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Ultra-supercritical Energy Storage

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ABSTRACT

We develop an electro-geothermal battery for large scale ultra-supercritical energy storage. The technology relies on the proven concept of underground natural gas storage extended for the supercritical CO_2 and H_2O cycle. Storing gas in sedimentary formations is already one of the largest-scale proven technologies for energy storage. New ultra-supercritical H_2O and CO_2 generators operate at extreme temperatures (more than 600°C), achieve close to 50% efficiency and are proposed as the next technology to lower emissions of conventional power plants. These generators put forward new challenges for energy storage especially when they are used in conjunction with renewable energy sources such as Concentrated Solar Power. We test the ultra-supercritical reaction, deformation and fluid flow of targeted reservoir rocks in bespoke X-Ray and Neutron beam transparent fluid flow and deformation cells. Our goal is to facilitate the design of ultra-supercritical generators that store supercritical CO_2 efficiently. We aim at identifying suitable reservoirs that can store and dispatch large amounts of energy without the need of an intermediate heat transfer medium such as molten salt or graphite.

1. INTRODUCTION

Global carbon emissions hit a historic high in 2018 according to the International Energy Agency (IEA). Energy-related CO_2 emissions rose 1.7% to 33.1 Gt CO_2. 560 million metric ton increase in carbon emission last year was equivalent to the total emissions of the international aviation industry. While emissions from all fossil fuels increased, the power sector accounted for nearly two-thirds of emissions growth. The Intergovernmental Panel on Climate Change (IPCC, https://www.ipcc.ch) demands immediate actions and emphasises that Carbon Capture, Use and Storage (CCUS) is an integrated suite of technologies that provides an important option in global efforts to reduce CO_2 emissions. Research from the Intergovernmental Panel on Climate Change (IPCC) has shown that climate action will be 138% more expensive without carbon capture and storage (CCS) and that meeting the 2°C target could actually be impossible without it.

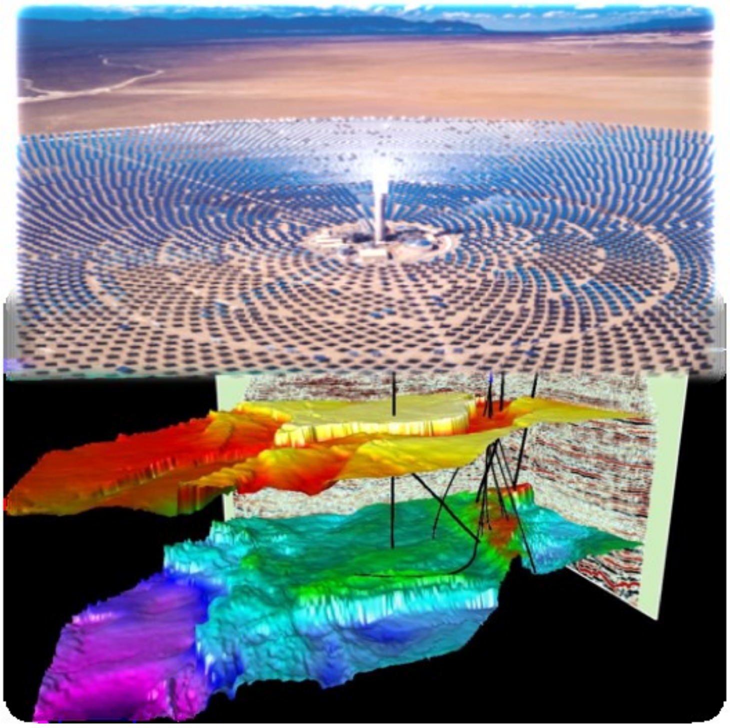

Figure 1: Conceptual design of an ultra-supercritical concentrated solar power plant (CSP) with an underground ultra-supercritical CO_2 geothermal battery.

The IEA released a recent report (IEA 2019) highlighting that carbon capture, utilisation and storage (CCUS) is expected to play a critical role in this sustainable transformation. For some industrial and fuel transformation processes, CCUS is touted to be one of the most cost-effective solutions available for large-scale emissions reductions. In the IEA Clean Technology Scenario (CTS), which sets out a pathway consistent with the Paris Agreement climate ambition, CCUS is expected to contribute almost one-fifth of the emissions reductions needed across the industry sector. CCUS is already a competitive decarbonisation solution for some industrial processes, such as ammonia production, which produce a relatively pure stream of CO_2.

