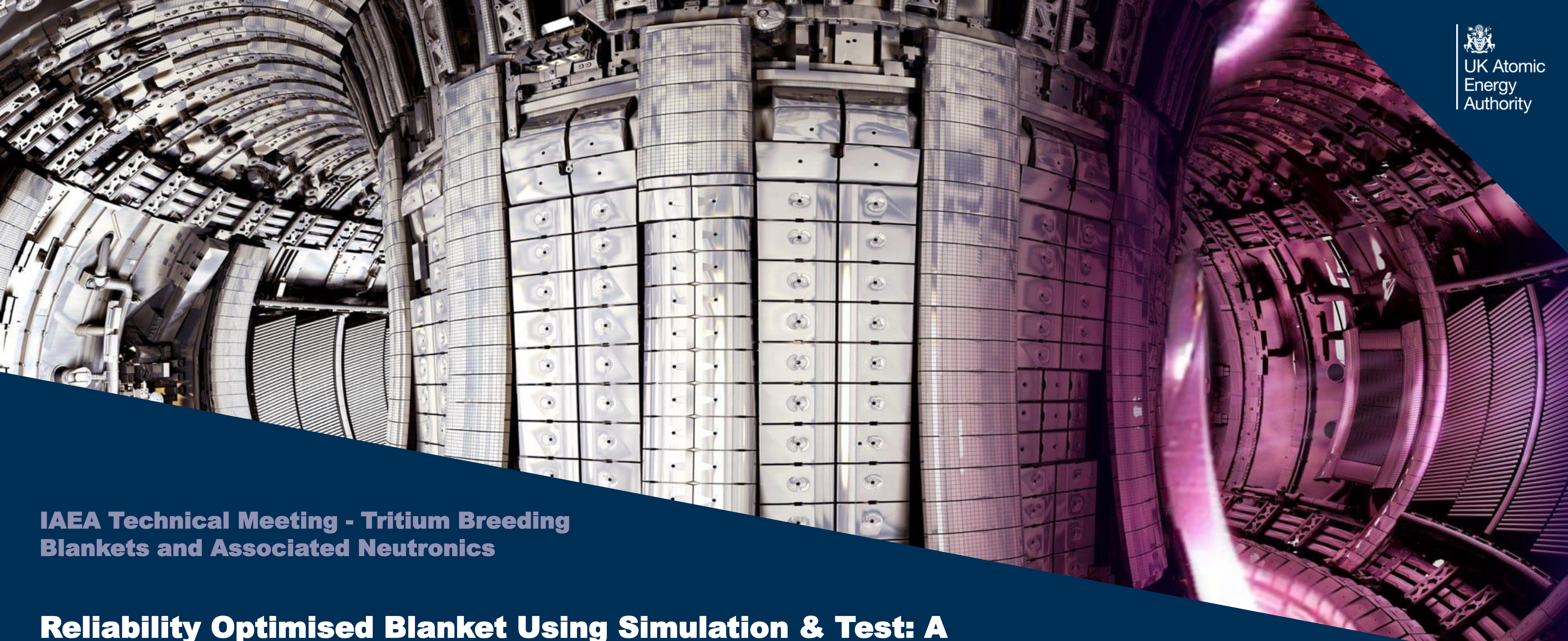

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IAEA Technical Meeting - Tritium Breeding Blankets and Associated Neutronics

Reliability Optimised Blanket Using Simulation & Test: A Novel Approach to Breeder Blanket Design

David Pickersgill, James Bailey, Michelle Baxter, Tom Barrett, Tom Deighan

Content

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ROBUST – Introduction

Reliability Optimised Blanket Using Simulation & Test

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The primary objective of ROBUST:

- Address the pre-concept & concept design/analysis of blankets through the application of **Model Based Systems Engineering (MBSE)** & the development of an **Analysis Workflow**
  a) By engaging with industry standard engineering rigour and processes
  b) To enable a structured and logical approach to blanket concept down-selection

<u>This is a low-fidelity, design space exploration-type analysis workflow</u>

- Attempts to quickly explore the available design space and provides a basis to down-select blanket concepts – **comparative assessment**
- These concepts can then be studied further with more accurate, higher-fidelity analysis (or other workflows)

Initial phase of the project has been a collaboration between UKAEA & Kyoto Fusioneering Ltd.

