Progress in the Safeguards Approaches for the Molten Salt Reactors

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Presentation Overview

- Concept of 3S (Nuclear Safety, Security, Safeguards)
- Introduction to Nuclear Safeguards
- Safeguards in Current Commercial Power Reactors
- Typical Advanced Nuclear Reactor
  - Molten Salt Fast Reactor (MSFR)
- Safeguards Challenges of Advanced Nuclear Reactors
- Conclusion

Nuclear {
- Safety
- Security
- Safeguards

3S

What are Safeguards?

- The safeguards system is comprised of measures by which the a competent authority such as IAEA independently verifies the declarations made by States about their nuclear material and activities
- Safeguards are designed to ensure that safeguarded items are not used in such a way as to further any military purpose
- Measures are implemented under various types of agreements and protocols

Objectives of IAEA Safeguards

- **Objective 1:** *timely detection* of diversion of significant quantities of nuclear material from peaceful nuclear activities to the manufacture of nuclear weapons or of other nuclear explosive devices or for purposes unknown, and deterrence of such diversion by the risk of early detection

- **Objective 2:** the *detection of undeclared* nuclear material and activities in a State

What Material is Safeguarded?

- Uranium
- Plutonium
- Thorium
- Any material containing one or more of the above except ores and ore residues

Significant Quantity (SQ)

- Approximate amount of nuclear material for which the possibility of manufacturing a nuclear explosive device cannot be excluded
  - accounts for unavoidable losses due to conversion and manufacturing processes
  - not critical masses
  - used in establishing the quantity component of the IAEA inspection goal

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.

Material Unaccounted For

- So the MUF calculation for this facility is very easy:

$$MUF = (PB + X - Y) - PE$$

$$\sigma_{MUF} = \sqrt{(\sigma_{PB}^2 + \sigma_X^2 + \sigma_Y^2) + \sigma_{PE}^2}$$

$$MUF < 1\,SQ$$

$$|MUF| < 3\,\sigma_{MUF}$$

$$3\,\sigma_{MUF} < 1\,SQ$$

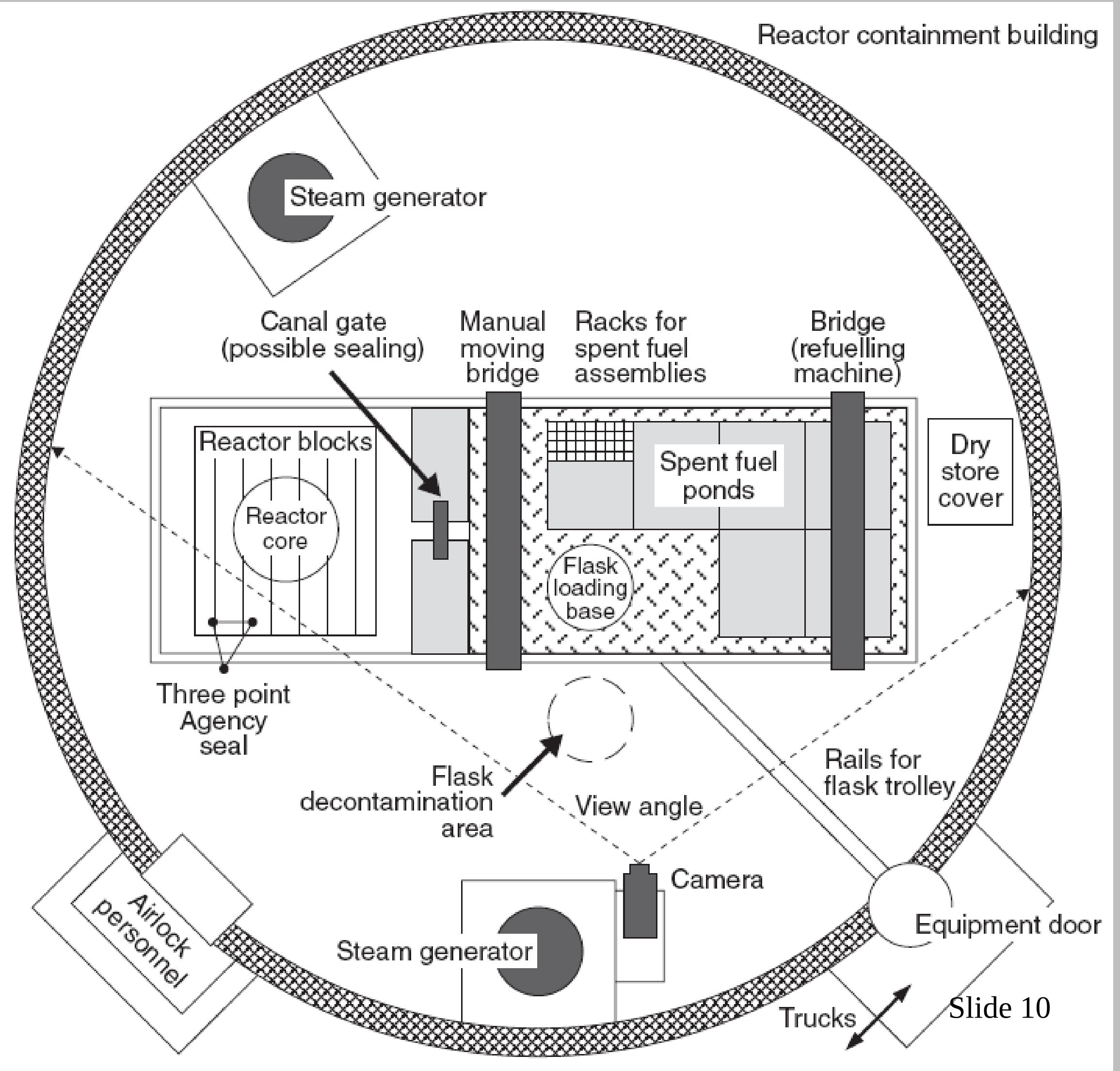
- where
  - PB is the beginning physical inventory
  - X is the sum of increases to inventory
  - Y is the sum of decreases from inventory
  - PE is the ending physical inventory

