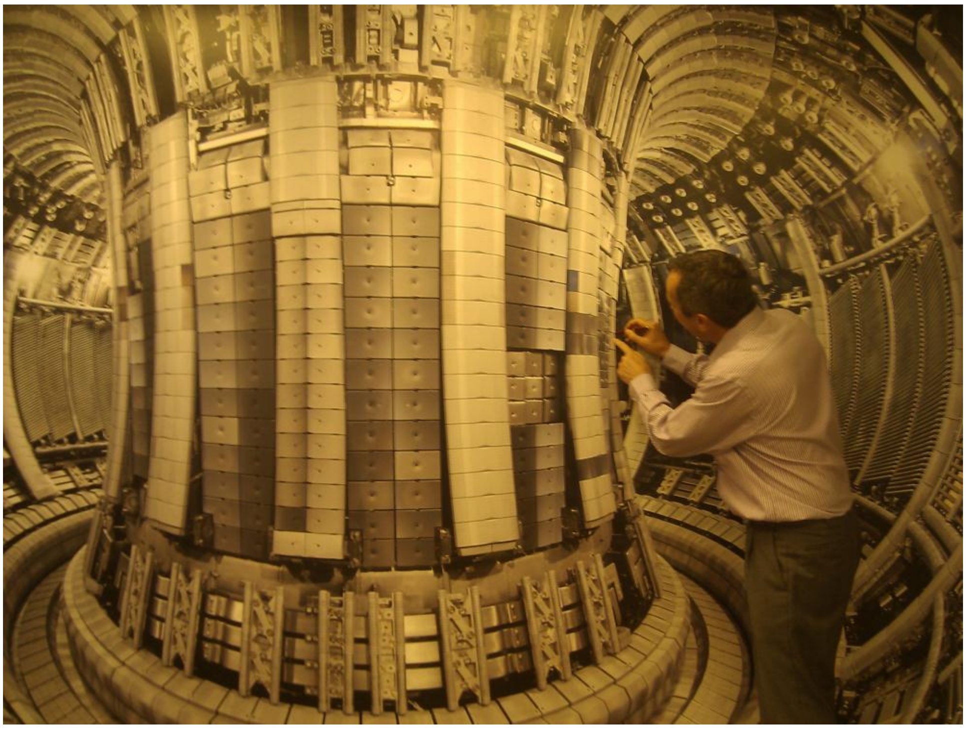
Designing Energy Storage for Pulsed Fusion Reactors

Towards the end of 2012 we carried out a very interesting thermal design study as part of Europe's pulsed fusion reactor design research. The task was to prepare a conceptual design of a liquid salt energy storage system for client: Culham Centre for Fusion Energy. This required us to carry out steam cycle thermodynamic design, heat exchanger design and energy storage optimisation. As always, and most importantly, we needed to understand the **energy system**.

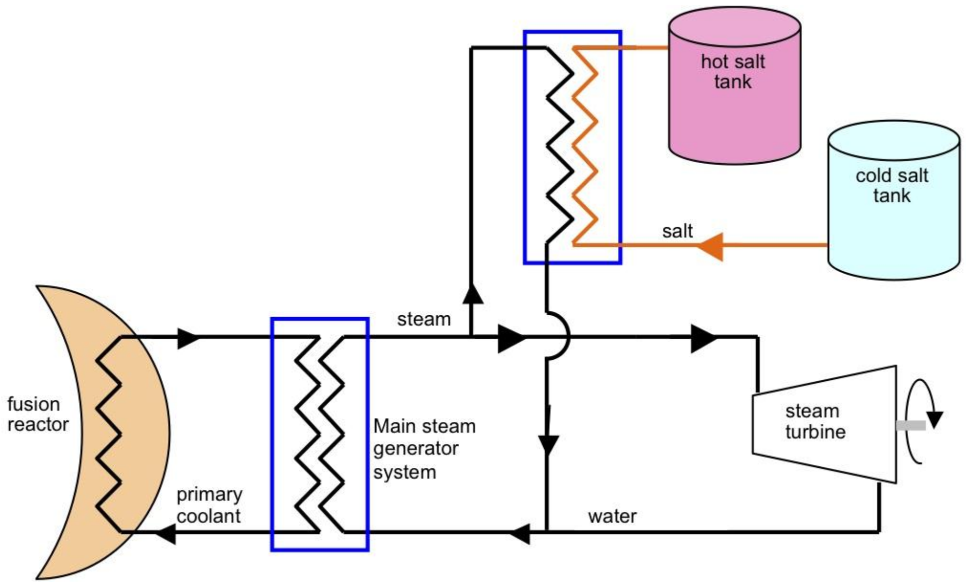
As part of the fun, Jim took the opportunity of fixing the fusion reactor for Culham, as shown below:



