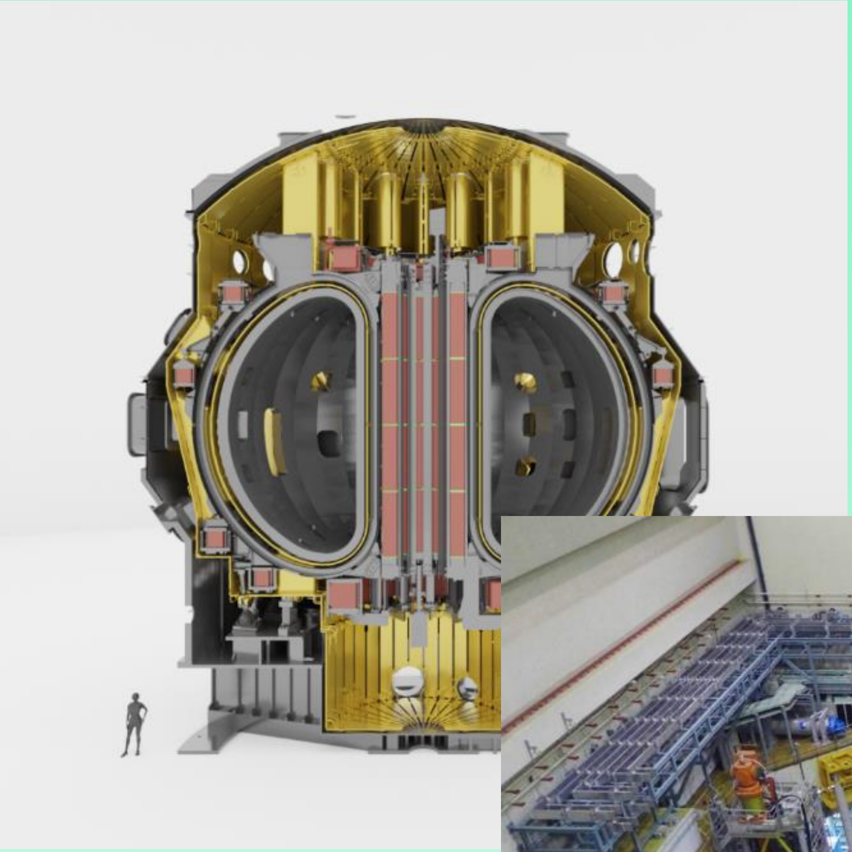
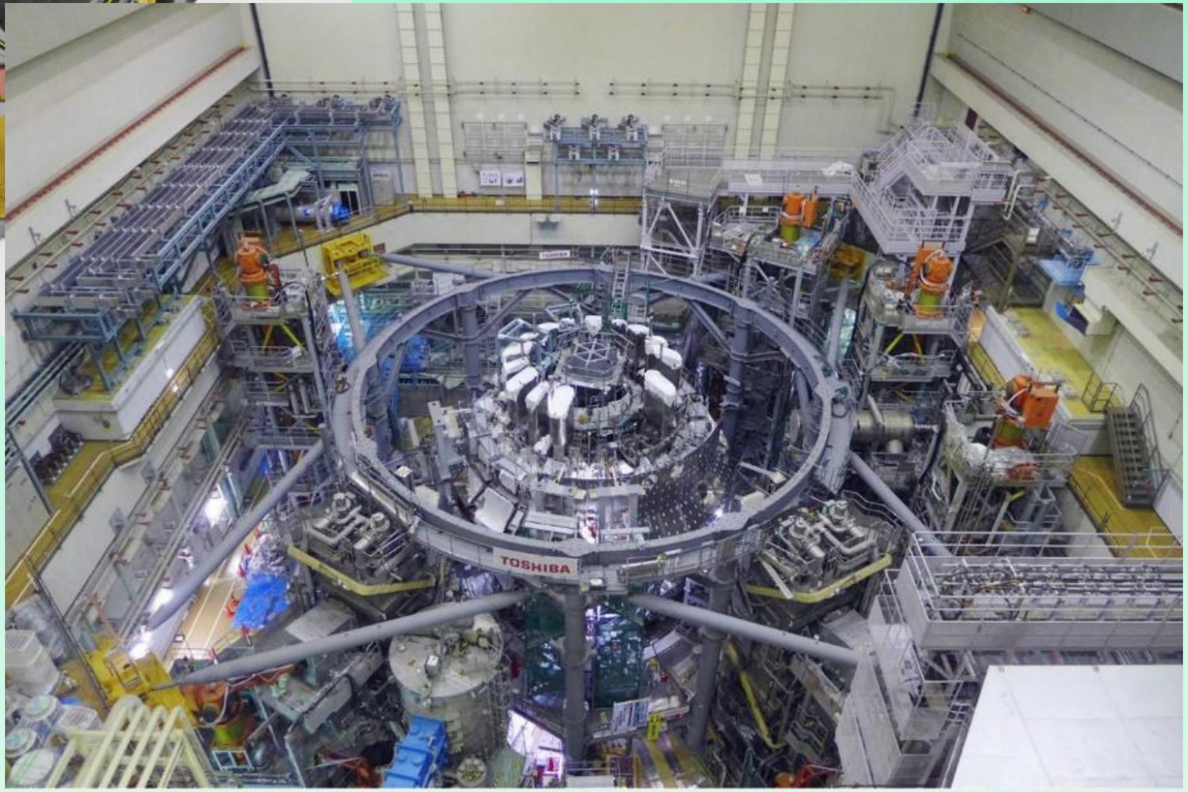
JT-60SA is a joint international fusion experiment being built and operated by Japan and Europe, in Naka, Japan, using infrastructure of the previous JT-60 Upgrade experiment.





Neutron emission rate	JT-60SA Expected	JT-60U Permitted
n/sec	4×10^{17}	2×10^{17}
n/week	5×10^{20}	3.1×10^{18}
n/3months	3×10^{21}	2.1×10^{19}
n/year	4×10^{21}	3.1×10^{19}

Divertor Tokamak Test Facility (DTT)

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A facility of the Italian Association on Fusion currently under construction near Rome

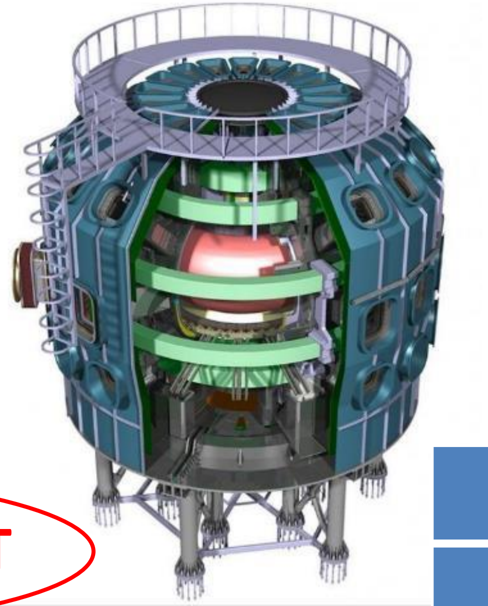
A "mini-ITER" is being built in Frascati, near Rome in Italy.

The Divertor Test Facility or DTT will explore the physics and technology of the plasma thermal power exhaust which could be used in the European DEMO, the post-ITER demonstration fusion power plant

NO TRITIUM AS FUEL

- ✓ Superconducting machine
- ✓ D-D operation
- ✓ P_{add} 45 MW
- ✓ Long pulses up to 100 s
- ✓ Max Neutron Flux:

DD yield 10^{17} n/s + 1% DT



Main parameters	
R (m)	2.11
Vol (m^3)	29
q_{95}	3
I_p (MA)	5.5
B_T (T)	6
H_{98}	1

Annual Average > 10^7 n/s

↳ **Category A permit in Italy**

Some info on ITER

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- ITER is under construction since 2006 in Cadarache (France).
- In 2010 ITER obtained the construction license for a basic nuclear installation, according to the French Nuclear Law.
- Presently, some ITER buildings, as well as several systems and components are under construction or already on site.
- **ITER will show the scientific and engineering feasibility of plasma phenomena (confinement, burn, steady-state, disruption control) and plasma support systems (low temperature superconducting magnets, fueling, heat & current drive systems).**
- Most of the components placed inside the ITER VV are not DEMO relevant because of the very different nuclear environment.
- ITER is not connected to the grid to deliver electrical energy

Present picture for ITER

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Schematic of a fusion facility

