Key Issues for the Safety and Licensing of Fusion

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Outline

- Background - history of safety studies
- Anticipating licensing requirements for fusion
- Review of outcomes of the studies
  - Public safety - internal events
  - Public safety - external events
  - Occupational safety
  - Environmental impacts in operation
  - Long-term environmental impacts
- Conclusions - list of key issues

Background - a decade of safety studies

- Series of European studies of fusion safety
  - SEAFP, SEAFP-2, SEAL, SEAFP-99
  - all summarized in “Safety and Environmental Impact of Fusion” (SEIF), Ian Cook et. al., 2001.
- Recently completed European “Power Plant Conceptual Studies” (PPCS)
  - updated earlier assessments, and confirmed with improved modeling
  - see Ian Cook’s presentation O-I-4.2 (this afternoon)
- Extensive and comprehensive safety studies of ITER
  - culminating in Generic Site Safety Report (GSSR), 2001
- Safety analyses as part of reactor studies in US and Japan

Licensing - what will be required?

- Difficult to predict licensing requirements for a fusion power plant in mid-21st Century
- Likely to include need to *demonstrate* adequate performance for:
  - **public safety** in normal operation, off-normal events and accidents
  - **occupational safety** in normal operation, during maintenance, and in off-normal events and accidents
  - **minimal environmental impact** in normal and abnormal operation
  - **minimal long-term environmental impact** from wastes
- Specific criteria cannot be anticipated
  - may be tougher targets than at present
  - focus of environmental concerns may change

Public safety - accidents

- Analyses of postulated accident scenarios, in ITER and conceptual power plants, have been extensive
- No-evacuation criterion has been satisfied, even in conservative analyses of extremely unlikely or hypothetical sequence

> Based on IAEA Basic Safety Standards 1996:
>
> Evacuation recommended if avertable dose is **50 mSv** in no more than **1 week**.

- Systematic identification of events to be analysed is essential
  - to ensure study is comprehensive

Transparent method of presentation is also important

PPCS accident analyses - summary

- Dose to Maximum Exposed Individual at 1km, 7-day exposure, using 95% percentile from weather distribution

Plant Model	Dose [mSv]			
	Bounding Accident Sequence	Ex-VV LOCA	Ex-VV LOCA + in-VV LOCA	LOFA + in-VV LOCA
Water-cooled lithium-lead	1.16	0.0017	0.16	
Helium-cooled pebble bed	18.1			0.42

- "Bounding accident sequence" is hypothetical event based on total and prolonged loss of all active cooling, with no operation of any active safety system, and no operator intervention
  - now analysed with improved, 3-D modeling

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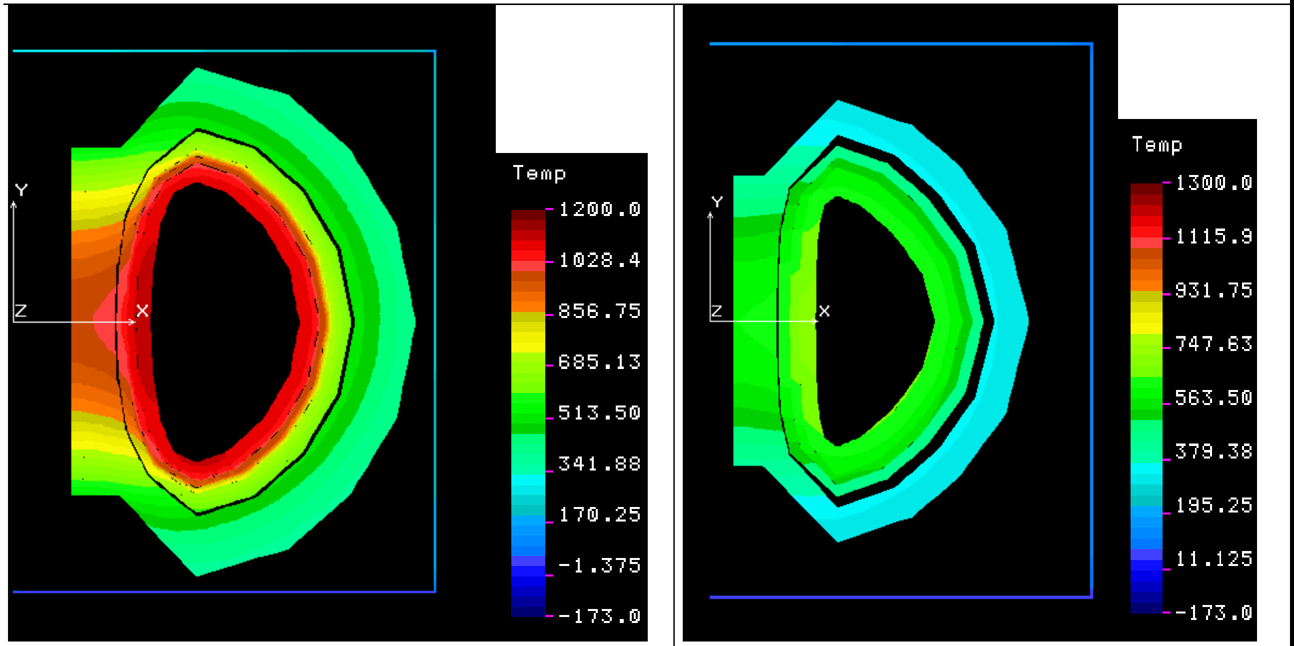
PPCS accident analyses - summary