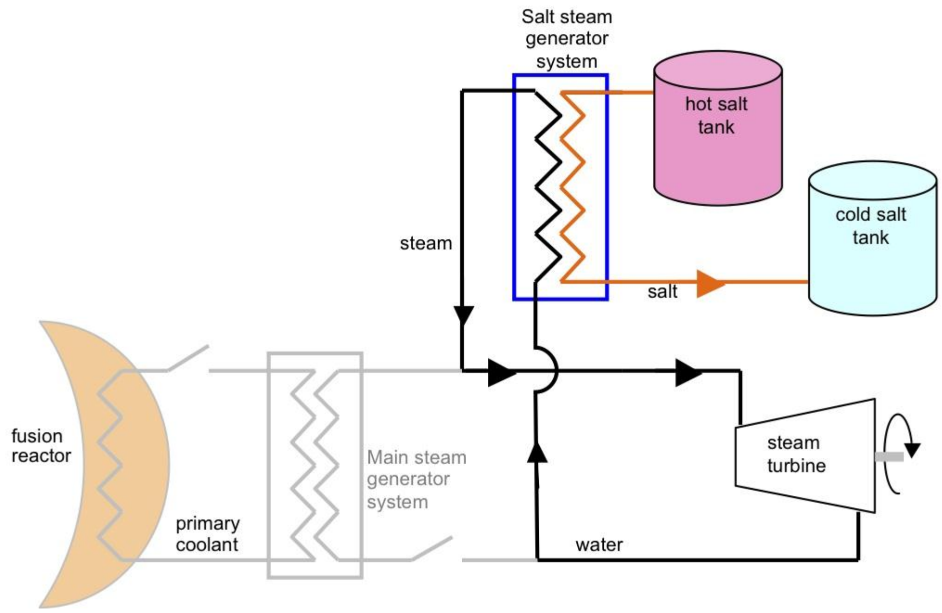
(OK, it's not that easy, but I think you will agree that standing in front of this half-size photo of JET, the European fusion experiment at Culham, makes for beautifully trickery)

Outline

It seems that advanced design work on fusion reactors is leading to a view that fusion reactors may operate in bursts of power. One option might be that the "on" period may be approximately two hours and the "off" period half an hour. If energy can be stored from the "on" period and used during the "off" period then a stable and continuous flow of power can be delivered to the electricity grid, making it a more valuable energy system. Our study was to design the steam/salt/turbine/heat exchanger arrangement, which could deliver this, assuming the energy store medium is liquid salt. The schematic below shows the proposed arrangement during charging:



The discharging arrangement is shown below:



The powers and flows involved are very large, and even bigger than the Combined Cycle Gas Turbine plant performance work we have carried out previously, and this generated so many zeros in some of the results that it made sense checking some of the results a little unfamiliar.

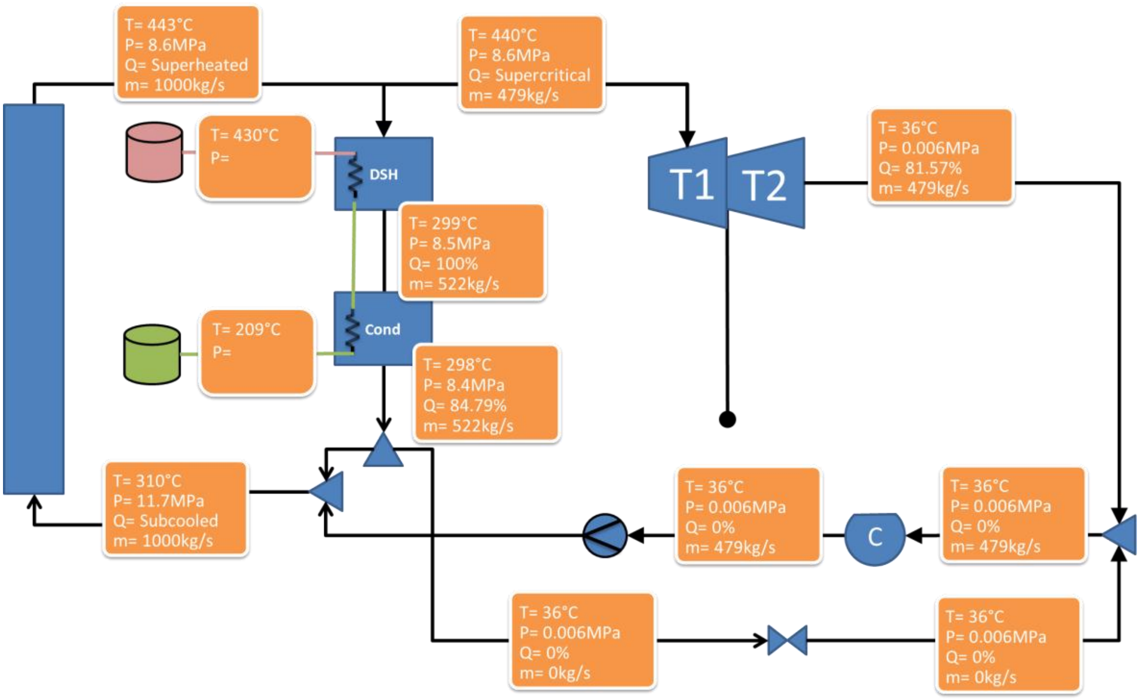
This table summarises an example of the main parameters.