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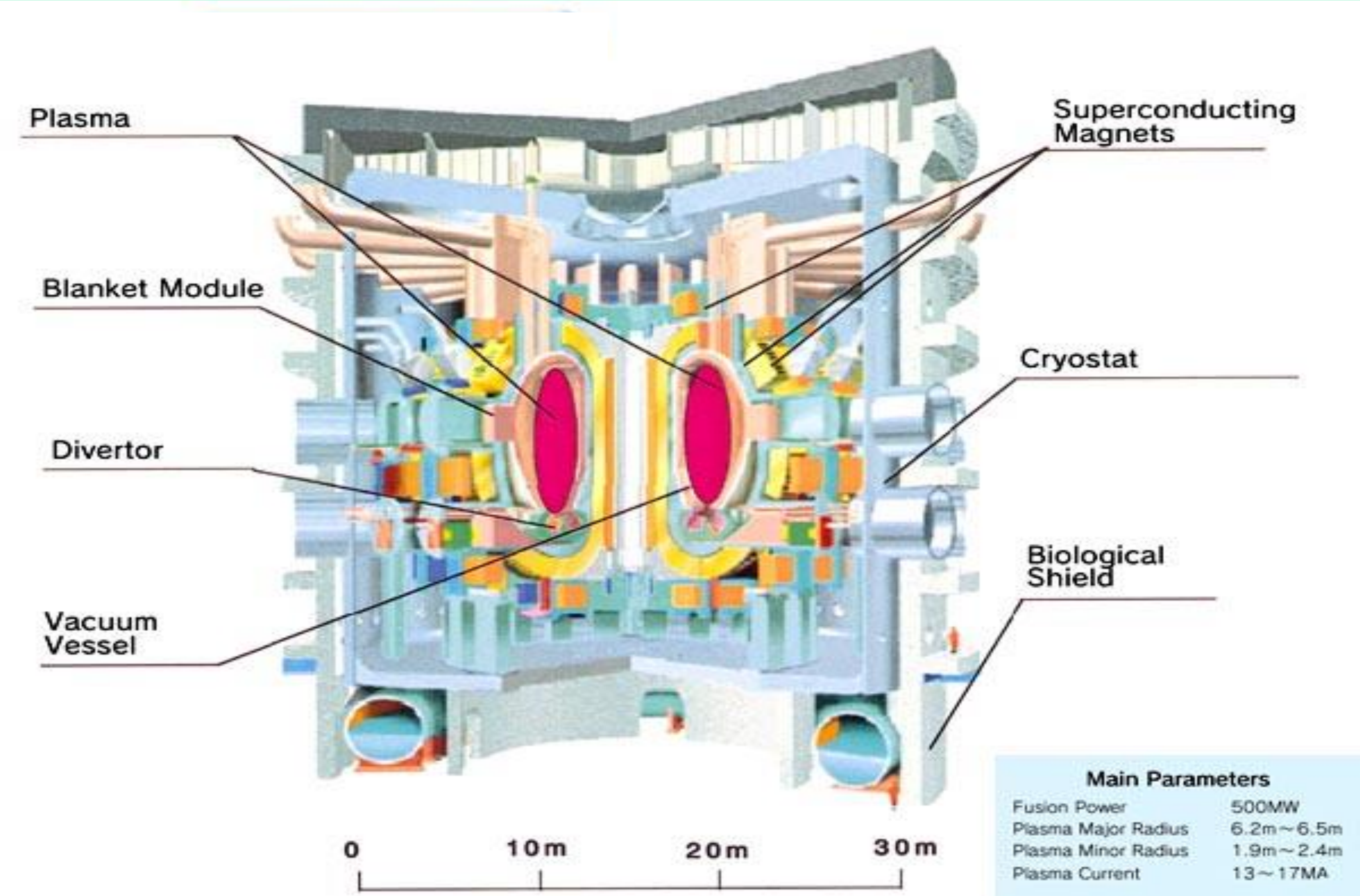

Radiological source terms for workers

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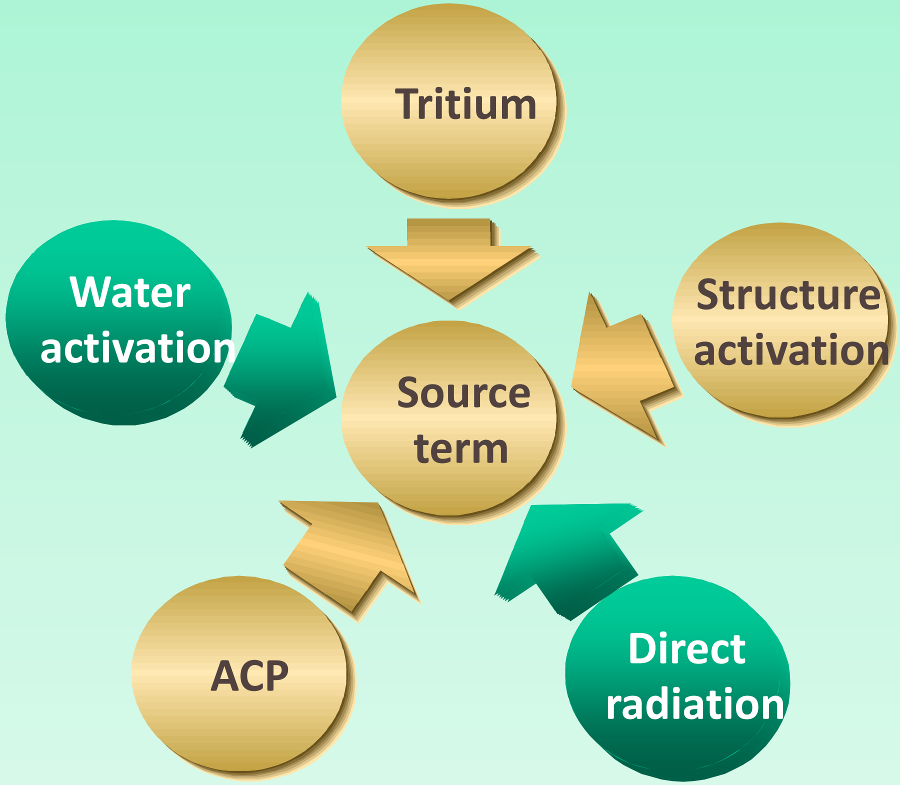
- **Primary neutron field resulting from the fusion reaction $^{2}H + ^{3}H \Rightarrow ^{4}He + n$ occurring in the vacuum vessel**
- **Gamma radiation emitted by activated products, including**
  - **plasma facing components,**
    vacuum vessel structures,
    loose contamination from activated dust generated in the vacuum vessel,
    activated corrosion products generated in the cooling loops
    activation of the inner wall of cooling water pipes
- **Activation of the cooling water**
- **Tritium used as fuel for the fusion reaction**
- **Wastes containing tritium and gamma emitters**

$D + T \Rightarrow ^{4}He + n$

$D + D \Rightarrow T + p$

$D + D \Rightarrow ^{3}He + n$



Activated dust

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An administrative limit of 1000 kg of dust is used for ITER at the end of life demonstrating that also this conservative inventory is not a risk for workers and population.
According to this assumption the materials and characteristics of the process in the plant, the percentage composition of the dust is supposed to be:

- 50% Beryllium, - 30% Tungsten, - 20%Tritium

Radionuclides mixture			
Radionuclide	Grams	Specific activity Bq/g	Total activity Bq
^{7}Be	5,00E+05	1,23E+16	6,125E+21
^{187}W	3,00E+05	2,45E+16	7,35E+21
^{3}H	2,00E+05	3,3775E+14	6,755E+19

The water cooling system

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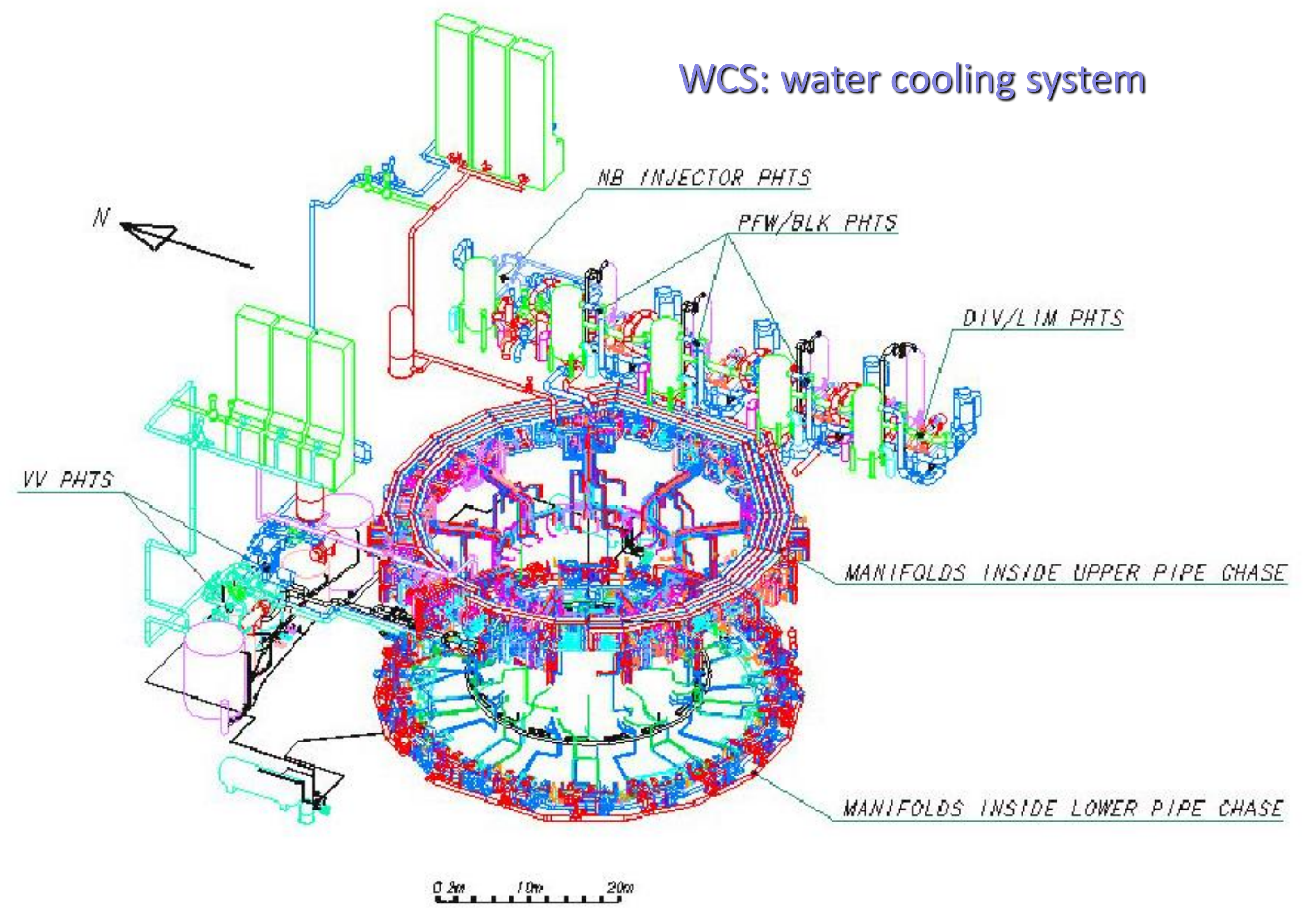
WCS: water cooling system



