Challenges Related to Tritium Transport in Fusion Reactors:

from ~~component~~ MATERIAL to system level

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The tritium issue

Data source: Pearson et al, Fusion Engineering and Design 136 (2018) 1140–1148

$$\mathrm{T} \rightarrow \mathrm{He} + \mathrm{e}^{-}$$

Half-life: 12 years

The tritium issue

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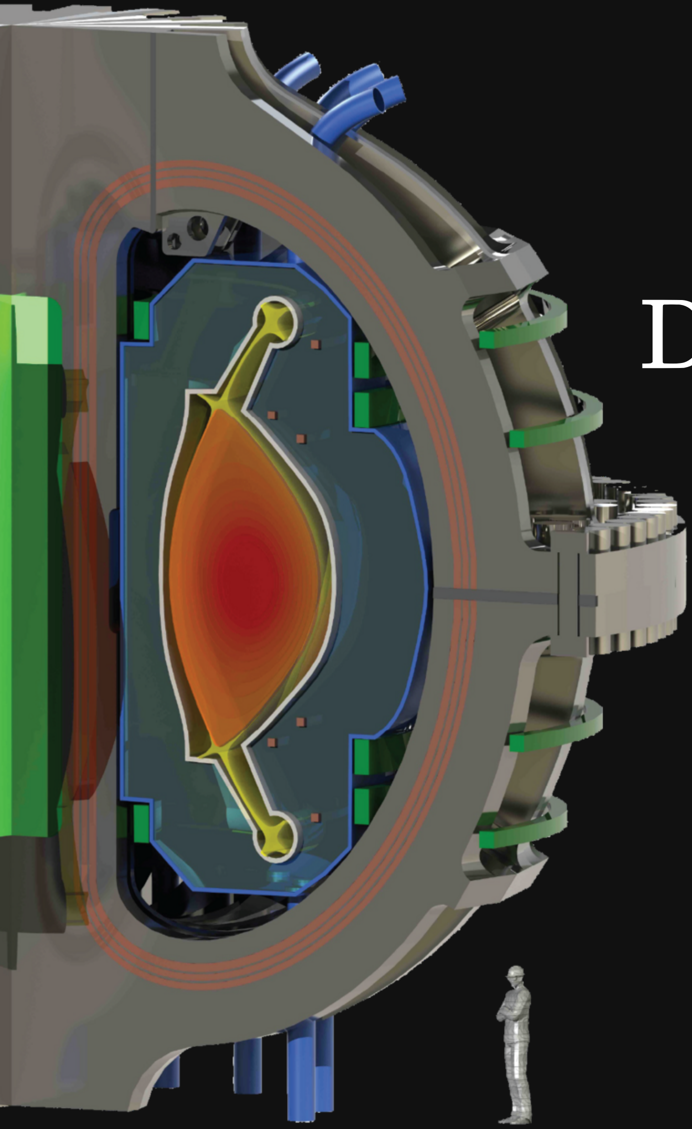
$$\mathrm{T} \rightarrow \mathrm{He} + \mathrm{e}^{-}$$

Half-life: 12 years

+ radiological safety & regulatory issues

The breeding blanket



$$\mathrm{D} + \mathrm{T} \rightarrow \mathrm{He} + \mathrm{n}$$

$$\mathrm{n} +^{6}\mathrm{Li} \rightarrow \mathrm{T} + \mathrm{He} + 4.8\ \mathrm{MeV}$$

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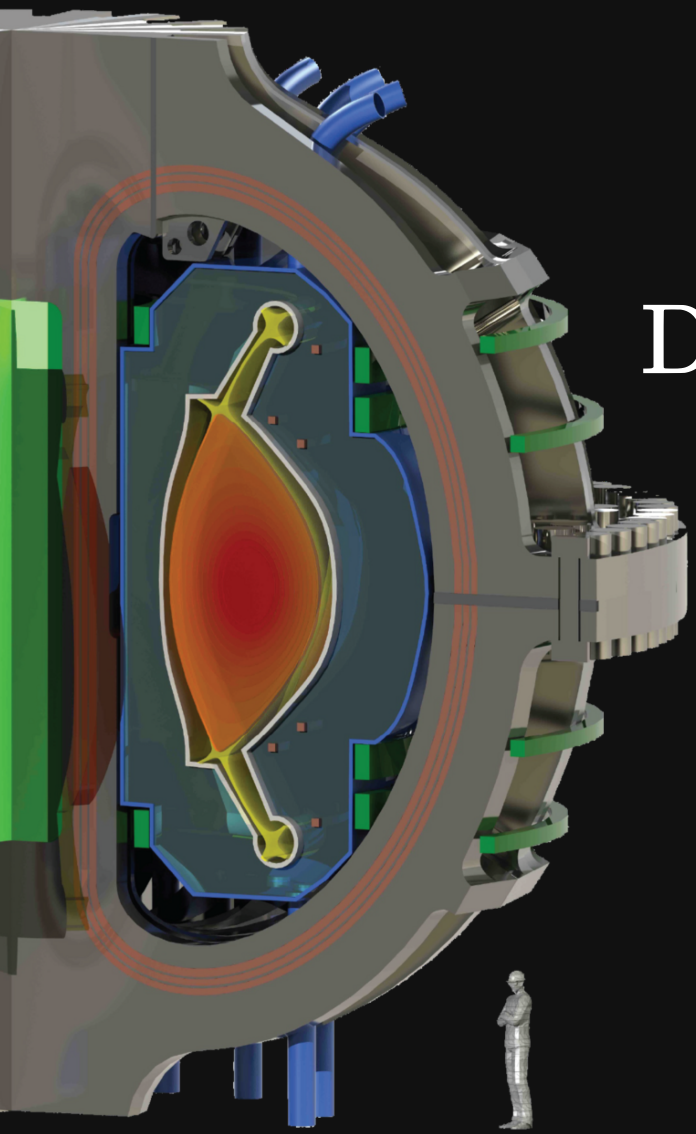

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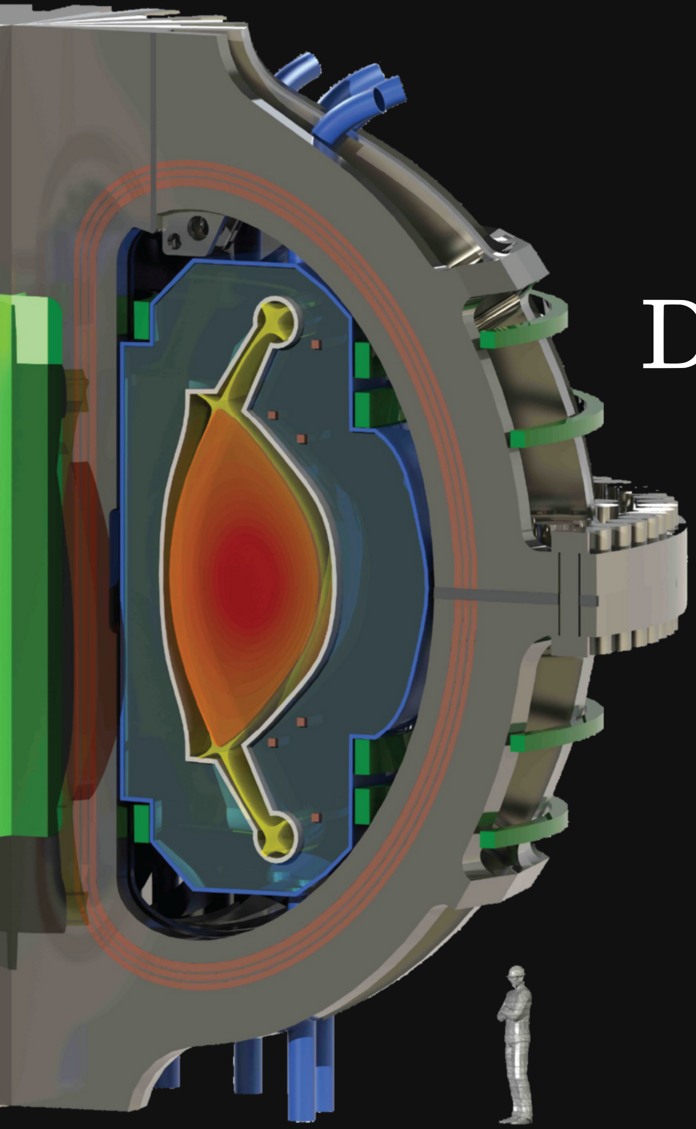

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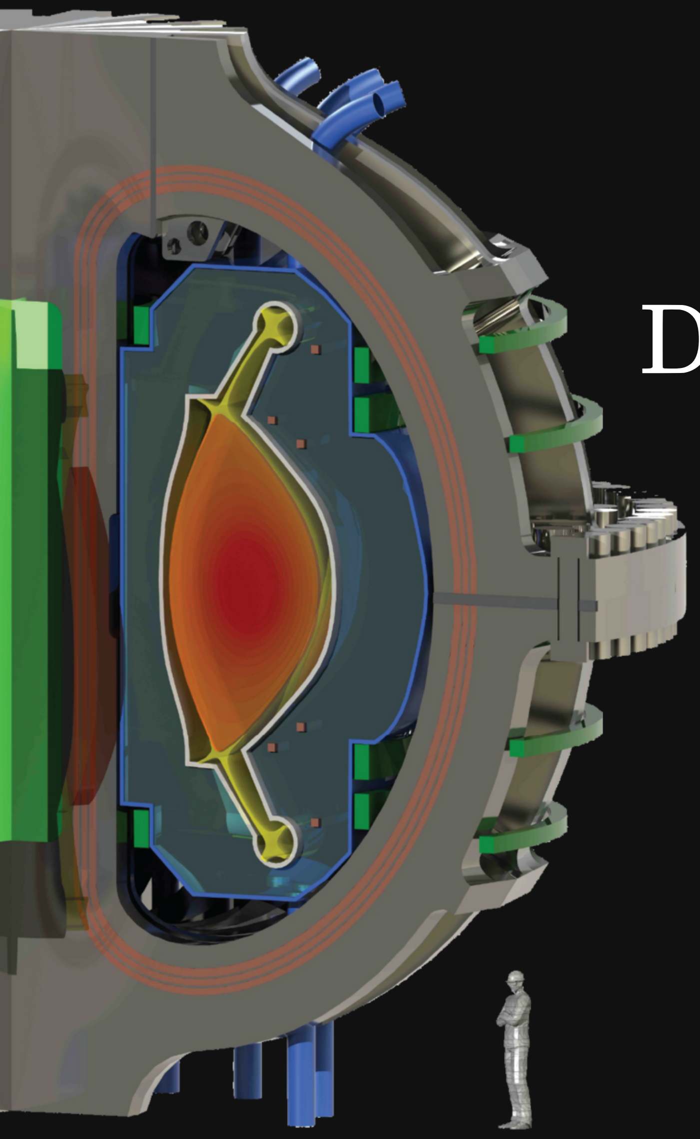

