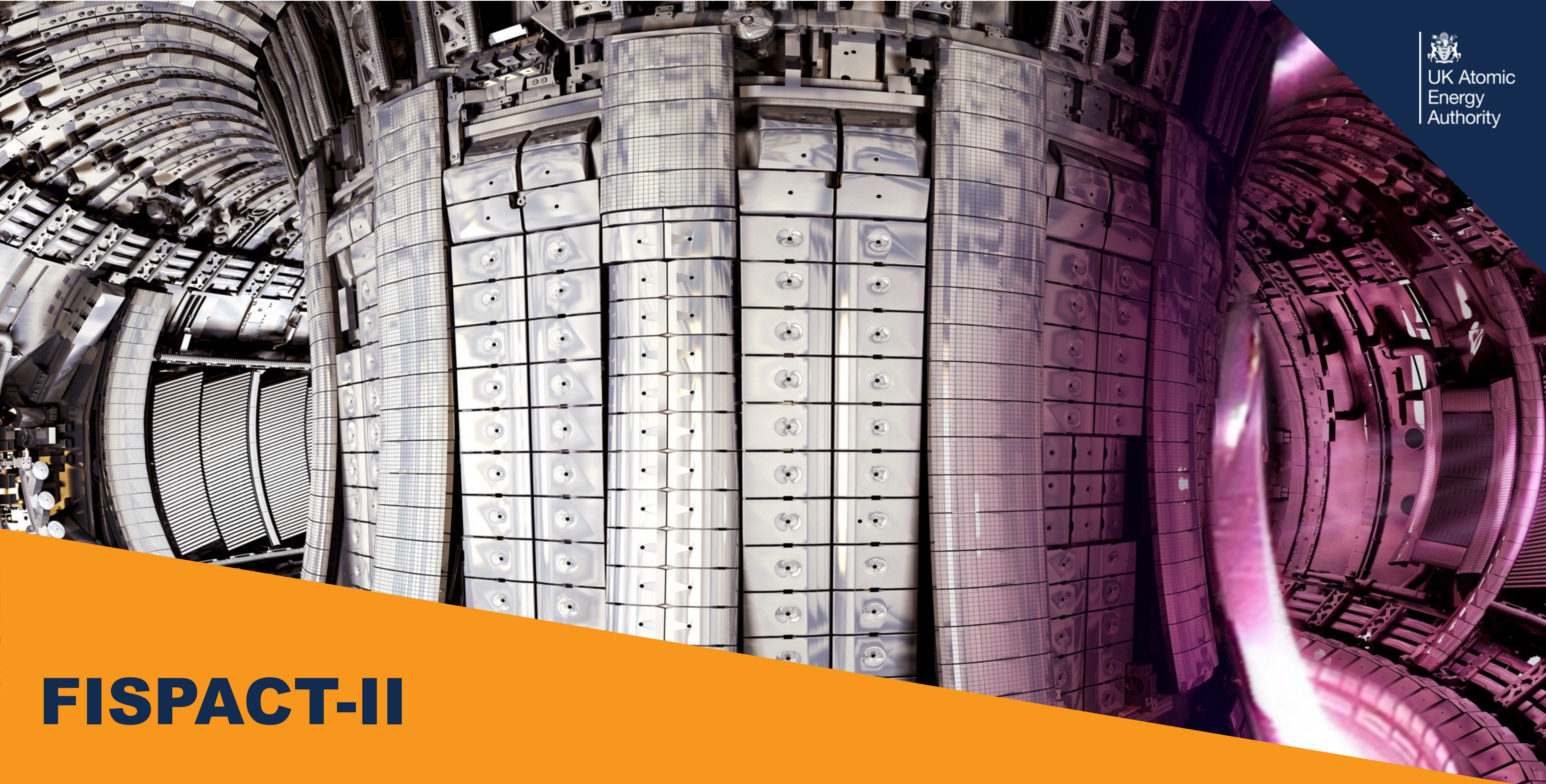

FISPACT-II

Case Study : Waste Assessments

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United Kingdom Atomic Energy Authority

FISPACT-II workshop

Online, November/December 2020

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Overview

1. FISPACT-II and waste assessments
2. Fusion Waste Prospects
   - EU DEMO waste assessments with FISPACT-II
   - Waste expectations from fusion
3. Assessment of possible steels for fusion
4. Conclusions

FISPACT-II and waste assessments

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- Before disposal radioactive materials are classified based on there nuclide content and activity.
- These classifications determine how the waste will be disposed of.
- For example low level waste (LLW) can typically undergo near surface disposal.
- Knowledge of activities and sources of activity is required for waste assessments.

How can what a sample contains be determined before disposal?

- FISPACT-II can model the nuclide evolution of a material under irradiation. Providing information on activities and sources of activity during and after decommissioning.
- From knowledge of a materials starting composition and the irradiation conditions a components possible disposal routes can be determined.

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How to do a waste assessment with FISPACT-II?

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1. Run a FISPACT-II calculation:
   - Define the material to be studied.
   - Define the flux and irradiation schedule.
   - Define cooling times, these are when the material will be assessed.

MASS or FUEL keywords.

Fluxes file and FLUX keyword.

Using the ATOMS keyword.

2. Apply waste criteria to FISPACT-II output to determine the waste classification

   Waste criteria are typically limits on activity from a given sources.

   e.g. UK LLW $\beta+\gamma$ activity limit = 1.2×10^{7} Bq kg^{-1}

Need to sum β and γ Bq and divided my mass in kg, then compare to limit.

Output file

```
0  TOTAL NUMBER OF NUCLIDES PRINTED IN INVENTORY =   117
0  TOTAL CURIES    TOTAL ALPHA    TOTAL BETA     TOTAL GAMMA
                   CURIE-MeV      CURIE-MeV      CURIE-MeV
   5.02240E-05   0.00000E+00   5.20711E-05   6.88742E-05
0  ALPHA BECQUERELS = 0.000000E+00  BETA BECQUERELS = 1.763358E+06   GAMMA BECQUERELS = 9.492956E+04
0  TOTAL ACTIVITY FOR ALL MATERIALS        1.85829E+06 Bq
                                           3.99783E-04 Ci/cc           DENSITY    7.96E+00 gm/cc
   TOTAL ACTIVITY EXCLUDING TRITIUM        1.85829E+06 Bq
                                           3.99783E-04 Ci/cc
0  TOTAL ALPHA HEAT PRODUCTION             0.00000E+00 kW
   TOTAL BETA  HEAT PRODUCTION             3.08680E-10 kW
   TOTAL GAMMA HEAT PRODUCTION             4.08290E-10 kW              TOTAL HEAT PRODUCTION 7.16970E-10 k
0  INITIAL TOTAL MASS OF MATERIAL          1.00000E-03 kg              TOTAL HEAT EX TRITIUM 7.16970E-10 k
0  TOTAL MASS OF MATERIAL                  1.00000E-03 kg
   NEUTRON  FLUX DURING INTERVAL           1.11600E+10 n/cm^2/s
```

