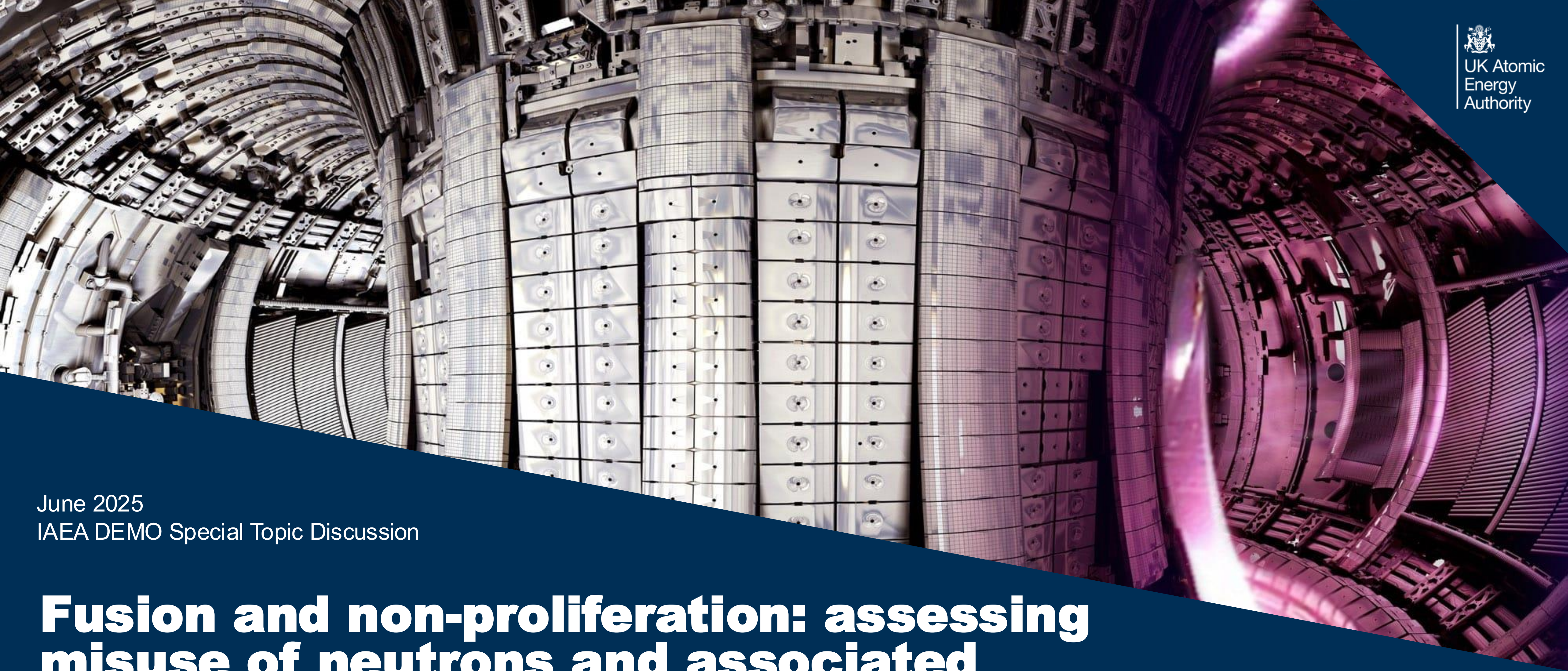

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IAEA DEMO Special Topic Discussion

Fusion and non-proliferation: assessing misuse of neutrons and associated signatures in fusion systems

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UKAEA

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PPPL

SRNL

MPIL

Several others

Some views are of the authors, not necessarily of UKAEA or other organisations listed