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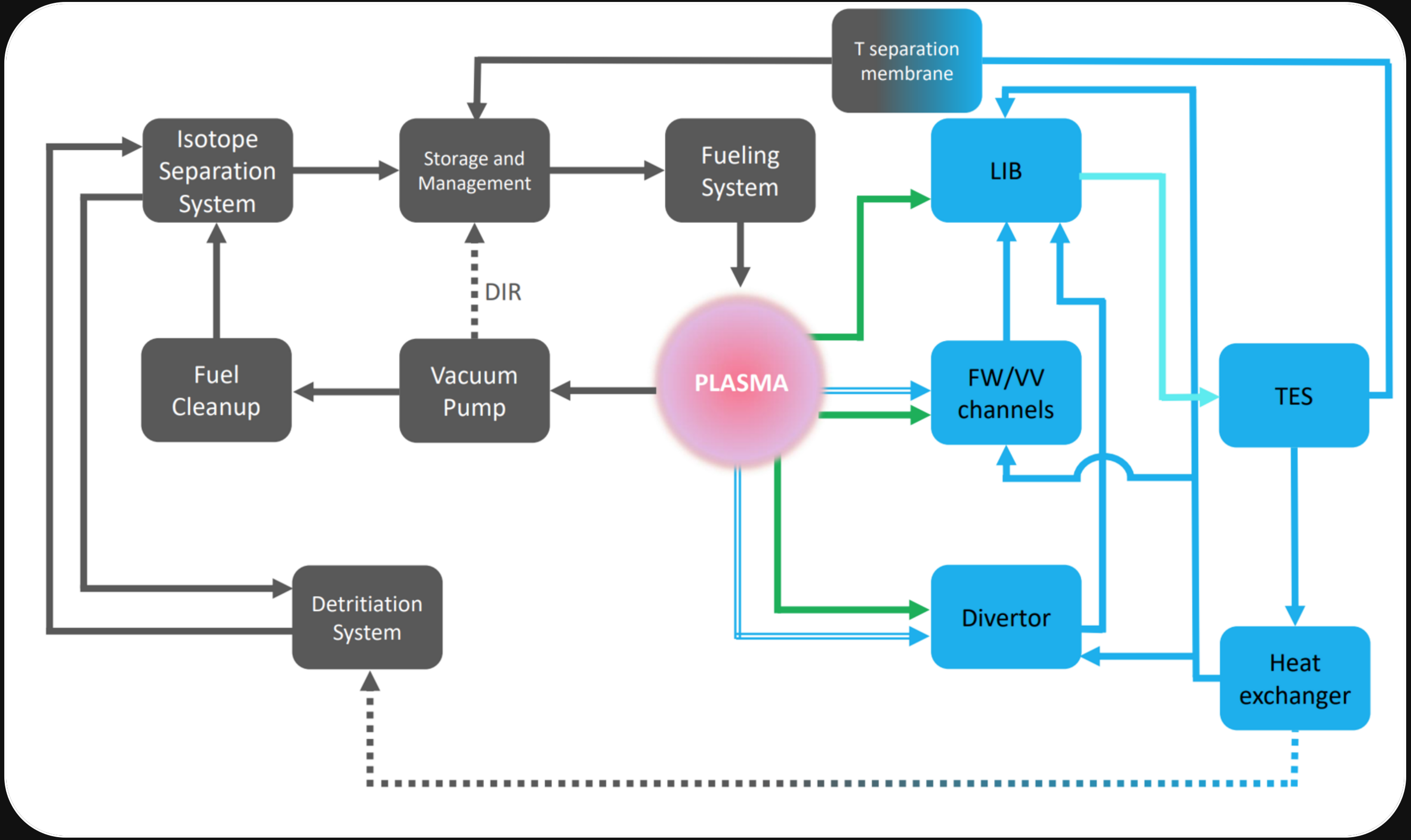
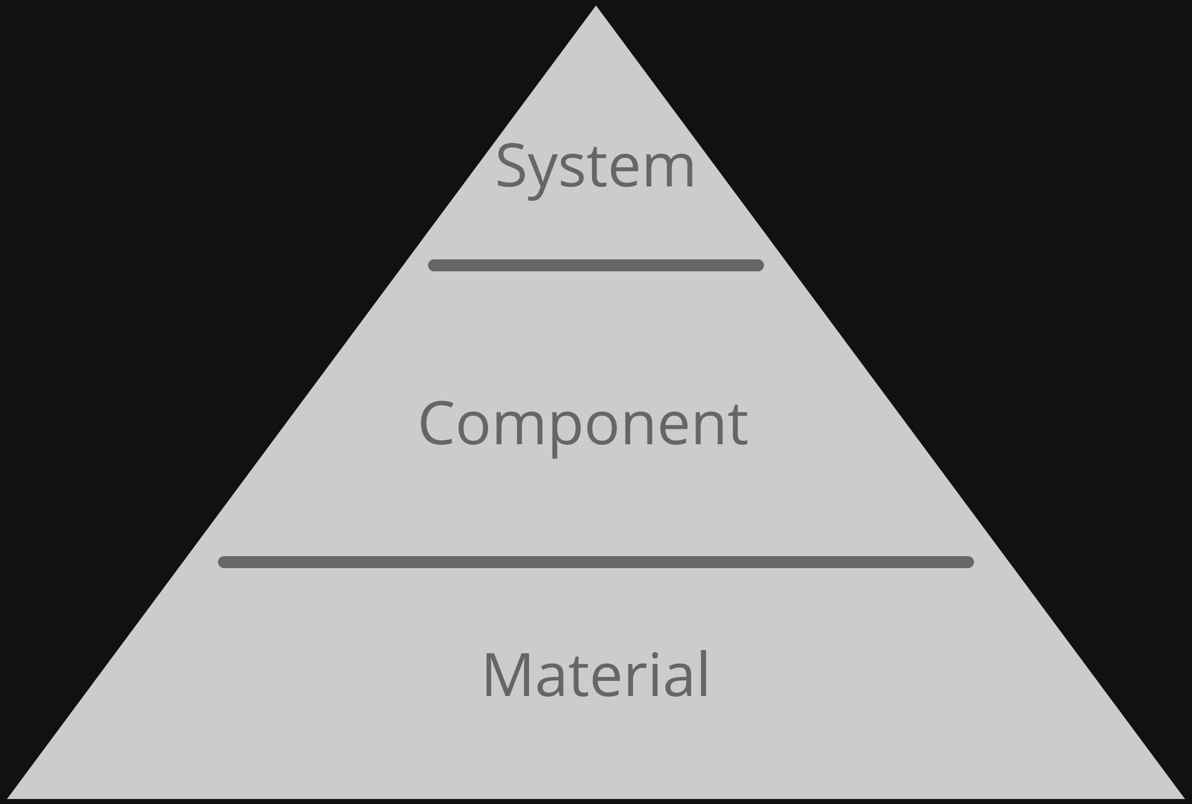
$$\text{TBR} = \frac{\text{tritium produced}}{\text{tritium consumed}} > 1$$

The breeding blanket is only one component of the fuel cycle



Samuele Meschini *et al* 2023 Nucl. Fusion 63 126005

Multi-scale tritium design



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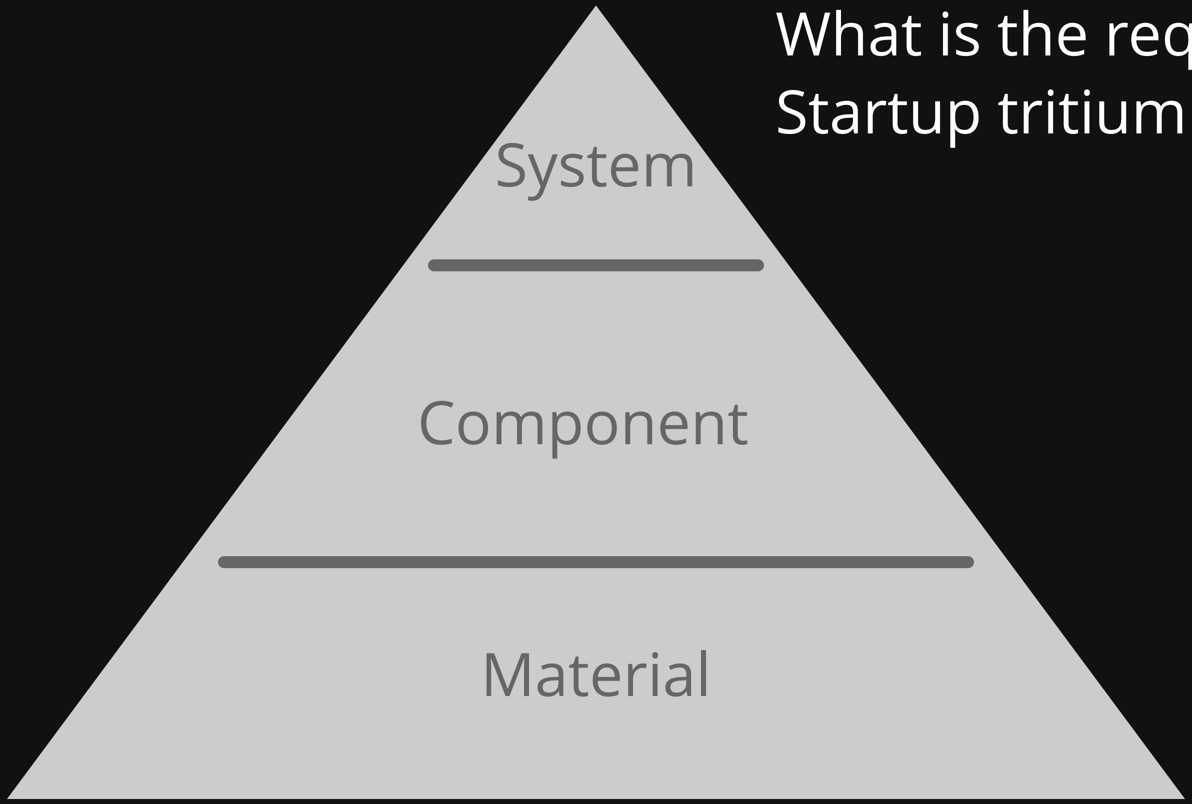

What is the required TBR?
Startup tritium inventory?

