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Update on the ASTRI High-Temperature Solar Sodium Facility

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Abstract. The Australian Solar Thermal Research Institute (ASTRI) has been developing technologies designed to collect and store solar energy at high-temperature to drive more efficient power cycles, or for providing heat to high-temperature thermal industrial processes. ASTRI is pursuing two alternative pathways: one is based on the use of liquid sodium as a heat transfer fluid, and the other is based on the use of solid fluidous particles. The current work describes ASTRI's completion of the design and construction of a nominal 1MW high-temperature solar sodium test facility, which will be operational at CSIRO's solar field at the National Energy Centre in Newcastle, Australia, by 2024.

Keywords: CSP, Solar, Sodium, High-Temperature

1. Sodium Test Loop Design and Construction

Sodium has a large liquid temperature range (99 °C to 883 °C) and outstanding thermal properties suited for industrial concentrated solar thermal (CST) applications, as it is for other industries. These properties of sodium improve the efficiency of solar receivers leading to reduced LCOE. Yet sodium is one of the most reactive metals, and is a class 4.3 hazardous substance which, in contact with water, produces hydrogen gas and caustic sodium hydroxide. Hydrogen has the potential to ignite explosively in the presence of air, and liquid sodium can burn in air producing lots of dense white caustic smoke.

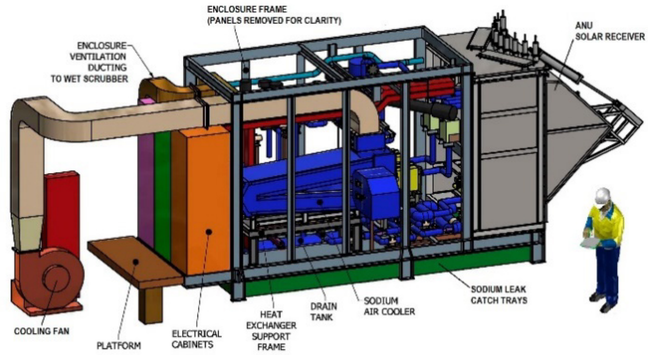
CSIRO has developed for ASTRI a high-temperature sodium test loop rated up to 740 °C at the solar receiver outlet. The sodium test loop will be a test bed for a range of technologies applied to CST applications. The design is an innovative solar engineering solution establishing a unique approach to health, safety, and environment to de-risk this experimental infrastructure.

An extensive literature search on the history and risks of sodium fire incidences spanning several decades was conducted by CSIRO. Specialists from the alkali metals industry were also engaged (Creative Engineers Inc, and expertise previously involved with Argonne National Laboratory) to provide safety guidance and input into the design.

This secondary fire and smoke management system has added significant complexity and cost, now making the complete system comprised of two system modules: a self-contained sodium test loop that can be tested on the ground initially and then installed atop the solar tower and connected to services; and a self-contained fume wet scrubber system located on the ground and connected by an air duct.

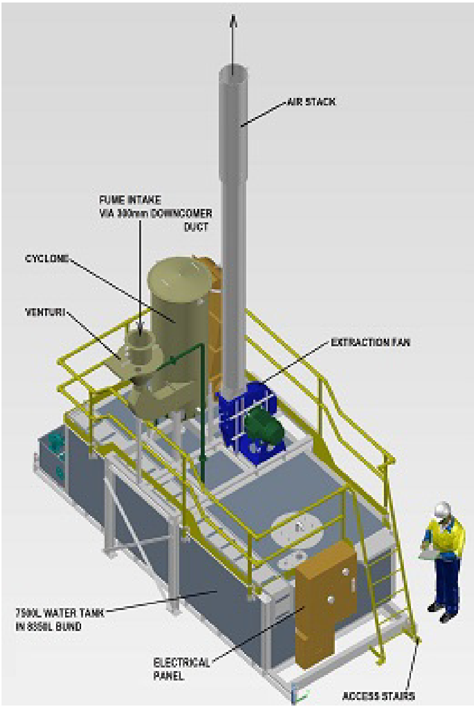
The resultant design produced a modular system that is not only a high-temperature circulating sodium loop as a testbed for a range of technologies applied to a CST application, but also a system designed to detect a sodium leak using temperature & smoke detection, and inventory control, and take appropriate action (Fig 1). This involves shutting down the sodium flow to allow sodium to drain to a central storage tank, thus preventing further sodium leakage and intentionally letting the small amount of leaked residual sodium combust, all while having a scrubber operating to extract and neutralise the sodium oxide smoke. With safety being of the highest priority, the system is designed to be intrinsically safe. Description of the design process and the commencement of construction is described in detail by [1].