Issues for Power Reactor Safeguards

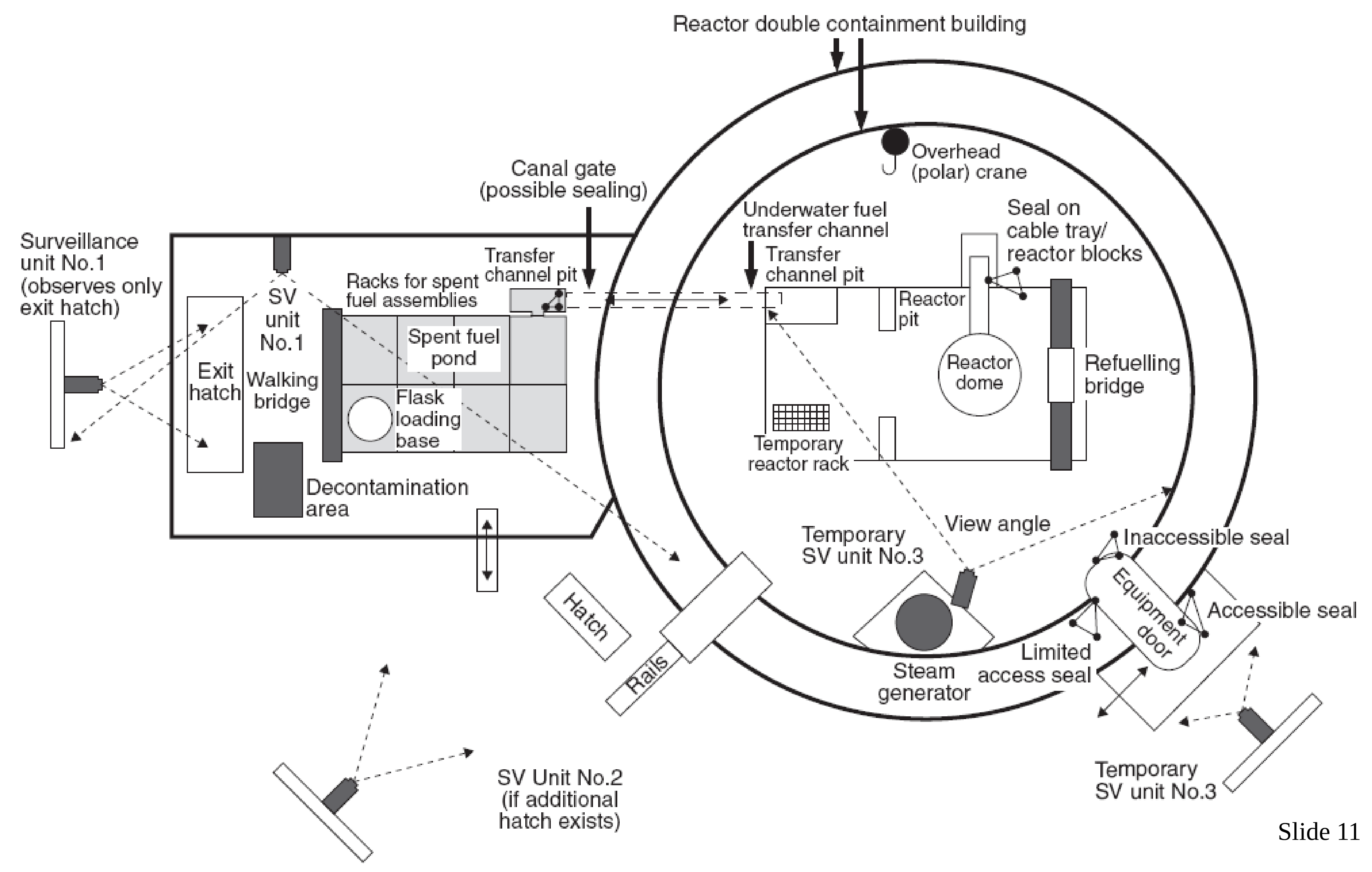
- Off-load
  - refueling infrequent with large number of items moved per refueling
  - LWRs are off-load with open vessels
  - FBRs are off-load but without open vessels
- On-load
  - high frequency of movements with a small number of items moved per refueling
  - CANDUs are on-load without open vessels
- Fuel type
  - could change the SQ value, the timeliness criteria, etc.
- Fuel receipt
  - fuel is verified by inspection and NDA measurement (on a random selection basis)