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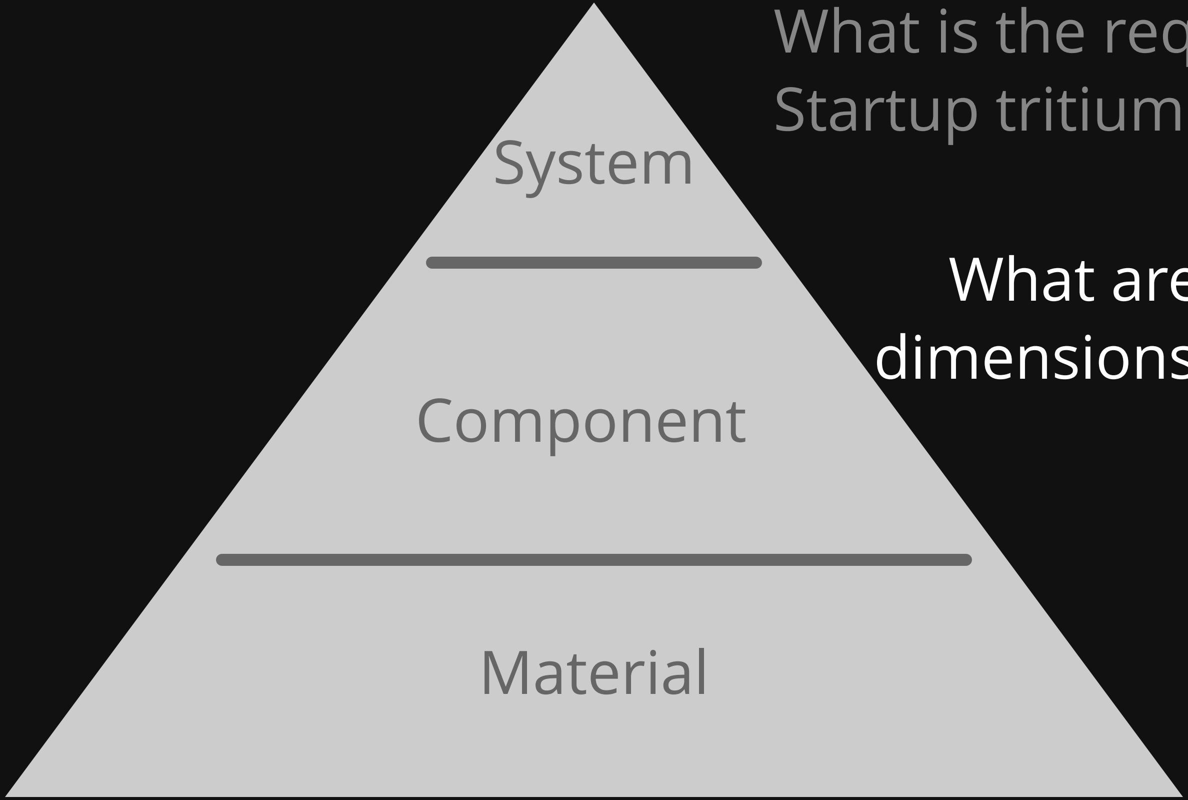

What is the required TBR?
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What is the T concentration
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What are the minimum
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How much T is retained in
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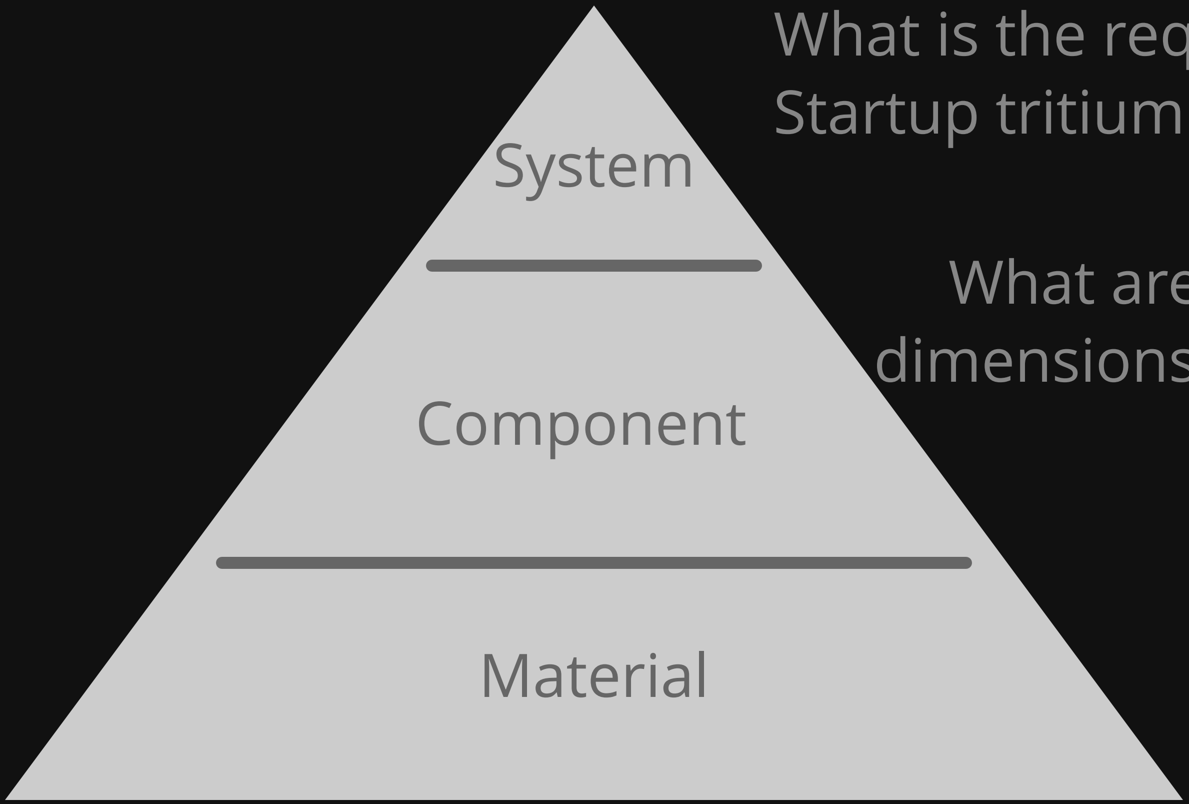

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Trapping properties of tungsten?

Permeation reduction factor of coating X?

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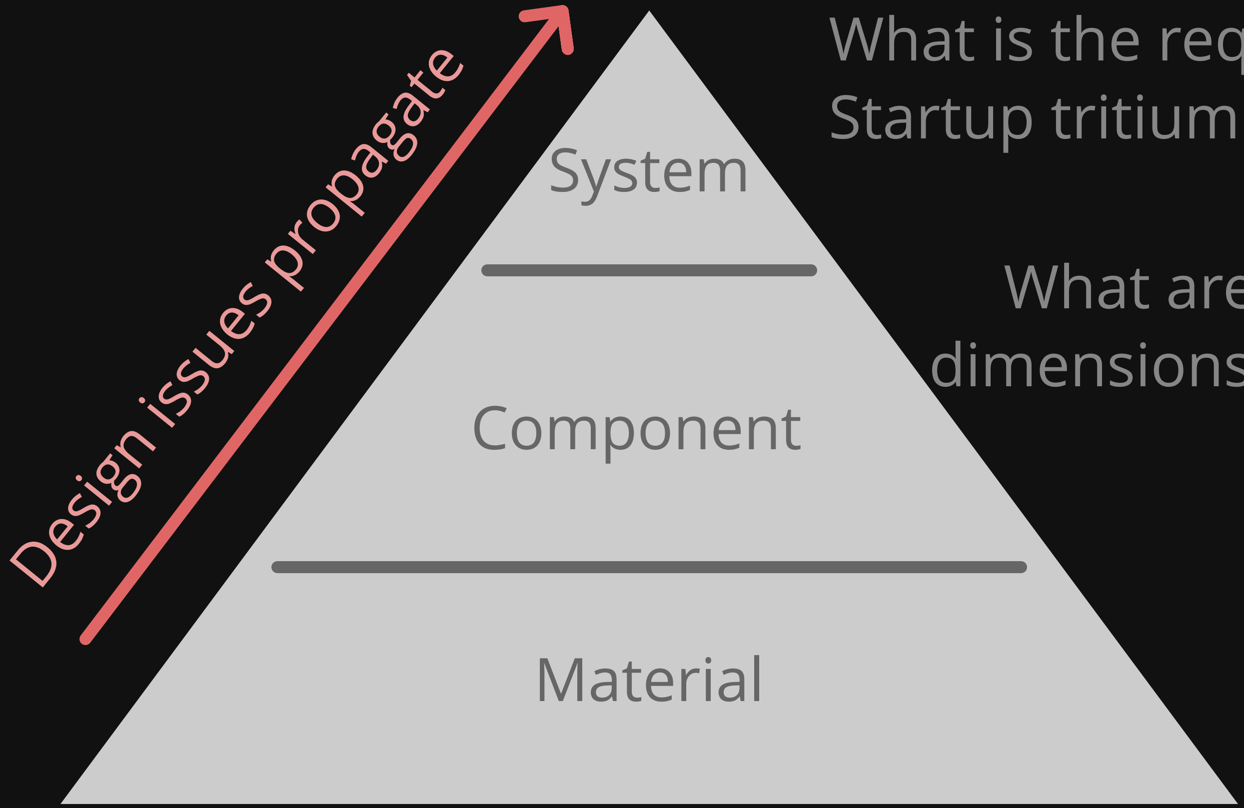

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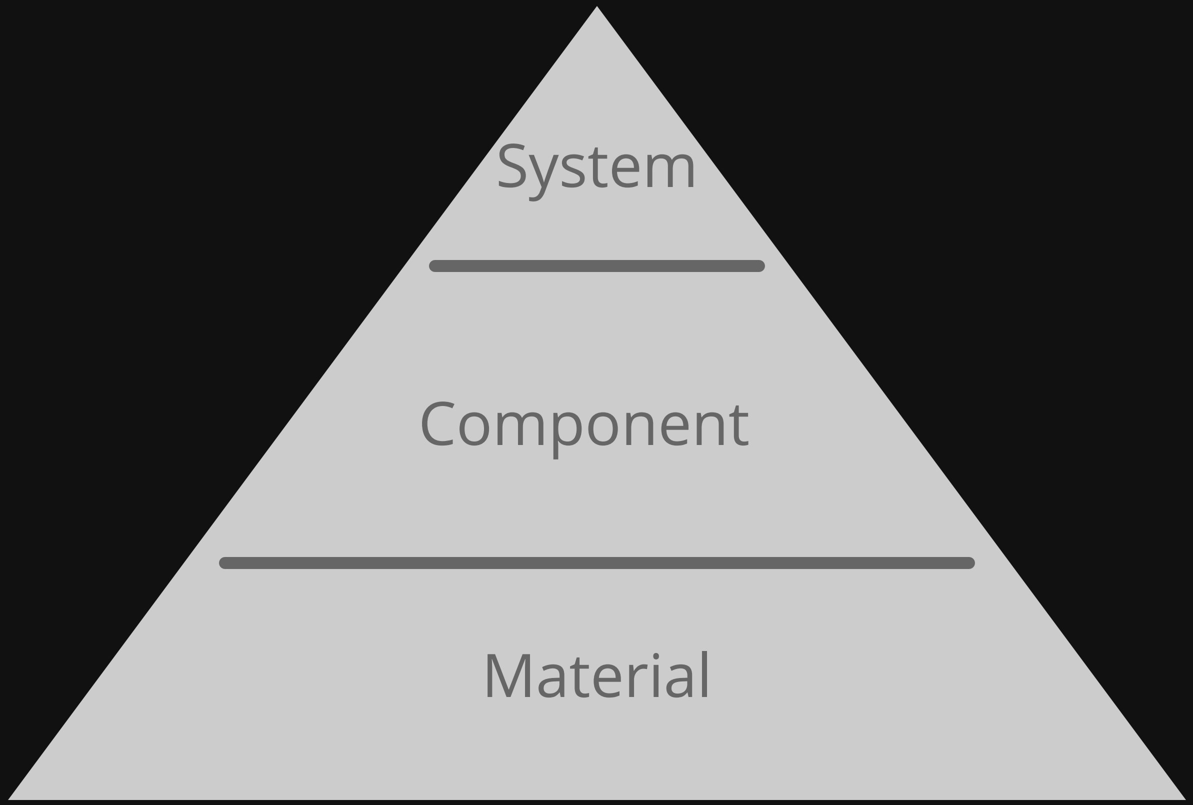
Outline