electric power output	0.5 GWe & 1GWe
Outlet steam temperature from main steam generator	443ºC
Steam pressure	8.6 MPa
Cold feedwater temperature into main steam generator	150ºC
Cold salt temperature	288°C

We built the thermodynamic model in Excel from first principles and utilised REFPROP to automatically obtain thermo physical properties values for steam/water. We like to work from first principles on concept designs as this teaches the designer sensitivities much better than simply running a proprietary program.

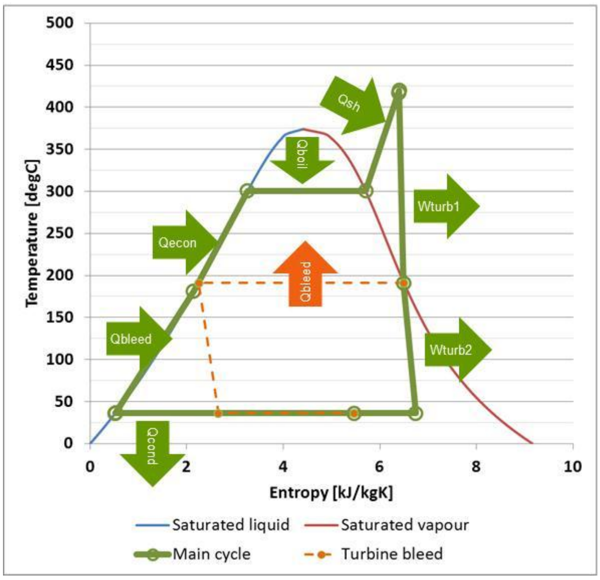
In the end we carried out two designs, using two different salts.

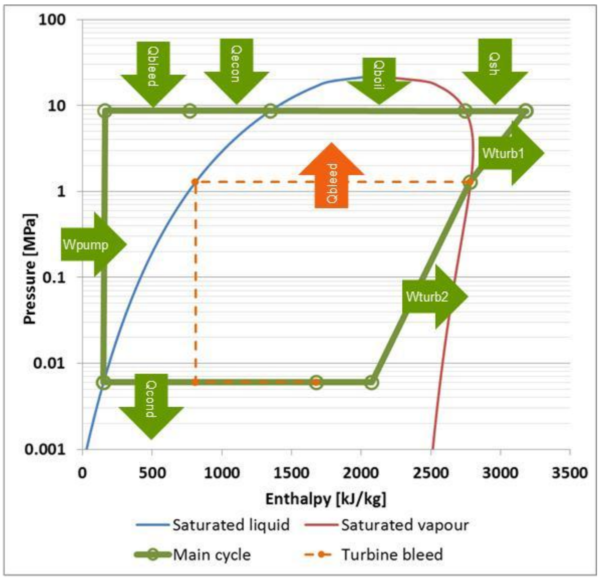
In the first design study, our calculations found the Rankine cycle thermodynamic efficiency during charge to be poor at only 16.6%, and it was agreed we should try some modifications to the thermodynamic design including: a salt with lower melting temperature, a higher boiler water feed temperature and a modification to the flow arrangements to improve efficiency. This did indeed raise thermal efficiency on charge to 29% and illustrates how altering thermodynamic design points and arrangements can have a big impact on system thermodynamic efficiency. This yet again underlines the need for engineers to understand the wider system and interactions between system components. The final thermodynamic arrangement is shown in the flow diagram below. The heat source (reactor) is shown on the left of the diagram and you can see the 1000kg/sec flow going in, sub-cooled at 310°C, and coming out superheated at 443°C.



