Tritium inventory evolution modelling for demonstration and future fusion power plants

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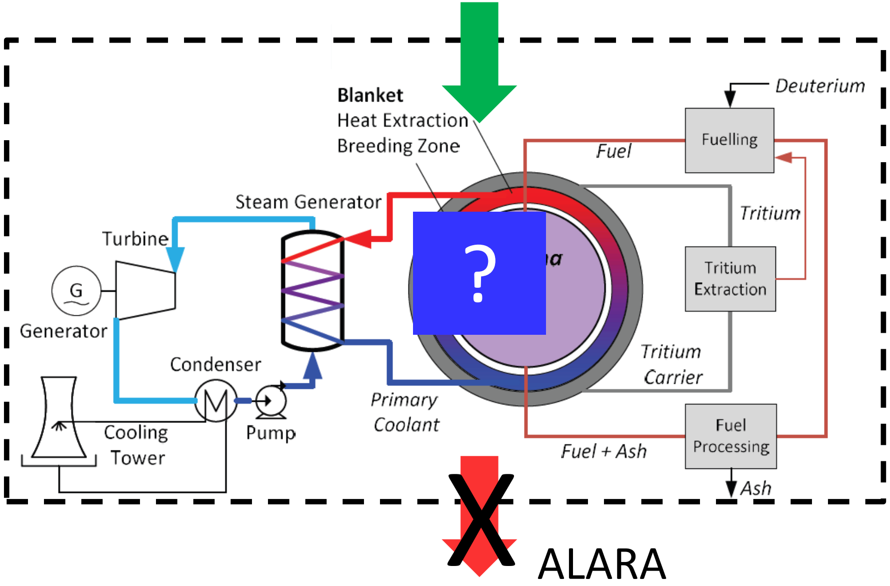
Motivation

- Fusion power plants need tritium inventory to operate
- Extrapolation from ITER/DEMO concepts: **several kg/GW$_{\mathbf{e}}$**
- EU-DEMO: (Only) Tritium self-sufficient (*M4 EUROfusion Roadmap*)
- Tritium breeding performance can hamper fusion power rollout
  - FPPs need doubling times < 3 yrs

    S. Ferry et al., Fus. Sci. Tech., 79, 13-35, (2022)

- What is the tritium breeding performance of DEMOs/FPPs?

→ **Plant wide tritium balance**



The power plant tritium balance

- A minimum operational inventory is required

$$\frac{dT_{tot}}{dt} = 0$$

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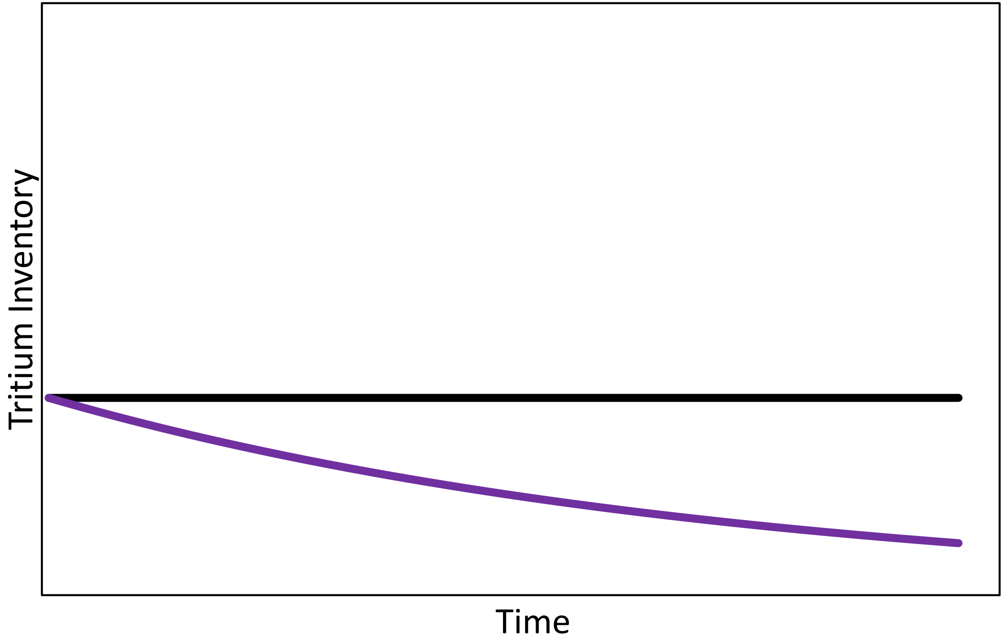
- Tritium decays

  $t_{1/2} = 12.3\ yrs$

$$\frac{dT_{tot}}{dt} = -\lambda T_{tot}$$



The power plant tritium balance

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  $t_{1/2} = 12.3\ yrs$
- Tritium is burned

$$\frac{dT_{tot}}{dt} = -\lambda T_{tot} - F_{T,burn}$$

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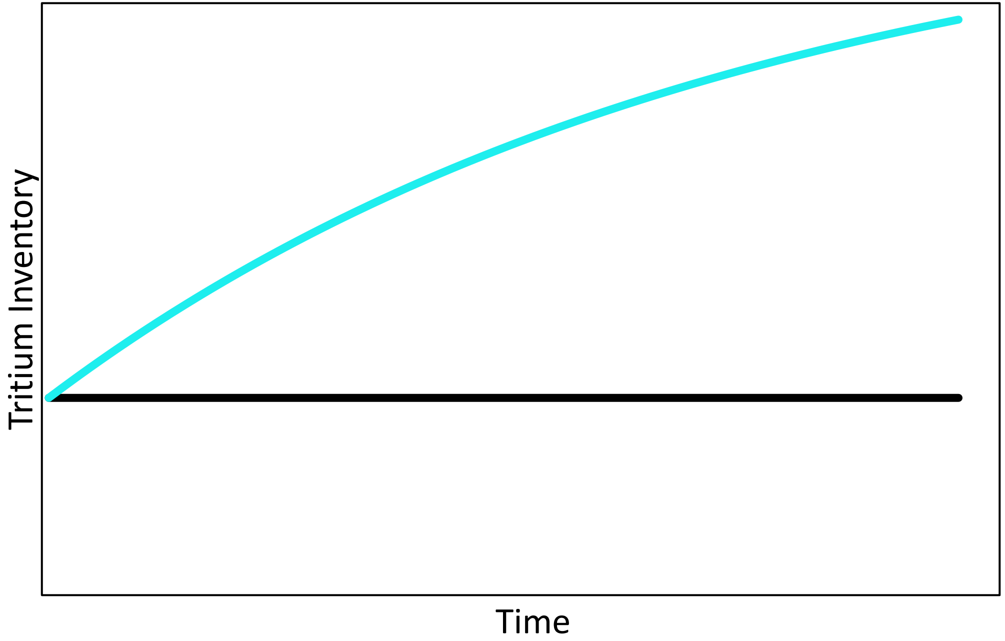
- Tritium is burned
- … and bred (TBR > 1)

