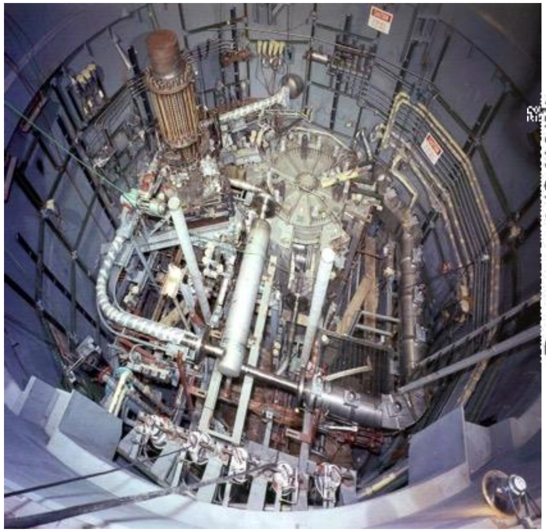
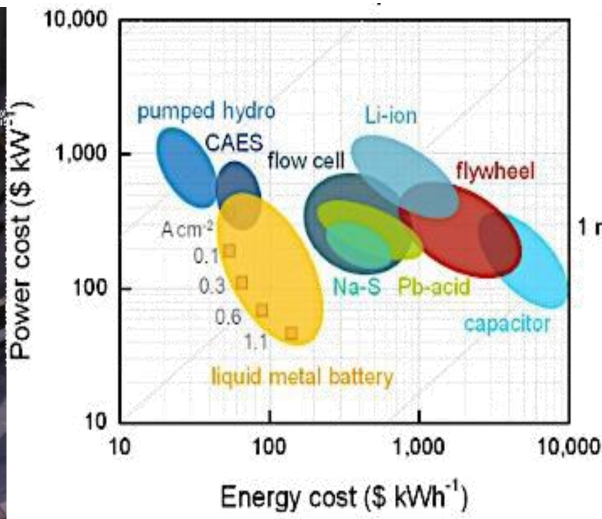
High-temperature molten salt is a central challenge to three promising green energy technologies:

Crescent Dunes CSP power plant, Tonopah, Nevada



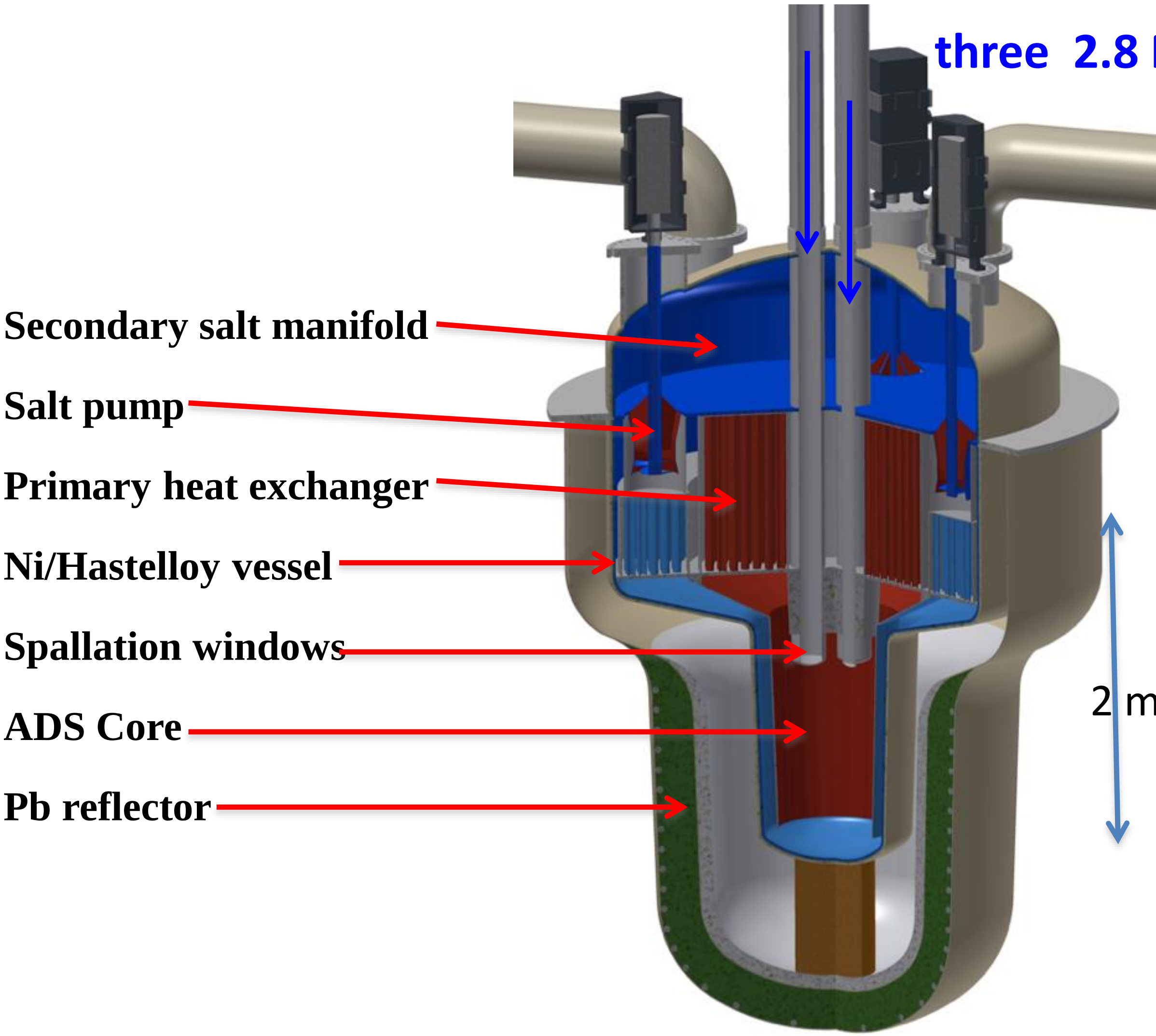
Molten Salt Reactor Experiment (MSRE) at ORNL.



