FISPACT-II

Waste Assessment of Fusion Steels

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FISPACT-II workshop

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Radioactive Waste and Fusion

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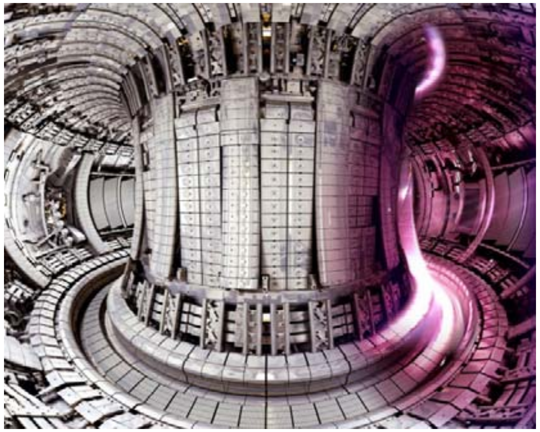

- Current Public perception is that fusion is a source of abundant clean nuclear energy.
- Fission power plants can produce extremely long lived and highly active waste. Particularly true of spent fuel.
- Fusion power plants won't produce radioactive waste right?

- Currently planned Fusion reactors will use Deuterium-Tritium (DT) reactions to generate energy.

$$^2H + ^3H \rightarrow ^4He + n$$

- Most of the energy carried by the neutron, which will impinge on to the plasma housing causing activation.
- Leaving radioactive waste at reactor end of life. For the DEMO reactor this could be on the order of 1000kgs

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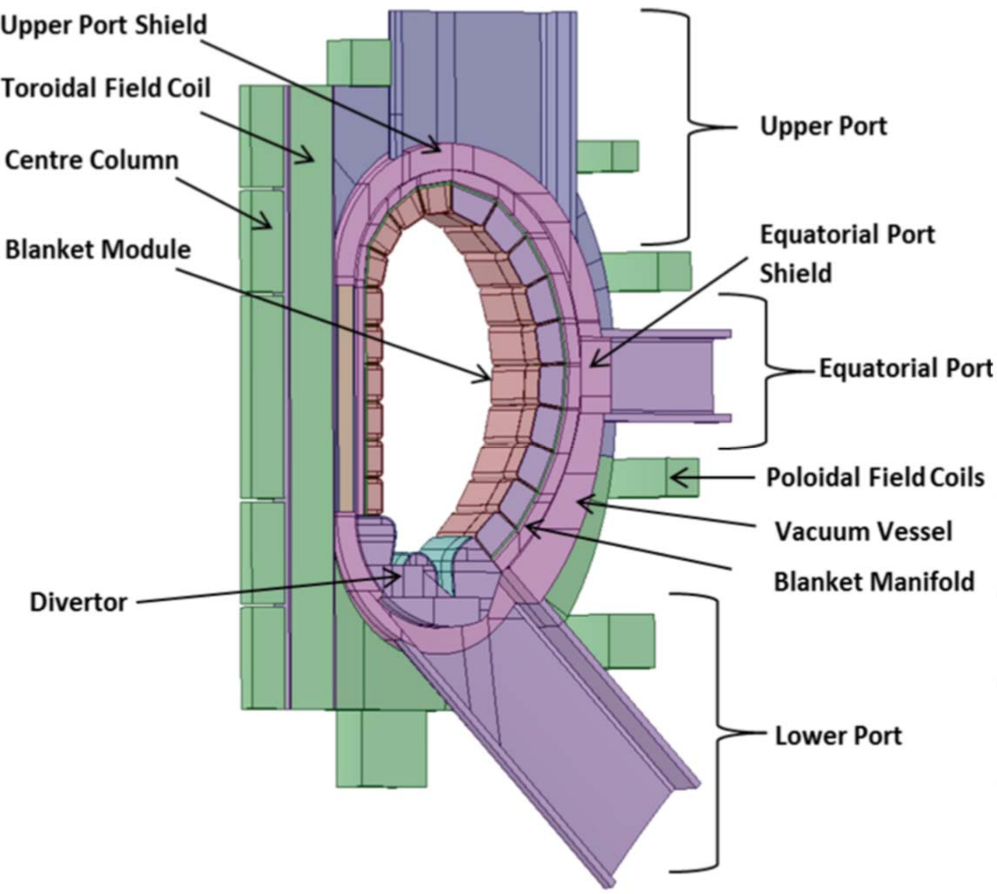
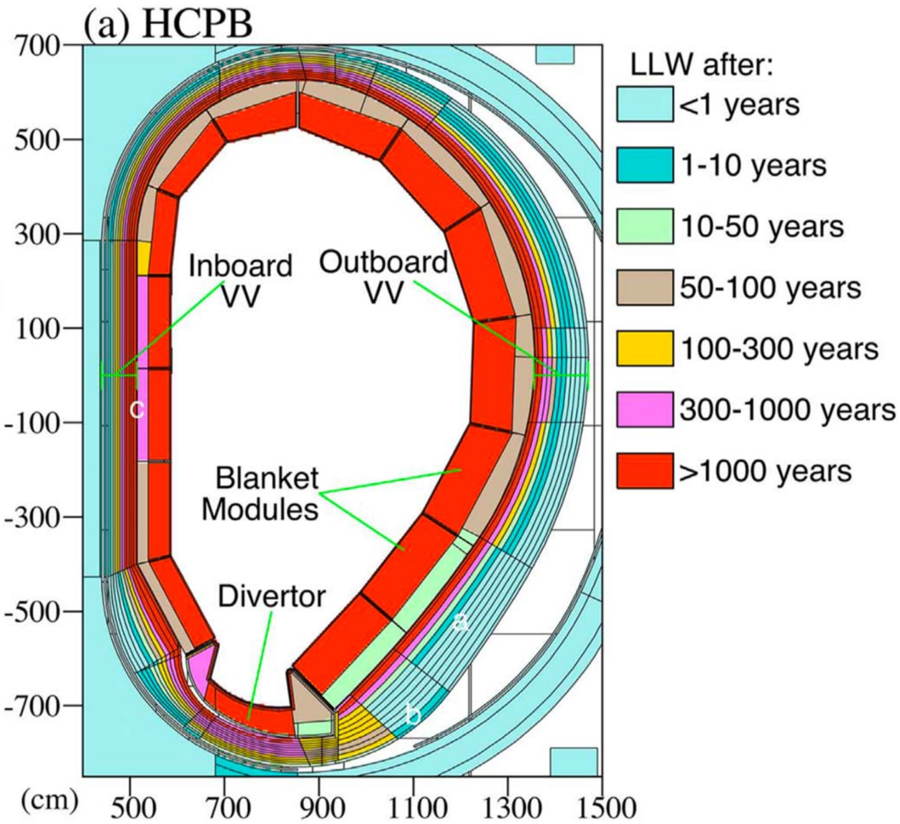
Current Waste Expectations for DEMO

