Overview of safety issues related to liquid lithium

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Outline

- Key safety issues in liquid lithium chemical reactions:
  - Liquid Li - air reactions
  - Liquid Li - concrete reactions
  - Liquid Li - CO_2 reactions
  - Liquid Li - water reactions
- Overview of working Na/Li systems
- Overview of fusion concepts using liquid Li
- Preliminary safety analysis for HAPL chamber
  - Decay heat removal capability
  - Simulation of Li fire
- Summary

Key safety issues with liquid lithium chemical reactions

- Direct energy release from chemical reaction could lead to high temperatures and pressures causing facility damage and accident propagation

- Indirect energy release from secondary chemical reactions involving initial reaction products (i.e., Li-H2O reaction produces H2 gas which may lead to hydrogen combustion) may cause facility damage and accident propagation

- Dominant issue in accident scenario with Li chemical reactions is mobilization of tritium and activated structural materials

- It's critical to minimize and avoid when possible chemical reaction risk

Liquid Li – air reactions

- **$6Li + N_2 \rightarrow 2Li_3N$ + 69 kJ/mole-Li (at 500 °C)**
- **$4Li + O_2 \rightarrow 2Li_2O$ + 302 kJ/mole-Li (at 500 °C)**
- If we consider air is 79% N_2 and 21%O_2:

Chemical energy stored (GJ/kg-Li)	Total chemical energy (GJ)
0.015	7500

takes ~ 1 GJ to melt 1 tonne of steel

- Assumes all Li inventory (500 ton total, 300 within blanket) is available to react with unlimited air
- To avoid excessive energy release, a cover gas (Ar, He) should be used

Need thermal-hydraulics calculations to address accident with Li leak and simultaneous air ingress event

Li reactions with concrete and CO_2

- Liquid lithium interactions with concrete:
  - Above 100 C, water vapor is released and reacts with Li
  - Chemically bound water is continuously released over 200 - 800 C
  - Above 800 C Li will react with other concrete constituents (in some cases exothermically)

Contact between Li and concrete should be minimized by using liner over concrete, catch pans, and suppression tanks

- Liquid lithium reacts with CO_2:
  - **4Li + 3CO2 $\rightarrow$ 2Li2CO3 + C + 320 kJ/mole Li (@ 500 °C)**

CO_2 should not be used as a cover gas for Li

Liquid Li – water reactions

- Excess Li: **$2Li + H2O \rightarrow Li2O + H2$ + 160 kJ/mole-Li (at 25 °C)**
- Excess H20: **$2Li + 2H2O \rightarrow 2LiOH + H2$ + 200 kJ/mole-Li (at 25 °C)**

Reaction type	**Chemical energy stored (GJ/kg-Li)**	**Total chemical energy (GJ)**	**Potential H_2 release (kg/kg-Li)**	**Total potential H_2 production (kg)**
Excess Li	0.022	11000	0.144	72035
Excess H2O	0.029	14500	0.144	72035

- Using the ITER limit of 10 **kg of H_2**, water spill should be limited to 90 kg (reacting with 70 kg Li), energy release = 1.6 GJ

Water use in the reactor building should be avoided or minimized

Overview of liquid metal reactors

- ↑ **EBR-I** (1951) and ↑ **EBR-II** (1964-94), at Idaho, first experimental breeder. In 1955 EBR-I suffered a partial meltdown due to operator error. It was subsequently repaired for further experiments.
- ↑ **DFR,** *Dounreay Fast Reactor*, 1959-94, Dounreay, Scotland, using a Na-K coolant. PFR (1970) followed and closed down in 1994 as the British government withdrew major financial support for nuclear energy development
- ↓ **Fermi 1,** 1963-72, Monroe, Michigan. World's first commercial liquid-metal-cooled FBR. Shut down in 1966 due to high temperatures caused by blockage of coolant nozzles. Na fire in 1970, ran till 1972 when operating license renewal was denied.
- ↓ **Phenix,** 1973-90, France. Shut down after a bubble of Ar gas was thought to have found its way into the heart of the reactor, causing a sudden drop in energy output. The reactor had previously shut off 3 times for undetected bubble of Ar gas in 1989.
- ↑ **Superphenix,** 1984-97, France. A capsule containing 2 GBq of Kr-79 broke during experiments in 1990. The radiation release was 200,000 Bq/m3 and remained inside the plant. The plant was temporarily closed due to a Na leak of ~10 to 30 litres in the second cooling circuit. Also in trouble with corrosion product contamination in the primary sodium coolant. Closure in 1997 due to cost issues.