CCUS is a new trend which can transform the industry. However, research into the utilization aspect has lagged behind the standard carbon capture storage (CCS) technologies which in most cases underpin CCUS. The notable exception is CO_2-Enhanced Oil Recovery (EOR), which has a strong track record and is an established CCUS technology already operating on a commercial scale. However, research into other CCUS technologies is still in its infancy or at the pilot-scale (Liu, Were et al. 2017). Due to the recent nature of these technologies commercial viability studies are not yet robust as most of these options are very early stage in their technological development.

This work forms part of a multi-national initiative combining three different innovations in this sector: (1) The innovation of a concentrated solar power central receiver plant capable of generating ultra-supercritical CO_2 above 750º C for next generation generators; (2) Novel ultra-supercritical CO_2 generators with more than 50% thermal efficiency; (3) An underground ultra-supercritical CO_2 battery (Figure 1).

Each of these innovations is led by different groups. The above-ground projects (1) and (2) are led by our partners. The below ground project (3) is subject of the present paper. The project is in the early stages of feasibility study and started in April 2019 comprising a tightly integrated set of project engineering milestones for the coming three years shown in Figure 2.

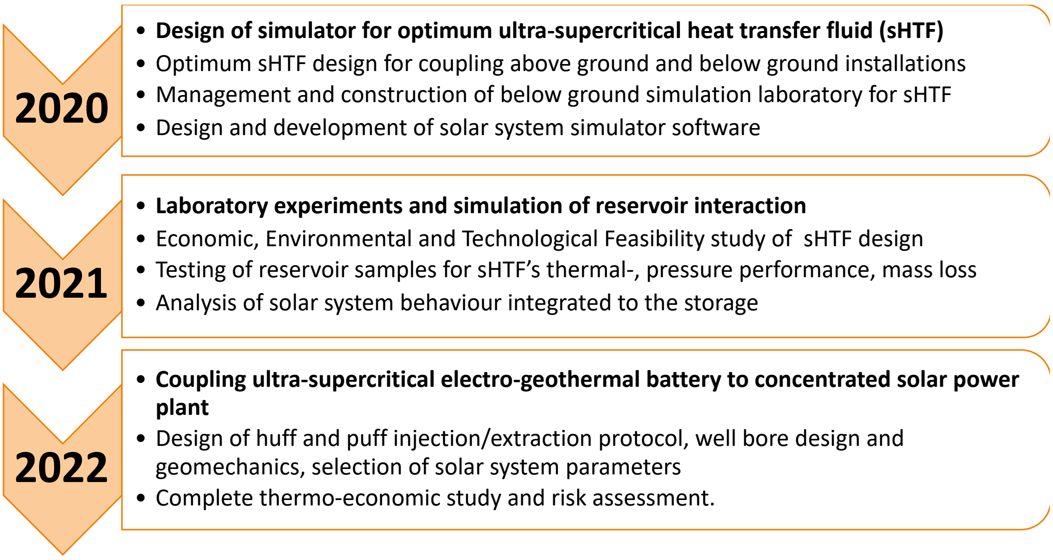

Figure 2: Project Milestones for thermo-economic assessment of the proposed technology.

The project milestones illustrate the need for a tight coupling of the above- and below- ground design and we therefore briefly discuss the above ground technologies before addressing the research carried out for assessing the viability of the below ground concept.

2. MATERIALS AND METHOD

2.1 Ultra-supercritical Concentrated Solar Power

The design of the ultra-supercritical concentrated solar power plant follows on a modification of the simulation work for a grid-connected solar thermal power plant commissioned at Gurgaon near New Delhi in India (Desai, Bandyopadhyay et al. 2014). The project leader S. Kedare (IIT Bombay) currently investigates the replacement of the standard molten salt solution (Figure 3) by ultra-supercritical CO_2 heat transfer fluids allowing to reach the targeted 750º C. These results can be used to plan the operation and the appropriate control strategy of the power plant. The simulation results will be validated with actual plant data, after commissioning.