Vast Solar Pty Ltd, an Australian-based solar thermal company, and experts using sodium as a solar heat transfer fluid were engaged as the specialist construction contractor and project partner with ASTRI. Vast Solar completed the detailed engineering and procurement activity in 2022, and construction was completed in May 2023.



(a)

(b)



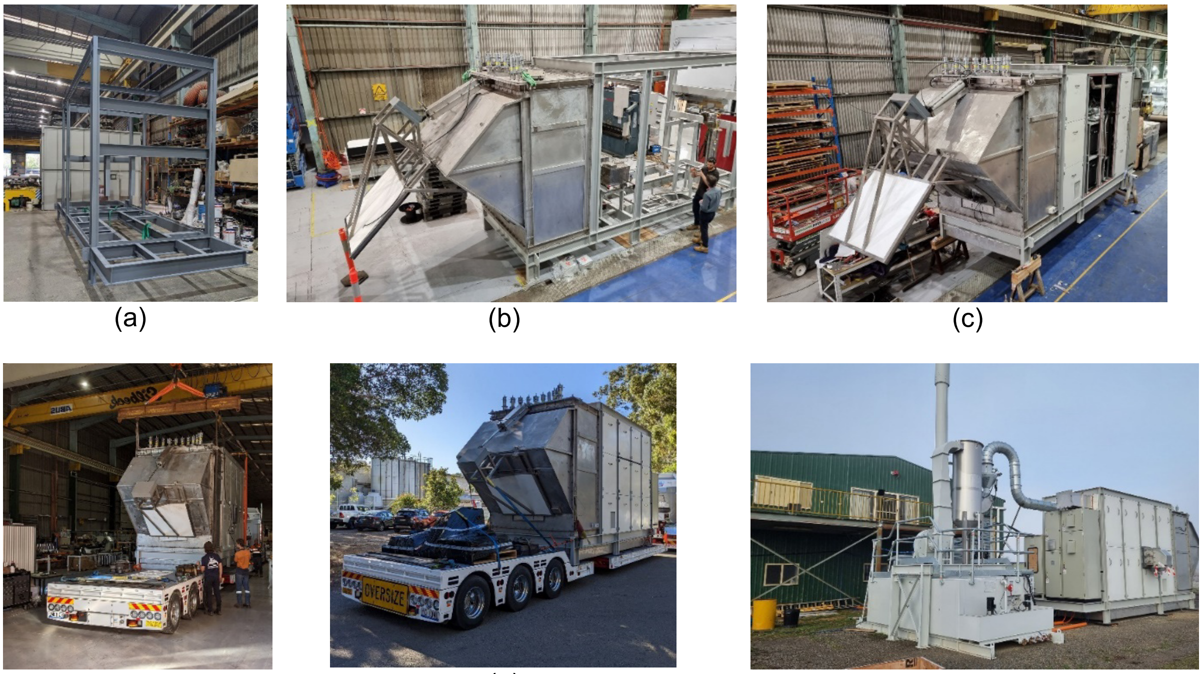
(c)

(d)

Figure 1(a) The final design of the sodium loop module with integral solar receiver attached, **(b)** the constructed sodium module with weather-proof enclosure panels **(c)** The final design of the scrubber system, and **(d)** the completed scrubber system at Vast Solar.

2. Construction Completion

The construction activity of both modules occurred from August 2022 to April 2023.



(a) (b) (c)

(d) (e) (f)

Figure 2 The various stages of the sodium loop module construction showing the **(a)** steel base frame, **(b)** the integral solar receiver attached, **(c)** enclosure fit-out of equipment, **(d)** crane loading for transport, **(e)** fully built sodium module with weather-proof enclosure panels, and **(f)** both modules placed at the Jemalong site for testing by Vast Solar.

3. Systems Testing

In May of 2023, both modules were delivered to Vast Solar's Jemalong site in NSW where the sodium test loop module was initially connected to the scrubber module, filled with liquid sodium, commissioned, and tested on the ground. The fire detection and response systems were tested for reliability and repeatability, and then the modules were delivered to CSIRO for site installation and planned on-sun testing to commence in 2024.

