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Material compatibility and degradation mechanisms for the next generation of Concentrated Solar Power Plants

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The ever increasing growth of global industrialization and population has led to a drastic increase in electricity consumption. In turn, the steadily increasing price of fossil fuels and the pressing concerns of environmental sustainability has seen an increasing demand for clean energy sources. Issues such as global warming have provided the impetus for the advancement of renewable technologies, such as solar energy. Concentrated Solar Power (CSP) technology is a highly promising solution for the large-scale production, storage and management of green energy (Sarvghad, Delkasar Maher, et al., 2018). It has the potential to generate electricity at considerably lower costs and without carbon emissions.

The next generation of CSP plants will see a significant improvement in efficiency and competitively lower costs in energy production. This will be achieved by the integration of an energy storage system and utilising novel power cycle designs. CSP systems usually consist of three main subsystems (as seen in Fig. 1); a heliostat field that reflects sunlight and concentrates it onto a central receiver to raise the temperature of a Heat Transfer Fluid (HTF), a Thermal Energy Storage (TES) system that stores thermal energy for later use in the form of molten salt (also referred to as a Phase Change Material or PCM), and a power block that utilizes the heat from the HTF to operate a turbine for the generation of electricity.

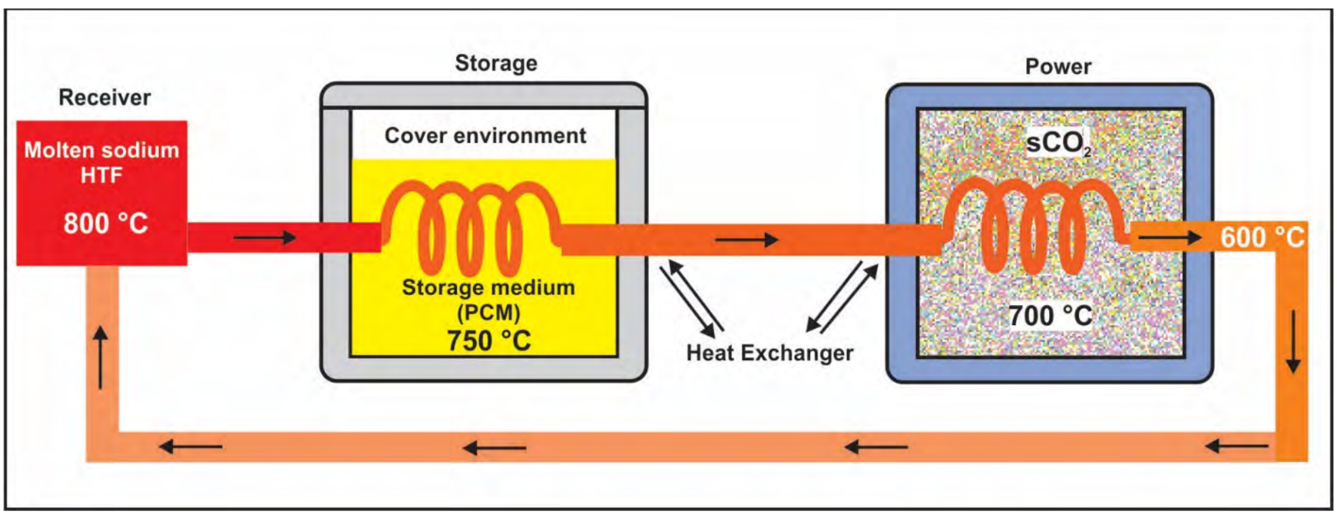

Figure 1. Proposed CSP configuration; tower system using a sodium receiver, PCM storage for 4-6 hours and sCO_2 power block

The schematic for a next generation CSP plant as shown in Figure 1 is a proposed design that is part of a test program led by the Australian Solar Thermal Research Institute (ASTRI), which is an initiative comprised of several international collaborations with leading research institutions, industry bodies and universities. The unique aspects of this proposed design include operational temperatures never seen before in existing CSP plants, with the receiver subsystem running at temperatures as high as 800 °C. The use of liquid sodium as one of the main HTFs, latent heat PCM as the main thermal energy storage medium and a supercritical carbon dioxide Brayton cycle for power generation will all lead to vastly improved efficiency and reduced cost of power generation.