Overview of liquid metal reactors (cont.)

- **Fast reactors from Soviet Union:** BN-350 produced 130 MWe plus 80,000 metric tons of fresh water per day. BN-600 commenced operation in 1980 and produced 600 MWe. Plans for larger plants were cancelled by the breakup of the Soviet Union. The BN-600 is still operational. A second reactor (BN-800) is scheduled to be constructed before 2015.

- **MONJU**, 1994-?, Japan. Leak of 640 kg of non-radioactive Na from the secondary occurred on 8 December 1995. The Na fire caused damage to a ventilation duct and an access walkway grating. The reactor was shut down manually and remains in the shut-down state pending a review of safety and possible plant improvements. No injuries or exposure to radiation occurred. There was no effect on the environment. The accident has classified as Category 1 on the international scale of 0 to 7 by a committee of independent specialists.

- **FFTF,** 1982-92, Hanford, Washington. 980 m^3 (950 ton) Na. Shutdown due to non-proliferation efforts. Shutdown activities prepared worst case accident analysis: leak of 265 m^3 of molten Na at 177 C. Entire inventory burns releasing NaOH aerosol. Even the facility is expected to remain intact, assumed 35% release of NaOH. Onsite dose 2.5 e-4 rem, offsite 3.9 e-4 rem.Toxicological consequences are worse: onsite 166 mg/m3 and offsite 0.05 mg/m3. (ERPG-1 = 2 mg/m3, ERPG-2 = 40 mg/m3, ERPG-3 = 100 mg/m3).

- **IFR,** (1983-94), ANL. Breakthrough in passive safety. Safety tests were carried out at EBR-II in 1986. Cancelled in 1994 due to non-proliferation efforts

Overview of other Li systems

- **FMIT:** Pioneering work for IFMIF. Cancelled in 1983 with little surviving documentation.

- **IFMIF:** Li hazards recognized as one of the major safety problems. IFMIF loop contains 21 m^3 Li. FMEA approach has identified 2 major hazards:

  radioactive material in Li loop (T and Be-7): should be removed by trapping

  risk related to Li loop operation: vacuum environment with Ar flushing

- **LPTL:** Lithium processing test loop, ANL. Started operations in 1978, for fusion blanket development work. Contains 0.2 m^3 Li. In 1979, leak spilled 0.076 m^3 (40 kg) on metal-lined concrete cell floor. Fire developed immediately.
  - Failure of EM pump channel (SS316) was due to high stress combined with local corrosion
  - Accident complicated by failure of DPD on reservoir tank (plastic faced pressure differential gauge melted, forcing Li upwards towards leak)
  - Large airborne release to contiguous areas could have been reduced if LPTL cell was more tightly sealed and used graphite microspheres in stead of powder as fire suppressant
  - Additional investigation is recommended in trapping of corrosion products in high magnetic field regions of EM pumps

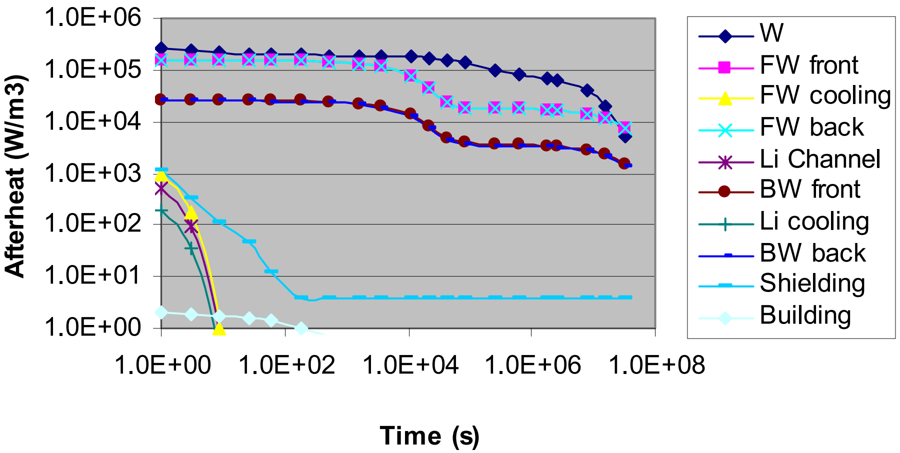
Overview of past fusion concepts using Li

