Development of a Packed Bed thermal Energy Storage Prototype with Sodium as the Heat Transfer Fluid

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ASTRI
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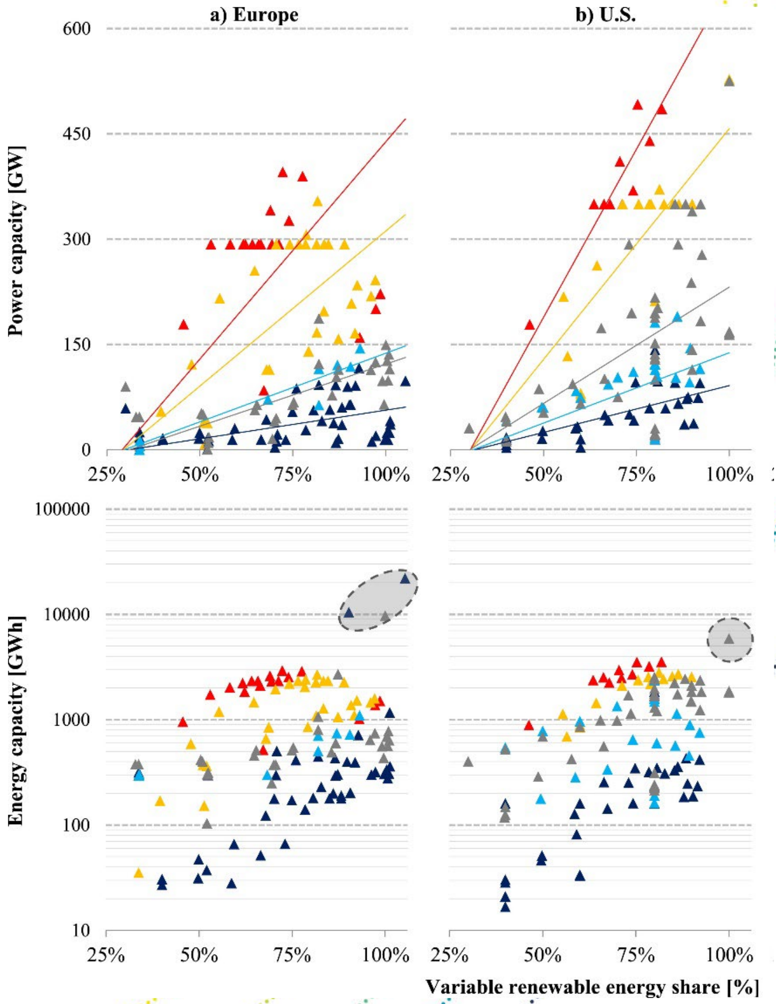
Overview

- Motivation
- Options for sodium-based thermal storage
- Introduction to the packed bed storage concept
- Choice of Material
- Performance Modelling (CFD, system modelling, TEA)
- Prototype testing
- Conclusions

Motivation

- Thermal storage technologies have the benefit of low cost per unit of stored energy compared to electrochemical batteries
- Thermal storage is considerably more compact the electrochemical storage.
- Longer duration storage is likely to become more needed in future electricity grids
- Selection of an appropriate thermal storage technology depends on the application
  - ➢ Temperature at which heat is required is a key factor



Impact of power mixes on the requirement of EES power capacity [GW] and energy capacity [GWh] based on studies in Europe and the USA

Source: Cebulla, J. Cleaner Production, 181.

Why sodium?

- Sodium is an attractive heat transfer fluid for several reasons:
  - ➢ Liquid phase over a large temperature range (98–881°C)
  - ➢ Outstanding thermal conductivity (64.2 $Wm^{-1}K^{-1}$ at 700°C)
  - ➢ Extensive experience at scale, via the nuclear industry
- For CSP, sodium benefits solar receiver performance and is an enabler of plant modularity
- It could allow heat transport into the core of industrial processes
- **However** for energy storage there are certain drawbacks of sodium
  - ➢ Moderate specific heat capacity (1.26 $kJkg^{-1}K^{-1}$ at 700°C)
  - ➢ Higher cost than alternative bulk storage materials (~$3 USD/kg)
  - ➢ It is a flammable material, hence minimising inventory is preferable
- Sodium is best used in concert with other storage mediums

Photos: MSSA.