Both technologies require molten salt heat transfer at ~800 C.
Both technologies face major challenges for reliability and cost from the materials challenges at 800 C: strength, corrosion, radiation damage.
We have patent-applied-for technology that addresses those challenges.

290 MW ADAM Core

three 2.8 MW proton drive beams



Molten salt fuel:

70 NaCl – 15 $TRUCl_3$ – 13 UCl_3

Fast fraction 20% E_n>1 MeV

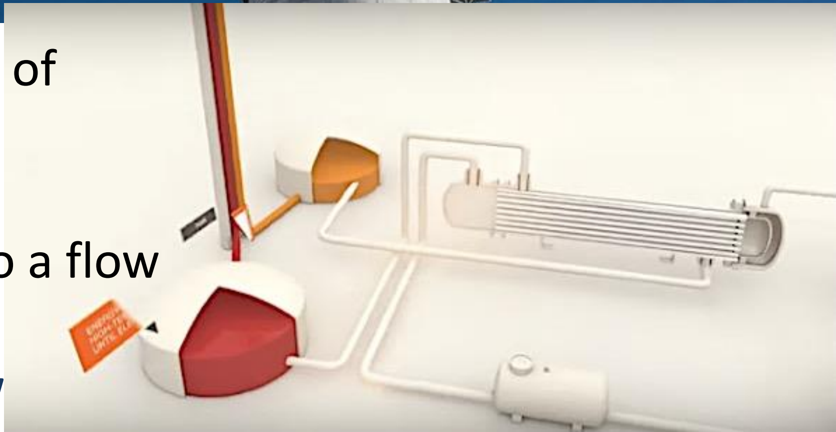
All fuel salt in one vessel

575 –675 C operating temp

First wall problem: vessel wall sees n damage, high-temp, salt corrosion, hydrostatic pressure. It must be a safe barrier!

High-Temperature Molten Salt is required for cost-effective green energy:

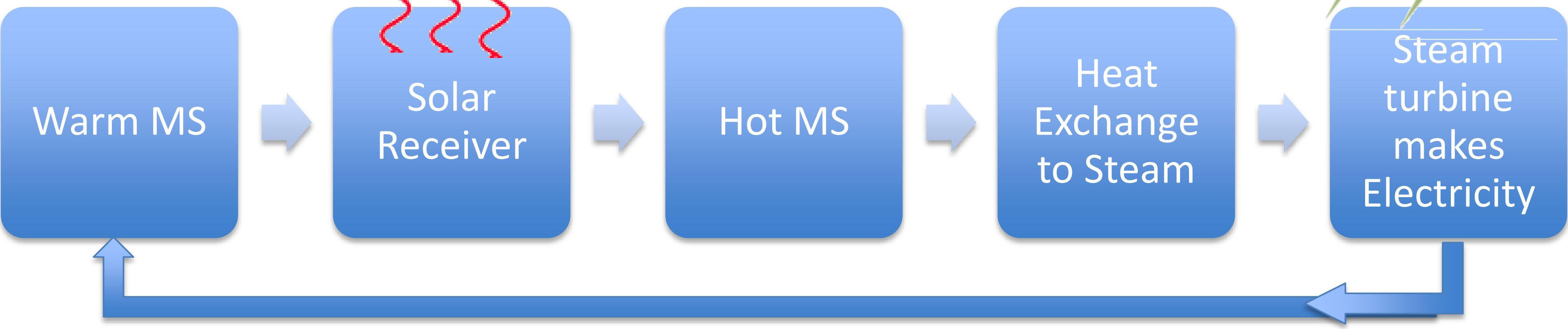
Crescent Dunes CSP power plant, Tonopah, Nevada

