Toward the Ultimate Goal of Radwaste-Free Fusion: Recycling and Clearance, Avoiding Disposal

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Outline

If we ask members of general public:

What concerns them the most about **nuclear energy**?

Answer: 1- Safety

2- Waste (what will be done with radioactive waste (radwaste)?)

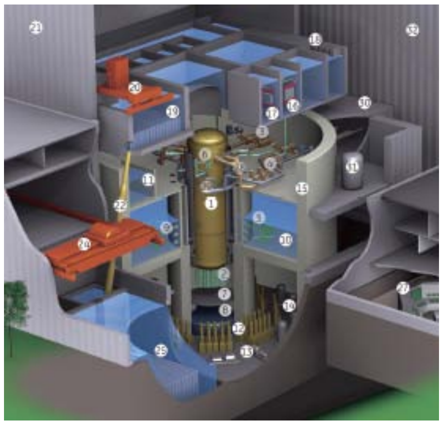
This talk:

- Introduces a new source of nuclear energy: **fusion** – safer and less radioactive than **fission**
- Presents an integrated strategy to handle the continuous stream of activated materials generated during operation and after shutdown.

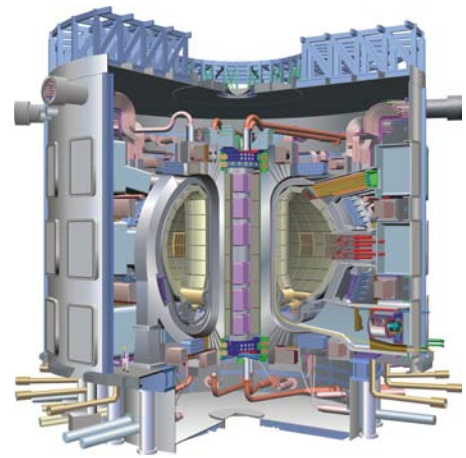
Nuclear Power: What Are The Options?

Fission

Gen-III BWR



Fusion



ITER

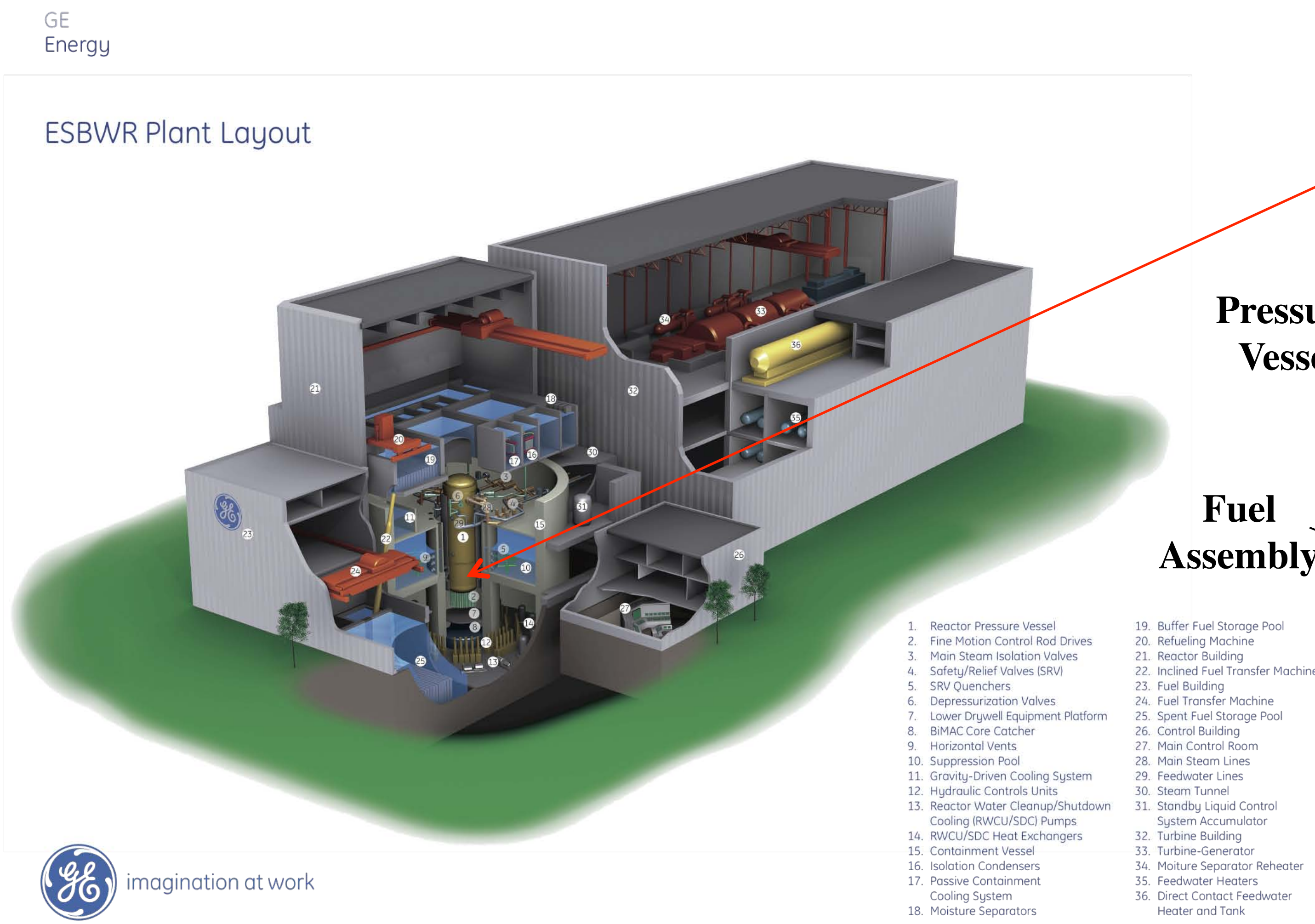
Fission status:

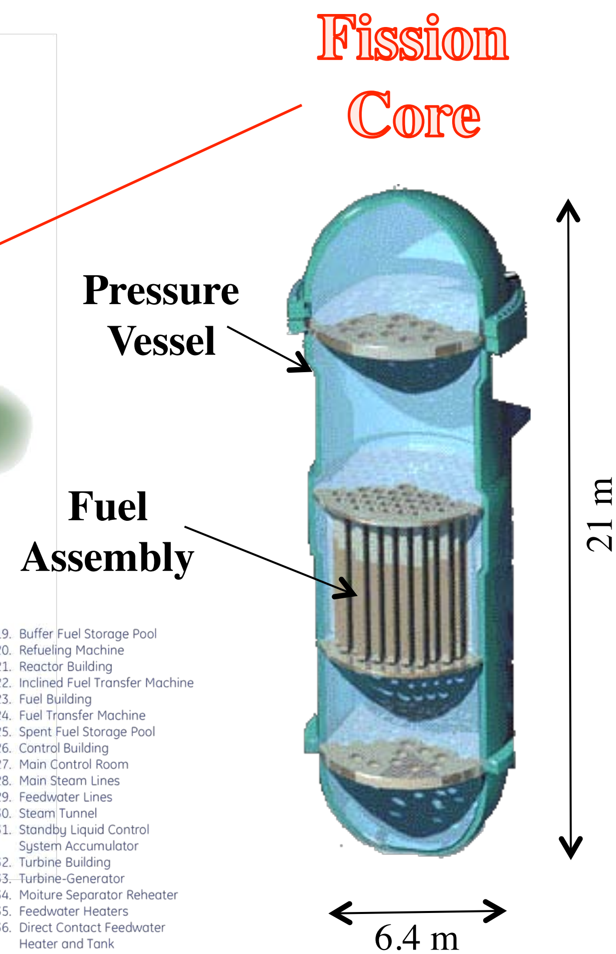
- Well developed concept
- 104 reactors (Gen-II type) providing 20% of US energy
- Nuclear provides ~16% of worldwide electricity
- More advanced Gen-III & IV designs under development around the world.