ACP in the WCS components

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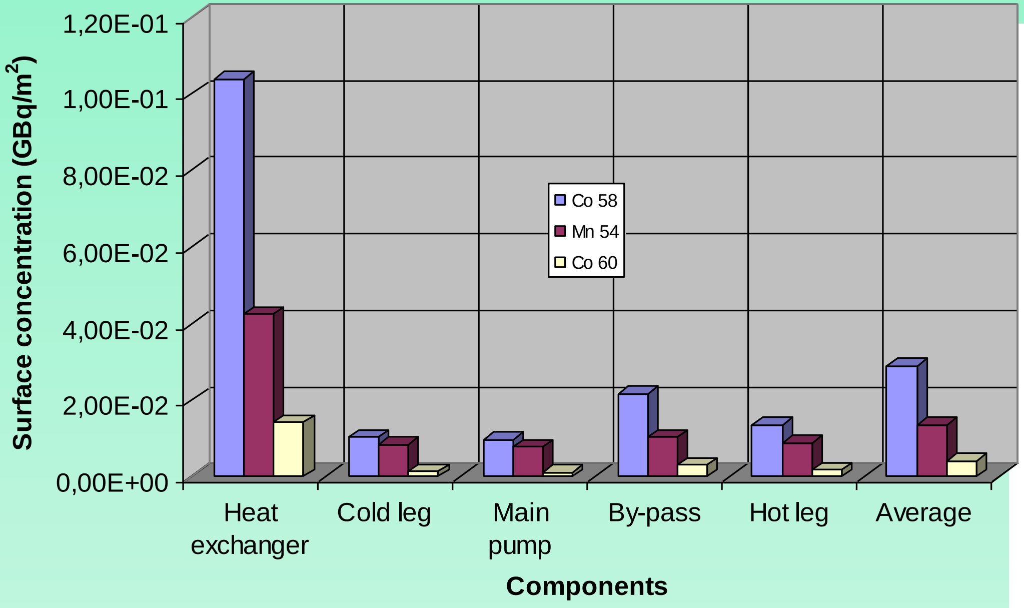

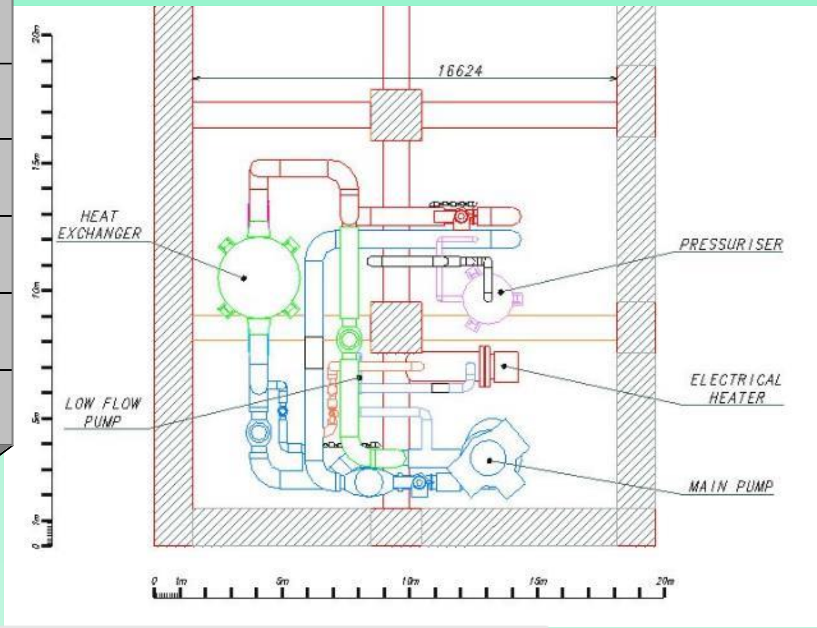

	Radioisotopes						
	Mn 54	Mn 56	Co 58	Co 60	Cr 51	Ni 57	Co 57
Components	[GBq m^{-2}]	[GBq m^{-2}]	[GBq m^{-2}]	[GBq m^{-2}]	[GBq m^{-2}]	[GBq m^{-2}]	[GBq m^{-2}]
Hot leg	8,77E-03	1,44E-15	1,34E-02	1,74E-03	2,77E-05	1,86E-04	1,07E-02
Heat exchanger	4,25E-02	9,09E-16	1,04E-01	1,42E-02	1,14E-05	1,08E-04	9,48E-02
Cold leg	8,34E-03	1,04E-15	1,03E-02	1,33E-03	1,62E-05	1,85E-04	8,30E-03
Main pump	7,73E-03	1,26E-15	9,56E-03	1,21E-03	1,88E-05	2,20E-04	7,44E-03
By-pass	1,04E-02	2,71E-16	2,17E-02	3,07E-03	1,35E-06	2,11E-05	1,96E-02

Activated Corrosion Products (ACP) generate on the inner walls of the In-vessel pipes that are under neutron flux

Erosion and corrosion processes make it possible the dilution of the ACP in the cooling water

Cooling water transports the ACP in all the primary cooling loop where they are released to the inner walls by chemical reactions and deposition

Dose rates around system components

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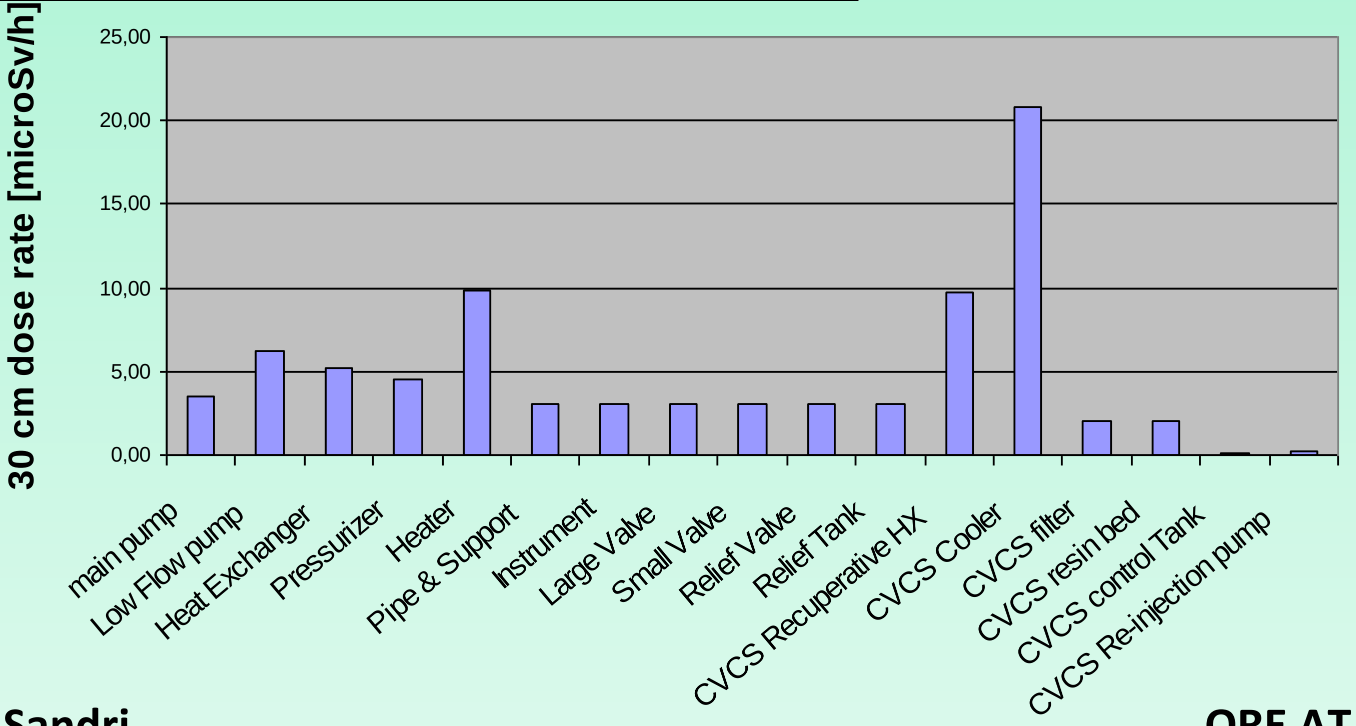
System-Component	Close (30 cm) [microSv/h]	Near (1 m) [microSv/h]	System-Component	Close (30 cm) [microSv/h]	Near (1 m) [microSv/h]
main pump	3,52	1,58	Small Valve	3,02	1,35
Low Flow pump	6,17	2,36	Relief Valve	3,02	1,35
Heat Exchanger	5,23	3,36	Relief Tank	3,02	1,35
Pressurizer	4,48	1,57	CVCS Recuperative HX	9,72	3,42
Heater	9,84	3,76	CVCS Cooler	20,80	7,30
Pipe & Support	3,02	1,35	CVCS filter	2,02	0,71
Instrument	3,02	1,35	CVCS resin bed	2,02	0,71
Large Valve	3,02	1,35	CVCS control Tank	0,12	0,04
			CVCS Re-injection pump	0,18	0,06



In the assessment the pipe's wall shielding effect was considered

The conversion coefficient from the ACP surface activity concentration to the dose rate outside of the components were calculated with the MCNP code