$$\frac{dT_{tot}}{dt} = -\lambda T_{tot} - (1 - TBR)F_{T,burn}$$

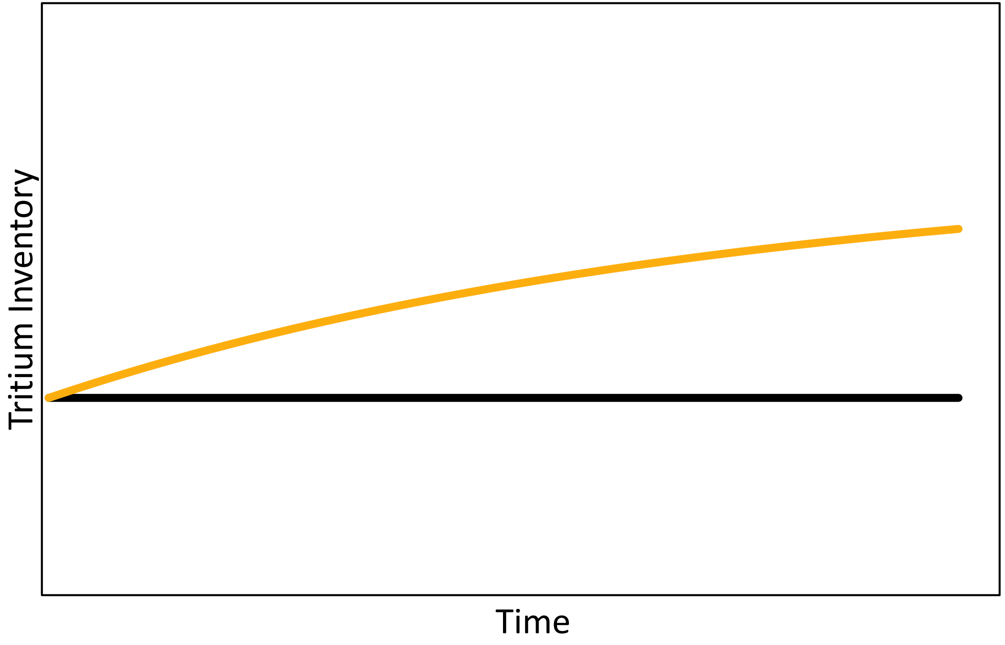


The power plant tritium balance

- A minimum operational inventory is required
- Tritium decays always

  $t_{1/2} = 12.3\ yrs$
- Tritium is burned
- … and bred (TBR > 1)
- …during plasma operation
  - < 100% availability

$$\frac{dT_{tot}}{dt} = -\lambda T_{tot} - Av(t)(1 - TBR)F_{T,burn}$$



The power plant tritium balance

$$T_{free} = T_{tot} - T_{seq}$$

$$\frac{dT_{tot}}{dt} = -\lambda T_{tot} - Av(t)(1 - TBR)F_{T,burn}$$

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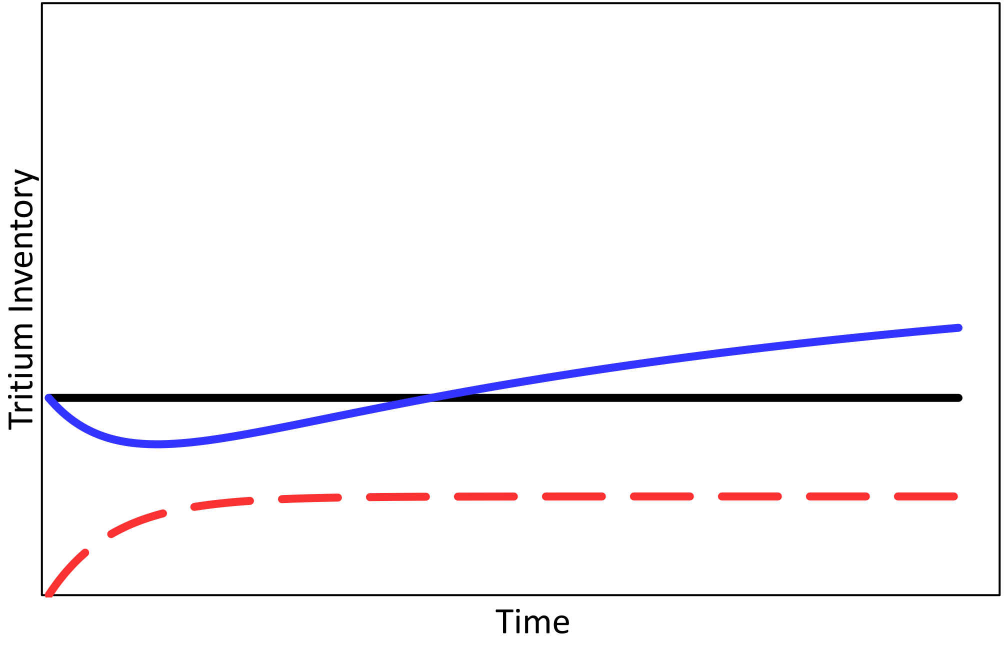

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- Only free tritium is usable for plant operation