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KYOTO FUSIONEERING

ROBUST - High Level Strategy

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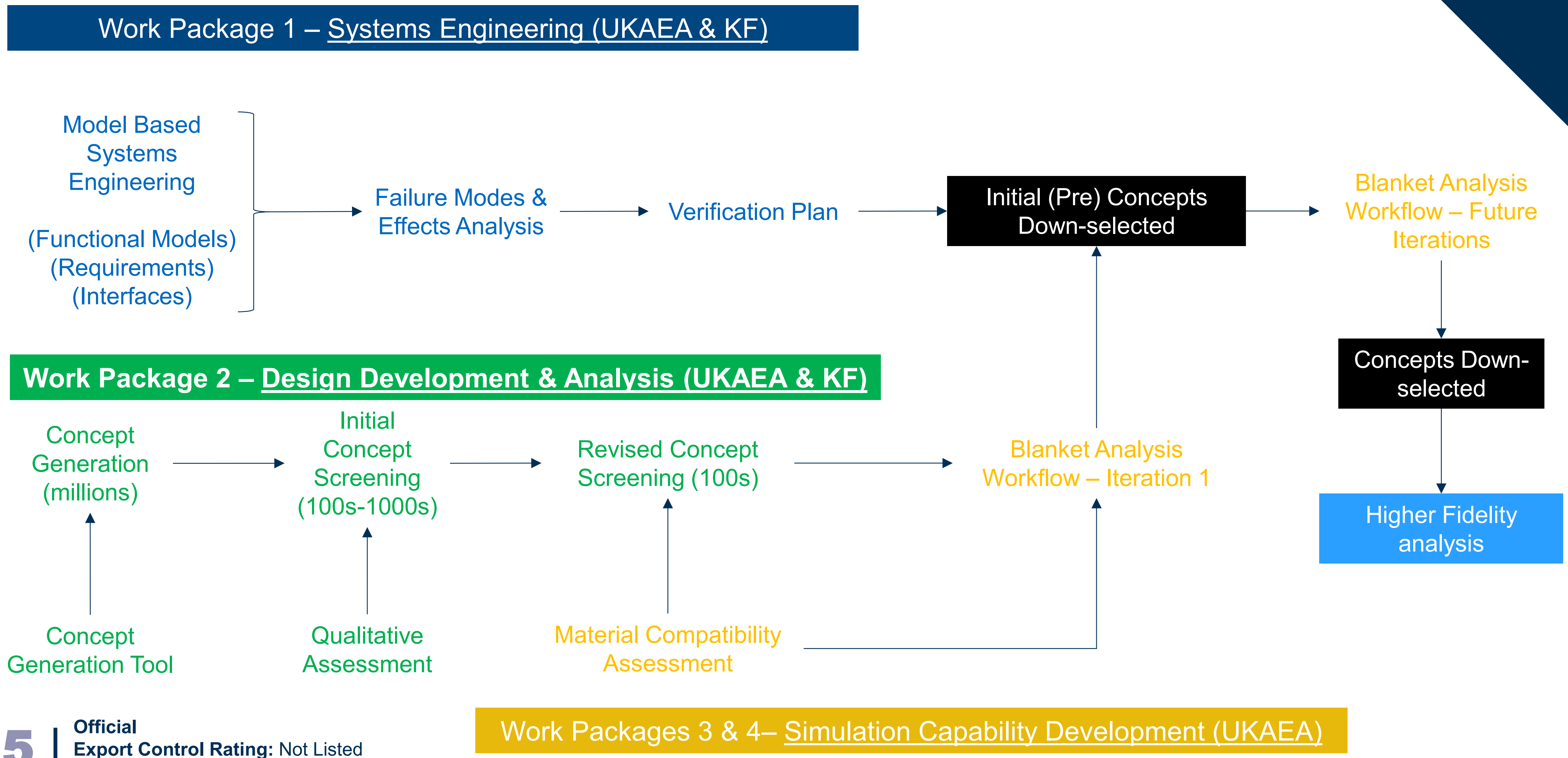

Work Package Overview

Systems & Risk Engineering (WP1)

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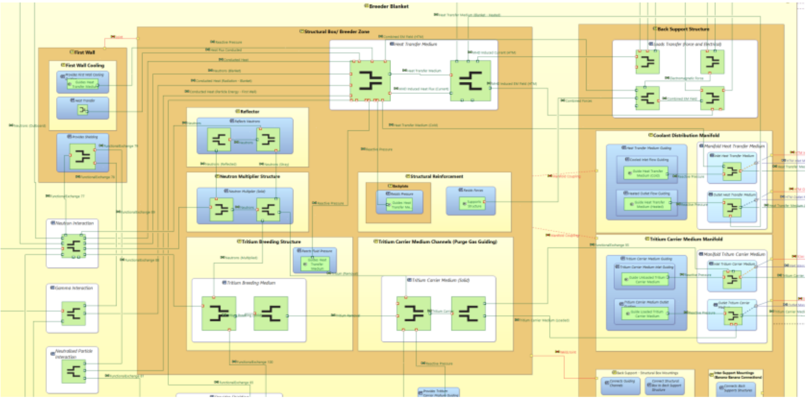
Model-Based Systems Engineering (MBSE)

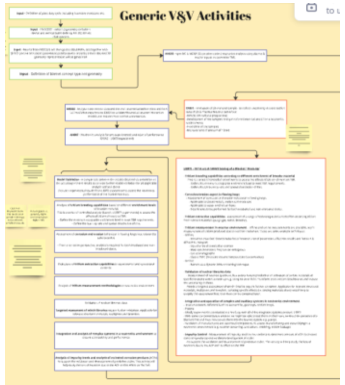


Systems modelling and requirements generation in the context of the system

- *Provides a Basis for a Design – Functional Models*
- *Define of the System Requirements*
- *Defines the Blanket Interfaces*
- *Defines the physical components in the design*

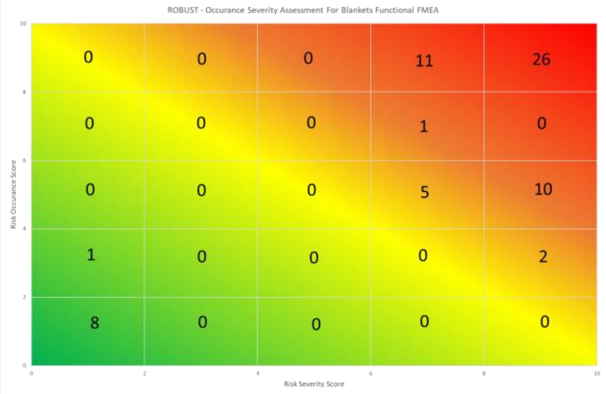
Starts to define the 'roadmap' of analysis and experiments required to provide verification of a blanket design

Verification Planning



Understanding what experimental and analysis capability is required to assess and develop blanket designs