Temperature distributions after 100 days

Peak values:

1140 ºC (EUROFER structure)

935 ºC (SiC/SiC)



He-cooled pebble bed (EUROFER structure) He-cooled lithium-lead (SiC/SiC structure)

- "Bounding accident sequence" is hypothetical event based on total and prolonged loss of all active cooling, with no operation of any active safety system, and no operator intervention
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Accident analyses - source terms

- Four classes of radioactive sources for potential accidental release:
  - **in-vessel tritium**, absorbed or co-deposited on plasma-facing surfaces, and in blanket
  - **dust**, eroded from plasma-facing surfaces
  - **activated corrosion products** (water-cooled systems only)
  - **activation products in solid structure** volatilized mainly by oxidation

Accident analyses - source terms

- in-vessel tritium
- dust
- activated corrosion products
- activation products in solid structure

Estimated by engineering judgement (in-vessel tritium, dust)

Calculated by detailed computational modeling (activated corrosion products, activation products in solid structure)

In-vessel tritium and dust inventories

- Assumed quantities vulnerable to mobilization:

	European power plant studies	ITER	
		Limit	Assumed in analyses
Tritium	1kg	450g	1kg
Dust	10kg	100kg	350kg

- These are assumptions based on tritium retention and dust generation in current experiments

Important to remove uncertainties on these values, by
  - better understanding of tritium retention
  - understanding plasma-materials interactions and dust generation
  - development of tritium and dust removal techniques

External hazards

- High profile due to public concern about externally-initiated event (e.g. act of terrorism)
- Principal safety function is confinement
  - insufficient energy from internal events to cause large breach
  - but what about arbitrarily energetic external events?
- Analyses of possible structural damage from earthquakes, or aircraft impact, can be done for specific sites
  - e.g. done for Cadarache as part of preparation for ITER licensing
- But is a good result possible just based on vulnerable inventory?

Inventory-based approach to external events

- Worst case release using current PPCS assumptions:
  - 1kg tritium (assume 100% HTO)
  - 10kg dust (steel and tungsten)
  - 505g activated corrosion products from each of 6 coolant loops (water-cooled plant only)
  - 10kg solid activation products volatilized by oxidation (need to postulate substantial extra energy input)
- Total dose from above to most exposed individual at 1km: 1 - 2 Sv

Inventory-based approach to external events

- Improvements required are modest.
  Release mass limits to comply with 50mSv no-evacuation criterion:

Source term	Mass release for 50mSv	Approx. reduction factor required on present assumption of complete release of vulnerable inventory
Tritium as HTO	110 g	9
Tritium as HT	59 kg	-
Dust (W and steel)	930 g	11
ACPs (water-cooled plants only)	500 g	6

Inventory-based approach to external events

- Mobilizable inventories could be reduced by
  - improved determination of in-vessel tritium and dust inventories
  - estimate of fraction of tritium that could actually be released as HTO
  - estimate of fraction of dust that could actually be released without re-deposition
  - improve water chemistry to reduce corrosion (or don't use water coolant!)
  - improve knowledge of volatility of solid activation products

Occupational Safety

- Most personnel doses arise in maintenance operations
- Difficult to quantify for conceptual power plants, with no detail of maintenance procedures
- Conservative assumptions in European power plant studies led to collective doses:

helium-cooled plant	0.2 person-Sv/yr
water-cooled plant	2 person-Sv/yr

  – latter value is too high, and should be reduced
- Preliminary assessment for ITER: 0.26 person-Sv/yr

Occupational safety

- Occupational doses may be reduced by
  - design optimization, with localized shielding
  - improved maintenance procedures
  - adjustment of water chemistry
- Many improvements can be made only once plant is operating
- Development of fusion materials is important
  - to extend component lifetimes and reliability
  - reduce frequency of maintenance operations
- In addition to maintenance operations, planned and unplanned, attention may turn to potential for direct harm to personnel in an accident

Environmental impact during operation

- In principle, potential for radioactive releases as effluents
  - leakages from cooling systems, detritiation systems, ventilation systems, fuel cycle plant
- Studies have consistently shown that these will be extremely small
- PPCS results: Max doses µSv/yr