Testing conducted at the test site:

- Electrical power systems.
- Heat tracing system.
- All sensors tested, corrected, and tested again.
- Sodium melting and system fill (250 kg).
- Argon cover gas system tested.
- Sodium cold trap and plugging meter (sodium conditioning devices).
- Piping fill from drain tank and drain down tested.
- Sodium circulation pumps and flowmeters.
- Expansion tank and level probes tested/adjusted; and a
- Complete rigorous Shake-Down testing of all control and safety systems (June to August 2023), checking the reliability, repeatability and building trust.

4. Fire and Emergency Shutdown Tests

Before the equipment was permitted to be placed on the CSIRO National Solar Energy Centre site, and before on-sun operational tests can commence, a series of fire and emergency shutdown tests were commenced, leading to final acceptance by CSIRO.

Both the sodium main skid and the wet venturi fume scrubber skid were placed beside each other on the ground at VAST's Jemalong site, connected to mains power, digital comms connection of the scrubber to the main skid, fume ducting connected, and smoke detector suctions lines connected. Figure 3 shows the two modules together, connected by power cables placed on the ground with protective orange coloured electrical conduit. Also connecting the two skids are an ethernet cable for digital comms connection, electrical power to the scrubber, and smoke detection line.

Figure 3 Both the sodium test loop module and wet venturi fume scrubber module connected together at Vast's Jemalong site.

Also shown in figure 3 in the foreground (left) is the sodium temporary storage and transfer vessel used to transfer molten sodium to the central storage tank within the main skid, and (right) the argon cover has pack of gas bottles.

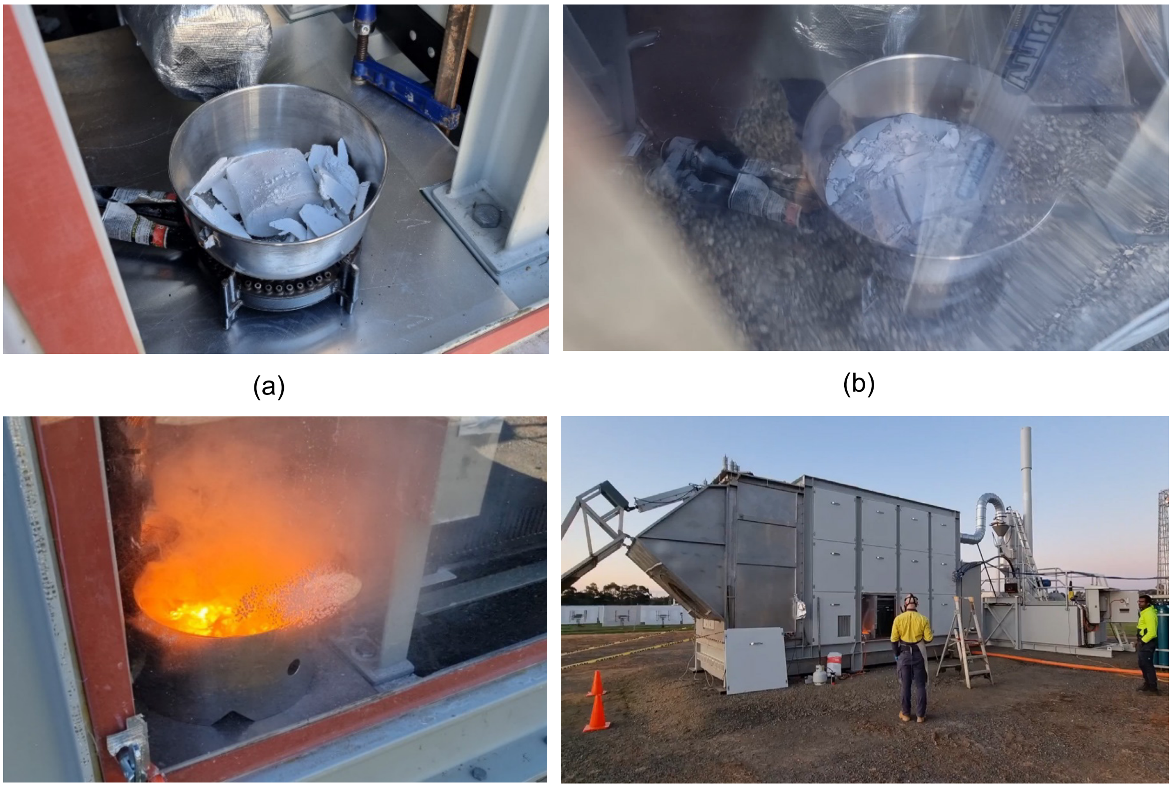
Fire testing was necessary to test the emergency shutdown response to check for repeatability and reliability of all systems involved. This meant a sodium fire had to be set inside the main module, which was done by removing one weather-proof enclosure panel to gain access to inside the module enclosure. In its place a transparent Perspex cover was mounted with a hinge to allow opening for access, and once the fire is lit it can be closed to contain extraneous smoke emissions and to protect personal. Essentially the main skid enclosure functioned as a large fume hood where the fire can be observed at close range without risk to testing personal.