Molten salt storage with sodium HTF

Sodium can be coupled to molten salt storage

- Nitrate salt, ~ 565 °C, e.g. Vast Solar
- Chloride salt, ~ 700 °C, e.g. Gen3 Liquids, TerraPower
- Incorporates a sodium-salt heat exchanger

Pros and cons

☑ The configuration is as close as is possible to conventional CSP plants, which are deployed at scale

☑ The Gen3 Liquids Pathway project found this configuration has promising LCOE of 58.4 USD/MWh$_e$ (Turchi, 2021)

☒ There is added complexity and cost in managing two different fluids (pumps, purification systems, etc.)

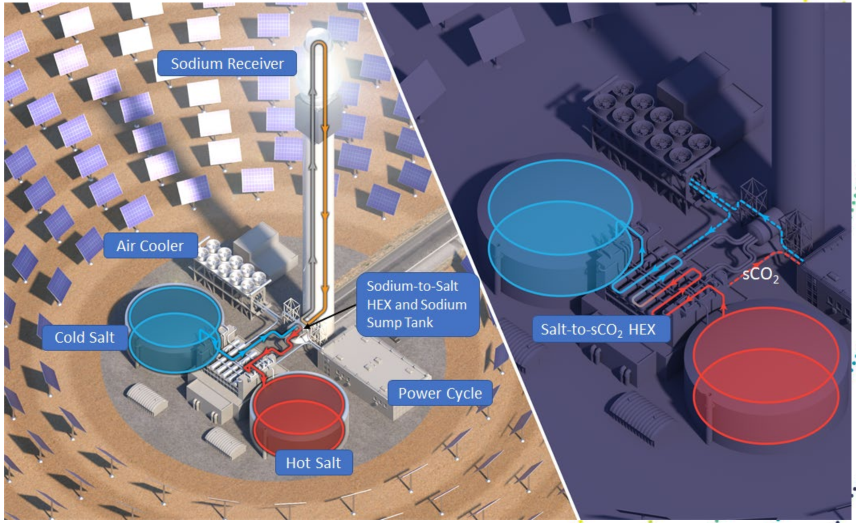


Image: NREL

Other storage options with sodium

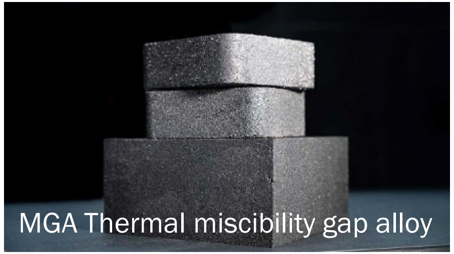
- Several alternative sodium-compatible thermal storage options are being developed/commercialised
- Sensible energy storage in solid material e.g. graphite (Graphite Energy)
- Latent energy storage in phase change materials e.g. carbonate & chloride salts (UniSA), Al & Al-Si (Azelio)
- Combined sensible/latent energy storage, i.e. a PCM embedded in a solid matrix material, e.g. Al in graphite (MGA Thermal)

Pros and cons

☑ Lower complexity, potentially lower cost

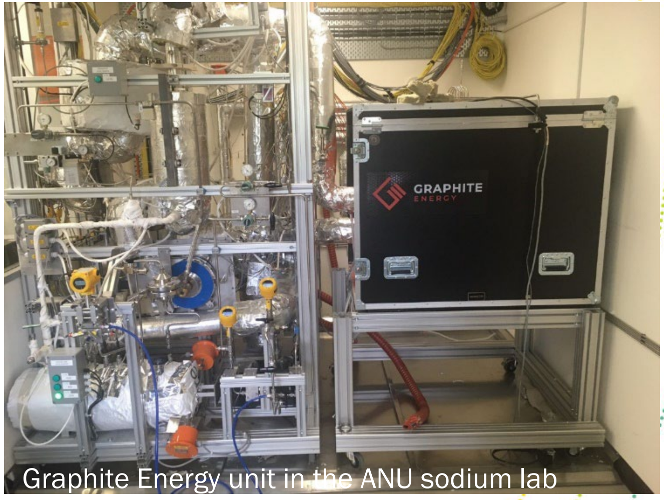
☒ Lower maturity and commercial readiness