$\beta+\gamma$ activity (in Bq kg^{-1}) = 1.86×10^{9} Bq kg^{-1}

In this example the limit is breached

For a complete waste assessment all relevant criteria need to be considered at all relevant timesteps

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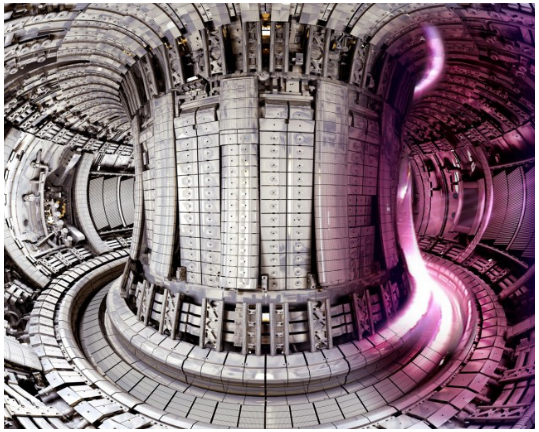
Fusion Waste Prospects

Waste assessment of complete reactor systems, example with EU DEMO

Radioactive Waste and Fusion

- 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. Primarily from the nuclear fuel.
- Fusion power plants won't produce radioactive waste, right?



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

$$^{2}\mathrm{H} + {}^{3}\mathrm{H} \rightarrow {}^{4}\mathrm{He} + n$$

- Most of the energy carried by the neutron. These impinge on to the reactor components causing activation and material damage.
- Leaving radioactive waste at reactor end of life. Currently hoped to be low-level waste after 100 years.

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Complete Reactor waste assessments

- Complex nuclear devices will need complete waste assessment of their materials prior to decommissioning.
- EU DEMO, a fusion reactor concept, has had several waste assessment performed on its geometry using FISPACT-II.

How is a complete reactor assessment performed?

Initial Reactor Geometry

Run Neutron transport (e.g. MCNP) to find flux spectra

Flux tallied in geometry subdivisions

Run FISPACT-II for relevant materials and irradiation schedules

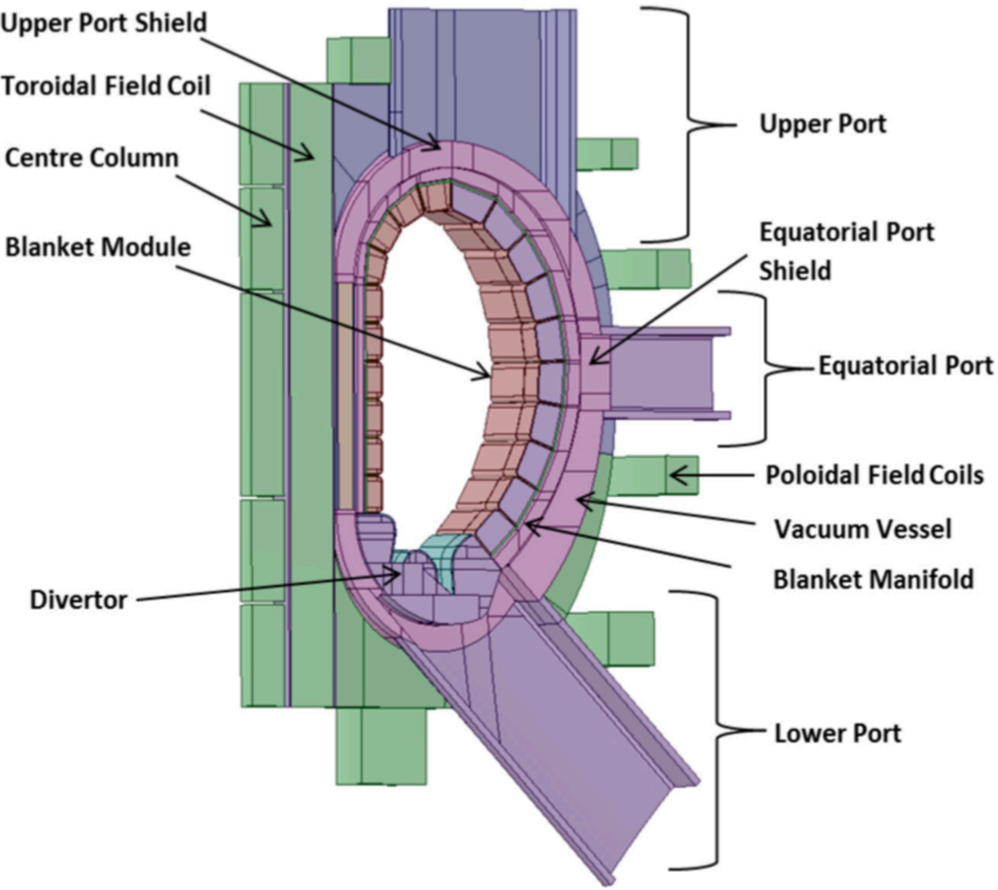
Analyse outputs according to the waste criteria being studied

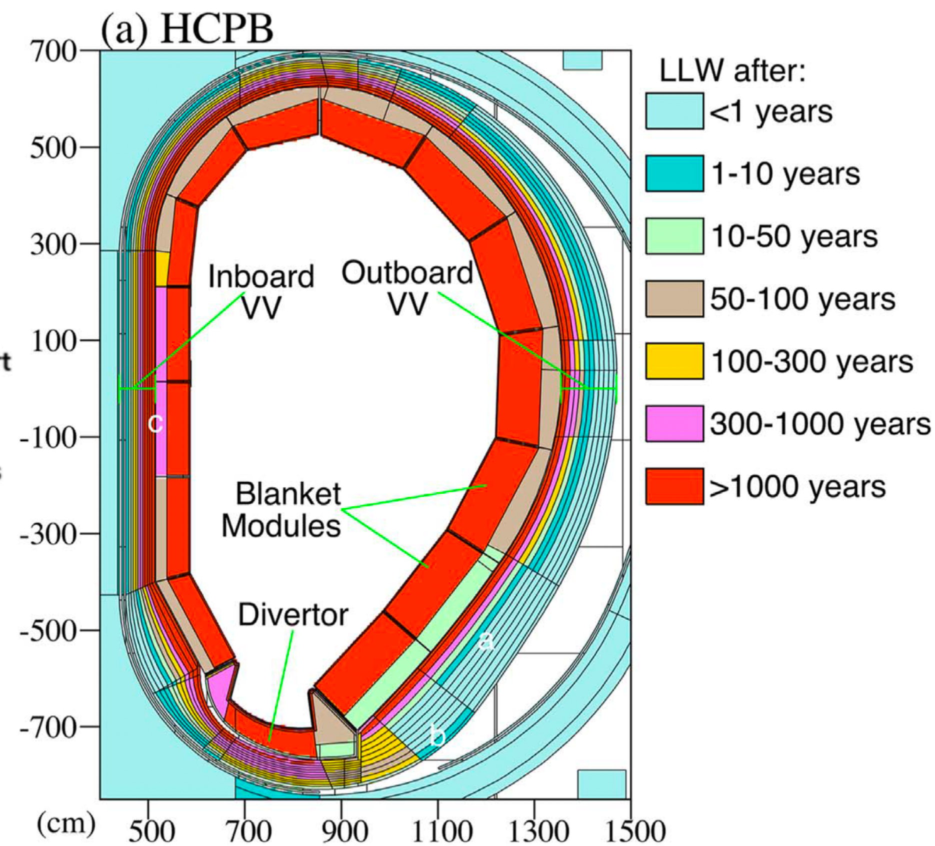
Consolidate results

- This is a multistep process and requires careful set up of multiple FISPACT-II inputs.
- This can be automated with external scripting.

