

Integrated Management Strategy for Fusion Activated Materials: US Position and Regulations

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All Fusion Studies Demonstrated Adequate Performance in Several Safety and Environmental Areas

#### **Environmental impact:**

- Minimal long-term environmental impact
  - $\Rightarrow$  No high-level waste (HLW)<sup>\*</sup>

 $\Rightarrow$  Low-activation materials with strict impurity control

- **Minimal radwaste volume**  $\Rightarrow$  avoid geological disposal ! \_
- **Minimal radioactive releases**<sup>#</sup> during normal and abnormal operations.

#### **Occupational and public safety:**

- No evacuation plan following abnormal events (early dose at site boundary < 1 rem<sup>%</sup>) to avoid disturbing public daily life.
- Low dose to workers and personnel during operation and maintenance activity (< 2.5 mrem/h).
- **Public safety** during normal operation (bio-dose << 2.5 mrem/h) and following credible accidents:
  - LOCA, LOFA, LOVA, and by-pass events.
  - External events (seismic, hurricanes, tornadoes, airplane crash, etc.).

No energy and pressurization threats to confinement barriers (VV and cryostat):

- No melting, no burning
- Decay heat problem solved by design
- Chemical energy controlled by design

- Chemical reaction avoided

- No combustible gas generated
- Stored magnet energy controlled by design
- Overpressure protection system
- Rapid, benign plasma shutdown.

<sup>\*</sup> HLW legal definition: spent fission fuel and residues of treatment of spent fission fuel. In fusion designs, HLW is used for components with Waste Disposal Rating > 1. This may include the Greater Than Class C (GTCC) waste – not formally defined yet by NRC. <sup>#</sup> Such as T, volatile activated structure, corrosion products, and erosion dust. Or, from liquid and gas leaks.

<sup>&</sup>lt;sup>%</sup> 1 rem (= 10 mSv) accident dose stated in Fusion Safety Standards, DOE report, DOE-STD-6002-96 (1996).





calendar year

- There is worldwide interest in building fusion power plants by 2030-2050.
- **Pressing Q**: what should we do with activated materials generated during operation and after decommissioning?
- Geological disposal is NOT environmentally attractive option.

#### • We propose <u>integrated</u> <u>management strategy</u> that can <u>handle</u> the **sizable** activated materials generated by fusion and <u>minimize</u> radwaste burden for future generations.



## Options for Radwaste Management

- **Disposal in space** not feasible
- Ice-sheet disposal @ north/south pole not feasible
- Seabed disposal (reconsidered by MIT)
- Geological disposal (preferred US option over past 50 y. Before 1980, <u>NRC</u> did not look at back-end of fuel cycle when considering environmental impact statement for reactor applications. <u>A lesson learned for fusion</u>...)
- Transmutation of long-lived <u>fission</u> and <u>fusion</u>\* radionuclides

 $\Rightarrow$  proliferation concerns for fission only)

**Recycling / reprocessing** (reuse within nuclear industry)

**Clearance** (release to commercial market if materials are slightly radioactive)

<sup>\*</sup> L. El-Guebaly, "Managing Fusion High Level Waste – a Strategy for Burning the Long-Lived Products in Fusion Devices," *Fusion Engineering and Design*, **81** (2006) 1321-1326.

# Geological Disposal

# The big picture... and problems:

Disposal <u>cost</u>, <u>Volume</u> of fusion activated materials, Status of US <u>repositories</u>, Political <u>situation</u>.



### Radwaste Disposal in Geological Repositories is Costly, Specially HLW





# Fusion Generates Only Low-Level Waste (Class A or C)

All fusion materials are carefully chosen to minimize long-lived radioactive products (e.g., low-activation ferritic steel (FS), vanadium, and SiC structures)





## Status of Geological Disposal

• **Operational commercial repositories**:

	US	Europe	Japan
LLW	3	6	1
HLW			

- LLW represents ~ 90% of radwaste volume. It comes from many places: hospitals, labs, 104 commercial fission reactors, and DOE facilities (including TFTR).
- At present, many US utilities store LLW, GTCC, and HLW at 121 temporary locations in 39 states because of limited and expensive offsite disposal options.
- NRC determined <u>that HLW can be stored onsite for century</u> until US find more permanent solution (cumulative 60,000 tons of spent fuel + 2,000 more ton/y).
- Proposal for new LLW repository in Texas is facing problems.
- Other states tried to develop new disposal sites, but changed their mind because of strong opposition from public and environmentalists.
- <u>Concern</u>: Geological conditions change over millennia even hardest rock behaves like dynamic liquid. If water infiltrates, it will corrode radwaste packages. Over time, radioactivity would leak and contaminate groundwater.



