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# Safety for fusion

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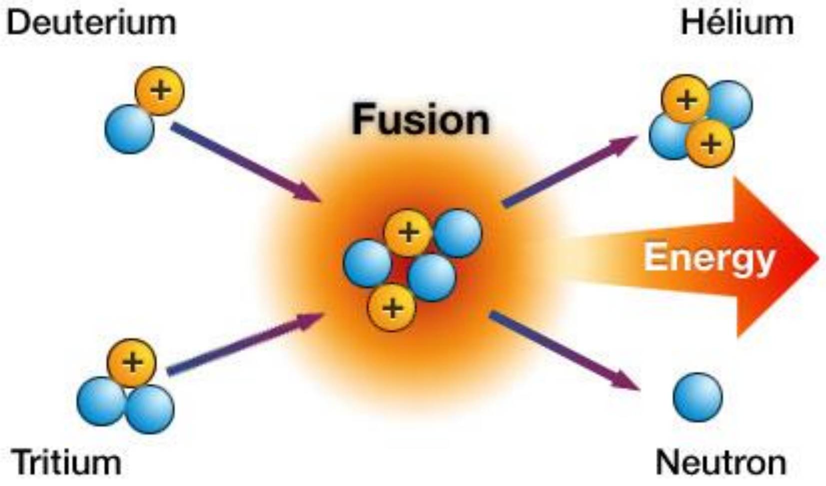
# Nuclear Fusion

- Fusion reaction for energy production on Earth is
  D + T → He + n
- Requires plasma which is ionised high temperature gas.
- We need high quality void, high temperatures and a strong magnetic field to produce and contain plasma.
- A tokamak contains the plasma and we need a high energy pulse start the fusion reaction.



# Fusion reactors

- Tokamaks have been built that can reach a self sustaining fusion reaction for a few seconds.
- The Joint European Torus (JET) design currently holds the world record for fusion power generated (16 MW(th) output from an input of 24MW(th))
- ITER is the next iteration of fusion reactor and is intended to sustain fusion reaction for a prolonged period time, demonstrating the use of fusion as an energy source. It is being built in Southern France.
- DEMO will be a fusion reactor producing electricity. It will need to be able to breed its own tritium in a blanket. DEMO is in the pre-design phase.

# Nuclear safety

- Currently, fusion installations are considered nuclear installations, therefore fall under the same standards and regulations used for fission reactors.
- In the UK, the Nuclear Installations Act regulates licensed nuclear site. The Act states that:
  - Licensee should secure that no occurrence involving nuclear matter causes:
    - injury to any person,
    - damage to any property of any person other than the licensee, or
    - significant impairment of the environment,
  - where the injury, damage or impairment arises out of or results from the radioactive properties, or a combination of those and any toxic, explosive or other hazardous properties, of that nuclear matter.

## Safety for fusion

- ITER currently falls under French nuclear safety regulations, enforced by the Institut de Radioprotection et de Sûreté Nucléaire (IRSN).
- A safety analysis has been performed for ITER before construction started.
- The analysis included identification of accident scenarios.

# Accident analysis for fusion

- Inevitably, the safety analysis for a fusion reactor considers accident scenarios that are very different than those considered in fission reactors:
    - Loss of Vacuum Accidents (LOVA).
    - Break in a cryoline or cryo-cooled component causing release of helium cryogen.
    - Hydrogen explosions (potentially containing radioactive tritium), in-vessel and ex-vessel.
    - Radioactive leaks deriving from poor tritium inventory and management.