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!





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Current Waste Expectations for DEMO

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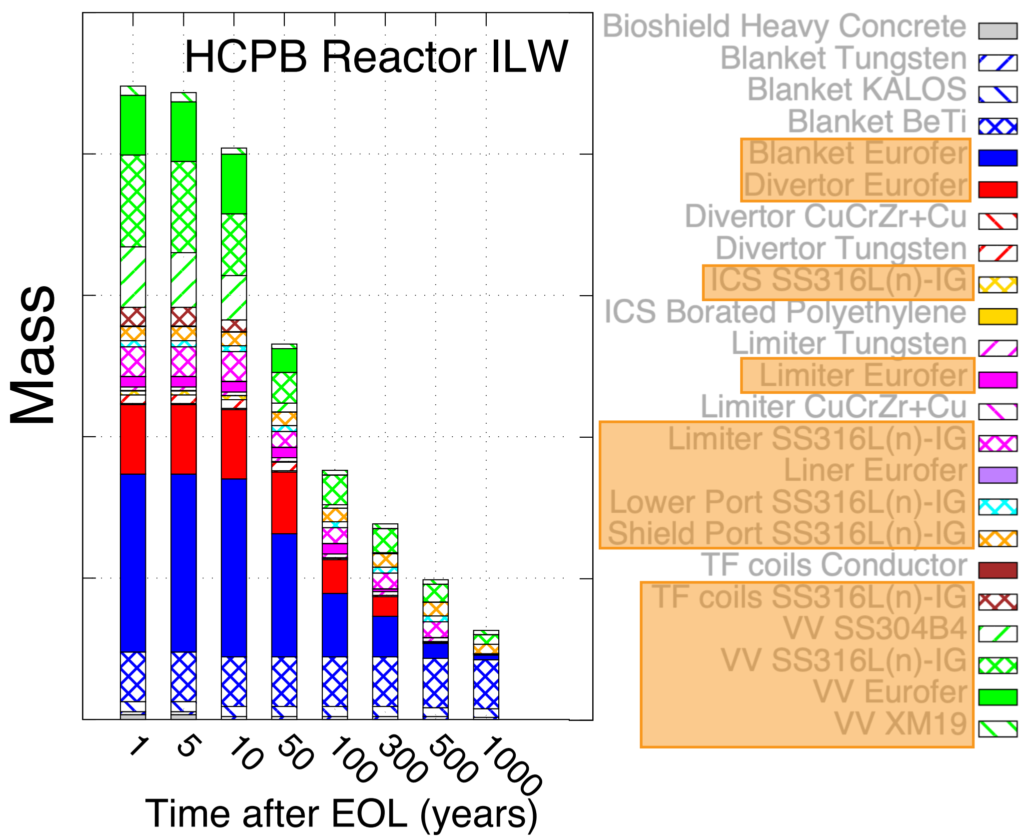
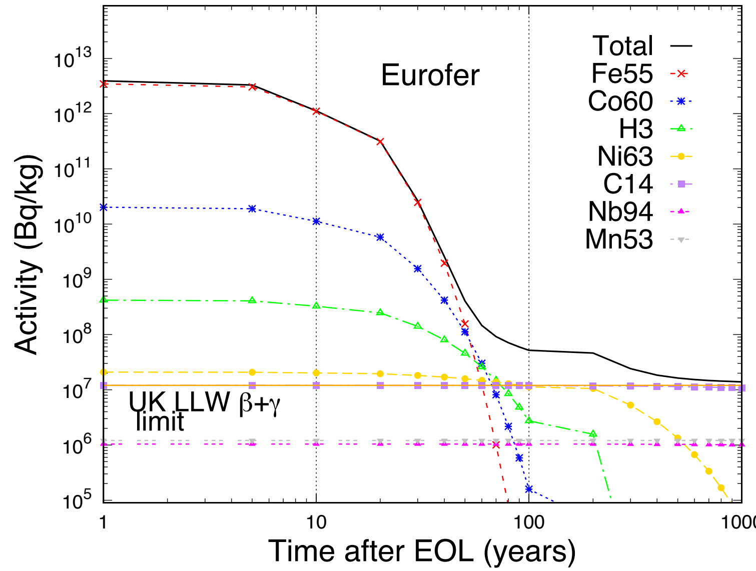
- Further analysis reveals that a major contributor to expected DEMO waste are activated steels.
- If steel radioactivity could be reduced DEMO's waste prospects should improve.

Eurofer and traditional stainless steels





- Long term Eurofer Activity dominated by ^{14}C.
- How could this radioactivity be reduced?

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Waste Assessment of possible steels for fusion

Waste prospects of possible steels for fusion applications

Waste Expectations for Fusion Steels

- Proportions of DEMO's Blanket and Vacuum Vessel are not expected to be called Low Level waste, by UK waste standards, for over 1000 years.

- What if different materials are used? DEMO is mostly planning to use the steels Eurofer and SS316.

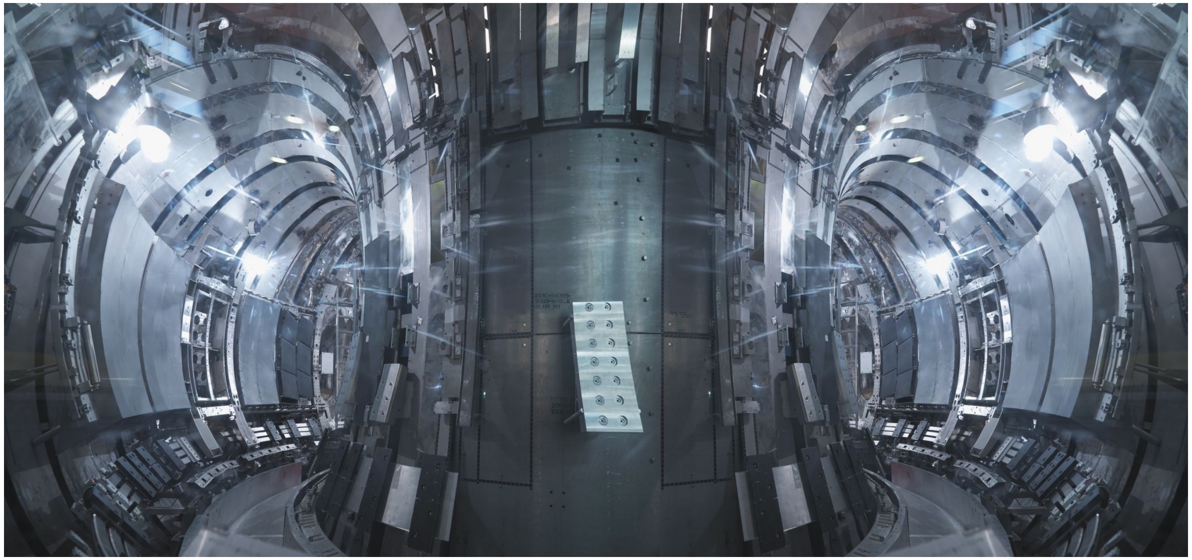
European Developed Reduced Activation(RA) Steel

Traditional Stainless Steel

- Are other possibilities available which could have improved waste prospects?

