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SCO2 Power Cycle Prototype using Thermal Energy Storage

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ABSTRACT

High costs and short service life of electric power storage technologies are driving a need for new solutions in energy storage. Solar and wind need to become dispatchable if their penetration is to exceed about 20%-30% of the total electric power generated. This represents a broad opportunity to apply sCO2 power conversion technology to renewable power firming.

Peregrine has developed a new combination of technologies for storage of renewable power by combining our high-performance sCO2 turbine power system with a technology developed in Australia for Thermal Energy Storage (TES). Peregrine is currently engaged in testing a proof-of-concept technology demonstrator at our lab in Wiscasset, Maine. This thermal storage technology stores heat at a constant temperature by utilizing the latent heat of solidification of suspended metal chips in a graphite suspension. The result is a dramatically increased thermal storage capacity by volume and improved discharge rate when compared to other thermal storage media available in the thermal storage market.

Peregrine has completed the first phase of a campaign to test a Thermal Energy Storage (TES) System integrated with Peregrine's sCO2 Power Conversion System that will ultimately produce 1MWe. To the authors knowledge, this is the world's first TES system specifically tested and designed to be used with an SCO2 power conversion system and will enable the storage of renewable power well beyond the discharge duration capability of Lithium-Ion batteries, which are seen as the incumbent technology in this market sector.

This paper will present test results from Phase I of the test campaign demonstrating black start capability and describe controls strategies for managing power demand transients when employing a constant temperature heat source.

INTRODUCTION

Peregrine Turbine Technologies, LLC has been developing high-performance turbomachinery and heat exchangers specifically designed for sCO2 thermal cycle applications since 2012. Peregrine's unique approach to turbomachinery design has resulted in the highest performance systems in sCO2 power cycles currently known to the author. Peregrine's turbopump is designed to produce 5.7 kg/sec of sCO2 flow at 43MPa and is capable of turbine inlet temperatures of 750°C, all while maintaining turbine casing temperatures under 300°C.

Peregrine's proprietary microchannel heat exchanger designs achieve high performance at very high pressures with minimal thermal inertia and with proprietary technology that significantly mitigates thermo-mechanical fatigue.

To demonstrate system performance and validate each component of the design, Peregrine has constructed a high-performance test rig utilizing proprietary components both in turbomachinery and heat exchangers. In addition, Peregrine has married this power conversion system to a novel proprietary Thermal Energy Storage (TES) system design that utilizes phase-change material at high temperature to maximize power storage density and discharge rate.

A description of the components and the operation of the system, together with test objectives and results, are the subjects of this paper.

