Nuclear and Environmental Features of Pulsed Driven Fusion Energy

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Fusion Power Plants Demonstrate Adequate Performance in Several Safety and Environmental Areas

Environmental impact

- **Minimal greenhouse gas emissions**
- **Minimal radioactive releases**[#] during normal and abnormal operations
- **No high-level waste**
- **Minimal low-level waste** through recycling/clearance
- **Low activation materials** with strict impurity control

  $\Rightarrow$ minimal long-term environmental impact.

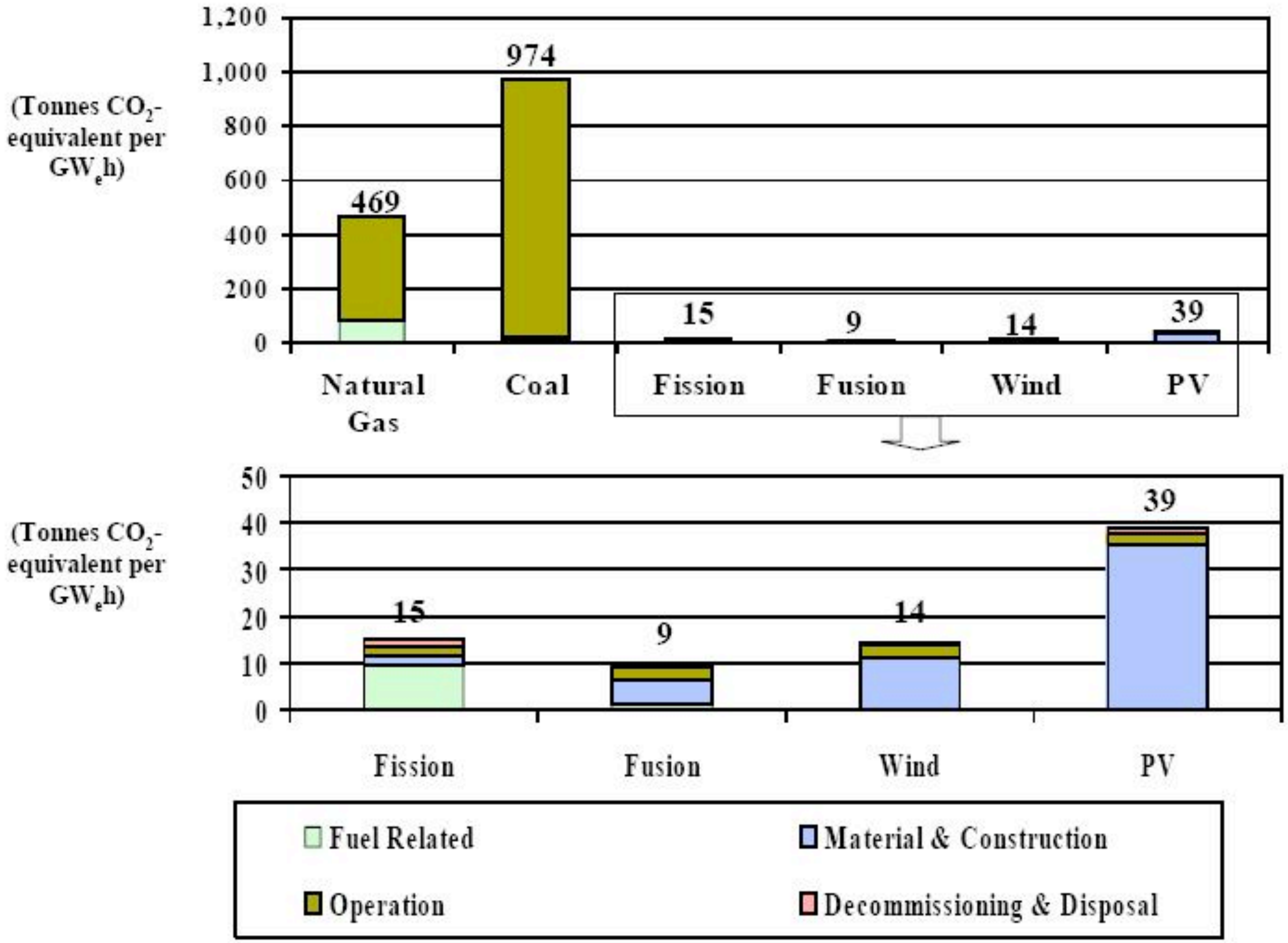
Occupational and public safety:

- **No evacuation plan** following abnormal events (early dose at site boundary < 1 rem[*]) 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, etc.)

