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Status of fusion technology: needs and challenges

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Technical Meeting on Synergies between Nuclear Fusion Technology Developments and Advanced Nuclear Fission Technologies

6-10 June 2022

IAEA, Vienna

Outline #1 - Fusion Technologies needs and challenges

- Development of Fusion Materials to withstand harsh service conditions
- Fusion materials irradiation facilities under reactor-relevant conditions
- Development of High Temperature Energy Conversion Systems
- Steady State operation of Fusion Facilities for energy production
- Computational tools, design and safety analyses codes
- Regulatory sized for fusion energy facilities licensing

Strong synergies and communalities with nuclear fission
Moderate synergies and communalities with nuclear fission

Outline #2 - Fusion Technologies needs and challenges

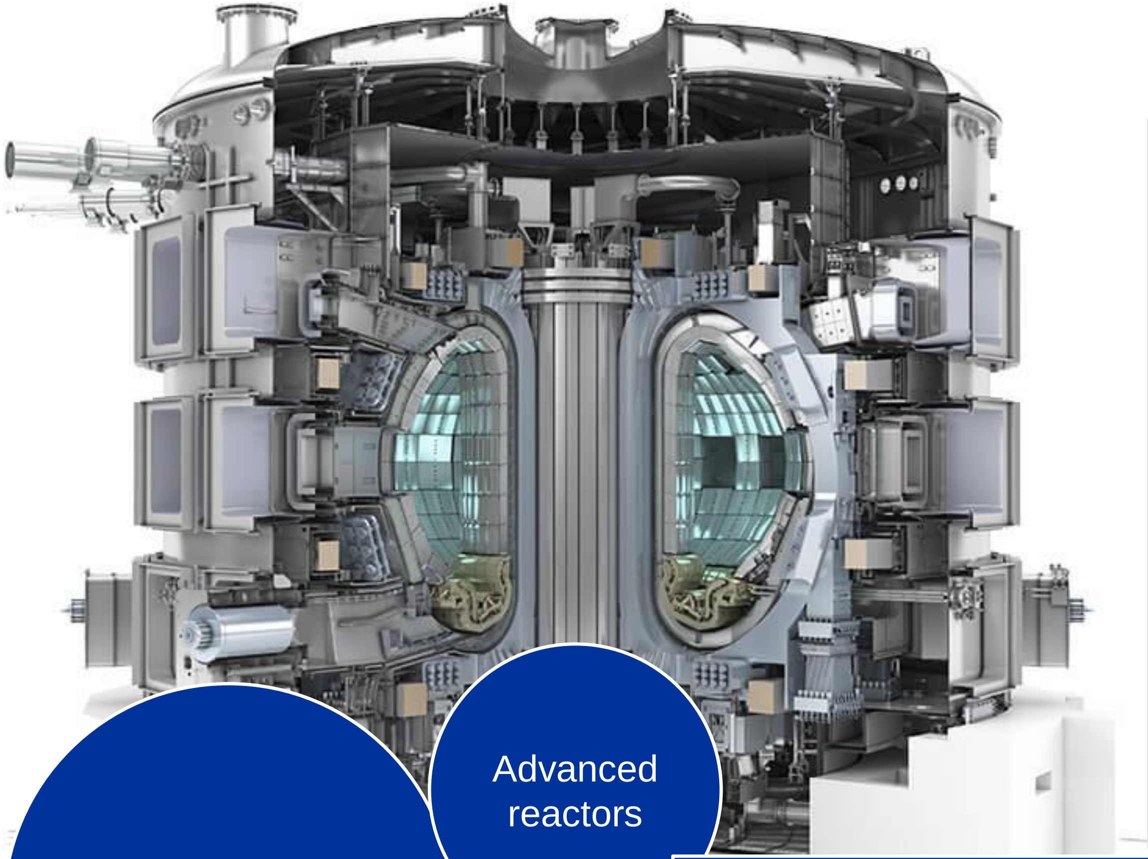
- Underlying and enabling new technologies for Fusion Energy deployment
- Demonstration of Blanket technologies: (T breeding, power extraction and shielding of the rest of the machine) and breeder material supply (Li, Pb).
- Effective, reliable and feasible Fuel Cycle
- Minimisation of radioactive waste hazards to reasonably achievable levels
- Fusion Energy Safety aspects not common to fission
- Remote Handling and In-Service Inspection validation

Strong synergies and communalities with nuclear fission
Moderate synergies and communalities with nuclear fission

Fission-Fusion Synergy: Materials

- No other technological sector has so strong synergies for fission & fusion
- Harsh environment: high T (> 500 C), n-flux (>100 dpa), aggressive environment (HLM, supercritical water, gas)
- *Production of He and H due transmutation reactions due to 14 MeV neutrons*
- High T mech. performances (resistance to thermal creep, T/M fatigue, etc.)
- Resistance to irradiation creep and swelling
- Resistance to corrosion/erosion/oxidation, → coatings development
- Tailor existing materials or develop new ones by modelling, qualification (testing, characterization), industrial production and final application
- Common design codes, AdvMan techniques (powder metallurgy, AM, HIP)

Fission-Fusion Synergy: Materials



	Present Generation			Next Generation	
	Fission (Gen II&III)	**Fusion (ITER)**	**Fusion/GenIV Demonstrators**	**Fission (Gen IV)**	**Fusion (Reactor)**
Structural material	**Austenitic steels, Zircaloy**	**Austenitic steels**		**F/M steels, ODS Superalloys? SiC_f-SiC?**	**F/M steels, ODS SiC_f-SiC?**
T_{max} (struct.mat)	<300 °C	<300 °C		**500-1000°C**	**550-1000°C**
DPA max (internal components)	~1 dpa	~3 dpa (TBM)		**~30-100 dpa**	**~150 dpa**
He production	~ 0.1 appm	~30 aapm		~3-10 appm	~1500 appm

Growing synergies between fission and fusion research towards demonstration plants, F. Carré, Ph. Magaud [FISA 2019]

Comparable service conditions:
high temp. (>500 °C) & **high dpa** (>100 dpa)

Materials

Advanced reactors

- Materials and Fuels Modelling and Qualification (testing; charact.)