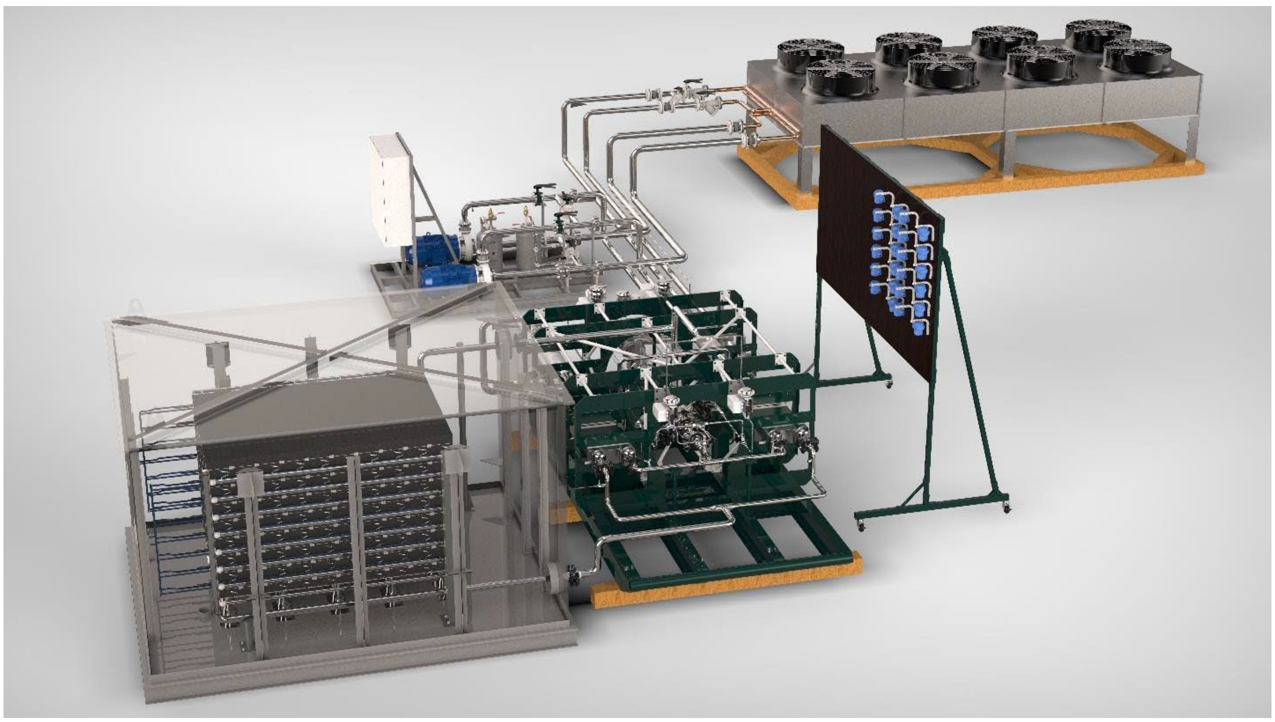

Figure 1 - Luna Test Rig Layout

Peregrine has assembled the key components of the system in a test rig referred to here as the Luna Test Rig. The overall system layout is shown in Fig. 1 above with the P&ID shown in Fig. 2.

Notable components include ambient cooling heat exchanger (COTS), the cooling flow pump skid, the TES vault which is the primary heat source, the Luna Test Rig skid itself, and the test rig instrumentation.

Test Objectives

Program goals include the following:

- Design and optimization of control strategies for power control, compressor inlet condition management, secondary flow management, and anomaly mitigation.

- Optimization of discharge start parameters.
- Operation of turbopump at points well above the limits tested previously at Sandia National Labs
- Validation of turbopump thrust balance.
- Compressor map validation.
- Characterization of transient performance of TES discharge
- Exploration of TES charging characteristics using direct electrical heating elements