Typical Layout of an LWR Type I Plant Design

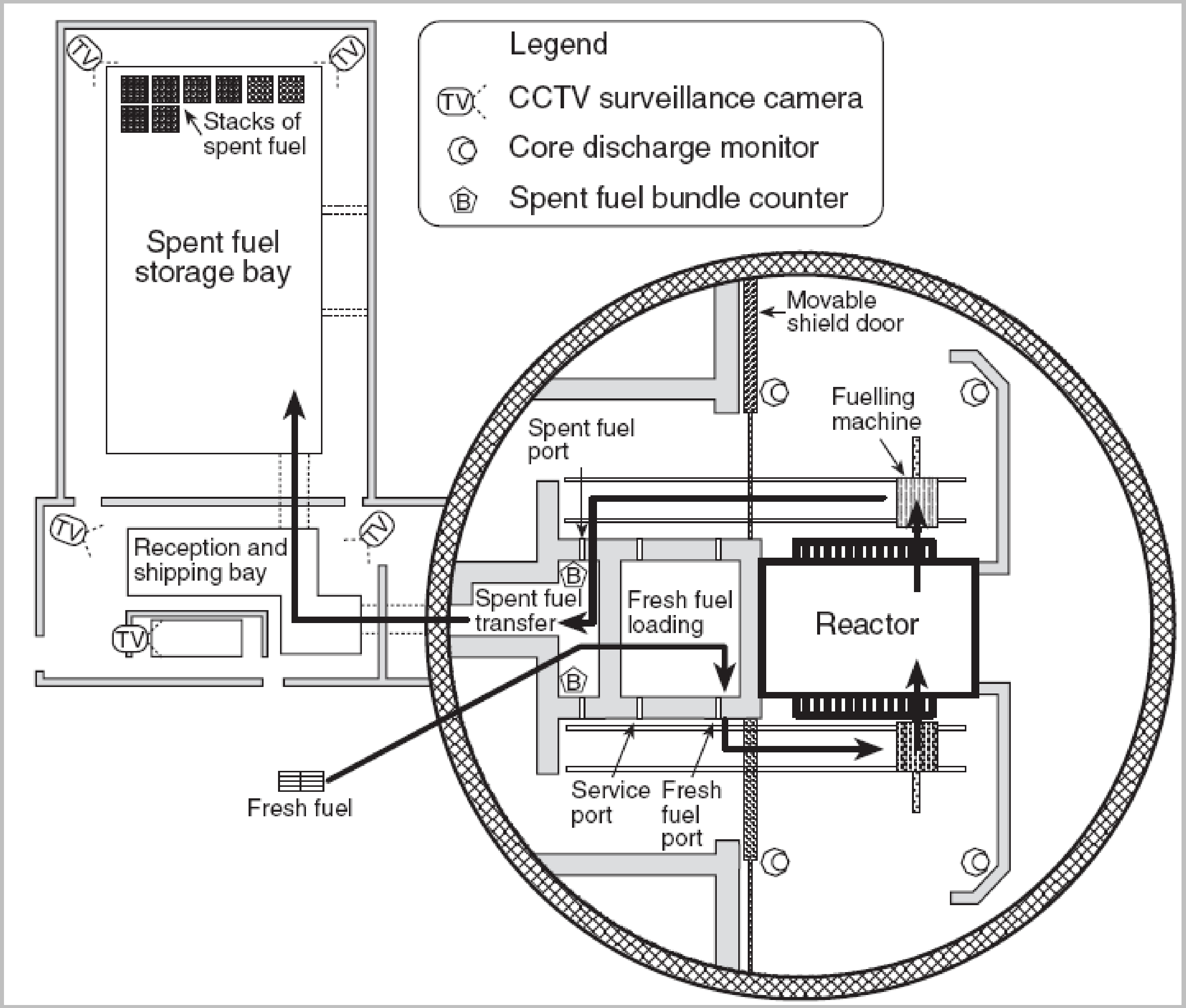
These are mostly BWRs, VVERs, and
PWRs of Siemens design