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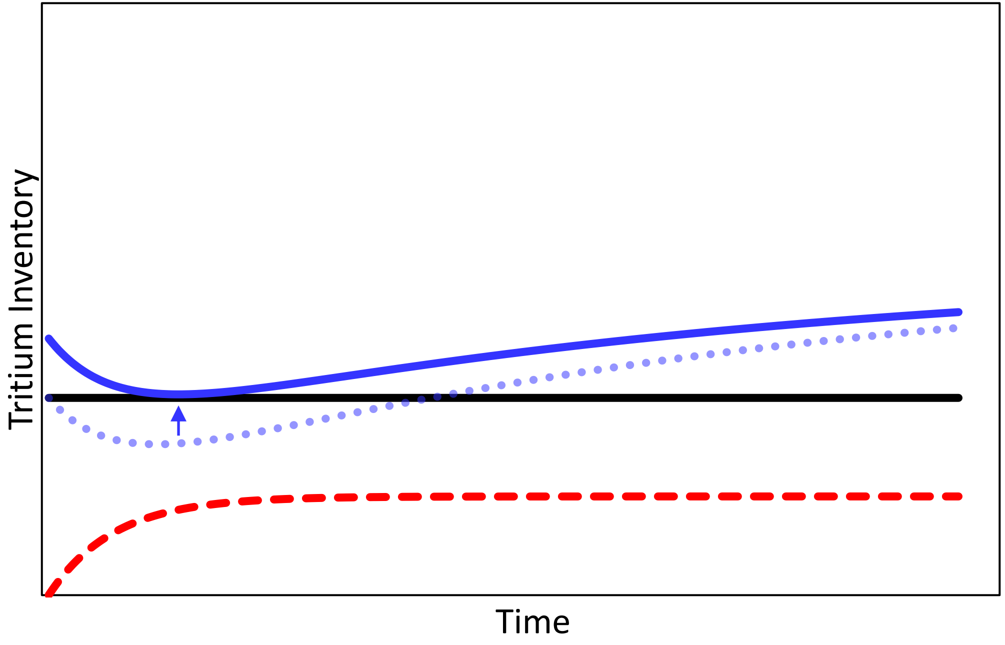

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- Only free tritium is usable for plant operation
- Excess inventory can be exported/sold

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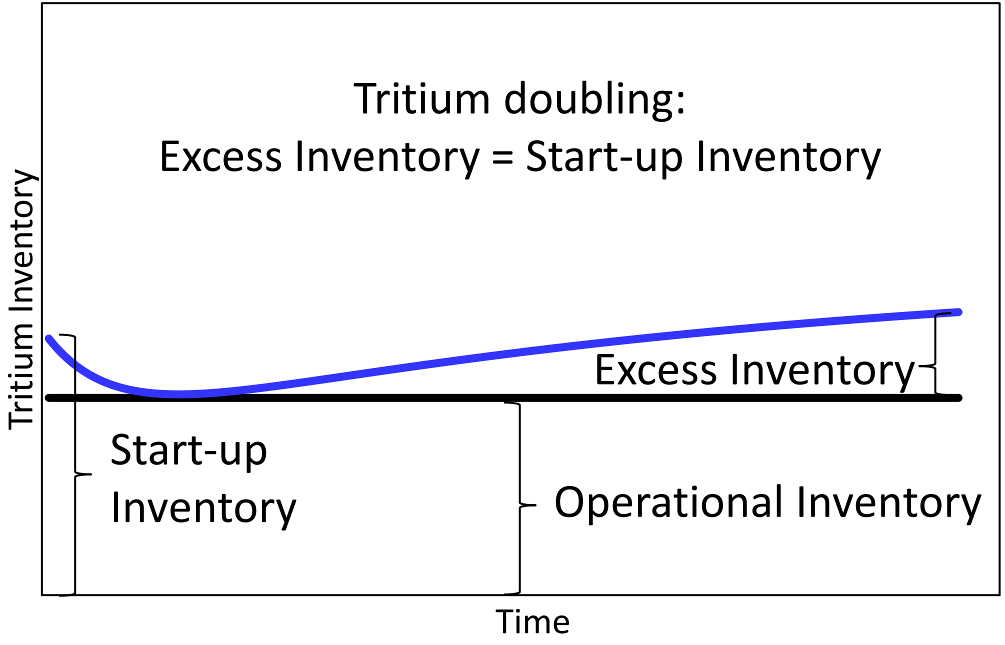

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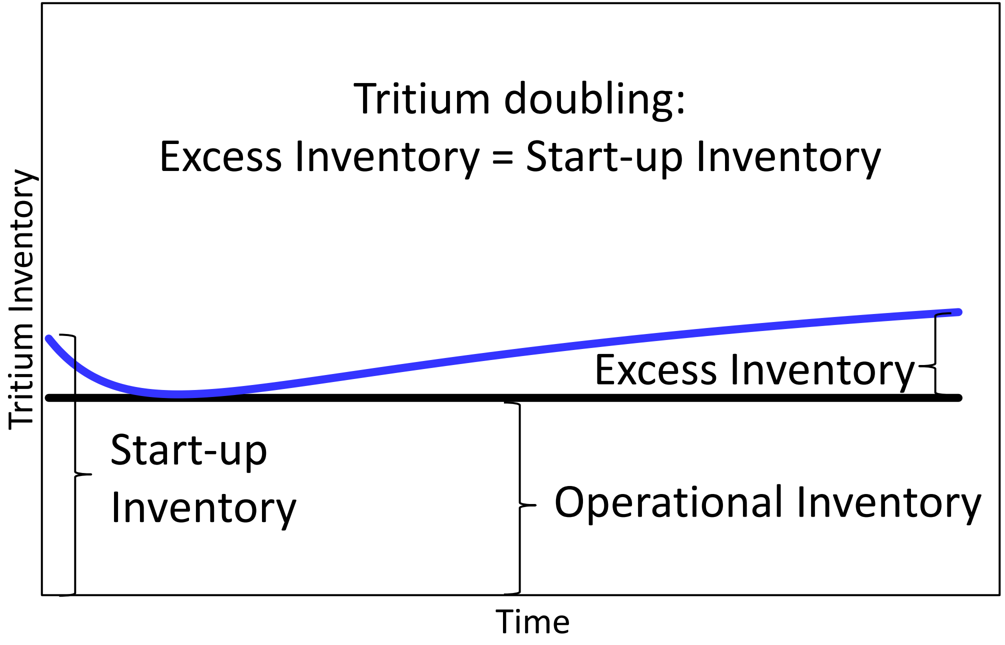
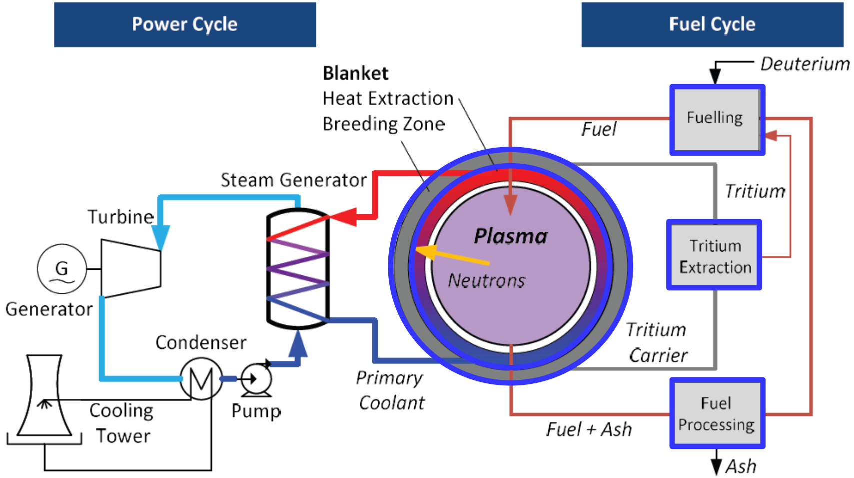


How much tritium is needed to operate?