Fusion status:

- Still under development
- 100s experimental devices worldwide
- 1st international large-scale experiment (ITER) under construction in France
- 1st power plant will be built in 30-50 years.

Example of Advanced Fission Reactor
(ASBWR)

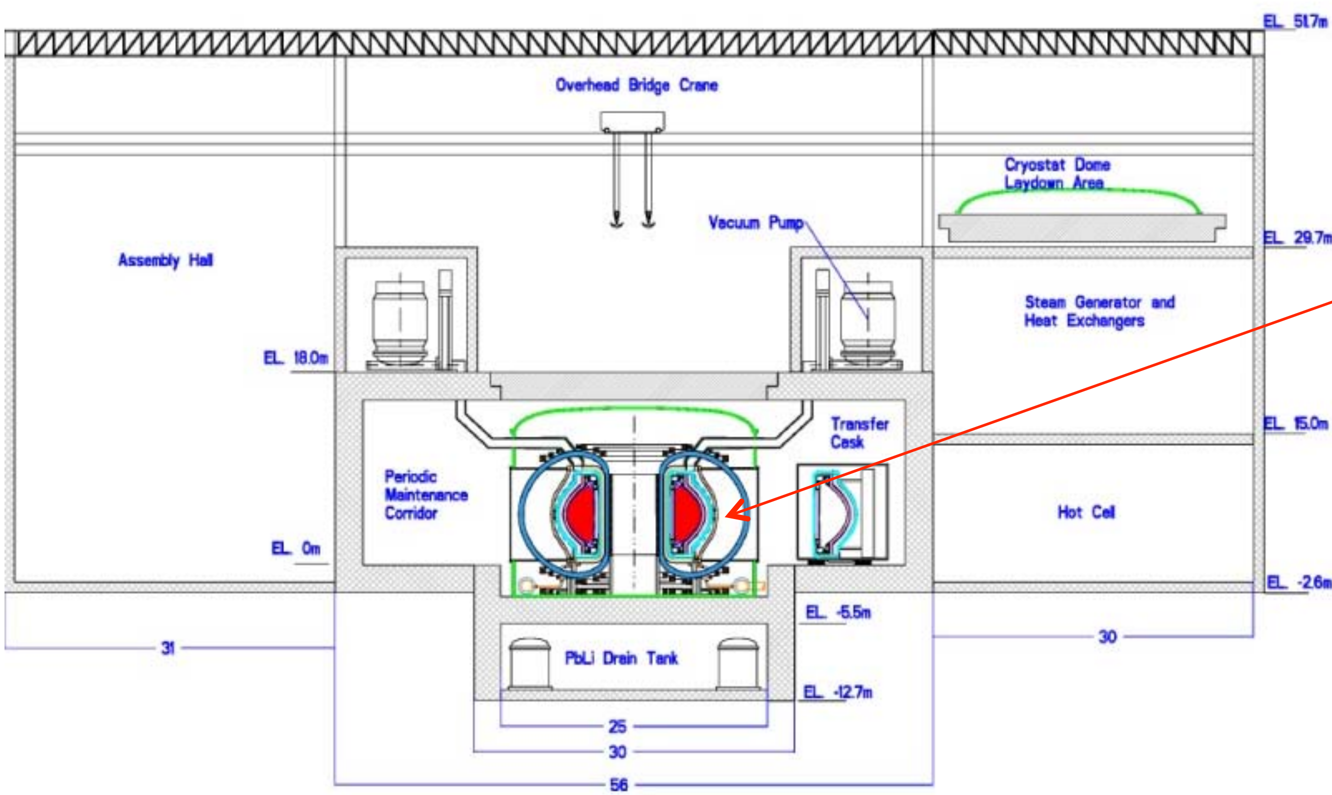




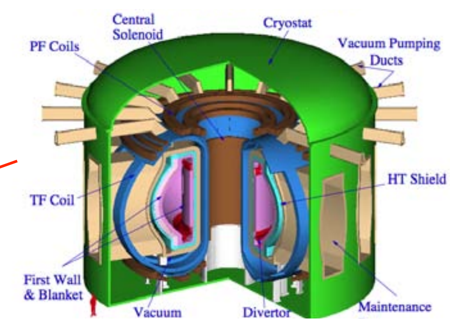
http://www.gepower.com/prod_serv/products/nuclear_energy/en/downloads/esbwr_lv.pdf

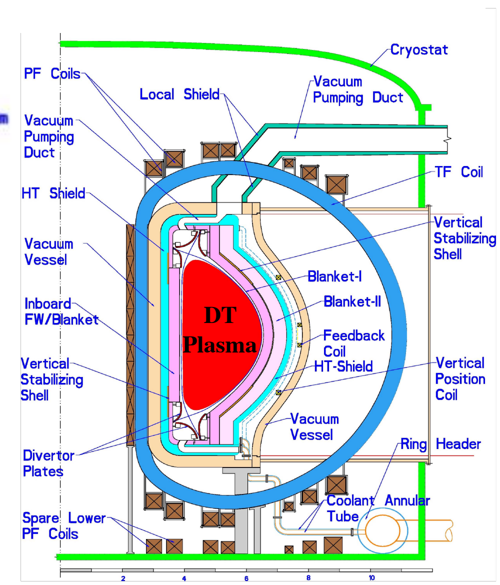
Example of Fusion Power Plant

(ARIES-AT)