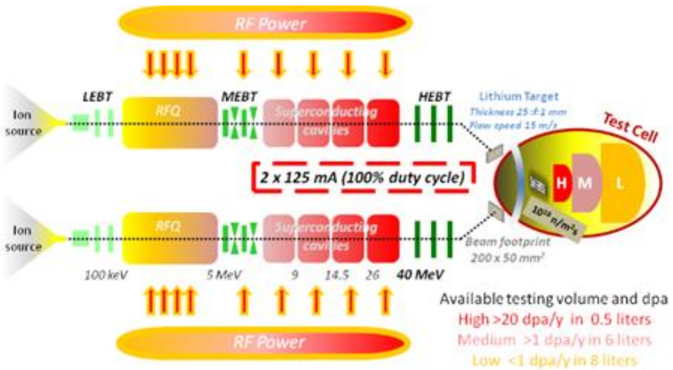
Fusion Facilities

- Materials-coolants compatibility
- Efficient energy generation

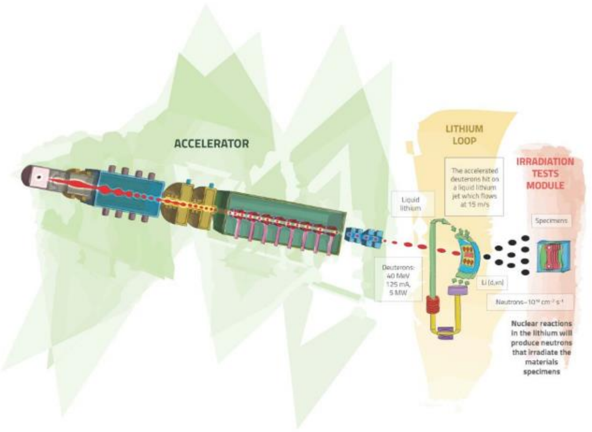
https://fusionforenergy.europa.eu/the-device/

Fusion Materials Irradiation Facilities

- Fission MTR experience relevant, neutrons energy up to 2 MeV
- Fusion neutron irradiation facilities n > 14 MeV are crucial
- Two large projects are under way
  - ✓International Fusion Materials Irradiation Facility (IFMIF) → EU-JA BA
  - ✓IFMIF-DEMO Oriented Neutron Energy Source (IFMIF-DONES) →EU Fusion Roadmap
- IAEA CRP on development of steady-state CFNS [IAEA-TECDOC 1998]
- The issue is the timeline: ready <start of DEMO construction (2040)



https://www.ifmif.org



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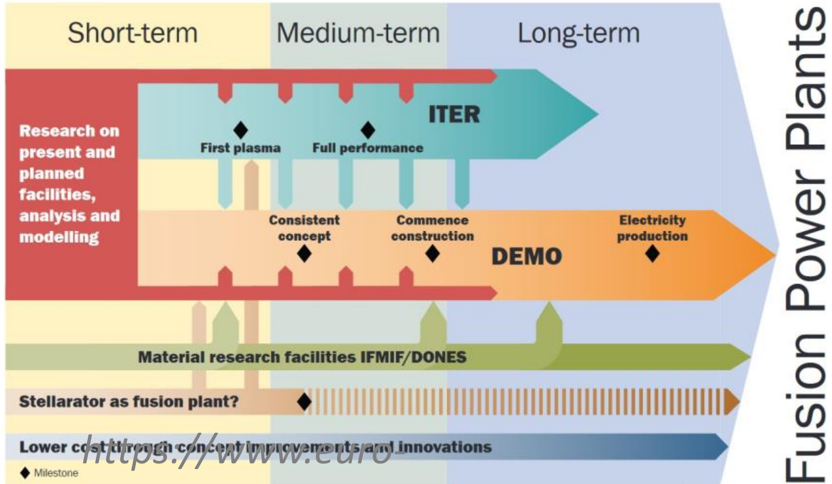
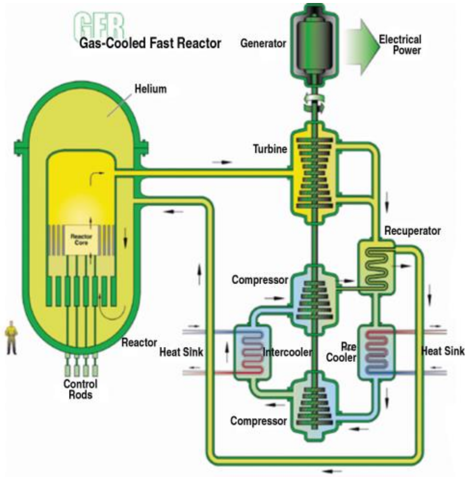


https://www.euro-fusion.org/fileadmin/user_upload/Target_groups/Roadmap_Illustrated.jpg

High Temperature Power Conversion Systems

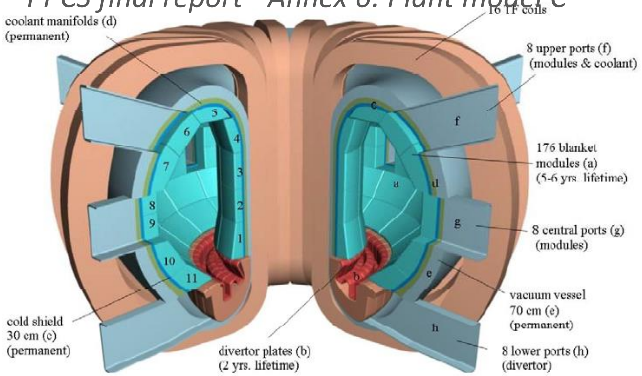
Future fusion facilities will use high-T He and HLM power conversion system similar to some of the six concepts in Gen IV. Potential synergies are in the design and performance of SSCs relative to He technology, (components tightness, thermal insulation, purification, specific T removal & containment). Others, related to LM, are for materials behaviour and components qualification.



GenIV – GFR

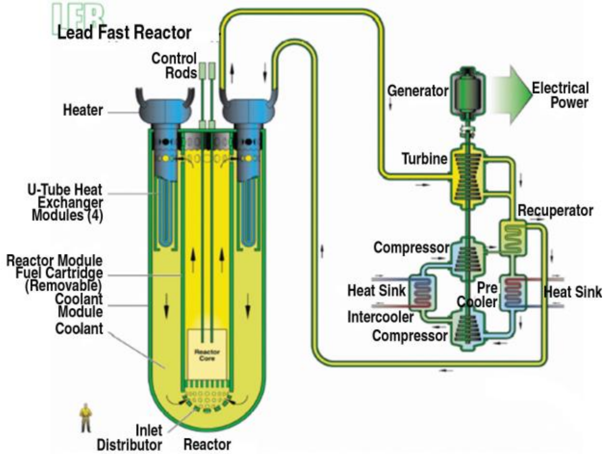
https://doi.org/10.1051/rgn/20071108

PPCS final report - Annex 6: Plant model C



PPCS Model C

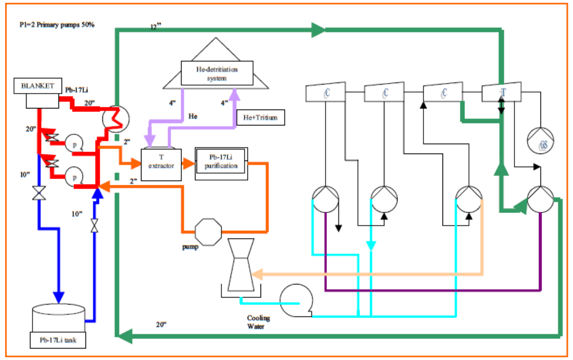
DC He/LiPb
BK 300-480/480-700
DIV 540-720/ ---
He Brayton cycle