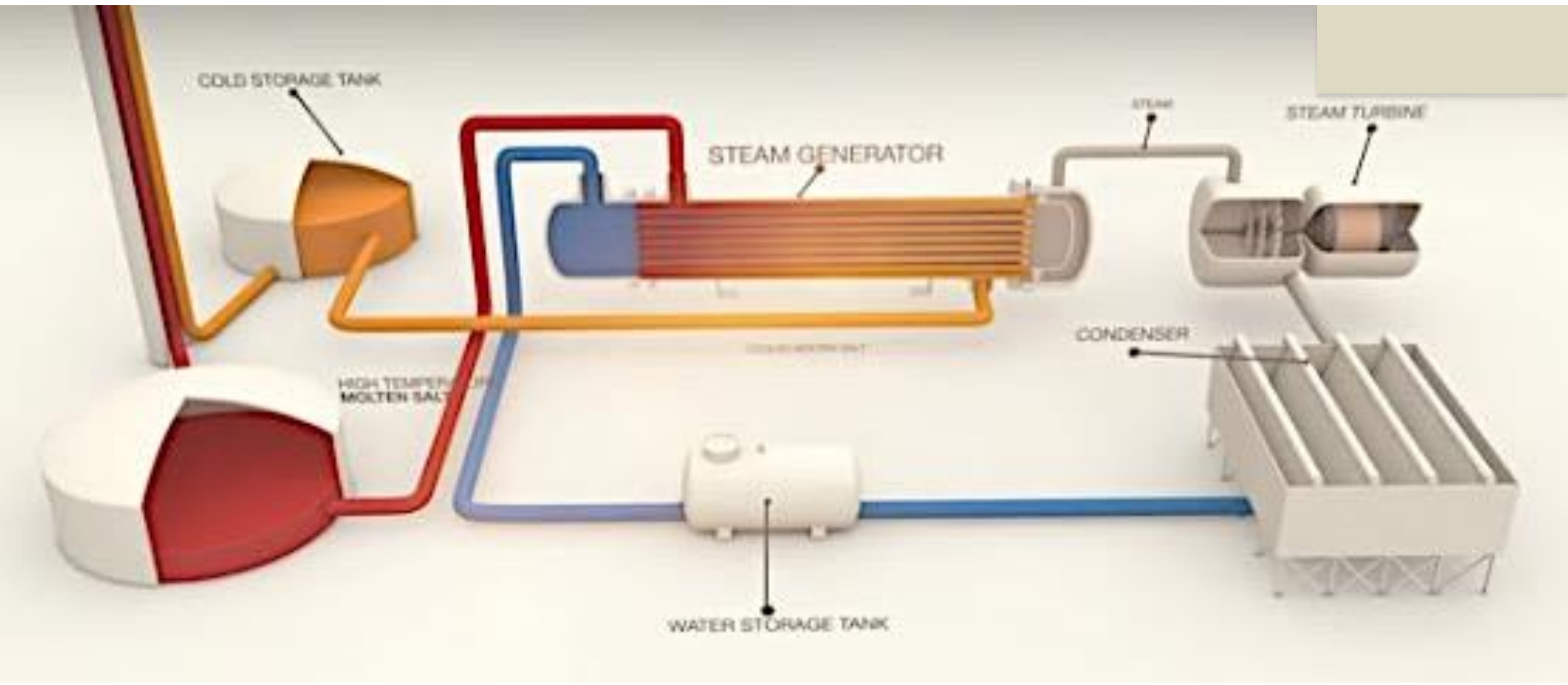


Sunlight is collected from a one square kilometer of land, and concentrated by mirrors to a ‘tower of power’.
There it is absorbed and the heat is transferred to a flow of molten salt.

$(1000\ W/m^2)(1000\ m)^2 = 1000\ MW$

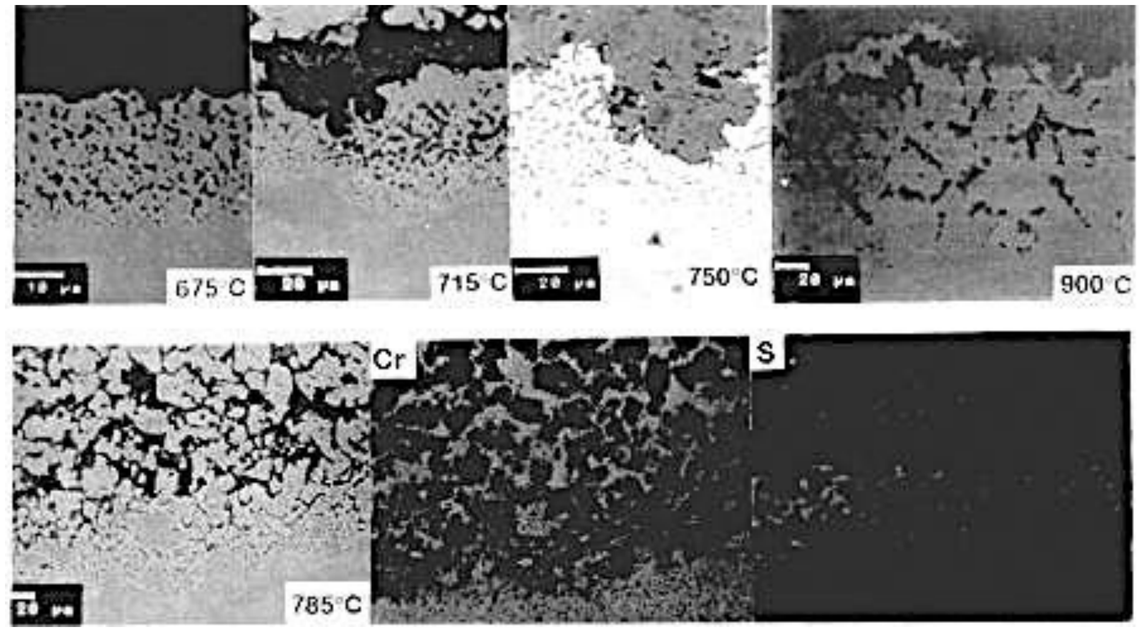
Concentrated Solar Power





How to contain hot molten salt in vessels?