- Operational tritium inventories occur along the tritium pathway
  - Breeder & Neutron Multiplier
  - Tritium Extraction
  - Fuel Cycle

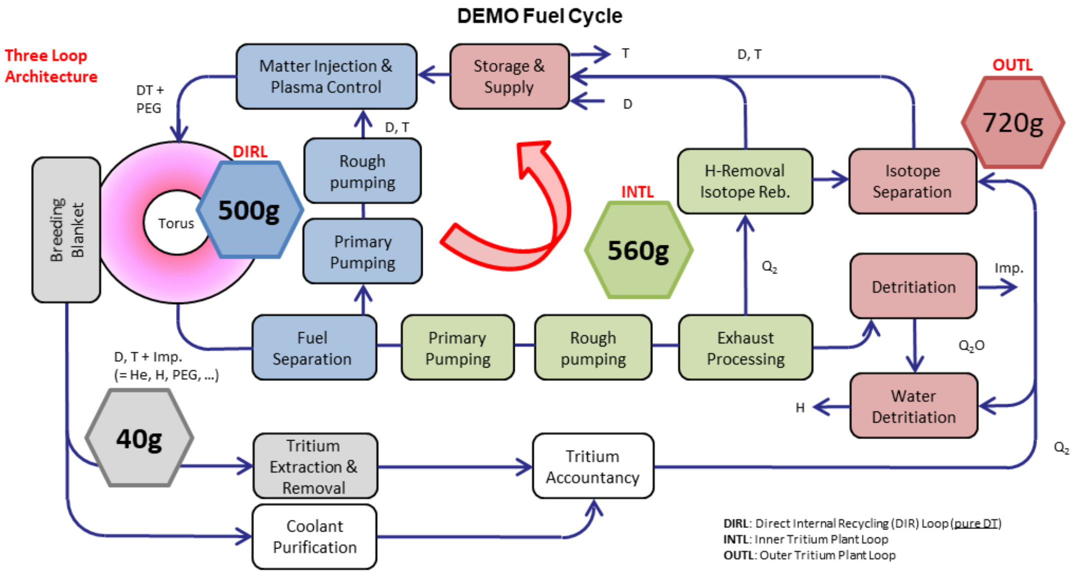


How much tritium is needed to operate?

- Operational tritium inventories occur along the tritium pathway
  - Breeder & Neutron Multiplier
  - Tritium Extraction
  - Fuel Cycle
- Continuous Fuel Cycle
  - Steady state inventories

$\sum \sim 2\ kg$ **(EU-DEMO)**

J. Schwenzer et al., Fus. Sci. Tech., 664–675, (2022)

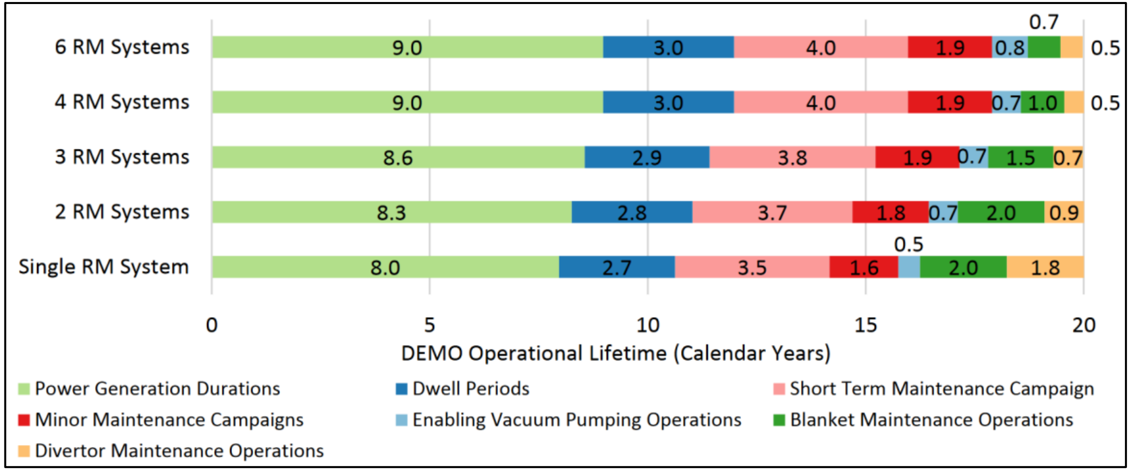


G. A. Spagnuolo et al., Fus. Eng. Des., 112933, (2021)

What availabilities can be expected? I

- Availability measures achieved “**full power time**”
- Fusion power plants don’t run day and night
  - Dwell phases (Tokamaks)
  - Scheduled maintenance
  - Unscheduled maintenance / repairs

$$Av = \frac{\int P(t)dt}{P_{max} \cdot t_{max}} = \frac{Full\ power\ time}{Total\ time}$$