Background: some previous analysis on fusion and non-proliferation

- A. Glaser and R.J. Goldston 2012 Nucl. Fusion 52 043004
- G. Franceschini, M. Englert, & W. Liebert, (2013). Nuclear Fusion Power for Weapons Purposes: An Exercise in Nuclear Proliferation Forecasting. The Nonproliferation Review, 20(3), 525–544.
- M. Englert, The proliferation risks of intense neutron sources (2012)
- G. Franceschini; M. Englert (2013): Safeguarding Fusion Reactors . A plea for a proliferation-resistant design of nuclear fusion , HSFK Report , No. 7
- P. Sauter, Safeguarding Nuclear Fusion – Nuclear Non-Proliferation Law in a Fusion-Powered Future (May 15, 2023). Max Planck Institute for Comparative Public Law & International Law (MPIL) Research Paper No. 2023-13
- J. L. Ball et al 2025 Nucl. Fusion 65 036038
- S. Desai et al., Building a path toward global deployment of fusion: Nonproliferation and export considerations, Atlantic Council issue brief, April 2025
- M. Diesendorf, D. Roser, & H. Washington, (2023). Analyzing the Nuclear Weapons Proliferation Risk Posed by a Mature Fusion Technology and Economy. Energies, 16(3), 1123
- IAEA Consultancy Meeting (held in 2013)
- US Workshops, PPPL and SRNL - numerous contributors
- Office of Technology Assessment at the German Bundestag (TAB) 2024 study.

(examples, not a comprehensive literature review)

Theoretical proliferation concerns

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- **Misuse of neutrons to breed special fissionable material from source material (focus of this presentation)**

- Diversion of tritium or lithium-6 inventories and production technologies to use as boosters (Alex Somers, SRNL)

- Aquiring fundamental inertial confinement fusion knowledge to inform the design of thermonuclear weapons

Basic idea: misuse of neutrons

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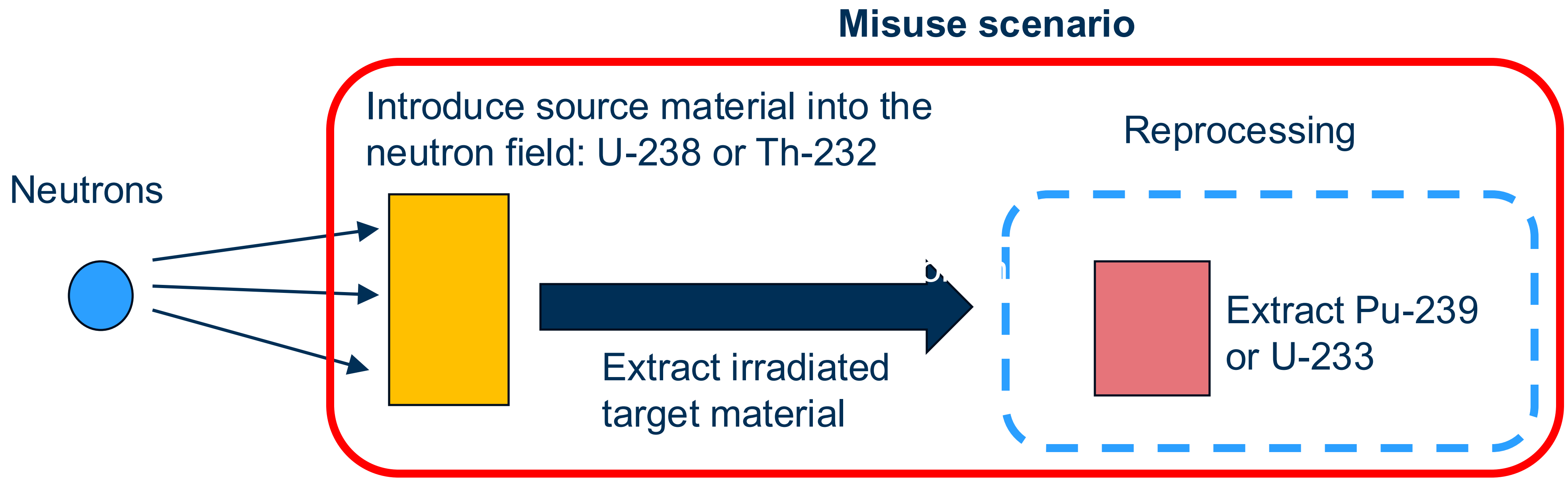