G30 alloy:
35Ni19Cr:



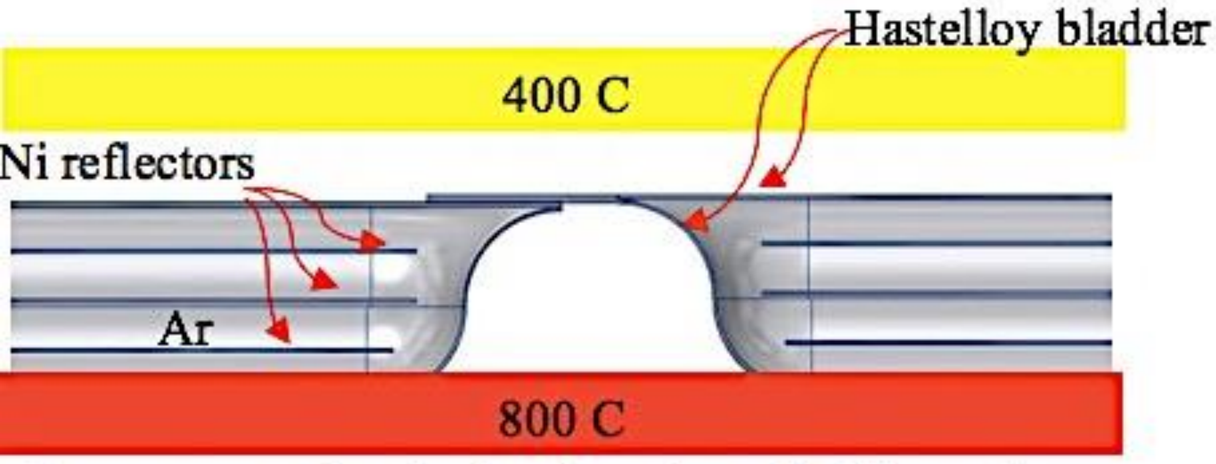
Steels can are stable in contact with molten salt up to ~550 C.
But at higher temperatures they corrode severely.
Only high-nickel alloys are stable with molten salt at 800 C, and they are very expensive: $20/kg

Carnot Efficiency of a heat engine: $$\epsilon = \frac{T_{hot} - T_{cold}}{T_{hot}}$$

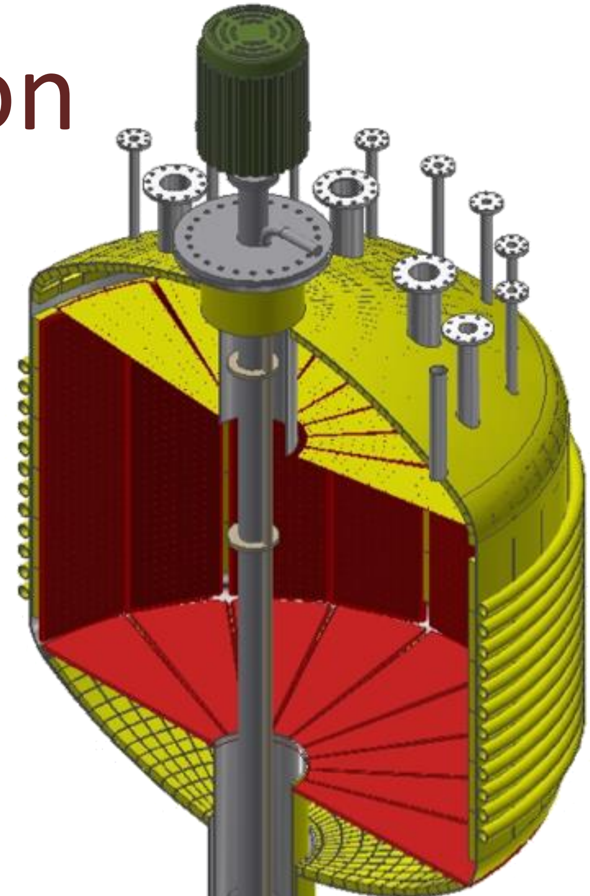
T_{cold} = 200 C = 470 K; T_{hot} = 550 C = 820K ε =43%

T_{hot} = 800 C = 1070K ε =56%

Hermetic Bladder Insulation



Cross-section detail of radiant heat shield panels.



Problem: only Hastelloy N can contain molten salt at 800 C without corrosion, but it is expensive.

Solution: line the vessels and piping with hermetic insulating bladders: a hermetic blanket containing multi-layers of shiny Ni foils that reflect heat so vessel walls operate at 400 C while molten salt is at 800 C with very little heat loss.