# CRA for fusion

- At CRA we have 20 years of experience in providing safety case and PSA services to our clients.
- After working across a wide variety of nuclear fission technology, we have recently started working with clients in the nuclear fusion domain.
- Overview of 2 recent projects we are working on for clients:
    - RAMI analysis of the Neutron Activation System (NAS) for the Helium Cooled Pebble Bed Test Blanket Module For ITER
    - An optioneering study to identify seismic mitigation solutions for the Remote Maintenance Handling tool for DEMO

# ITER – RAMI ANALYSIS FOR HELIUM COOLED PEBBLE BED TEST BLANKET MODULE

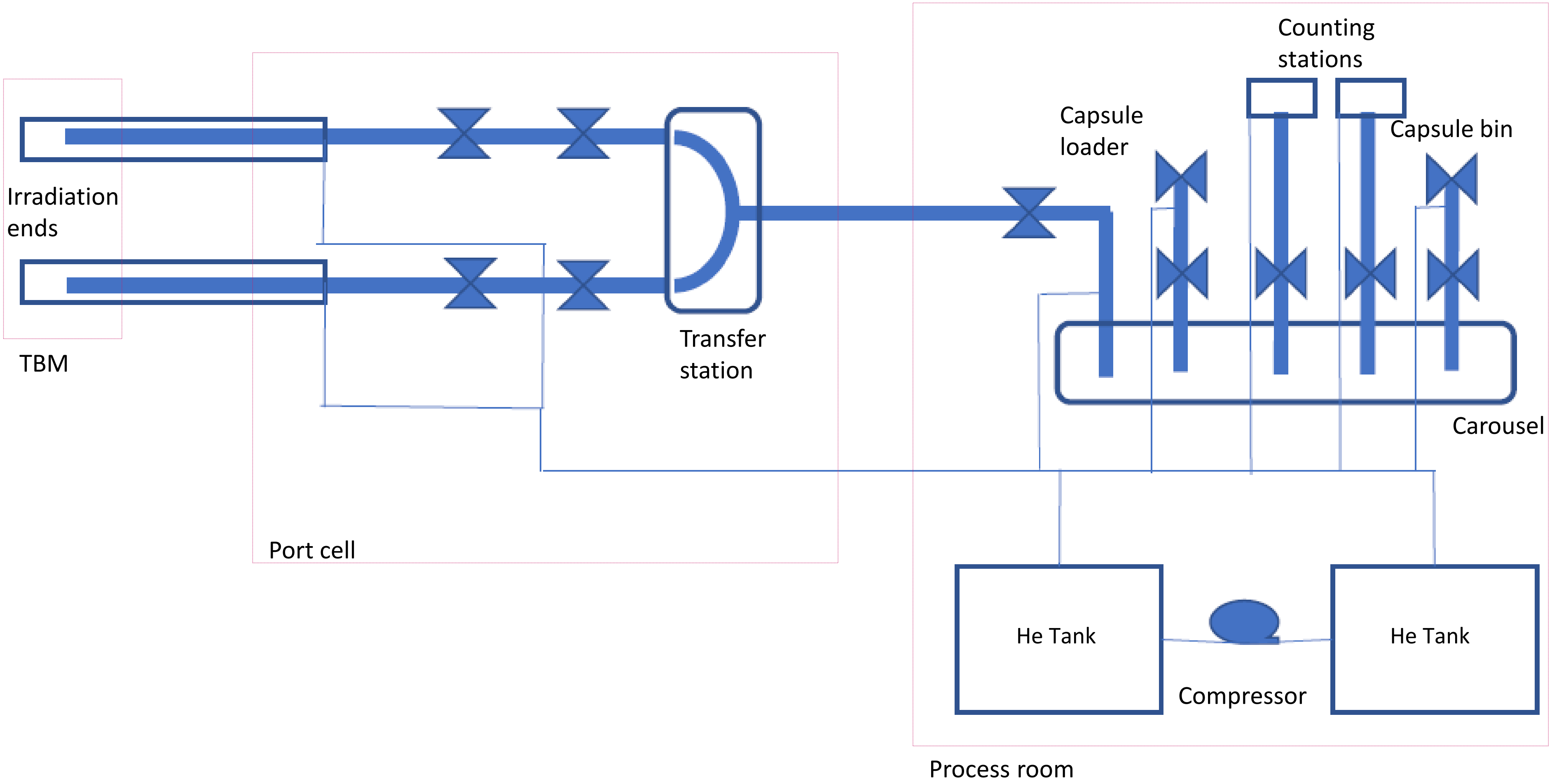
# ITER - Tritium Breeding Test Programme

- A number of different designs of tritium breeding systems are being tested at ITER.
- The EU are responsible for two of these:
    - Water Cooled Lithium-Lead (WCLL) Test Blanket Module (TBM)
    - Helium Cooled Pebble Bed (HCPB) Test Blanket Module (TBM)
- Out client IDOM have won a framework contract for the preliminary design of the HCPB TBM ancillary systems.
- The HCPB TBM will use Lithium based ceramic pebbles as a breeder material and Beryllium pebbles as a neutron multiplier.
- It will be located in a port of the ITER vacuum vessel (together with the WCLL TBM).