- FISPACT-II simulations suggest that near-plasma components will fail to be Low Level Waste (LLW) for over 1000 years!





Waste Expectations for Fusion

- DEMO's Blanket and Vacuum Vessel are not expected to be called Low Level waste, by UK and IAEA standards, for over 1000 years, will this be true for all fusion plants?

- What if different materials are used? DEMO is using the steels Eurofer and SS316.

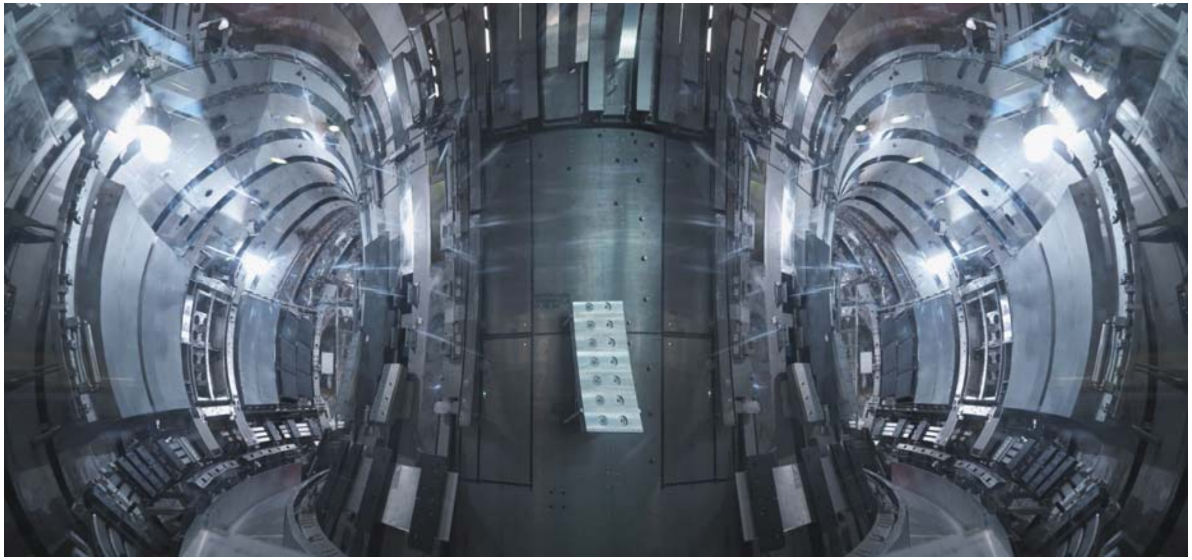
European Developed Reduced Activation(RA) Steel

Traditional Stainless Steel

- Other possibilities

RA steels
- Hiperfer
- CLAM
- F82H
- …

Stainless steels
- XM19
- Inconel 718
- T91
- …



Waste Expectations for Fusion

- **What is Low Level Waste really? Near Surface but what else?**
- Different countries have differing definitions of what classes as Low Level waste, so which one should be used?

Activity Source	**UK** (Bqg^{-1})	**Spain** (Bqg^{-1})	**Japan** (Bqg^{-1})	**Russia** (Bqm^{-3})	**US** (Bqm^{-3})
$^{3}\mathbf{H}$	-	1×10^{6}	-	1×10^{8} (Bqg^{-1})	1.48×10^{12}
$^{14}\mathbf{C}$	-	2×10^{5}	1×10^{10}	3×10^{12}	2.96×10^{12}
$^{94}\mathbf{Nb}$	-	1.2×10^{2}	-	7.4×10^{9}	7.4×10^{9}
$^{99}\mathbf{Tc}$	-	1×10^{3}	1×10^{8}	1.1×10^{11}	1.11×10^{11}
α	4×10^{3}	3.7×10^{3}	1×10^{5}	1×10^{3} (Bqg^{-1})	-
$\beta+\gamma$	1.2×10^{4}	3.7×10^{4}	-	$1\times10^{4}(-^{3}H)$ (Bqg^{-1})	-