Process flow diagram of steam turbine cycles - Charging

No thermodynamic design is complete without appropriate diagrams of either temperature / entropy or pressure / enthalpy and these are both shown below. Again we built Excel to generate these automatically.



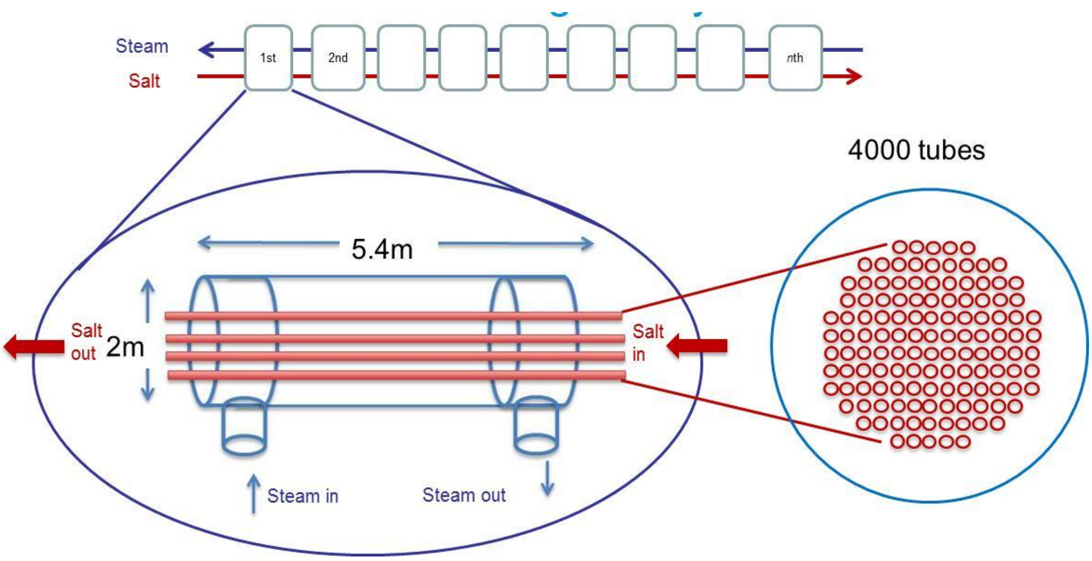


Temperature- Entropy (TS) **Pressure Enthalpy (PH)**

The Rankine thermodynamic efficiency during charge was calculated in a similar manner and shown to be 36%. However when carrying out the design of heat exchanger in detail we found a problem with achieving the required full power.

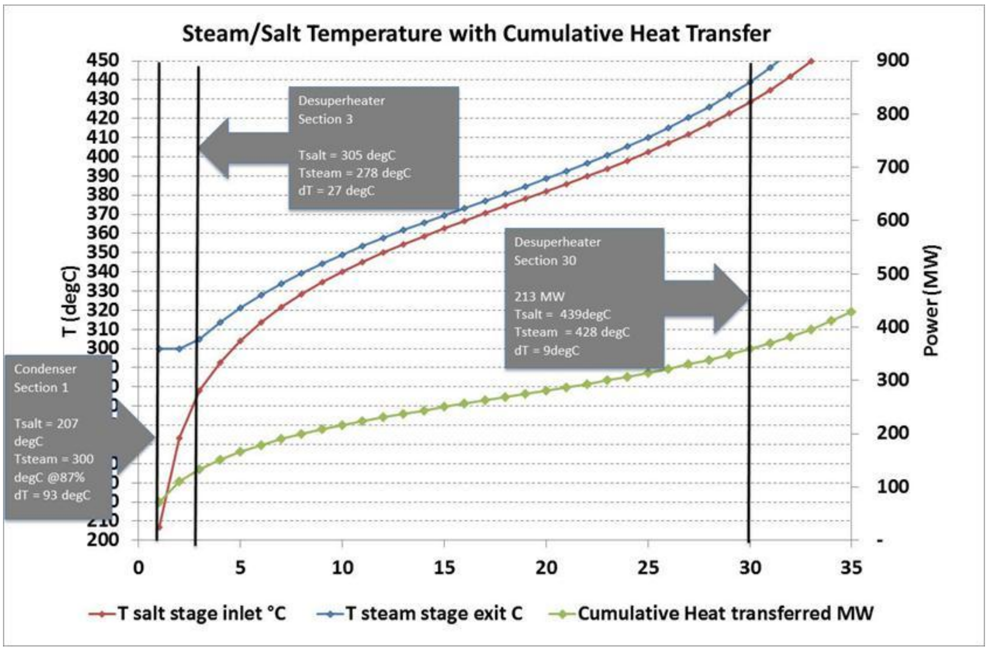
Heat Exchanger Design

Parallel to the thermodynamic cycles assessment we carried out a concept heat exchanger design for heat transferred between the molten salt and the steam/water. We approached this task by creating our own heat exchanger model in MS Excel and this calculated the overall heat transfer coefficient of the fluids within shell and tube heat exchangers. We altered the design dimensions until we found a reasonable physical design, and settled on separate heat exchanger modules of 5.5m long, 2m diameter, consisting of 4000 tubes of 2mm thickness. To achieve the full heat transfer required in the 500MWe case we needed a total of 30 of these heat exchanger modules and with each weighing approximately 17,500kg (17.5 tonnes) we estimated initial cost of these in the region of £10 million.