2.2 Ultra-supercritical CO_2 Generator

Ultra-super critical generators are the most efficient thermal generators presently reaching close to 50% efficiency. This project targets a higher efficiency. The ultra-supercritical water cycle is already used in the world's most efficient coal fired power plant (RDK-8) producing close to 1 GW electric (https://www.ge.com/power/case-studies/rdk8) in Karlsruhe, Germany. A desktop sized ultra-supercritical CO_2 prototype generator (10 MW capacity) has recently been constructed by Doug Hofer from GE electric (Figure 4). The turbine is made from a nickel-based alloy that can handle temperatures up to 715º C and pressures approaching 3,600 PSI (250 bar). It replaces steam with ultra-supercritical CO_2, allowing for a more compact higher efficiency design.

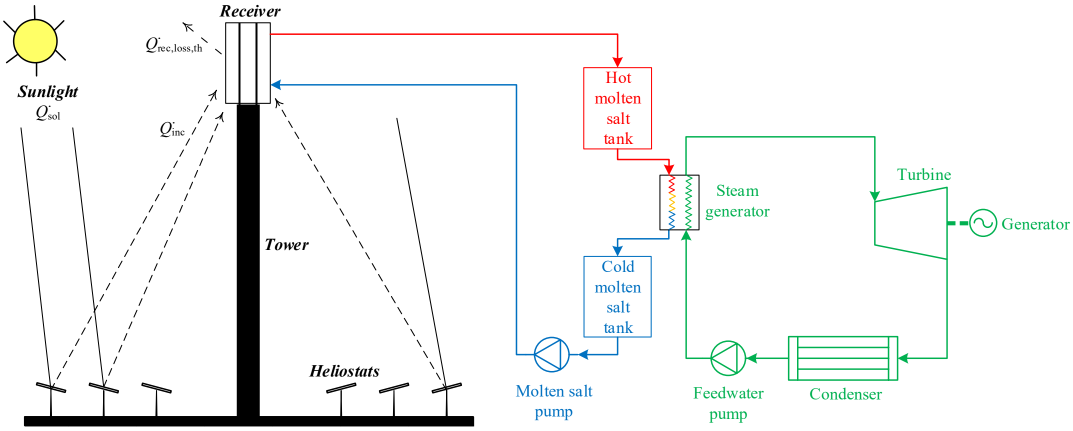

Figure 3: IIT-B Central receiver / LFR CSP plant: Tracking, receiver design and thermal system integration.

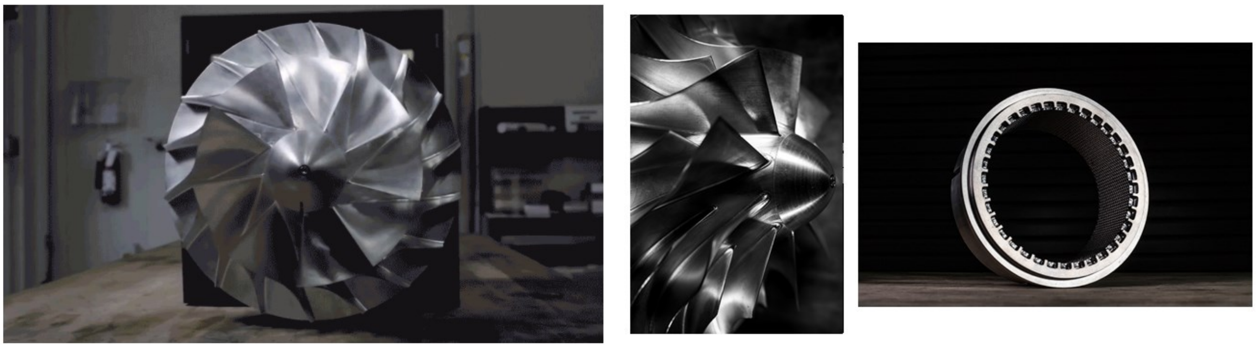

Figure 4: 10 MW$_e$ ultra-supercritical Co$_2$ generator from GE that fits the desktop (images from GE Website).

Combing technologies shown in Figure 3 and 4 harvests key innovations from two sectors. The central solar-thermal tower-heliostat technology (Figure 3) allows higher solar-thermal conversion efficiency (about 50-60%) and the ultra-supercritical generator can reach efficiencies above 50% (Figure 5).