No energy and pressurization threats to confinement barriers (VV, cryostat, and bio-shield):

- Decay heat problem solved by design
- Chemical reaction avoided
- No combustible gas generated
- Chemical energy controlled by design
- Overpressure protection system
- Rapid, benign plasma shutdown

Fusion Releases Minimal Amount of Greenhouse Gases



DT Fusion is Easiest to Achieve

Fusion fuel cycles:

D + T → n (14.07 MeV) + ^{4}He (3.52 MeV)

D + D → n (2.45 MeV) + ^{3}He (0.82 MeV)

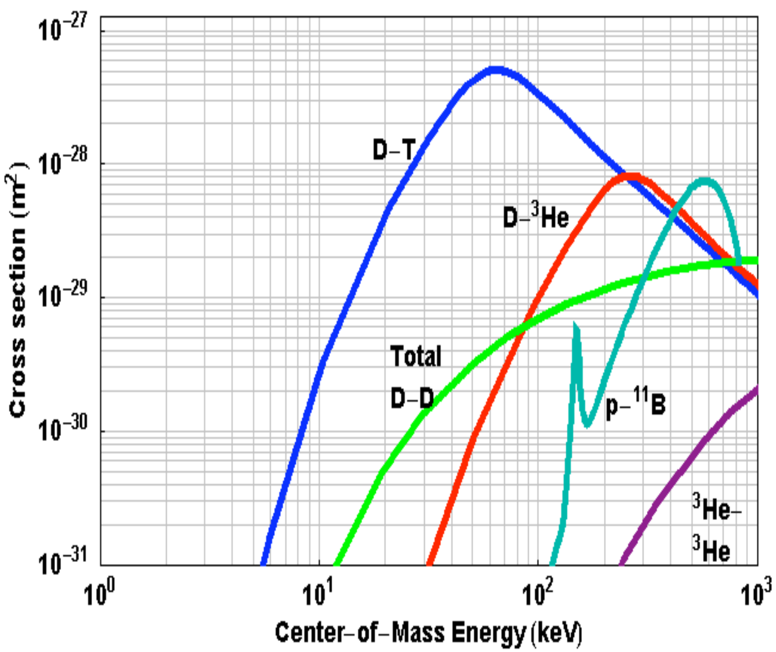
→ p (3.02 MeV) + T (1.01 MeV)

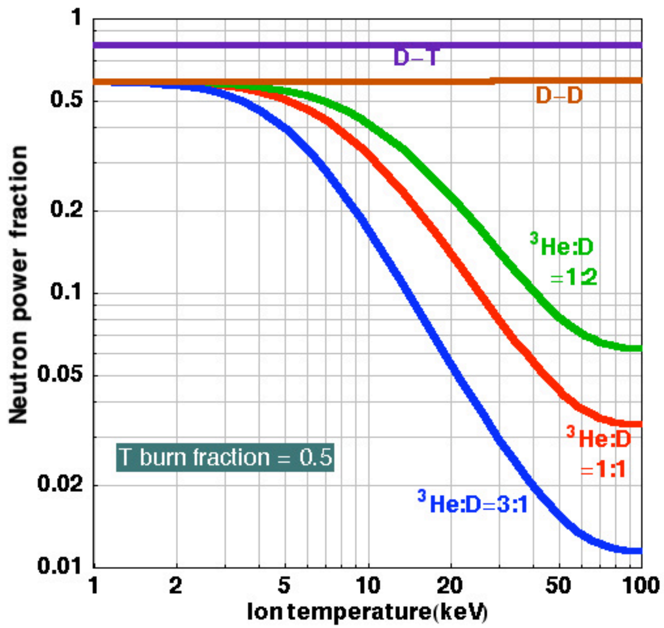
D + ^{3}He → p (14.68 MeV) + ^{4}He (3.67 MeV)

^{3}He + ^{3}He → 2 p + ^{4}He (12.86 MeV)

p + ^{11}B → 3 ^{4}He (8.68 MeV)

- While DT fusion is easiest to achieve, it produces large amount of energetic neutrons
- No radioactivity produced within fuel
- Neutrons activate materials surrounding fuel in reactor chamber
- Proper choice of material in reactor chamber reduces radioactivity production

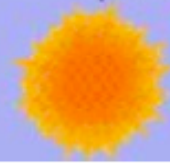




D-T Fusion Represents a Nearly Inexhaustible Energy Source

Fuels: **Deuterium**: abundant in sea water

Tritium: Half-life~12 years…must be produced?