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?

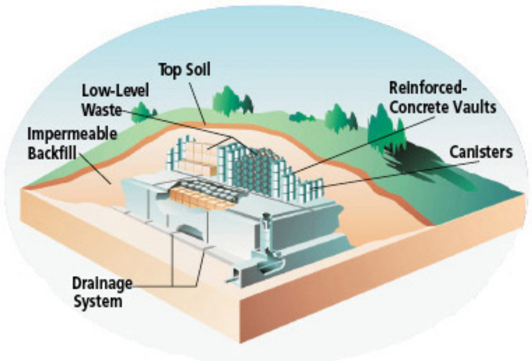
	Activity Limits (Bqkg^{-1}) [† Bqm^{-3}]						
Country	α	$\beta+\gamma$	^{3}H	^{14}C	^{63}Ni	^{94}Nb	^{99}Tc
UK	4×10^{6}	1.2×10^{7}	-	-	-	-	-
US	-	-	$^\dagger1.48\times10^{12}$	$^\dagger2.96\times10^{12}$	$^\dagger2.59\times10^{14}$	$^\dagger7.4\times10^{9}$	$^\dagger1.11\times10^{11}$
France	-	-	2×10^{8}	9.2×10^{7}	3.2×10^{9}	1.2×10^{5}	4.4×10^{7}
Russia	1×10^{3}	$1\times10^{7}(-^{3}\mathrm{H})$	$^\dagger1\times10^{11}$	$^\dagger3\times10^{12}$	$^\dagger2.59\times10^{14}$	$^\dagger7.4\times10^{9}$	$^\dagger1.1\times10^{11}$
Spain	3.7×10^{6}	3.7×10^{7}	1×10^{9}	2×10^{8}	1.2×10^{10}	1.2×10^{5}	1×10^{6}
Japan	1×10^{7}	-	-	1×10^{13}	1×10^{10}	-	1×10^{11}

Example limits from complex waste management systems

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

- Some systems divide low level waste into multiple categorisations.
- E.g. Spain uses 2 levels of Low Intermediate Level waste and a Very low-level waste class.

Low-Level Waste Disposal



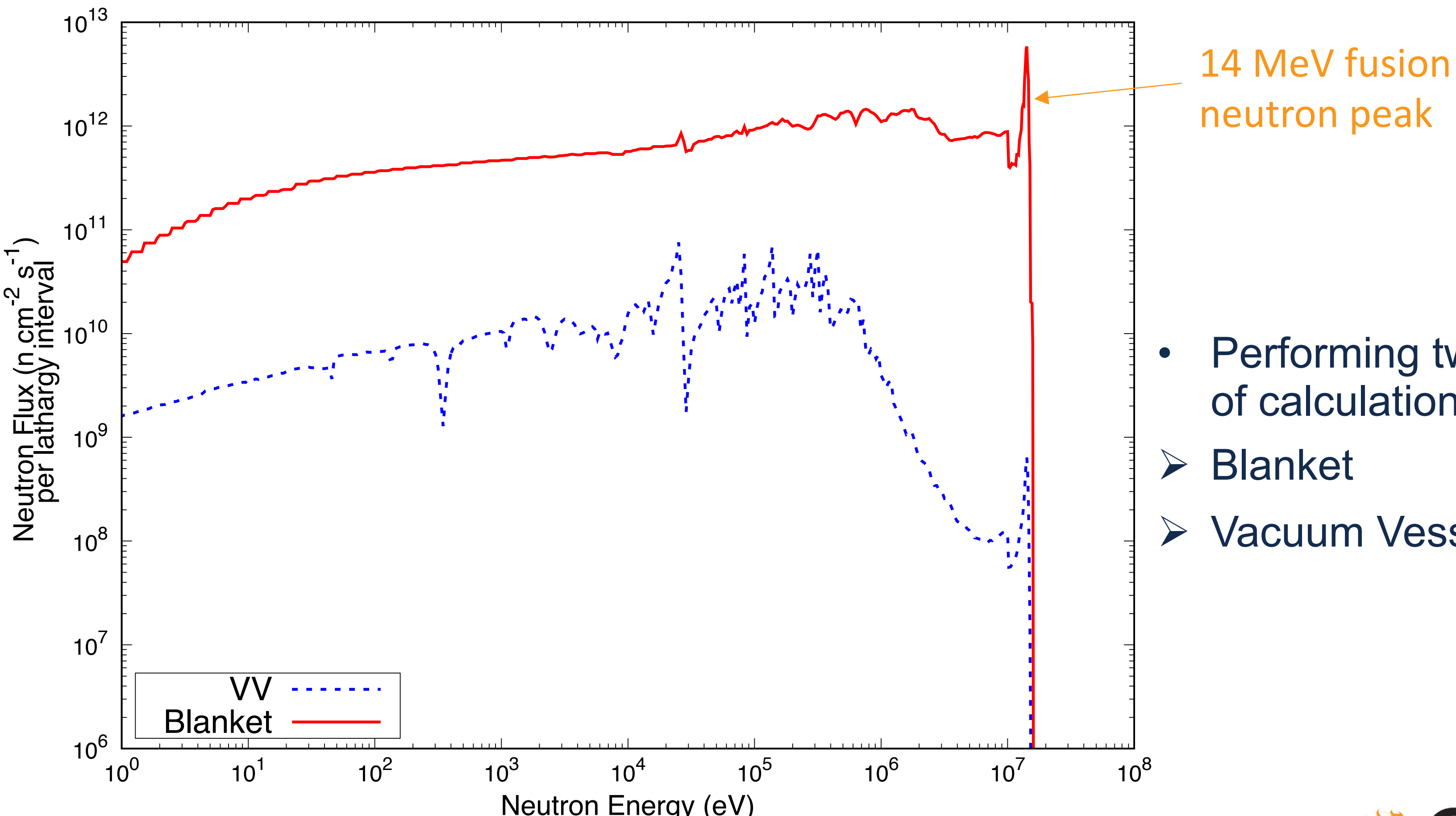
Source: U.S. Nuclear Regulatory Commission

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

FISPACT-II calculations for fusion waste assessments – Flux Spectra

UK Atomic Energy Authority

- Use the DEMO model. It is the closest we have to a commercial fusion plant.
- Fluxes derived from MCNP calculations, tallied in 709 energy groups.