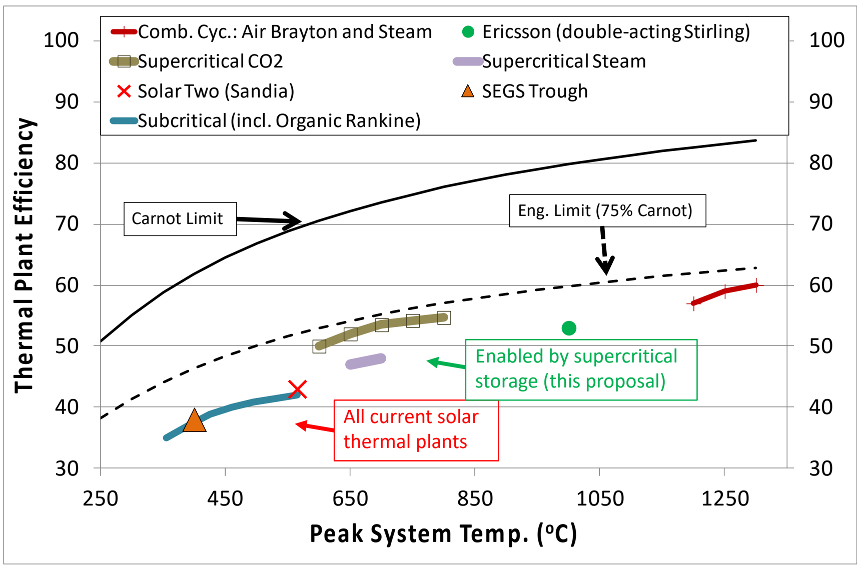

Figure 5: Thermal plant efficiencies for ultra-supercritical generators can breach 50% conversion efficiencies.

2.3 Underground Ultra-supercritical Heat Storage

This project develops an electro-geothermal battery for large scale ultra-super critical energy storage and carbon capture storage and utilisation. The technology relies on the proven concept of underground natural gas storage extended for the supercritical CO_2 and H_2O cycle. Storing gas in sedimentary formations is one of the largest-scale proven technologies for energy storage. The global market is estimated to be worth US $763.60 Billion at present. We propose to broaden the novel energy storage option and extend the technology for the supercritical CO_2 and H_2O cycle as an alternative to the above ground salt storage option. This allows tapping into much higher temperatures than 566° C offered by molten salt. It also offers better synergy with the technology of existing CO_2

sequestration technologies. Our innovation therefore simplifies the design of the ultra-supercritical generators, stores supercritical CO_2 more efficiently and dispatches large amounts of energy without the need of an intermediate heat transfer medium.

Our EUReKa research group at the University of New South Wales, Sydney (Australia) currently performs laboratory studies to assess this technology for a geothermal battery concept discussed later. The first targeted source of the CO_2 is a coal fired power plant in New South Wales, Australia.

The ultra-supercritical CO_2 geothermal battery is controlled by five important factors:

1) Structural setting: The ideal site for CO_2 storage is an anticlinal structure with sufficient permeability and size; the structure needs to have a suitable seal at the top (e.g. abandoned hydrocarbon reservoir).
2) Depth of the target structure: The depth of the structure is controlled by the critical point of CO_2 and the pressure needed to operate the above ground CO_2 generator. It needs to be at a greater depth than the critical point of CO_2. The critical point is defined by the temperature-pressure pair 31.7 °C and a pressure of 1071 PSI (73.9 bar = 7.39 MPa).
3) Chemical composition of the target structure: Since supercritical CO_2 is an effective solvent and can be highly reactive, the chemical composition of the target structure is important.
4) Permeability of the target structure: We recommend a permeability >100 mDarcy. Permeability is expected to be enhanced due to the Thermo-Hydro-Chemo-Mechanical (THMC) interaction of the CO_2 with the host reservoir.
5) Mechanical stability of the target structure under load: By using the huff and puff method in day and night cycles the target structure is going to be cyclically loaded and mechanical stability of the seal must be proven. Considerations of the chemical reactions and the thermal cracking of the reservoir need to be taken into account to protect seal integrity.

Most of the above controls are within standard engineering limits. The key challenges for the underground storage project are the extreme conditions that could result in lack of stability of the target reservoir, the seal and the materials for handling extreme conditions. In order to develop an ex-situ testing laboratory for testing reservoir rock samples, samples of seals and engineering materials at extreme condition we have developed a worldwide unique ultra-supercritical material testing laboratory described in the next section.