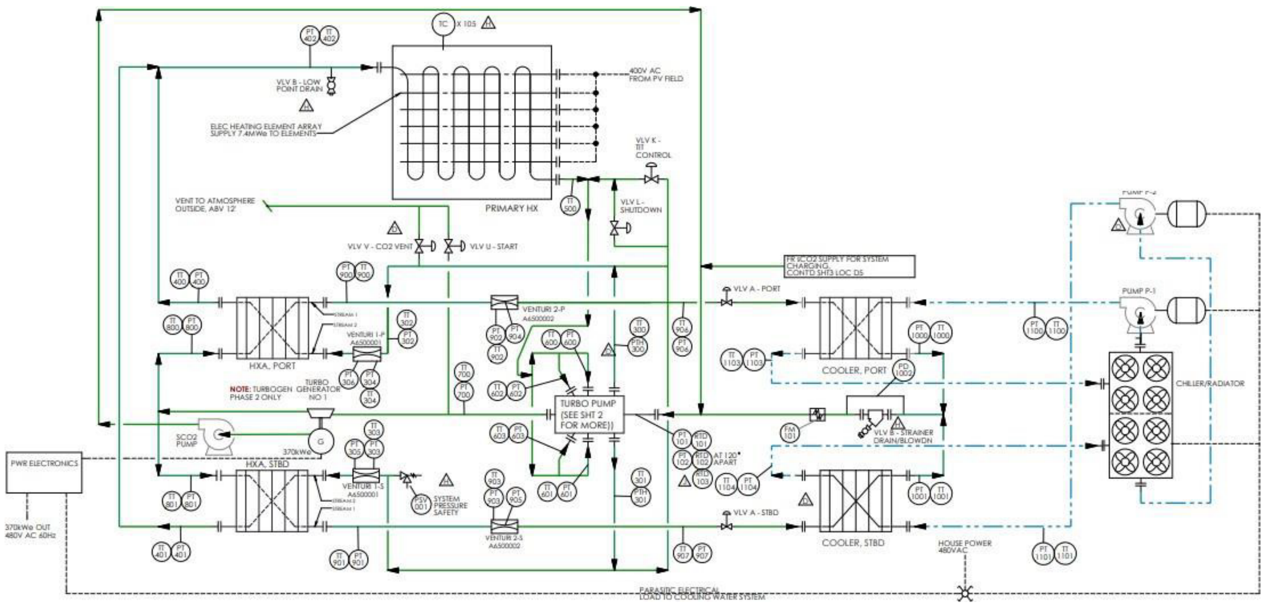

Figure 2 – Luna Rig P&ID Diagram

Starting Procedures

In early testing at Sandia national Labs, the practice for starting the turbopump at Sandia involved preconditioning of the loop so that all components achieved a temperature approaching the targeted steady state values. This was accomplished by pumping sCO2 flow through a bypass pump loop that created a mass flow rate below about 1 lbm/s. This flow rate delivered good preheating results without causing the turbopump rotor to spin. Higher mass flow rates showed intermittent rotation of the turbopump rotor which would occur at speeds well below the lift-off speed of the gas dynamic bearings and could lead to premature bearing wear. To mitigate this, the flow rate was kept below 1.0 lbm/s.

The Luna Test Rig discussed here does not employ a preconditioning pump regime. The cost and additional valving required as well as the power demands to operate it are less than ideal for a commercial system. Instead, the Peregrine Turbine system uses the thermal syphoning effect through the TES vault to drive a modest flow that is sufficient to preheat piping and turbomachinery outside of the TES and does so without any moving parts to maintain. This has proven adequate to maintain supercritical conditions throughout the system.