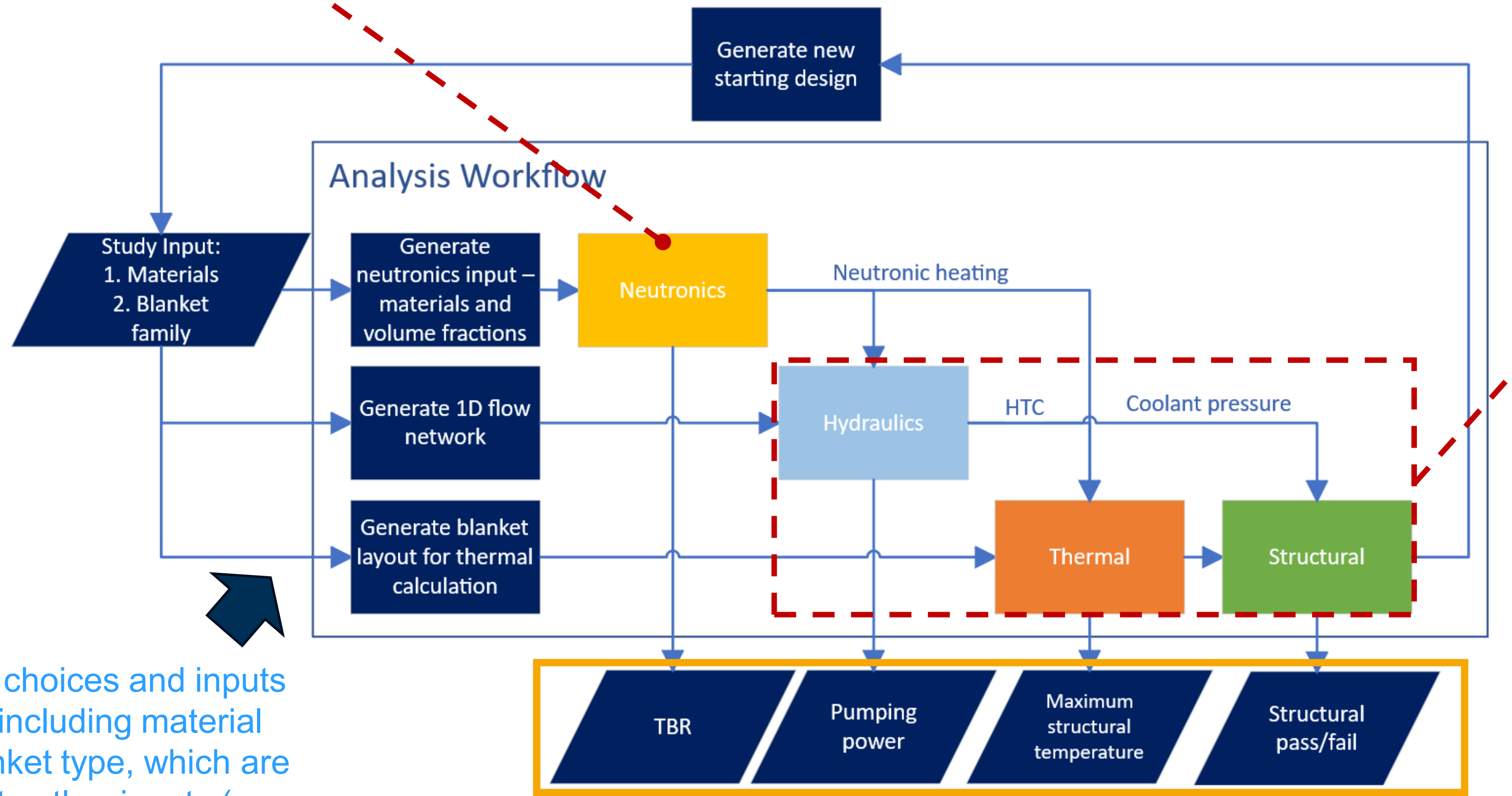
Failure Modes & Effects Analysis (FMEA)



How will the system fail, and how can we mitigate such failures early in the design?

Defines a non-design specific view of risk in the design based on the functional models – mitigation built in before a concept is created

Simulation Capability Development (WP3 & 4)



A custom Modelica library has been built to support 1D Hydraulic, Structural and Thermal Assessments. These are automated, linked analysis which passes data between them

Performance criteria

Various design choices and inputs are required, including material choice and blanket type, which are used to calculate other inputs (e.g. volume fractions)

The workflow outputs simple performance criteria, which gives a comparative assessment of a concept's performance (to other concepts)

Simulation Capability Development (WP3 & 4)