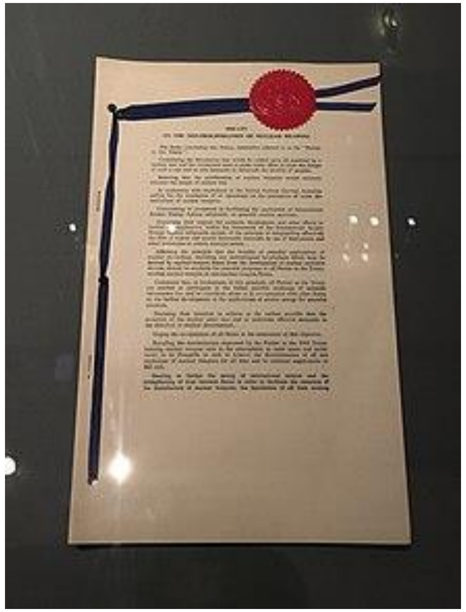
- The breeding of weapons-grade fissile material in significant quantities, from source material, is theoretically possible using intense non-fission neutron sources
- Fusion (DT) power plants and high-power accelerator-based neutron sources are within scope
- Plant modifications would be necessary together with material processing/reprocessing capabilities
- How to mitigate misuse concerns without unreasonably hindering progress in development of beneficial nuclear technologies to society?

Fusion: dual use & proliferation concerns

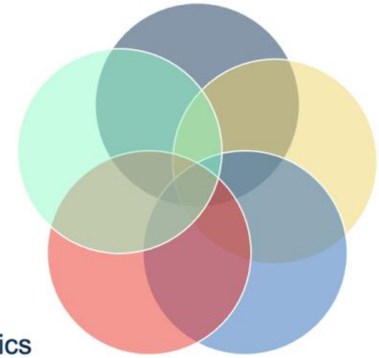
- Fusion power plants, based on DT fuel; an intense neutron source
  - 1 GW fusion power ~ 3.56×10^{20} n/s
- Fusion power plants do not use source or special fissionable material. This distinguishes them from nuclear (fission) power plants - *a clear advantage with regard to potential proliferation concerns*
  - Hybrid fission-fusion machines, by definition, use source or special fissionable material - no advantage
  - Some breeding blanket designs include Be as a neutron multiplier; incidental production of Pu through U impurities in Be
- The assessment of misuse risk depends on the specific design
  - Blanket technology and the plant's potential to be modified are key aspects to consider
  - Material processing/reprocessing would also be required
- Reasonable expectation that controls should be proportionate to the risks as fusion energy technology is developed

Fusion's place within the global non-proliferation regime?

- Treaty on the Non-Proliferation of Nuclear Weapons – 'NPT'
  - Entered into force 1970
  - Distinctions between NWS and NNWS
- Three pillars of the NPT: non-proliferation, peaceful uses of nuclear energy, and disarmament
- As fusion technologies progress towards commercial demonstration and deployment, how will/should fusion plants be handled within the Non-Proliferation Treaty (NPT) and the global non-proliferation regime
  - In this discussion space there are some different national, private industry, public organisation perspectives
  - International collaborative activities needed to develop thinking in this area as the technology evolves e.g. through IAEA
- **Aim to collate views and establish some actions from the international DEMO community**



The treaty, source: Wikipedia



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Scale of machine is an important consideration

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Some scenarios*

1. An undeclared small machine is built i.e. without the knowledge of the international community (clandestine scenario)
   - Small physical dimension and power profile to minimise the possibility of detection?
   - If sufficiently low fusion power, some or all tritium needs may be supplied externally
   - What's the lowest fusion (and thermal) power machine that might trigger concern? (see later example analysis)
2. Covert production in a declared GW scale facility without international community knowledge
   - Clandestine operation of DEMO (GW scale) machine widely considered to not be credible - (e.g. see Goldston and Glaser's conclusion)
   - Balancing tritium self-sufficiency requirements with available neutrons for misuse
3. Breakout scenario for a GW-scale machine

*Discussed in detail in: A. Glaser and R.J. Goldston 2012 *Nucl. Fusion* **52** 043004

Factors that might impact the level of concern

- Neutron output rate and spectrum; availability of machine (capacity factor); Fraction of blanket that is utilisable
  - Time required to produce 1 SQ (smaller quantities could be considered)
  - Isotopic purity
- Facility design information
  - Access and ease of installation of quantities of target material into blanket region. Access and ease of removal of materials, remote handling
  - Ancillary facilities e.g. hot cells, reprocessing facilities
  - Power handling systems and arrangements
- Oversight body inspection frequency
  - Should be sufficient to allow an inspection regime to deter any misuse
  - Compare the speed with which an SQ could be bred and the time gap between inspections