# ITER – He Cooled Pebble Bed Test Blanket Module

- The HCPB TBM has the following four ancillary systems:
  - Helium Cooling System – HCS
  - Coolant Purification System – CPS
  - Tritium Extraction System – TES
  - Neutron Activation System – NAS
- CRA is currently developing a RAMI analysis for the NAS. Scope of the RAMI is to identify the system's most critical failure modes in terms of the system's availability to measure the neutron flux, fluence and spectrum at the TBM.
- The RAMI includes the following steps:
  - Functional Analysis
  - Failure Modes, Effects and Criticality Analysis (FMECA)
  - Reliability Block Diagram (RBD)

# ITER – HCPB Neutron Activation System



# ITER - Components of RAMI analysis

- Functional Analysis provides a link between the system's components and their functions.
- Failure Modes, Effects and Criticality Analysis (FMECA) – the FMECA is carried out on the components identified by the Functional Analysis. Its output is a list of the system's most critical failure modes.
- Reliability Block Diagram (RBD) – the failure modes identified in the FMECA have been modelled using an RBD to quantify the overall availability of the system and the contribution of the different failure modes.

# ITER – RAMI Results of the RAMI analysis

- Based on the results of the RBD, the estimated average availability of the NAS system over a two year cycle is cycle ~ 80%.
- The FMECA identified blockage of the Transfer Line Pipework at the Port Cell as having the highest contribution to NAS failure. A blockage at the port cell cannot be repaired until the long term maintenance.
- An action plan was drawn that suggested a series of improvements to improve availability of the system.

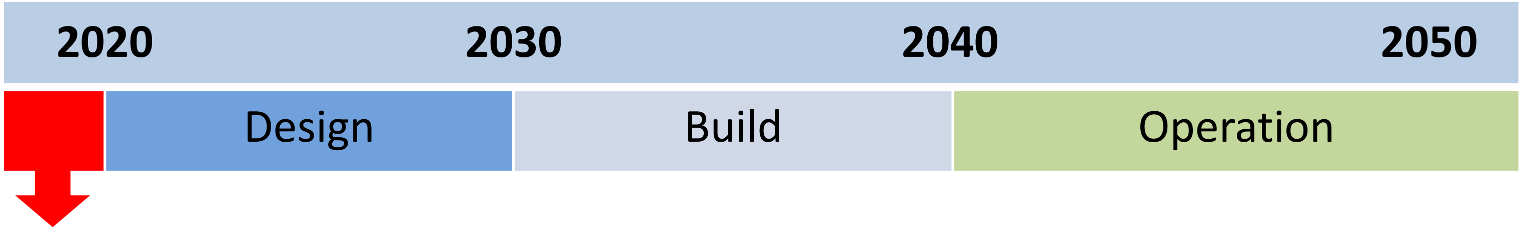
## ITER – RAMI Updated results

- If the action plan is fully implemented, the updated availability over two years is ~ 97%. This is an increase of approximately 17% higher than the original value.
- The most risk significant failure mode in the new configuration will be blockage of one of the irradiation ends. With both ends having the same risk significance.

# DEMO – MITIGATION STRATEGIES AGAINST SEISMIC EVENTS FOR REMOTE BLANKET HANDLING TOOL

# DEMO

- (EU) Demonstration power plant following ITER. It aims to:
  - Demonstrate net production of electricity using fusion.
  - Demonstrate all of the technologies required, including adequate reliability.