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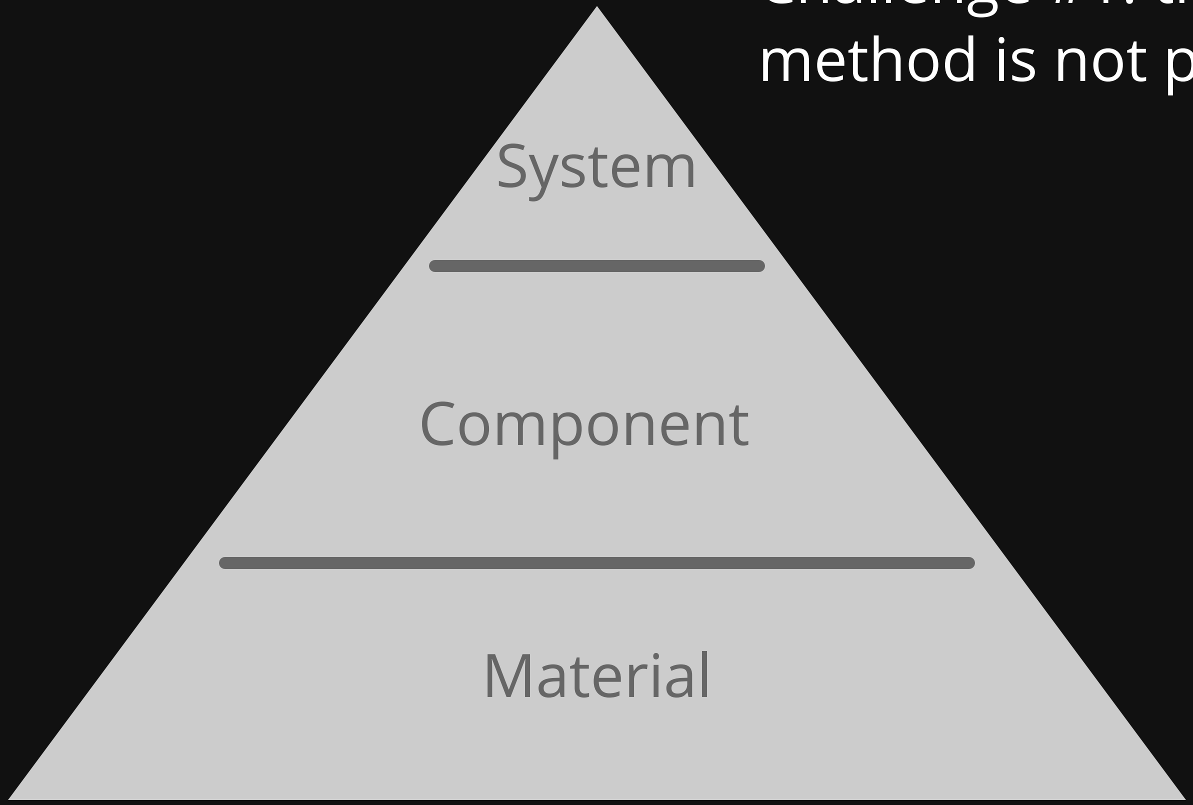
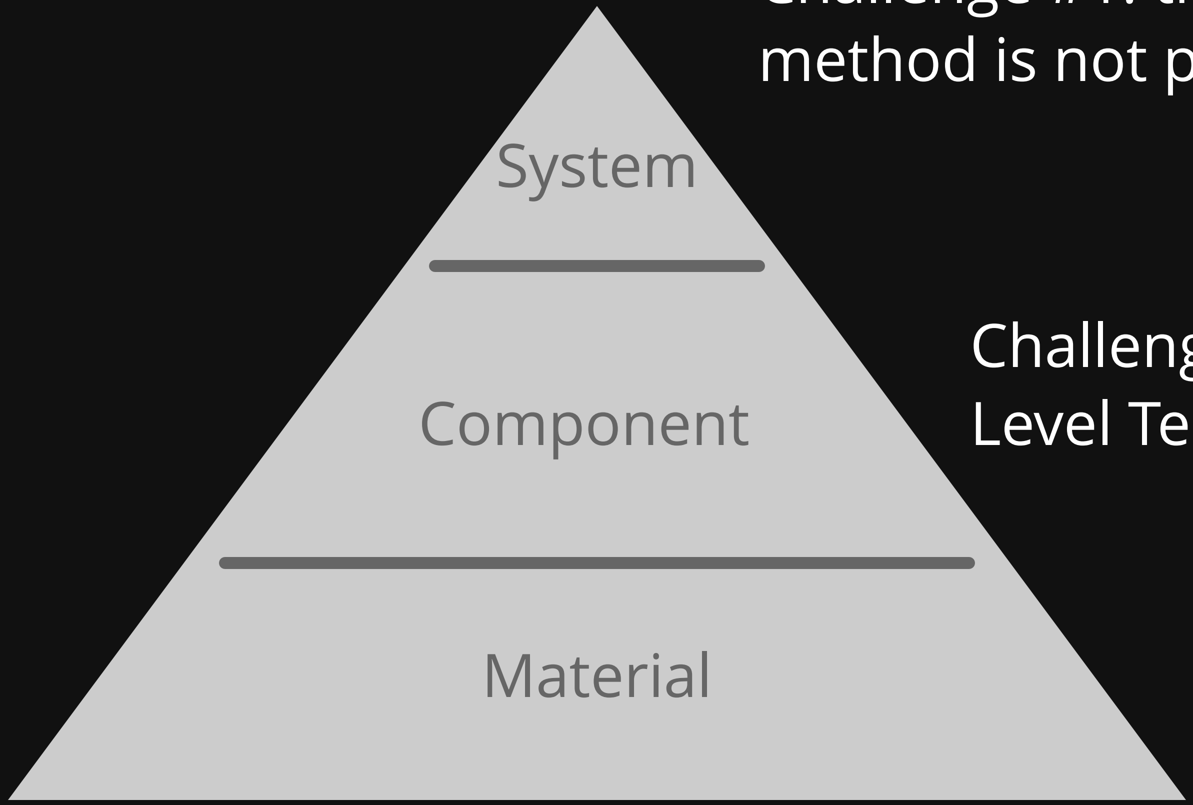