https://doi.org/10.1051/rgn/20071108

GenIV – LFR

PPCS final report - Annex 7: Plant model D

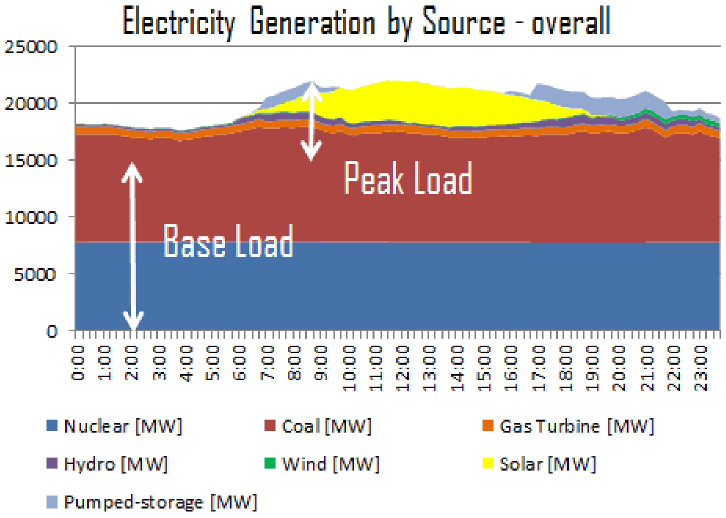


PPCS Model D

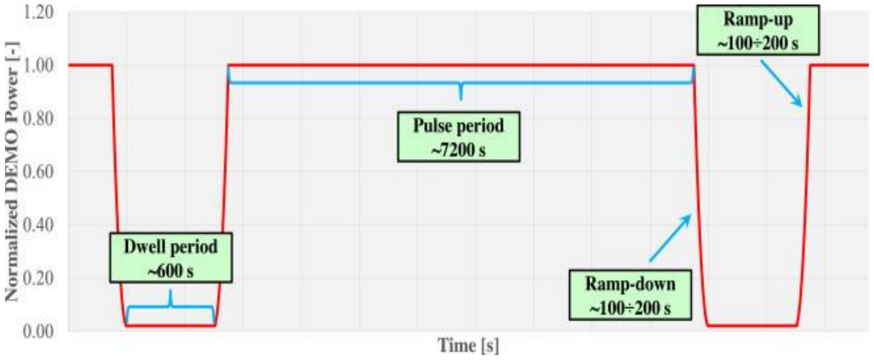
SCLL LiPb
BK 700-1100
DIV 600-990

Steady State operation for energy production

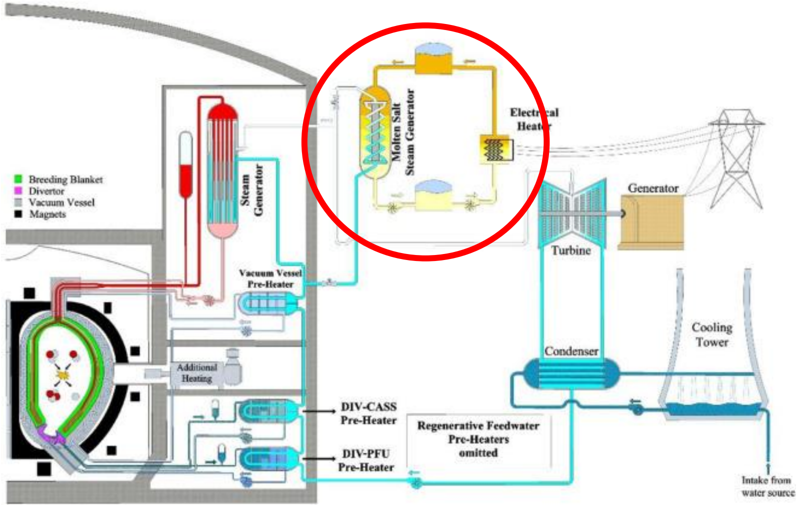
- Electricity production → load following is required for NPPs
- H generation, desalination, heat distribution are more tolerant (also MIF)
- Steady state plasma (by current drive, or Stellarator, Speromak) (for MFE)
- For DEMO (Tokamak) decouple the PHTS from the PCS by IHTS based on molten salt technology derived from Concentrating Solar Power (CSP) plants (interest for Gen IV)



Base Load vs Peak Load Power Plants



Fusion Engineering and Design Volume 178, May 2022, 113093



EU-DEMO WCLL BoP - Direct-coupling (DCD) with small ESS

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Computational tools, design & safety analyses codes

- Blanket design, directly or by adaptation, using nuclear engineering design methods, computational tools and codes
  - ✓ n- transport (MCNP, Tripoli4) transmutation (FISPACT-II, ACAB). Adaptation with n-energy range extended → 14 MeV
  - ✓ Nuclear data files, synergic efforts pursued to commonly merge (ENDF/B, JEFF-3,2, JENDL, CENDL, BROND-2, FENDL-2.1. → FENDL-3)
  - ✓ Thermal-hydraulic (RELAP5 → ATHENA, MELCOR 1.8.2); thermo-mechanical (e.g., CAST3M)
- Fusion core phenomena (plasma physics and interactions, hydrodynamics, particle radiation, MHD), tritium behavior, SuperConducting magnet quench
- System analysis (for CoE) (e.g. PROCESS)
- Design and construction rules codes developed for fission (ASME Sec-III RCC-MRx)
- Safety analyses codes, (in addition to n-transport and activation) from fission analogues

Regulatory sized for fusion facilities licensing

- ➢ Fusion facilities currently regulated in different ways:
  - radiological substance / accelerator / nuclear installation (e.g. ITER as INB)
- ➢ Current framework generally applicable but needs to address specificity of fusion
  - ✓ radioactive source term differs since no fissile materials are handled as fuel;
  - ✓ fusion reaction would intrinsically terminate in the event of a disturbance;
  - ✓ fusion generates no long-lived radioactive waste.
- ➢ Proposal for a fusion regulatory framework should be:
  - ✓ tailored to the safety concerns of future fusion facilities: proportionate/graded to the hazard/risk potential (i.e. dose to public as well as radioactive inventory);
  - ✓ flexible and adaptable to account for existing and future variations of technology and uncertainty associated with future development;
  - ✓ transparent to support an appropriate regulatory control and licensing (important role of public acceptance);
  - ✓ technology neutral and enable for innovation & rapid pace of development.

Underlying and Enabling Technologies

- Among the most recent lines of R&D, it is worth mentioning
  - Artificial Intelligence (AI), and Machine Learning (ML)
    - TCV Lausanne different set of plasma configurations produced and controlled by an autonomous learning system (with DeepMind)
    - TAE experiments to increase plasma lifetime and evolution (with Google AI)
  - High Temperature Superconducting magnets
    - CFS and MIT experiment in September 2021, large HTS superconductor coil made of REBCO tapes (270 km) was ramped up to a field of 20 T
  - Additive Manufacturing (AM)
  - Improvement in power electronics and high-speed servocontrols