- UWMAK-I (1974), UWMAK-III (1976), BCSS (1983), HYLIFE-I (1985), ESECOM– VLi TOK (1989), ARIES-RS (1996)
- Typical materials are PCA austenitic steel, Ferritic steel, V alloy
- Li inventory: from 870 tonnes in HYLIFE-I to 270 in ARIES-RS
- T inventory: from 1 kg in HYLIFE-I (molten salt extraction) to 100 g in ARIES-RS (cold trapping with added protium)
- Common safety features:
  - Multiple containment to liquid breeder release
  - Segmented inventory
  - Inert gas
  - Steel liner over concrete
  - Minimized use of water or no water at all
  - High heat capacity materials (i.e. steel balls) to cool down spill (also hollow graphite microspheres that float on surface to prevent contact with air)

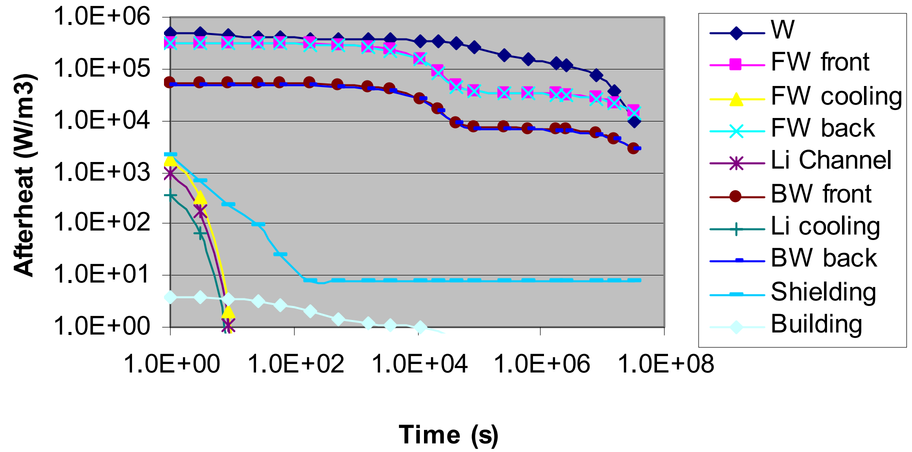
Preliminary safety assessment for HAPL chamber

- Neutron transport and activation calculations for Li blanket in 10.5 m radius chamber (input from M. Sawan)
- 2 scenarios considered: operation at 5 Hz (FW lifetime = 10 yrs) and 10 Hz (FW lifetime = 5 yrs)

Case of 5 Hz, NWL = 1 MW/m^2



Case of 10 Hz, NWL = 2 MW/m^2

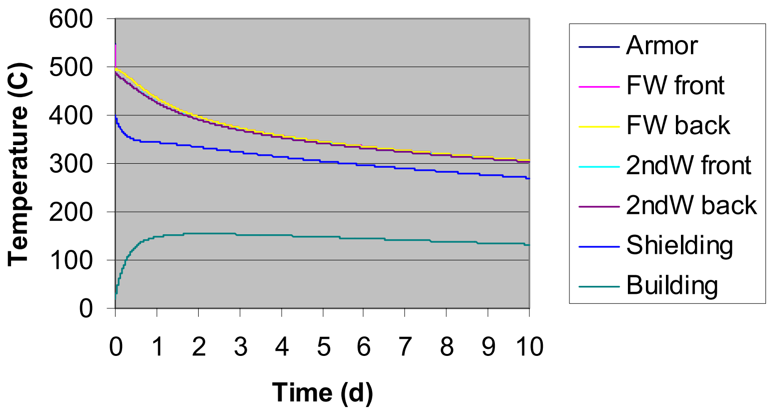


- The FW afterheat in the case of 10 Hz increases by a factor of ~2
- WDR is equivalent in both cases, and WDR < 0.2 for W armor and FS blanket structures