Reaction		Ignition Temperature		Output Energy
Fuel	Product	(millions of °C)	(keV)	(keV)
D + T	^{4}He + n			
		45	4	 17,600

^{6}Li + n --> T + ^{4}He + 4.8 MeV + others

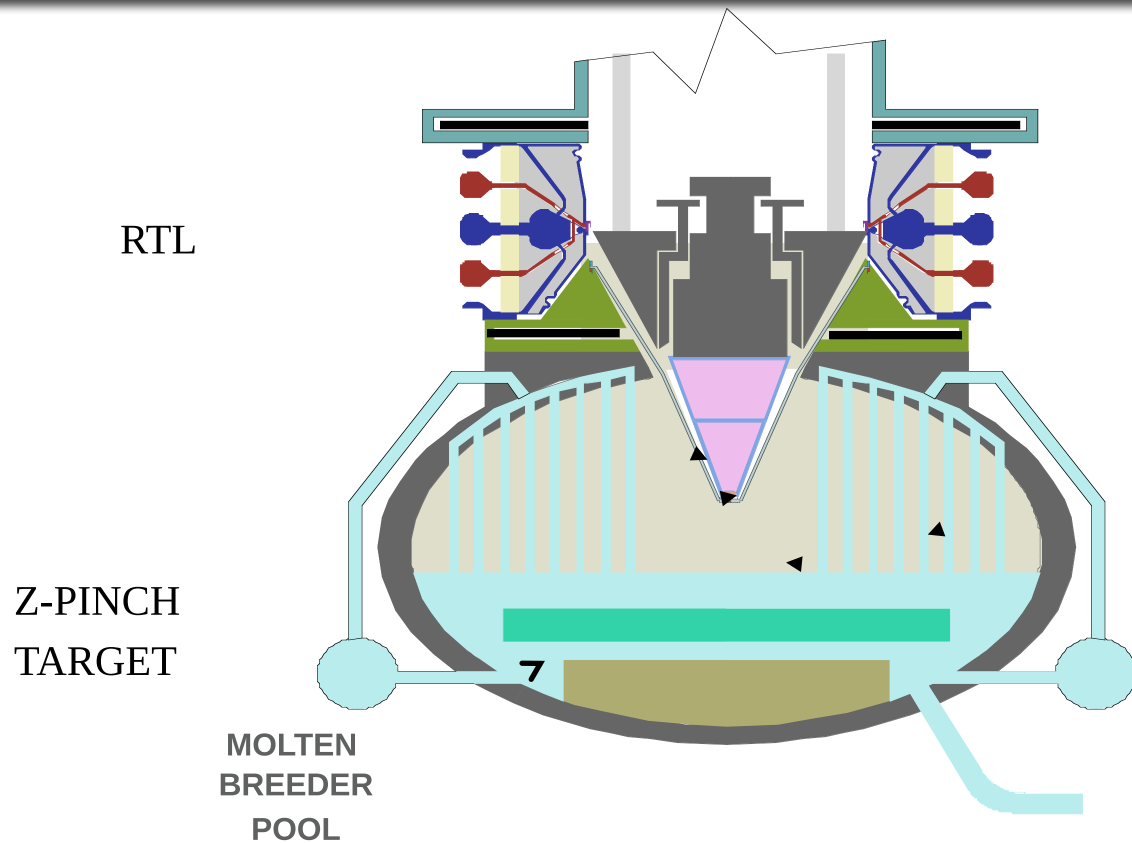
T_{bred} / T_{burned} > 1

"Real" fusion fuel cycle:

^{6}Li + D = 2^{4}He + 22.4 MeV

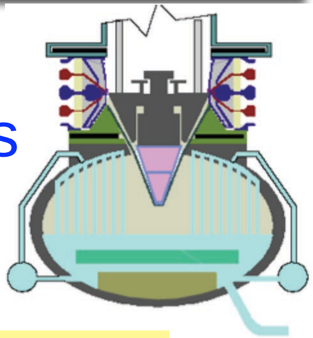
No Resource Concern

Z-pinch IFE Reactor Concept



- Liquid breeder jets and pool required for **tritium breeding**, **recovering fusion energy**, and **shielding structural chamber wall**
- Two liquid breeder options considered: ***Flibe (F_4Li_2Be), LiPb ($Li_{17}Pb_{83}$)***
- ***Both have low tritium solubility leading to low tritium inventory***

Z-pinch Reactor is Fuel Self-Sufficient

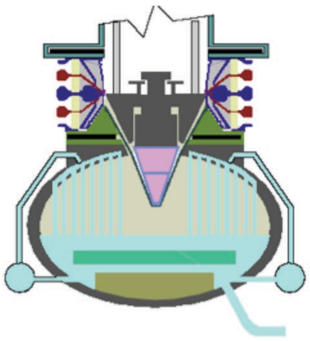


- Tritium self-sufficiency ensured for both breeders

	Tritium Production per Fusion	
	Flibe Breeder	**LiPb Breeder**
Jets	0.840	0.711
Nozzle Zone	0.019	0.053
Pool	0.246	0.362
RTL Foam	0.011	0.005
Overall TBR	**1.116**	**1.131**

Liquid Breeder Recovers and Multiplies Fusion Energy

	Thermal Power (GW)	
	Flibe	**LiPb**
Jets	2.546	2.372
Pool	0.474	0.566
Chamber Wall	0.139	0.320
Nozzle Zone	0.062	0.158
RTL Support Structure	0.074	0.104
RTL	0.018	0.017
RTL Foam	0.033	0.023
Total	**3.346**	**3.560**
Overall Energy Multiplication	***1.115***	***1.187***



- Target Yield 3 GJ
- Rep Rate 0.1 Hz
- 10 Chambers

- Liquid breeder recovers surface heat deposited by x-rays and ion debris
- Neutron interactions result in volumetric nuclear heating that is higher than fusion neutron energy with net energy multiplication

Cleanup Systems Needed for Flibe and LiPb

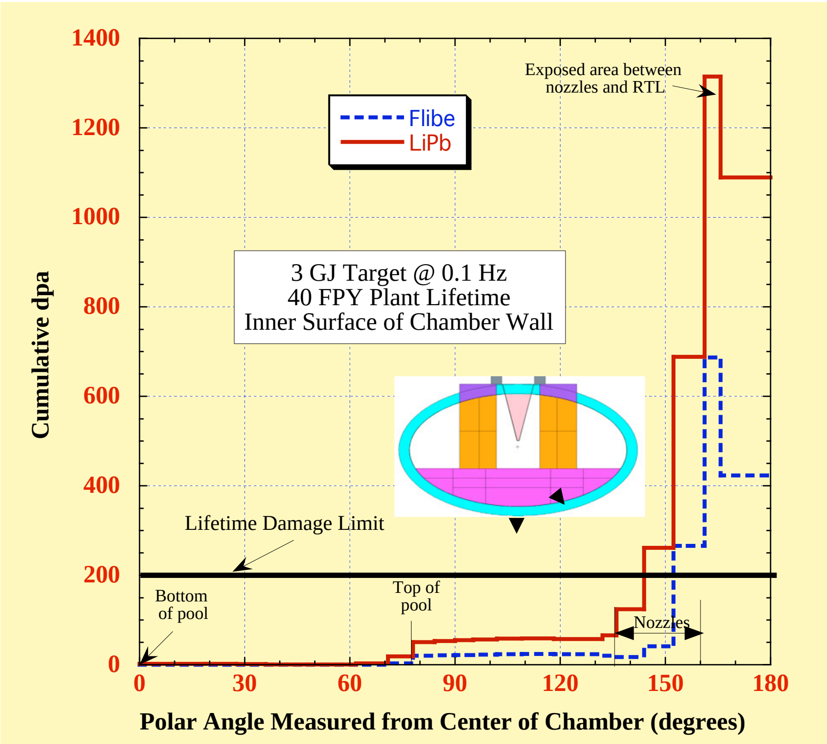
Flibe:

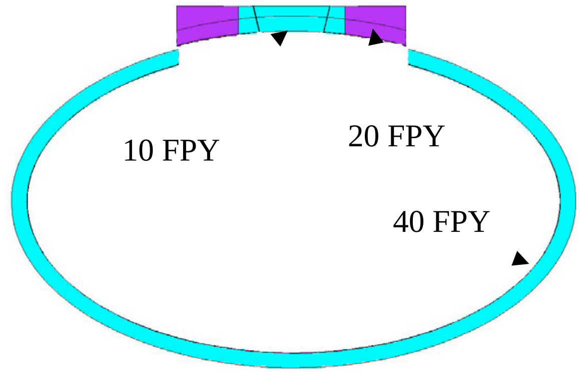
- **Flibe dissociates under irradiation** and has a compatibility problem with FS if radiolysis byproducts cannot be controlled by chemical means.
- Neutrons interact with Flibe and produce extremely **corrosive free fluorine** and the less corrosive **tritiated hydrofluoric acid** (TF).
- A reduction and oxidation (**REDOX**) agent, such as beryllium, is essential for the viability of Flibe to control free fluorine and TF and minimize corrosion (to eliminate carrying radioactive corroded material).
- Experimental work on REDOX to limit corrosive effects of F and TF is being performed at INL as part of US-Japan collaboration.

LiPb:

- Neutrons interact with Pb and Bi, producing hazardous radionuclides **^{210}Po** (138 d) **and ^{203}Hg** (47 d).
- **Controlling Bi impurity** can limit ^{210}Po inventory.
- Online purification system is necessary to remove ^{210}Po and/or ^{209}Bi.

Thick Liquid Breeder Protects Chamber Wall, Reduces Radioactivity and Waste Volume





Chamber wall waste volume from 10 units:

Replaceable part	150 m^3
Permanent part	630 m^3
Total	***780 m^3***

- Thick liquid breeder jets and pool reduce radiation level at chamber wall by ~2 orders of magnitude
  - ***Longer lifetime for chamber wall***
  - ***Reduced radwaste volume***
  - ***Reduced radioactivity level***

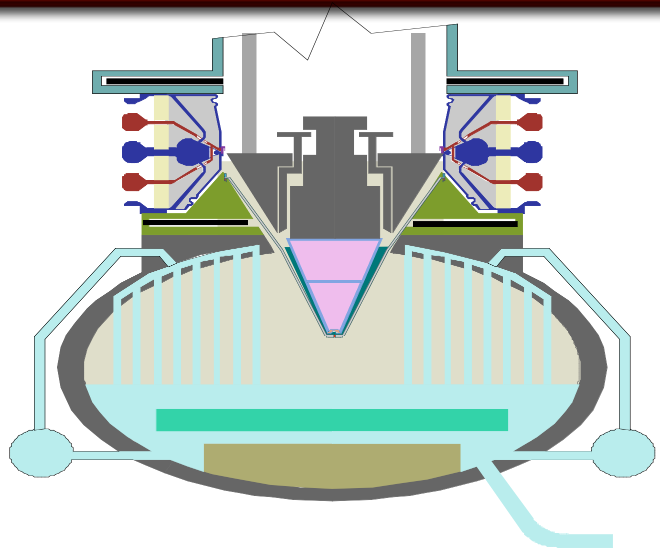
Careful Choice of Chamber Wall Material Eliminates Generation of High-Level Waste