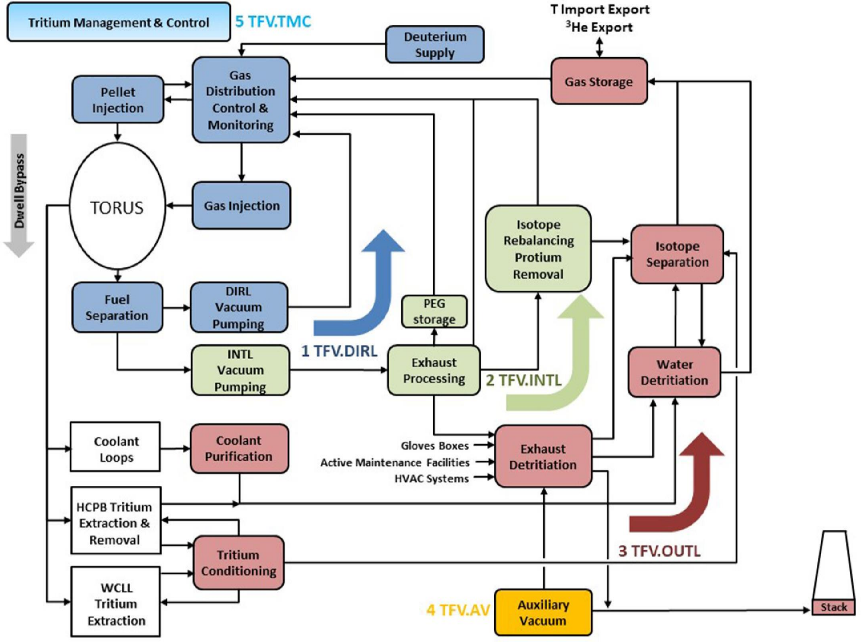
    Relevant for the progress of MIF

Demonstration of Blanket technologies and Breeder Material Supply

- A Tritium Breeding Blanket (TBB) for T breeding self-sufficiency is mandatory for DEMO. TBB is included in the ITER missions *"**ITER should test TBMs concepts that would lead in a future reactor to T self-sufficiency, the extraction of high-grade heat and electricity production**"*.
- The selection of the four ITER TBSs for the initial configuration is under way
- One of the key goals is TBR > 1, (TBR = 1.05 – 1.10)
- DEMO will demonstrate self-sufficiency, but uncertainties for the initial T quantity to start
- Other DEMO BB functions : <u>power extraction and shielding</u>, (on SCs mag. $< 5 \times 10^{-5}$ W/cm^3)
- Supply of Li and Li-6 industrial process separation (enrich. 40-60% for ceramic breeder, up to 90 % for liquid LiPb eutectic) are key issues for the decades to come
- Competition with Li demand for batteries market (Electric Vehicles)

Effective, reliable and feasible Fuel Cycle

- Other than T self-sufficiency, plant availability and safety, for the DEMO Fuel Cycle some top requirements
  - ✓ Ensure technology feasibility (e.g., accordance with TBR)
  - ✓ Allow start-up and licensing (minimize T inv., also for safety)
  - ✓ Guarantee economic convenience (scalability from ITER TBM Program?)



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Minimization of Radioactive Waste Hazard

- Fusion NPPs will generate large amount of mildly radioactive materials
- Fusion waste is significantly different from the fission NPPs waste
- Maximizing the reuse of materials through recycling & clearance
  - ✓ to reduce the space required in repositories,
  - ✓ recover valuable resources (through less mining of materials), and
  - ✓ more important, minimize the environmental impact of fusion.
- Recycling/clearance approach, in addition to R&D already under way, requires “ad-hoc” policy and regulatory framework by governmental agencies
- Experiences from fission facilities are valuable, as approaches and concepts for managing mildly activated are the same.
- Fusion will benefit from the ongoing fission recycling experience (e.g.; decommissioning) and related governmental regulations

Fusion Energy safety aspects not common to fission

- Accidents:
  - Explosions due to hydrogen (jeopardize VV Integrity), or fire at an auxiliary tritium plant
  - Activated dust and also tritiated explosion in case of LOVA with air ingress in the VV
  - Plasma events: disruptions, sudden increase in fuelling rate or auxiliary heating, (more likely in experimental facilities). In steady-state plants frequency shall be much lower, but be considered in the list of unlikely events
- The TF coils magnetic energy in >> ITER → impact the VV integrity (arc or quench)
- Spills & energy release from cryogenic fluids (liq. He or N) in the cryostat. O_3 formation
- Be toxicity; (impurities, such as natural uranium and/or thorium → TRU)
- Increased inventory of T in DEMO or in commercial facilities. DEMO T production 10^4 greater than ITER TBM, challenges for effective T extraction, permeation and detritiation systems. DEMO may adopt Gen IV approach on multiple barriers (DID) against releases
- For extreme external hazards, such as earthquakes, flooding and aircraft crashes, safety standards and categorization could be like fission reactors

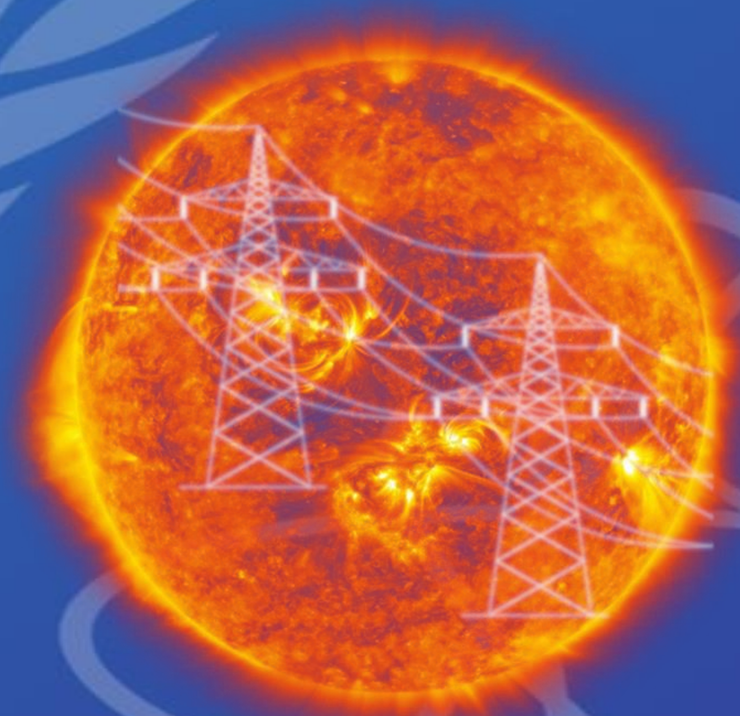
Remote Handling and In-Service Inspection

- Remote Handling (RH) and in-service inspection (ISI) is another potential area of synergies
- RH procedures and tools will play a major role in fusion facilities operation; in-vessel components (IVCs) periodical replacement and recycling
- RH conditions should be more severe in fusion with a harder radiation spectrum, but the complication is due to the complexity of activities, if recycling includes IVCs refabrication
- Principal design aspects: remote controllability, radiation hardened electronics and CAD supported operations are of common interest. Working on very high radiation field in fission, e.g., management of spent fuel and HLW vitrification of (γ-dose rates thousands of Sv/h)
- Fission experience of ISI are wide and relevant. (e.g. control of Phenix core supporting structure weldings)
- ITER IVVS to monitor the status of the FW and Divertor PFCs and to estimate the quantity of tokamak dust. Relevant background from experimental plants, (JET, Tore Supra, JT-60SA, etc.)