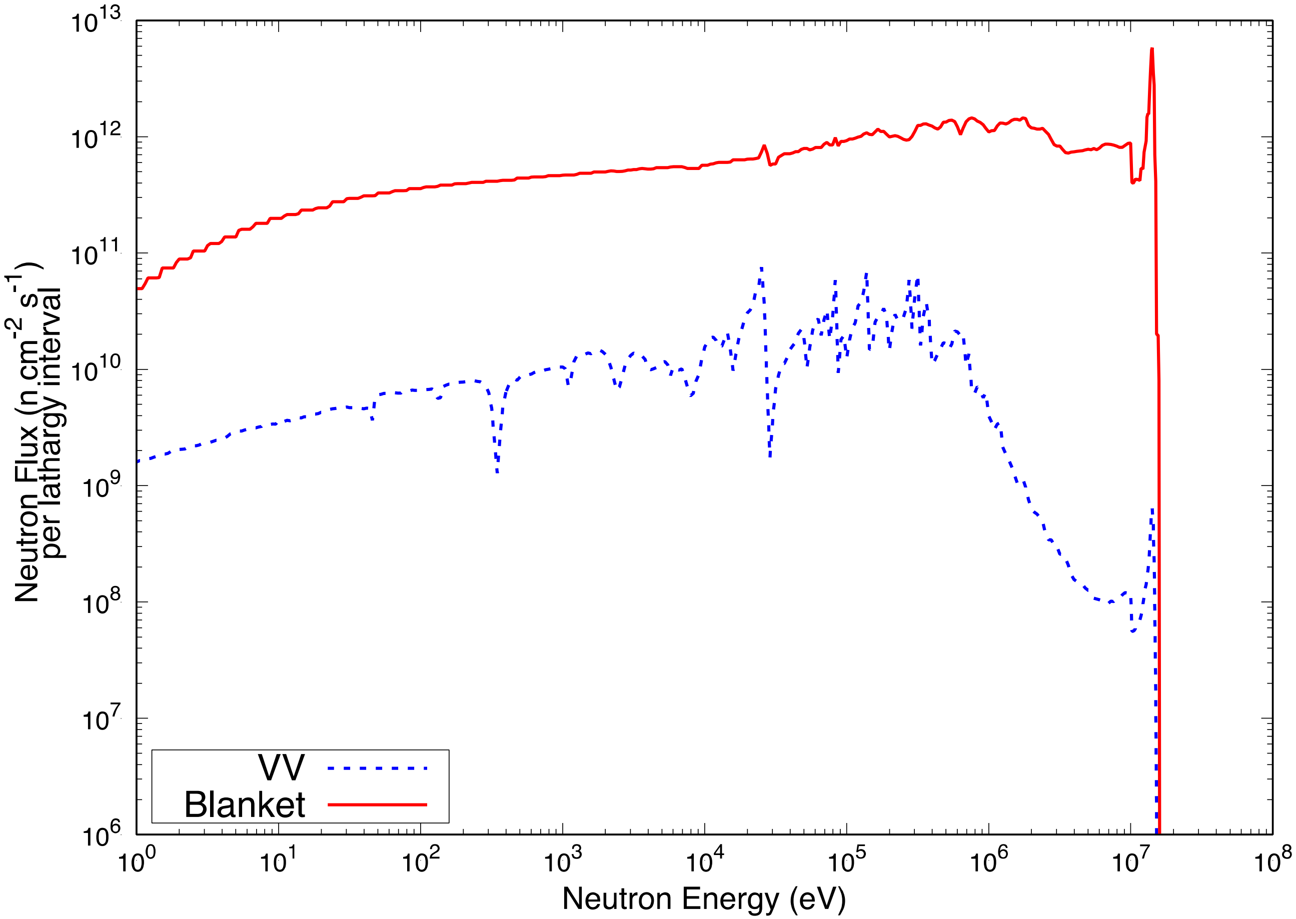
- Countries can include limits on over 100 nuclides in waste criteria. Need to study them all.

- **Analyze FISPACT-II outputs with different criteria to understand classification possibilities.**

Source: U.S. Nuclear Regulatory Commission

FISPACT-II calculations for fusion waste assessments

- Use the DEMO model. It is the closest we have to a commercial fusion plant
- Extract neutron fluxes from Monte Carlo transport calculations .e.g. MCNP



- Performing two sets of calculations.
  - ➢ Blanket
  - ➢ Vacuum Vessel

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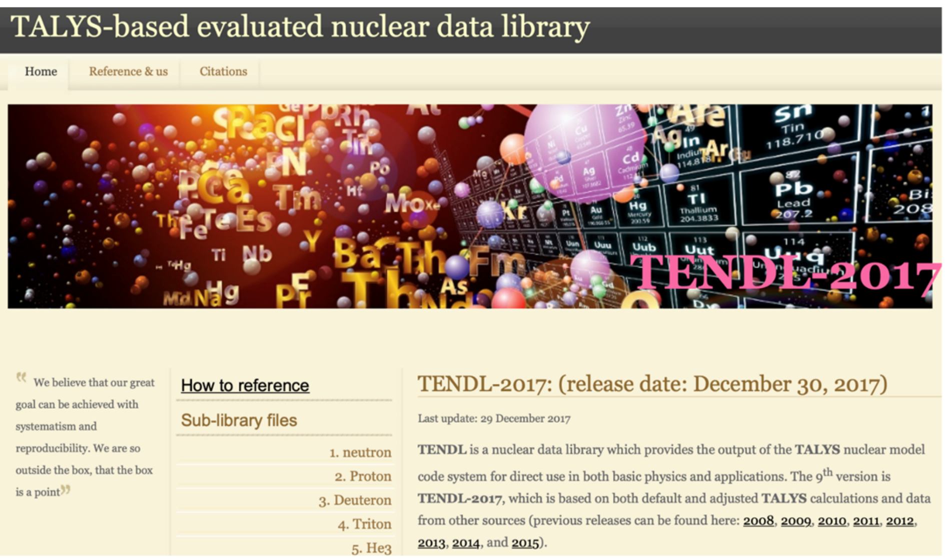
FISPACT-II calculations for fusion waste assessments

Select Nuclear Data set.