A-286 Steel

WDR = 110

F82H Steel

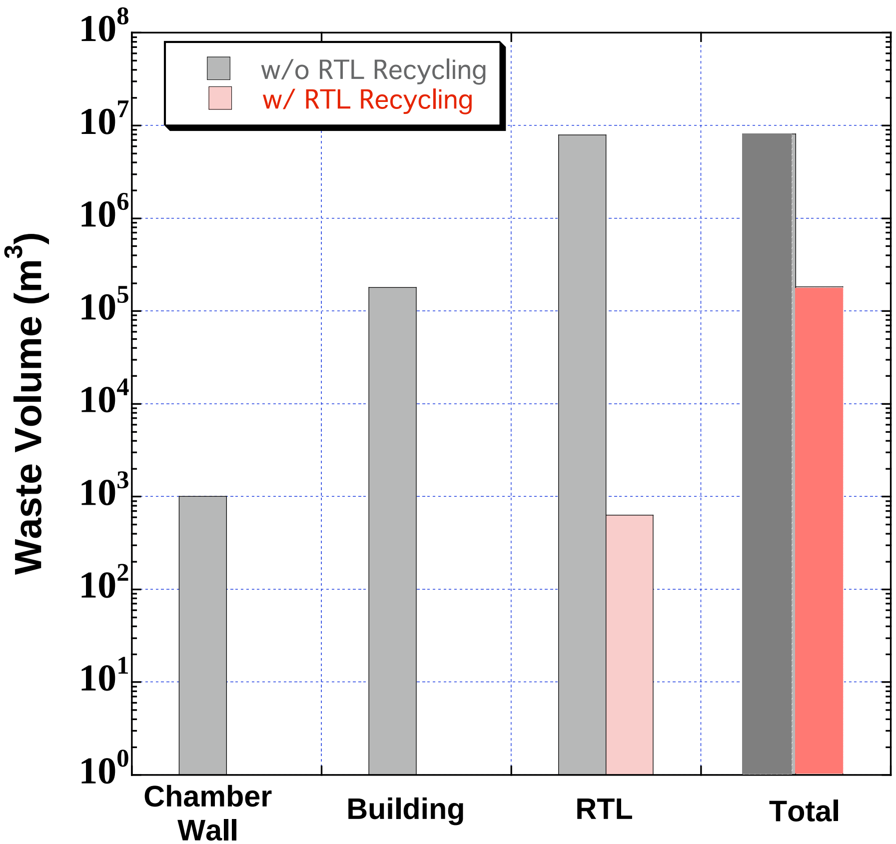
WDR = 0.9



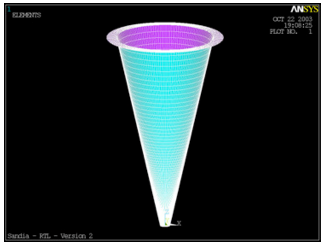
	Dominant Radionuclides
A-286 steel	99% Tc-99 (from Mo **alloying element**)
F82H steel	91% Nb-94 (from Nb **impurity**)
	8% Tc-99 (from Mo **impurity**)

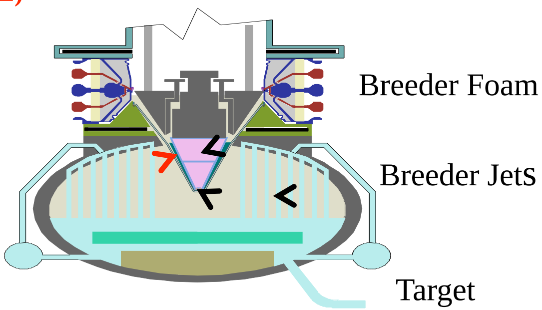
- A-286 steel generates high-level waste (WDR >> 1)
- F82H steel qualifies as LLW (WDR < 1)
- **F82H is preferred steel** based on activation consideration
- Controlling Nb and Mo **impurities** leads to a more attractive design

Recycling is a "Must" for RTL to Minimize Radwaste Stream and Enhance Economics



Recyclable Transmission Lines (RTL)
Top diameter = 1 m
Bottom diameter = 0.1 m
Length = 2 m
Total thickness = 0.142 cm
50 kg / RTL