Images: MGA Thermal



MGA Thermal miscibility gap alloy

Images: ANU



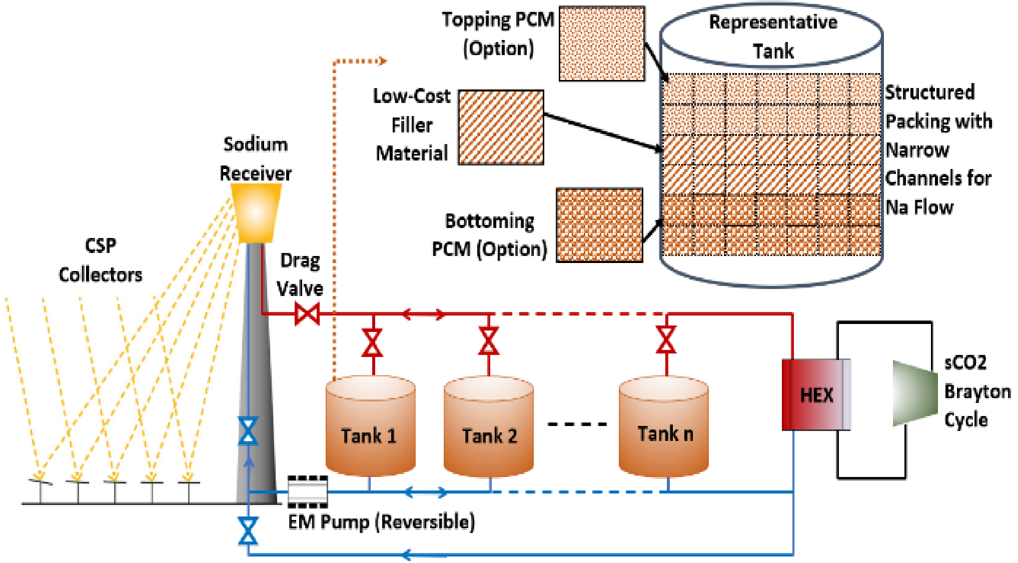
Graphite Energy unit in the ANU sodium lab

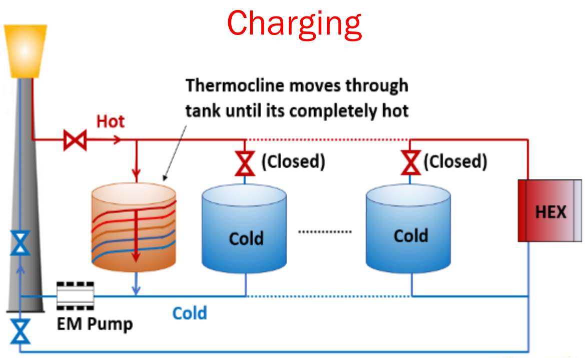
Images: Azelio

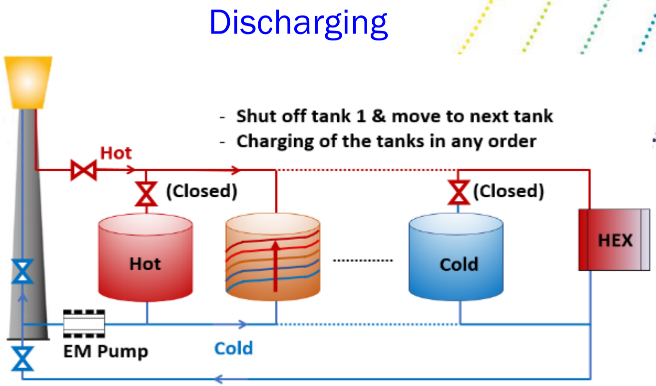
Azelio PCM storage unit with aluminium and sodium

Packed bed thermal energy storage concept

- Sodium is in direct contact with a solid material in what is known as a packed bed thermocline.







Other work on packed bed thermoclines

- Packed bed thermocline storage systems are most frequently studied in a configuration with natural rock beds and air (e.g. Allen et al. 2014; Fricker 1991)
- Other material combinations have been tested, such as solar salt and ceramic materials like quartzite, silica and basalt (e.g. Pacheco et al. 2002; Klasing et al. 2020).
- Direct contact between sodium and solid materials has been proposed previously (Niedermeier et al. 2018)
- Tightly packed bed storage concepts have been tested in air-ceramic storage systems, such as at the Jülich Solar Power Tower (Zunft et al. 2011).
- Nested hexagonal structures (cast iron clad with stainless steel) have been suggested in combination with sodium (Forsberg 2021).