Typical Layout of an LWR Type II Plant Design

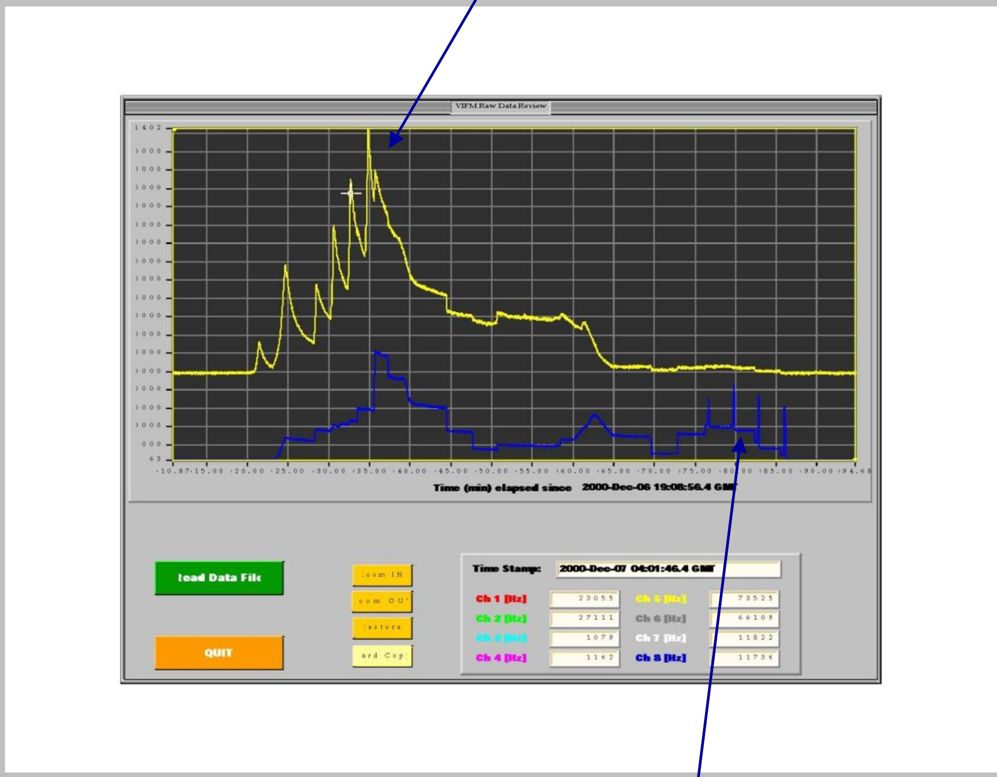


Location of Safeguards Equipment at a CANDU with CDM



CDM Data

- Peak 1: removal of the channel plug from the reactor face where the spent fuel will be removed
- Peak 2: removal of the radiation shield plug
  - allowing direct access to the fuel
- Peaks 3-6: removal of four pairs of spent fuel bundles
  - eight bundles total from the reactor



Molten Salt Fast Reactor (MSFR)

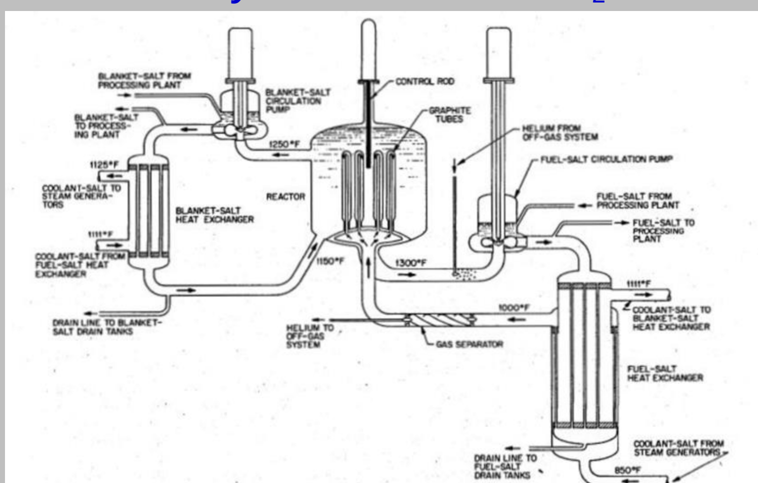
Power: 2225 MWth (1000 MWe)

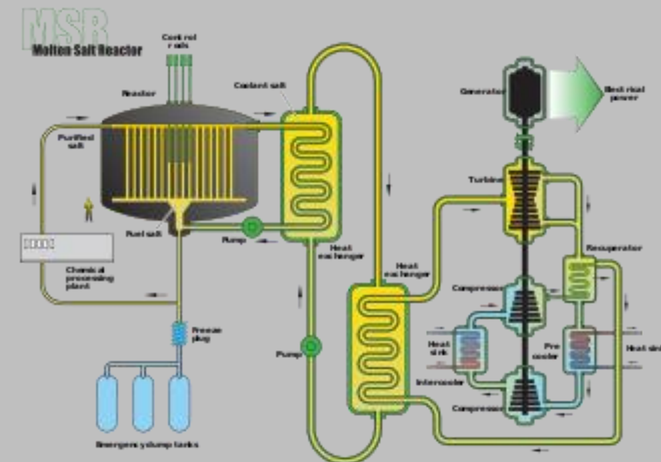
3000 MWth (1500 MWe)

Fuel: LiF-BeF_2-UF_4 (63.6-36.2-0.22 mole %)

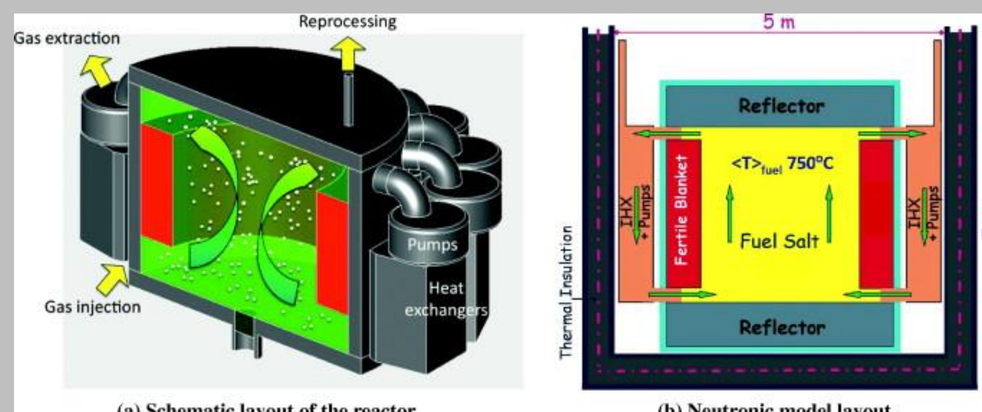
Blanket: LiF-BeF_2-ThF_4-UF_4 (71-2-27-0.0005)