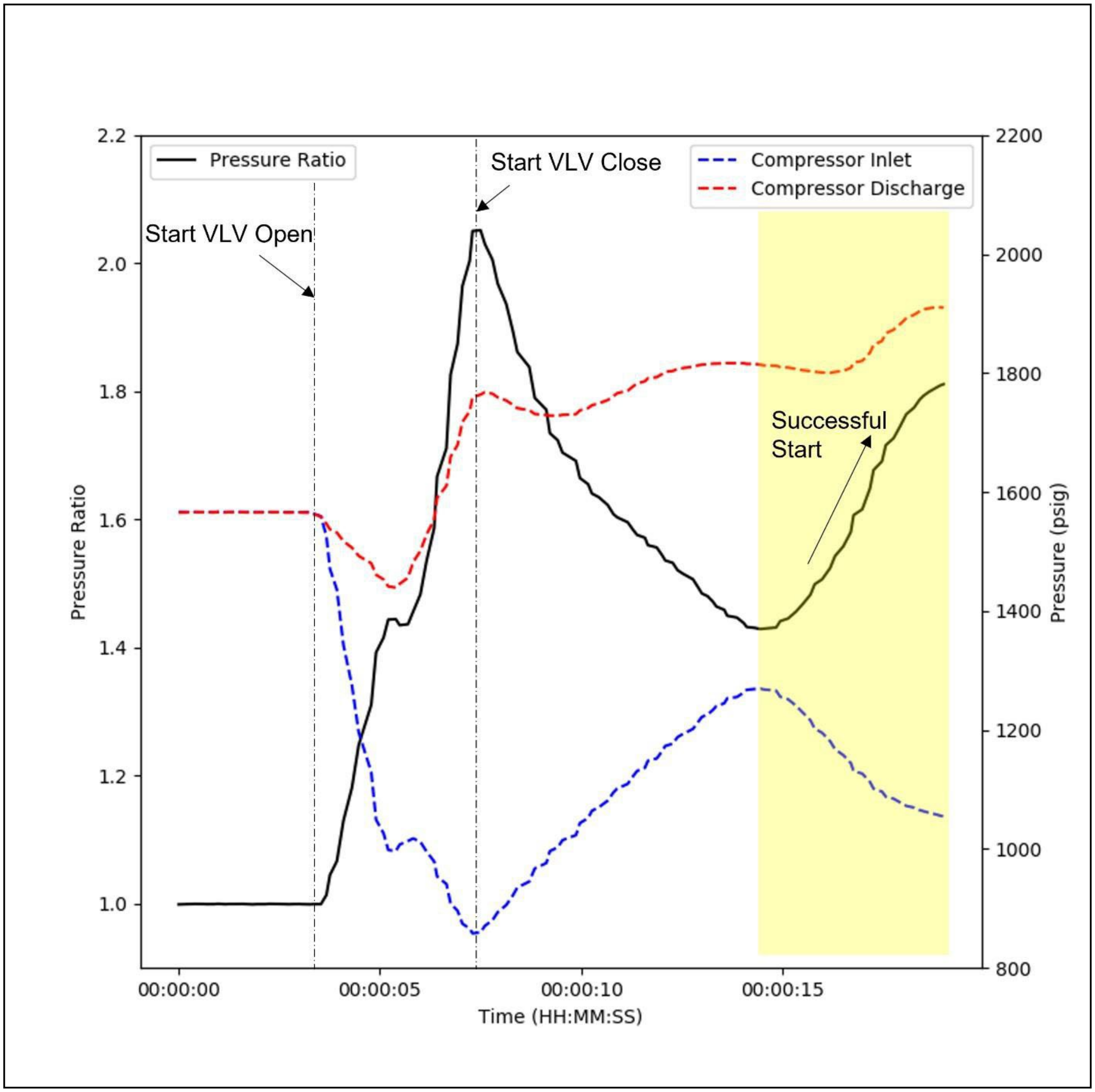

Figure 3– Details of a Successful Discharge Start

To effect start, Peregrine utilizes a patented method which is referred to as the discharge start. Since the turbopump does not have an integral motor/generator, a motive force outside of the turbopump is required to achieve a start. Others have proposed using a motor driven pump for starting. Peregrine's method does not require additional hardware outside of an additional valve which is used to discharge a predetermined mass of sCO_2 from the loop downstream of the HP turbine. The discharge can either be to the external environment or to a large plenum at low pressure. Either way, the pressure differential created across the HP turbine wheel by opening the valve results in sufficient flow to activate the HP turbine, driving the compressor, and effecting a flow and pressure ratio increase. With sufficient duration and addition of heat at the HP turbine inlet, a start may be achieved. This approach eliminates or reduces the cost, complexity, and maintenance needs of starting the system while enabling black-start capability. An example of this start method is depicted in Fig. 3.

For the last three years, the Peregrine turbopump has been tested at Sandia National Labs under a Combined Research and Development Agreement (CRADA) for long term durability, having completed over 600 hours of runtime. The turbopump was integrated with Sandia's existing test loop originally designed and built by Barber Nichols (BNI) which incorporated a Turbo Alternator Compressor (TAC). The system was originally designed for a Max Allowable Working Pressure (MAWP) of 2500 psi and 500°C (Rapp, Stapp 2019). The BNI compressor in this loop is designed to operate at 75,000 rpm with a pressure ratio of 1.8 and a mass flow rate of 3.5 kg/s (Wright 2010). By contrast, the Peregrine turbopump, designed partly under funding from the US Air Force Research Lab and the US Office of Naval Research is designed for operation at 121,000 rpm with a pressure ratio of 5.5 and mass flow rate of 5.7 kg/s, which is the system operating design point to produce 1MWe from the downstream three-stage turbogenerator expansion.

Because of the MAWP limitations of the Sandia loop, the Peregrine turbopump was limited to part power operation during initial testing there. The need for a higher capability test rig was evident. Peregrine received funding from the Maine Technology Institute in the form of a Development Award. That, combined with private investment, enabled Peregrine to construct the Luna test rig which can achieve pressures of 4000 psi (27.6 MPa) at 538° C with unlimited life, and ultimately will achieve 6220 psi (42.9 MPa) with limited calculated life of piping and TES.

Thermal Energy Storage

Because of the heat-agnostic characteristic of closed Brayton cycle engines, the heat can be from any of a variety of sources. Peregrine has system designs utilizing heat from air- combustible fuels like fossil fuels, biomass and refuse-derived fuels, process waste heat recovery, thermal energy storage, CSP and nuclear reactors. One of Peregrine's targeted initial demonstrator units employs the TES vault as the primary thermal source. This is intended to be an alternative to grid scale Lithium-ion battery storage. The Peregrine system has a 20-year field life compared to the 8–10-year life of Li-ion solutions. There are also no hazardous or environmentally unfriendly materials in the Peregrine system. Peregrine's TES system is projected to be about 1/3 the annualized capital cost when compared to commercially available Li-ion systems of the same power and storage duration.