3. ULTRA-SUPERCRITICAL MATERIAL TESTING

Testing of novel alloys and ceramics used for handling the extreme temperatures, stresses (volumetric and deviatoric), chemical aggressive environments in the reservoir cannot be done in existing laboratory environments. The same applies to reservoir samples and core samples from the seal as well as the contact area between rock and engineering materials. In 2014 the UNSW has funded a strategic Centre of Excellence for Unconventional Resources Knowledge, Science and Technology (EUReKa) which aims at addressing the challenge of investigating extreme conditions through a new multidisciplinary fundamental science approach. A research team for testing materials at extreme conditions has been formed that combines a recent multiphysics, multiscale geomechanics theory with laboratory and modern computational assisted petrophysics and material science concepts. This solid science base has allowed the team to build the platform for enabling a transformational approach for combining the disciplines of science and engineering into an earth science engineering discipline. As part of this Centre which comprises theory, numerical modelling and experiments, a material testing facility has been constructed. This laboratory allows tackling the difficult problem of testing reservoir rocks and engineering materials at reservoir conditions in a controlled laboratory environment. As part of this centre the team and its collaborators have built an integrated 4-D X-Ray & Neutron imaging Microscopy (4D-XRM) facility allowing multiscale imaging of materials from molecular-scale to sub-micron tomographic resolution to the micro and beyond scale using radiography, scattering and tomography techniques.

3.1 A 4-D X-Ray and Neutron Imaging Microscopy (4D-XRM) Laboratory

The unique innovation of 4D-XRM provides a comprehensive suite of load cells to explore time-evolution of materials under load as the fourth degree of freedom. Specifically, the 4D-XRM facility allows monitoring of temporal structural changes of solid, liquid or gaseous domains of materials under chemo-mechanical loads and fluid flow. This can be achieved via the construction and certification of X-Ray and Neutron beam transparent thermal, pneumatic, hydraulic, chemical and mechanical loading cells available as portable equipment to support the world-leading expertise and facilities in Australia and overseas. A seamless integration of time lapse information on scales ranging from the crystallographic through the sub-nano- to the cm-scale is provided by constructing uniaxial load, flow and heating cells for the Small Angle X-Ray Scattering (SAXS) and Small Angle Neutron Scattering (SANS) facilities in the University of Queensland and at both Australian Nuclear Technology Organization (ANSTO) sites, respectively. Triaxial flow and deformation X-Ray and Neutron beam transparent cells have been constructed for 4D-XRM imaging at the micro-Computer Tomography (micro-CT) facilities in the Australian Synchrotron, the Neutron Reactor at Lucas Heights, Queensland University (UQ), Queensland University of Technology (QUT), University of Sydney (USyd) and the University of New South Wales (UNSW), Sydney. The portable cells allow using a network of laboratories each with its specific strength and is currently also extending its applications to international Synchrotron and Neutron source real and inverse space imaging facilities.

High X-ray flux Synchrotron sources and very bright and energetic Neutron sources offer new insights into material behaviour through new X-ray optics and Neutron detector technologies, reducing sampling times for tomographic image collection of tomographic images down to the millisecond regime and pushing the spatial resolution down to tens of nanometres and below. This allows material testing capabilities for extreme environments and allows the team to take full advantage of these advanced specifications. Bespoke X-Ray and Neutron beam transparent cells have been built to investigate the behaviour of materials under (extreme) loads. An example is pore formation under exposure of materials to corrosive fluid, effects of mechanical stress on a material in the presence of corrosive fluid, changes in physical properties as a function of temperature, stress, pH, fluid flow-rate etc...