The higher working temperatures of this proposed design and the different environments (whether it is liquid sodium, molten salt or supercritical carbon dioxide as summarised in Table 1) will require careful selection of materials to meet the challenging high-temperature and corrosive conditions each of the subsystems will experience. There is a multitude of degradation mechanisms that threaten the structural integrity of the CSP plant, specific to each of the subsystems. The use of liquid sodium as the main HTF can lead to significant corrosion from the dissolving of alloying elements in the walls of the containing vessels, such as the piping and the receiver of the plant. The penetration of liquid sodium through grain boundaries can lead to liquid metal embrittlement in the structural alloys, while its movement can erode the piping system. For the molten salts used in the energy storage system, corrosion mechanisms include oxidation, fluxing, de-alloying and the accumulation of impurities. The sCO_2 Brayton cycle generator is susceptible to degradation by the oxidation, carburization and the erosion of the turbine components (Sarvghad, Delkasar Maher, et al., 2018).

Table I. Summary of operating conditions and environments of each subsystem of the CSP Plant

	Subsystem of Plant		
	Tower Receiver	**Thermal Energy Storage**	**Power Block**
Operating Temperatures (°C)	600 – 800	600 – 750	600 - 700
Environment	Liquid Sodium	Molten Salt (Phase Change Material)	Supercritical CO_2

Furthermore, at these highly elevated temperatures, and with the cyclic operation of the CSP plant, all of the structural alloys will be subject to mechanically driven degradation processes such as thermal fatigue, stress-assisted corrosion and transient creep. The overall degradation of these systems will be dependent on the complex interplay between all of these degradation mechanisms, many of which reinforce one another, exacerbating the entire process.

This research project endeavours to find a solution in the design and material choices to rectify the aforementioned degradation issues and take advantage of the next-generation equipment and technologies to generate power at commercially competitive costs. Through exhaustive characterization and testing of alloys within the different operating environments (see Fig. 2 for corrosion characterization of alloys in molten salt), the objective will be to find combinations of materials where the effects of the degradation mechanisms will be mitigated. This search for material compatibility is achieved by testing a matrix of candidate alloys to determine which alloy will be suitable for use in the different subsystems of the CSP plant.

Not only is it crucial to ensure the selection of materials meet the operating requirements for the reciever, TES and power block systems, it is imperative to ensure these materials are cost effective and practical to be used on an industrial-scale (Sarvghad, Will, & Steinberg, 2018). The search for suitable candidate materials is an exhaustive process that requires rigorous testing, however with the appropriate choices, the realization of a next generation CSP plant that can achieve cost parity with traditional fossil fuel power plants can finally be achieved.

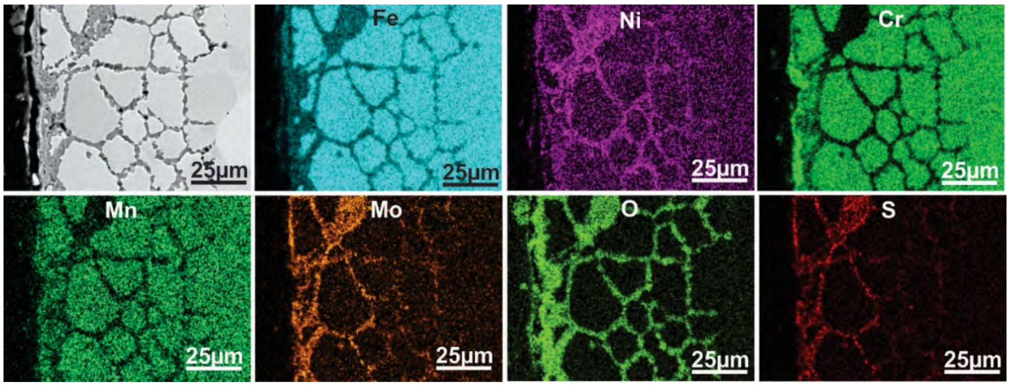

Figure 2. Cross-sectional Scanning Electron Microscope (SEM) image and its corresponding elemental analysis of stainless steel 316 alloy after 120 h exposure to the molten eutectic mixture of NaCl+Na_2SO_4 at 700 °C in air for corrosion analysis (Sarvghad, Steinberg, & Will, 2018)

References

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