Patent applied for – Texas A&M University

Aggie technology: Hermetic Insulating Bladder

Steel pipe contains warm MS at 500 C

Patent applied for – Texas A&M University

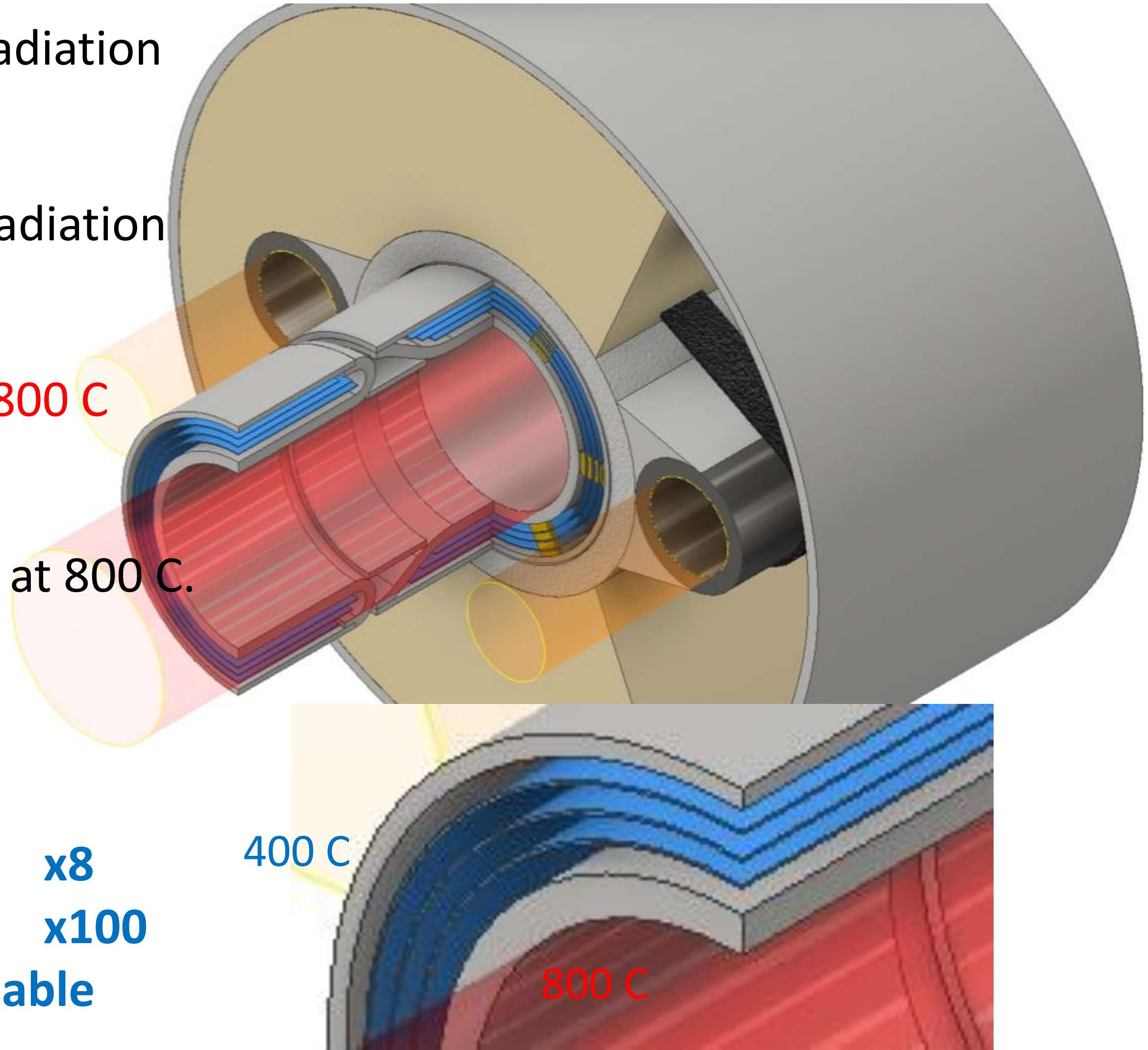
Multi-layer shield contains heat radiation from hot salt inside.

Three Ni foil shields reflect heat radiation to block heat transfer.

Temperature gradient 400 C ➡ 800 C with very small heat transfer.

Hastelloy N tube contains hot MS at 800 C.

Steel vessel thickness:	1”
Hastelloy N thickness:	1/8”



Reduce expensive material x8
Reduce heat loss from hot salt x100
Make molten salt @ 800 C affordable