#### 4 Large-Scale Repositories in US: 3 for LLW & 1 for TRU/HLW





#### 3 US Commercial LLW Repositories will be Closed <u>Before</u> Building 1<sup>st</sup> Fusion Power Plant

- **Barnwell facility** in SC:
  - 1971 2038.
  - Receives Class A, B, C LLW.
  - Supports east-coast reactors and hospitals.
  - $870,000 \text{ m}^3 \text{ capacity} \Rightarrow \text{ can accommodate } \sim 110 \text{ fusion power plants}^*$ .
  - 90% Full.
  - In July 2008, Barnwell facility closed to all LLW received from outside Compact States: CT, NJ, SC.
  - 36 states lost access to Barnwell, having no place to dispose 91% of their Class B & C LLW.
  - NRC now allows storing LLW onsite for extended period.
- **Richland facility** in WA:
  - <u>Class A, B, C LLW</u>.
  - Supports 11 northwest states.
  - 1,700,000 m<sup>3</sup> capacity  $\Rightarrow$  can accommodate ~200 fusion power plants<sup>\*</sup>.
  - Closure by 2056.
- **Clive facility** in Utah:
  - Receives nationwide <u>Class A LLW only</u>.
  - Disposes 98% of US Class A waste volume, but does not accept sealed sources or biological tissue waste – a great concern for biotech industry.
  - 4,571,000 m<sup>3</sup> capacity.
  - <u>– Closure by 2024.</u>

<sup>&</sup>lt;sup>@</sup> 1000 1-GW<sub>e</sub> fusion power plants needed to supply electricity for US<sub>10</sub>



## Recently, LLW Emerges as Hurdle for New US Reactors

- At present, LLW is more serious issue than HLW, presenting significant shift for regulators and utilities.
- There is no counterpart rule for LLW as for HLW. <u>NRC may allow storing</u> <u>LLW onsite for extended period</u>.
- Building onsite storage for LLW is viewed as short-term option for new reactors. Not simple as it will :
  - Increase already hefty cost of building new reactors (\$5-8B) as onsite LLW facility could <u>add significant operating cost</u> (for extra land, construction and operation of LLW facility, well packing in expensive containers, documentation and accurate inventory of LLW, packaging, monitoring and inspections, compliance with State and Federal regulations, audits, etc.)
  - Add another <u>inconvenience for utilities</u> that want low operating costs and high plant availability
  - Increase <u>complaints from environmentalists</u> (already upset at onsite storage of HLW).
- Utilities are forced to present disposal plans for LLW before building new reactors, affecting reactor applications.
- Lack of space for LLW has grabbed attention of US politicians.



US Needs National Solution for LLW and HLW Disposal Problems

# **Recycling and Clearance**

# The solution...

(Relatively <u>easy to apply</u> from <u>science</u> perspectives, but <u>real challenge</u> from <u>policy</u>, <u>regulatory</u>, <u>and public acceptance</u> perspectives)



## Handling Radioactive Materials is Important to Future of Fusion Energy

- **Background**: Majority of <u>earlier fusion power plant designs focused on disposal</u> of active materials in repositories, <u>adopting fission</u> radwaste management approach preferred in 1970s.
- Fusion will need to present integrated management plan before building any facility.
- **New strategy** should be developed, calling for <u>major rethinking</u>, <u>education</u>, <u>and research</u> to make this new strategy a reality:
  - Avoid geological disposal
  - Minimize volume of radwaste by:
    - Clever designs
    - Promoting <u>new concepts</u>:
      - <u>Recycling</u> Reuse within nuclear industry, if technically and economically feasible