Fusion Power Core

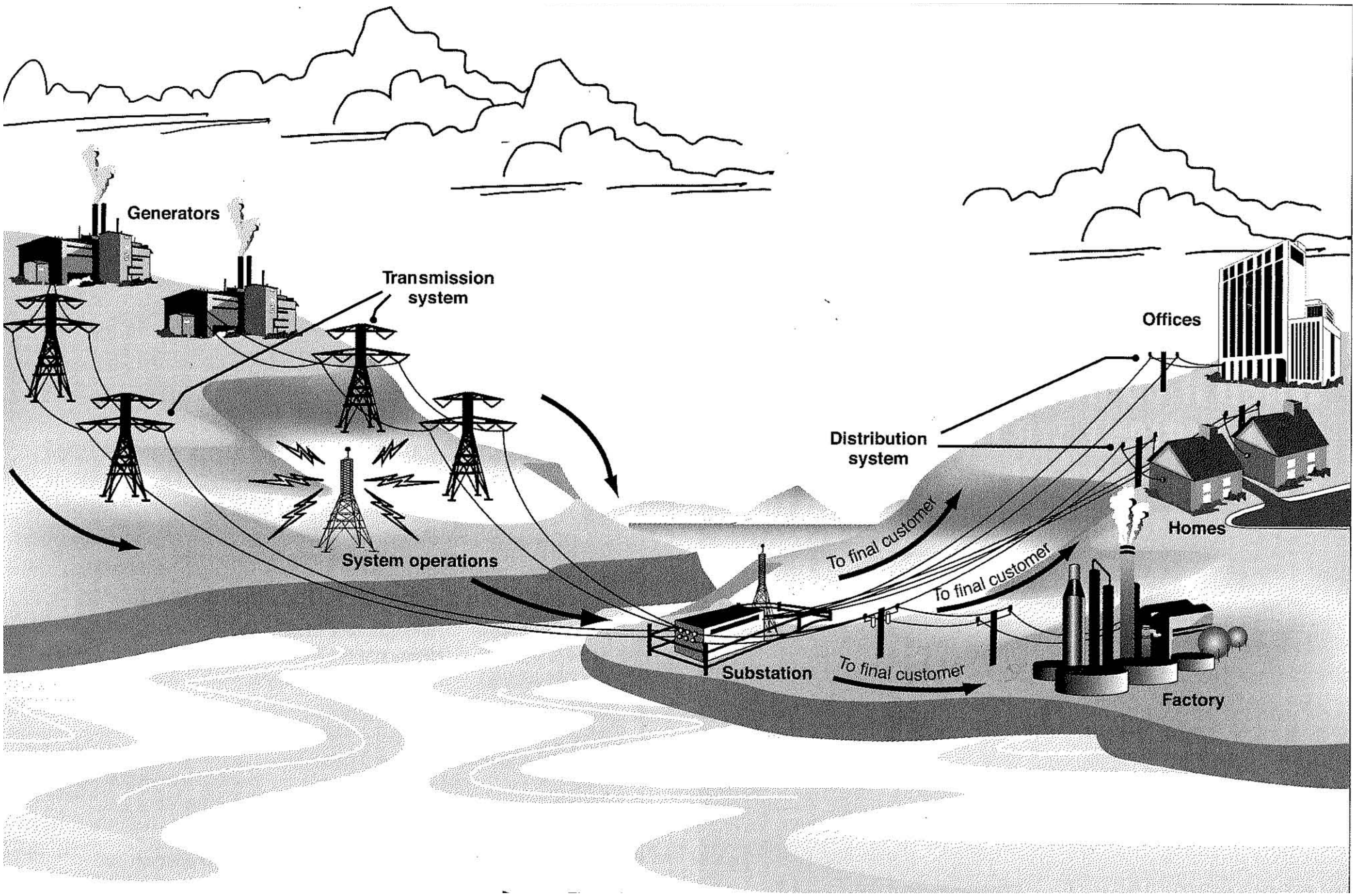




ARIES website: http://aries.ucsd.edu/ARIES/

Flow of Power from Generators to Customers

Power Plants

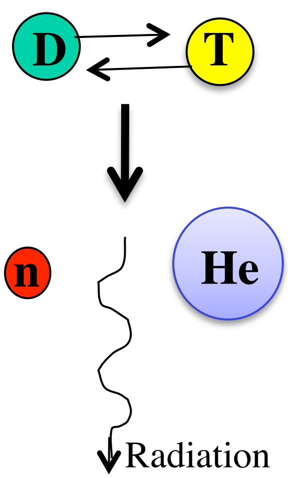


Customers

Nuclear Process

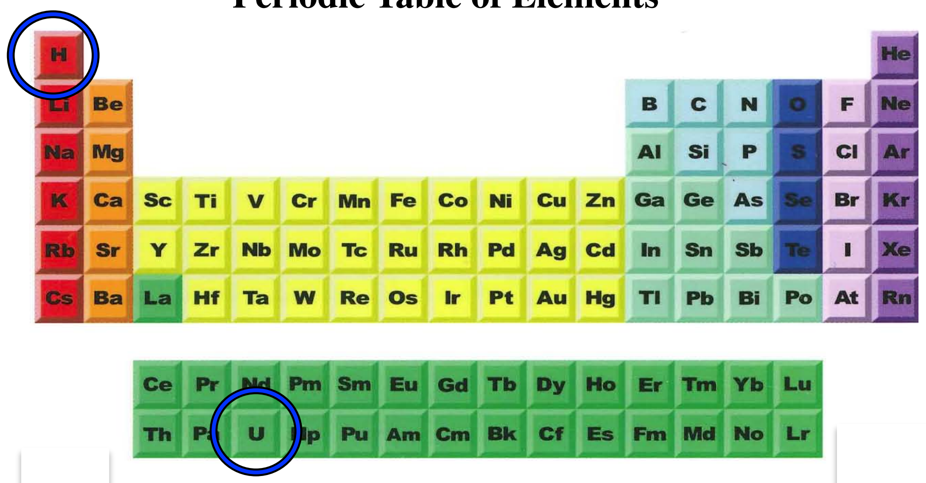
Fusion

Hydrogen isotopes fuse, generating **energetic** neutrons, He, and radiation



(No Radioactive Products)

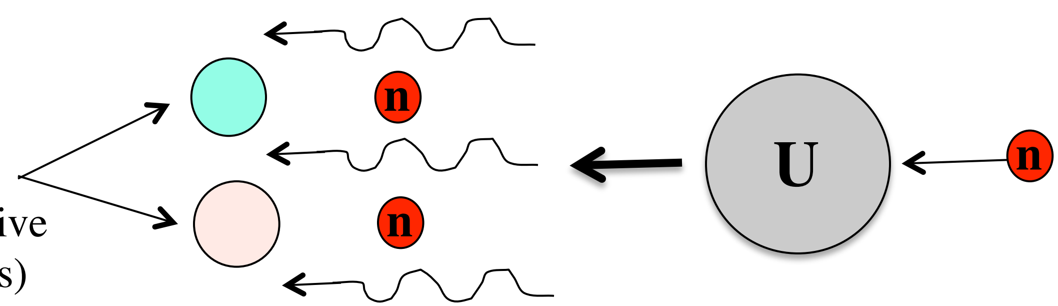
Periodic Table of Elements



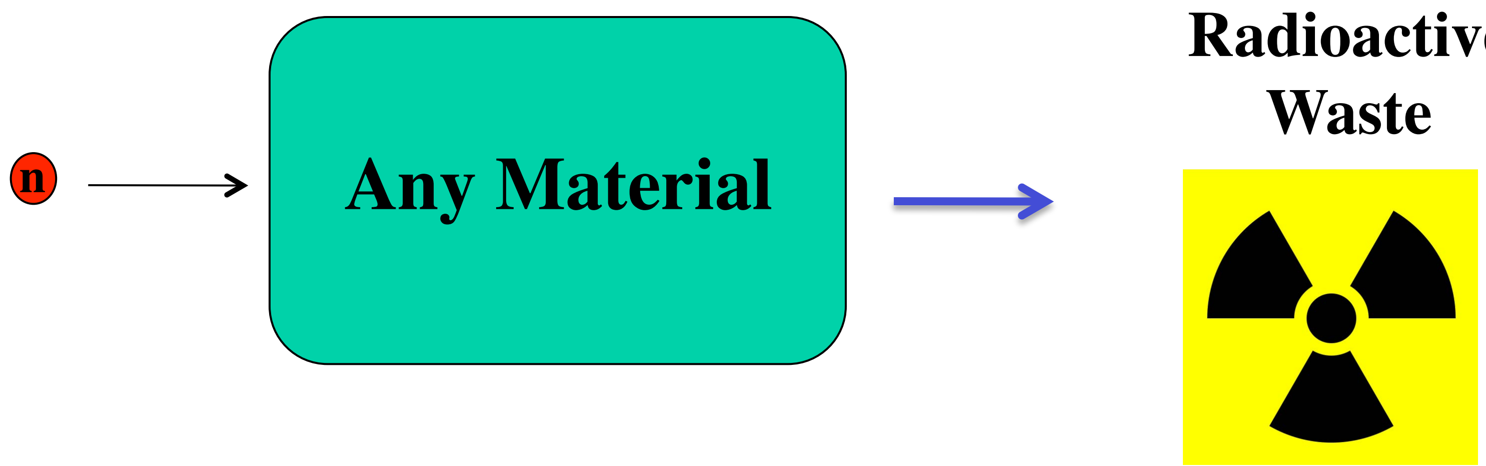
Fission

Uranium absorbs neutron, forming unstable nucleus that separates into fragments:
many fission products, few neutrons, radiation

Fission Products
(some remain radioactive for thousands of years)



Neutrons Activate Surrounding Components



- **Activation level depends on:**
  - Neutron source strength (how many neutrons per second?)
  - Neutron energy spectrum (high energy or low energy neutrons?)
  - Duration of exposure to neutrons (seconds or years?)
  - Distance from neutron source (materials close to source activate more)
  - Unique properties of material:
    - Ability to activate easily
    - How long it remains radioactive (seconds, hours, days, years, or millions of years).

The Practical Reality

- There is worldwide interest in building new nuclear power plants.

- **Pressing Q**: what should we do with activated materials generated during operation and after decommissioning?

- Geological disposal is NOT environmentally attractive option.