➢ Will use TENDL 2017, contains about 2800 isotopes and uses 709 group structure.




```
# index of nuclides to be included
ind_nuc  /opt/fispact/nuclear_data/TENDL2017data/tendl17_decay12_index

# Library cross section data
xs_endf /opt/fispact/nuclear_data/TENDL2017data/tal2017-n/gxs-709

# Library probability tables for self-shielding
prob_tab  /opt/fispact/nuclear_data/TENDL2017data/tal2017-n/tp-709-294

#fluxes
fluxes  fluxes
```

FISPACT-II calculations for fusion waste assessments

- Create input file for each steel studied.
- Studying 1kg of steel under DEMO conditions

Steel
Eurofer
Hiperfer
Rusfer
CLAM
F82H
XM19
Inconel 718
SS316
Steel 660
ASTM G91 T1
ASTM G91 T2
T91-DEMO

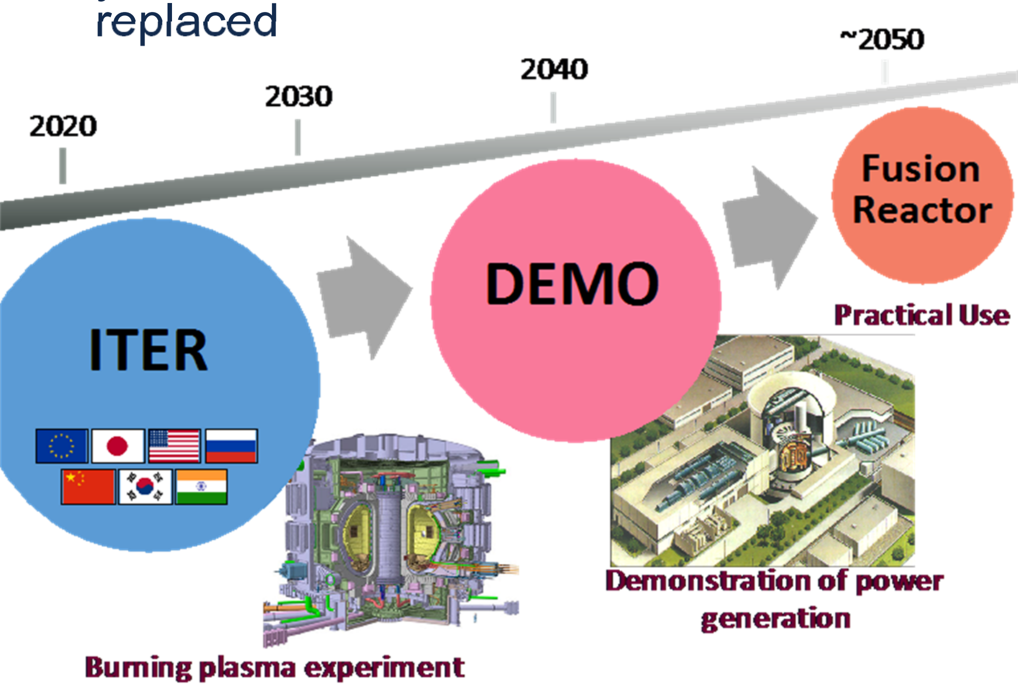
RA steels


```
DENSITY  7.9
FUEL 57
Fe54 5.5986142E+23
Fe56 8.7886269E+24
Fe57 2.0296772E+23
Fe58 2.7011278E+22
B10 1.1028313E+20
B11 4.4670238E+20
C12 5.2060516E+22
C13 5.8435810E+20
N14 1.7134914E+22
N15 6.2944161E+19
O16 3.7550434E+20
O17 1.4303206E+17
O18 7.5280034E+17
Al27 8.9277948E+20
Si28 5.1418120E+21
Si29 2.6107671E+20
Si30 1.7209990E+20
P31 3.8885435E+20
S32 5.3538258E+20
S33 4.2258149E+18
S34 2.3720908E+19
S36 1.1268840E+17
Ti46 1.0379370E+19
Ti47 9.3603041E+18
Ti48 9.2747530E+19
Ti49 6.8063502E+18
Ti50 6.5169859E+18
V50 5.9108439E+19
V51 2.3584267E+22
Cr50 4.5290826E+22
Cr52 8.7338850E+23
Cr53 9.9035245E+22
Cr54 2.4651969E+22
Mn55 6.0289324E+22
Co59 5.1092946E+20
Ni58 6.9849353E+20
Ni60 2.6905703E+20
Ni61 1.1696794E+19
Ni62 3.7286095E+19
Ni64 9.5010797E+18
Cu63 1.9665464E+20
Cu65 8.7651618E+19
Nb93 1.2963892E+20
Mo92 2.7947682E+19
Mo94 1.7420220E+19
Mo95 2.9981611E+19
Mo96 3.1412894E+19
Mo97 1.7985200E+19
Mo98 4.5443233E+19
Mo100 1.8135861E+19
Ta180 4.7924757E+17
Ta181 3.9932505E+21
W180 4.3239498E+19
W182 9.5487224E+21
W183 5.1563101E+21
W184 1.1040485E+22
W186 1.0244158E+22
```