TABLE II. SIGNIFICANT QUANTITIES

Material	SQ
Direct use nuclear material	
Pu[a]	8 kg Pu
^{233}U	8 kg ^{233}U
HEU ($^{235}U \geq 20\%$)	25 kg ^{235}U
Indirect use nuclear material	
U ($^{235}U < 20\%$)[b]	75 kg ^{235}U (or 10 t natural U or 20 t depleted U)
Th	20 t Th

[a] For Pu containing less than 80% ^{238}Pu.
[b] Including low enriched, natural and depleted uranium.

Significant quantity (SQ): the approximate amount of nuclear material for which the possibility of manufacturing a nuclear explosive device cannot be excluded.

https://www.iaea.org/sites/default/files/iaea_safeguards_glossary.pdf

Neutron multiplication in sub-critical systems

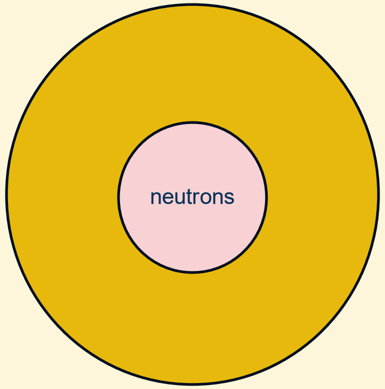
A sub-critical system contains source or fissile material but cannot sustain a nuclear chain reaction on its own

- i.e. $k_{eff} < 1$

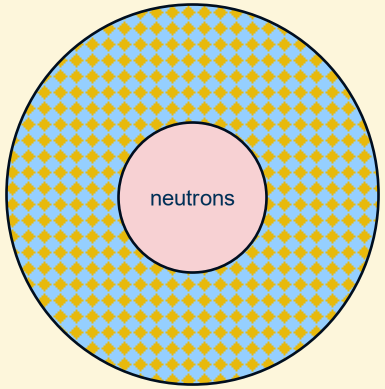
An external source of neutrons can be used to drive the system

- Breed fissile material from source material
- Induce fission reactions - > release energy

Subcritical systems with higher k_{eff} have (by definition) higher neutron multiplication



Homogenous case



Heterogenous case

Neutron multiplication in these source material cases are different. If suitable moderator/coolant is used with geometric optimisation, then

$$k_{eff,\ hom} < k_{eff,\ het}$$

What’s the lowest fusion power to achieve 1 SQ/y in sub-critical systems? An example case

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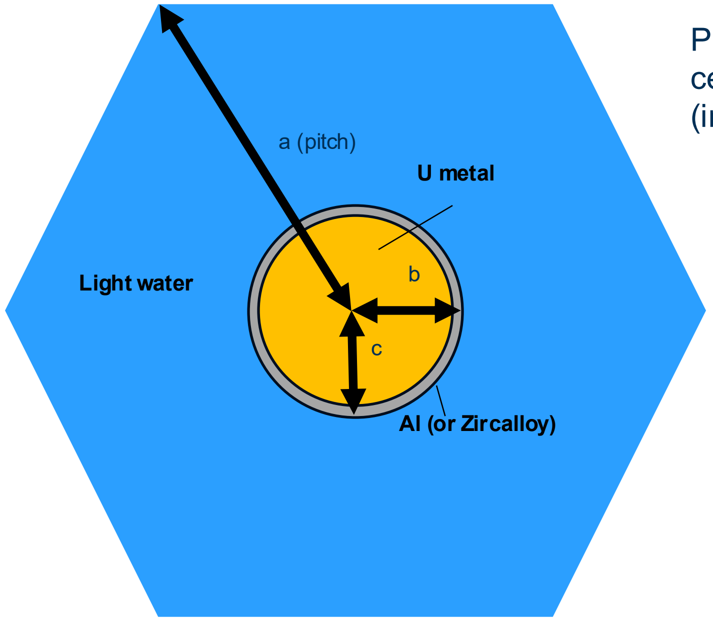
- The answer is somewhat arbitrary, as it depends on k_{eff} (the effective neutron multiplication factor for the system)
- Previous published work has, in most cases, studied misuse and production in homogenous blanket materials (k_{eff} not necessarily optimal)
- Higher neutron multiplication systems -> more fission-like spectra in targets
    - Clearly, the limit of k_{eff} =1 is a self-sustaining fission reactor
    - For subcritical systems, there are isotopic composition tradeoffs – fission versus (harder) fusion spectra
- In our work, several sub-critical assembly case studies have been explored systematically, adopting a pin cell approach
- Example case shown to determine optimum k_{eff}
    - Natural and depleted U metal, Al cladding with light water moderator/coolant in a heterogeneous matrix