- Need to develop integrated management strategy for radioactive materials to minimize 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 years. Before 1980, Nuclear Regulatory Commission (NRC) did not look at back-end of fuel cycle when considering environmental impact statement for reactor applications).
- **Transmutation of long-lived radionuclides** (⇒ proliferation concerns for fission, not for fusion).
- new **Recycling / reprocessing** (reuse within nuclear industry).
- new **Clearance** (release to commercial market if materials are slightly radioactive, containing 10 μSv/y (< 1% of background radiation)).

Geological Disposal

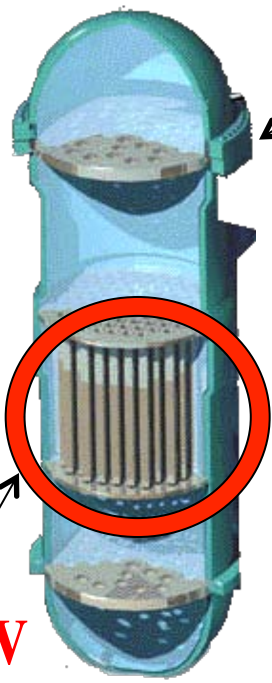
The big picture… and problems:

Volume of activated materials,
Pathways to human beings,
Disposal cost,
Status of US repositories,
Political situation.

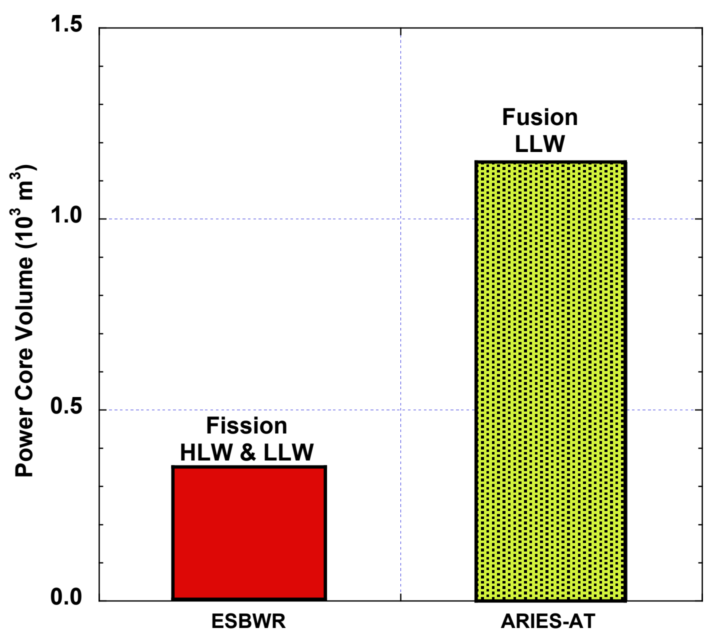
Unlike Fission, Fusion Generates Only Low-Level Waste, but in Large Quantity

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

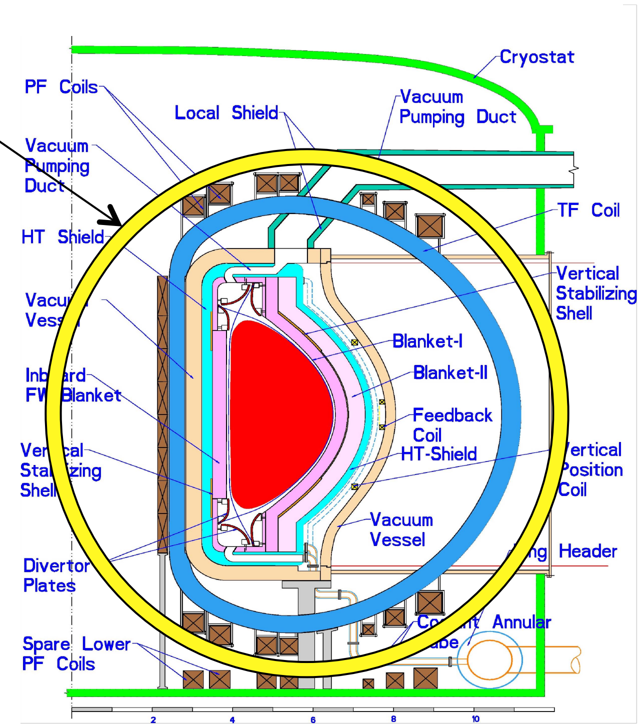
LLW
(pressure vessel
and surroundings)



HLW
(fuel rods)



LLW



LLW = Low-Level Waste
HLW = High-Level Waste

Today's US Radwaste Management Strategy: Disposal

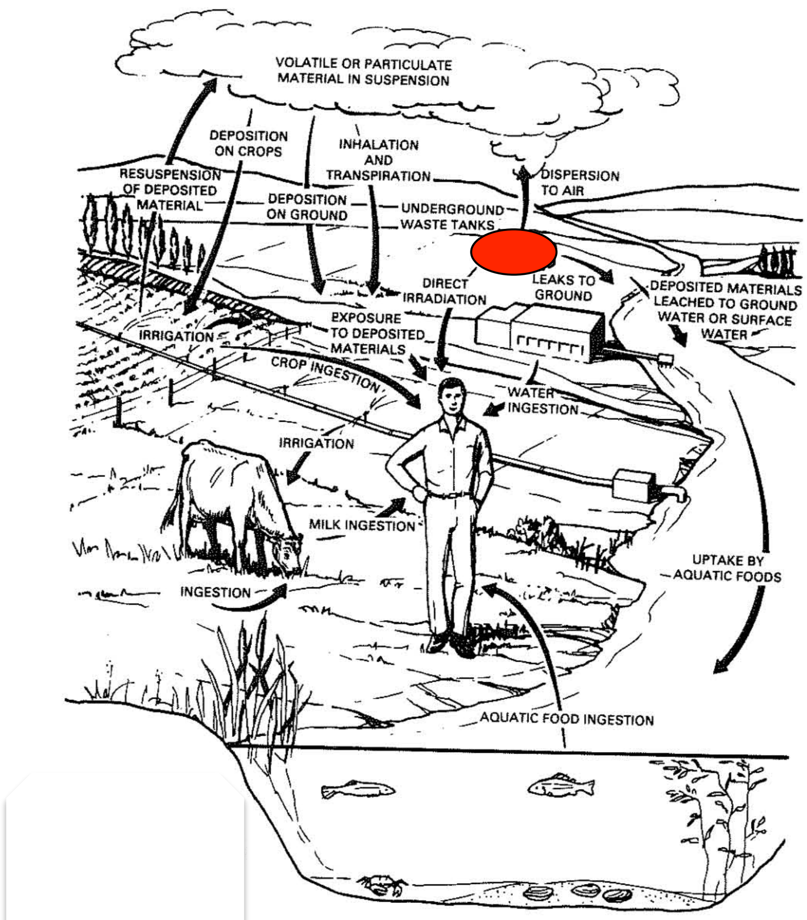
Concerns:

- Geological conditions change over millennia (even hardest rock may behave like dynamic liquid!)
- Water is prime carrier for wastes. If water infiltrates, it will corrode HLW packages
- Over time, radioactivity would leak, contaminate groundwater, and eventually reach humans.

Goal of safe waste disposal:

- No radioactive material reaches human beings
- Repository licensees must provide evidence that pathways will not result in excessive dose to worker and public.