$Av_{max} \approx$ **50% (EU-DEMO)**

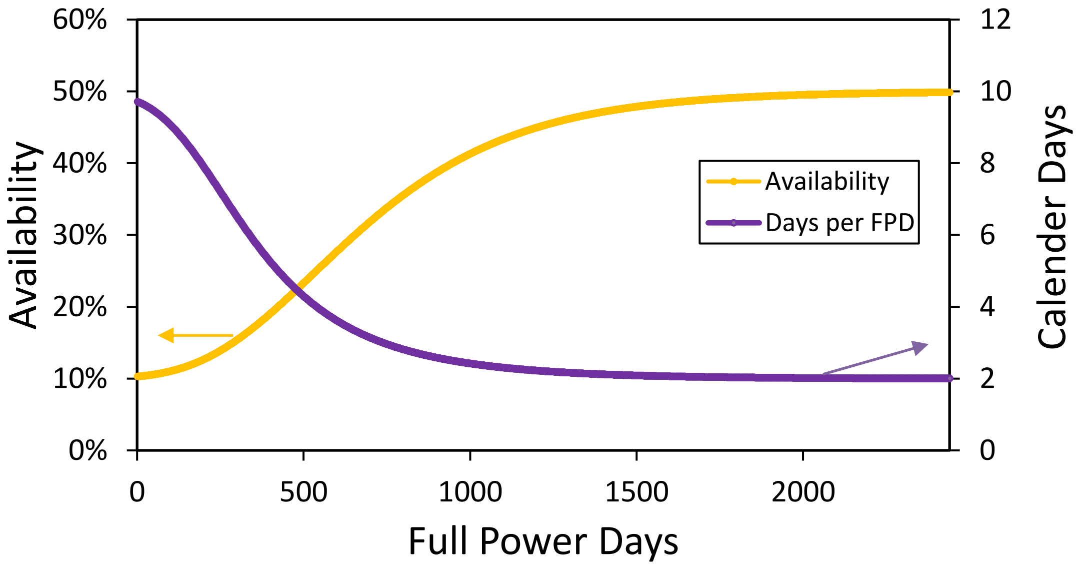
I. Farquhar et al., Fus. Eng. Des., 145, 29-32, (2019)

What availabilities can be expected? II

- DEMOs may not achieve nominal availability from day 1

→Time dependent availability (Sigmoid) M. Coleman et, Fus. Eng. Des., 141, 79 -90, (2019)

- Average Total: $Av > 30\%$ (EU-DEMO)



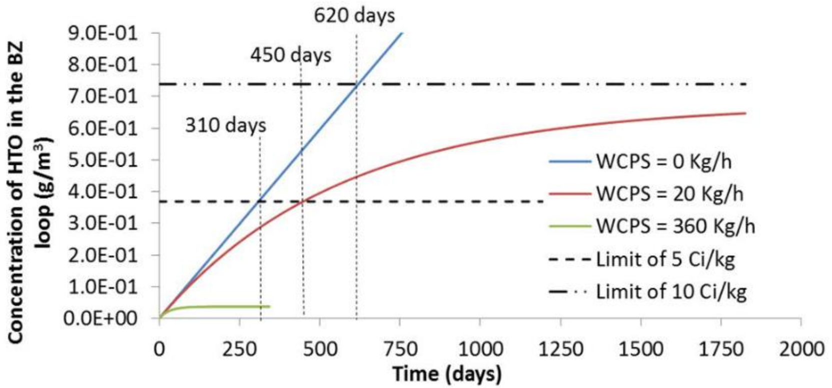
How much Tritium can become unavailable ?

- Parasitic inventories accumulate in sinks and are unusable for operation
- Sinks can become saturated / reach equilibrium inventories

→ Limited growth behaviour

- Sinks in EU-DEMO:
  - Coolants: up to 0.16 kg (Water)

    < 0.1 g (Helium)



G. A. Spagnuolo et al., Fus. Eng. Des., 112573, (2021)

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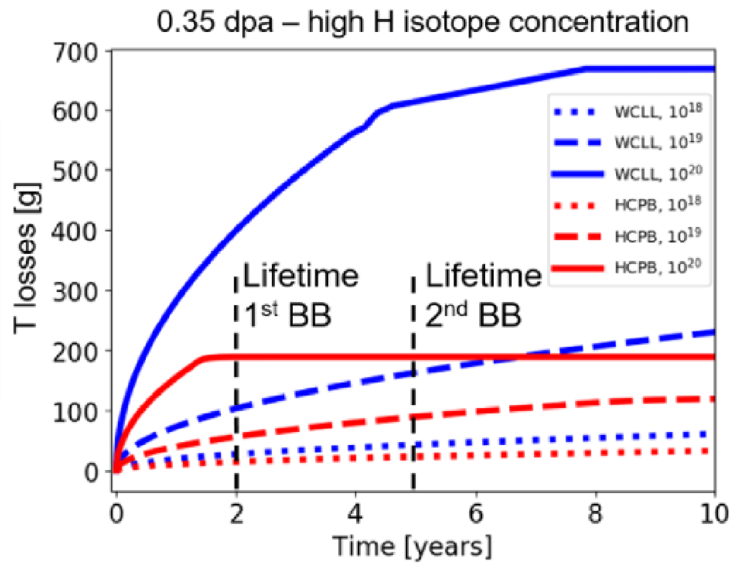
→ Limited growth behaviour

- Sinks in EU-DEMO:
  - Coolants: up to 0.16 kg (Water)
    < 0.1 g (Helium)
  - First wall: up to 0.65 kg (WCLL)
  - Structural materials (Blankets) (< 4 g WCLL, < 2g HCPB)