Parameterised pin cell arrangement (infinite lattice case)

What's the lowest fusion power to achieve 1 SQ/y in a sub-critical system?

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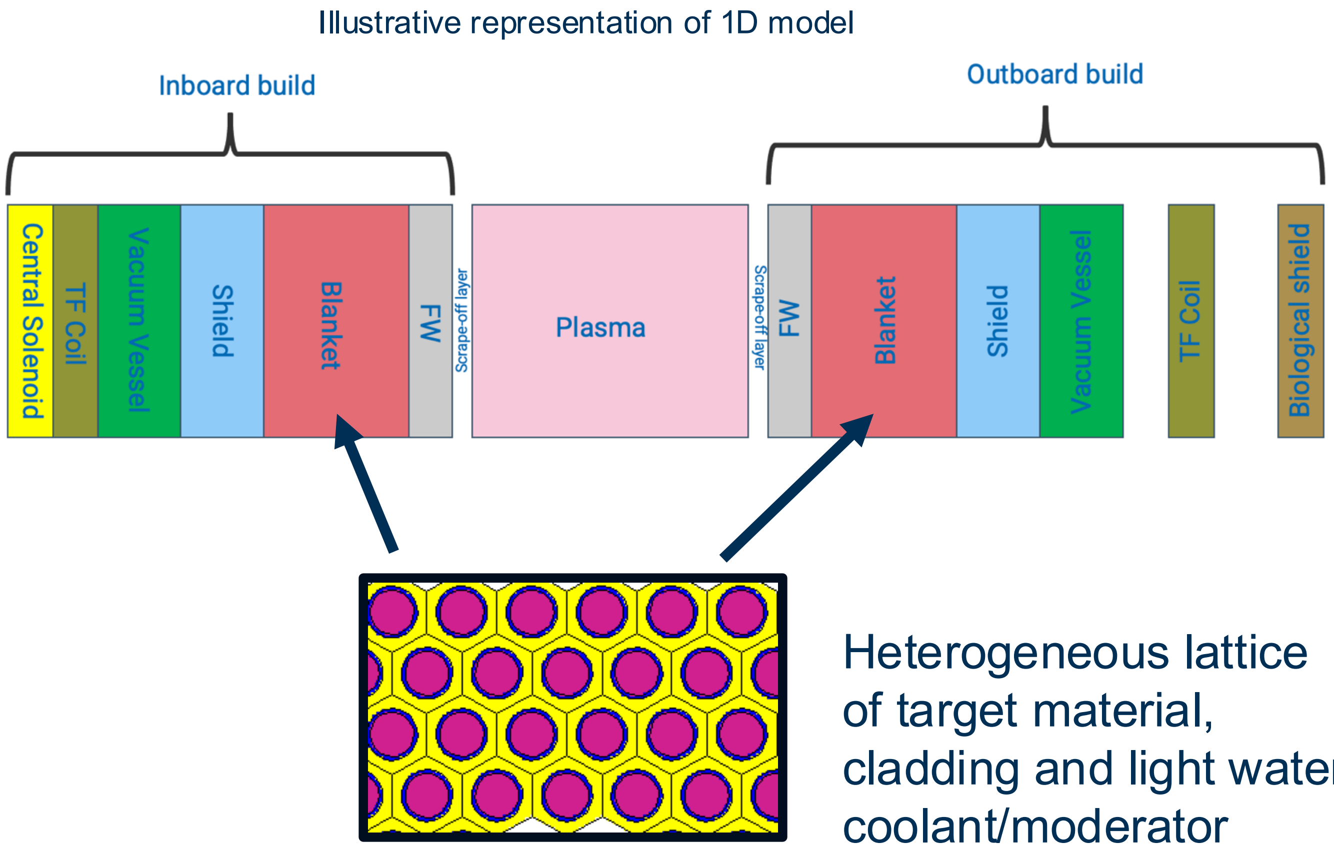
- A simple 1D fusion study for the nat. U case indicates a 14.1 MeV neutron source output of ~5E16 n/s (equivalent to a continuous fusion power of ~140 kW, or ~1.5E24 emitted neutrons/y) could in principle achieve 1 SQ/y
- Significant nuclear heating is unavoidable ~16.8 MW at full power per SQ/y Pu-239
  - An important detection signature for small fusion systems
- Other systems being investigated