Pin Breeder model integrated ✅

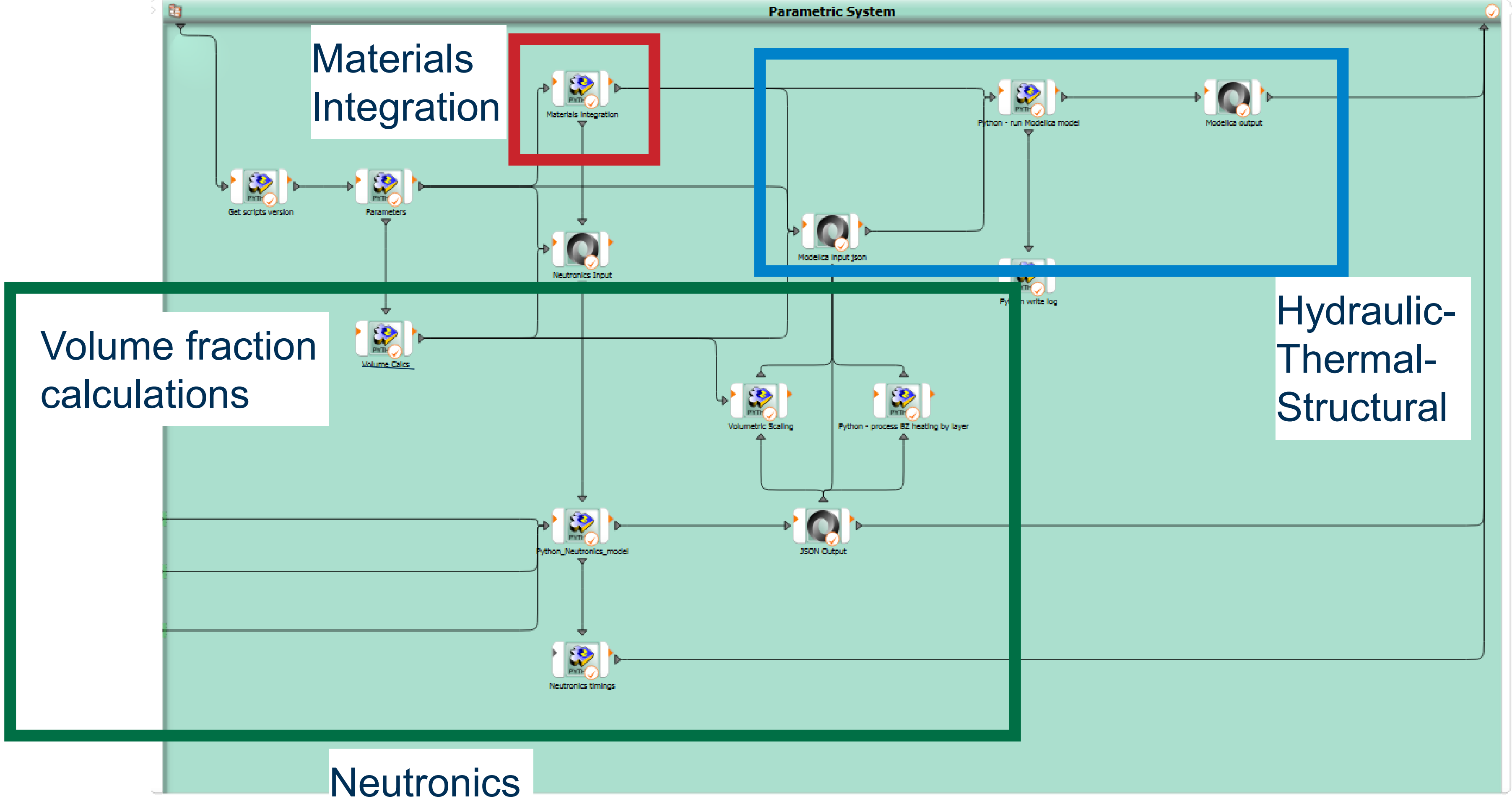
An **Analysis Workflow** has been developed in **Ansys Optislang** to allow for fast and iterative analysis of blanket concepts:

- Neutronics
- Thermal Hydraulics
- Structural

Simple, performance criteria are output:

- TBR
- Pumping Power
- Structural Pass/Fail
- Maximum Structural Temperature

Validated vs. typical analytical solutions (but more validation is required – e.g. with FE models)



Design & Analysis (WP2)

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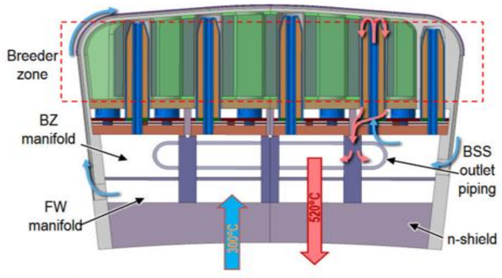
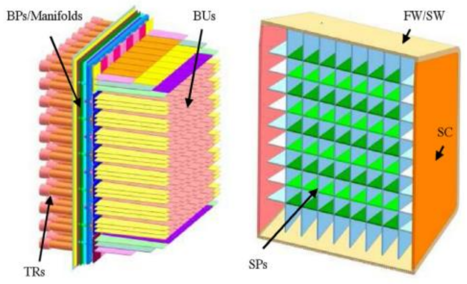
*Helium Cooled Pebble Bed**



G. Zhou et al., Energies 16(14) (2023), 5377

Helium Cooled Lithium Lead



EU DEMO HCLL (Aiello et al., 2014)

Examples of Blanket Concepts chosen in the Down-Selection

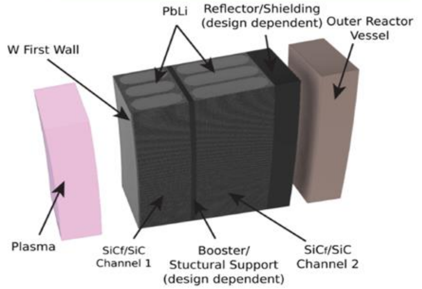
Blanket Type	Number	Structural	Breeder	Multiplier	Coolant	Purge
Solid Breeders	1	P91	Li2O	Be12Ti	He	He
	2	Eurofer	Li2O	Be12Ti	He	He
	3	P91	Li4SiO4	Be12Ti	He	He
	4	Eurofer	Li4SiO4	Be12Ti	He	He
	5	P91	KALOS	Be12Ti	He	He
Liquid Metal Breeders	6	P91	LiPb	-	-	-
	7	Eurofer	LiPb	-	-	-
	8	SiC	LiPb	-	-	-
	9	SiC	LiPb	-	He	-
	10	Eurofer	LiPb	-	He	-
	11	P91	LiPb	-	He	-
	12	P91	LiPb	-	CO2	-

From approx. **15 million initial concepts**, **12 Blanket concepts** have been down-selected using a combination of:

- A materials down-selection/optioneering
- A material compatibility assessment
- Initial TBR studies using the analysis workflow (TBR > 1.3)

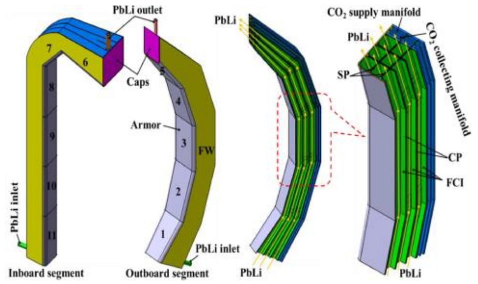
Similar but not identical to existing concepts in literature

Self-Cooled Lithium Lead



R. Pearson et al., IEEE Trans. Plasma Sci. 50(11) (2022), 4406-4412

*CO2 Cooled Lithium Lead**



CFETR COOL (Chen et al., 2021)