	Water-cooled power plant		Helium-cooled power plant	
	gas	liquid	gas	liquid
Tritium (HT + HTO)	0.87	0.05	0.28	0.003
Activation products	0.02	0.02	0.004	0
total	**0.89**	**0.07**	**0.28**	**0.003**

- Site-specific study for ITER at Cadarache also gave < 1 µSv/yr
  - compared with natural background ~ 2500 µSv/yr

Long-term environmental impact

- At end of plant life, material activated by neutron flux
  - fixed components plus blanket and divertor replacements during operation
  - much of it at low level of activation
  - decays relatively quickly
  - *but* large total mass
- Massive ex-vessel components (TF coils and supporting structure) decay to very low level after some years
- Strong motivation to remove this from regulatory control
  - "Clearance"
  - for reuse, recycling or disposal as normal non-active scrap

Clearance of active material

- IAEA proposal in 1996, to set nuclide-by-nuclide Clearance Levels
  - based on maintaining maximum public dose < 10 μSv/yr
- European Commission recommended Clearance Levels for implementation of Basic Safety Standards
- Germany set this into national law, with Radiation Protection Ordnance 2002
  - hopefully, other countries will follow
- This would allow Clearance of ~ 50% of active material from a fusion power plant
  - for remainder, consider recycling within nuclear industry

Recycling of active material

- Radiological criteria for suitability of material for recyling
  - based on ability to handle and process it

- Limits adopted in European power plant studies:

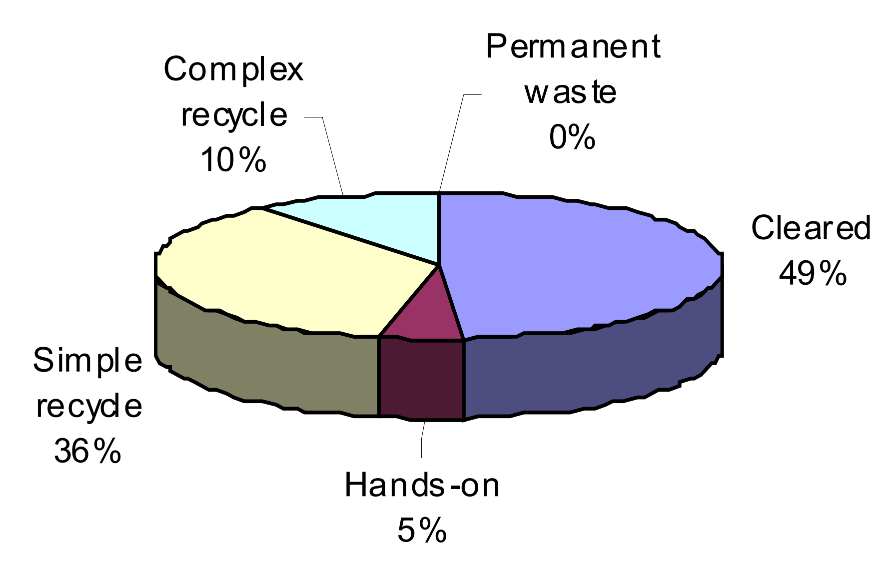
Category	Gamma dose rate	Decay heat
Hands-on recycle	< 10 μSv/hr	
Simple recycle	< 2 mSv/hr	< 1 W/m^3
Complex recycle	2 – 20 mSv/hr	1 – 10 W/m^3
Permanent disposal	> 20 mSv/hr	> 10 W/m^3

These limits should be re-evaluated
  - 20 mSv/hr as upper limit for remote handling limit is probably far too conservative

- Nevertheless, results based on them in PPCS are good

Categorization of active material

- PPCS result for complete active inventory of 1.5 GWe power plant 100 years after end of plant life



- Note **no** permanent disposal waste
  - result holds for all power plant designs and variants
  - *except* when TZM molybdenum alloy used in divertor (reminder of importance of materials selection)

Recycling potential

- Recycling of fusion material seems possible on radiological grounds
- But there are other factors
  - Will there be feasible recycling operations for the relevant materials?
  - Will the processing be economically viable?

Proper evaluation of potential for recycling is essential

- If it is decided that some material does need long-term disposal
  - studies show low and intermediate-level repositories for fission reactor waste are suitable for almost al fusion waste
  - only a small quantity would require deep geological disposal

Conclusions - key issues 1

- Studies have show very good safety performance expect from fusion, but some key issues have been noted:
  - A transparent presentation is needed of accident selection for analyses
  - in-vessel tritium and dust inventories must be better determined
  - improved analyses to allow inventory-based approach to limit consequences of external events
  - materials development, to increase component lifetimes and reliability

Conclusions - key issues 2

- Uncertainties in occupational doses should be reduced where possible
- May need more complete assessment of potential direct hazards to personnel in accident sequences
- Re-evaluation of criteria used to categorise active material for recycling
- Full appraisal of feasibility of recycling of fusion materials