G. A. Spagnuolo et al., Fus. Eng. Des., 112933, (2021)

$\sum < 1\ kg$ **(EU-DEMO)**

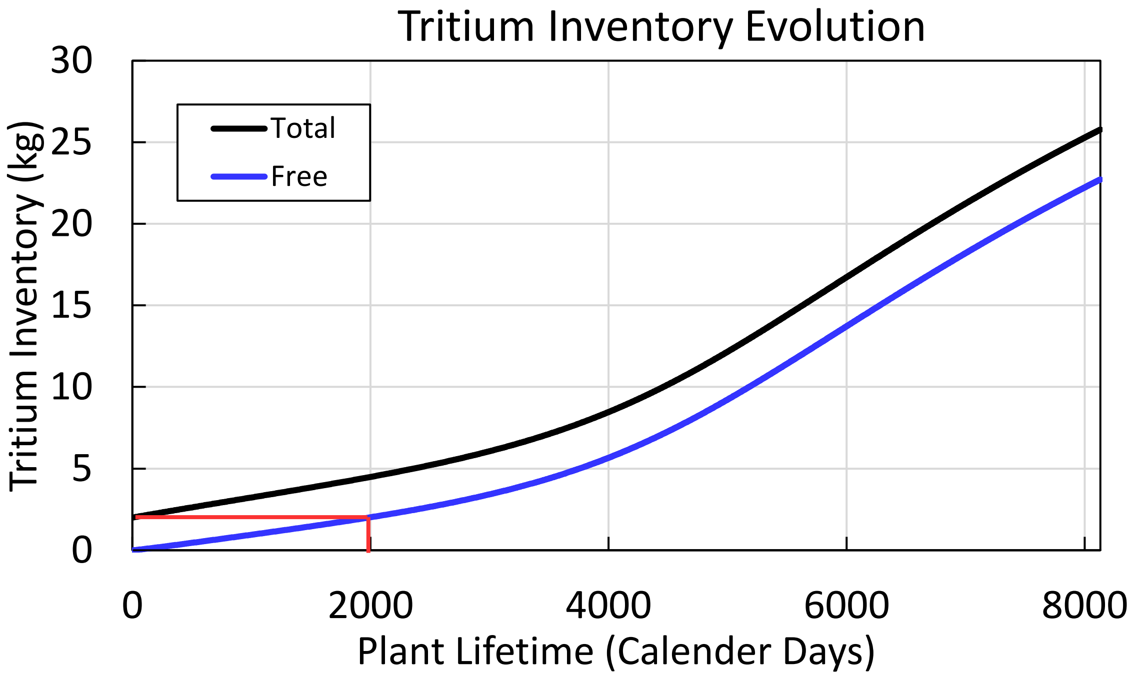


R. Arredondo et al., Nucl. Mater. Energy., 101039, (2021)

Example Case

EU-DEMO:

- $P_{fus} = 2\ GW$
- $TBR = 1.05$
- $T_{op} = 2\ kg$
- $T_{seq} = 1.0\ kg$
- $Av = 0.3\ (0.1 \rightarrow 0.5)$



- ➢ Doubling time: **5.4 years**
- ➢ Sequestration slow enough to be compensated by excess breeding

→ Negligible excess start-up inventory required

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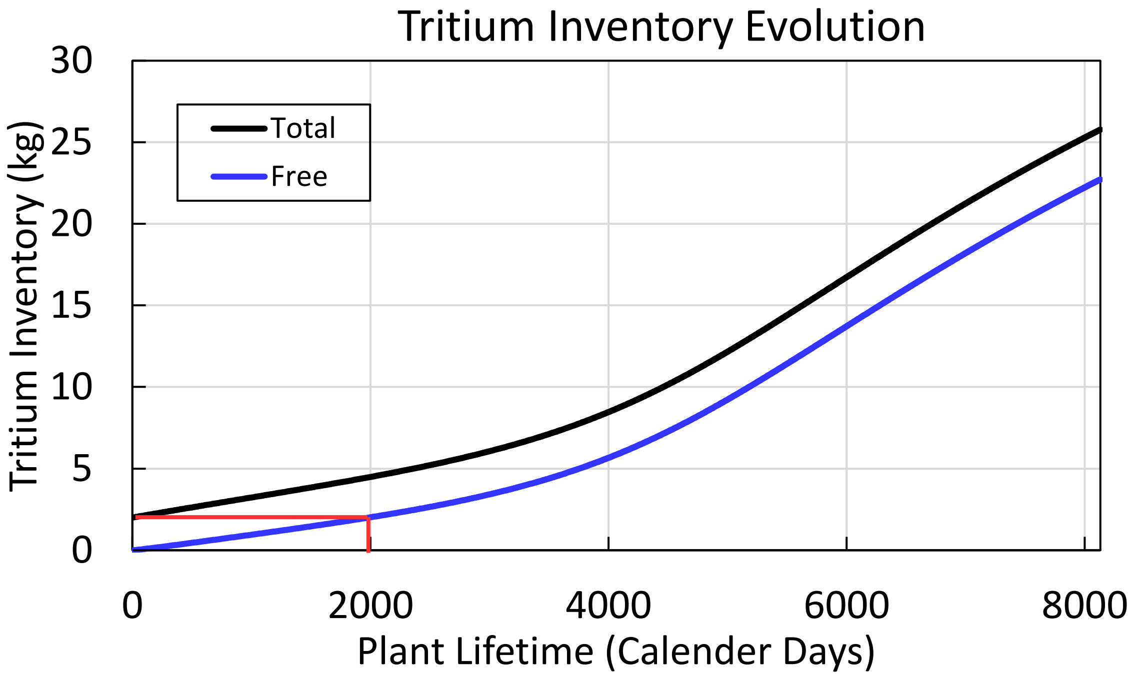

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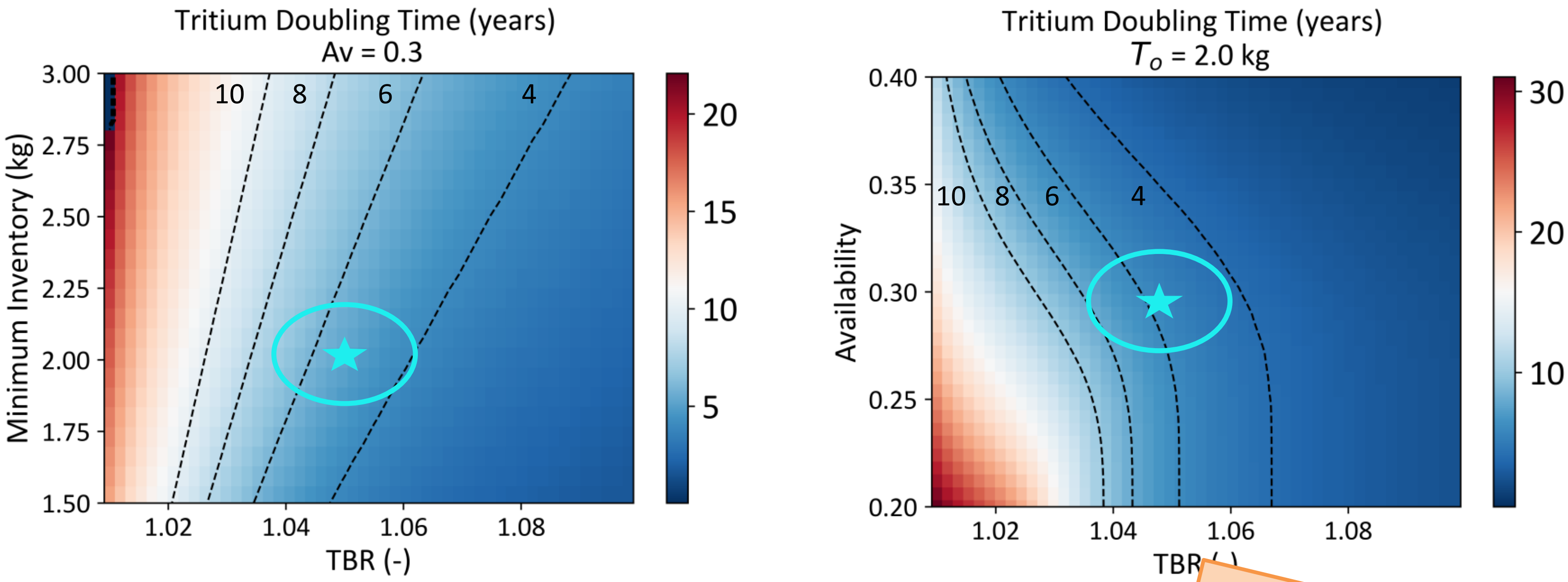
Predicted DEMO performance