Challenge #1: the residence time method is not predictive

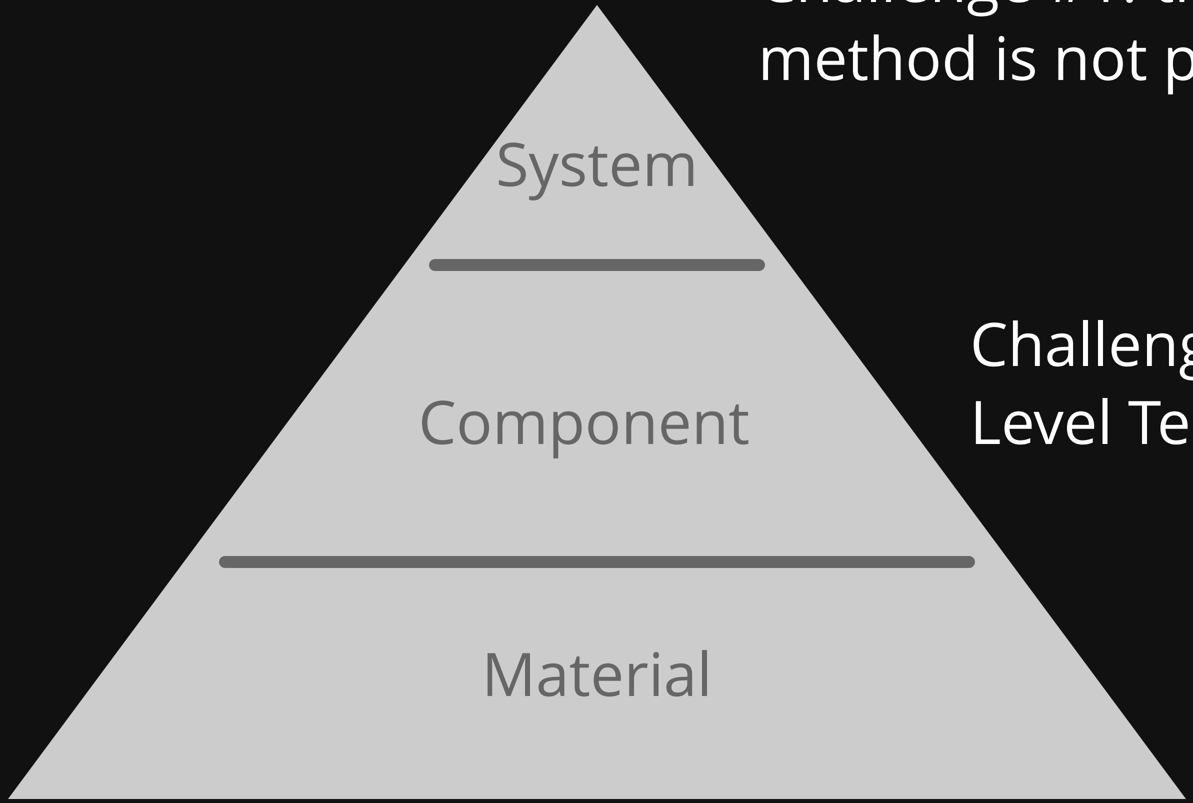
Outline



Challenge #1: the residence time method is not predictive

Challenge #2: Component-Level Testing Remains Limited

Outline

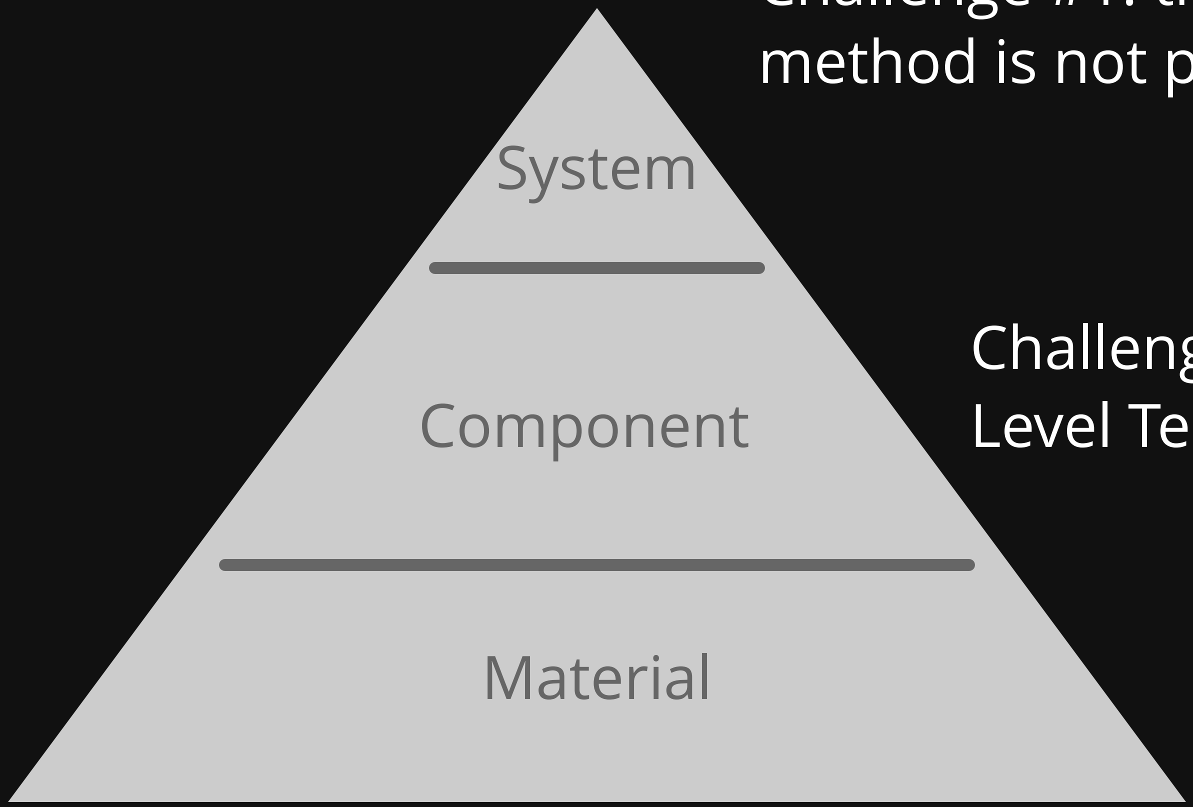


Challenge #1: the residence time method is not predictive

Challenge #2: Component-Level Testing Remains Limited

Challenge #3: Experiments for Property Measurements Are Not Standardised

Outline



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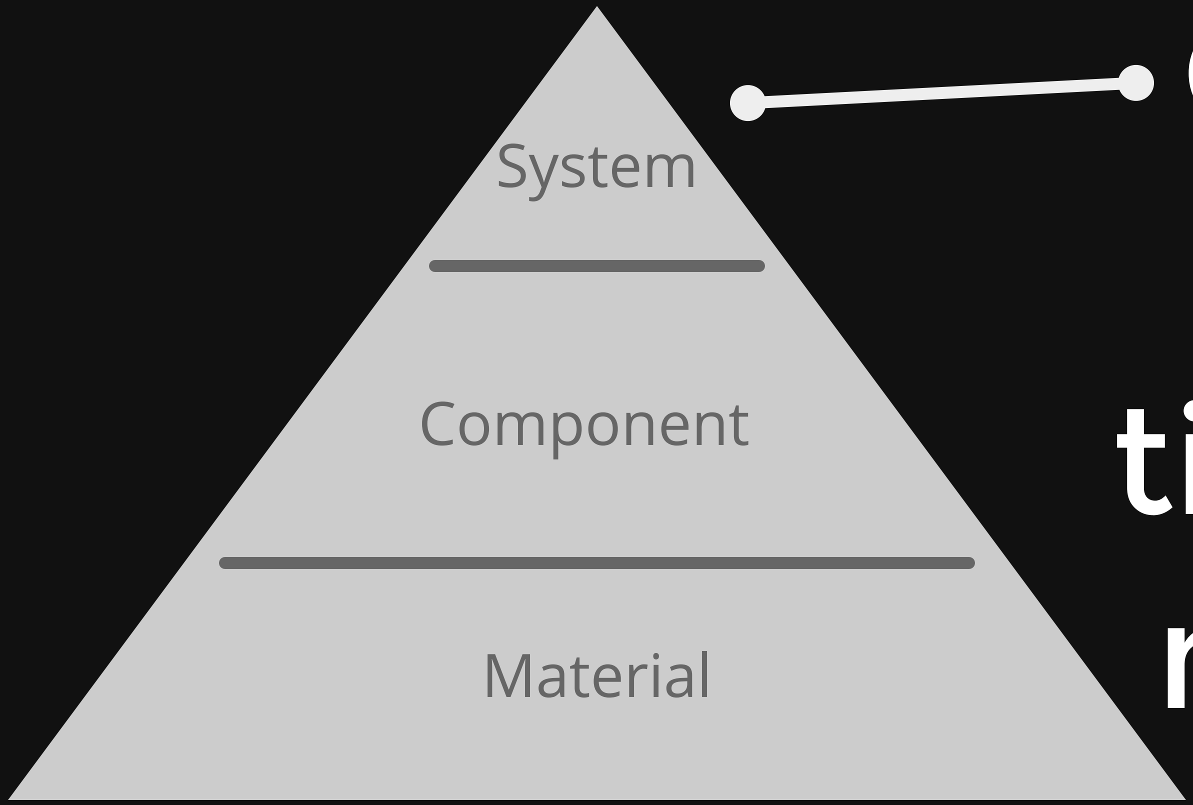
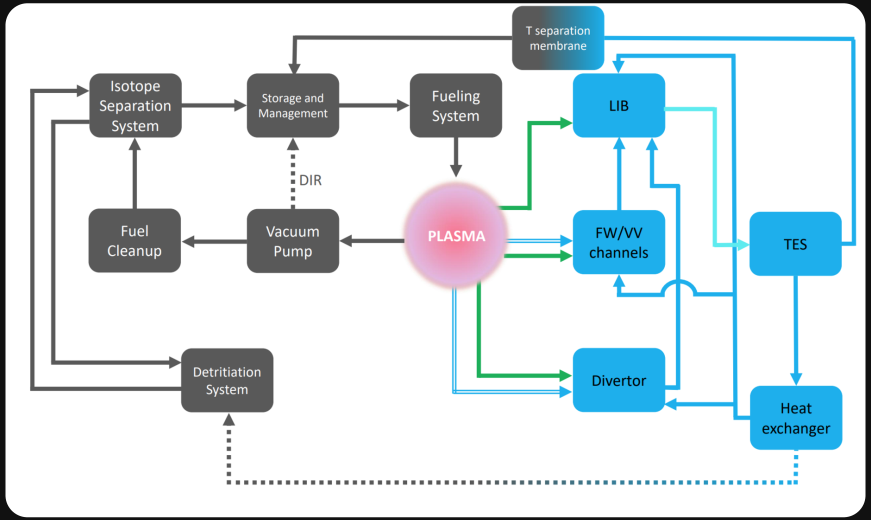
Challenge #3: Experiments for Property Measurements Are Not Standardised

Challenge #4: Data on Transport Properties is Scarce and Variable



Challenge #1: the residence time method is not predictive

Context: system fuel cycle modelling and the residence time method



Goal: to model tritium mass fluxes between components

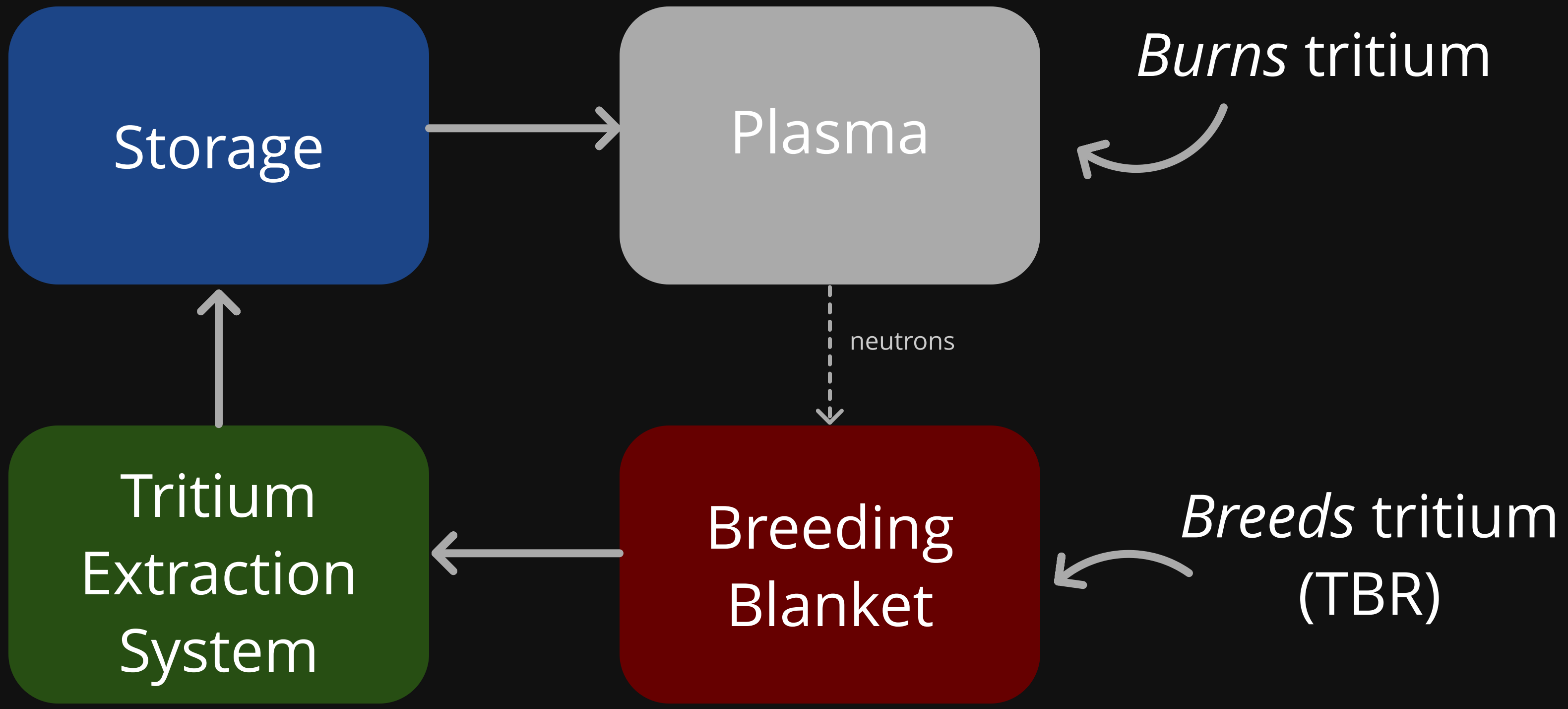
For each component i

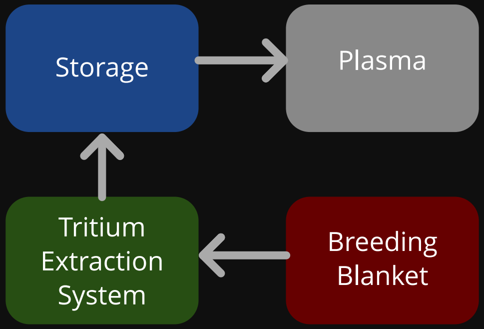
$$\underbrace{\frac{dI_i}{dt}}_{\text{inventory evolution}} = \underbrace{\sum F_{\text{in}}}_{\text{tritium in}} - \underbrace{\frac{I_i}{\tau_i}}_{\text{tritium out}}$$

Residence time

Samuele Meschini *et al* 2023 Nucl. Fusion 63 126005

Illustration with a simple fuel cycle model





https://remdelaportemathurin.github.io/interactive-plots/fuel_cycle/fuel_cycle_residence_time_plotly_dark.html

Startup inventory

Limitations

- How to estimate the residence time?
- What if there are several phases in the blanket (eg. LiPb and coolants)?
- Great simplifications need to be made for permanent trapping

Source: remdelaportemathurin.github.io/interactive-plots/fuel_cycle/

Challenge #1: the residence time method is not predictive

Current situation

- System-level tritium models often use fixed residence times for each subsystem.
- Approach is empirical and lacks connection to material physics.

Risks & implications

- Large uncertainties and increased safety and performance risks.
- Inconsistent assumptions across organisations → poor comparability.
- Weak technical basis for regulatory review.