In order to fully demonstrate the integration of a thermal storage medium with an sCO2 power cycle, Peregrine undertook the construction and test of the first TES system married to an sCO2 heat engine. The overall test system is referred to as the Luna Rig and is a Proof of Concept (POC) prototype that is being tested in two phases. In the first phase, the turbopump which was previously tested at Sandia National Labs is integrated with Peregrine's proprietary recuperator design as well as the TES primary heat source. Flow expansion through the Turbogenerator is simulated with two controlled valves downstream of the recuperators. Once phase I objectives are achieved, the Peregrine-designed turbogenerator employing a high-speed Permanent Magnet Generator (PMG) and radial inflow turbine will be integrated with the system to initially produce up to 350kW in a single stage expansion. At design point, the system will produce 1MWe by expanding across three independent stages in series, each powering its own PMG.

Figure 4– Assembly and Wiring of the TES Vault Internal Heaters and Instrumentation

The Peregrine TES employs technology that utilizes latent heat of fusion of aluminum particles suspended in graphite bricks. The bricks are assembled into Peregrine's primary heat exchanger and interleaved with resistance electric heaters that are used to initially charge the vault with its heat load. The instrumentation and electrical power wiring assembly is shown in progress in Figure 4. Individual manifolds and tubing-runs that form the primary heat exchanger and are integrated with the thermal storage medium. The TES was assembled and tested at a remote location and subsequently delivered to Peregrine's test lab. The delivery and installation of the TES vault is shown in Fig. 5 below.

Figure 5- Delivery and Installation of the Peregrine Thermal Energy Storage Vault

There are four independent heating zones within the TES, each controlled separately and powered by a 3-phase 480V electrical supply. Figure 6 shows the results of a heating zone test prior to enclosing the thermal bricks within the insulated enclosure.

The intended application is to store renewable power such as solar or wind to enable increased penetration of renewables in the grid supply and provide renewable power around the clock. The system may also be used to manage grid demand near the point of use to mitigate demand charges and reduce peak grid loads. Because of the 1MWe power rating of the system, it may be utilized for EV charging from the grid to avoid demand charges.

To the author's knowledge, this is the first instance of a thermal energy storage (TES) medium integrated with an sCO2 power producing cycle.

RESULTS AND DISCUSSION

To date, Peregrine hasconducted numerous charges of the TES system to confirm electrical charging characteristics and control. A full test rig charge brings the TES system to an internal temperature of 680°C. To date, the system has been recharged multiple times to this temperature which exceeds the latent heat temperature of the storage media, maximizing the energy storage density potential of the system.

Numerous starts have been conducted with various settings of turbine inlet temperature, discharge valve duration of actuation, flow metering of discharge and stutter starts to determine optimal settings. Data graphs of key running thermodynamic conditions like compressor inlet compressor discharge temperature and pressure, Turbine inlet and discharge temperature and pressure, rotor speeds and various other conditions are shown in Fig.7 & 8 below.

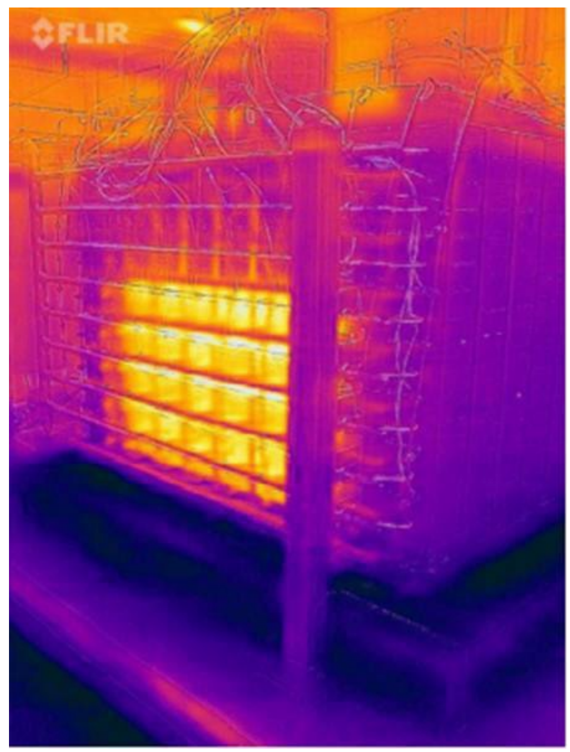

Figure 6- IR Image of TES Heater Test

Figure 9 shows the average temperature of the thermal energy storage vault as a test is run using the vault as the heat source for operation. Although the average temperature drops across the duration of the test, TIT remains constant by means of the throttle control PLC that mixes compressor discharge flow with TES outlet flow to achieve the prescribed target turbine temperature. The initial sudden drop in average temperature is attributed to local temperature effects within the media related to the location of the thermocouples and shows the initial temperature shock of relatively cold flow entering the TES from an unheated recuperator.