#### • Why?

- Limited capacity of existing LLW repositories
- Political difficulty of building new ones
- Tighter environmental controls. 13



## Benefits to Fusion Energy

- **Broad application** to any fusion concept:
  - MFE or IFE
  - Experimental devices
  - Demo
  - Power plants.
- <u>Solve</u> fusion <u>large</u> radwaste problem (see next VG).
- <u>Minimize</u> radwaste burden for future generations.
- <u>Promote</u> fusion as <u>nuclear</u> energy source with <u>minimal</u> <u>environmental impact.</u>



#### Fusion Generates <u>Large</u> Amount of Activated Materials Compared to Fission





## Radwaste Volume Comparison

(Actual volumes of components; not compacted, no replacements; bioshield excluded)



Fusion <u>Must</u> Incorporate Environmental Constraints at Early Stages of Conceptual Designs

# Radwaste Minimization

(Recommended for <u>all</u> fusion concepts.

Only knob we have for worst case scenario:

no changes to today's US waste management strategy (disposal)

⇒ Continue developing low-activation materials for fusion applications to avoid HLW generation)



#### ARIES Project Committed to Radwaste Minimization by Design





Applied to most recent power plant study (ARIES-CS) with DCLL system





## **ARIES Compact Stellarator**



#### **ARIES-CS:**

3 Field Periods.
LiPb/He/FS System.
7.75 m Major Radius.
2.6 MW/m<sup>2</sup> Average NWL.
3 FPY Replaceable FW/Blanket/Div.
40 FPY Permanent Components.
~78 mills/kWh COE (\$2004).



**ARIES-CS** Cross Section @  $\phi = 0$ 



## ARIES-CS LLW Classification for Geological Disposal





#### All ARIES-CS Components can Potentially be Recycled in < 1 y Using Advanced RH Equipment



- At early cooling periods (<10 y):
  - Main contributor to dose of FS-based FW is <sup>54</sup>Mn (from Fe)
  - Impurities have no contribution to FW recycling dose.
- Developing <u>advanced recycling tools could relax stringent specifications</u> <u>imposed on some impurities.</u>
- <u>Advanced RH equipment</u> will be developed in 20-50 years to support fission <u>AFCI</u> and <u>MOX</u> fuel reprocessing systems.



#### 70% of ARIES-CS Active Materials can be Cleared in < 100 y after Decommissioning







## Recycling & Clearance Flow Diagram





## **General Observations**

- Several fusion studies indicated recycling and clearance are technically feasible, providing <u>effective means to minimize radwaste volume</u>.
- Recycling and clearance should be pursued despite lack of details at present.
- Fusion <u>recycling technology</u> will benefit from <u>fission</u> developments and accomplishments in 20-50 y (in support of MOX fuel and AFCI programs).
- Fusion materials contains tritium that may introduce complications to recycling and disposal

 $\Rightarrow$  detritiation prior to recycling is necessary for fusion components.

- Several **critical issues** need further investigation for all three options:
  - Disposal
  - Recycling
  - Clearance.



## Key Issues and Needs for Disposal

#### **Issues:**

- <u>**Only low-level waste**</u>  $\Rightarrow$  continue developing low-activation materials
- Accurate measurements and **reduction of** <u>impurities</u> that prevent shallow land burial
- <u>Large volume</u> to be disposed of ( $\geq 8,000 \text{ m}^3 \text{ per 1 GW}_e \text{ plant, including bioshield}$ )
- <u>**High disposal cost**</u> (for preparation, characterization, packaging, interim storage, transportation, licensing, and disposal)
- Any toxic waste (such as Be, V, and Mo) or mixed waste<sup>#</sup>? design dependent
- <u>Limited capacity</u> of existing LLW repositories
- <u>Political difficulty</u> of building new repositories
- Prediction of <u>repository's conditions</u> for long time into future
- Radwaste <u>burden</u> for future generations.

#### **Needs:**

- Official specific activity limits for fusion LLW issued by legal authorities<sup>\*</sup>
- <u>Fusion-specific repositories designed for T-containing materials</u>
- <u>Reversible</u> LLW repositories (to gain public acceptance and ease licensing).