- Conceptual studies of key technologies
  - Our Client, RACE, is working on DEMO Remote Maintenance as a EUROfusion consortium member and is responsible for identifying a feasible strategy and demonstrate and substantiate key technologies for Remote Maintenance for DEMO

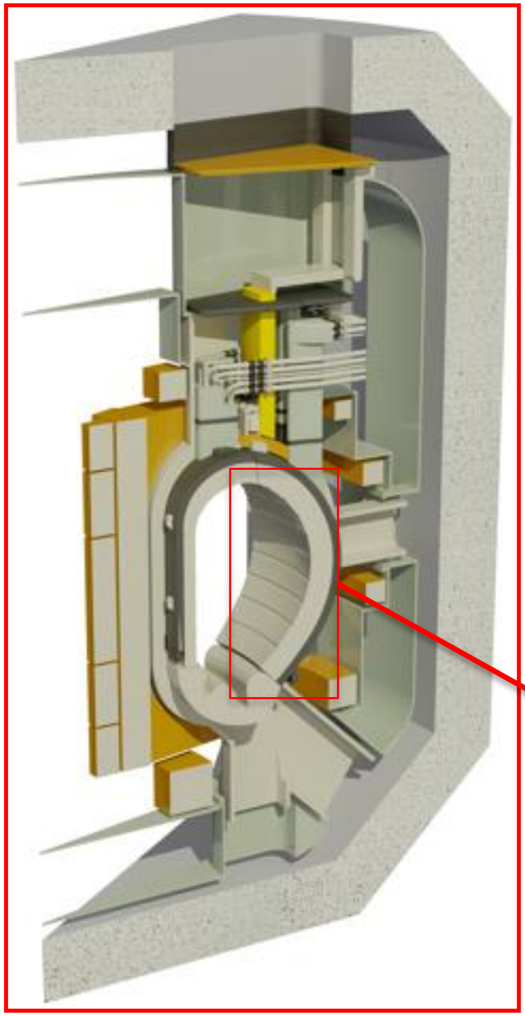
# Environment for DEMO remote maintenance

- High level of radiation
    - 2000 Gy/h in centre of machine during maintenance (not in operation)
    - 2-200 Gy/h in equipment operation areas (in access ports)
- High Temperatures
    - 50°C ambient
    - 120°C component surface
- Magnetic field
    - 0.04T (Earth's field <= 0.65µT)
- Ultra-high vacuum compatibility
    - Places restriction on:
        - Lubricants
        - Hydraulic oil
        - Cutting fluids
        - Dust/debris
    - Maintenance takes place at atmospheric pressure
- Given the harshness of the operating environment, maintenance can only be performed remotely by automated systems.

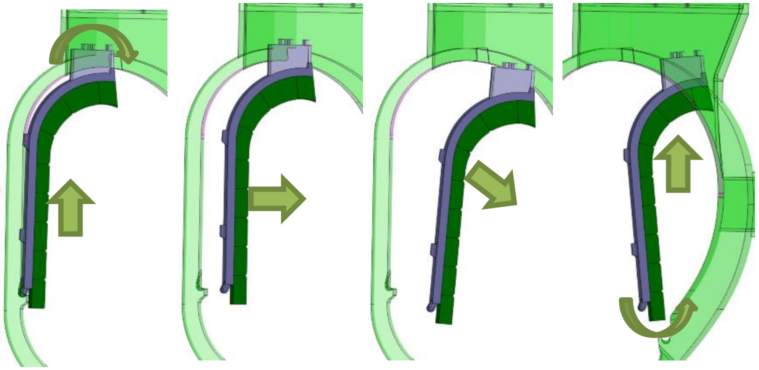
# DEMO - Project scope

- CRA is in partnership with Assystem for this project. We are providing safety expertise to the Assystem design engineering team.
- The scope of the project is to:
- Investigating methods for:
    - Minimising seismic loads transferred to remote maintenance equipment.
    - Asset protection technologies, such as (but not limited to) air bags, restraints or crash structures.
    - Requirement reduction, such as (but not limited to) risk minimisation through “Time at risk” analysis.
- Assessing the likelihood of regulatory approval of potential final design.