The development platform for the 4-D XRM laboratory is an extension of UNSW's open source Tyree Micro-CT facility into a proto-typing, certification and long-time scale imaging platform networked with ANSTO's light and neutron source facilities. The Tyree XRM is a custom-made Helical X-Ray Micro-CT based on Australian National University's (ANU) and UNSW 's spin off company which has been commercialized through a trade sale to FEI (now owned by ThermoFisher). The source and detector are located on a vibration free platform inside a lead-clad room with a remote-control room. The specifications of the open source X-Ray laboratory room with temperature stability of <0.5º C; housing a 3D-X-Ray 180kV/20W GePhoenix X-ray source with diamond windows and detector 3.75fps readout rate, 3072x3072 pixels. This allows to record tomographic images at resolutions approaching sub-micron level in helical scanning mode (exact reconstruction method). The scanner allows a helical setup capable of up to 100 mm travel. The Tyree facility is hooked up to its own parallel compute infrastructure 256 CPUs 1024 GB memory 1800 service units for reconstruction process 2519x2519x5119 blocks as well as a dedicated link to the Raijin Supercomputer in Canberra. The facility also provides a visualization and training laboratory and includes a sample preparation laboratory including Plasma Cleaner, Centrifuge, Microdrill etc. Sample selection from up to 1.7 m long and 100 mm wide samples is supported by an ITRAX Core Scanner which allows XRF multi-element analysis down to 100 microns resolution, radiographs and optical selection (50 microns) at 1 second per point measurement. The facility also allows access to top of the range petrophysical and chemical characterization e.g. NMR, Microfluidics, Reactive Chemistry, Geomechanics, Mercury Intrusion Porosimetry etc...

3.2 Testing Cells for Extreme Environments

Our group has designed versatile µ-CT/Neutron source high pressure tomography deformation cells for chemically aggressive environments with SAXS, and SANS capability for uniaxial, triaxial, torsion testing with fluid flow ranging from cryogenic conditions -200ºC to 700ºC. The cells are custom built for trial in the local laboratory and prepared for the Synchrotron if needed. The prototype Neutron and X-Ray Neutron and X-Ray scattering- and tomography cells (Figure 6 + 7) have been built and successfully tested in late 2018 at the Neutron Reactors in Maryland (NIST) and at the world's most powerful Neutron source (60 MW) in Grenoble (ILL). The cells are designed by Dr. Tomasz Blach (UNSW).

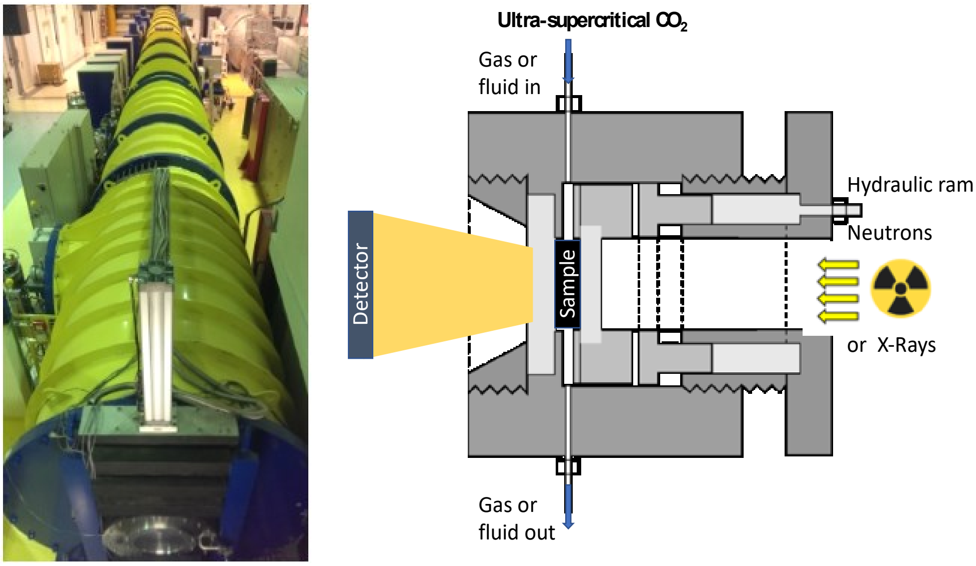

Figure 6: Uniaxial cell for ultra-supercritical CO_2 material testing. The detector is in the yellow vacuum tube (D11 at ILL).

The specifications of the uniaxial cell (Figure 6) are:

Sample size: up to 30mm diameter, 5mm thick;
Fluid pressure range: vacuum to 100MPa;
Sample temperature range: 20C – 700C;
Uniaxial Stress: piston, applied in the beam direction, hydraulic up to 100MPa, externally controlled;
High pressure windows: exchangeable, Be, Ti, Sapphire, Alon, Diamond;
Vacuum windows: exchangeable, Al, PIC, Alon;
To be used for: IR, visible light, UV surface analysis, X-Ray and neutron scattering;
Range of investigation: sub atomic scale to millimetre scale.