<sup>&</sup>lt;sup>#</sup> Radioactive and chemically toxic (e.g., containing T)

<sup>\*</sup> NRC may not get involved until Demo is designed and needs to be regulated.



## Key Issues and Needs for Recycling

#### **Issues:**

- Separation of various activated materials from complex components (such as magnets)
- <u>Radiochemical or isotopic separation processes</u> for some materials, if needed
- Treatment and <u>remote re-fabrication</u> of radioactive materials
- Radiotoxicity and radioisotope buildup and release by subsequent reuse
- **Properties of recycled materials**? Any structural role? Reuse as filler?
- Handling of <u>T containing materials</u> during recycling
- Management of <u>secondary waste</u>. Any materials for disposal? Volume? Radwaste level? **Burn of long-lived products in fusion facilities**\*?
- <u>Energy demand</u> for recycling process
- <u>Cost</u> of recycled materials
- Recycling plant capacity and support ratio

#### **Needs:**

- <u>R&D program</u> to address recycling issues
- Radiation-resistant remote handling equipment for fusion use
- <u>Reversible assembling process</u> of components and constituents (to ease separation of materials after use)
- Efficient detritiation system
- Large and low-cost interim storage facility with decay heat removal capacity<sup>#</sup>
- Nuclear industry should accept recycled materials
- Recycling <u>infrastructure</u>.

<sup>\*</sup> L. El-Guebaly, "Managing Fusion High Level Waste – a Strategy for Burning the Long-Lived Products in Fusion Devices," *Fusion Engineering and Design* 81 (2006) 1321-1326. <sup>#</sup> e.g., heat pipes.



## Key Issues and Needs for Clearance

#### **Issues:**

- <u>Discrepancies</u> between proposed US-NRC & IAEA clearance standards<sup>#</sup>
- Impact on clearance index prediction of <u>missing fusion</u> <u>radioisotopes</u>

(such as <sup>10</sup>Be, <sup>26</sup>Al, <sup>32</sup>Si, <sup>91,92</sup>Nb, <sup>98</sup>Tc, <sup>113m</sup>Cd, <sup>121m</sup>Sn, <sup>150</sup>Eu, <sup>157,158</sup>Tb, <sup>163,166m</sup>Ho, <sup>178n</sup>Hf, <sup>186m,187</sup>Re, <sup>193</sup>Pt, <sup>208,210m,212</sup>Bi, and <sup>209</sup>Po)

• <u>Radioisotope buildup and release</u> by subsequent reuse.

#### **Needs:**

- Official <u>fusion-specific clearance limits</u> issued by legal authorities\*
- Accurate <u>measurements and reduction of impurities</u> that deter clearance of in-vessel components
- Reversible assembling process of components and constituents
- Large and low-cost <u>interim storage</u> facility
- Clearance <u>infrastructure</u>
- <u>Clearance market</u> (Some experience exists in several EU countries: Sweden, Germany, Spain, and Belgium. At present, <u>US industry</u> does not support unconditional clearance claiming it could erode public confidence in US products and damage US markets).



<sup>#</sup> L. El-Guebaly, P. Wilson, and D. Paige, "Evolution of Clearance Standards and Implications for Radwaste Management of Fusion Power Plants," *Fusion Science & Technology*, **49**, 62-73 (2006).

<sup>\*</sup> NRC may not get involved until Demo is designed and needs to be regulated.



US Industrial Experience Demonstrates Economical and Technical Feasibility of Recycling at High Doses