Conclusions

- Many and relevant synergies from nuclear fission experience
- But also communalities for materials development, activated metals management, remote handling, liquid metal, for the road to walk (Gen IV and advanced fission plants, DEMO & commercial fusion facilities)
- The first (licensing) and last (decommissioning and radwaste management) steps of the plant life require a regulatory sized approach for fusion facilities (due to the different hazard/risk potential)
- Design, construction, operation, a part the fuel cycle and plasma control, of fusion facilities have many synergies with fission experience

Thank you

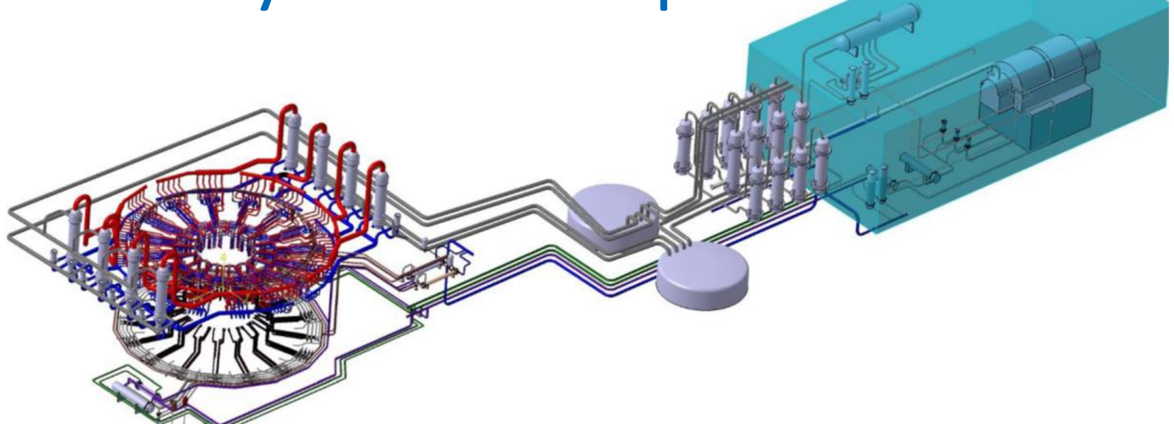


Website: https://nucleus-new.iaea.org/sites/fr/Pages/fusion.aspx

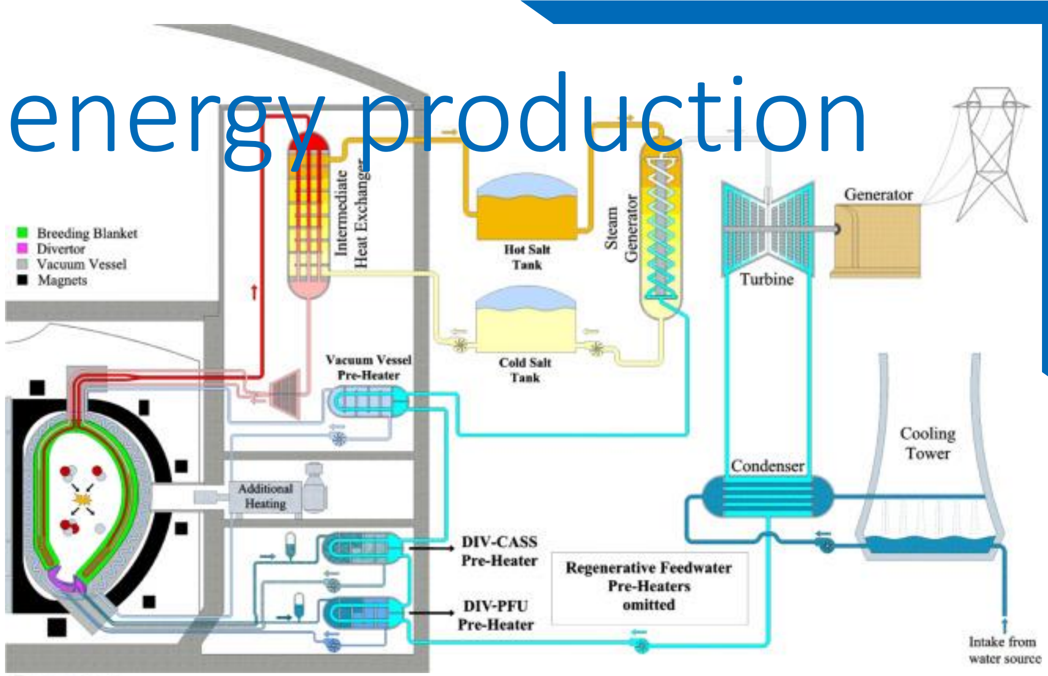
Email address: FFSynergies@iaea.org

Spare Slides

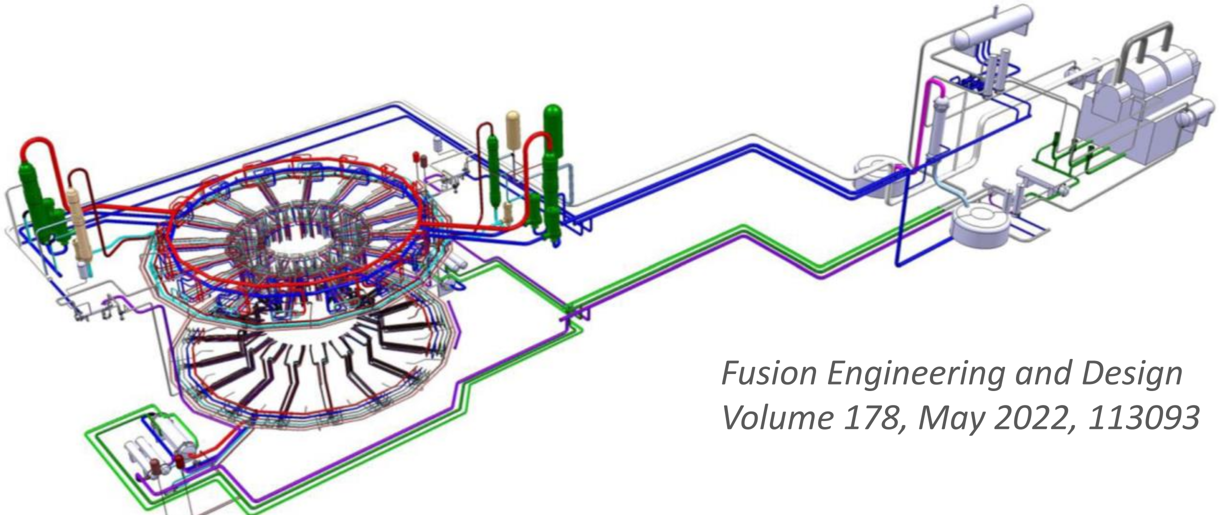
Steady State operation for energy production