Secondary Coolant: LiF-BeF_2



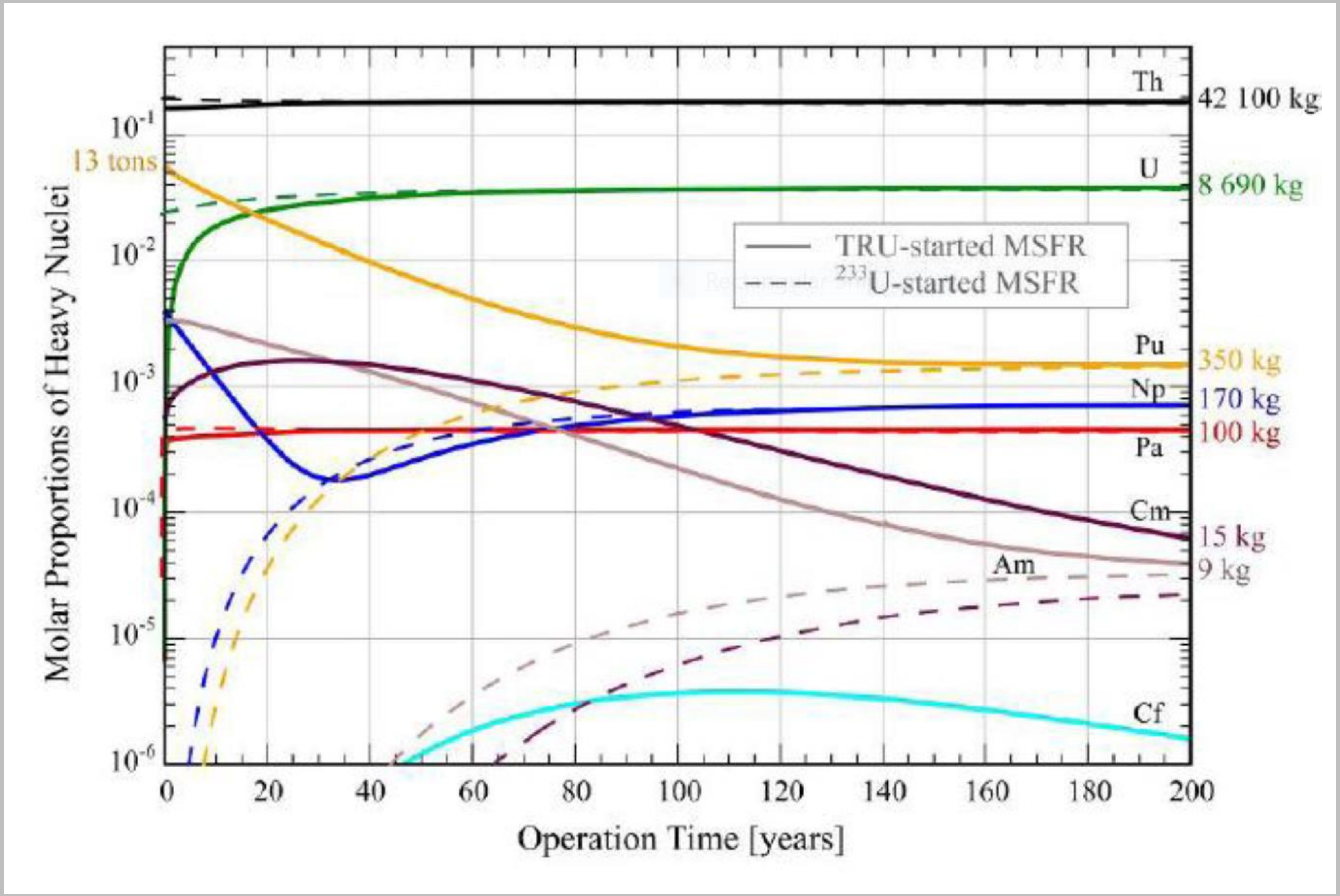


Gen IV Molten Salt Reactor (Epithermal)