Example: Eurofer's Complex composition

FISPACT-II calculations for fusion waste assessments

- Set Irradiation and Cooling Schedules
- DEMO is planned to operate for over 20 years, the Vacuum Vessel will not be replaced



DEMO aim : Waste to be ‘Low Level’ 100 years after reactor End of Life

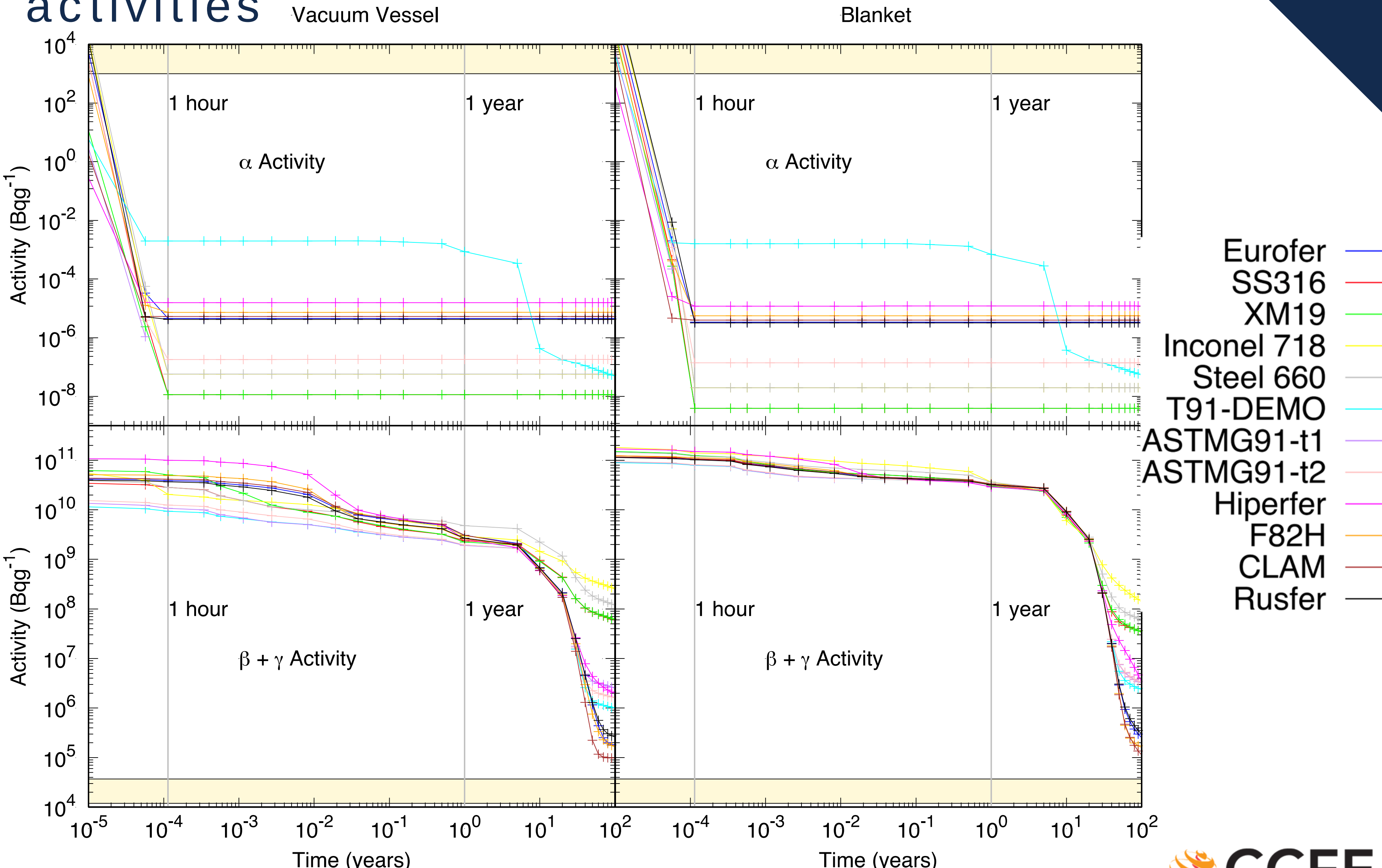
- Sample should be allowed to cool for up to 1000 years

```
PULSE 10
FLUX 7.47205E+13
TIME 179.19 DAYS
ATOMS
ENDPULSE
PULSE 48
FLUX 0.00000E+00
TIME 1 HOURS
ATOMS
FLUX 2.49068E+14
TIME 4 HOURS
ATOMS
ENDPULSE
FLUX 0.00000E+00
PULSE 10
TIME 24.35 DAYS
ATOMS
ENDPULSE
PULSE 10
FLUX 7.47205E+13
TIME 179.19 DAYS
ATOMS
ENDPULSE
PULSE 48
FLUX 0.00000E+00
TIME 1 HOURS
ATOMS
```

Need to account for maintenance shutdown periods.