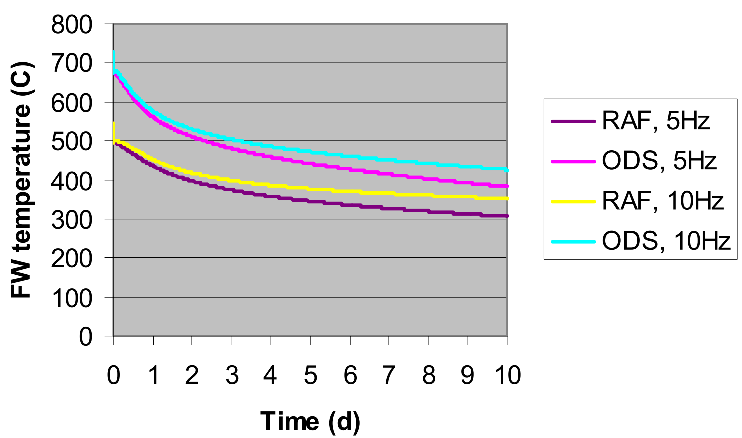
Loss of flow accident and decay heat removal

- We have used the heat transfer code CHEMCON to simulate a loss of flow accident and assess dissipation of afterheat during the accident

Baseline design: RAF at 545 C, 5 Hz



FW temperature evolution: baseline vs enhanced design, at 5 and 10 Hz



- Decay heat rapidly transfers through radiation to cooler structures (confinement building)
- In case of enhanced design (with ODS steel) the starting temperatures are higher but same trend can be observed
- In case of 10 Hz operation, increased afterheat results in slower transfer, but also decreases gradually due to radiation

Themal-hydraulics assessment of Li fires

- INL experts modified MELCOR code to predict the consequences of lithium spill accidents
  - introduced EOS for Li, new subroutine computes the critical mass flow
  - reaction rate assumption adopted for this model is similar to that adopted for the LINT code (thermal equilibrium)

- Lithium-air reaction tests at the HEDL used to benchmark new MELCOR capability gave good agreement (B.J. Merrill : *Fusion Engineering and Design* 54 (2001) 485–493)

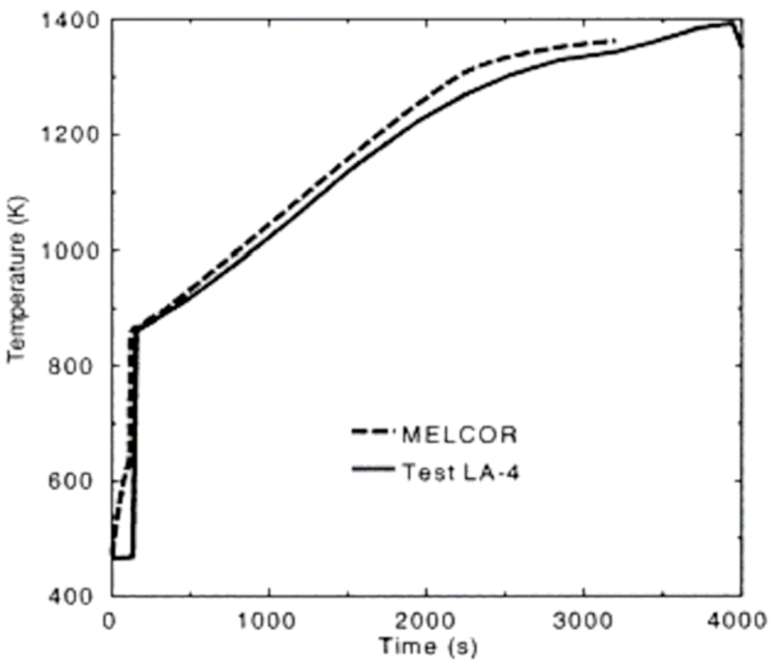
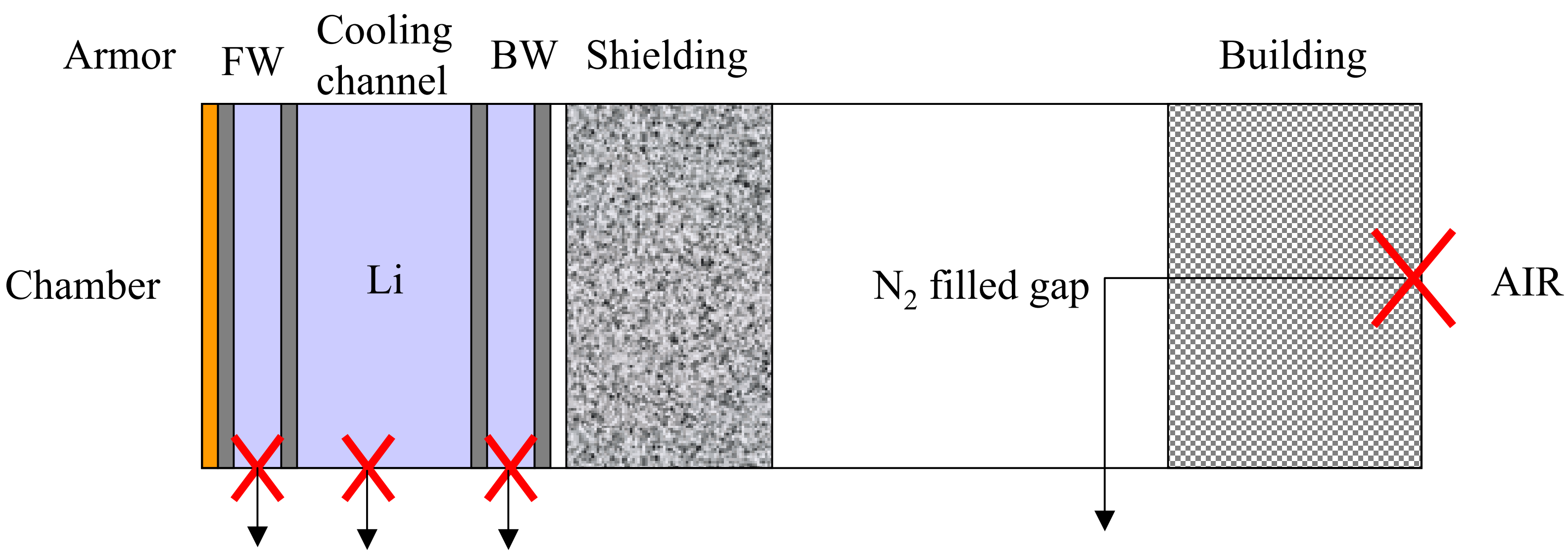