Path forward

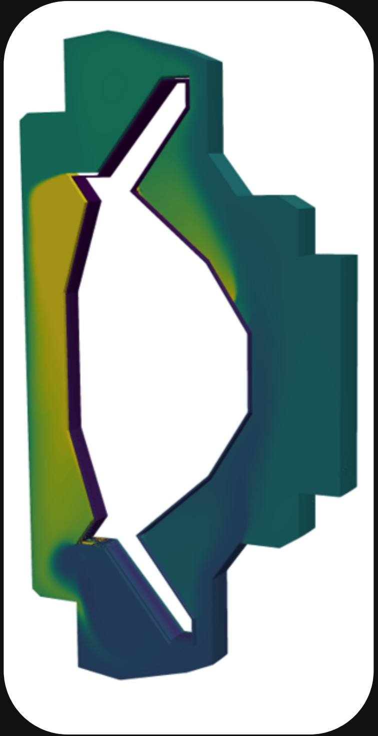
Move towards *physics-informed* component-level models

Challenge #1: the residence time method is not predictive

Path forward

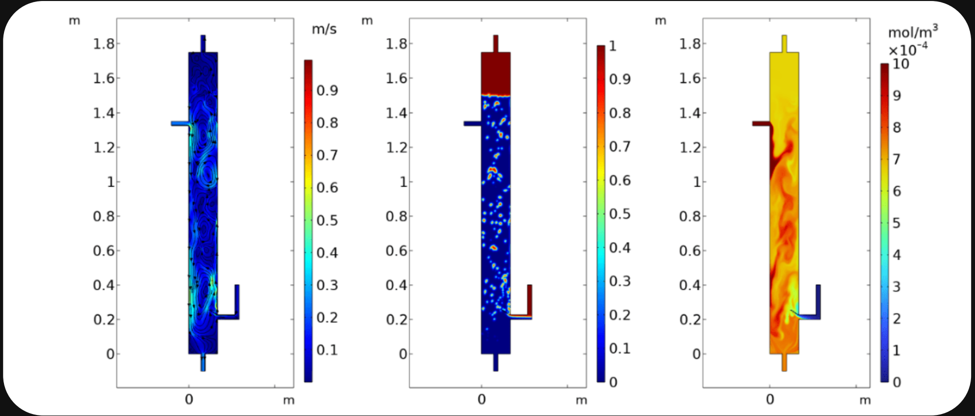
Move towards *physics-informed* component-level models

FESTIM model of an ARC's breeding blanket



Dark *et al*, Tritium 2025, 10.13140/RG.2.2.28729.84321

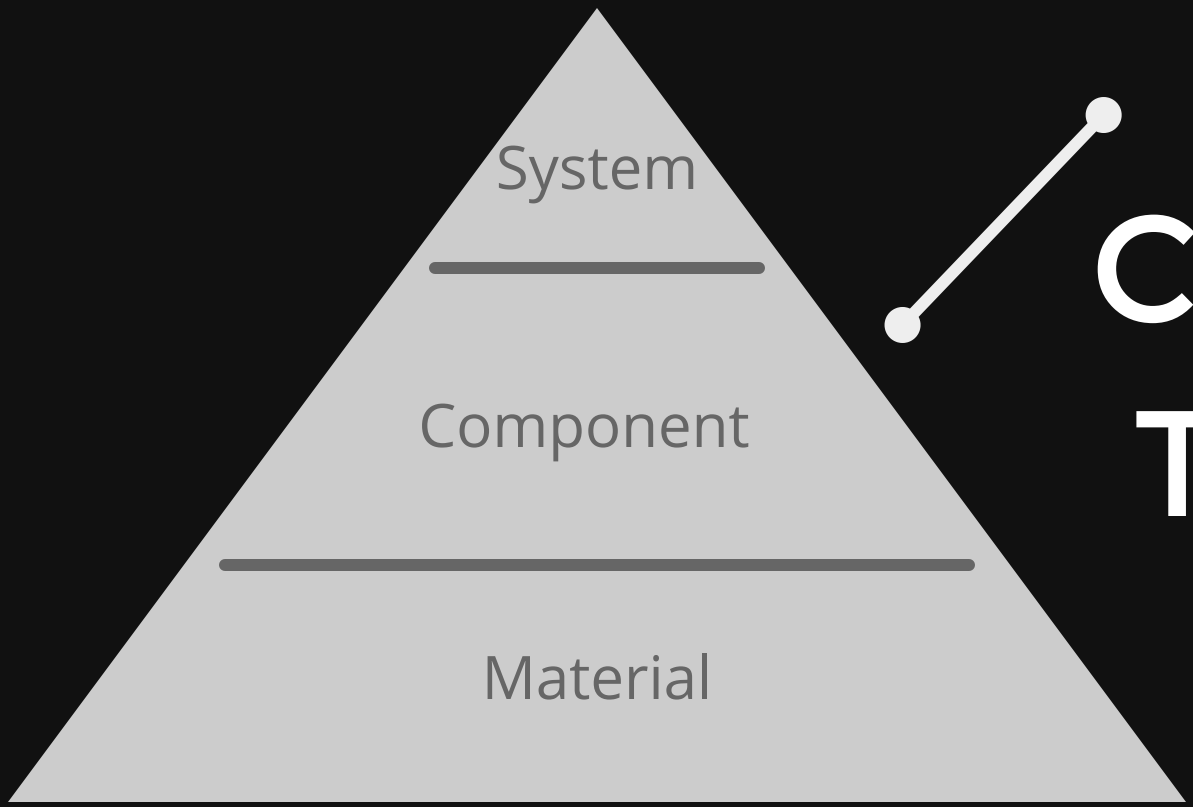
COMSOL model of a bubble column T extractor



Teng Wang *et al* 2025 *J. Phys.: Conf. Ser.* 3011 012054

Other physics-informed models:

- Simpler 1D models
- Surrogate models
- Empirical experimental laws
- ...



Challenge #2: Component-Level Testing is limited

Challenge #2: Component-Level Testing is limited

Current situation

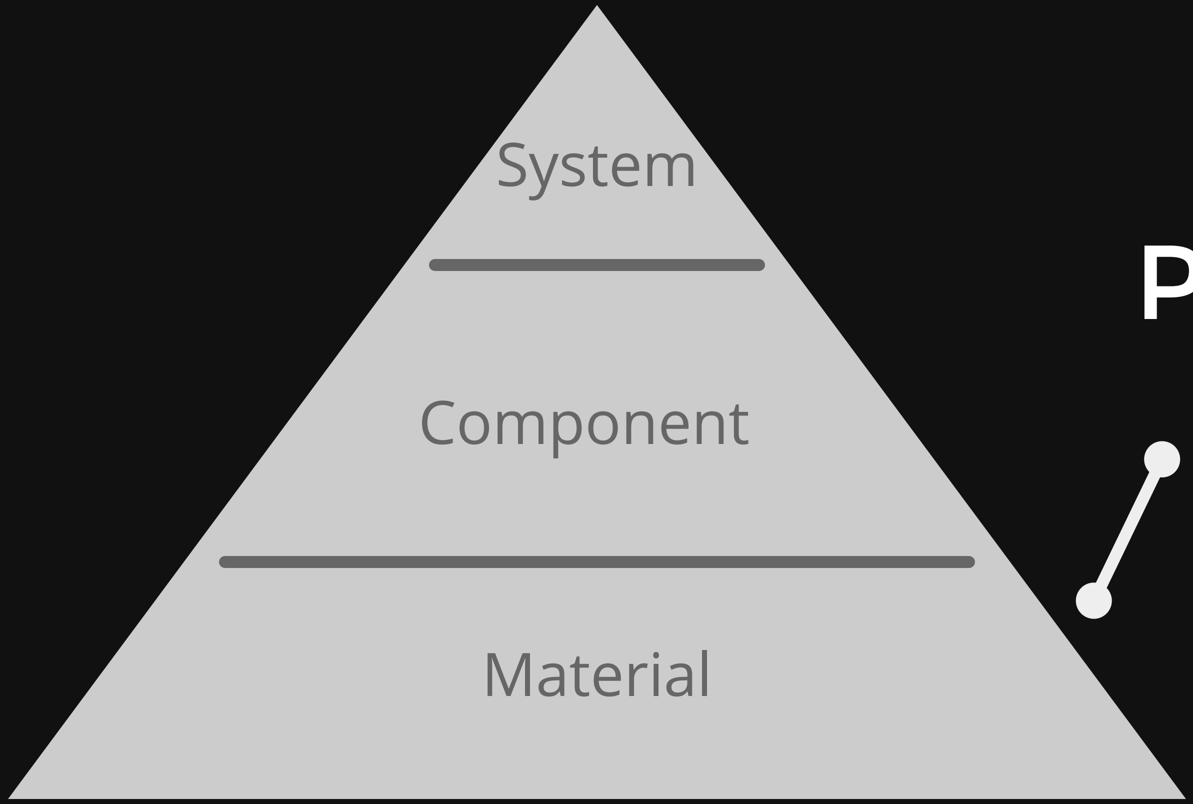
- only few integrated tritium breeding tests + extraction tests exist under "relevant" *combined* conditions
- other hydrogen experiments are focused on coupon tests

Risks & implications

- Large uncertainty in system-level tritium recovery predictions.
- Missing data for code validation and licensing.

Path forward

- More component level experiments such as LIBRA
- A dedicated fuel cycle component test facility



Challenge #3:

Property Measurements are not Standardised

Context: hydrogen transport properties

Governing equations
for H transport

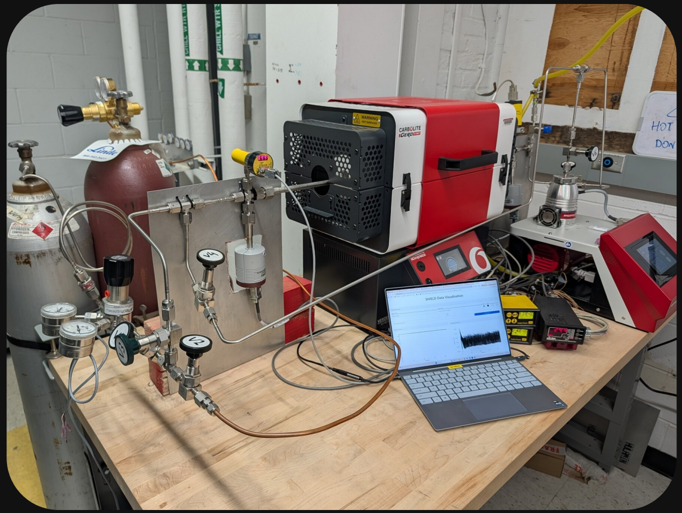
$$\frac{\partial c_m}{\partial t} = \nabla \cdot (\underline{D} \nabla c_m) - \underline{k}\, c_m\, (\underline{n} - c_t) + \underline{p}\, c_t$$

$$c = \underline{K_S}\, \sqrt{P}$$

$$\varphi = \underline{k_d}\, P - \underline{k_r}\, c^2$$

Material properties

- Properties can be obtained experimentally (gas driven permeation, plasma-driven permeation, absorption, thermo-desorption, electro-permeation...)
- Simple in principle, complex in practice.



MIT's SHIELD permeation rig

Challenge #3: Property Measurements are not standardised

Current situation

- No standards for experiments (except electro-permeation ASTM)
- No standard way of disseminating results (units, dimensions…): see Challenge #4
- Hard to quantify tritium retention/trapping
- Few inter-laboratory comparisons (round Robins).