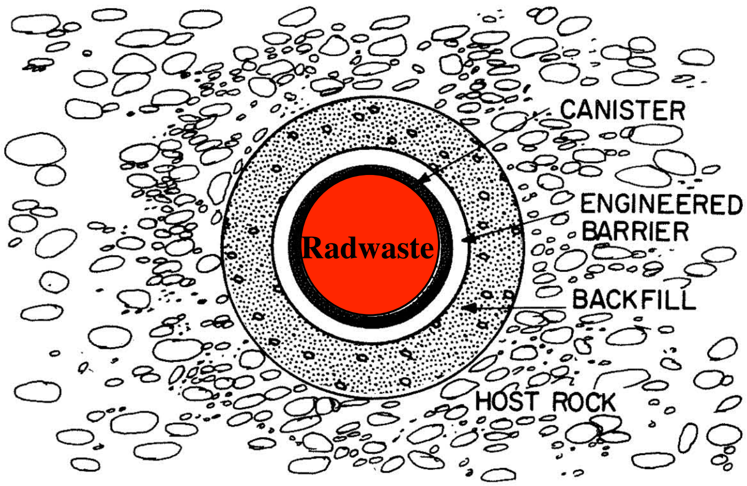
Dispersed Radionuclides Can Affect Living Organisms Through Several Pathways



Example of underground source of radioactivity

Multiple Barriers are Essential to Prevent Migration of Radwaste

- Several obstacles must be placed between radwaste and habitations
- Materials should be:
  - Compressed and mixed with natural compounds that bind wastes strongly
  - Placed in metal container that resists corrosion by groundwater
  - Surrounded with:
    - Bentonite clay that swells when becomes moist, preventing passage of water, or
    - Concrete walls
  - Covered with geological medium (soil or rocks) that filters radioactive materials from flowing water.
- Considerable distance is maintained between disposal site and civilization.



Choices of Geologic Medium

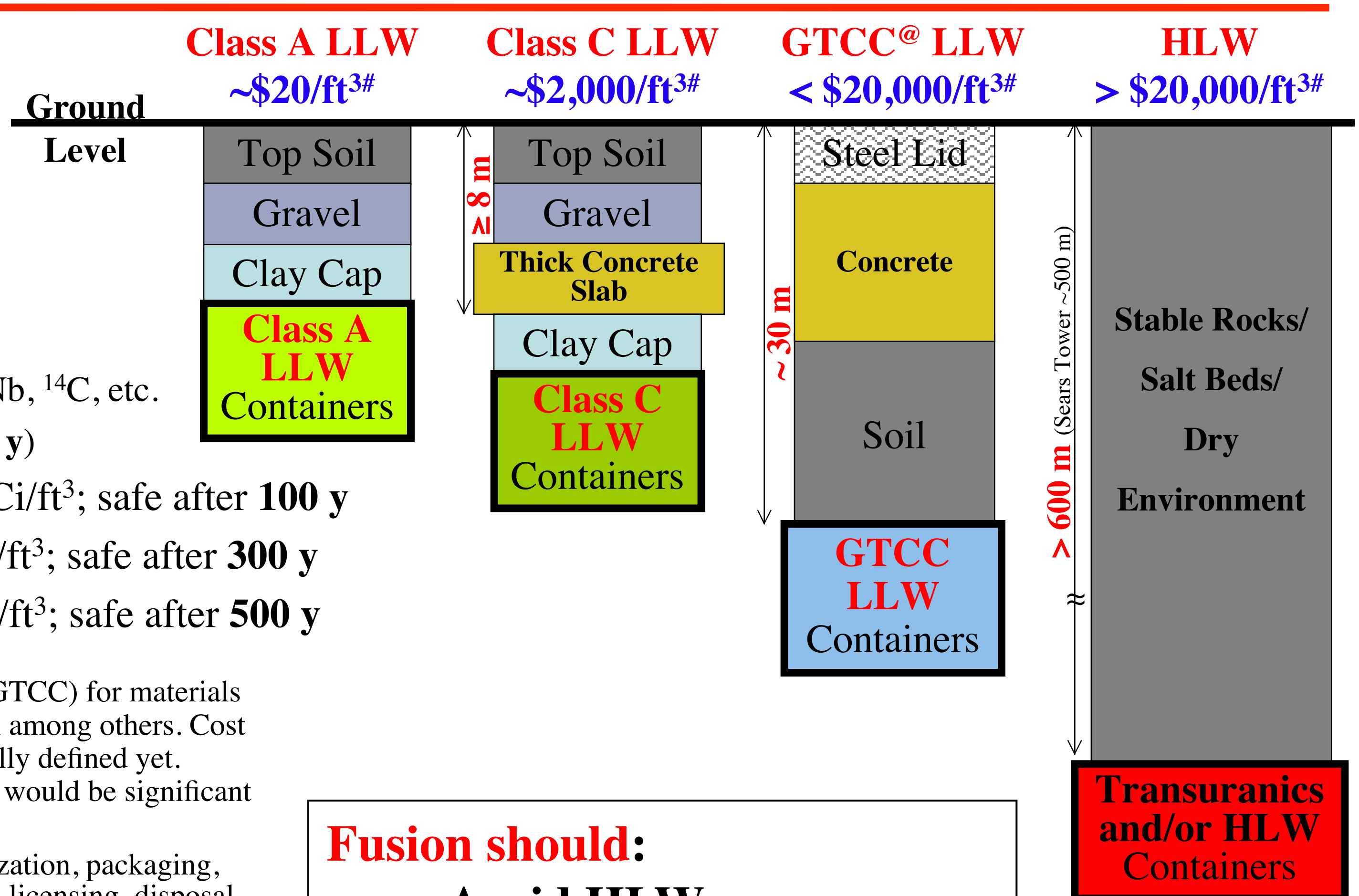
Candidate materials:

- Rock salt
- Basalt
- Granite
- Tuff
- Argillaceous materials (clay and shale).

Evaluation of disposal sites involves:

- National survey to find large deposits of main types of rock
- Studies of each medium and measurements of properties (density, heat conductivity, porosity, and permeability).

Radwaste Disposal in Geological Repositories is Costly, Specially HLW



HLW (e.g., transuranics, ^{94}Nb, ^{14}C, etc.
; active > **5,000 y**)

LLW*: **Class A:** < 0.1 Ci/ft^3; safe after **100 y**

Class B: < 2 Ci/ft^3; safe after **300 y**

Class C: < 7 Ci/ft^3; safe after **500 y**

@ Greater Than Class C Waste (GTCC) for materials containing ^{60}Co, ^{63}Ni, and ^{59}Ni among others. Cost effective option, but not formally defined yet. Saving and ease of disposition would be significant compared to HLW.