Fig. 2. Comparison of MELCOR predicted pool temperature with data from test LA-4.

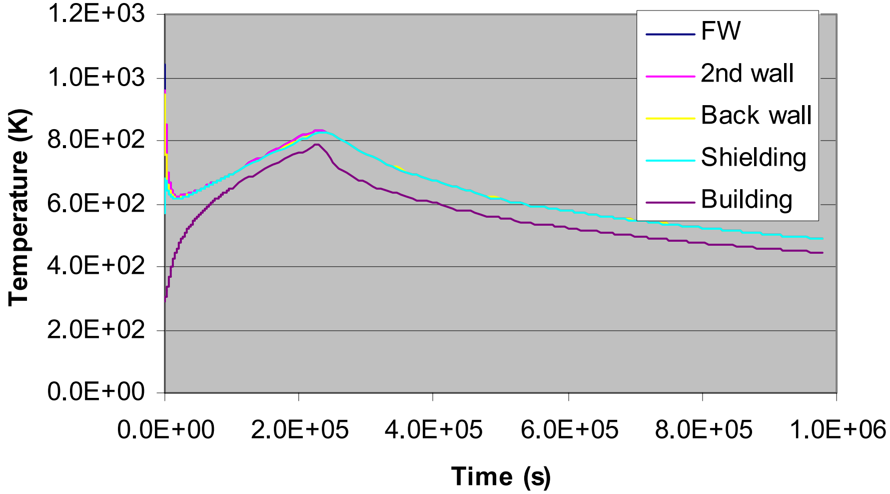
MELCOR model for assessment of Li fires

		r in (cm)	r out (cm)	thickness (cm)	vol (m3)
armor		1050	1050.1	0.1	1.39
FW front		1050.1	1050.45	0.35	4.85
FW cooling channel		1050.45	1050.75	0.3	4.16
FW back		1050.75	1050.95	0.2	2.78
Inner Li Channel		1050.95	1109.15	58.2	853.35
BW front		1109.15	1109.35	0.2	3.09
BW cooling channel		1109.35	1109.65	0.3	4.64
BW back		1109.65	1110	0.35	5.42
gap		1110	1113	3	46.57
Shielding		1113	1163	50	813.83
Building		2000	2100	100	5282.06