Numerous tests were conducted with sodium fires lit both inside the main skid enclosure, beneath the electromagnetic flow pumps, and also on the floor inside the receiver cavity.

The response expected upon detection of a sodium fire are aimed at verifying the functionality of four key system responses. These are:

1. Sodium smoke is detected by the VESDA VLI-880 series detector by Xtralis. Signal sent to control system.
2. Scrubber fan ramps up from 40% speed (cooling ventilation mode) to 100% speed for smoke fume entrainment mode.
3. Solar receiver aperture door closes to limit an smoke emitted from the aperture.
4. Sodium in circulation throughout the test loop is released by sodium valves failing open (or driven open) to allow all possible sodium to return to the central drain/storage tank.

Figure 4 below shows the general sequence of steps, where (a) sodium ingots are prepared and cleaned and placed into a stainless-steel crucible. Sodium oxide forms on exposed metal surfaces and appears white. The gas burner is lit (b) and melting of the sodium has commenced. Complete melting takes about 5 minutes and the oxides float on the surface of molten sodium. Convection currents can be observed moving on the surface of the sodium pool. As the sodium is fully melted it continues to heat, where at approximately 120 to 125 °C a small bright orange spot appears on the surface, which then grows to the full extent of the crucible diameter and a fully developed burn is underway (c). Copious amounts of dense white smoke is also observed rising from the surface of the sodium pool fire, which then becomes entrained into the air flow toward the scrubber connecting duct. Once a fully developed fire is established the gas supply to the burner is shut-off and the sodium continues to burn.



(a) (b) (c) (d)

Figure 4 Sodium fire tests **(a)** sodium ingot and offcuts crusted in a sodium oxide layer, placed in the melting crucible **(b)** sodium melting in the crucible with oxides floating on the surface, **(c)** sodium combustion well underway and **(d)** emergency shut-down test during observation by Vast Solar.

The sodium fire is allowed to continue burning until the fire puts itself out, usually by forming a thick oxide layer, which itself limits air exposure to continue fuel the fire. Not all of the sodium is consumed and approximately 30-60% remains in the crucible.

5. On-Sun Operation Plans

In October 2023 the main sodium module was delivered to CSIRO’s solar site and placed on its standby pad for the SolarPACES Technical Tour. Here it will remain until preparation works on the solar tower are completed to receive the main sodium module. Refer to figure 5, showing the main module placed on its storage pad at the base of solar tower 2.

Figure 5 The main sodium module placed on its storage pad by crane at the base of solar tower 2.

Site preparations are underway to incorporate the systems into solar field 2. The on-sun testing is expected to commence in 2024, to gather operational data on solar receiver performance, and the sodium to air cooling heat exchanger.

Data availability statement

This submission is on preliminary data. Data supporting the final results will be updated in later submissions and will be deposited in a FAIR-aligned public repository.

Author contributions

Wilson Gardner: Conceptualisation, Investigation, Project administration, Formal Analysis, Supervision, Writing – Original Draft, Wesley Stein: Conceptualisation, Supervision, Project Administration, Funding acquisition, Michael Rae: Conceptualisation, Investigation.

Competing interests

Competing interests arise when issues outside research may fairly be viewed as impacting the work's neutrality. All potential competing interests must be disclosed (“The authors declare the following competing interests: …”). If there are no potential competing interests please state “The authors declare that they have no competing interests.”

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References

1. W. Gardner, “Design and Construction of a High-Temperature Solar Sodium Facility” In SolarPACES2022, Albuquerque, N.M., 2022