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Export Control Rating: Not Listed

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Analysis Methods - Example

Context slide of low fidelity analysis

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Low-Fidelity Analysis Workflow - ROBUST

- Forms a Basis of a design (i.e. Pre-Concept/Concept)
- Can rapidly Determine Impact of change / Design space exploration
- Validated vs. analytical solutions, but further validation with FE models required
- Comparative analysis only, used only to make design choices, not accurate predictions of a concept's absolute performance
- Computationally inexpensive - 10s of seconds per analysis

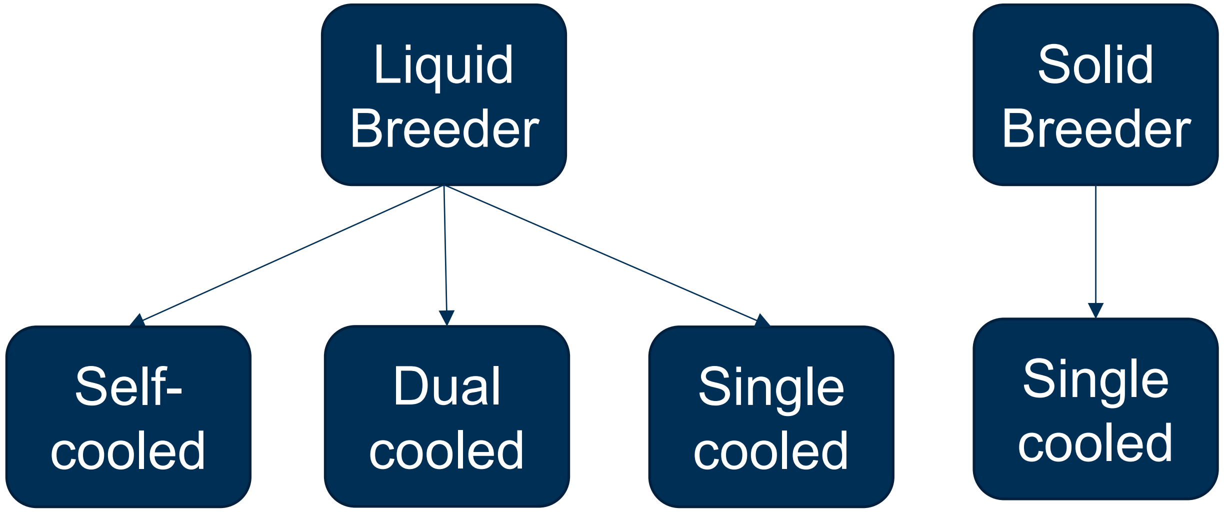
Higher Fidelity Analysis /Workflows

- Provides a more accurate view of a concept's performance
- Computationally more expensive
- Still absolutely required following the 'ROBUST' style workflow

These two styles of analysis/workflow should work together, with the first being a stepping stone to more detailed analysis

Blanket Definition

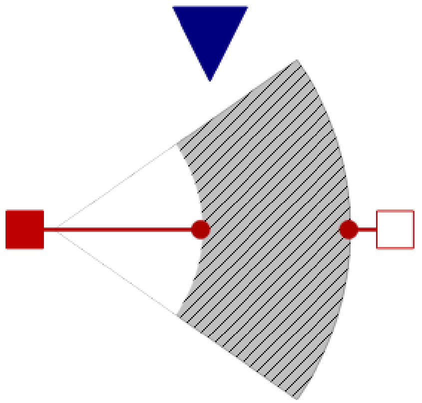
1. Define blanket concept 'families'
2. Develop primitives to represent designs
3. Assemble individual concepts for assessment

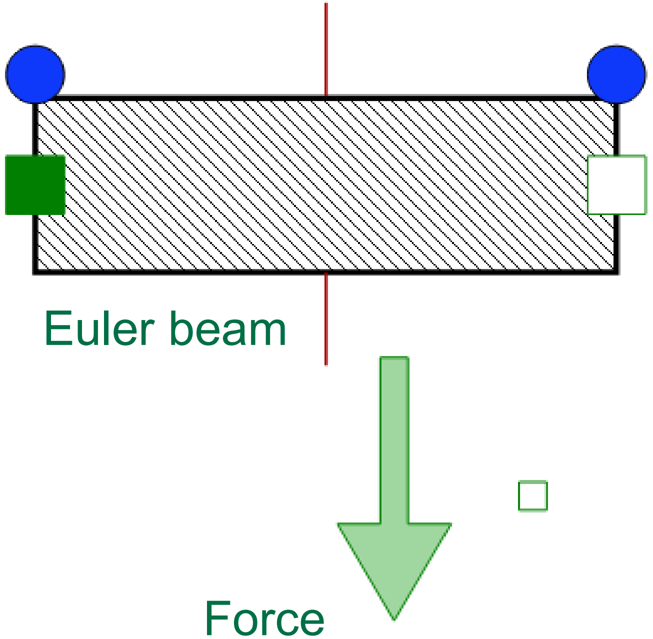


Modelica Library – ARTEMIS Suite

- Library of primitives for hydraulic, thermal, structural analysis
  - Extension of Modelica standard library
  - Applicable to other architectures or components
- Primitive components assembled into representations of components for analysis