Better performance required for FPPs

- 4 - 8 years to breed the first two kg of excess tritium
- Time to 100 GW_{el} : **> 50 years**
- Bad performance in multiple parameters can be mission critical

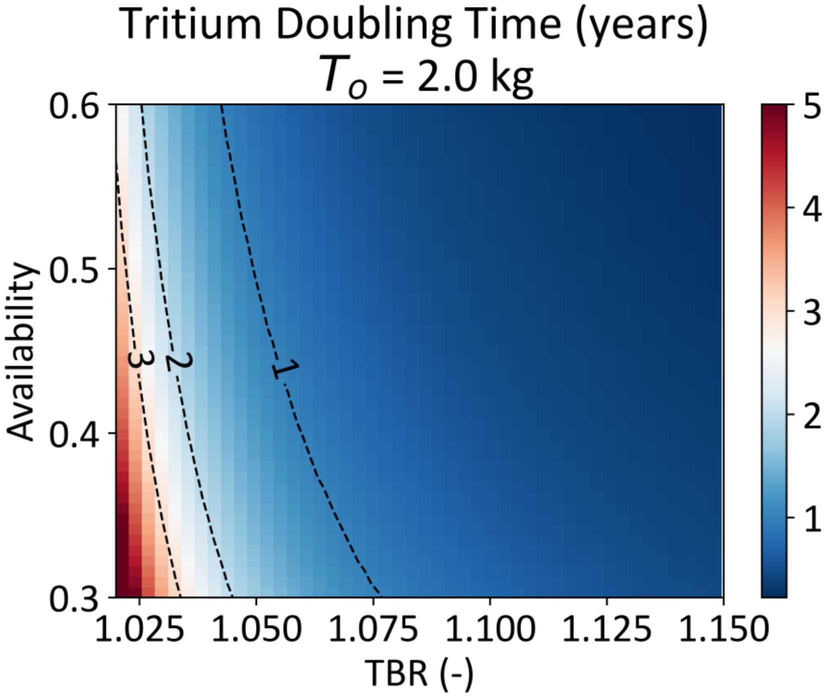
Improved performance

Improving tritium breeding performance:

- Constant availability
- Higher availability
- Lower operational inventory
- Higher TBRs

➢ Significant benefits from constant availability

➢ Very low availabilities (Av < 30%) still detrimental



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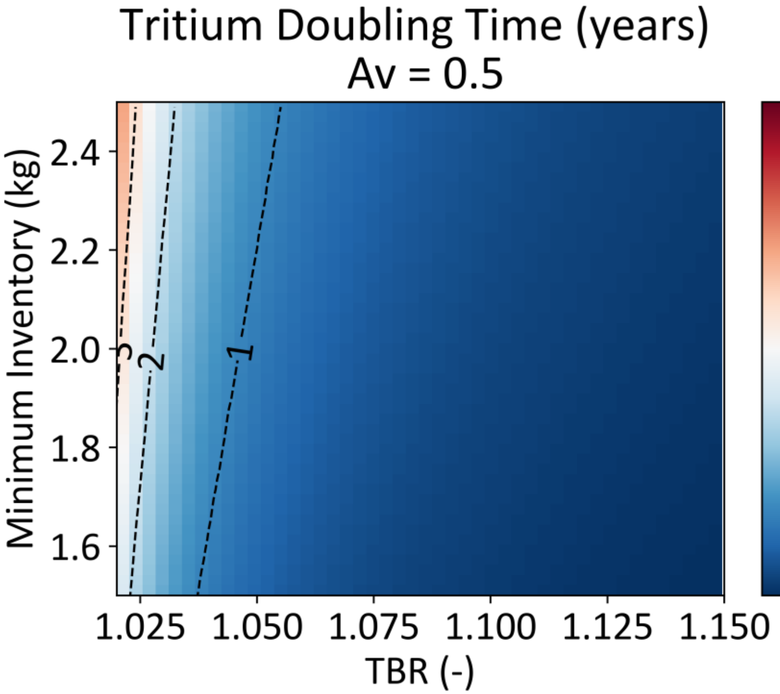

➢ Close to linear impact of operational inventory
➢ Extremely high TBRs (>1.1) unnecessary

Takeaway and caveats

Tritium breeding performance depends on more than just TBR

- Many aspects limited by technologies

ToDo	Options
Lower Operational Inventories	**Improved fuel cycle technologies** (Isotope Separation, Vacuum Pumping)
Raise Initial Availability	**Integrated Test Facilities** (DIPAK, CHIMERA, UNITY, H3AT…)
Increase Plant Lifetime	**Advanced Blankets & Materials** (SiC, Liquid First Walls, ODS steels)
Reduce Tritium Sequestration	
Mitigate Impact of Exploding Global Tritium Stockpiles	**Continuous Accountancy** **Tuneable TBR** (Lithium Isotopic Tailoring)

Thank you!

Back-up Slides

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Simplified (w/o decay):