EU-DEMO HCPB ICD BoP layout



EU-DEMO HCPB ICD BoP simplified scheme



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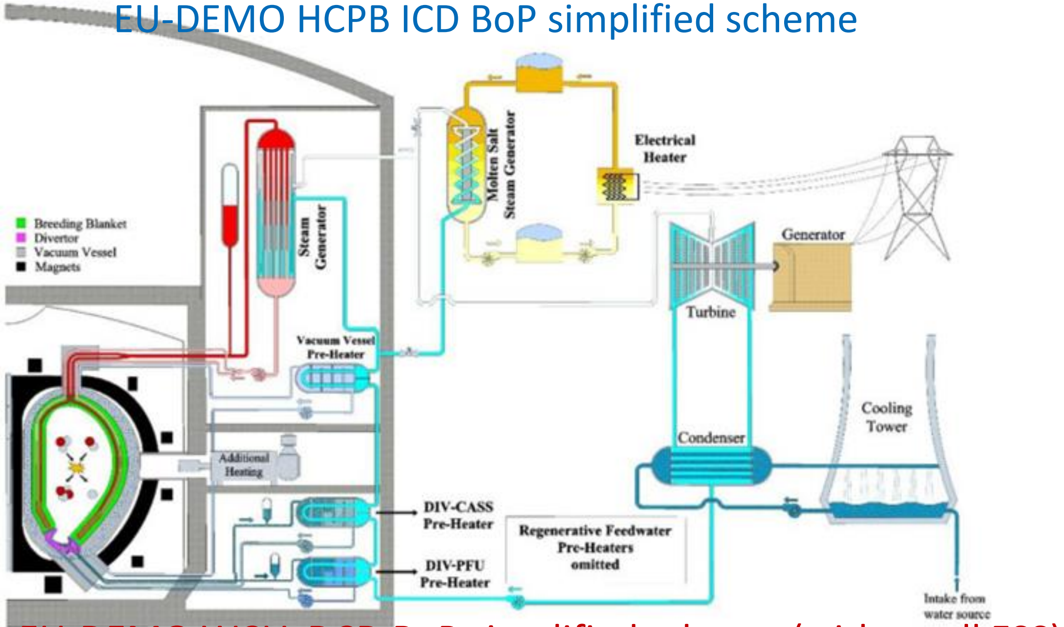
EU-DEMO WCLL DCD BoP layout (with small ESS)



EU-DEMO WCLL DCD BoP simplified scheme (with small ESS)

Steady State operation for energy production

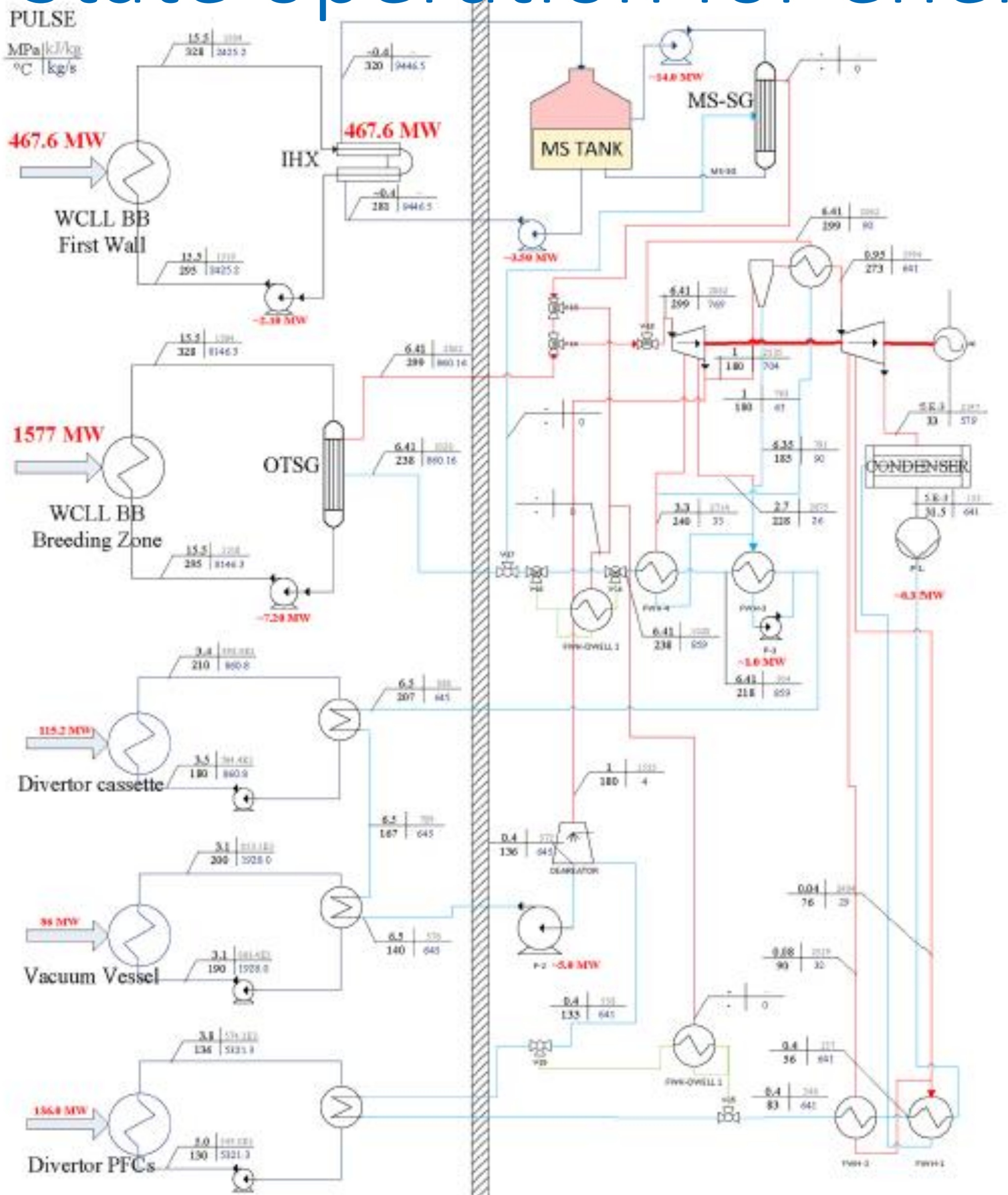
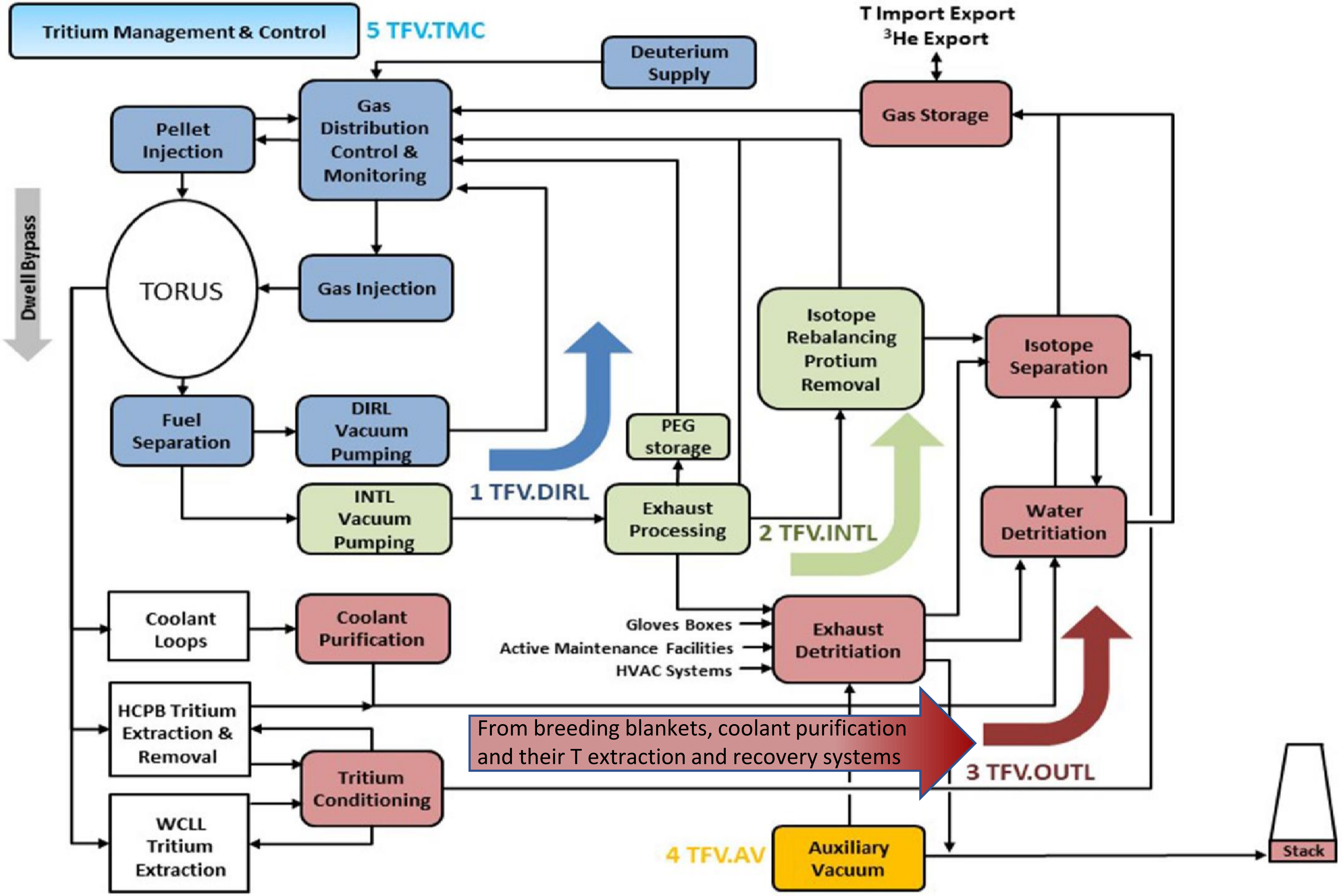