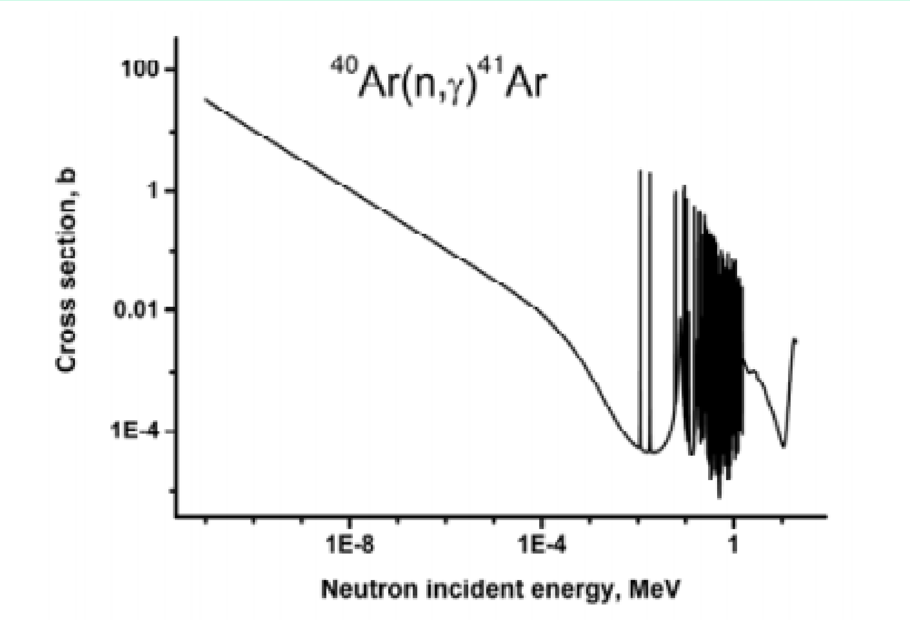
Air activation

The following radionuclide could be generated by neutron induced reactions:

^{3}H, ^{11}C, ^{13}N, ^{16}N, ^{14}O, ^{15}O, ^{37}S, ^{37}Ar, ^{41}Ar, ^{39}Cl and ^{40}Cl

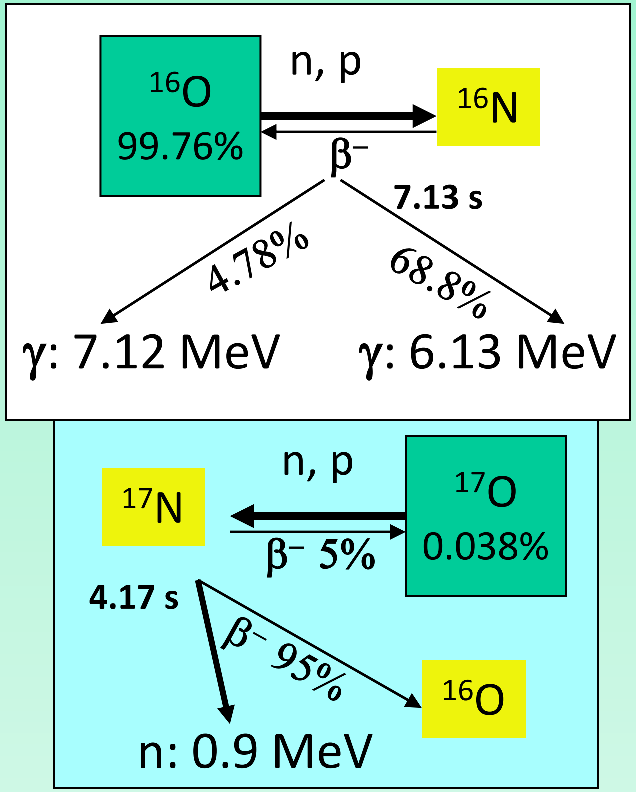
Those mostly contributing to the dose are:

^{15}O (for 30 %), ^{11}C, ^{13}N, ^{41}Ar, ^{39}Cl and ^{40}Cl



Not an issue from the ORE point of view

Water activation: ^{16}N and ^{17}N



Water activation produces two main radioisotopes: ^{16}N and ^{17}N

The first one decays producing high energy gamma rays (6-7 MeV), but has a short half life

The second one produces a delayed neutron that activates the component inner walls and could increase the dose rate

The usual assumption is that this contribution can be neglected owing to the distance from the tokamak core to the premises external to the bioshield

Tritium

^{3}H

Tritium is part of the fuel mixture and in principle can contaminate the atmosphere of tokamak and tritium buildings

Evaluations related to ITER plant showed that its contribution to the occupational exposure is of the order of 20-30% of the total

Tritium is also produced in the reaction

D + D => T + p

That is common in many experimental nuclear fusion facilities

Tritium source term in JET

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- Tritium was injected into JET initially in 1991 and then in 1997
- The quantity injected in 1991 was only 5 mg
- That injected in 1997 was 35 g
- **Impact of the 1991 D/T operation on worker doses was negligibly small**
- **On average, since 1997, the tritium dose was in the order of 1% of the total worker dose**
- This is an important result, not only for JET, but also for ITER
- **It shows that radiation protection measures used at JET (typically, fully pressurized plastic suits), worked well at reducing the tritium dose to a small percentage of the total dose**

DTT in-vessel contact dose rate

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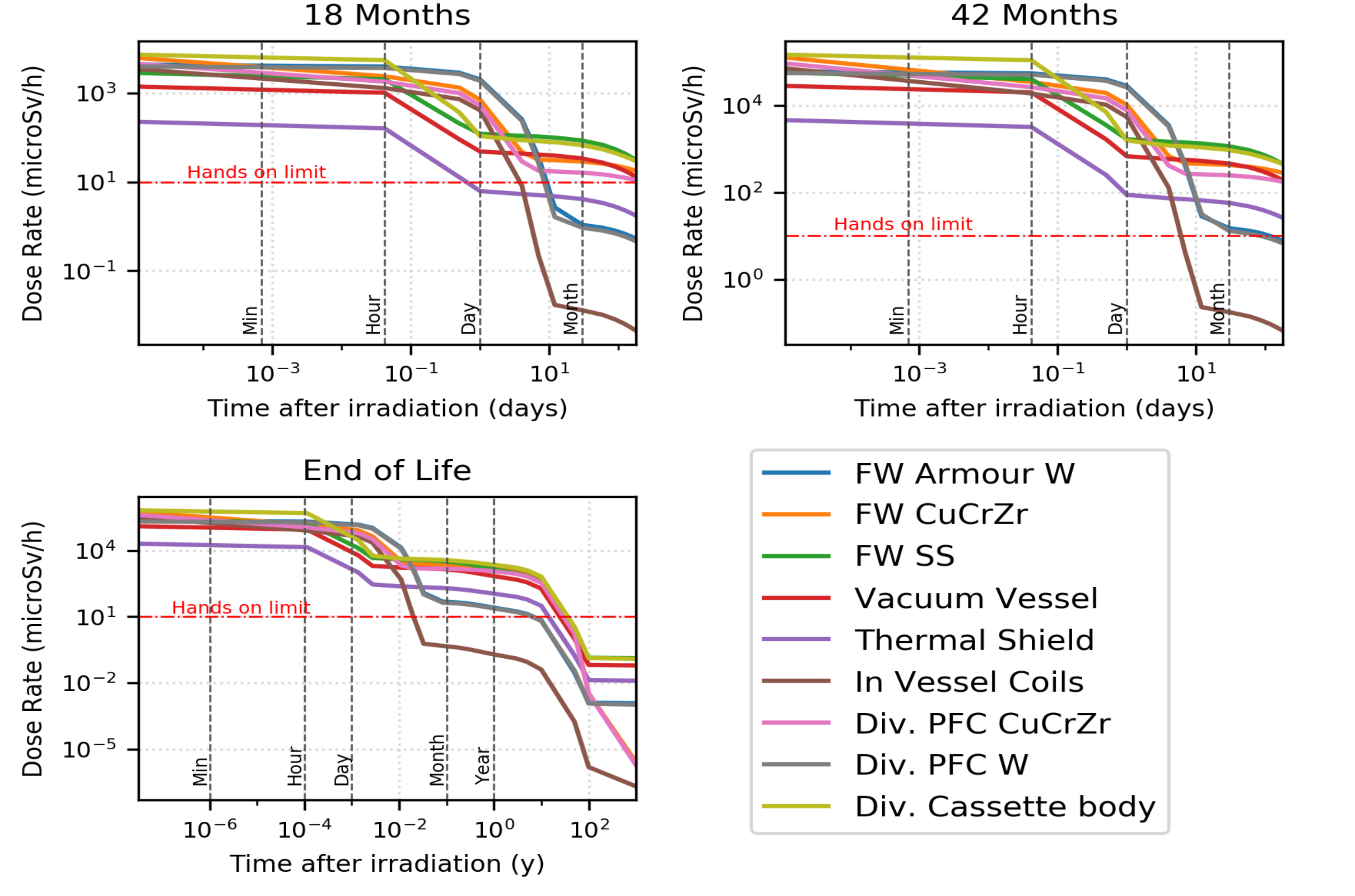

ITER Individual dose assessment

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individual doses were calculated at least for the operators involved in the following activities:

- Normal surveillance in the tokamak building
- TCWS components routine maintenance
- Hands-on assistance for RH maintenance of the in-vessel components

ITER dose during normal surveillance

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- During the normal surveillance the operator undergo to an average dose rate of 1 μSv/h
- its annual shift is of about 2000 hours,
- annual individual dose rate for this operator is therefore 2 mSv.