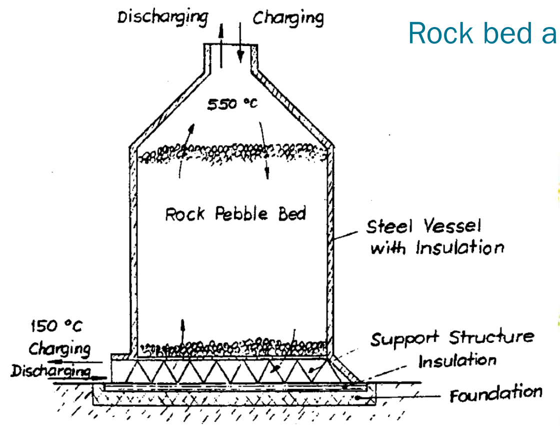


Diagram: Fricker 1991

Rock bed and air

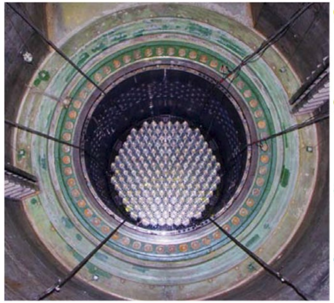
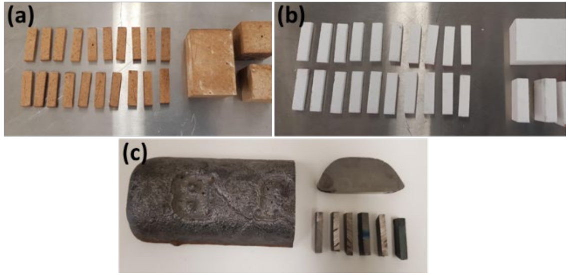


Diagram: Forsberg

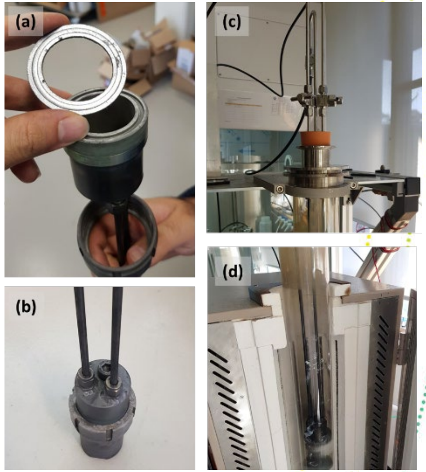
Hexagonal fuel rods in sodium in a Russian light water reactor

Choice of material

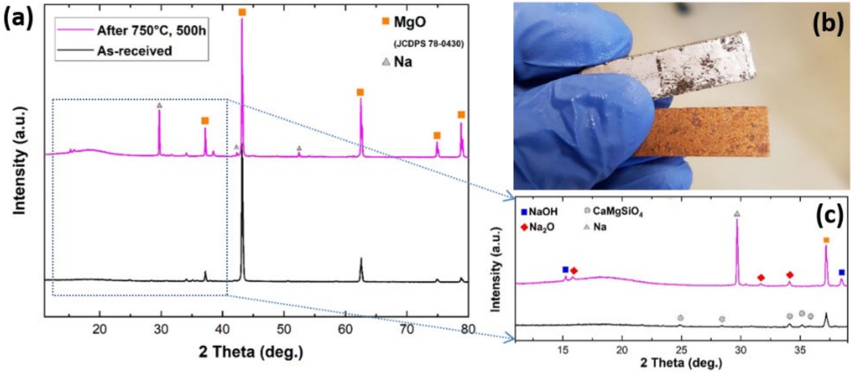
- Magnesia (MgO) was down selected for experimental investigation over several other filler materials of interest (Al_2O_3, pig iron)
- Based on FactSage modelling, MgO was predicted to have good thermodynamic stability in sodium at 750°C
- Samples of ~97% purity commercial grade magnesia bricks were sourced from several different bulk manufacturers
- The remaining ~3% is predominately SiO_2, CaO and Fe_2O_3 based on the manufacturer data sheets.
- Samples were cut from the bricks and immersed in sodium at 750°C for a 500 hour period.
- Although a colour change was observed, x-ray diffraction analysis indicated that the main crystalline phase (MgO) was unchanged



Samples of (a) magnesia, (b) alumina, (c) pig iron



Experimental setup for testing samples in sodium at high temperature.