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

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FISPACT-II calculations for fusion waste assessments – Nuclear Data

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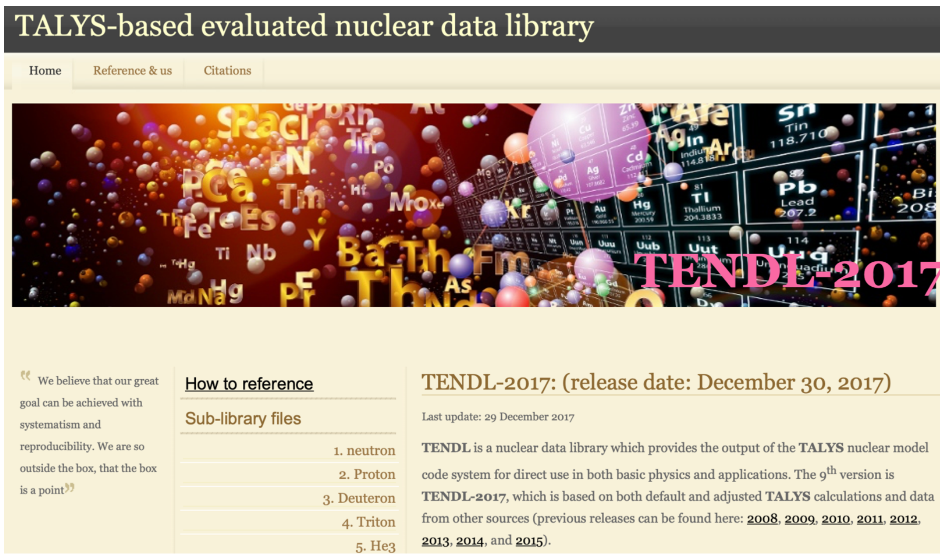
Select Nuclear Data set.

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



Example from "files" file

```
# 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
```

- Also use UK decay 2012 decay data library.

Remember that the choice of Nuclear Data can affect the outputs.
Both of these library are available for use with FISPACT-II.

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FISPACT-II calculations for fusion waste assessments – Steel Definitions

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

- Steel Compositions are a mixture of engineering standards and experimental compositions.

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

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 composition

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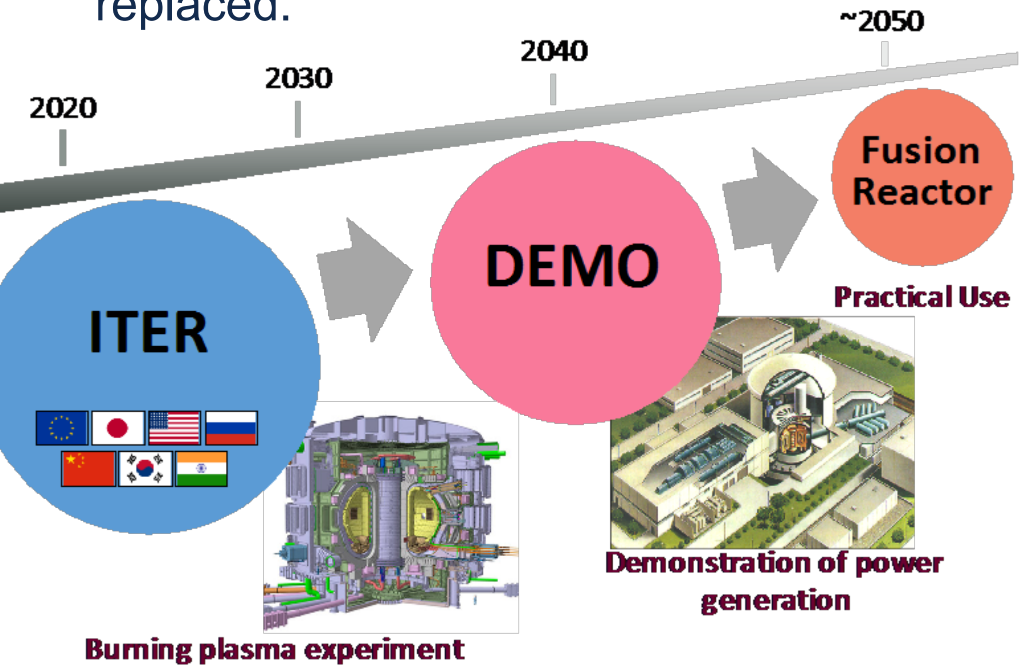
FISPACT-II calculations for fusion waste assessments – Irradiation Schedule

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

Need to account for maintenance shutdown periods.

FISPACT-II's alternative outputs


```
"inventory_data": [
  {
    "irradiation_time": 0.0E+0,
    "cooling_time": 0.0E+0,
    "flux": 0.747205E+14,
    "total_activity": 0.25114433516057053E-1,
    "alpha_activity": 0.19925778721290189E-2,
    "beta_activity": 0.23121855643928033E-1,
    "gamma_activity": 0.0E+0,
    "total_mass": 0.99999999999999978E+0,
    "total_heat": 0.19150250262055421E-17,
    "alpha_heat": 0.42655940255359924E-18,
    "beta_heat": 0.1485312690273825E-17,
    "gamma_heat": 0.31529333781175787E-20,
    "ingestion_dose": 0.38057061641231115E-8,
    "inhalation_dose": 0.59980236337468839E-7,
    "dose_rate": {
      "type": "",
      "distance": 0.0E+0,
      "mass": 0.0E+0,
      "dose": 0.0E+0
    },
    "nuclides": [
      {
        "element": "B",
        "isotope": 10,
        "state": "",
        "half_life": 0.0E+0,
        "zai": 50100,
        "atoms": 0.22056680437981689E+21,
        "grams": 0.3667335116426904E-2,
        "activity": 0.0E+0,
        "alpha_activity": 0.0E+0,
        "beta_activity": 0.0E+0,
        "gamma_activity": 0.0E+0,
        "heat": 0.0E+0,
        "alpha_heat": 0.0E+0,
        "beta_heat": 0.0E+0,
        "gamma_heat": 0.0E+0,
        "dose": 0.0E+0,
        "ingestion": 0.0E+0,
        "inhalation": 0.0E+0
      },
      {
```