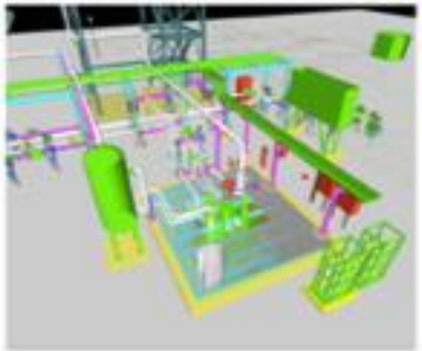
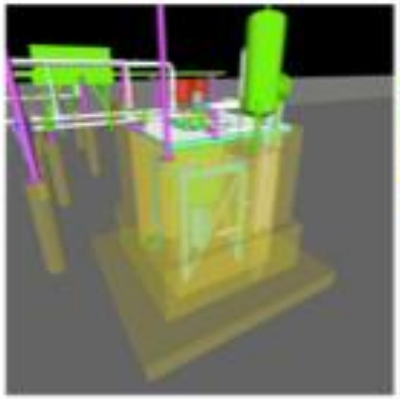
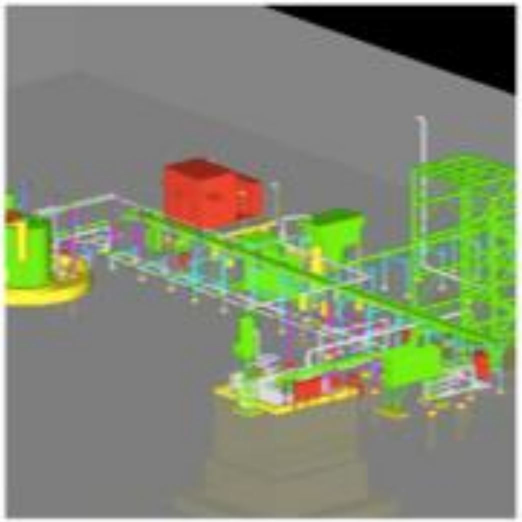
Developing high-temp ionic salts for CSP requires a capability to simulate near-full-scale flow up to 1000 C

- There is no present facility that can support flow of high-temperature ionic salts in industrial scale for process development of heat transfer/storage.
- There is no base for testing and certification of critical components – pumps, HX, valves, sensors.
- Shell has committed to donate its molten salt flow loop to Texas A&M. We will add a high-temp ionic salt secondary loop, to make a test bed for molten salt technology development.

Shell has committed to donate its large-scale $5M molten salt flow loop to Texas A&M University




<u>Primary loop</u>: 600 C molecular salt
<u>Secondary loop</u>: 600-1000 C ionic salt

Even a simple experiment in high-temp molten salt requires a long time for prep

- Ionic salts are hygroscopic, so starting salt mixture contains water. Water dramatically enhances corrosion in high-temp ionic salt.
- It is time-consuming to remove all water from molten ionic salt. If we have to de-water MS for each experiment, the prep time dominates the entire process.
- Texas A&M is developing a modular system in which MS is prepared and de-watered in a large reservoir vessel, then transferred to multiple experimental vessels.
- Transfer is done using a novel vacuum-jacketed transfer line, so transfer is safe and hermetic.
- The inventory of de-watered MS can be re-used for multiple experiments.

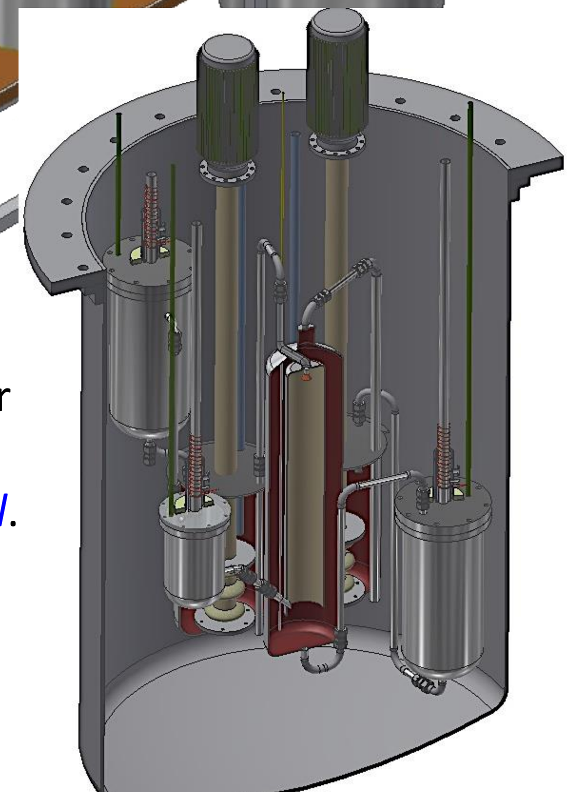
Texas A&M group is developing modular molten salt test system with safe hermetic transfer for rapid prototype testing

Testing of molten salt properties flowing in pumps, heat exchangers, valves requires a method for safe hermetic transfer from a reservoir vessel to an experimental vessel and back again.

Patent applied for – Texas A&M University

The Texas A&M group is developing a modular molten salt system for rapid prototype testing:

- Solid salts are mixed, melted, and de-watered in a *reservoir vessel*.
- MS is hermetically transferred to *multiple experimental vessels* using a vacuum-jacketed transfer line. Multiple experiments can be conducted in parallel.
- As each experiment is completed, MS can be transferred back to the reservoir and re-used in future tests.