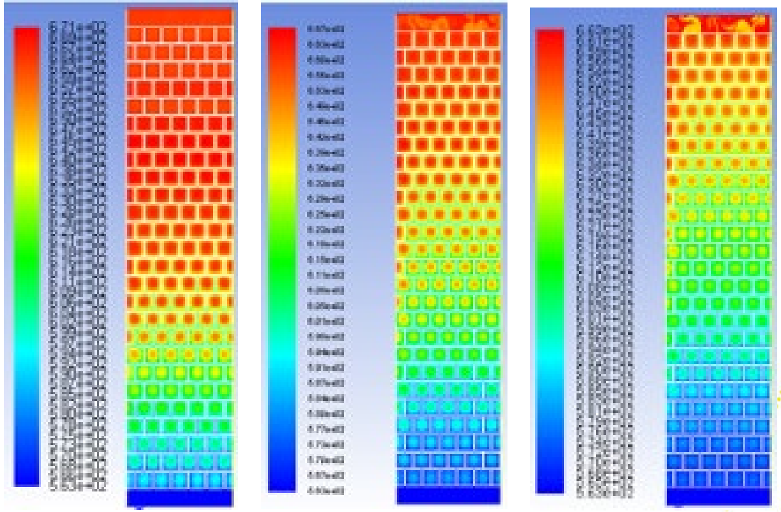


(a) XRD patterns and (b) appearance of the MgO sample from one supplier before and after immersion at 750 °C, (c) enlarged XRD patterns.

CFD modelling

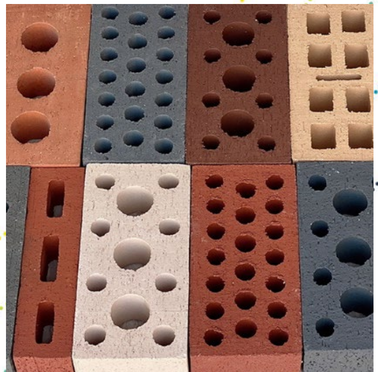
- Computational fluid dynamics (CFD) modelling has examined the effect of brick size and orientation on pressure drop
- Experimental results from testing of a thermocline storage tank using a packed bed of quartzite, silica sand and molten salt, were used for model validation (Pacheco, 2002)
- Significantly lower pressure drop was found for the brick structure than for a randomly packed bed filled with sand and small pebbles, even with very small gaps and a liquid fraction as low as 2%.
- Having smaller bricks significantly improves *thermal utilisation,* hence there is a tradeoff between cost and complexity

$$thermal\ utilisation = \frac{energy\ recovered\ in\ discharge}{maximum\ energy\ that\ could\ be\ extracted}$$



(a) 0.5 h (b) 1 h (c) 1.5 h

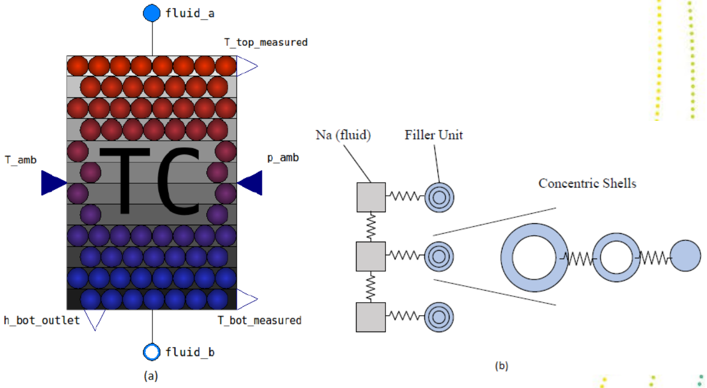
Spatial temperature distribution, changing with time.