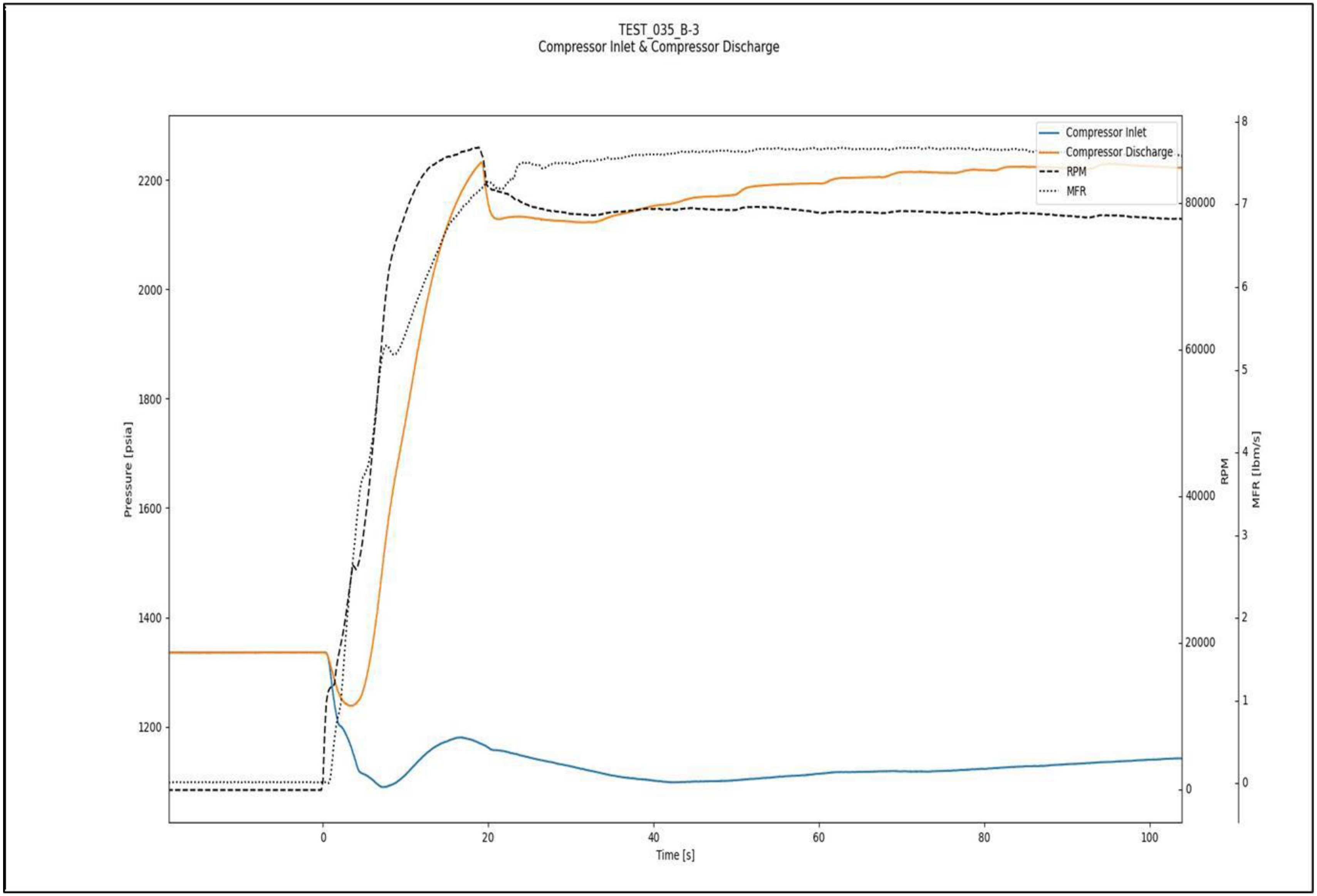

Figure 7- Compressor Inlet & Compressor Discharge