Heterogeneous lattice of target material, cladding and light water coolant/moderator

Hypothetical criteria to assess credibility of undeclared production: thermal power

- Binford* and Bragin et al. studied fission research reactors and derived approximate quantitative methods that the IAEA could use to judge credibility of undeclared production of a significant quantity of fissile material annually
  - Relationship was developed based on the fission reactor thermal power (thermalised neutron spectra)
  - But not directly applicable to fast reactors
- In the context of non-fission neutron sources, what if similar criteria based on neutron output (and other parameters e.g. spectral index) could be used for this purpose?
  - Fusion and accelerators can exhibit different neutron spectra to fission systems
  - Nevertheless, production of fissile material unavoidably produces some fission and releases significant energy

*Binford, F T. "Diversion assumptions for high-powered research reactors." , Jan. 1984.

Hypothetical criteria to assess credibility of undeclared production: neutron emission rate

- Neutron emission rate often reported, but the time integrated emission rate over a relevant time period e.g. 1 year is more relevant i.e. accounting for availability %
- If we consider 1.5E24 n/y as a hypothetical neutron threshold?

Then, what would fall in scope?

- Many (probably all) DEMO concepts - ~3.5e20 n/s, availability ~30%
- Materials testing facilities - ~1e19 n/s, availability ~80%

What *might* fall in scope?

- Some non-fission tritium production systems based on intense neutron source technology?
- Some proposed private fusion protypes?

What would not fall in scope? (too low neutron fluence)

- All current experimental fusion facilities (JET’s lifetime neutron budget was 2E21)
- Current commercially available DT generator technology
- Near-term fusion demonstrators (aiming for Q>1) would not produce sufficient neutron outputs due to low availability and fusion power

Detection: technical application of monitoring techniques?

Detection: radiological signatures

- Monitoring Coolant and Blanket Systems

  Analyse particle flow of fertile materials, potential diversion pathways, radiological fields and optimal assay points

- Evaluate background radiation levels (on/off-load) near coolant loops to establish detection baselines

  Gamma Spectroscopy: For identifying abnormal isotopic signatures in materials and coolant systems

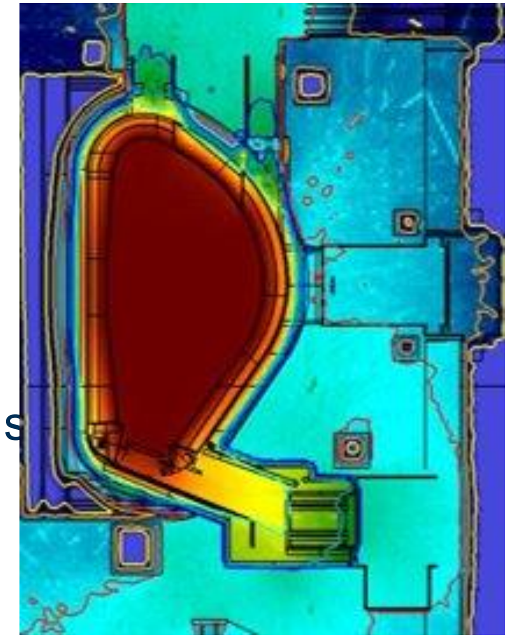
  Neutron Detection: To monitor for abnormal neutron emissions suggestive of unauthorised materials or reactions (post operation)