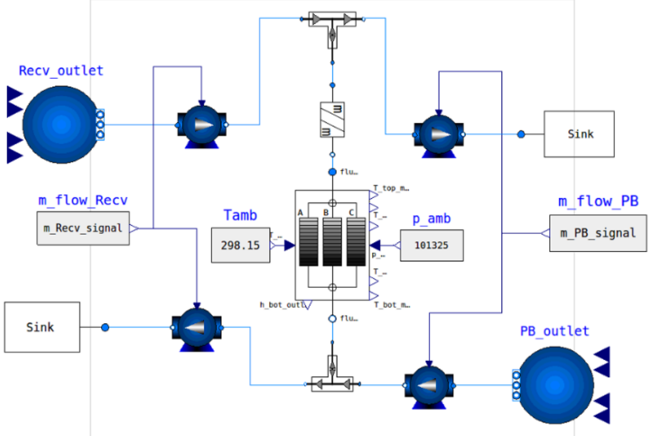
Porous clay bricks

Annual system modelling

- Annual system modelling has been carried out in SolarTherm
- Use of a simplified heat-transfer model that is discretised in 1D in the direction of the fluid flow, and where the filler elements are represented by spheres discretised in 1D radially.
- This model has been used to compare single tank and multi-tank configurations.
- For multi-tank configurations, it was found that the operating strategy is critical to performance.
- For example, when a storage tank nears the end of its discharge phase, it is beneficial to blend in hotter fluid from a second, fully charged tank to boost the overall outlet temperature, and keep the power block in operation for a longer period.



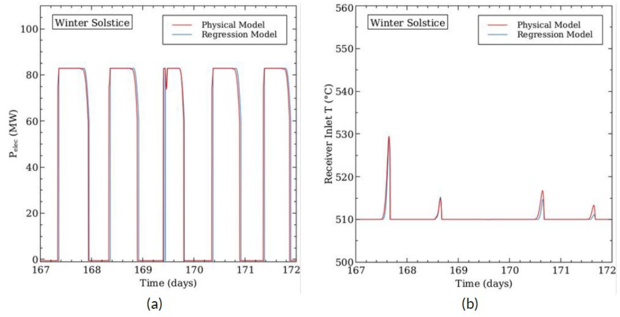
(a) Thermocline tank component model in SolarTherm (b) Discretisation scheme in the simplified heat-transfer model.



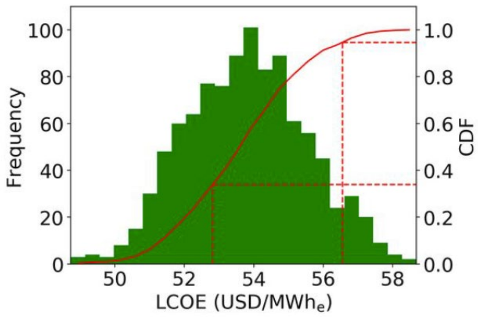
Three-tank storage system integrated in the system model to determine its storage effectiveness.

Techno economic analysis

- Technoeconomic modelling has been carried out for the single tank configuration
  - ➢ Based on MgO bricks at 1 USD/kg
  - ➢ Tank costs including stainless steel 316L at 4 USD/kg based on Gen3 CSP Liquids Pathway chloride salt tank (Turchi et al. 2021)
  - ➢ Sodium inventory at 3 USD/kg.
- A reduced-order (or surrogate) model for the storage was developed, introducing ~2% error, however with speedup of 40x.
- The result of the system optimisation and technoeconomic analysis is that a system based on the packed bed storage concept achieves levelised cost of energy (LCOE) of 56.55 USD/MWh_e
- Further reduction of LCOE is expected once simulation of multi-tank packed bed storage configurations is completed.



Comparison of the 'equilibrium cycle' regression model with the more detailed physical model