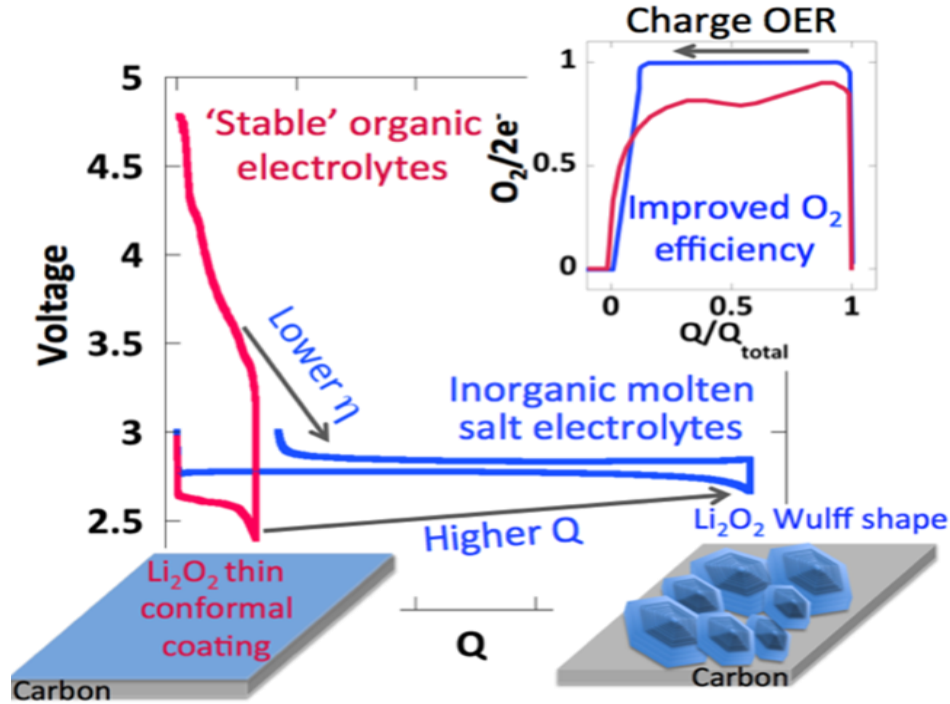
flow loop vessel

Hermetic Bladders would benefit Molten Salt Lithium–Oxygen Batteries

A Despite the promise of extremely high capacity: $2Li + O_2 \leftrightarrow Li_2O_2$, 1675 mAh/g$O_2$, many challenges currently impede development of Li/O_2 battery technology

Finding suitable electrode and electrolyte materials remains the most elusive challenge to date.

A radical new approach is to replace volatile, unstable and air-intolerant organic electrolytes with alkali metal nitrate molten salt electrolytes and operate the battery above the liquidus temperature (>80 ° C)



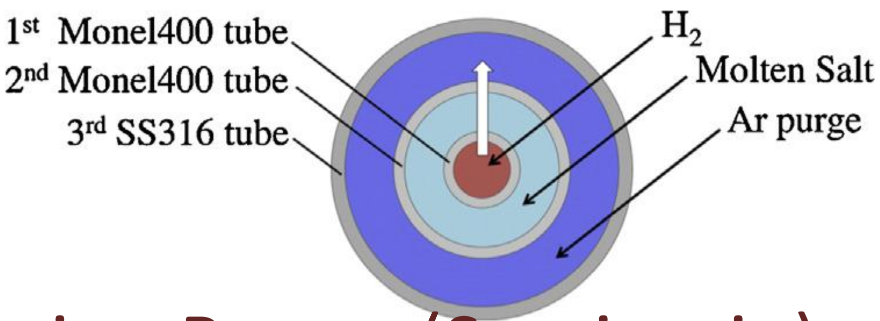
Intermediate temperature Li/O_2 battery using a lithium anode, a molten nitrate-based electrolyte ($LiNO_3$–KNO_3 eutectic) and a porous carbon O_2 cathode (energy efficiency, ~95% and improved rate capability)

Li_2O_2 electrochemically forms and decomposes upon cycling with discharge/charge over-potentials as low as 50 mV, showing that the cycle life of such batteries is limited only by carbon reactivity and by the uncontrolled precipitation of Li_2O_2.

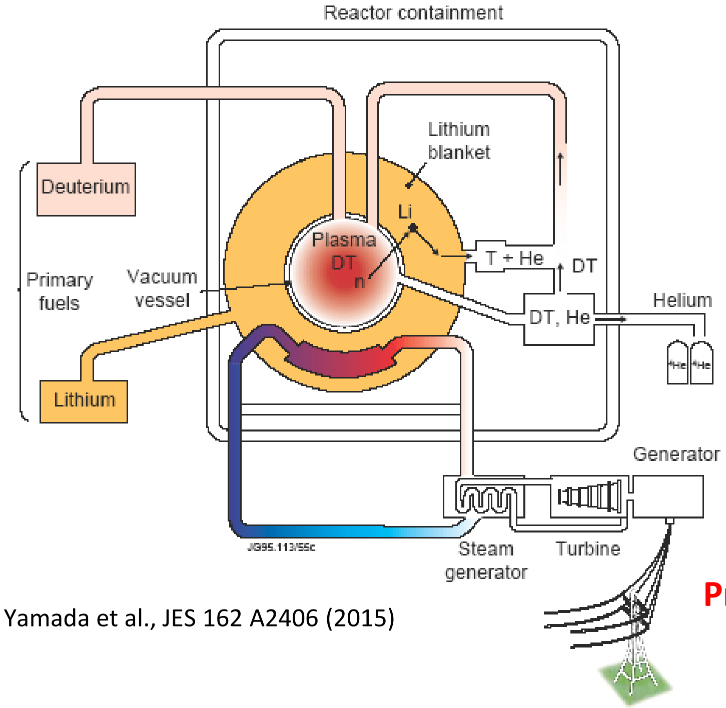
Presented by J. Seminario & P. Balbuena

Flinabe fluoride molten salts forblanket candidates

Fluoride molten salt Flibe (2LiF + BeF2) is a promising candidate for the liquid blanket of a nuclear fusion reactor, because of its large advantages of tritium breeding ratio and heat-transfer fluid.