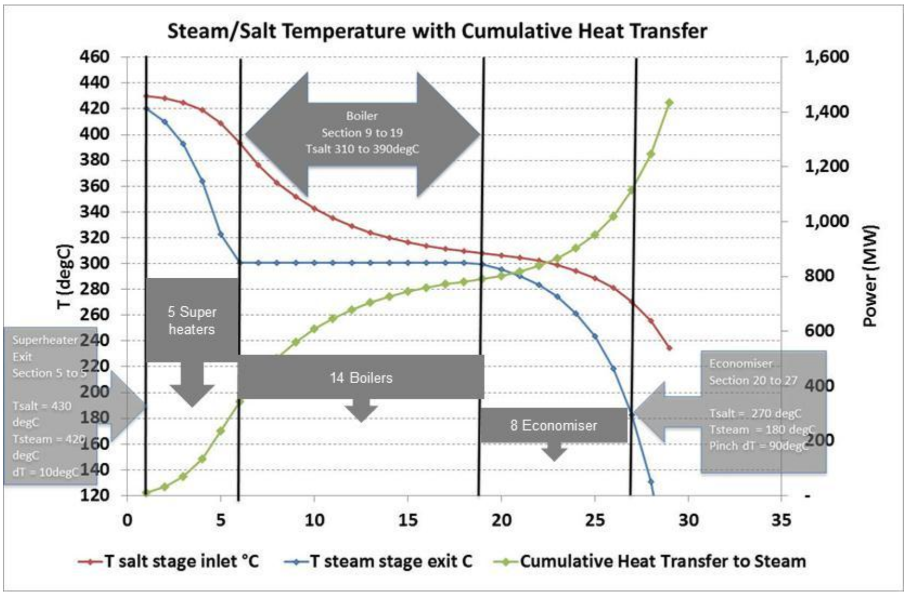
Charging and discharging mode

The previously explained thermodynamic cycle design provided the inputs for the heat exchanger design. During charging, molten salt is being heated from 207°C to 440°C in 30 multiple heat exchangers during which heat from superheated steam is extracted and cooled to 13% wetness fraction. This is shown in the diagram below, with salt flowing to the right and steam flowing counter to this.



Charging: 30 heat exchanger modules required

However, it was during the discharge cycle that something interesting arouse, which we hadn't expected. The plot below shows the temperature against the number of heat exchanger modules. This clearly shows the flat temperature profile of water, as it cools along its saturated line, produces a very small dT (difference in temperature) between the salt and the steam at about section 19. When we first ran this heat exchanger model we found that these two lines in fact converged and the full amount of heat could not be transferred, not matter how long we made the heat exchanger. This hadn't been anticipated during the previous thermodynamic design as that work had focussed on the end points of the model and not what happened along the length of the heat exchanger.



Discharging: 27 sections of heat exchangers

We needed to find a reasonable solution to this issue for this first concept study and decided that a reasonable approach would be to reduce power during discharge to 70% and this is what we settled on. The nice thing about this is that it preserves the Rankine thermodynamic efficiency at the fairly reasonable level of 36% during discharge.
In summary, for discharge, the work showed that the system:

- Required only 27 heat exchanger sections (30 required for charging)
- 8 sections of these bring the boiler feed water to boiling condition
- 14 required for boiling
- 5 required for superheat
- The superheated steam of 420degC will be used in a steam turbine power generator to produce 0.7 * 500MW = 350MW electricity.

The heat exchanger work again showed how important it is to understand the whole system behaviour, as we conclude that the heat transfer performance is very sensitive to fluids heat capacity.

Summary

We aimed to provide a solid concept study to the client to assist their understanding of steam turbine power generation and help them plan and assess their thermodynamic options. Unexpected results arouse, which we managed through regular contact with the client, and, between us, we tackled and overcame any obstacles. For us, this study proved to be an exciting challenging due to the novelty and constraints imposed by fusion reactors using energy storage and steam power generation.

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