ITER individual doses during TCWS maintenance

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- Maintenance of the TCWS components requires different kind of operations and the dose rates in general ranges from about 1 μSv/h to some tens of μSv/h.
- **For some special operations the worker could be required to go inside the Channel Head of the Heat Exchanger (HX) where the dose rate is as high as some hundreds of μSv/h.**
- An average individual effective dose for this activity has no meaning since the different operators will undergo to a completely different exposure.
- **Anyway, the most exposed operator could have an annual effective dose of about 10 mSv and the major quantity of the workers involved in this activity should stay below an annual effective dose of 6 mSv.**

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ITER Individual dose for RH hands-on assistance

- Hands-on assistance to the RH for in vessel components includes many working tasks and the same consideration already issued for the TCWS maintenance also applies to this working activity.
- **The most exposed operator could have an annual effective dose of about 10 mSv but the average worker should stay below an annual effective dose of 6 mSv**.

Hands on RH assistance in ITER

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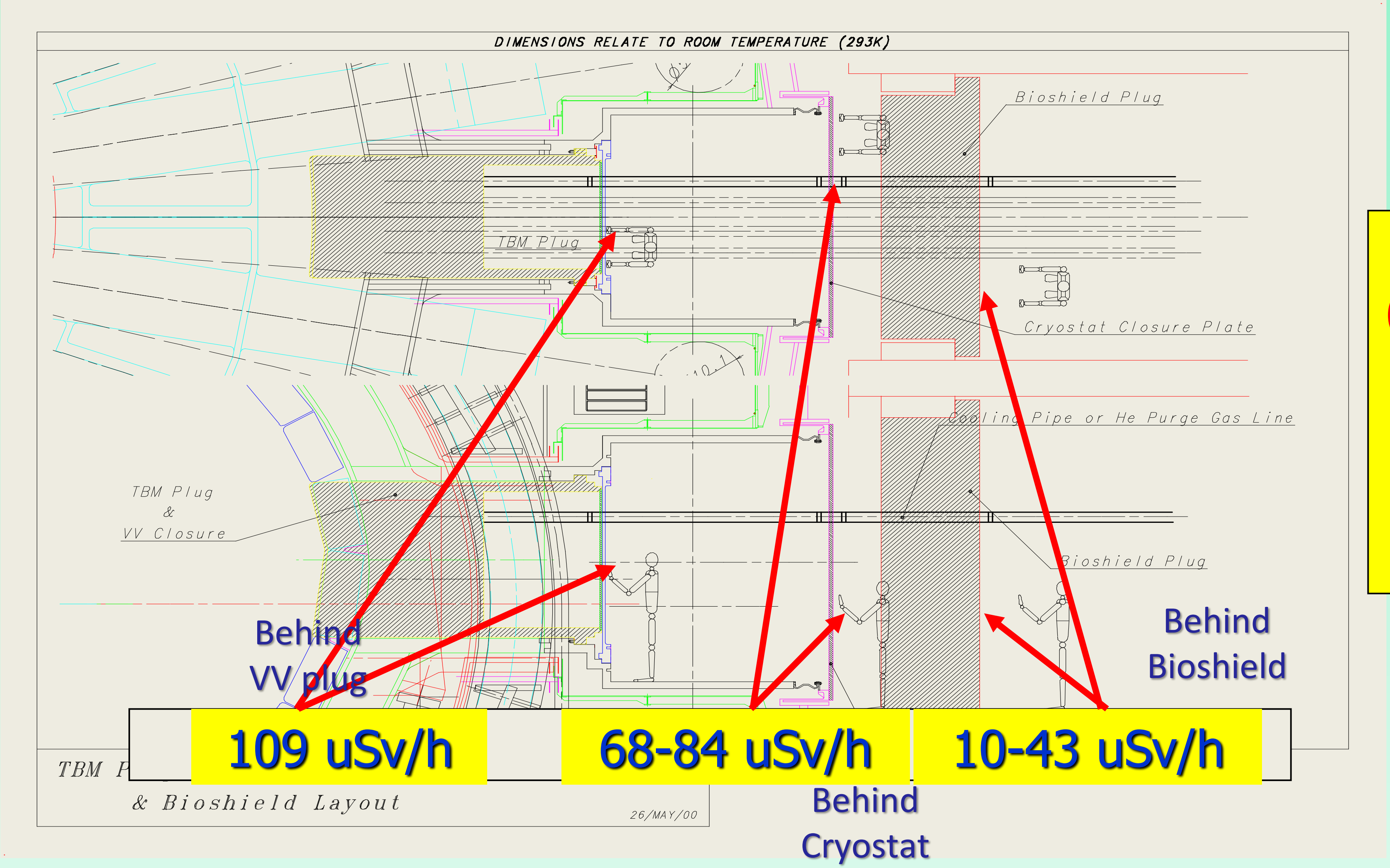

total ORE (collective dose) for each tokamak port:
9,43 person-mSv

Dose Rates for WCS Components

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5 days after shutdown at end of life [μSv/h]

System-Component	At 30 cm	At 1 m
Heat exchanger	7,4	4,8
Pressurizer	2,3	0,8
Pumps	2,5 – 8,1	1,1 – 3,1
Heater	3,8	1,4
Valves, welds and pipes	2,3	1,1

Individual dose after design basis accidents in ITER

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Individual dose objective set for ITER worker following an accident: ≤ 10 mSv.

The radiological consequences of an accident are assessed for the personnel likely to be present at the time of the accident concerned

The scenarios studied take account of the following conservative hypotheses:

- detritiation system operation within 5 minutes of detection signals requiring startup,
- personnel may be present in the building at the time of the accident and evacuate the location within 10 minutes after detection of the accident,
- possibility of returning to a safe state without the presence of personnel.

Accident scenarios (ITER design basis accidents)	**Max effective dose to a worker [mSv]**
Simultaneous rupture of a helium cooling line and of the cryogenic distillation columns	0,54
Simultaneous rupture of a fuelling line and of the second confinement barrier	0,43
Double ended guillotine break in the local air cooler (LAC) duct	0,90
Leak of high activity tritium in the Tritium Building	0,20
Accidental opening of the largest opening in a glove box	0,034

Collective dose assessment

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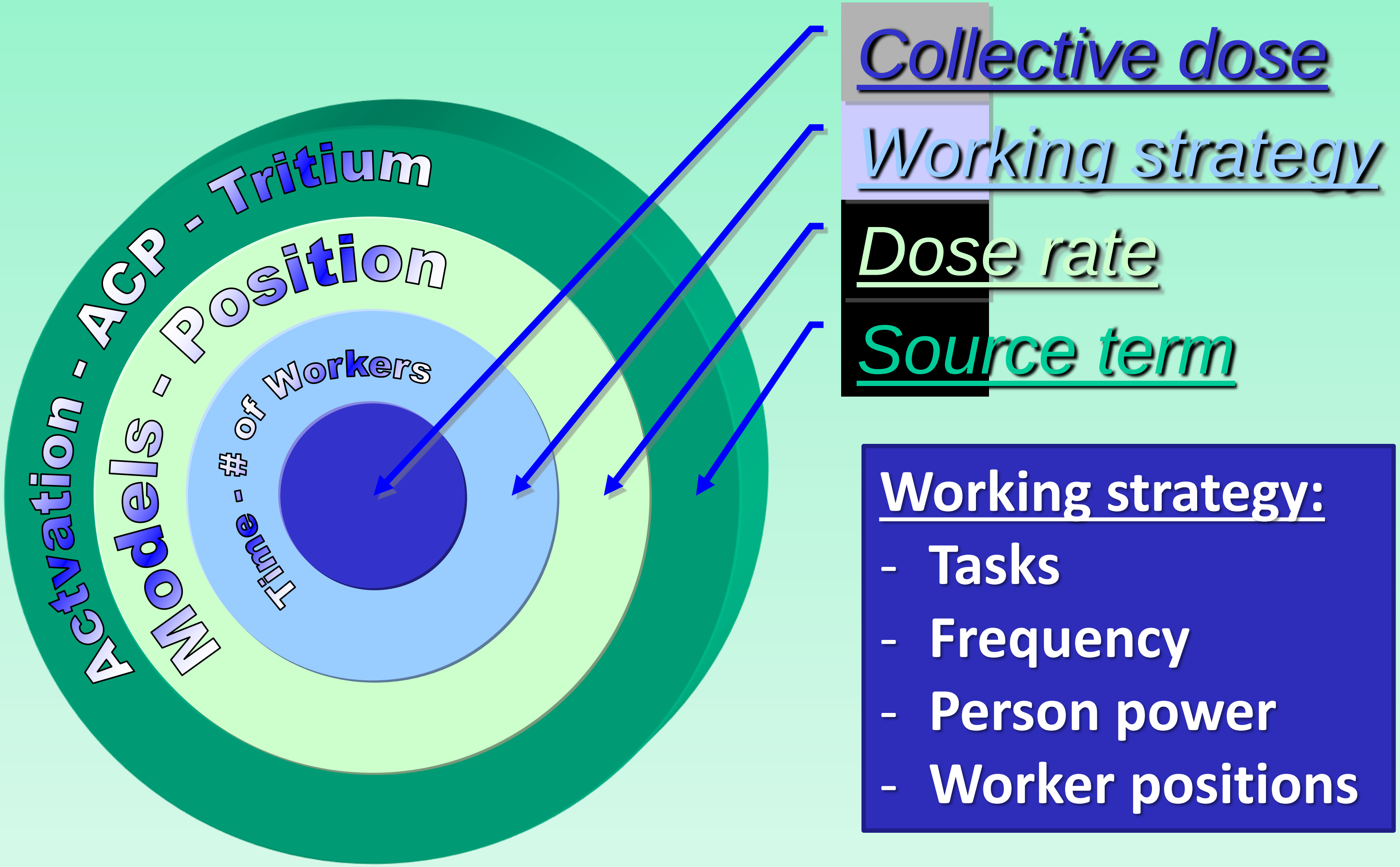
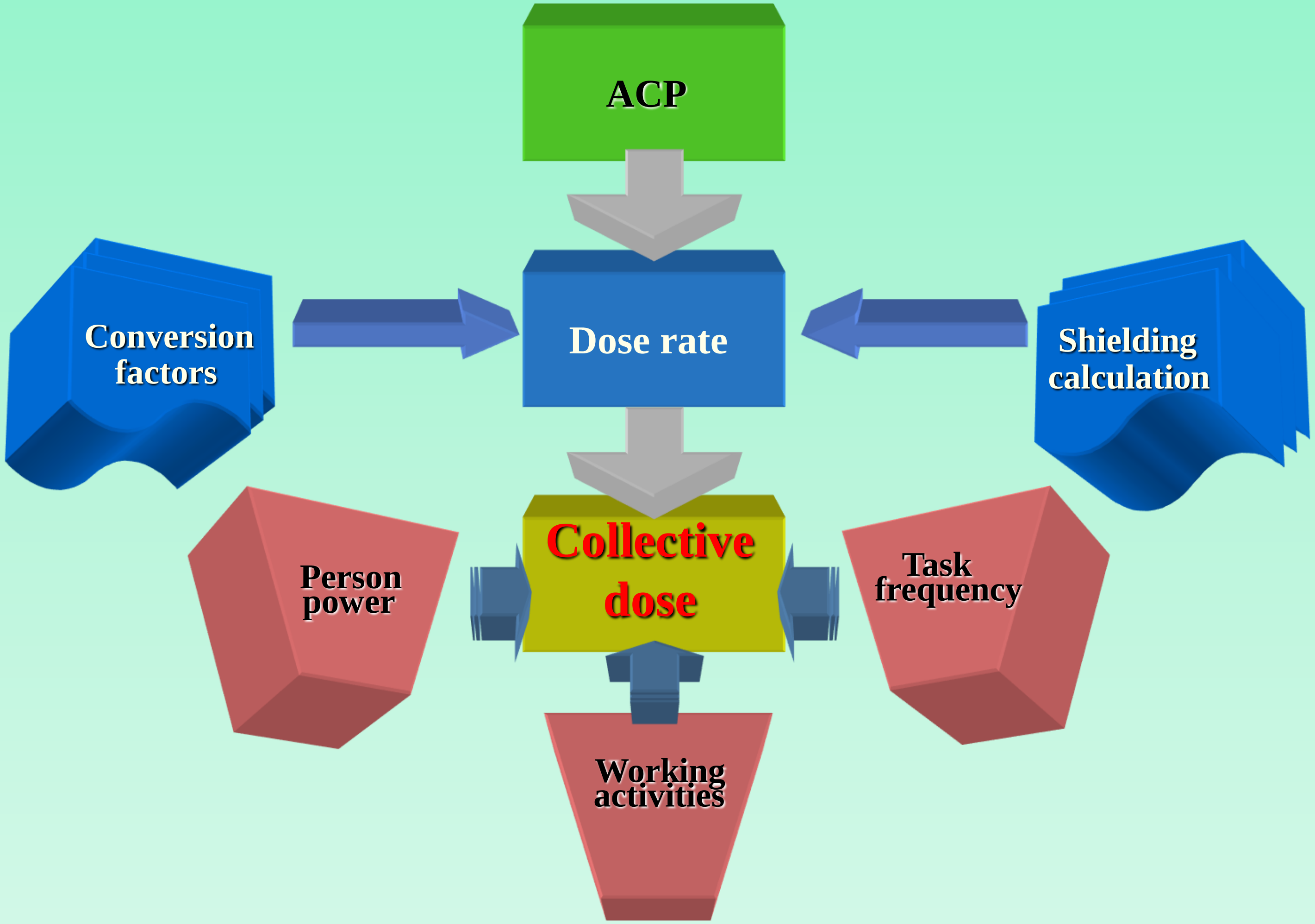