Fig. 4. Preliminary cycle configuration during pulse mode.

Emanuela Martelli et al.; Study of EU DEMO WCLL breeding blanket and primary heat transfer system integration, Fusion Engineering and Design, Volume 136, Part B, 2018, Pages 828-833, ISSN 0920-3796, https://doi.org/10.1016/j.fusengdes.2018.04.016

Effective, reliable and feasible Fuel Cycle



Tritium Management & Control

5 TFV.TMC

Deuterium Supply

T Import Export
^{3}He Export

Gas Storage

Pellet Injection

Gas Distribution Control & Monitoring

Dwell Bypass

TORUS

Gas Injection

Fuel Separation

DIRL Vacuum Pumping

1 TFV.DIRL

PEG storage

Isotope Rebalancing Protium Removal

Isotope Separation

INTL Vacuum Pumping

Exhaust Processing

2 TFV.INTL

Water Detritiation

Coolant Loops

Coolant Purification

Gloves Boxes

Active Maintenance Facilities

HVAC Systems

Exhaust Detritiation

HCPB Tritium Extraction & Removal

From breeding blankets, coolant purification and their T extraction and recovery systems

Tritium Conditioning

3 TFV.OUTL

WCLL Tritium Extraction

4 TFV.AV

Auxiliary Vacuum

Stack

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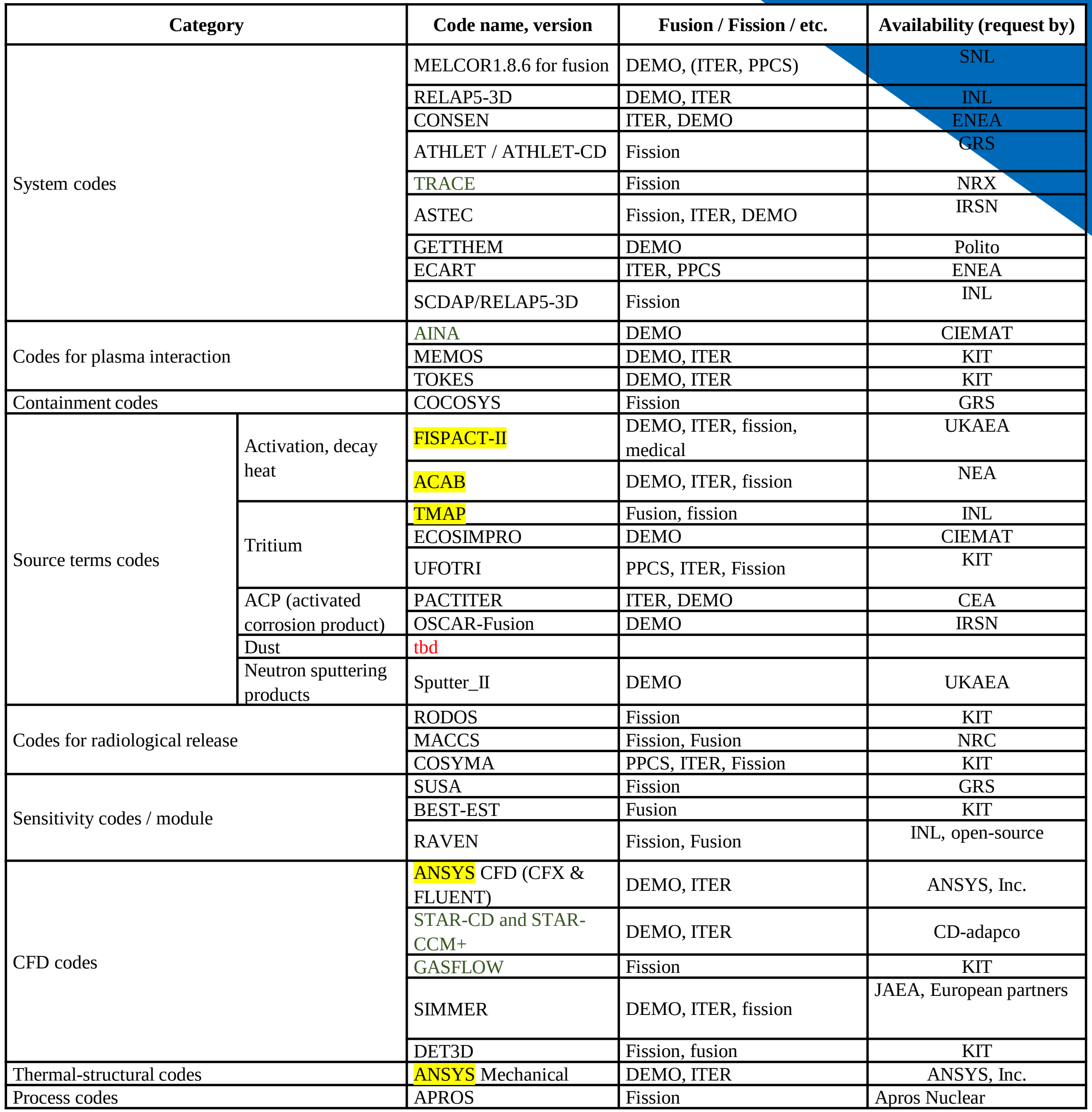
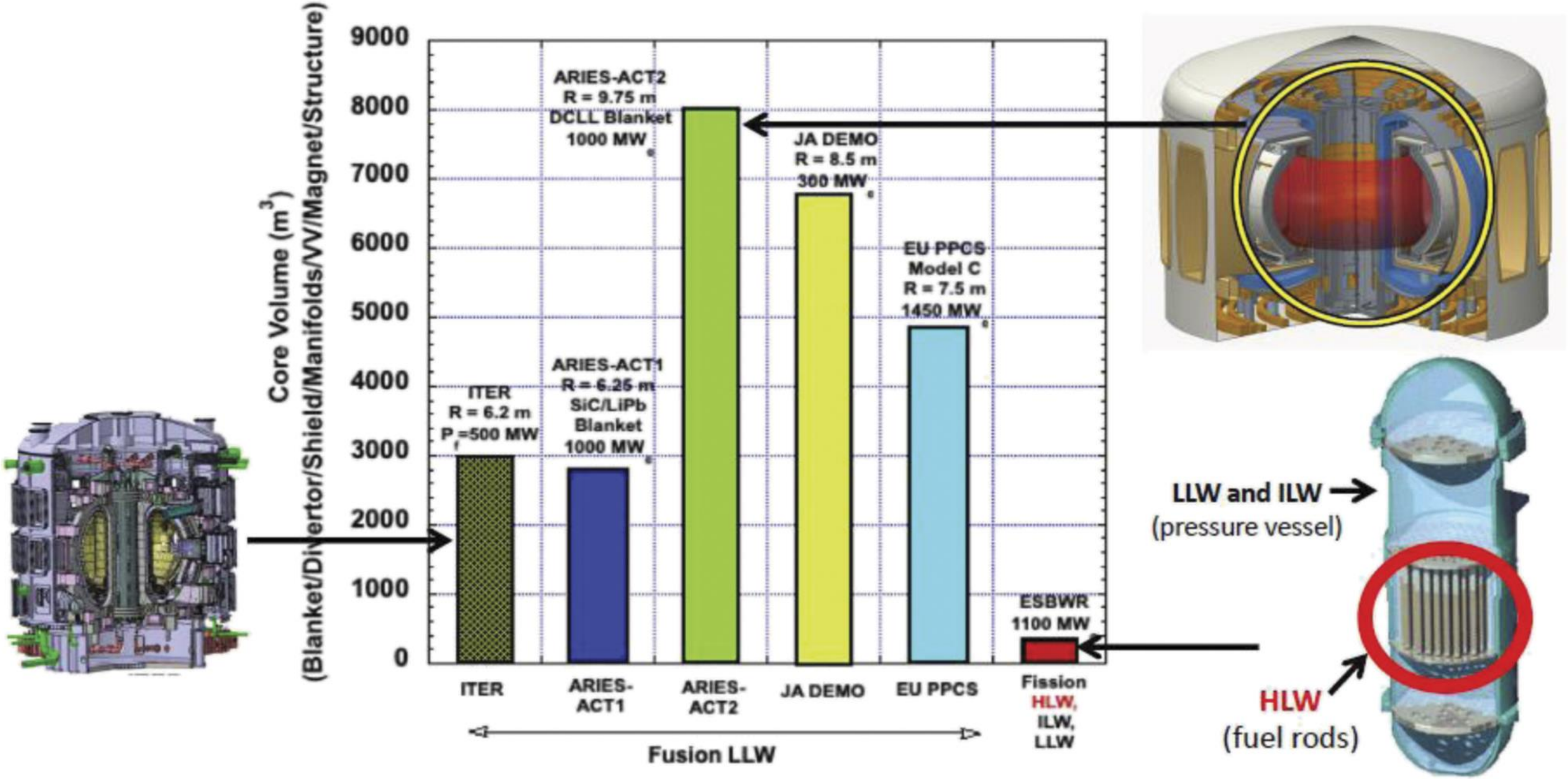
Safety analyses codes



Category		Code name, version	Fusion / Fission / etc.	Availability (request by)
System codes		MELCOR1.8.6 for fusion	DEMO, (ITER, PPCS)	SNL
		RELAP5-3D	DEMO, ITER	INL
		CONSEN	ITER, DEMO	ENEA
		ATHLET / ATHLET-CD	Fission	GRS
		TRACE	Fission	NRX
		ASTEC	Fission, ITER, DEMO	IRSN