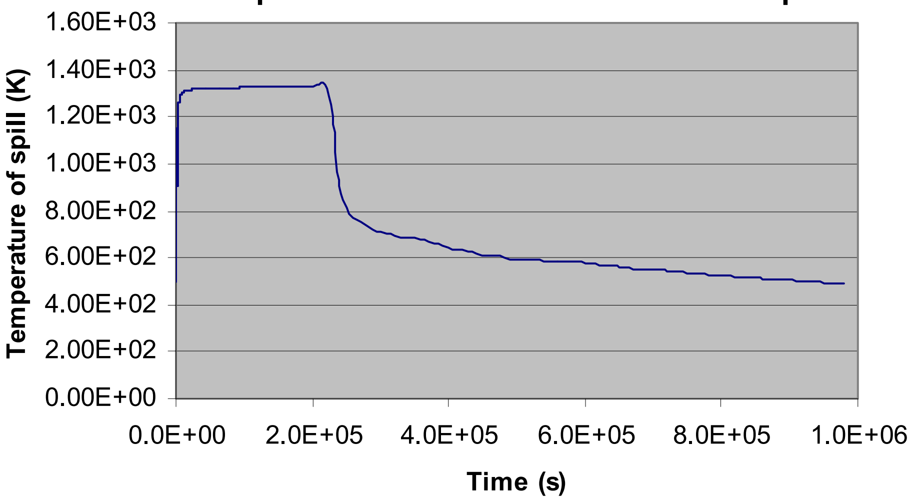


Results from ex-vessel Li spill and air ingress simulation

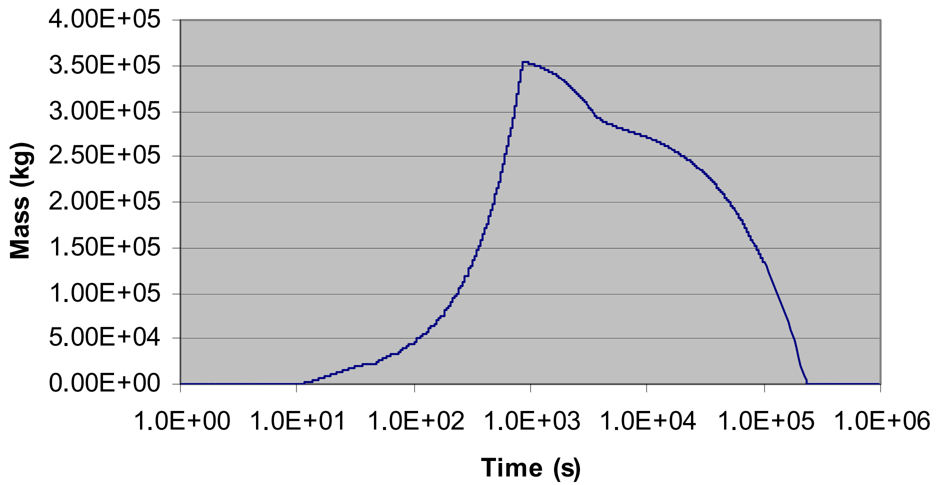
Temperature evolution during Li fire



Temperature evolution of Li spill



Mass of Li spill in confinement building



Tritium release

- In case of Li fire, tritium inventory in coolant is mobilized and available for release to the atmosphere
- Need to minimize tritium inventory in Li, possible approaches may include:
  - gas recovery, getters, cold trap, molten salt, permeation
- In case of elevated release and conservative weather conditions, a release of 200 g of tritium is enough to reach the 1 rem limit for no-evacuation
- The dose would be x10 larger in case of ground release, and 10x smaller if typical weather conditions were assumed in stead

Conclusions

- The use of lithium as both the breeder and coolant can simplify the design which may result in higher reliability
- However, careful design must be utilized to decrease the risk from a lithium spill:
  - Cover gas should be used with Li (Ar, He)
  - Water use should be avoided or minimized
  - All concrete that could come in contact with spilled lithium must be lined to avoid lithium-concrete reactions
  - Li inventory should be low pressure and segmented
  - Multiple containment to liquid breeder release (dump tanks)
  - High heat capacity materials (i.e. steel balls) to cool down spill
  - T inventory in coolant should be kept as low as possible to avoid radioactivity release in case of Li spill