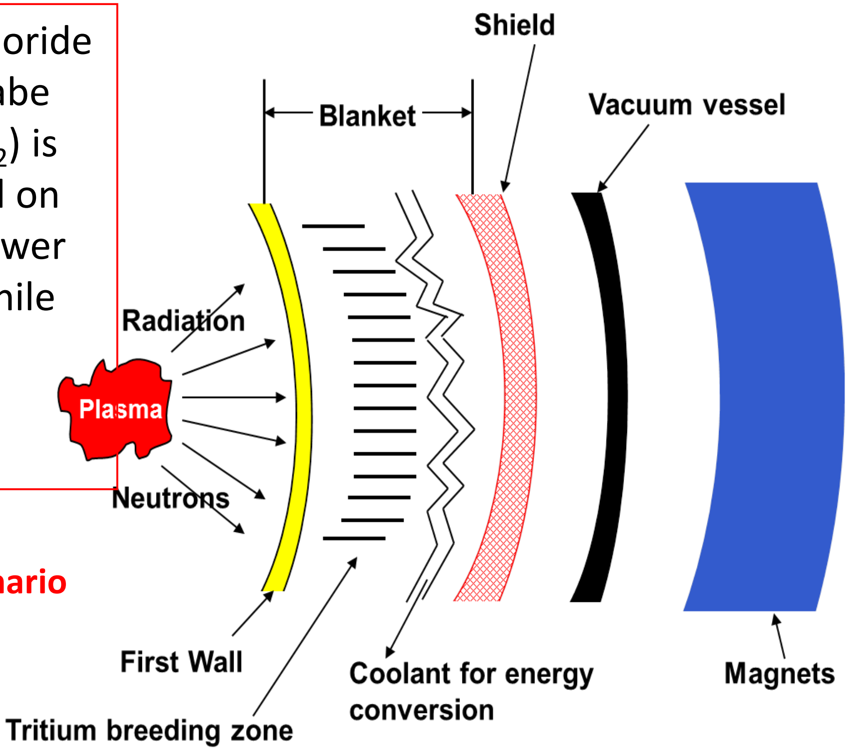


Example: Molten Salt in Fusion Power (Seminario)



Yamada et al., JES 162 A2406 (2015)

Another new fluoride molten salt Flinabe ($LiF + NaF + BeF_2$) is recently focused on because of its lower melting point while holding proper breeding properties.



Presented by J. Seminario

But its melting point is higher than other liquid candidates,

Texas A&M has a multi-discipline team for core technology and energy applications

- *Dan Barth* – 30 years experience with molten salt, widely consulted by industry
- *Peter McIntyre* – modular hermetic MS technology
- *Debiyoti Banerjee*– nanoparticle additives to MS to control critical properties – corrosion, viscosity, heat capacity
- *Yassin Hassan, Pavel Tsvetkov* – molten salt fission cores
- *Sam Mannan* – industrial safety, process design
- *Partha Mukherjee, Jorge Seminario, Perla Balbuena* – lithium-metal batteries, molten salt batteries
- *Abe Clearfield –* ceramics, corrosion, physical chemistry

Industries that use Molten Salt

- Concentrated solar power for electric generation.
- Concentrated solar power for desalinization.
- Chemical manufacturing (Dow),
- Enhanced oil recovery systems and oil refinery operations (Shell)
- Heat treating of metals, glasses and waste heat recovery system.
- High-Temperature processes in glass manufacturing, steel and Ti production (TiMet).
- Manufacture of ammonia-urea, ammonium nitrates, melamine, caustic soda.
- Extraction of high-value metals from ore
- Polymer production.
- Pharmaceutical manufacturing,

Molten salt technology to benefit mining industry

June 21 2016

A collaborative research funding partnership between the University of South Australia, the South Australian and Western Australian governments and Centrex Metals Limited is funding cutting edge molten salt technology that will significantly reduce energy and water usage, and therefore the cost of mineral processing using molten salts.

The research, based around the Oxley Potassium Project and undertaken by UniSA's School of Engineering and Future Industries Institute, will expand current molten salt research for solar energy applications into minerals processing and further strengthen engagement between the research sector and industry with a view to maximising successful technology development and commercialisation.

Safety, Security, Aesthetics

- Molten salt cannot burn or explode.
- Molten salt has very low vapor pressure, even @1000 C
- The vessel and piping operate at slightly positive pressure in order to force flow. But there is no standing head pressure, max pressure in any component ~40 psi.
- The vessel and piping are located in sub-grade open vaults. Any leak of molten salt would fall into the trough, freeze solid, and we would have to chip it out.
- There is no failure-mode scenario that could create a hazard to personnel at neighboring facilities.