		GETTHEM	DEMO	Polito
		ECART	ITER, PPCS	ENEA
		SCDAP/RELAP5-3D	Fission	INL
Codes for plasma interaction		AINA	DEMO	CIEMAT
		MEMOS	DEMO, ITER	KIT
		TOKES	DEMO, ITER	KIT
Containment codes		COCOSYS	Fission	GRS
Source terms codes	Activation, decay heat	FISPACT-II	DEMO, ITER, fission, medical	UKAEA
		ACAB	DEMO, ITER, fission	NEA
	Tritium	TMAP	Fusion, fission	INL
		ECOSIMPRO	DEMO	CIEMAT
		UFOTRI	PPCS, ITER, Fission	KIT
	ACP (activated corrosion product)	PACTITER	ITER, DEMO	CEA
		OSCAR-Fusion	DEMO	IRSN
	Dust	tbd		
	Neutron sputtering products	Sputter_II	DEMO	UKAEA
Codes for radiological release		RODOS	Fission	KIT
		MACCS	Fission, Fusion	NRC
		COSYMA	PPCS, ITER, Fission	KIT
Sensitivity codes / module		SUSA	Fission	GRS
		BEST-EST	Fusion	KIT
		RAVEN	Fission, Fusion	INL, open-source
CFD codes		ANSYS CFD (CFX & FLUENT)	DEMO, ITER	ANSYS, Inc.
		STAR-CD and STAR-CCM+	DEMO, ITER	CD-adapco
		GASFLOW	Fission	KIT
		SIMMER	DEMO, ITER, fission	JAEA, European partners
		DET3D	Fission, fusion	KIT
Thermal-structural codes		ANSYS Mechanical	DEMO, ITER	ANSYS, Inc.
Process codes		APROS	Fission	Apros Nuclear

Xue Zhou Jin, EUROfusion contribution Final Report on Deliverable SAE-4.4.5 GSSR Vol. 10: Safety models and codes, EFDA_D_2NVCD2 v1.2, February 2021

Minimization of Radioactive Waste Hazard



Fusion core volumes of several nuclear fusion plants and ESBWR (U.S. waste estimation)

Sehila M. Gonzalez de Vicente et al 2022 Nucl. Fusion 62 085001
https://iopscience.iop.org/article/10.1088/1741-4326/ac62f7/pdf