Thermal conductor with volumetric heating

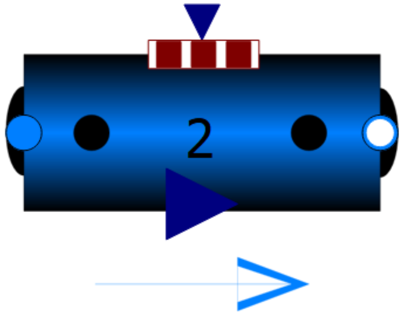




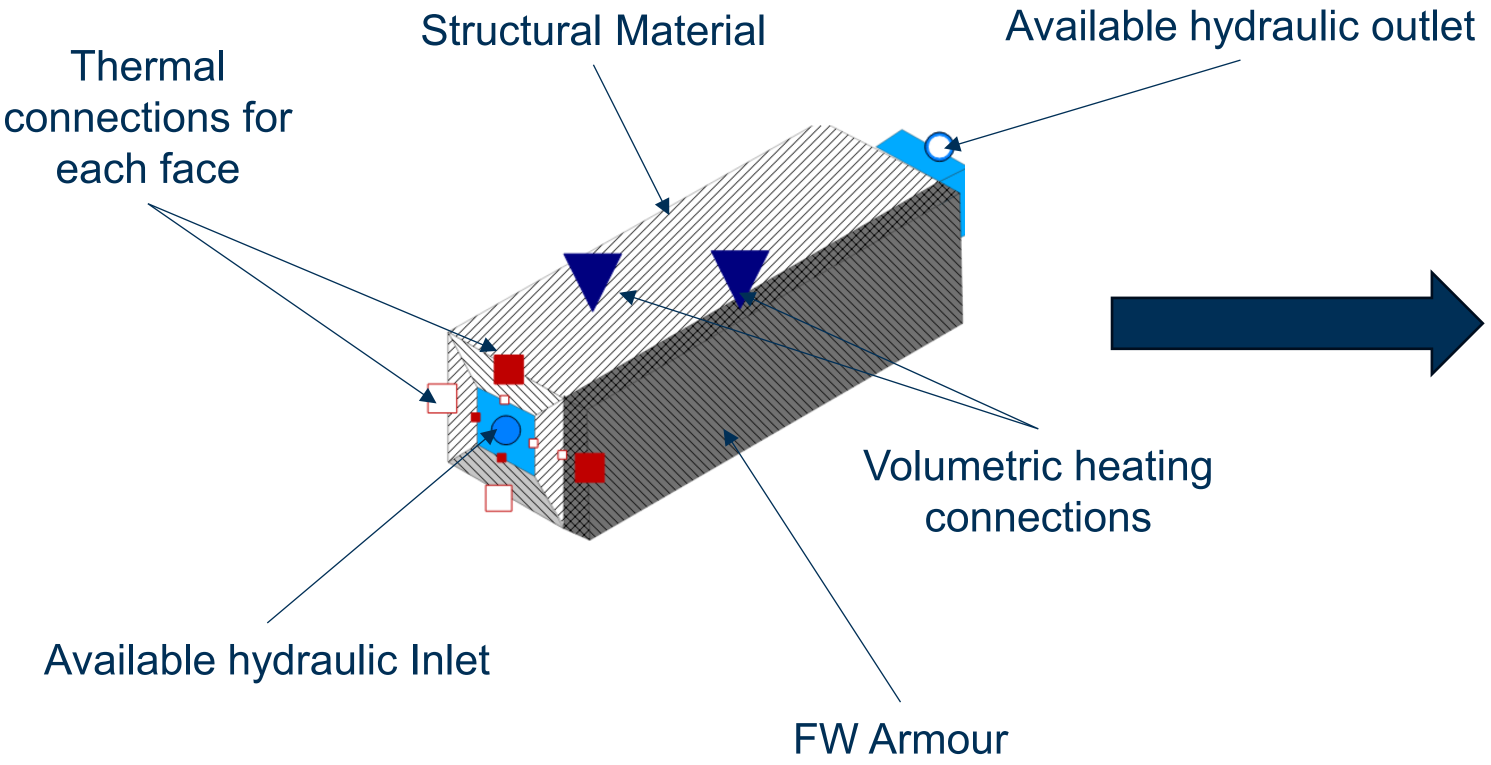
Euler beam

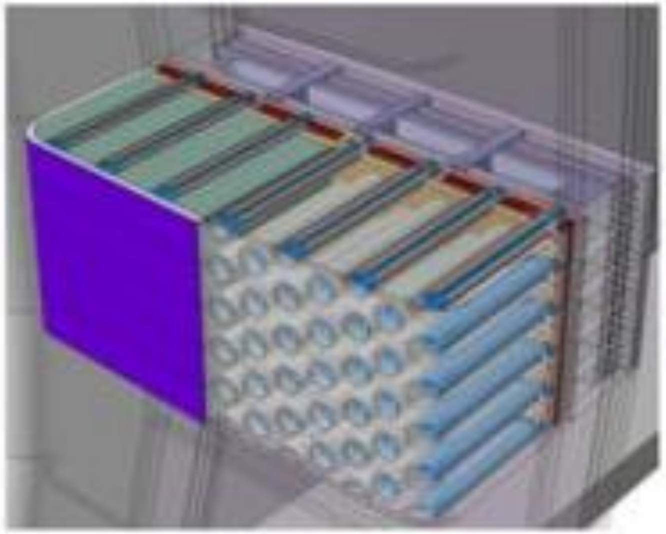
Force

Multi-wall pipe with volumetric heating



Solid Breeder Modelica Model Example – ARTEMIS First Wall Component





Zhou *et al. Energies* **2023**, *16*(14), 5377

Diagram of the ARTEMIS First Wall Component – demonstrating assembly of 'primitives' to create a simple first wall component model