Need short pulses to ensure short lived nuclide populations are reproduced correctly.

Results from FISPACT-II: total α and $\beta + \gamma$ activities



Results from FISPACT-II: total α and $\beta+\gamma$ activities

Activity Source	UK (Bqg^{-1})	Spain (Bqg^{-1})	Japan (Bqg^{-1})	Russia (Bqm^{-3})	US (Bqm^{-3})
^{3}H	-	1×10^{6}	-	1×10^{8} (Bqg^{-1})	1.48×10^{12}
^{14}C	-	2×10^{5}	1×10^{10}	3×10^{12}	2.96×10^{12}
^{94}Nb	-	1.2×10^{2}	-	7.4×10^{9}	7.4×10^{9}
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α	4×10^{3}	3.7×10^{3}	1×10^{5}	1×10^{3} (Bqg^{-1})	-
$\beta+\gamma$	1.2×10^{4}	3.7×10^{4}	-	$1\times10^{4}(-{}^{3}$H) (Bqg^{-1})	-

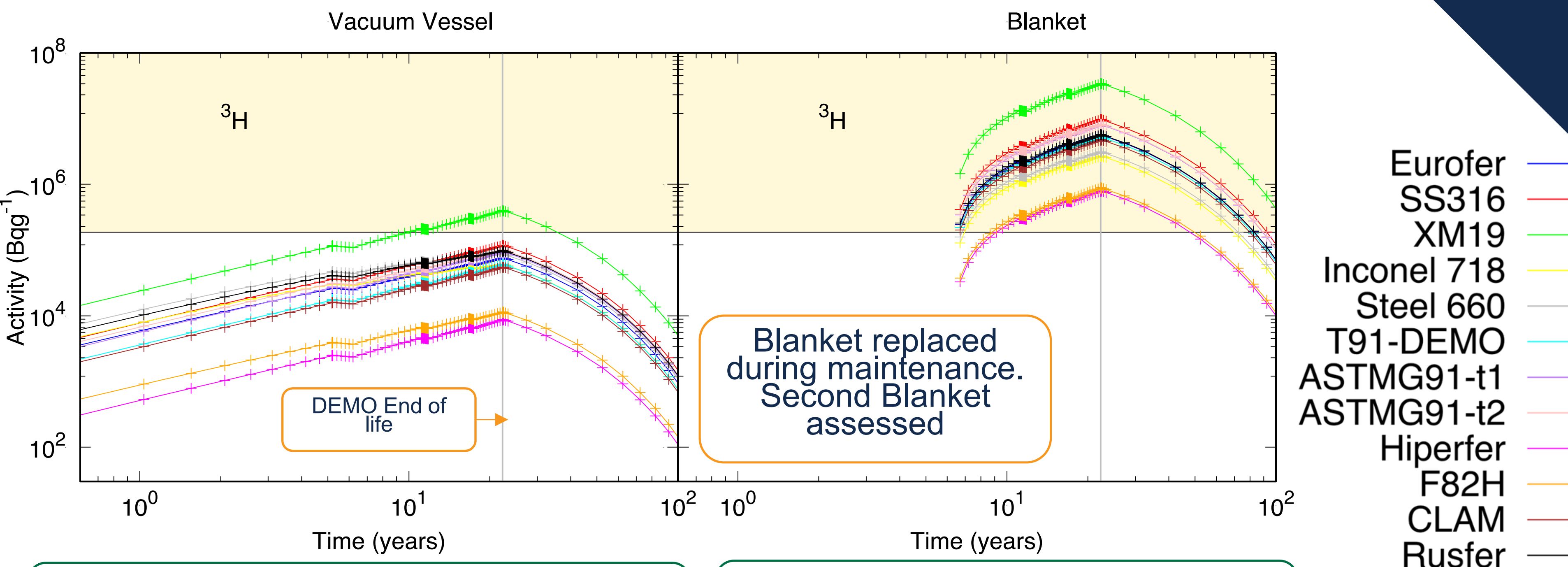
Need tritium activity for Russian limit

- All steels meet these limits
- α emitters are not a large contributor to activated fusion waste

- All steels breech these limits
- β emitters are a large problem

Conclusion : None of the Steels studied can be called Low Level under UK or Spanish criteria