- Passive and active assay methods for monitoring incoming/outgoing materials

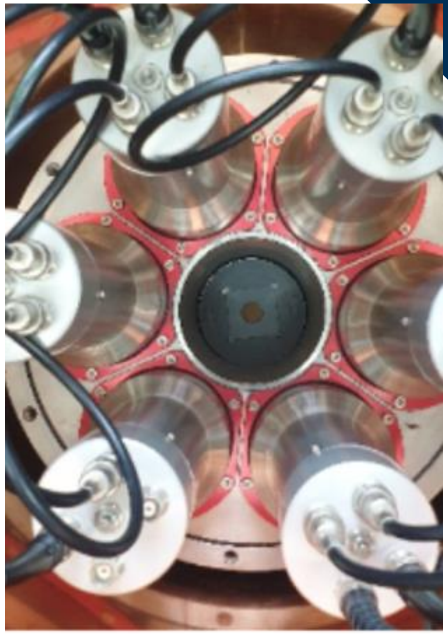
- Antineutrino Detection (more exploratory):

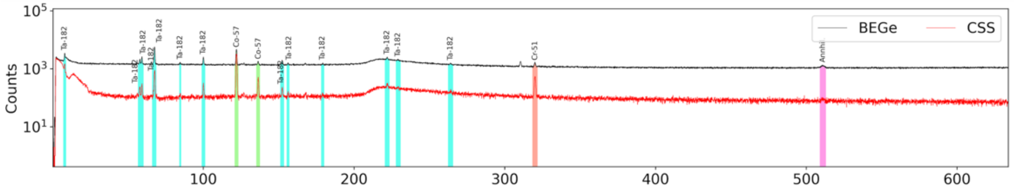
  Investigate potential background fields e.g. from Li-7(n,γ) $\rightarrow$ Li-8 $\rightarrow \beta^{-} + \bar{\nu}_e$

  Assess feasibility and sensitivity for monitoring fusion reactors.



BEGe CS system





JET KN1 Neutron Diagnostic

Detection: thermal signatures

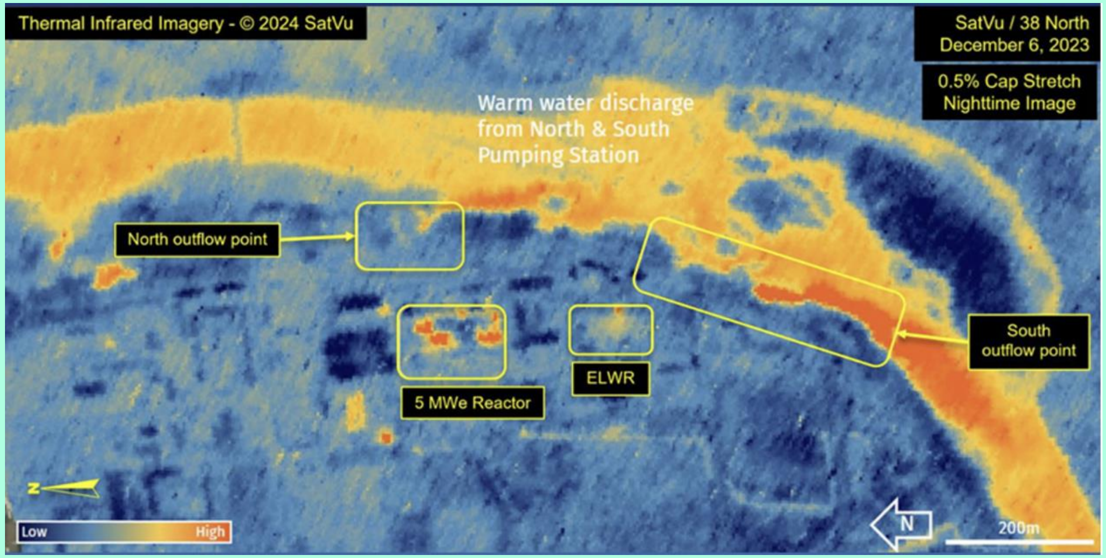
Producing fissile material from source material unavoidably generates excess heat, which could be detected

Thermohydraulic power monitoring

https://www-pub.iaea.org/MTCD/Publications/PDF/nvs1_web.pdf

The advanced thermohydraulic power monitor (ATPM) may be used to monitor the power output of a research reactor and can verify that the output is consistent with the operator declared power level. This system monitors the temperature and water flow in the reactor's primary cooling loop. These parameters are used to calculate the energy flow rate and the total energy produced in the reactor.