Initial concept exploration - HCPB

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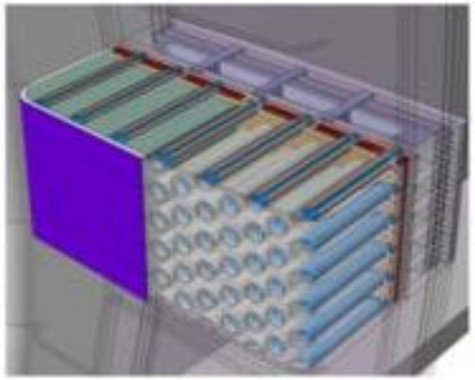
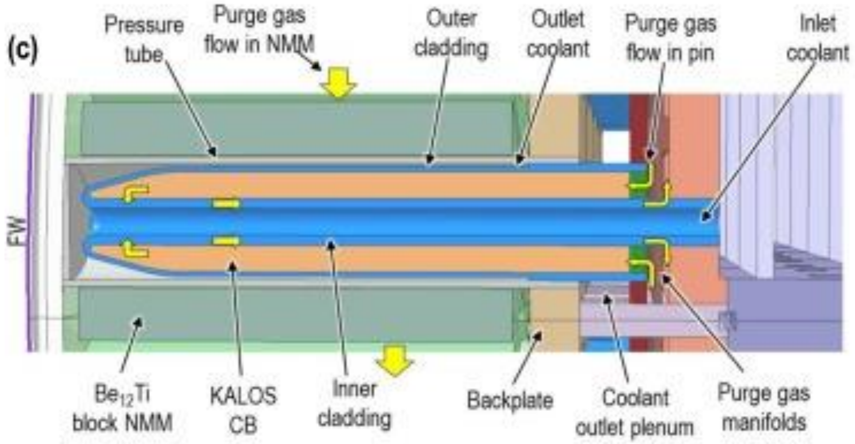
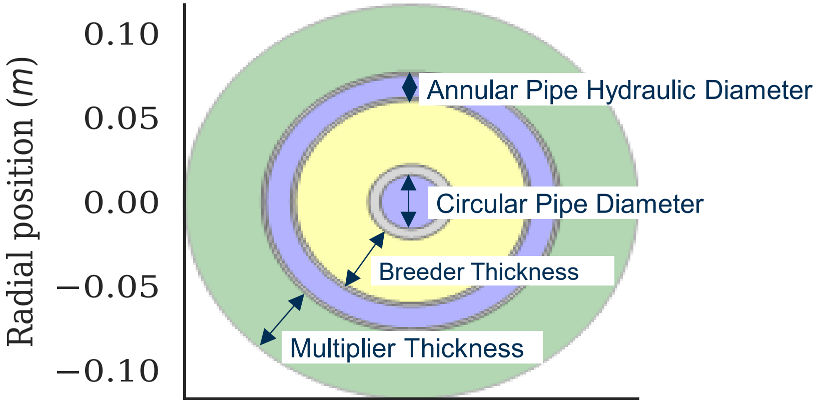
- Initial sensitivity analysis completed
  - Down-selection of optimisation parameters, guided by requirements/TBR study volume fractions
- Optimisation completed, with objective to increase net power output, with constraints:
  - TBR>1.3
  - Passing structural criteria
  - Passing temperature limits
- Geometric parameters varied – labelled in diagram
- This is a preliminary analysis, further study can be completed