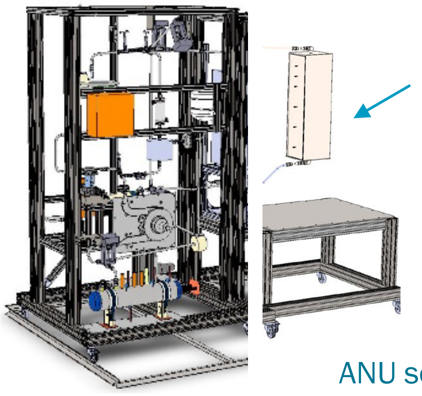


Probability distribution of LCOE due to uncertain factors

Prototype design

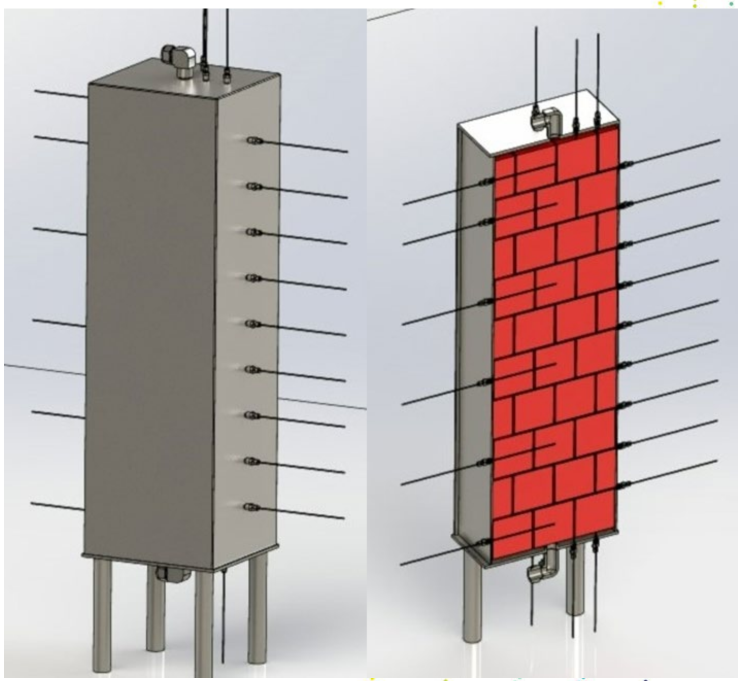
Key factors considered

- Potential for high thermal losses at laboratory scale
- Need to withstand vacuum (specific to operation of the ANU sodium lab)
- Dense temperature instrumentation to characterise performance
- Differences in thermal expansion between the tank and the bricks
- Uncertain geometric tolerances from the brick manufacturer



Location of the prototype unit during testing

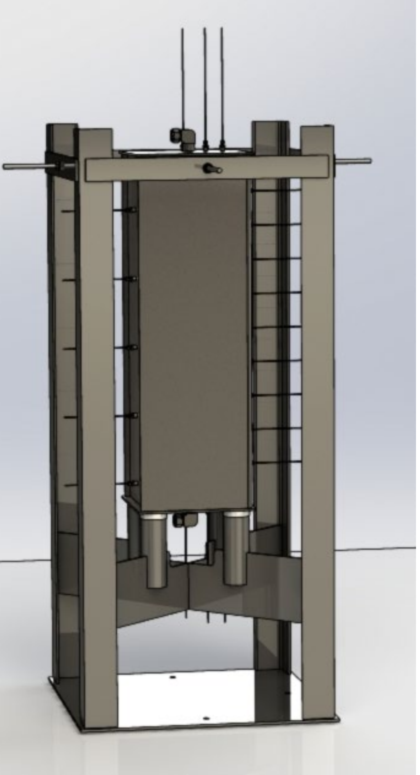
ANU sodium loop



(a) (b)

Packed bed storage prototype showing (a) the outer shell and (b) a cross-section view of the bricks.

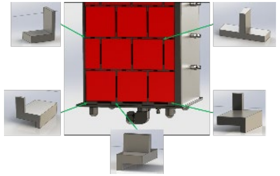
Detailed design



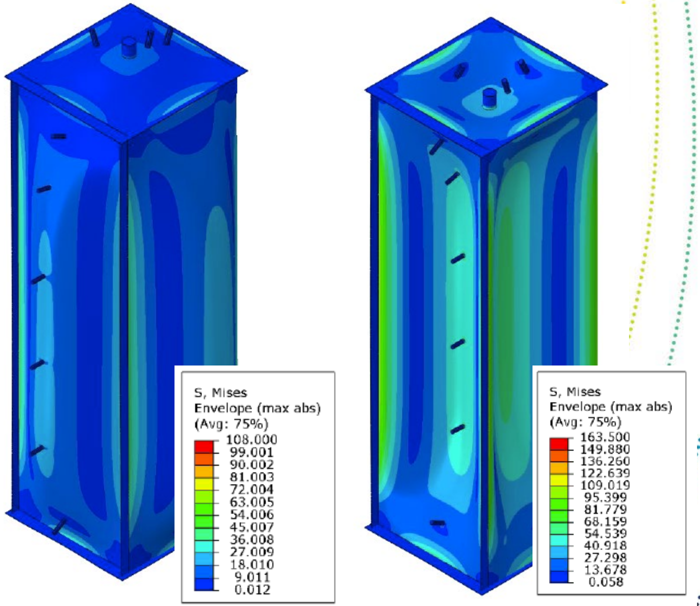
Detailed design including FEA modelling was carried out with support from *FE Consulting*

Design details include:

- A frame
- Instrumentation (51 thermocouples)
- Internal catch tray
- Brick spacers
- Thermal ‘break’ to the support frame
- Insulation (microporous ceramic boards)



CAD model of the full prototype assembly (left) and spacers (above)



FEA modelling of the tank under design loads (left) and full vacuum (right).