Results from FISPACT-II: Tritium Activity



All steels meet tritium requirements in Vacuum Vessel

Only XM19 fails to meet tritium criteria in Blanket

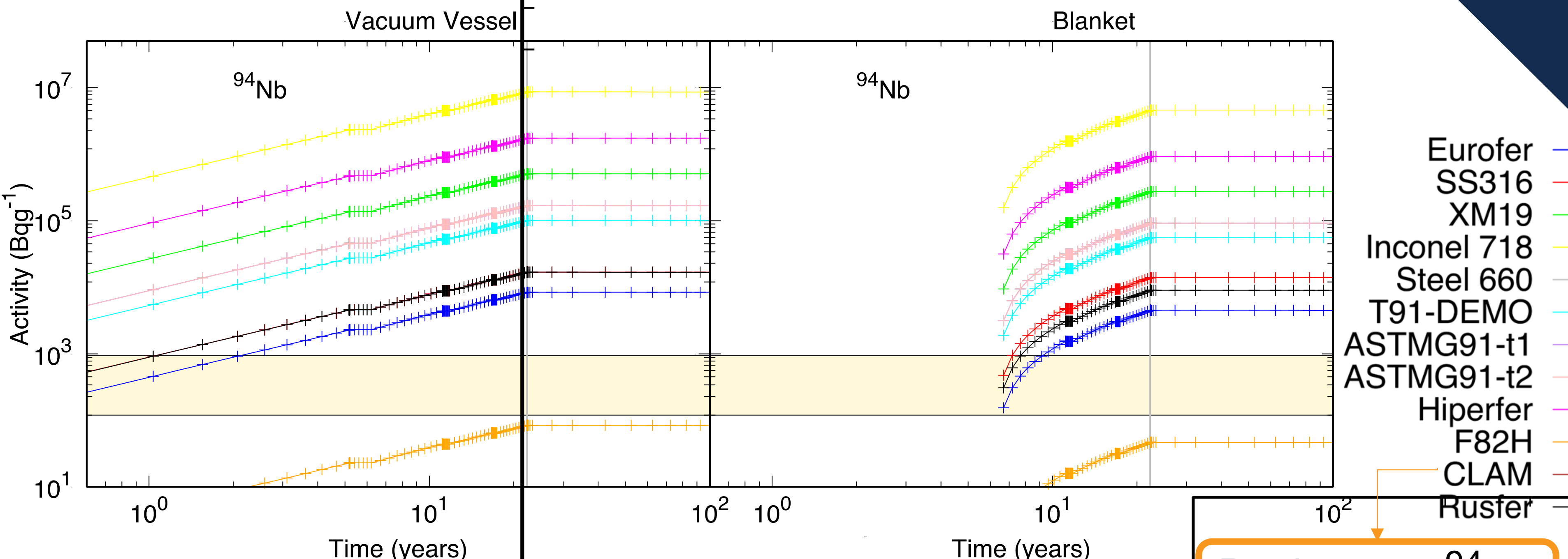
$$\beta + \gamma \leq 1\times10^4(-{}^3\mathrm{H})$$

After 100 years:

$$\beta + \gamma \approx 10^5\ \mathrm{Bqg}^{-1}$$

Conclusion : None of the Steels studied can be called Low Level under Russian criteria

Results from FISPACT-II: ^{94}Nb Activity



Produces no ^{94}Nb

F82H and CLAM meet all ^{94}Nb limits

Most steels fail to meet required criteria

Conclusion : Only two steels studied could possibly be Low Level under US criteria

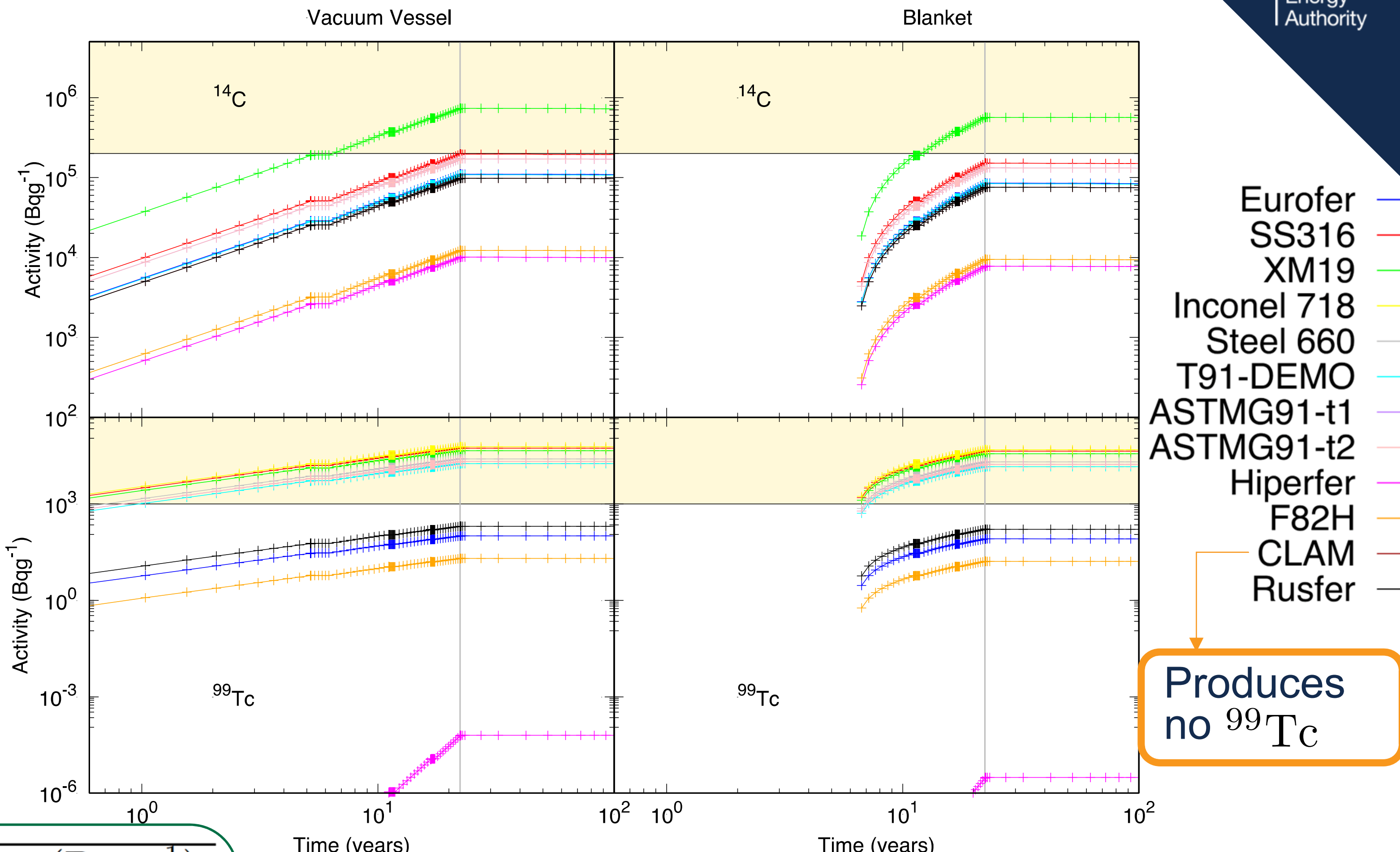
Results from FISPACT-II: ^{99}Tc and ^{14}C