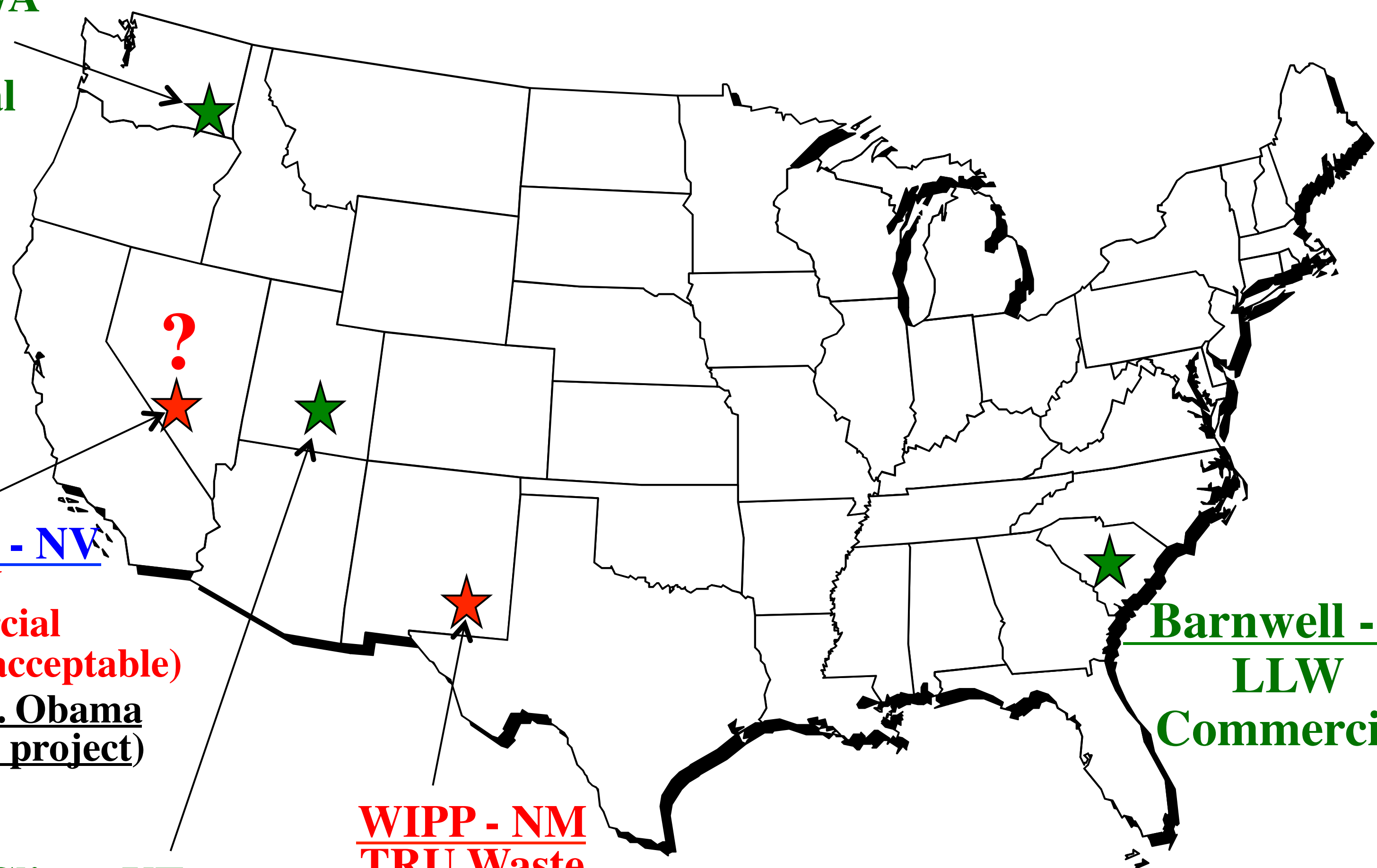
\# Cost of preparation, characterization, packaging, interim storage, transportation, licensing, disposal, and monitoring. Disposal cost comprises 15% of total lifecycle cost. Yucca Mountain HLW repository lifecycle cost estimates: $**8**B in 1983; $**57**B in 2001; $**96**B in 2008.

* From fusion, research labs, hospitals, food irradiation facilities, etc.

Fusion should:

- **Avoid HLW**
- **Minimize Class C LLW**
- **Tolerate Class A LLW**

3 Large-Scale LLW Commercial Repositories in US – None for HLW



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 Department Of Energy facilities.
- Problem of finding acceptable locations for disposal sites is becoming more social and political than technical.
- 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.
- After cancelling Yucca Mountain project in 2009, NRC determined that HLW can be stored onsite for 60 years until US finds 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.
- **Wisconsin Law**: Before building new nuclear power plant in Wisconsin, federally-licensed nuclear waste dump should be available to dispose of **all** nuclear waste from WI reactors.

3 US Commercial LLW Repositories will be Closed Before Building 1st Fusion Power Plant

- **Barnwell facility** in SC:
  - 1971 – 2038.
  - Receives Class A, B, C LLW.
  - Supports east-coast reactors and hospitals.
  - 870,000 m^3 capacity
  - **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:
  - Class A, B, C LLW.
  - Supports 11 northwest states.
  - 1,700,000 m^3 capacity
  - **Closure by 2056.**
- **Clive facility** in Utah:
  - Receives nationwide Class A LLW only.
  - 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^3 capacity.
  - **Closure by 2024.**

Recently, Even LLW Emerges as Hurdle for New US Fission 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. NRC may allow storing LLW onsite for extended period.
- 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 add significant operating cost (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 inconvenience for utilities that want low operating costs and high plant availability
  - Increase complaints from environmentalists (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 on Capitol Hill.

US Needs National Solution for LLW and HLW Disposal Problems

Recycling and Clearance

The solution…

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

Focusing on Fusion

Handling Radioactive Materials is Important to Future of Fusion Energy

- **New strategy** should be developed, calling for major rethinking, education, and research to make this new strategy a reality:
  - Avoid geological disposal
  - Minimize volume of radwaste by:
    - Clever designs
    - Promoting new concepts:

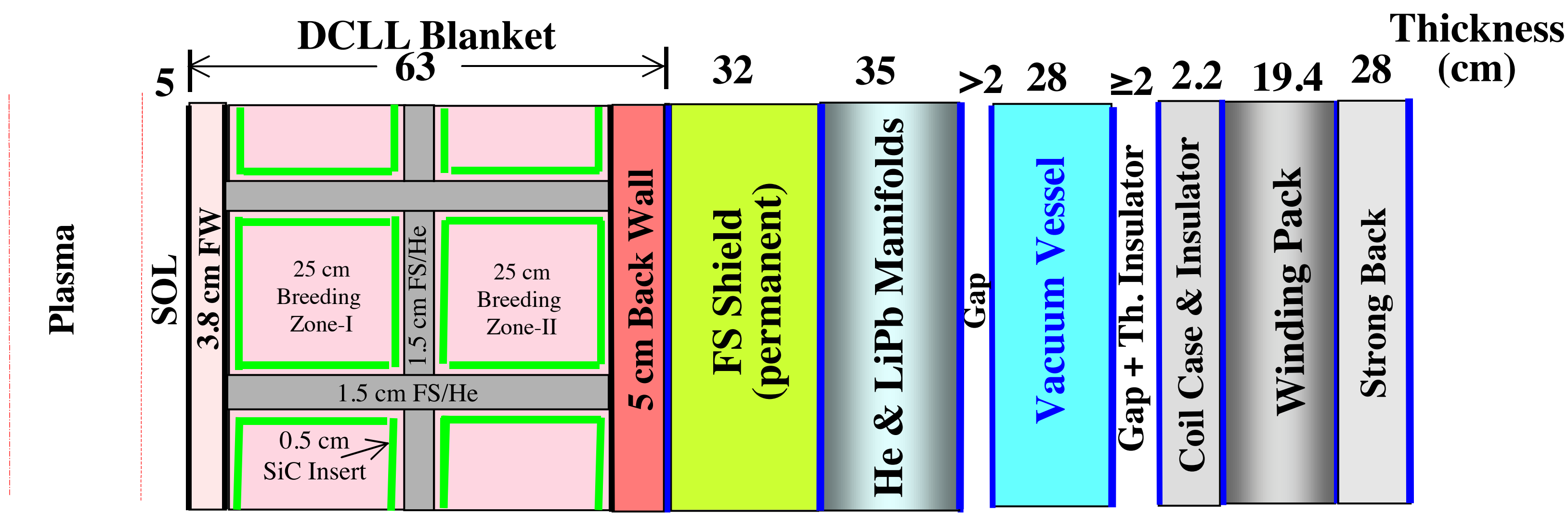
      Recycling – Reuse within nuclear industry, if technically and economically feasible

      Clearance – Unconditional release to commercial market to fabricate as consumer products (or dispose of in non-nuclear landfill). This is currently performed on case-by-case basis for US nuclear facilities. Clearable materials are safe, containing 10 μSv/y (< 1% of background radiation).

- **Why?**
  - Limited capacity of existing LLW repositories
  - Political difficulty of building new ones
  - Tighter environmental controls and stricter regulations
  - Uncertain geological conditions over long time
  - Promote nuclear as energy source with minimal environmental impact
  - Minimize radwaste burden for future generations.