Vessel material	Stainless Steel 316
Expected cycles in service	50 cycles
Shell temperature at full vacuum	200 °C
Liquid content	Sodium
Filler material	MgO
Filler material density	3580 kg/m^3
Maximum internal pressure	35 kPa.g
Maximum external pressure	F.V (short term < 1hr) @ Max 200 °C
Maximum temperature	750 °C

Fabrication

- Tank fabrication was carried out by *DME Engineering Services*
- ANU cut the bricks and placed them in the tank.
- *DME* welded on the last side of the tank.
- Scheduling of the testing in ANU's sodium loop is still to be determined

Bricks stacked up, with spacers, prior to cutting.

Bricks stacked in the tanks, with spacers, prior to the door being welded on

Finished prototype packed bed storage (excluding insulation)

Conclusions

- The packed bed storage concept builds upon prior modelling and experimental work in the CSP community with packed beds, such as ceramic or rock beds with air and salt.
- A material compatible with sodium (MgO) at high temperature has been identified and tested for a duration of 500 h in contact with sodium at 750°C without any significant structural or chemical degradation.
- Annual simulations and technoeconomic analysis show promising LCOE at 56.55 USD/MWh_e
- A laboratory-scale prototype has been fabricated, ready for testing in the ANU sodium lab
- Key benefits of this concept are
  - the filler material is already produced at commercial quantities at low cost;
  - the total tank volume is less than for a conventional 'two-tank' molten salt storage system;
  - the need for a second heat transfer fluid (i.e. the molten salt) with heat exchangers is avoided, simplifying the design, operation, and maintenance;
  - the liquid fraction of sodium (i.e. sodium inventory in the tank) can be kept below 5%, reducing costs and hazards associated with storing large amounts of sodium.

Acknowledgment

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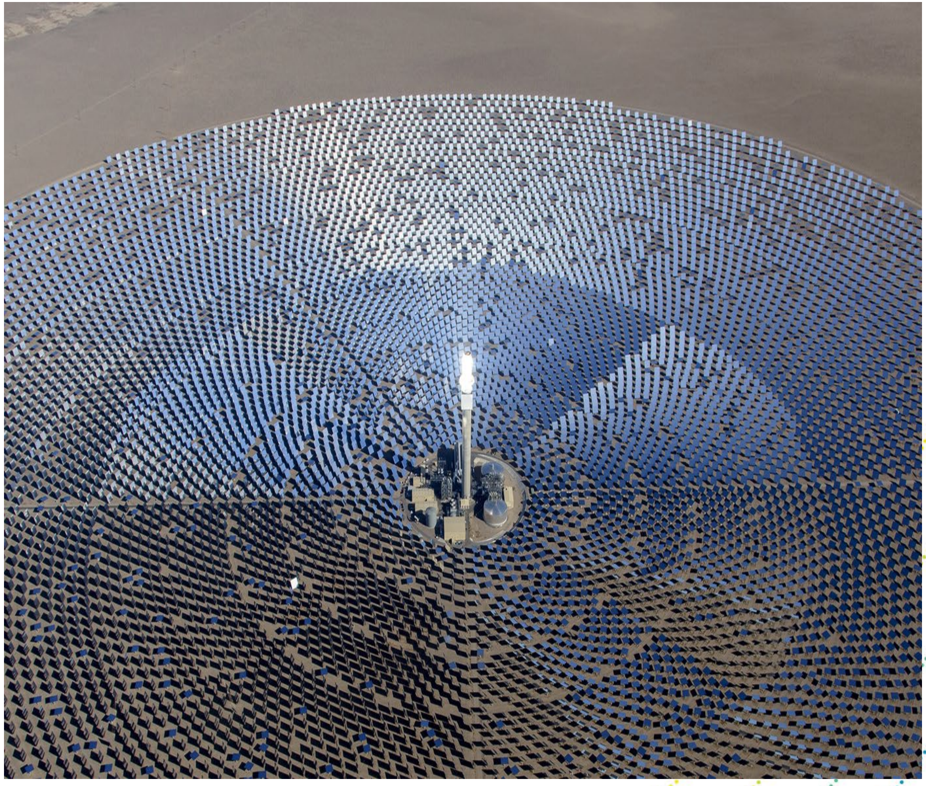

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Thank you

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