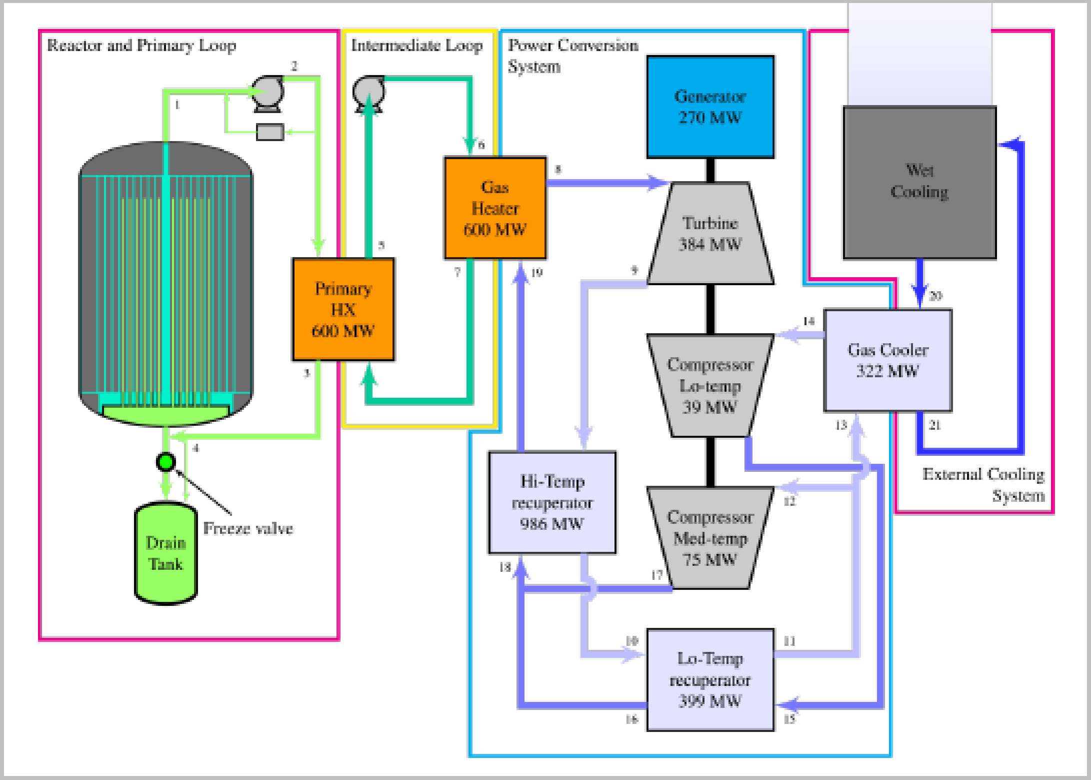
Molten Salt Fast Reactor (MSFR)

Thermal power (MWth)	3000				
Electric power (MWe)	1500				
Fuel molten salt initial composition (mol%)	LiF-ThF$_4$-^{233}UF$_4$ or LiF-ThF$_4$-(Pu-MA)F$_3$ with 77.5% LiF				
Fertile blanket molten salt initial composition (mol%)	LiF-ThF$_4$ (77.5–22.5%)				
Melting point (°C)	565				
Inlet/outlet operating temperature (°C)	650–750				
Initial inventory (kg)	^{233}U-started MSFR		TRU-started MSFR		
	Th	^{233}U	Th	Actinide	
	38 300	5 060	30 600	Pu	11 200
				Np	800
				Am	680
				Cm	115
Density (g/cm^3)	4.1249				
Dilatation coefficient (g/(cm^3 K)) [29]	8.82×10^{-4}				
Core dimensions (m)	Radius: 1.1275				
	Height: 2.255				
Fuel salt volume (m^3)	18				
	9 out of the core				
	9 in the core				
Blanket salt volume (m^3)	7.3				
Fuel salt cycle time in the system (s)	4.0				


Molar Proportions of Heavy Nuclei
Operation Time [years]
TRU-started MSFR
233U-started MSFR
Th
U
Pu
Np
Pa
Cm
Am
Cf
42 100 kg
8 690 kg
350 kg
170 kg
100 kg
15 kg
9 kg
13 tons
10-1
10-2
10-3
10-4
10-5
10-6
0
20
40
60
80
100
120
140
160
180
200

A Typical MSR Fuel Salt Processing

- Step 1: A small stream of fuel salt is removed from the reactor and held up in a drain tank (decay tank)- Short lived fission products decay
- Step 2: Uranium is temporarily removed from the salt and separated from fission products - Long lived fission products removal
- Step 3: U and freshly-bred U-233 are returned back to the fuel salt and back to the reactor