Zhou et al. Energies **2023**, *16*(14), 5377

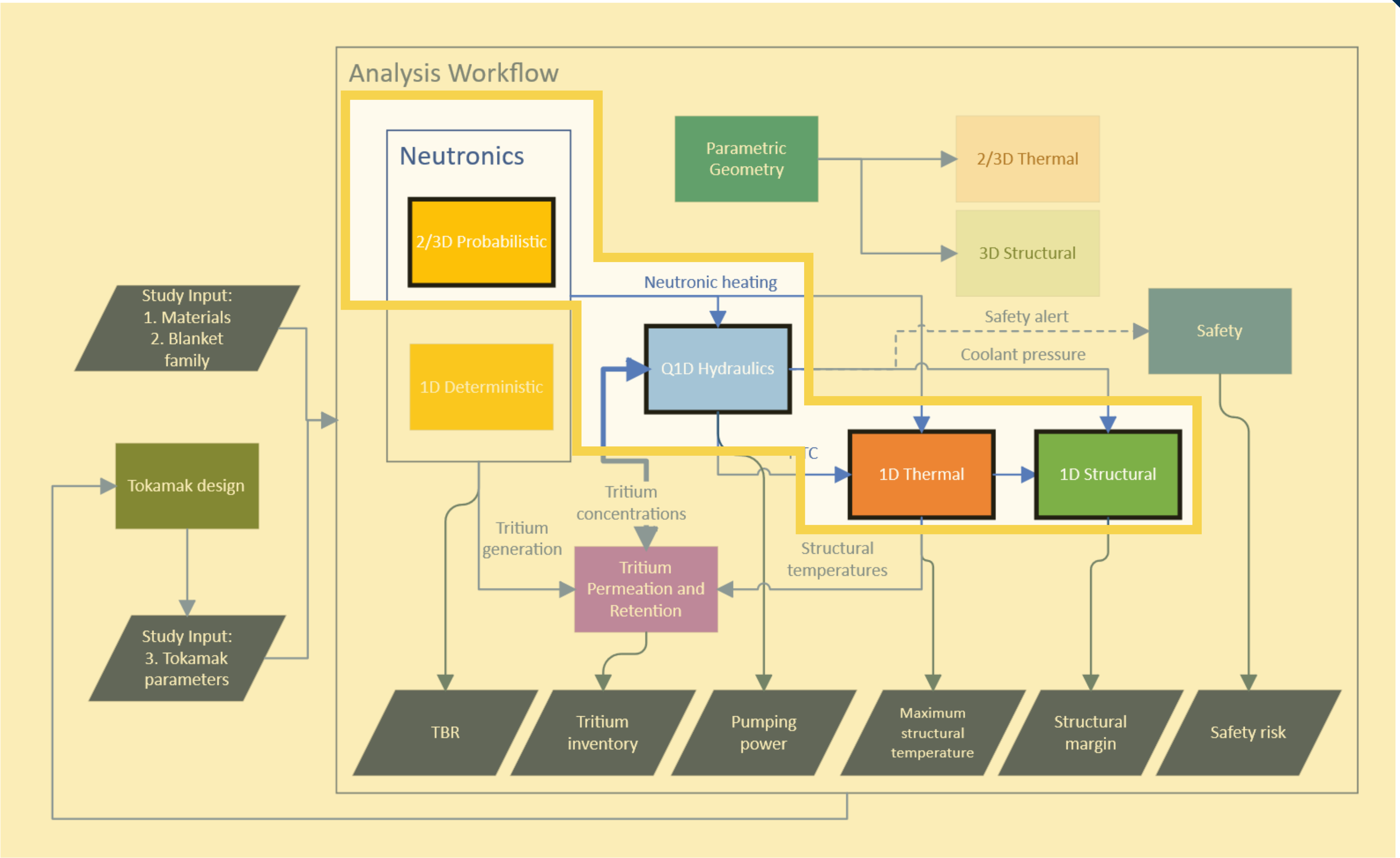


Ongoing/Future Work

Present Analysis Capability

The current workflow has the capability to perform the following analysis:
- Neutronics
- Thermal Hydraulics
- Structural

Simple, performance criteria are output:
- TBR
- Pumping Power
- Structural Pass/Fail
- Maximum Structural Temperature



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Analysis Capability in Development (25/26)

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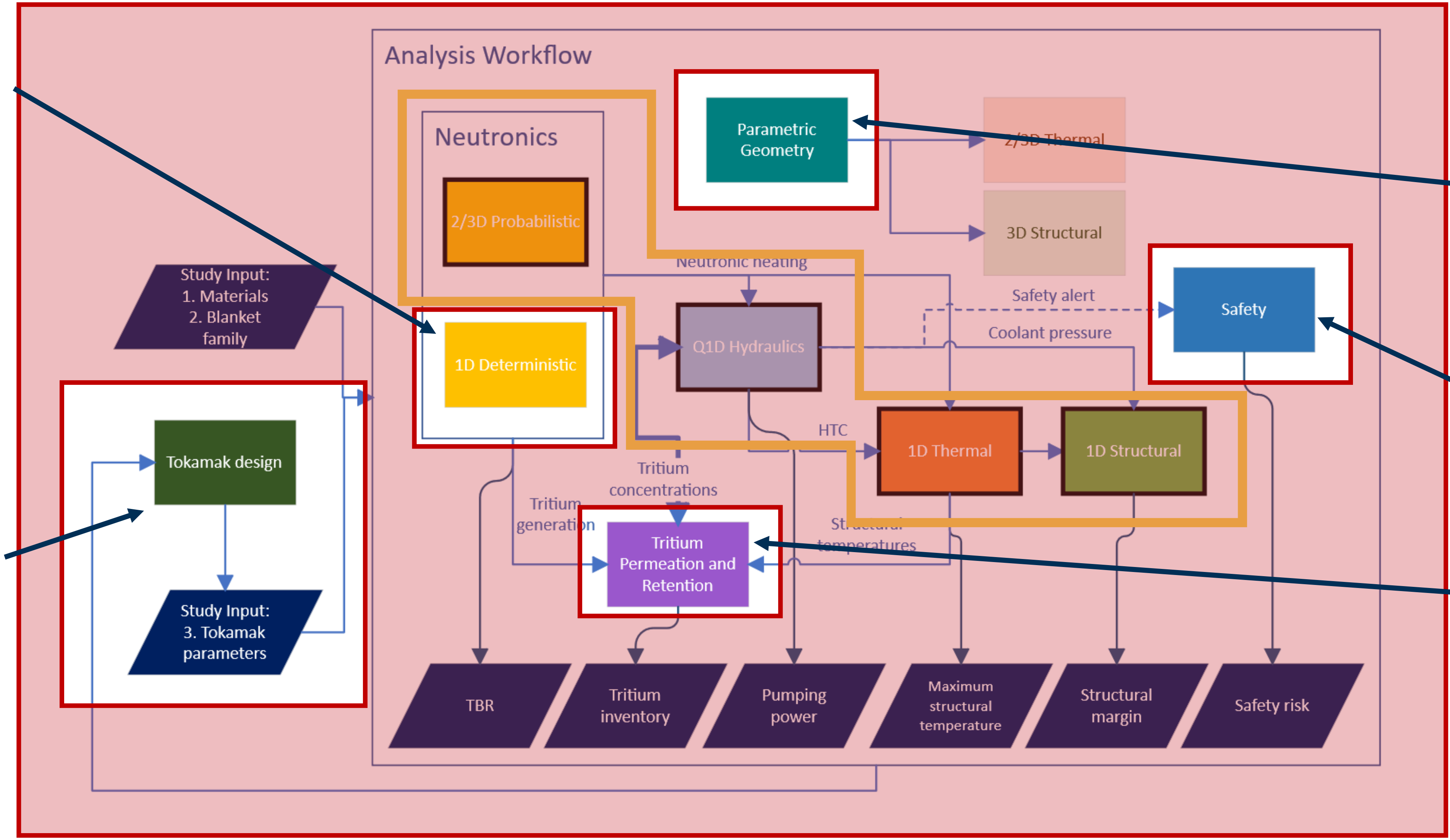
1D Deterministic neutronics

Integration with BlueMira and PROCESS for Tokamak and blanket geometry optimisation



Parametric Geometry for further geometrical design space exploration

Addition of safety analysis for preliminary safety assessments

Tritium Permeation & Retention modelling for tritium inventory assessment

Summary

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- ROBUST has combined the application of Systems Engineering Techniques (including MBSE) with the development of an Analysis Workflow in Ansys Optislang
- These tools have been used as a basis to down-select a range of Liquid metal and Solid Breeder blanket concepts – 12 in total
- Further capability is being developed, in parallel to more rigorous validation

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	8	SiC	LiPb	-	-	-
	9	SiC	LiPb	-	He	-
	10	Eurofer	LiPb	-	He	-
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	12	P91	LiPb	-	CO_2	-