Working strategy:
- Tasks
- Frequency
- Person power
- Worker positions

ACP collective dose assessment



WCS ORE for ITER-FEAT

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	Occupational Radiation Exposure due to				
	Airborne Tritium (Pers. mSv/y)	ACP (Pers. mSv/y)	Surveillance (5% of total) (Pers. mSv/y)	RP survey (10% of total) (Pers. mSv/y)	Total ORE (Pers. mSv/y)
PFW/BLK	2,08E+01	8,96E+00	1,57E+00	3,31E+00	3,47E+01
DIV	8,42E+00	6,89E+00	8,05E-01	1,70E+00	1,78E+01
NBI	8,90E+00	4,98E+00	7,32E-01	1,54E+00	1,62E+01
Total	3,81E+01	2,08E+01	3,11E+00	6,56E+00	6,87E+01

Collective dose for RH assistance

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System	Annual collective dose [pers-mSv/y]	% of total
Blanket and limiter maintenance and replacement	27,40	13,97
Divertor full repair and replacement	4,34	2,21
Divertor partial repair and replacement	2,00	1,02
Roughing pumps	TBD	TBD
Cryopumps	5,93	3,02
Pellet injector	TBD	TBD
Gas injection and wall conditioning	0,00	0,00
Ion Cyclotron Heating	31,00	15,80
Electron Cyclotron Heating	125,90	64,17
TOTAL	196,57	100,00

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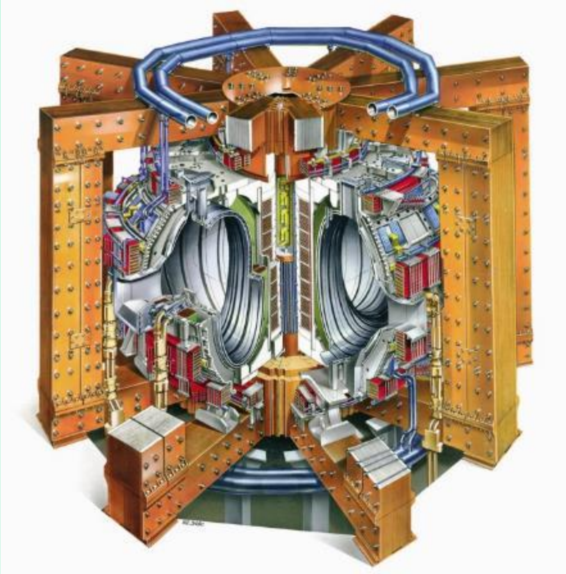
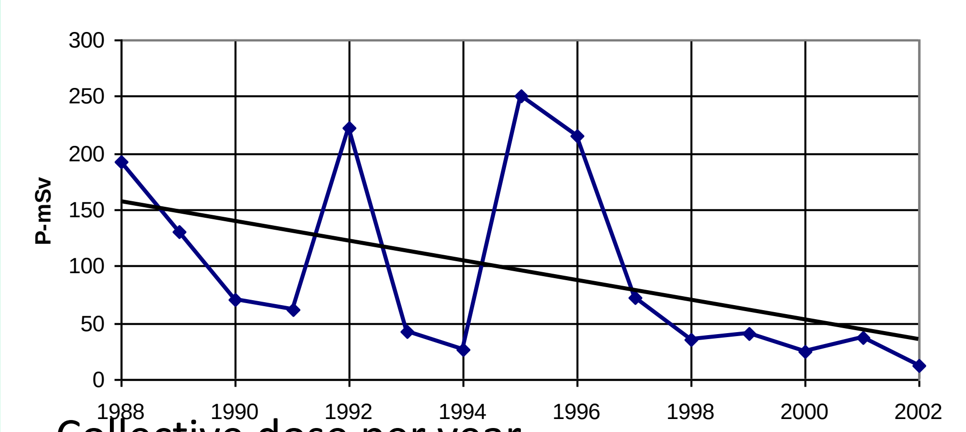
Collective dose at JET

In an experimental facility like JET the variability in the periodic shutdown time affects the annual worker doses

Anyway the Collective dose analysis at JET showed that although shutdown time has been in a slight upward trend, annual worker dose has been in a general downward trend

The reason is that collective doses during the years have been relatively low





Collective dose per year

Collective dose at NPPs

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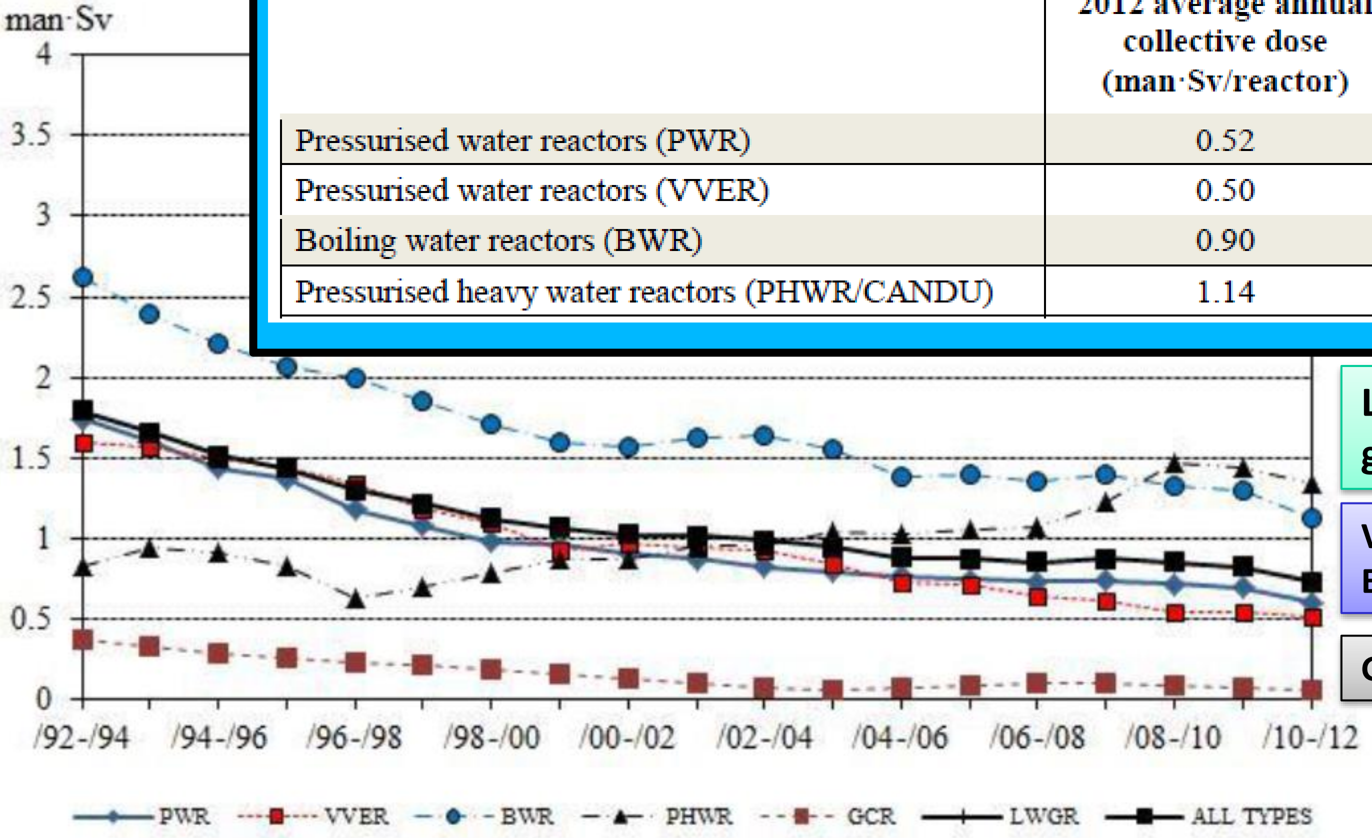
From ISOE: Information System on Occupational Exposure