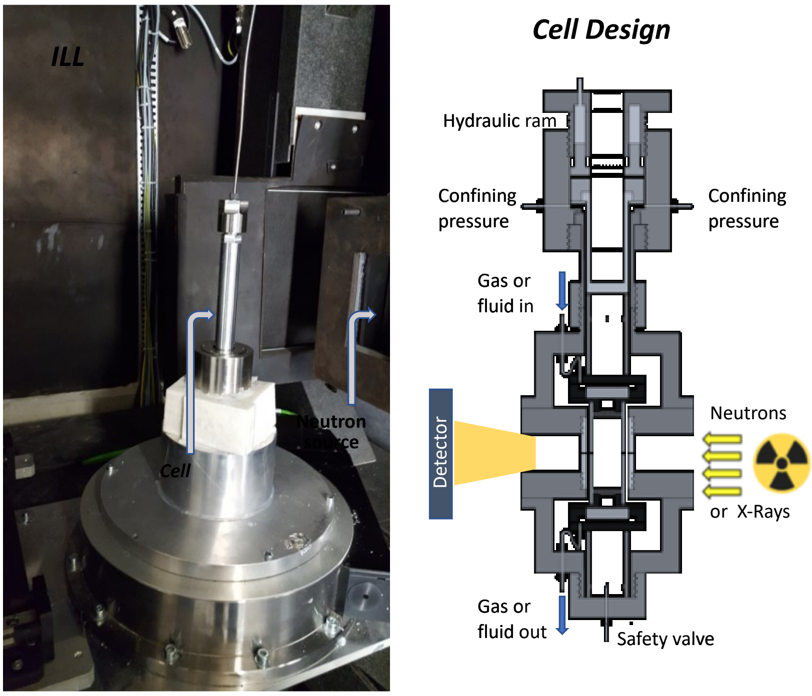

Figure 6: Triaxial cell for ultra-supercritical CO_2 material testing. (ILL = Institute Laue-Langevin, Grenoble)

The specification of the triaxial cell (Figure 7) are:

Sample size: Cylindrical cores, 18mm – 38mm diameter (Insert dependent);
Reactive fluid pressure range: vacuum to 100MPa, acid resistant;
Confinement fluid: He, Ar up to 100 MPa – Automatically controlled to keep positive confinement pressure on the sample;
Sample temperature range: 20ºC – 700ºC;
Uniaxial Stress: piston, applied perpendicular to the beam direction, hydraulic up to 100MPa, externally controlled;
High pressure windows: exchangeable, Be, Ti, Aluminium, Carbon Fibre, Alon;
Confinement windows: exchangeable, graphite, Teflon, clear Viton;
To be used for: X-Ray and neutron tomography, radiography;
Range of investigation: sub-micrometre to millimetre.

Figure 6 also shows a 40 m long evacuation tube with a position sensitive detector allowing multiscale SANS measurement for large scale structures (D11 at ILL Grenoble). The portable design of the cells shown in Figures 6 and 7 enables international research collaborations.

4. DISCUSSION AND CONCLUSION

We have described a suite of innovative technologies with transformative potential for clean energy generation. The technology harnesses the existing geothermal techniques for diurnal and seasonal storage of heat, new designs in ultra-supercritical generators and innovations in the concentrated solar power stations. Our ultra-supercritical laboratory allows material testing prior to costly field trial and will be particularly useful to screen for ideal reservoir sites.

Although the project prefers investigation of an abandoned gas reservoir the laboratory setup also allows the investigation of in situ mineral carbonisation of tight volcanic rocks or peridotites. Reconnaissance mapping revealed that peridotite weathering in Oman causes around 10^4 to 10^5 tons per year of atmospheric CO_2 to be converted to solid carbonate minerals. The ultra-supercritical CO_2 technology may give new support to the proposal of engineering in situ mineral carbonisation by using the chemical potential energy existing in volcanic reservoirs or mantle peridotite (Kelemen and Matter 2008). It also needs low energy for maintaining optimal temperature and pressure as the reaction is exothermic.

Core samples from a 1-2 km deep potential reservoir and its seal have been procured and are currently subject to testing for suitability of the ultra-supercritical CO_2 geothermal battery concept, the associated drilling, hydraulic/thermal fracturing and stability. The project is set up as an international initiative and seeking international partners and potential additional field sites.

ACKNOWLEDGMENTS

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