^{14}C

All steels but XM19 meet requirements

^{99}Tc

All RA steels meet requirements



Produces no ^{99}Tc

Japan $(\mathrm{Bqg^{-1}})$
-
1×10^{10} ^{14}C
-
1×10^{8} ^{99}Tc

Conclusion : All of the Steels could possibly be Low Level under Japanese criteria

Results from FISPACT-II: Final Waste Classification after 100 years

- Full waste criteria used to assess possible classifications
- All steels show the same classification behavior in the Blanket and Vacuum Vessel

No steel can be low level under UK, Spanish or Russian criteria.

All steels can be low level under Japanese criteria.

Steel	UK	Spain	Japan	Russia	US
Eurofer	Not LLW	Not LLW	LLW	Not LLW	Not LLW
Hiperfer	Not LLW	Not LLW	LLW	Not LLW	Not LLW
Rusfer	Not LLW	Not LLW	LLW	Not LLW	Not LLW
CLAM	Not LLW	Not LLW	LLW	Not LLW	LLW
F82H	Not LLW	Not LLW	LLW	Not LLW	LLW
XM19	Not LLW	Not LLW	LLW	Not LLW	Not LLW
Inconel 718	Not LLW	Not LLW	LLW	Not LLW	Not LLW
SS316	Not LLW	Not LLW	LLW	Not LLW	Not LLW
Steel 660	Not LLW	Not LLW	LLW	Not LLW	Not LLW
ASTM G91 T1	Not LLW	Not LLW	LLW	Not LLW	Not LLW
ASTM G91 T2	Not LLW	Not LLW	LLW	Not LLW	Not LLW
T91-DEMO	Not LLW	Not LLW	LLW	Not LLW	Not LLW

F82H and CLAM can be LLW in the US

Fusion Waste Classification: What does it all mean?

Does these results mean current fusion reactors need to make near plasma components from F82H or CLAM and dispose of them only in the US or Japan? **No**.

Not practical to transport waste over large distances.

Definition of Low Level varying across the globe

No single steels will meet a fusion reactors structural requirements

- Near plasma fusion waste should not be expected to be low level 100 years after shut by most international standards.
- It can be expected to be **Intermediate level** waste
- What an be done? Several possibilities:

Change components more regularly to avoid activation

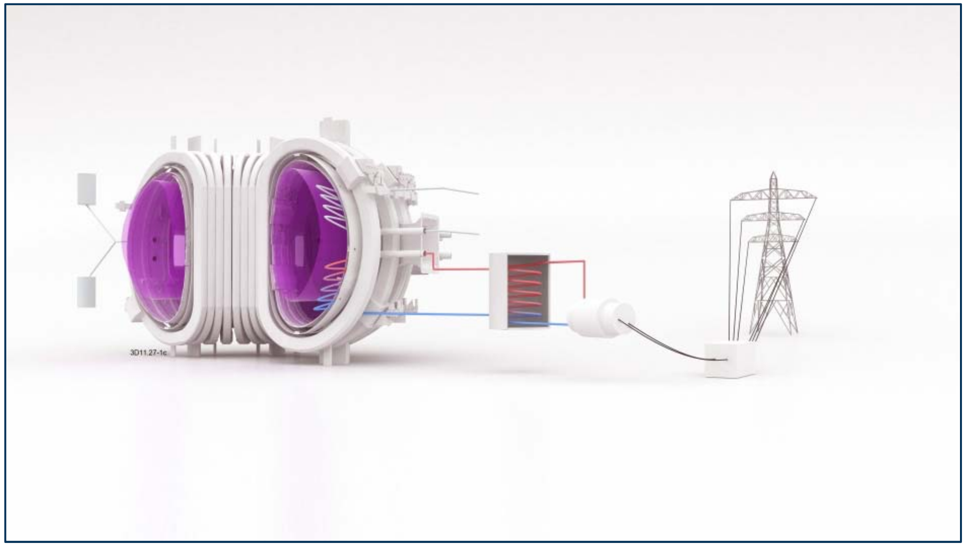
Change reactor running schedule to lower activation

Develop fusion specific waste repositories to ensure consistent disposal

Explore other fusion reactions e.g. aneutronic fusion reactions

Conclusion

- FISPACT-II is a ideal tool for activation analysis and waste classification.
- Straightforward to use for many calculations and is used on projects such as the DEMO fusion reactor.



- Fusion power plants (using DT fusion) will produce activated steel waste from near plasma components. This will be lower activity than that from fission plants.
- Use of currently available low activation materials will not solve this problem

- Fusion specific repositories probably needed for test/1st generation reactors
- Long term solution to fusion waste has yet to be found.

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Thank you for listening.
Now try the exercises

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