NEA/CRPPH/ISOE(2012)8

3-year rolling average collective dose per reactor for all operating reactors included in ISOE by reactor type, 1992-2012 (man·Sv/reactor)



	2012 average annual collective dose (man·Sv/reactor)	3-year rolling average for 2010-2012 (man·Sv/reactor)
Pressurised water reactors (PWR)	0.52	0.60
Pressurised water reactors (VVER)	0.50	0.51
Boiling water reactors (BWR)	0.90	1.12
Pressurised heavy water reactors (PHWR/CANDU)	1.14	1.34

LWGR: light water cooled grahite moderated

VVER: Water-Water Energetic Reactor, or **WWER**

GCR: gas-cooled reactor

European DEMO goals

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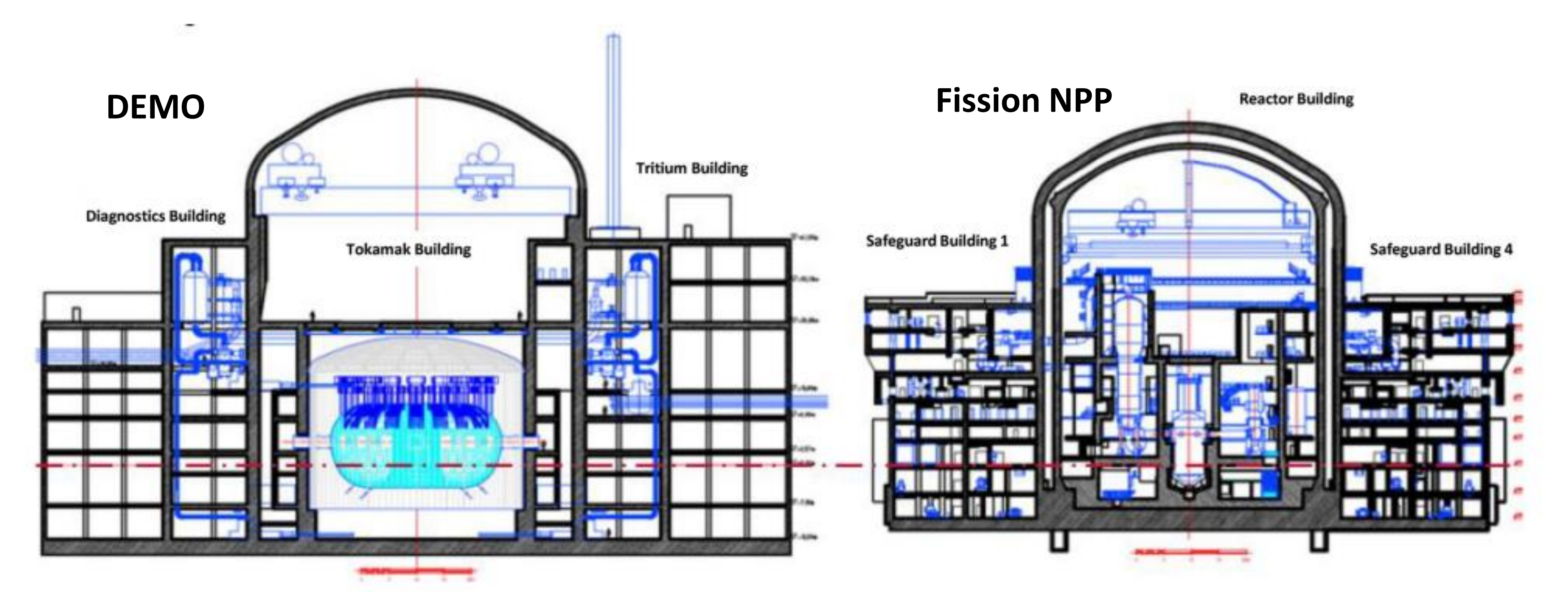
Conversion of fusion heat into electricity (~500 MWe)
Achieve tritium self-sufficiency (TBR > 1)
Reasonable availability/Several full power years

Minimize activation waste, no long-term storage
DEMO as a component test facility and pathfinder to a First-of-a-Kind (FoaK) Fusion Power Plant (FPP).

Lack of specific goals for individual worker's doses but for the collective dose maximum value of 700 p-mSv/y



DEMO will use low activation materials

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Special steels

es.: EUROFER, F82H

Cr 9% - W V Ta (Ni<0.001%)

T 250-550°C

Other advanced materials:

SiC_f/SiC

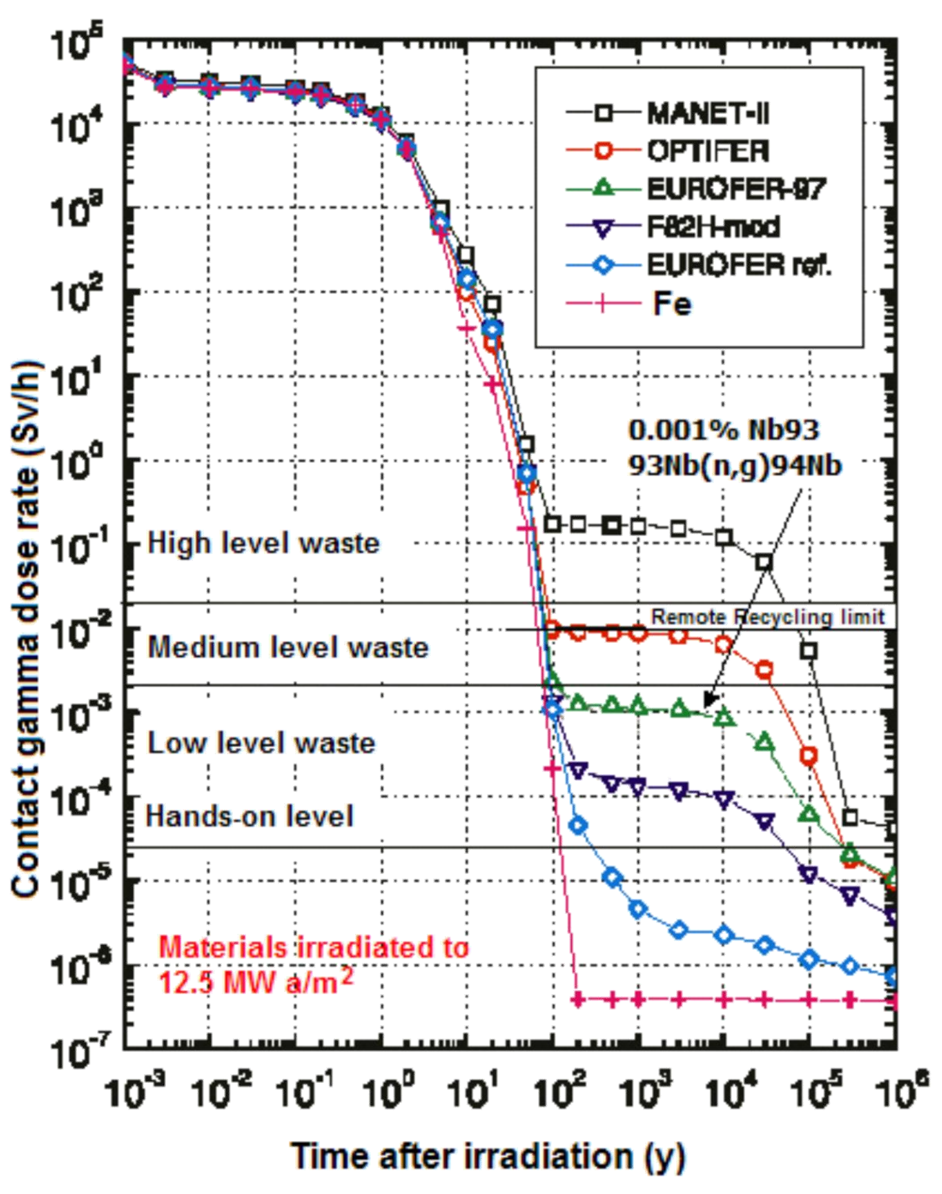
T → ~ 1000°C

V, V-4Cr-4Ti

T → ~ 550°C

W, W–La2O3

PFC T → 2000 °C



DEMO safety approach

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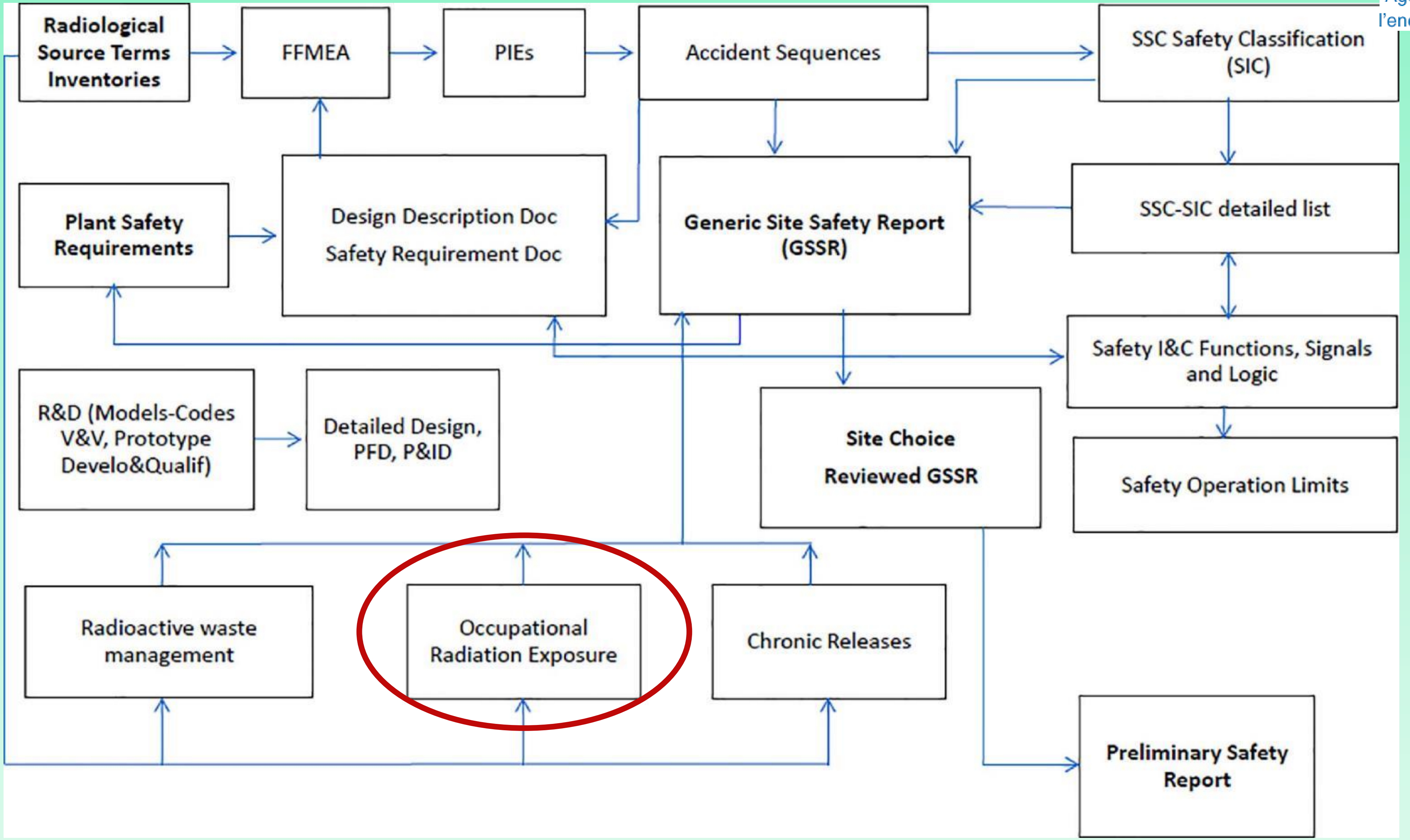

The DEMO’s low relibility demands frequent maintenance activities

- Recent studies confirmed the high number of anticipated yearly failure events requiring the stop of the DEMO reactor.
- Such reactor shutdown could be overcome with corrective maintenance that could be done in the order of a relative short time of outage
- In general, between 3 days and 2 months, but the higher frequency of events between 3 days and 2 weeks

Fast but frequent maintenance activities, are important source of radiological exposure for workers

Radiological zoning scheme for DEMO

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<table>
<tr><th colspan="2">Zone type</th><th>Zone identification</th><th>Maximum total effective dose (external plus internal)</th><th>Maximum external dose to hands, forearms, ankles and feet</th></tr>
<tr><td colspan="2">Unregulated</td><td>White</td><td>80 μSv/month</td><td></td></tr>
<tr><td colspan="2">Supervised</td><td>Blue</td><td>7.5 μSv/hr</td><td>200 μSv/hr</td></tr>
<tr><td rowspan="4">Controlled</td><td>Limited</td><td>Green</td><td>25 μSv/hr</td><td>650 μSv/hr</td></tr>
<tr><td>Specially regulated</td><td>Yellow</td><td>2 mSv/hr</td><td>50 mSv/hr</td></tr>
<tr><td rowspan="2">Forbidden without specific authorization</td><td>Orange</td><td>100 mSv/hr</td><td>2.5 Sv/hr</td></tr>
<tr><td>Red</td><td>above 100 mSv/hr</td><td>above 2.5 Sv//hr</td></tr>
</table>

Map of doses around DEMO

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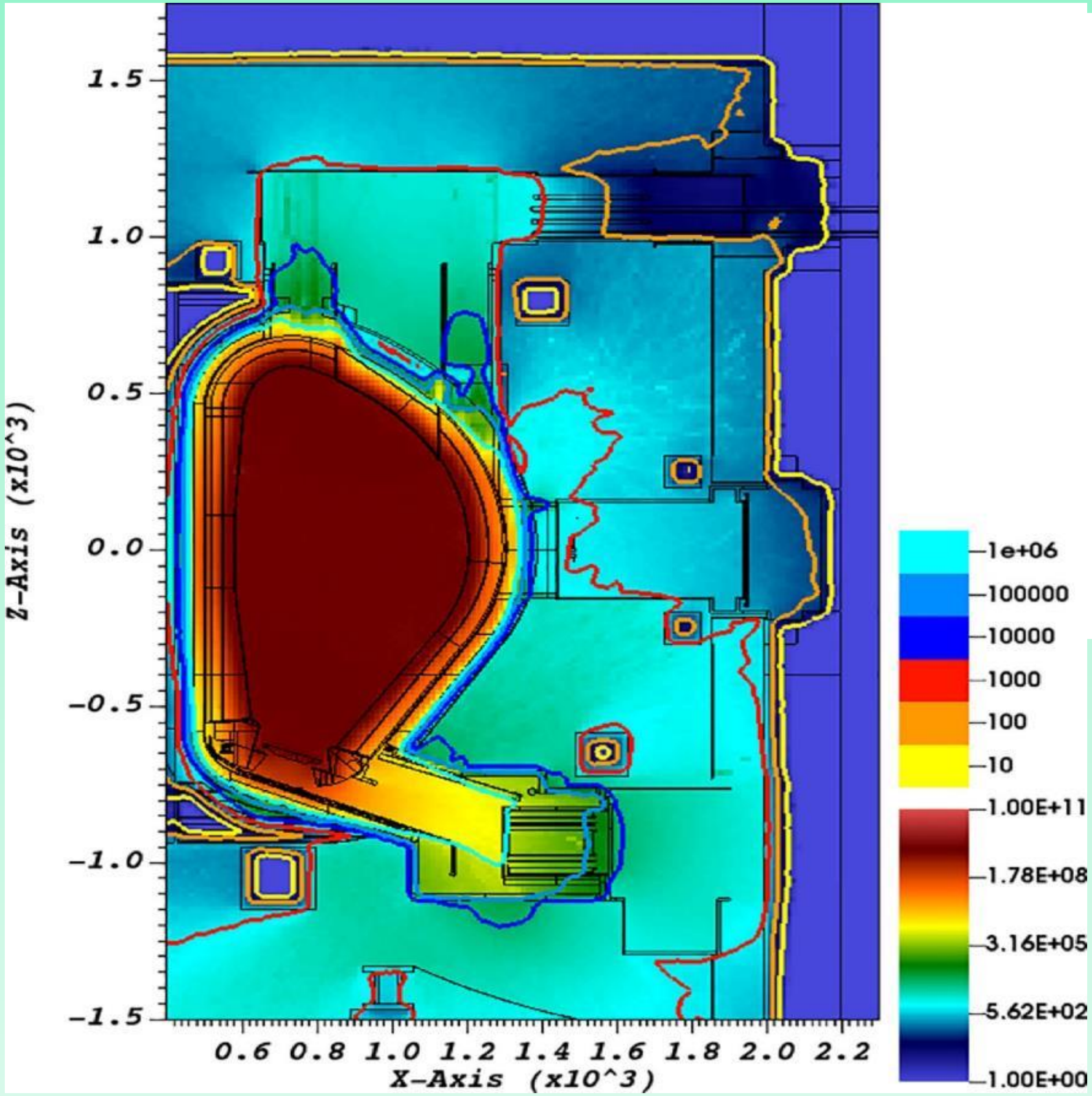

Provisional biological Shutdown Dose Rates (SDDR) [μSv/h] in Helium Cooled Pebble Bed (HCPB) DEMO after end of life (EOL) operation and 12 days cooling with prospective shielding improvements (upper color scale for isolines, lower color scale for dose mapping)

Typically, the target of 10 μSv/h after 1-day cooling is not fulfilled inside rooms with active loop components

The individual doses after accidents for DEMO workers

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- The analysis are still under way
- The anticipated results show a situation similar to that of ITER
- The objective set for DEMO worker following an accident is the same as that of ITER: ≤ 10 mSv.

THANK YOU

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