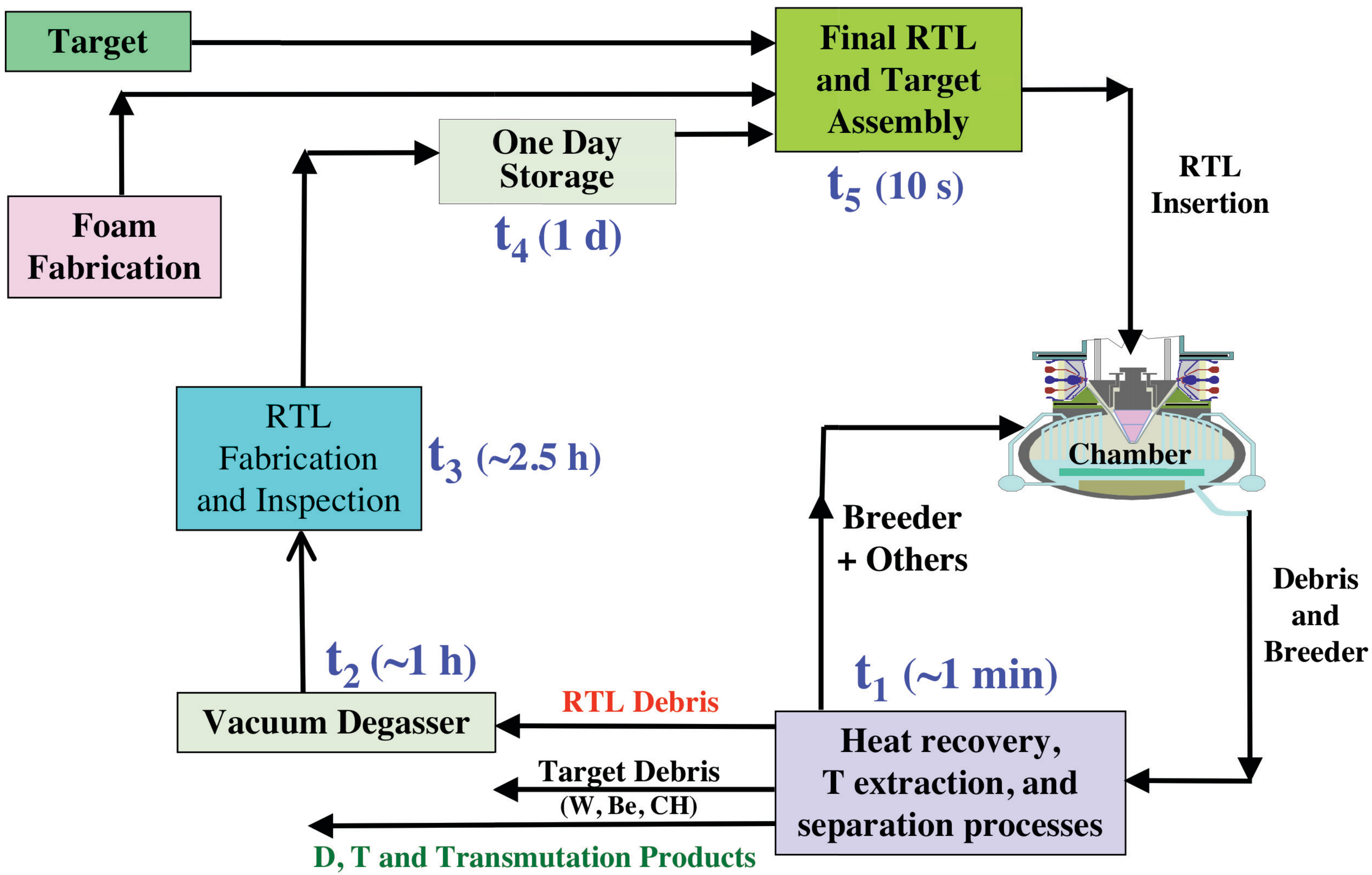


Chamber
(10 units / plant)