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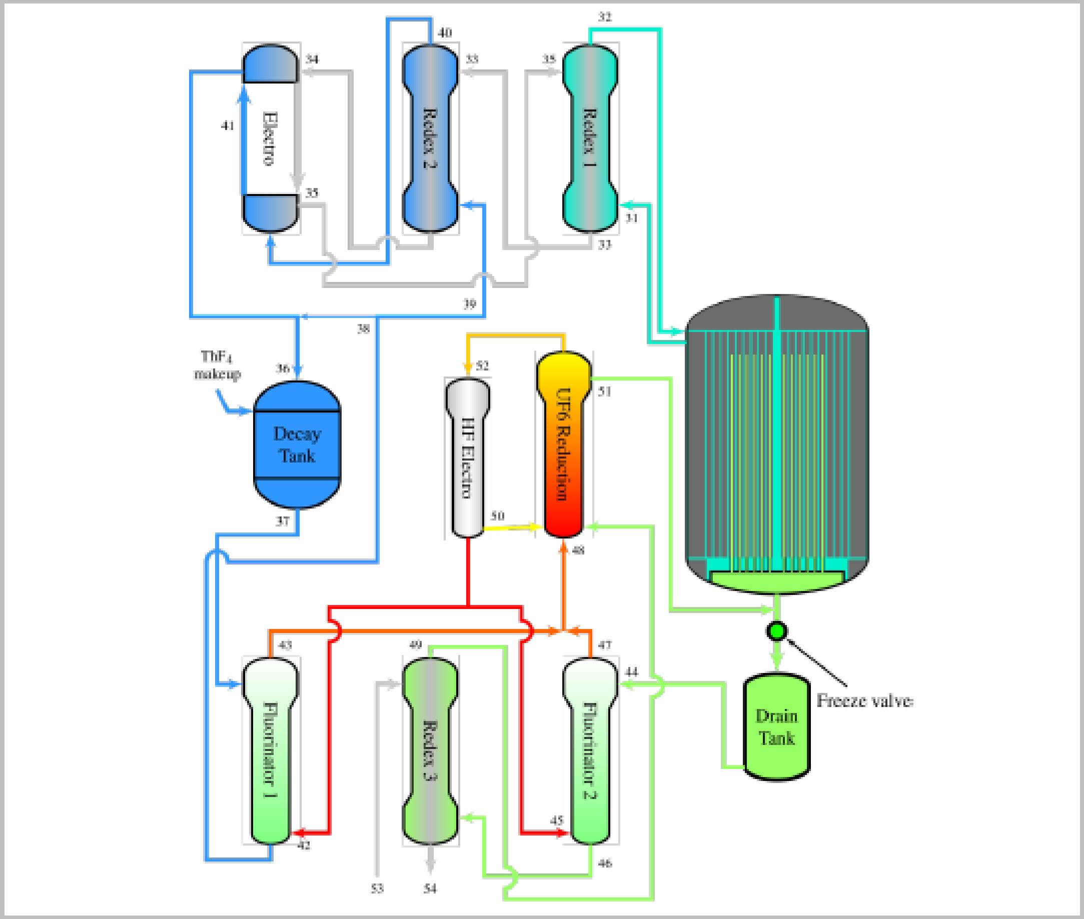
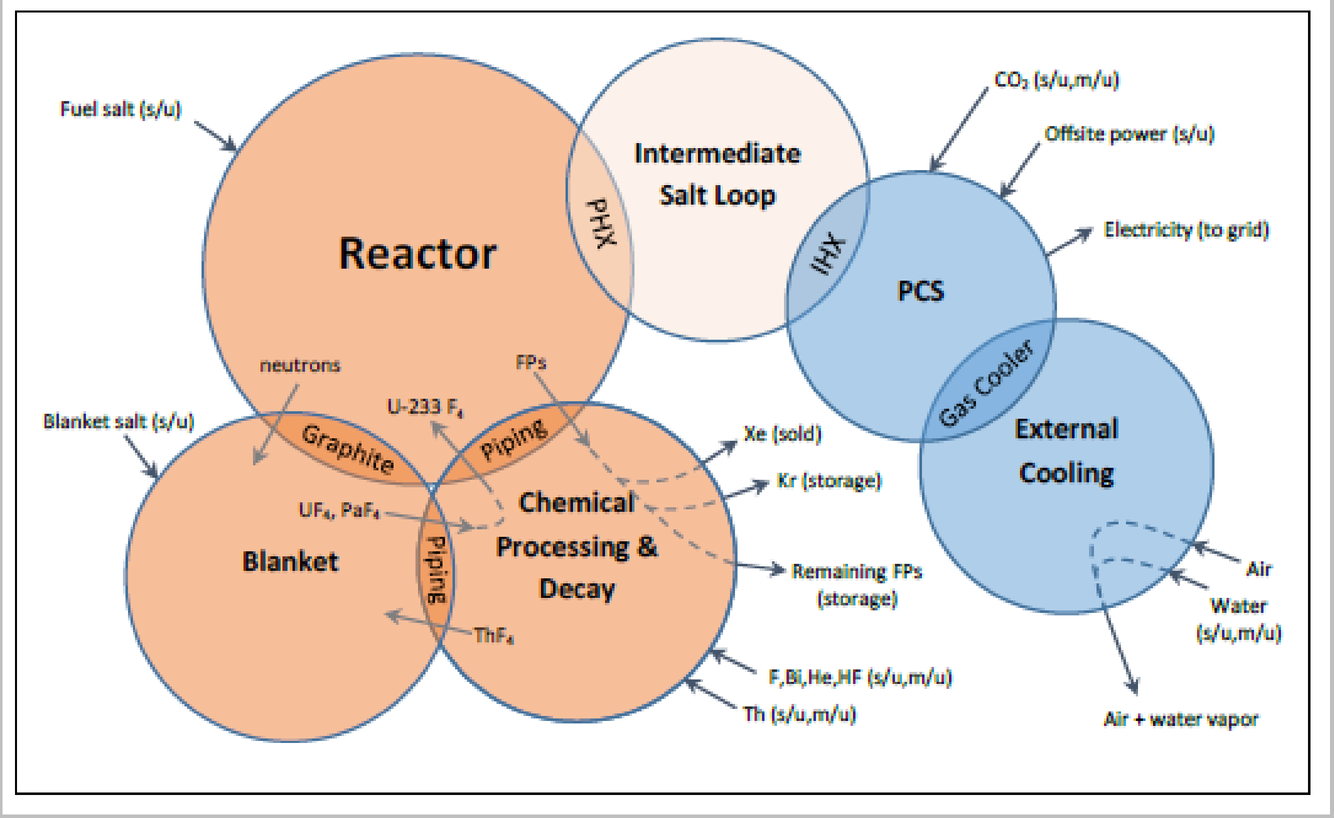