- **US recycled tons of metals and concrete** from fission plant D&D.
- In 1960s, <u>ANL-West</u> Hot Fuel Examination Facility <u>developed radiation resistant</u> <u>tools</u> to handle fission fuel rods for Experimental Breeder Reactor (EBR-II). RH equipment operated successfully at 10,000 Sv/h (needed for fusion).
- <u>INL</u> and industrial firm recycled activated Pb bricks for nuclear industry. <u>Cost</u> of Pb LLW disposal was ~\$5/pound while cost of recycling was ~\$4.3/pound including fabrication into brick shapes.
   <u>Savings</u>:
  - Recycling versus disposal cost
  - Disposal volume over entire lifecycle
  - Not requiring purchase of new Pb bricks.
- <u>INL</u> and industrial company fabricated shielding casks out of recycled SS:
  - Casks were designed, built, and tested for strength and impact
  - <u>Slag</u> from melting tends to collect some radionuclides
  - Composition adjustments after slag removal produced metal alloys with <u>properties very</u> <u>similar to those of fresh alloys</u>
  - Prototype casks functioned well and are still in use since 1996.
- Advanced recycling technology exists in US. <u>Adaptation to fusion needs</u> is highly desirable (radiation level, size, weight, etc.).



## Detritiation of Fusion Materials

- All activated materials as well as building atmosphere **contain T at various levels** – highest near plasma. Examples: beryllium, ferritic steel, vanadium, and SiC.
- T is precious plasma fuelling material (costing \$20-100k/g) and should be removed before recycling (or disposal).
- T-containing materials present significant challenges for transportation, recycling, and disposal\*.
- **Options** to handle tritiated materials:
  - Store materials for 60-70 y till T decays away (<u>not preferable</u> option for fusion materials)
  - **Heat materials** in reduced pressure atmosphere to > 300 °C to release and collect T (remote-handling logistics, hot cell equipment, and large ovens that handle sizable fusion components, heat them up, and capture T are very challenging).
- Efficiency of detritiation system?

<sup>&</sup>lt;sup>\*</sup> If not detritiated, radwaste will be classified as mixed waste: chemically toxic and radioactive.



#### Fusion program should start developing NOW

#### recycling approach before designing/building Demo (by 2030-2050)

and

#### <u>clearance</u> approach <u>before</u> decommissioning power plants (by ~2100),

hoping that US will be progressive with respect to

recycling/clearance perspectives



### 2007 FESAC and 2009 Renew Support Recycling/Clearance for Fusion

#### • Quote from Page 70 of 2007 FESAC report:

"Beyond the need to avoid the production of high-level waste, there is a need to establish a more complete waste management strategy that examines all the types of waste anticipated for Demo and the anticipated more restricted regulatory environment for disposal of radioactive material. **Demo designs should consider recycle and reuse as much as possible.** Development of suitable waste reduction **recycling and clearance strategies is <u>required</u> for the expected quantities of power plant relevant materials. Of particular concern over the longer term could also be the need to detritiate some of the waste prior to disposal to prevent tritium from eventually reaching underground water sources. This may require special facilities for the large anticipated fusion components. The <b>fission industry will be developing recycling techniques** for the Global Nuclear Energy Partnership (**GNEP**) and the US Nuclear Regulatory Commission (**NRC**) is **developing guidelines for the release of clearable materials** from fission reactor wastes both of which may be of value to fusion."

#### **Reference**:

M. Greenwald et al., "Priorities, Gaps and Opportunities: Towards A Long-Range Strategic Plan For Magnetic Fusion Energy," A Report to the Fusion Energy Sciences Advisory Committee, October 2007.



## Maturation of Recycling and Clearance Approaches

## It's matter of time (10-50 y) to develop recycling/clearance technology and regulations. **Fusion designers should:**

- Minimize radwaste volume by clever designs
- Promote environmentally attractive scenarios such as recycling and clearance, avoiding geological disposal
- Continue addressing critical issues for all three options
- Continue developing low-activation materials (specifications could be relaxed for some impurities while more stringent specs will be imposed on others to maximize clearance)
- Accurately measure and reduce impurities that deter clearance of in-vessel components
- Address technical and economical aspects before selecting the most suitable radwaste management approach for any fusion component.

#### **Nuclear industry and regulatory organizations should:**

- Continue developing advanced radiation-resistant remote handling equipment capable of handling > 10,000 Sv/h that can be <u>adapted for fusion use</u>
- Consider <u>fusion-specific</u> materials and <u>issue official guidelines</u> for unconditional release of clearable materials
- <u>Accept recycled materials</u> from dismantled nuclear facilities
- Continue national and international efforts to convince industrial and environmental groups that clearance can be conducted safely with no risk to public health.