No recycling for 40 FPY
Total RTL mass = 70 M Tons

With recycling
1.1 day RTL inventory
Total RTL mass = 0.005 M Tons

Recycling Flow Diagram

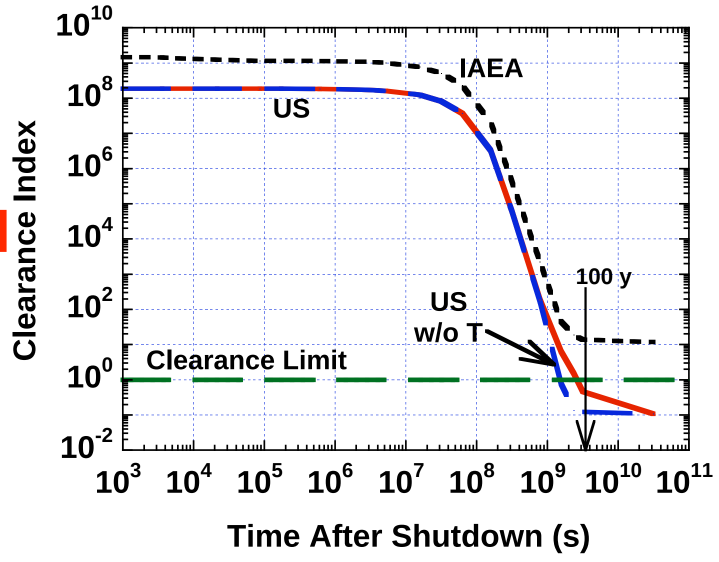


RTL Radwaste After Decomissioning is LLW and Can Be Cleared

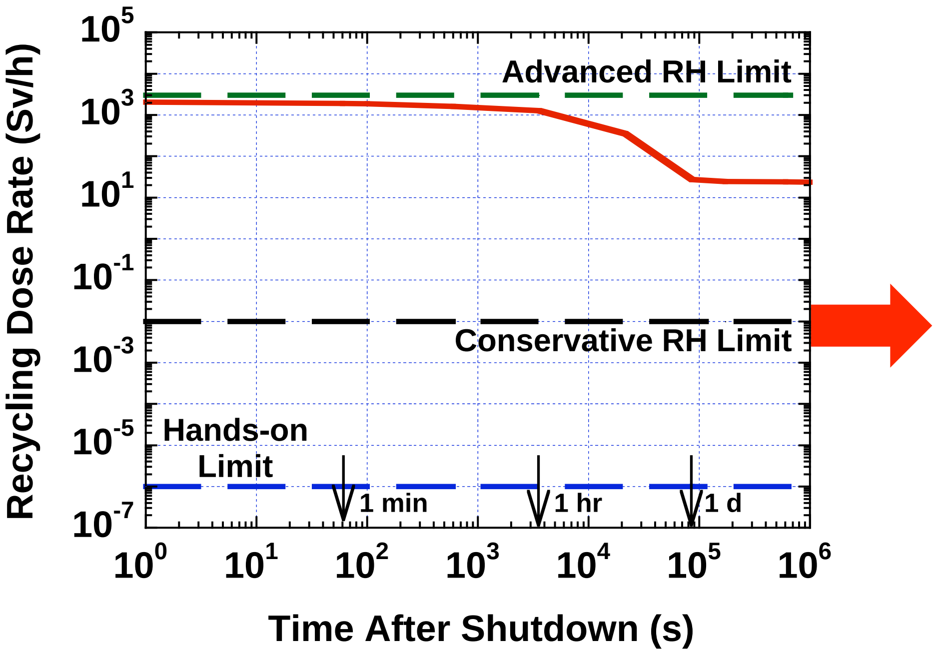
LLW	WDR	Limits
Class C	10^{-6} (^{32}Si)	1
Class A	10^{-4} (T,^{14}C)	1

Carbon steel RTLs generate very low-level waste (WDR << 1) and could qualify for clearance

According to U.S. guidelines, RTL waste could be stored for 50 y after decommissioning, then reused within nuclear industry or released to commercial market



Advanced Remote Handling Equipment Needed to Recycle RTLs



- Hands-on recycling not allowed.
- No personnel access to fabrication facility.
- Advanced remote handling equipment must be developed to handle 3000 Sv/h.
- Main contributors at 1 day: ^{54}Mn (90%, $T_{1/2}$=312.2 d) ^{56}Mn (9.6%, $T_{1/2}$=2.58 h).

Conclusions

- Fusion power plants offer several attractive environmental features:
  - Minimal greenhouse gas emissions
  - Minimal radioactive releases
  - No high-level waste
  - Low-activation, recyclable/clearable materials
  - No evacuation plan needed during accidents
  - No energy and pressurization threats to confinement barriers
- Abundant resources can fuel fusion power plants for thousands if not millions of years
- Thick liquid breeder in Z-pinch chamber protects chamber wall, reduces radioactivity and waste volume, ensures tritium self-sufficiency, and recovers and multiplies fusion energy

Conclusions (Cont.)

- Appropriate choice of low activation steel for chamber wall results in low-level waste
- Recycling is a “Must” requirement for RTL to minimize radwaste stream and enhance economics
- Carbon steel RTLs satisfy design requirements when recycled for entire plant life (40 FPY):
  - Class A low-level waste $\Rightarrow$ Near-surface shallow land burial
  - Clearance index < 1 $\Rightarrow$ Store waste for 50 y after decommissioning, then reuse within nuclear industry or release to commercial market
- Advanced remote handling equipment *must* be developed to handle dose rate of 3000 Sv/h or more