JSON

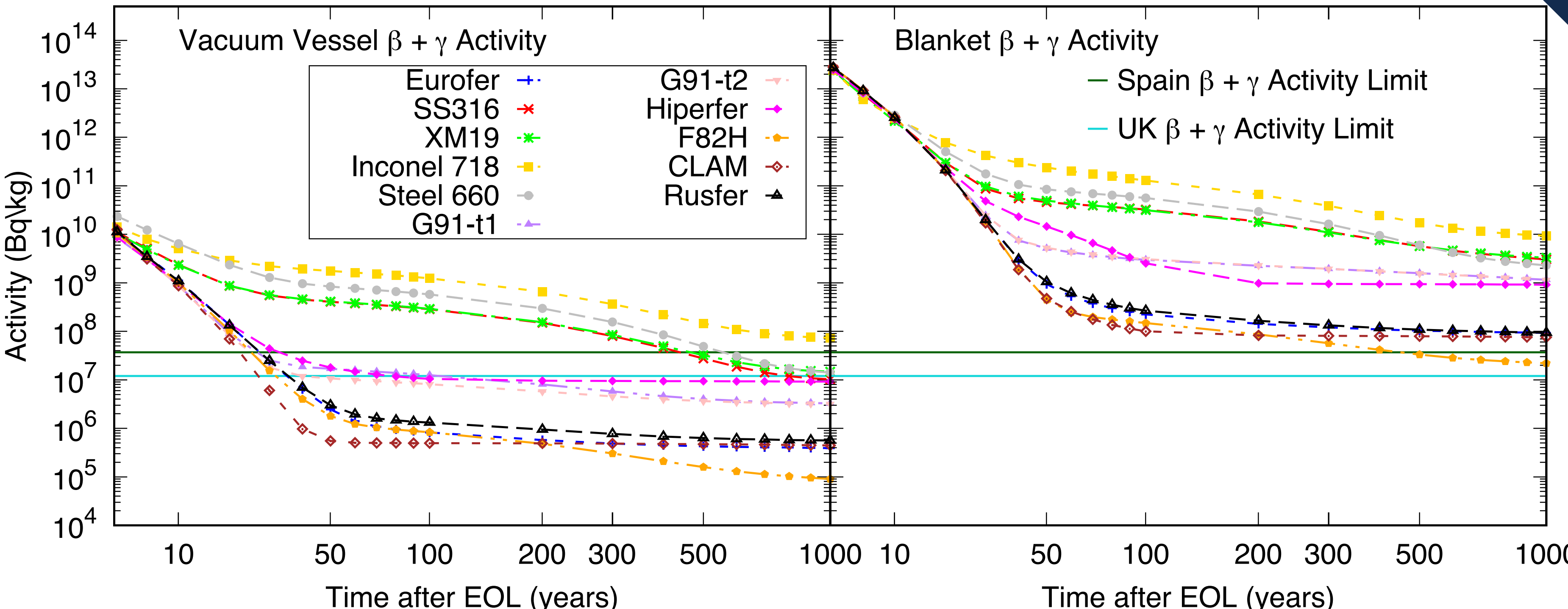
- JSON (**JavaScript Object Notation)** is a serialised data format. This is computer readable, but not necessarily easily human readable.
- FISPACT-II can output the nuclide inventory in JSON format with the **JSON** keyword.
- Python has the ability to read JSON files, parsers exist for C++ and Fortran.

TAB files

- The TAB files output inventory quantities in a simpler format for easier processing.
- For example "**TAB2**" will produce a file which has the activities (Bq) and the Dose rate (Sv/hr) of each nuclide.
- These can be output using the "**TAB1**", "**TAB2**", "**TAB3**" , "**TAB4**" keywords

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

UK Atomic Energy Authority



For all steels the alpha activity < 10^{-1} Bq/kg after 1 year. Not a concern to waste classification

All RA and at least one G91 steels meet UK and Spain activity after 100 years.

No Blanket steel can be UK limits. Only F82H meets Spain's limits after 500 years

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

Country	α	$\beta+\gamma$	^{3}H
UK	$\boxed{4\times10^6}$	$\boxed{1.2\times10^7}$	-
US	-	-	$^\dagger 1.48\times10^{12}$
France	-	-	2×10^8
Russia	$\boxed{1\times10^3}$	$\boxed{1\times10^7(-{}^3\mathrm{H})}$	$^\dagger 1\times10^{11}$
Spain	$\boxed{3.7\times10^6}$	$\boxed{3.7\times10^7}$	1×10^9
Japan	$\boxed{1\times10^7}$	-	-

Need tritium activity for Russian limit

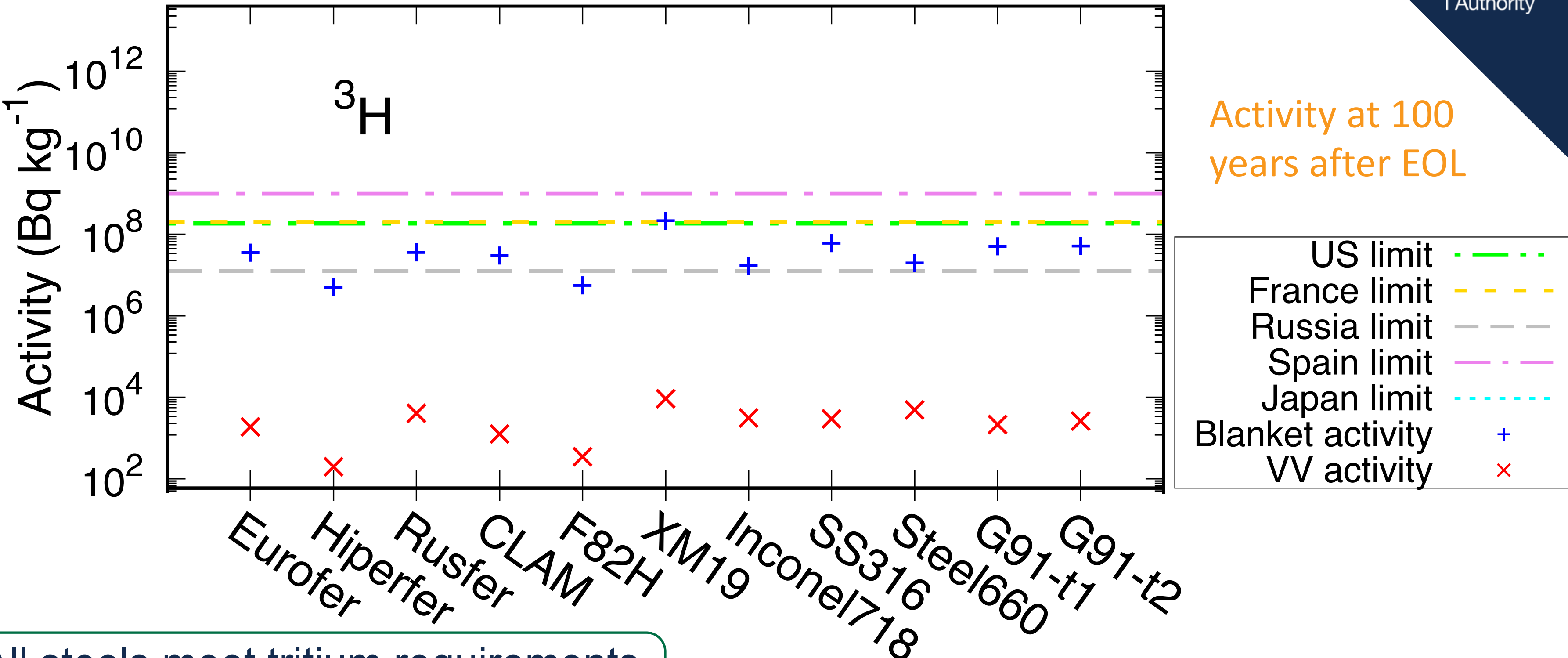
- All steels meet these limits
- α emitters are not a large contributor to activated fusion waste

Spain's $\beta+\gamma$ limits only prevent some LLW classifications, not all

- Blanket steels breach these limits and
- β emitters are a large problem.