Satellite / thermal imagery



Direct detection of heat sources
https://www.satellitevu.com/news/unlocking-hidden-insights-the-power-of-high-resolution-thermal-imagery
Example case study indicating thermal signature from reactors: https://www.38north.org/2024/01/north-koreas-pursuit-of-an-elwr-potential-power-in-nuclear-ambitions/

Detection: environmental sampling

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Environmental sampling is used to verify absence of undeclared nuclear material

- Uses sensitive techniques e.g. mass spectrometry to detect nuclear activity residues
- Focuses on swipe samples from nuclear sites and facilities under additional protocol.
- Samples analysed in bulk (entire sample) or particle mode (individual microparticles).
- Techniques include γ ray spectrometry, XRF, alpha/beta counting (alpha from Po-210 generated in LiPb)
- Particle analysis: fission track method - > particles identified and mounted for e.g. thermal ionisation MS, SEM, SIMS

IAEA ES kit

https://www-pub.iaea.org/MTCD/Publications/PDF/nvs1_web.pdf

Detection: other techniques

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Camera systems

https://www-pub.iaea.org/MTCD/Publications/PDF/nvs1_web.pdf

Open source information - publicly available information from external sources, including scientific literature, government reports, media, trade information and satellite imagery

Design information verification - e.g. facility design features, ancillary facilities, conduct engineering assessment of time needed to replace blanket modules and restart plant operations etc

Assessing physical properties - e.g. weight of blanket modules prior to installation

Summary: fusion non-proliferation discussion

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- Fusion plants that are not designed to and do not process, use, or produce nuclear material have the potential to realise a higher level of proliferation resistance than that of (fission) nuclear facilities
- Existing international safeguards agreements apply to designs that process, use or produce nuclear material
- For fusion designs that do not process, use or produce nuclear material, the IAEA does not currently apply any safeguards measures other than those needed to resolve questions, where applicable, relating to the accuracy and completeness of the information provided by Member States
  - As more information about fusion plant designs becomes available, further consideration is required to ascertain whether the scope of IAEA safeguards would apply more broadly to fusion plants
- Key fusion technologies and materials (e.g., tritium, lithium-6, and related technologies to produce or handle these materials) are covered as dual-use items under existing export control guidelines
  - Further considerations may be required to strengthen export controls
- Harnessing the benefits of fusion requires discussion on how to address non-proliferation without negatively impacting development or cooperation in the field of fusion
- Safe and secure deployment of fusion energy technology is key to the UK's international collaboration efforts. It includes the development of regulatory frameworks and an international non-proliferation regime
- Close working with international partners on these topics is needed to contribute expertise
- Such cooperation would ensure that controls are proportionate to the risks as fusion energy technology is developed

Some questions for the community to consider

- How can the fusion community support proportionate, effective non-proliferation strategies as technology evolves?
- What are the key proliferation concerns for large-scale fusion machines?
- What specific risks do small-scale fusion machines pose, especially in potential clandestine use?
- How can the current regulatory framework support non-proliferation in widespread fusion adoption?
- Near-term monitoring considerations – awareness in the community of how the IAEA is treating fusion now? i.e. under Complementary Access, where an Additional Protocol is in place
- Are IAEA Additional Protocol measures sufficient for emerging fusion technologies?
- How can fusion plant designs deter misuse or material diversion?
- What R&D is needed to enhance misuse detection in fusion systems and how can international cooperation support it?
- What improvements are needed in fuel inventory monitoring for fusion?
- How should non-DT fusion systems be addressed in non-proliferation efforts?
- How should the fusion community engage with the IAEA to meet non-proliferation objectives? What future IAEA initiatives (e.g., World Fusion Energy Group, technical meetings, coordinated research projects, INPRO, etc) would be most useful?
- How can the IAEA best support the DEMO community in this context?