Disposal, Recycling, and Clearance

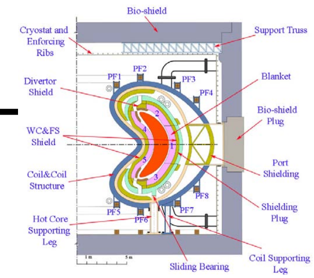
Applied to most recent fusion power plant study (ARIES-CS) with DCLL system



ARIES-CS LLW Classification for Geological Disposal

Temporary Storage (up to 100 y)

All ARIES-CS Components* (~8,900 m^3)



Class C LLW (~2,400 m^3) (27%)

> 8 m below ground surface

Thick Concrete Slab

Class C Repository (~\$2,000/ft^3)

Class A LLW (~6,500 m^3) (73%)

~ 8 m below ground surface

Class A Repository (~\$20/ft^3)

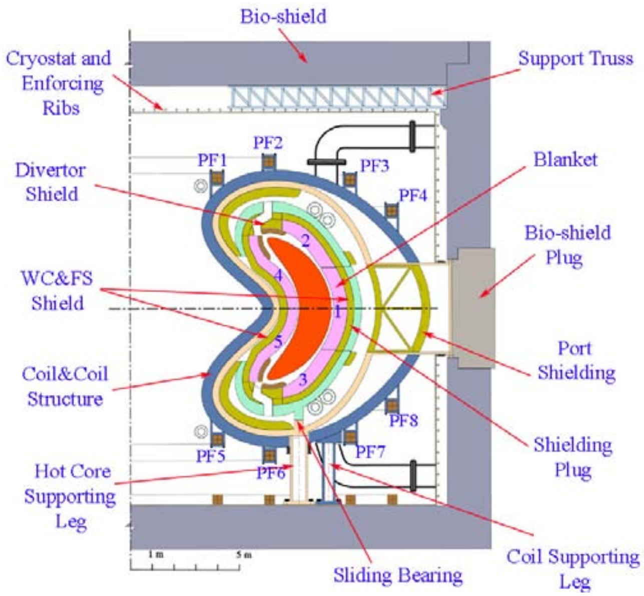
* Fully compacted, including replacements and bioshield

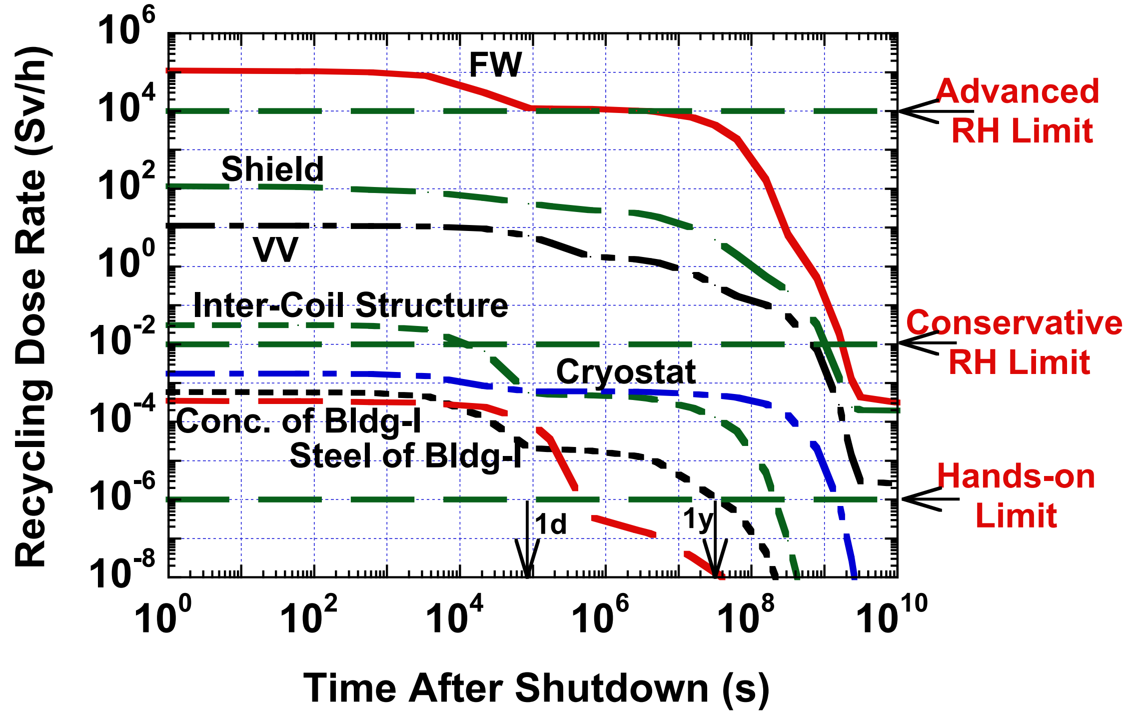
Least Hazardous Type of Waste

	Class C LLW	Class A LLW	Could be Cleared?
FW/Blkt/BW	√		no
Shield/Manifolds	√		no
Vacuum Vessel		√	no
Magnet:			
Nb_3Sn	√		no
Cu Stabilizer		√	√
JK2LB Steel*		√	√
Insulator		√	√
Cryostat		√	√
Bioshield		√	√

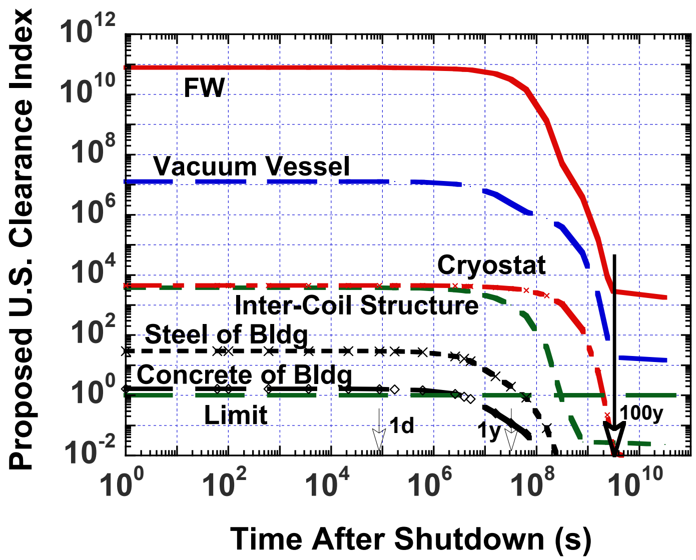
* Preferred over Incoloy-908 for clearance considerations.

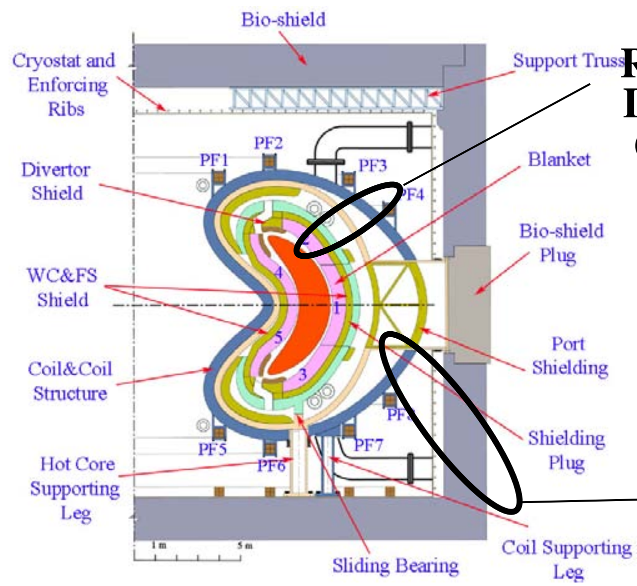
All ARIES-CS Components can Potentially be Recycled in < 1 y Using Advanced RH Equipment





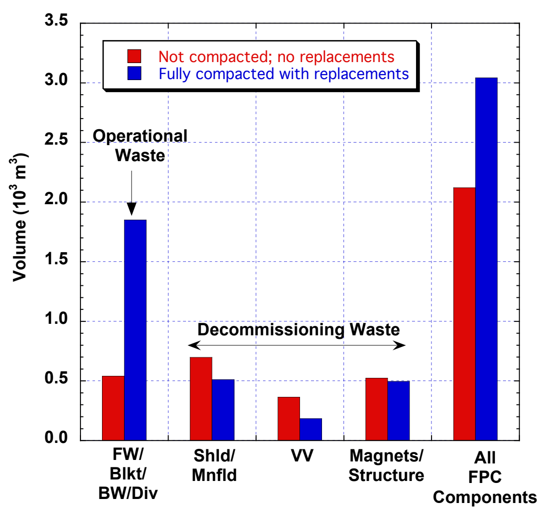
70% of ARIES-CS Active Materials can be Cleared within 100 y after Decommissioning