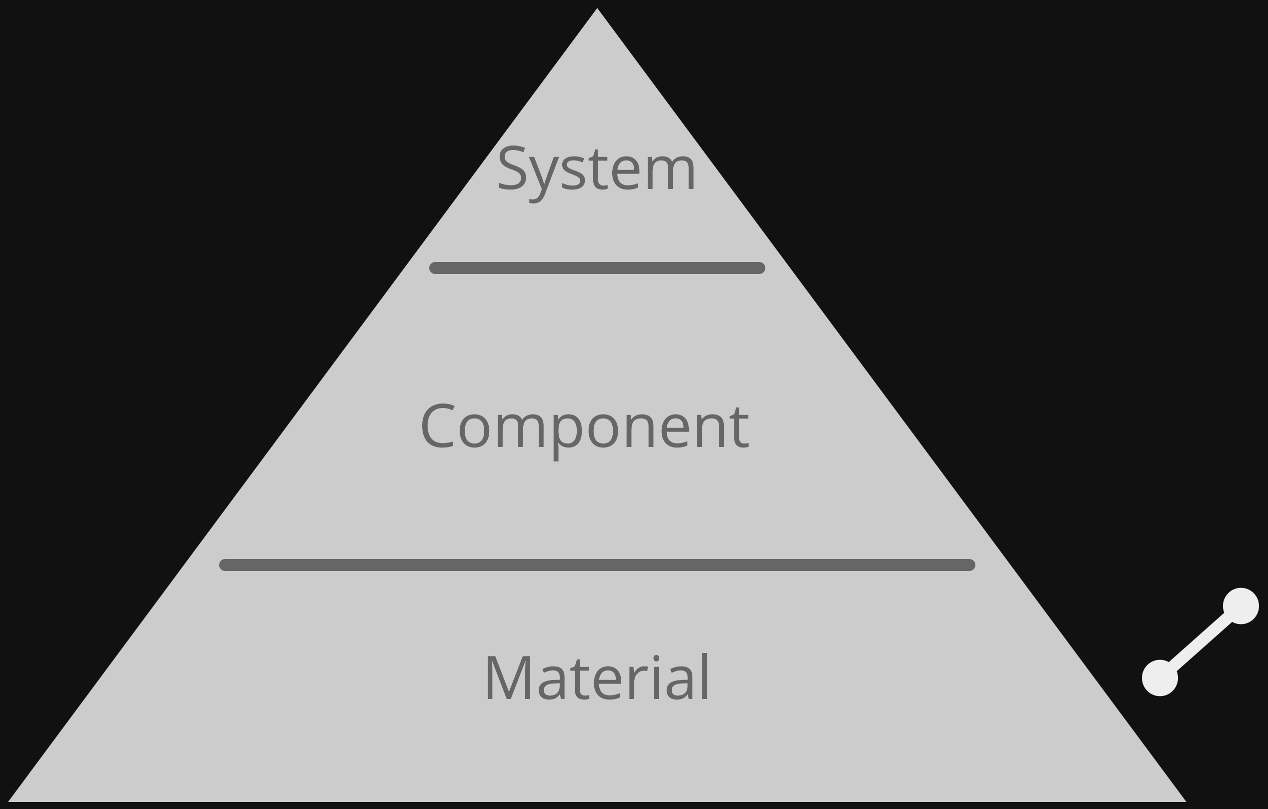
Risks & implications

- Poor reproducibility and large data scatter.
- Difficult to identify reliable reference values.
- Increased risk for dimensioning of components.

Path forward

Develop **standardised experiments & protocols**

for GDP, TDS, PDP…



Challenge #4:

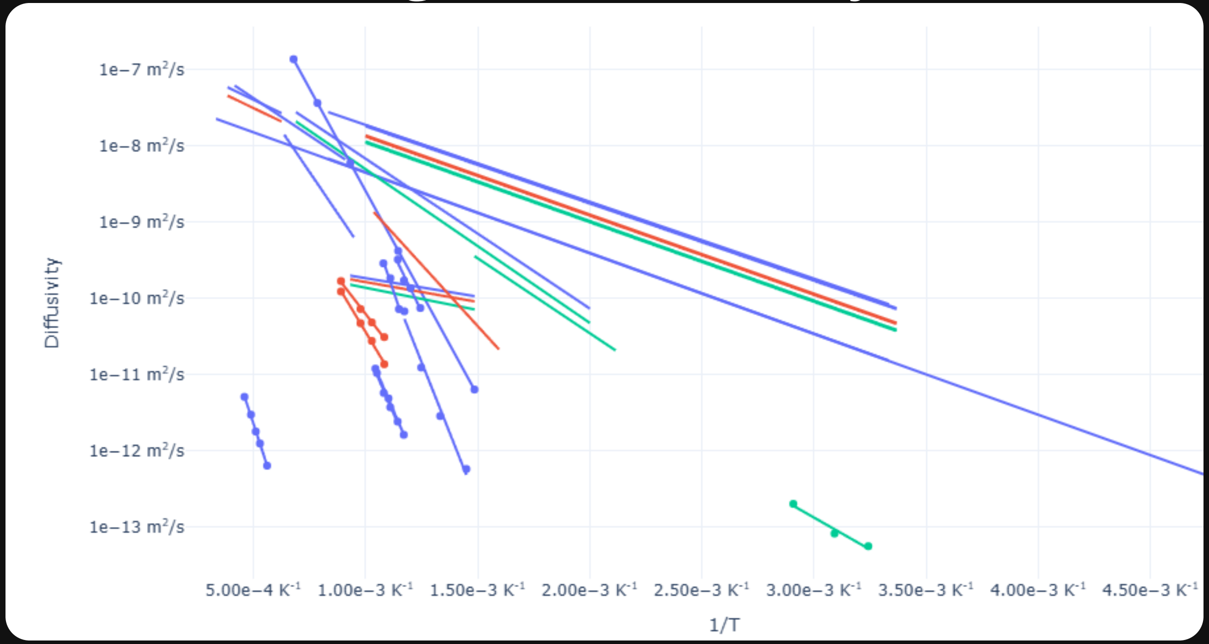
Data on transport properties

is scarce and variable

Source: HTM database v0.17

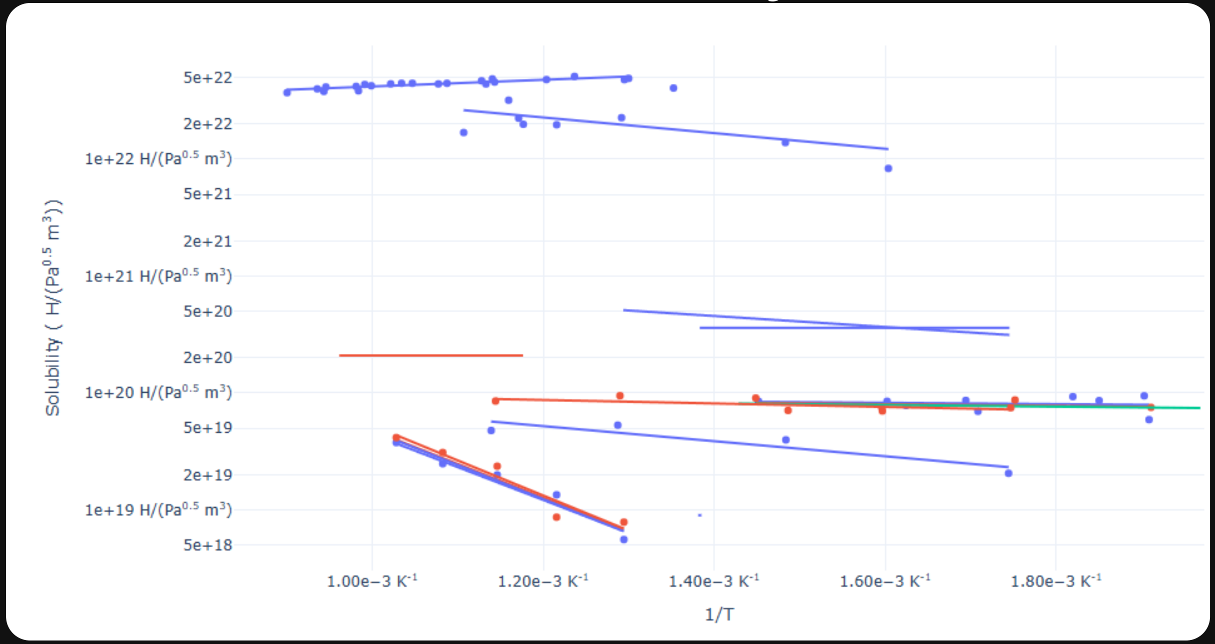
Context: hydrogen transport properties (next)

Tungsten's diffusivity



- Different tungsten grades?
- Different setups?
- Isotopic effect?
- Influence of trapping? effective diffusivity?

LiPb solubility



- 4 orders of magnitude variation!
- Composition?
- Difficulties measuring liquids?
- Mistakes in unit conversion?

Challenge #4: Data on Tritium Properties is Scarce and Variable

Current situation

- diffusivity, solubility, and trapping parameters vary by up to orders of magnitude in literature.
- several sources of truth (lit. reviews) and no unified database

Risks & implications

- unreliable component-level simulations
- poor reproducibility of model predictions.

Path forward

Establish a large hydrogen transport properties database

Challenge #4: Data on Tritium Properties is Scarce and Variable

Needs to be:

ath forward

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Needs to be:

Citable and Persistent

- Each dataset has a **DOI** and version number.
- Enables reproducibility and traceable references in reports, models, and standards.

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Version-Controlled, Openly Licensed, and Transparent

- Public Git repository or data platform (e.g. Zenodo, GitHub).
- Each update logged with changelogs and clear licence (CC-BY or similar).
- Extensible.
- Full provenance of every data point

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Peer-Reviewed and Curated

- Data vetted by subject-matter experts before inclusion.
- Documented acceptance criteria (e.g. residuals, experimental validation quality).