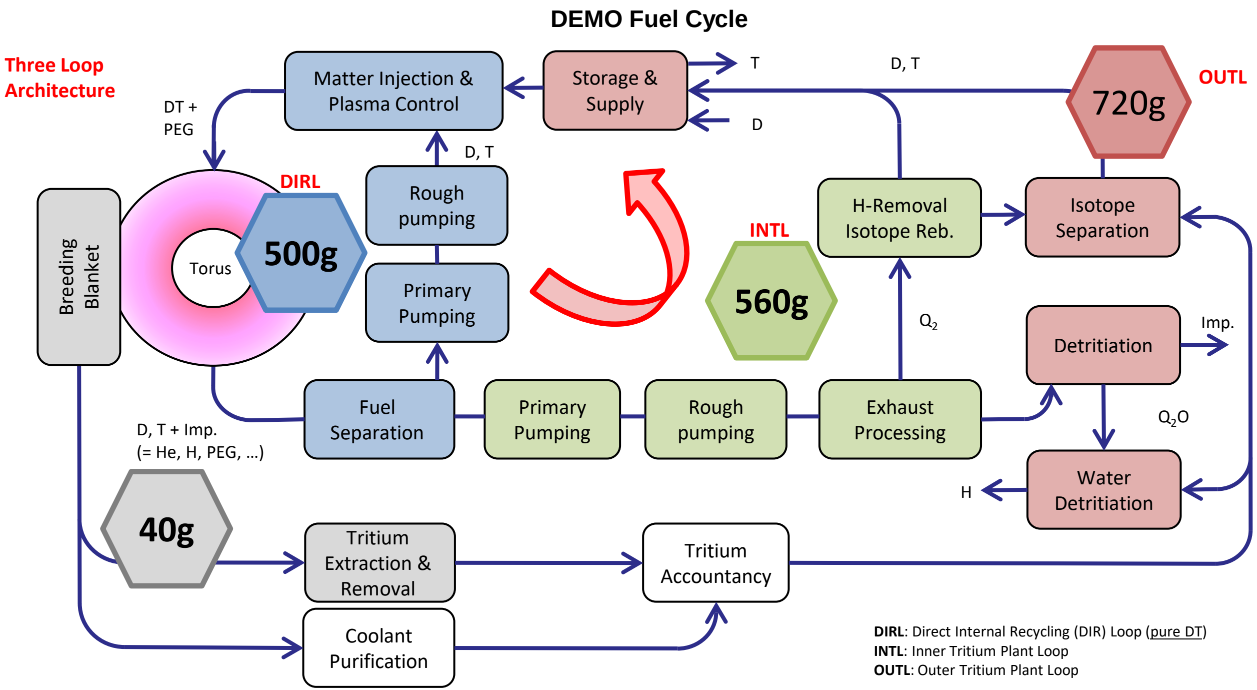
Excess tritium breeding rate:

2 GW_{fus} → 307 g/fpd Tritium consumption (154 g/GW/fpd)

- 5% Excess breeding: 15.4 g/fpd (5.6 kg/fpy)
- 15% Excess breeding: 46.1 g/fpd (16.8 kg/fpy)

50% Availability (constant):

- 5% Excess breeding: 2.8 kg/year
- 15% Excess breeding: 8.4 kg/year



DIRL: Direct Internal Recycling (DIR) Loop (pure DT)
INTL: Inner Tritium Plant Loop
OUTL: Outer Tritium Plant Loop

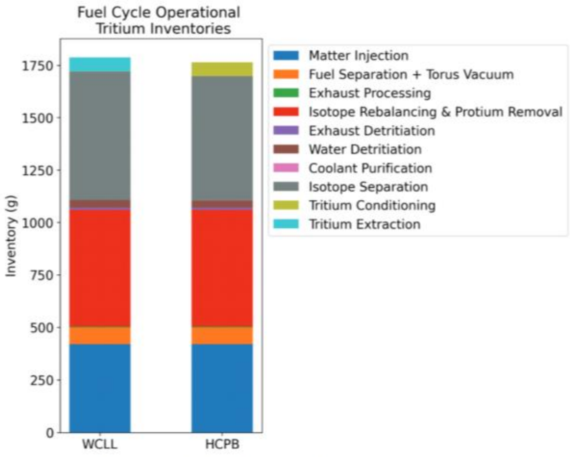
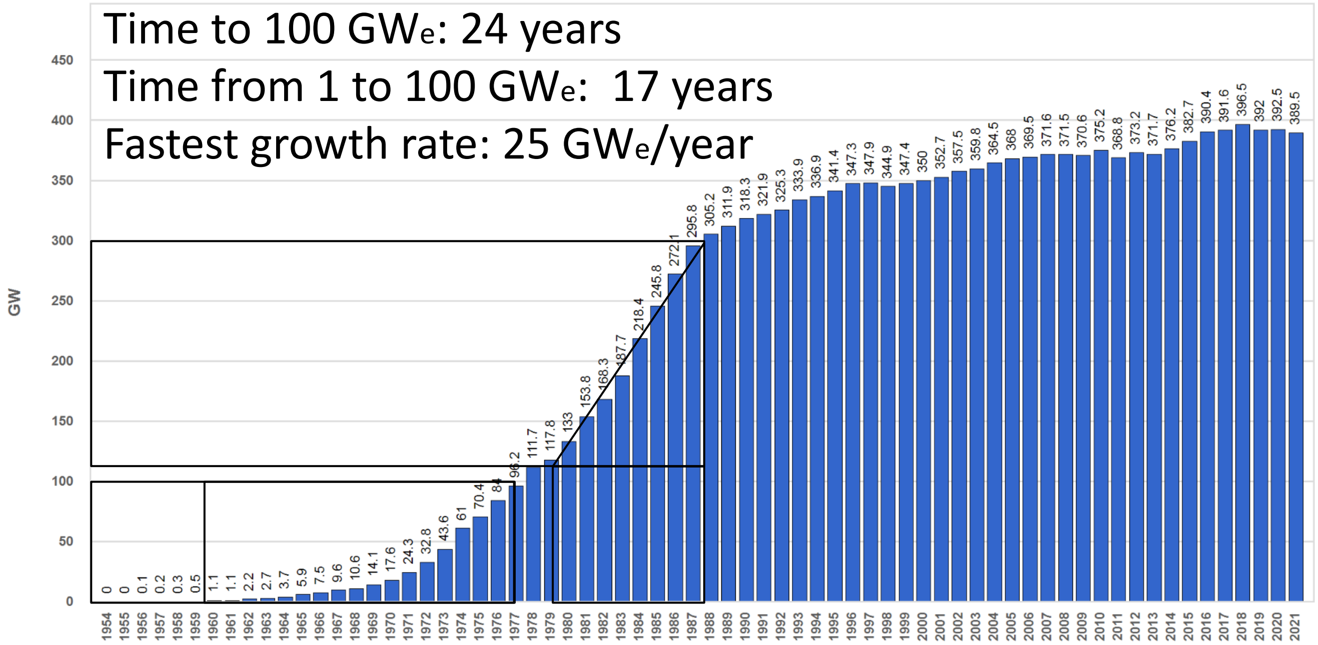


Fig. 3. Tritium inventories in the systems of the EU-DEMO FC for both blanket concepts.

Comparison to fission

Figure 9. Historical evolution of the worldwide nuclear power (as of 31 Dec. 2021)



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