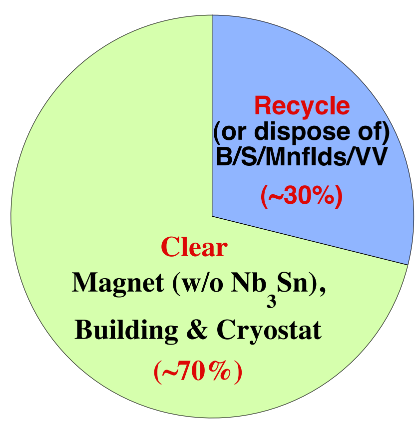




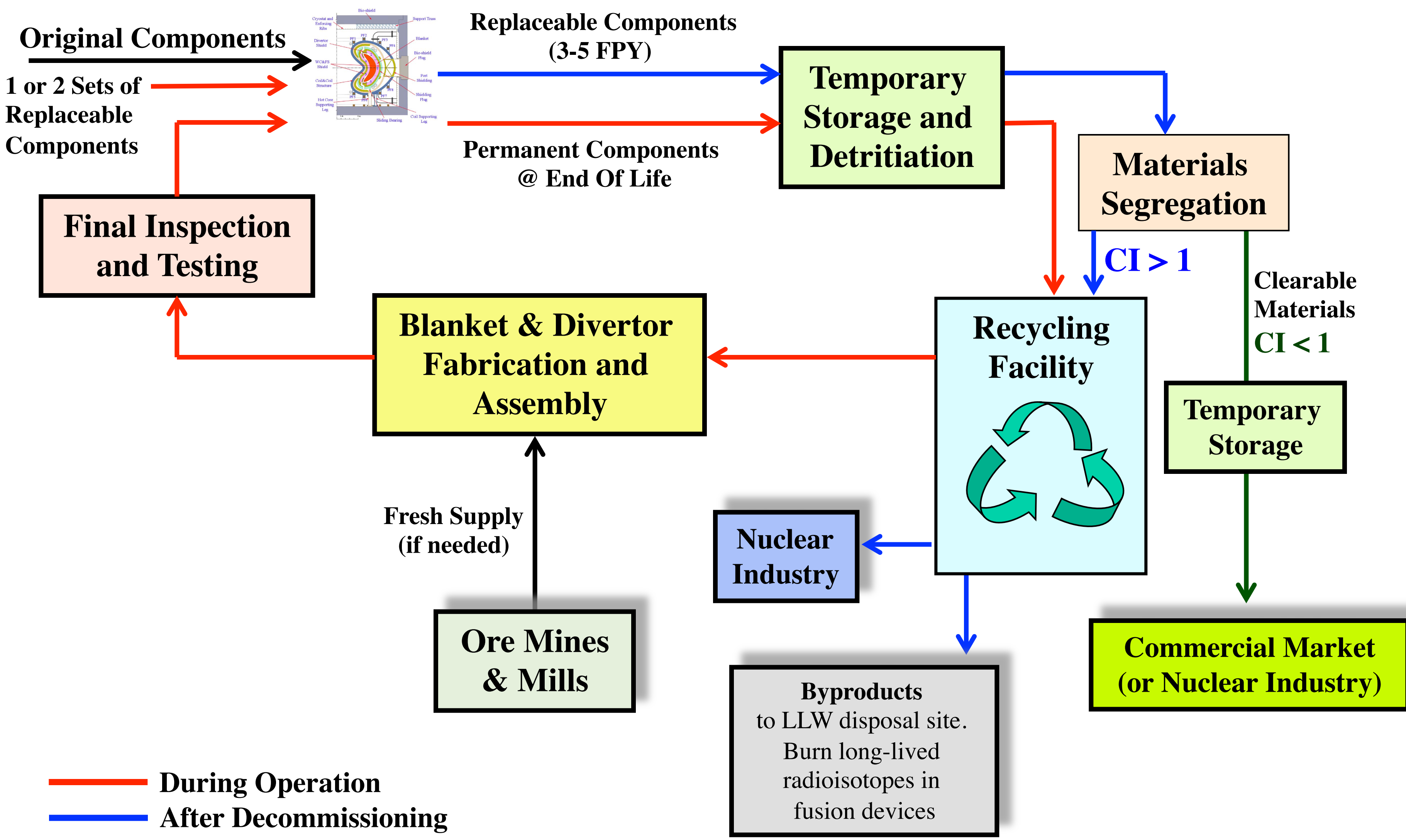
Recyclable or Disposable as Class A or C LLW

Clearable





Recycling & Clearance Flow Diagram



General Observations

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

  ⇒ detritiation prior to recycling is necessary for fusion components.
- Several **critical issues** need further investigation for all three options*:
  - Disposal
  - Recycling
  - Clearance.

* L. El-Guebaly, V. Massaut, K. Tobita, and L. Cadwallader, "Goals, Challenges, and Successes of Managing Fusion Active Materials," Fusion Engineering and Design 83, Issues 7-9 (2008) 928-935.

Key Issues and Needs for Disposal

Issues:

- **<u>Only low-level waste</u>** ⇒ 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** (≥ 8,000 m^3 per 1 GW_e plant, including bioshield)
- **<u>High disposal cost</u>** (for preparation, characterization, packaging, interim storage, transportation, licensing, and disposal)
- Any <u>toxic waste</u> (such as Be, V, and Mo) or mixed waste[#]? - 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 <u>specific activity limits for fusion</u> LLW issued by legal authorities
- <u>Fusion-specific repositories designed for T-containing materials</u>
- <u>Reversible</u> LLW repositories (to gain public acceptance and ease licensing).

[#] Radioactive and chemically toxic (e.g., containing T).

Key Issues and Needs for Recycling

Issues:

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

Needs:

- R&D program to address recycling issues
- Radiation-resistant remote handling equipment for fusion use
- Reversible assembling process 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#
- Nuclear industry should accept recycled materials
- Recycling infrastructure.

* 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.
# e.g., heat pipes.

Key Issues and Needs for Clearance

Issues:

- **Discrepancies between proposed US-NRC & IAEA clearance standards[#]**
- Impact on clearance index prediction of missing fusion radioisotopes
- Radioisotope buildup and release by subsequent reuse.

Needs:

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

\# 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).

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

- **US recycled tons of metals and concrete** from fission plant.
- **In 1960s**, ANL-West Hot Fuel Examination Facility developed radiation resistant tools to handle fission fuel rods for Experimental Breeder Reactor (EBR-II). RH equipment operated successfully at **10,000 Sv/h** (needed for fusion).
- INL and industrial firm recycled activated Pb bricks for nuclear industry. Cost of Pb LLW disposal was ~$5/pound while cost of recycling was ~$4.3/pound including fabrication into brick shapes.
  Savings:
  - Recycling versus disposal cost
  - Disposal volume over entire lifecycle
  - Not requiring purchase of new Pb bricks.
- INL and industrial company fabricated shielding casks out of recycled stainless steel:
  - Casks were designed, built, and tested for strength and impact
  - Slag from melting tends to collect some radionuclides
  - Composition adjustments after slag removal produced metal alloys with properties very similar to those of fresh alloys
  - Prototype casks functioned well and are still in use since 1996.
- More recently in 2010, DOE required decontamination of 15,300 tons of radioactive nickel and recycling into products that will be used in radiologically-controlled applications.
- Advanced recycling technology exists in US. Adaptation to fusion needs is highly desirable (radiation level, size, weight, etc.).

Maturation of Recycling and Clearance Approaches

It's just matter of time 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 for fusion
- Accurately measure and reduce impurities that deter clearance of fusion 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 adapted for fusion use
- Consider fusion-specific materials and issue official guidelines for unconditional release of clearable materials
- Accept recycled materials 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.