# DEMO - Remote Maintenance

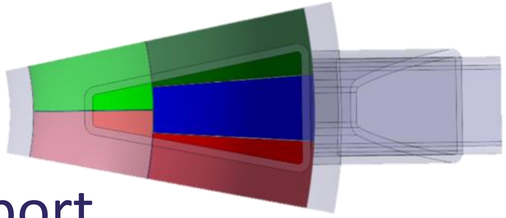


- Still in the pre-conceptual design phase. Various possible designs for the blanket and divertor are still being considered.
- The talk will focus on the single null, full blanket design.
- The remote handling tool needs to perform complex movement (at height) to be able to extract the blanket segments form the vessel.
- The blanket segments will be radioactive as they will have been irradiated to produce tritium.



# Blanket structure

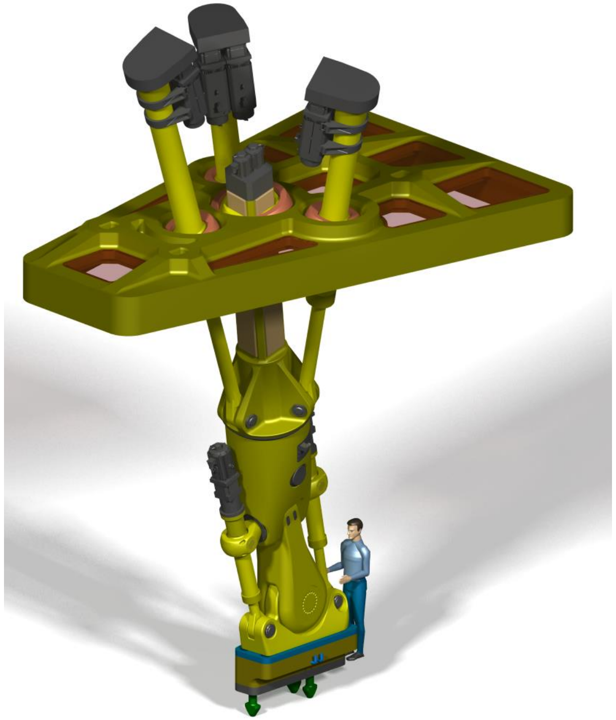
- In current stage of the design for DEMO, there are 16 access ports at the top of the vessel.
- There are 5 blanket segments that need to be extracted sequentially from each port for replacement, every 2-5 years.



- The blanket segments breed Tritium and are tightly packed (20mm clearance) to protect the vessel.
- Each blanket segment is about 10m tall and weighs up to 80 tonnes.

# Blanket handler

- Designed of blanket handler considered in the project is an Hybrid Kinematic Mechanism
- Tall (~10m) and slender machine to reach corners of port.
- 6 degrees of freedom.
- Lead screw based linear actuators common feature.
- Finite Element Analysis is used to determine peak loads and feasibility of design.



# Status of the project

- Reviewing the Finite Element analysis, including responses under seismic loads.
- Reviewing ONR and international regulatory requirements for dropped load safety cases.
- Understanding of the role of the blanket handler control system.
- The next steps will be:
    - Discussion of potential engineering solutions that mitigate the effect of seismic induced accelerations on the blanket handler and the suspended blanket segments.
    - Understanding the impact of the solutions on the future dropped load safety case.

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# RAMI action plan

- Improve the design of the pipework/capsules and prove by analysis/test that a blockage is less likely than the current failure rate estimate.
- Further recommendations were made to ensure the effects of blockages are minimised, such as; the use of filters to reduce the potential for foreign object build-up in the system, the development of procedures to remove a capsule if it gets stuck and the monitoring of pipework alignment.
- The inclusion of a standby compressor for use when the duty compressor fails to operate.
- The re-location of valves from the Port Cell to the Process Room. Components at the Port Cell cannot be maintained during ITER’s more frequent Short Term Maintenance period due to the high dose levels expected at this time, so any corrective maintenance would have to be postponed until the much less frequent Long Term Maintenance period. This significantly impacts the unavailability of these valves.