MSR Safeguards Challenges

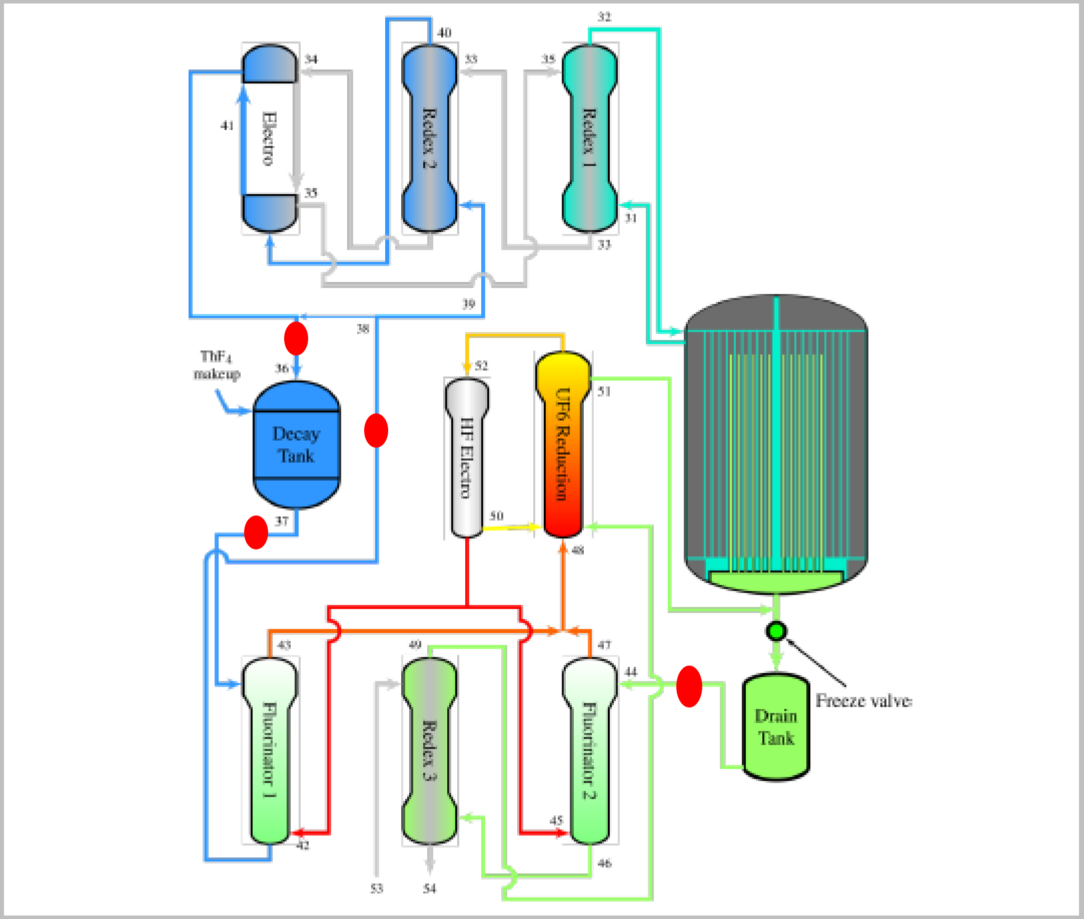


Safeguards Approach Preliminaries

- The use of a liquid fuel complicates the application of traditional safeguards
  - Changes the barriers to materials diversion
  - Lack of discrete fuel elements combined with continuous transmutation and online processing prevents traditional "item" accounting
  - Solid LEU fresh fuel salt in transport and storage accountancy resembles LWR fuel
  - Ease of access to nuclear materials depend on design details for the plant, including any processing that is done on the liquid fuel/salt mixture
  - Large volumes of materials being used at any one time in reactor
  - Access for measurements difficult
  - Correlation between current instrument signals and presence/quantity of fissile material not understood fully.
  - MSR blend features from both Bulk and Item Facilities

Safeguards Approach Preliminaries

- Evaluation of inventories and feed rates in fuel salt and blanket salt
- Nuclear material accounting (NMA)
- Fuel salt contains the majority of the fissionable material.
- K-Edge Densitometry for concentration



Conclusions

- Safeguards system is not ready for MSRs
  - Nuclear material flow Rate is known
- There are several next steps in safeguards determination
  - Material Balance Area (MBA) determination
  - Material Balance Period (MBP) determination
  - Key Measurement Point (KMP) determination
- Safeguards approaches for one MSR design may not be valid for another design
- Development of NDA technologies and other measurement instruments for deployment
- Safeguards inspector training