Conclusion : None of the Blanket Steels studied can be called Low Level under UK criteria may struggle under Spanish criteria.

Results from FISPACT-II: Tritium Activity



Activity at 100 years after EOL

All steels meet tritium requirements in Vacuum Vessel.

Russian limit: $\beta + \gamma \leq 1 \times 10^{7} (-{}^{3}\mathrm{H})$

After 100 years Hiperfer and F82H meet all limits under blanket conditions.

After 100 years:

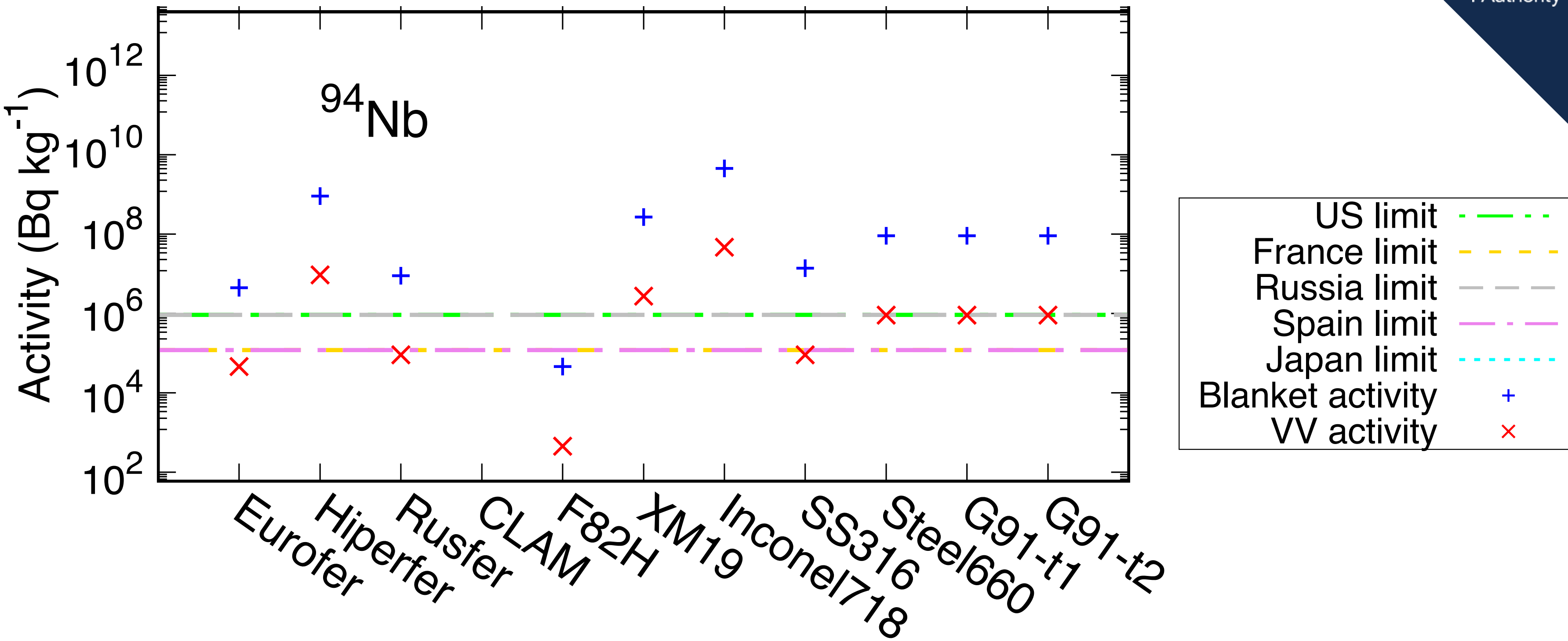
VV: $\beta + \gamma \gtrapprox 10^{5}\ \mathrm{Bq\ kg^{-1}}$

Blanket: $\beta + \gamma \gtrapprox 10^{8}\ \mathrm{Bq\ kg^{-1}}$

Conclusion : No Blanket Steels studied can be called Low Level under Russian criteria.

Some may in the Vacuum Vessel.

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



F82H and CLAM meet all ^{94}Nb limits. Serval VV steels meet the limits

Most Blanket steels fail to meet required criteria

CLAM produces no ^{94}Nb

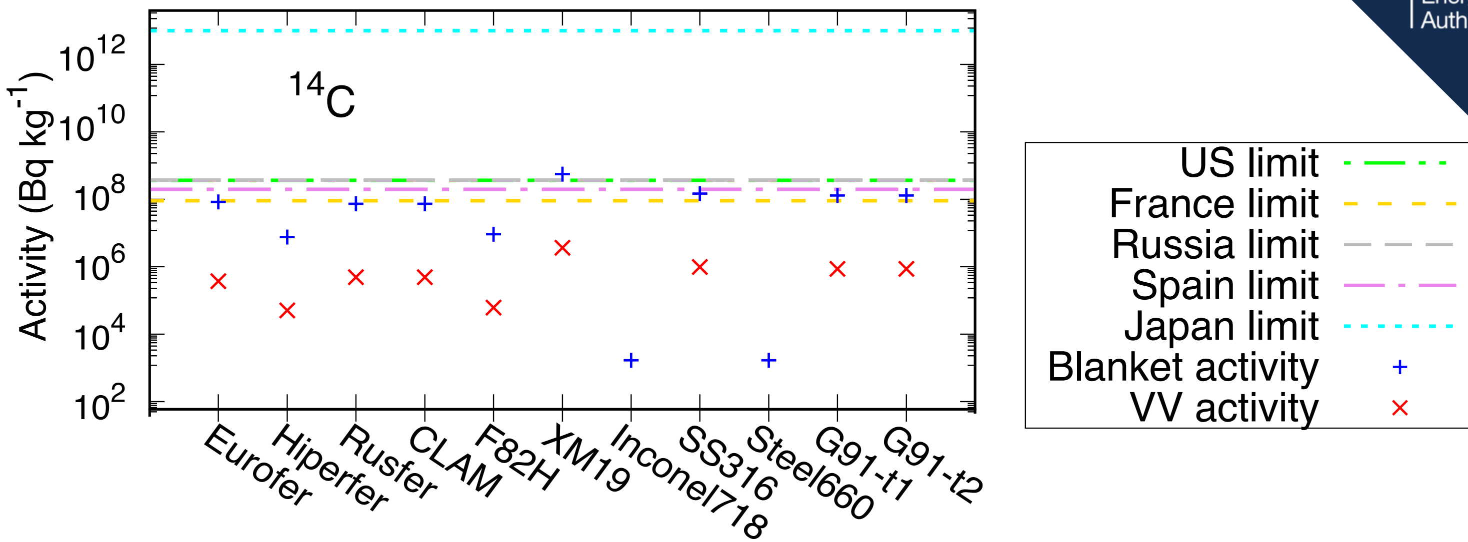
Conclusion : Only two steels can meet all limits, meaning most will struggle to be LLW, especially in the blanket.