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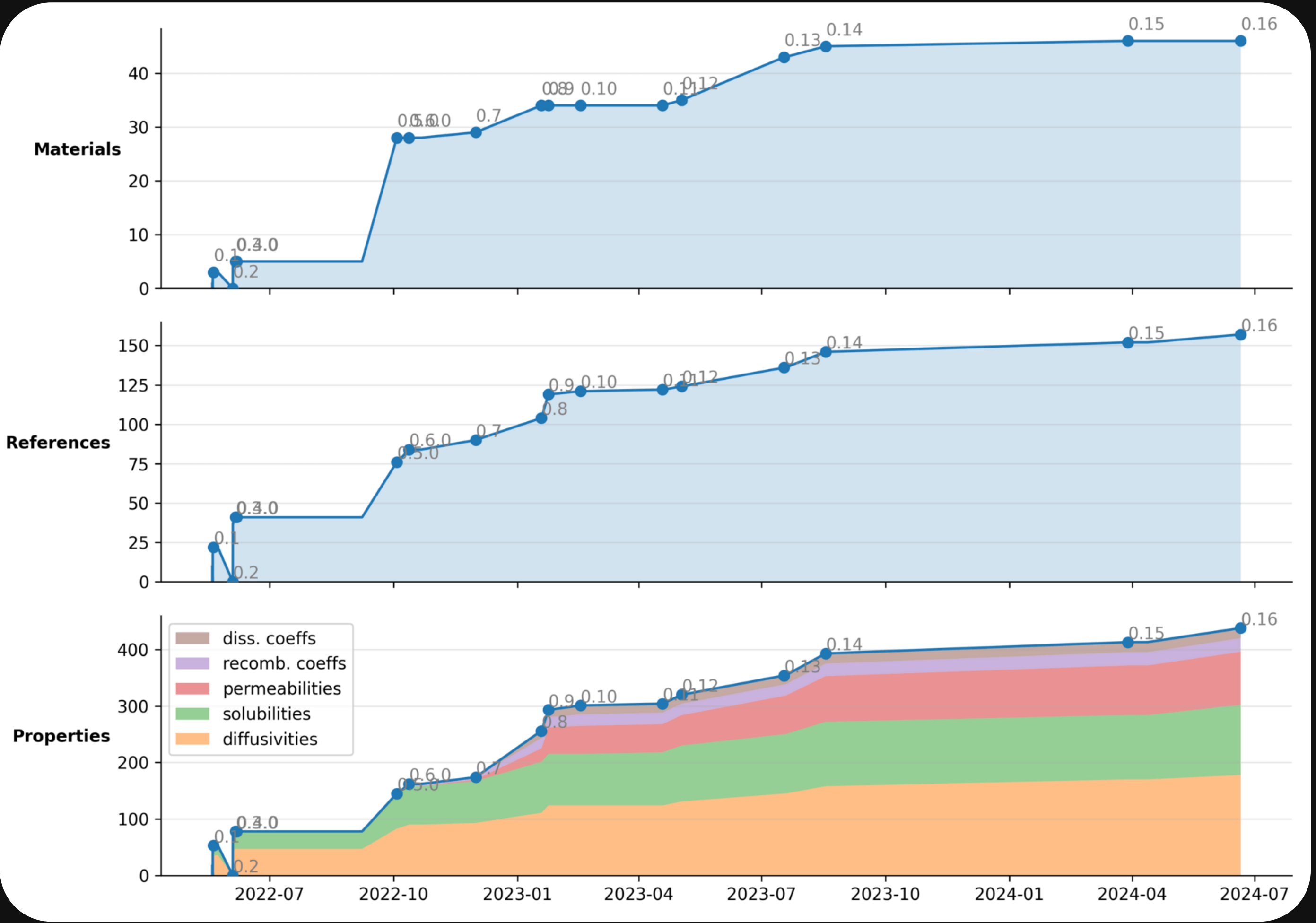
Standardised Format

- Machine-readable (e.g. JSON, CSV, or YAML) and **interoperable** with modelling codes
- Consistent units, naming conventions, and metadata schema (e.g. composition, phase, microstructure).

The HTM database

github.com/remdelaportemathurin/
h-transport-materials



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✅Standardised Format

✅Compatible with modelling workflows

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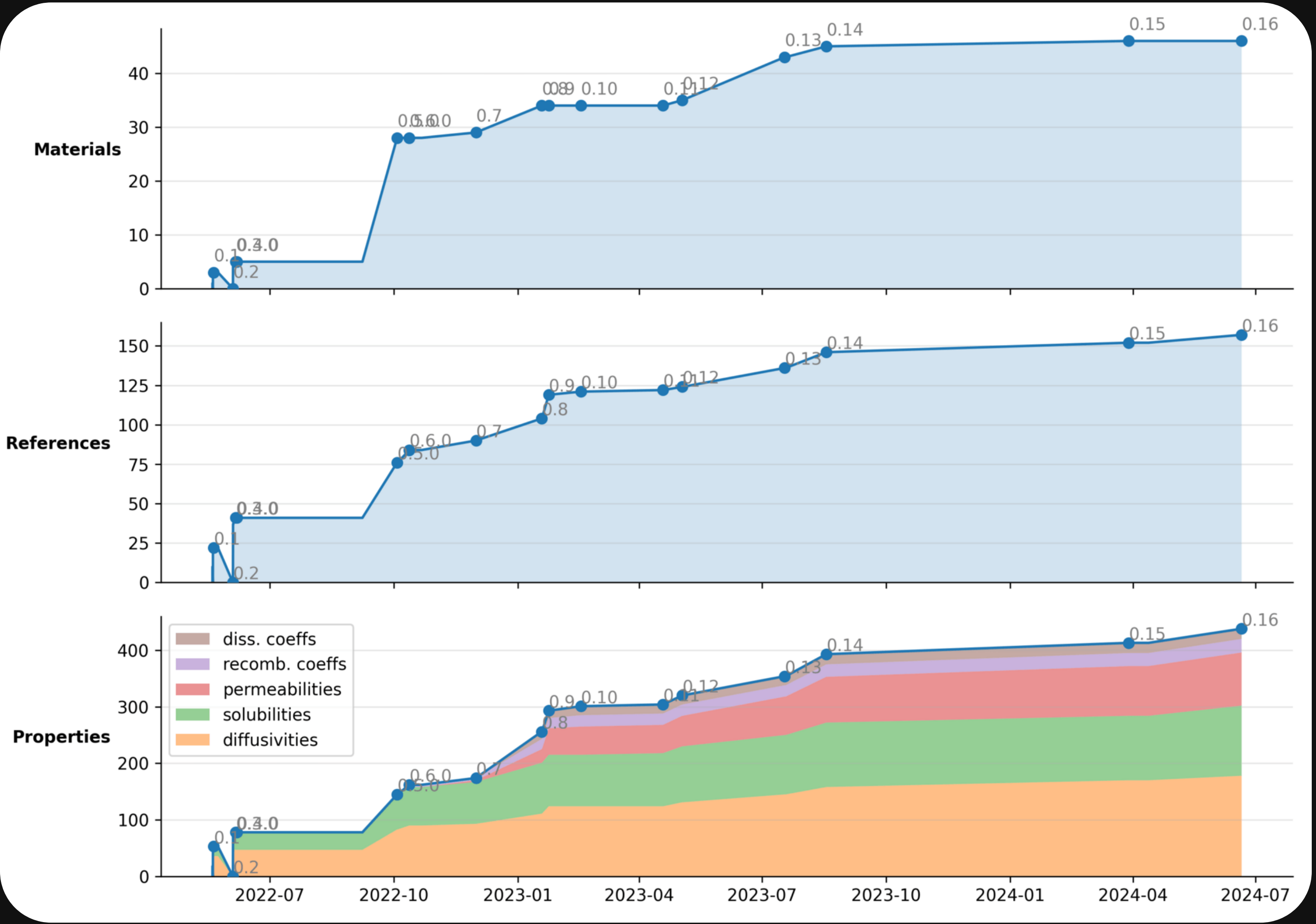

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✅Standardised Format

✅Compatible with modelling workflows

But lacks one crucial ingredient: incentives from research programmes

HTM dashboard

https://htm-dashboard-uan5l4xr6a-od.a.run.app/

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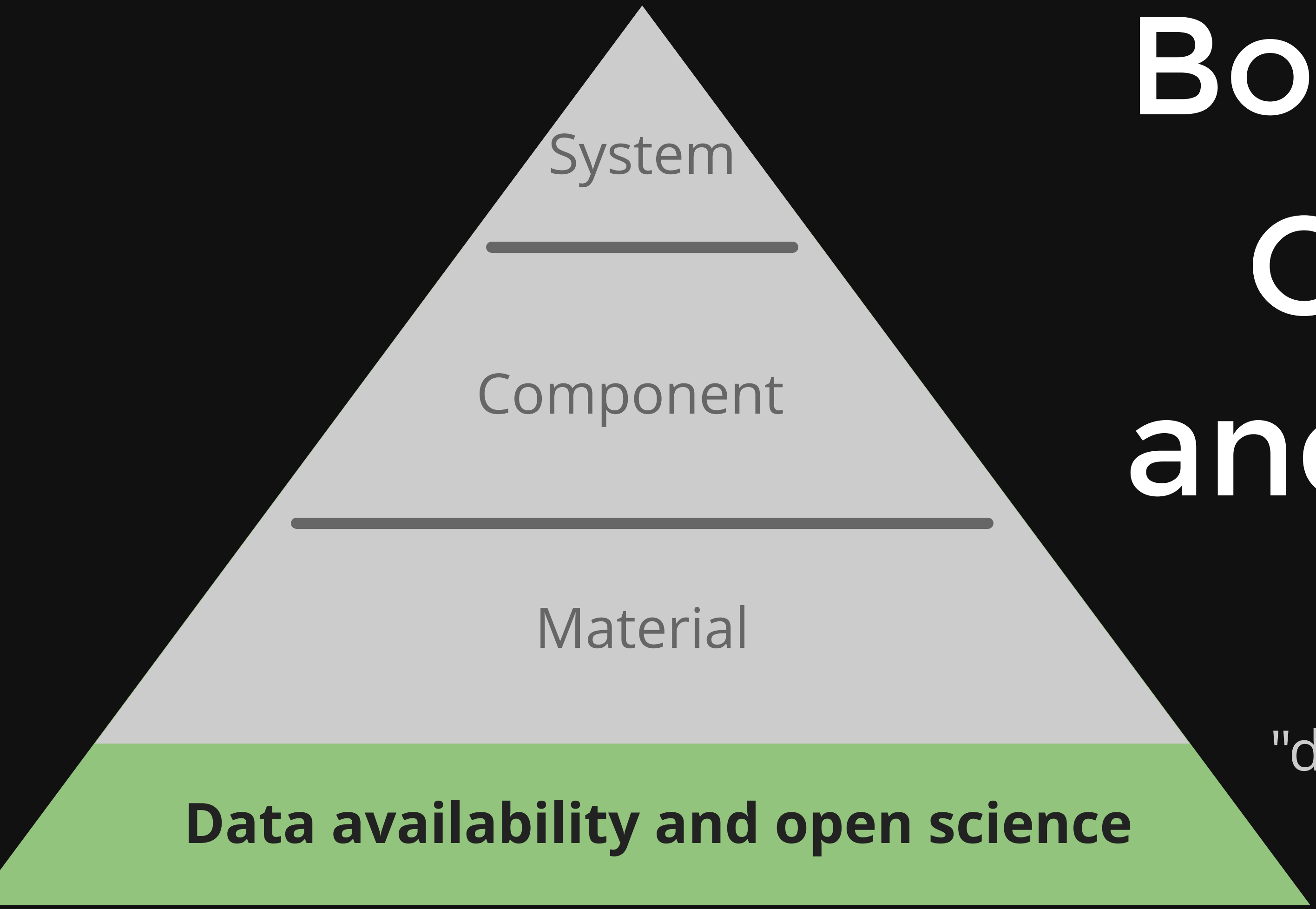

Bonus Challenge: Open-science and transparency

"dAtA WiLl bE aVaiLabLe uPoN rEqUeSt"

Challenge #5: Open-Science and Transparency

Current situation

- Many modelling tools and datasets are closed-source
- Lack of transparency when disseminating results.

Risks & implications

- Limited reproducibility
- Duplication of effort
- Slow progress toward standardisation and regulatory trust.

Path forward

- Support open-source initiatives and provide incentives to open-science
- Provide clear guidelines on how to do open-science

Unpopular opinion: open-science is more than publishing a paper at the end of a project

Challenge #5: Open-Science and Transparency

Current situation

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Risks & implications

Path forward

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Thank you!
Any question?

✉️ remidm@mit.edu

github.com/festim-dev

Plasma Science & Fusion Center