The VV results may allow some steels to be LLW under some LLW criteria.

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

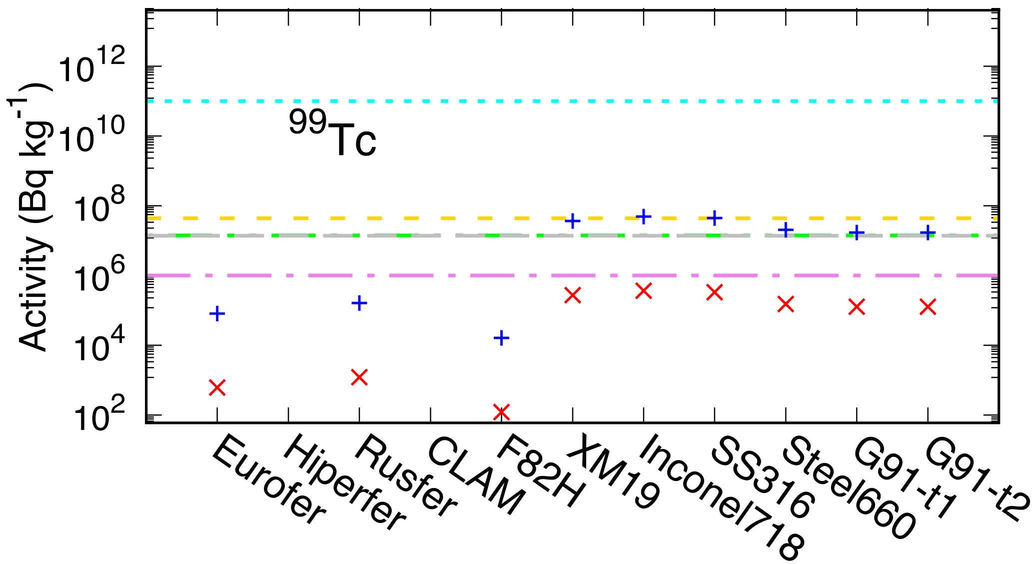
$^{14}\mathrm{C}$

All steels but XM19 can meet limits in the blanket. All steel can meet limits in the VV



$^{99}\mathrm{Tc}$

Traditional steels struggle to meet limits in the blanket



Conclusion : All 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

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

All steels in both regions are LLW by Japans requirements

Steels perform better in the Vacuum Vessel

	Blanket						Vacuum Vessel					
Steel	UK	US	France	Russia	Spain	Japan	UK	US	France	Russia	Spain	Japan
Eurofer	ILW	ILW	ILW	ILW	ILW	LLW	LLW	LLW	LLW	LLW	LLW	LLW
Hiperfer	ILW	ILW	ILW	ILW	ILW	LLW	LLW	ILW	ILW	ILW	ILW	LLW
Rusfer	ILW	ILW	ILW	ILW	ILW	LLW	LLW	LLW	LLW	LLW	LLW	LLW
CLAM	ILW	LLW	LLW	ILW	LLW	LLW	LLW	LLW	LLW	LLW	LLW	LLW
F82H	ILW	LLW	ILW	ILW	LLW	LLW	LLW	LLW	LLW	LLW	LLW	LLW
XM19	ILW	ILW	ILW	ILW	ILW	LLW	ILW	ILW	ILW	ILW	ILW	LLW
Inconel 718	ILW	ILW	ILW	ILW	ILW	LLW	ILW	ILW	ILW	ILW	ILW	LLW
SS316	ILW	ILW	ILW	ILW	ILW	LLW	ILW	LLW	LLW	ILW	LLW	LLW
Steel 660	ILW	ILW	ILW	ILW	ILW	LLW	ILW	ILW	ILW	ILW	ILW	LLW
G91 T1	ILW	ILW	ILW	ILW	ILW	LLW	ILW	LLW	ILW	LLW	ILW	LLW
G91 T2	ILW	ILW	ILW	ILW	ILW	LLW	LLW	LLW	ILW	LLW	ILW	LLW

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, Japan or Spain

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 down by most international standards. Better prospects in the Vacuum Vessel
- It can be expected to be **Intermediate level** waste
- What an be done? Several possibilities:

Change components more regularly to avoid build up of activation

Change reactor running schedule to lower activation

Develop specific waste repositories for activated steels

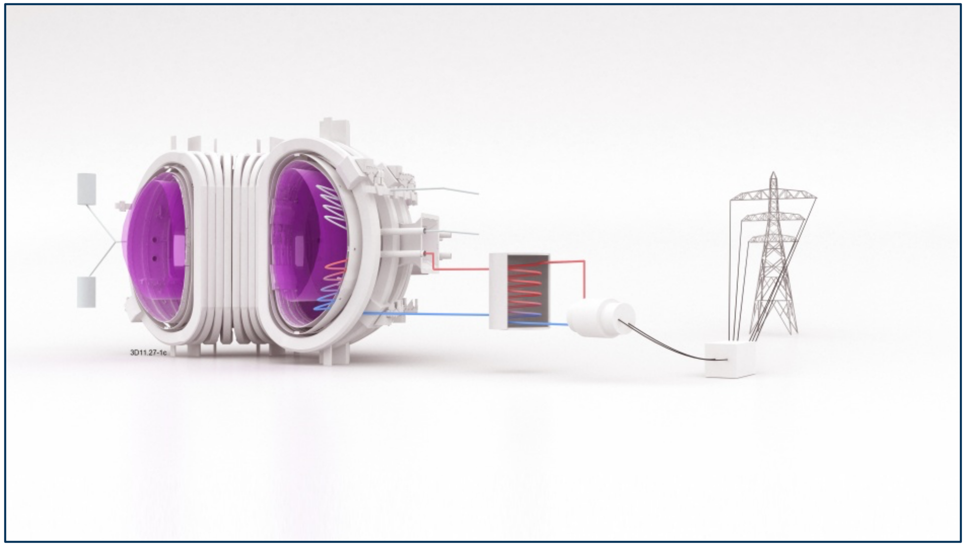
Lowering of material impurities

Additional shielding to isolate activity to aid disposal

Possible processing of steels e.g Tritium or Carbon removal

Conclusion

- FISPACT-II is an 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 are expected to produce activated steel waste from near plasma components
- Use of currently available low activation materials will not solve this problem.

- Steel specific repositories probably needed for test/1st generation fusion reactors
- Long term solution to fusion waste has yet to be found but is being studied.

FISPACT-II

Thank you for listening.
Now try the exercises

FISPACT-II workshop

Online, November/December 2020

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