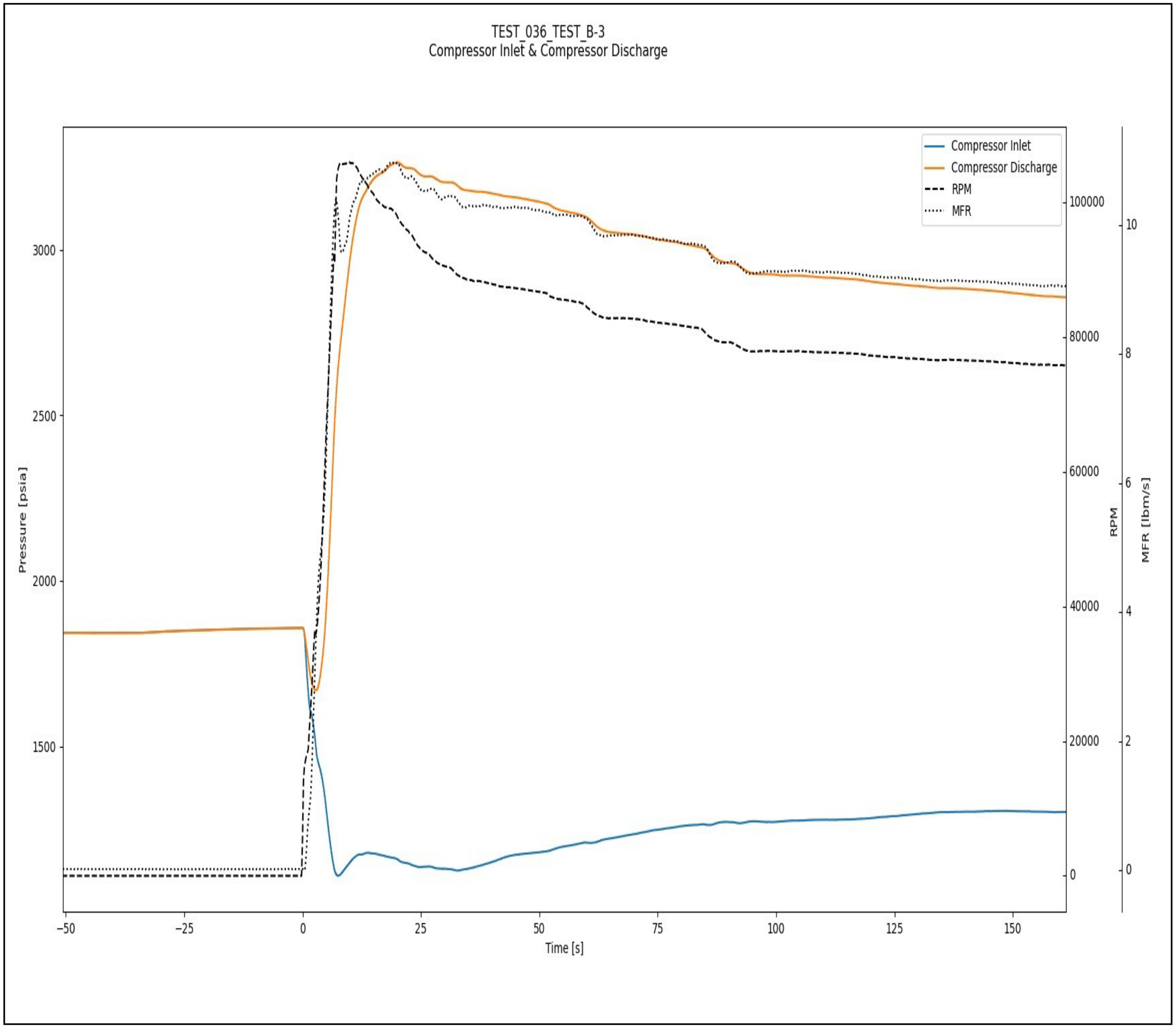

Figure 8- Compressor Inlet & Compressor Discharge

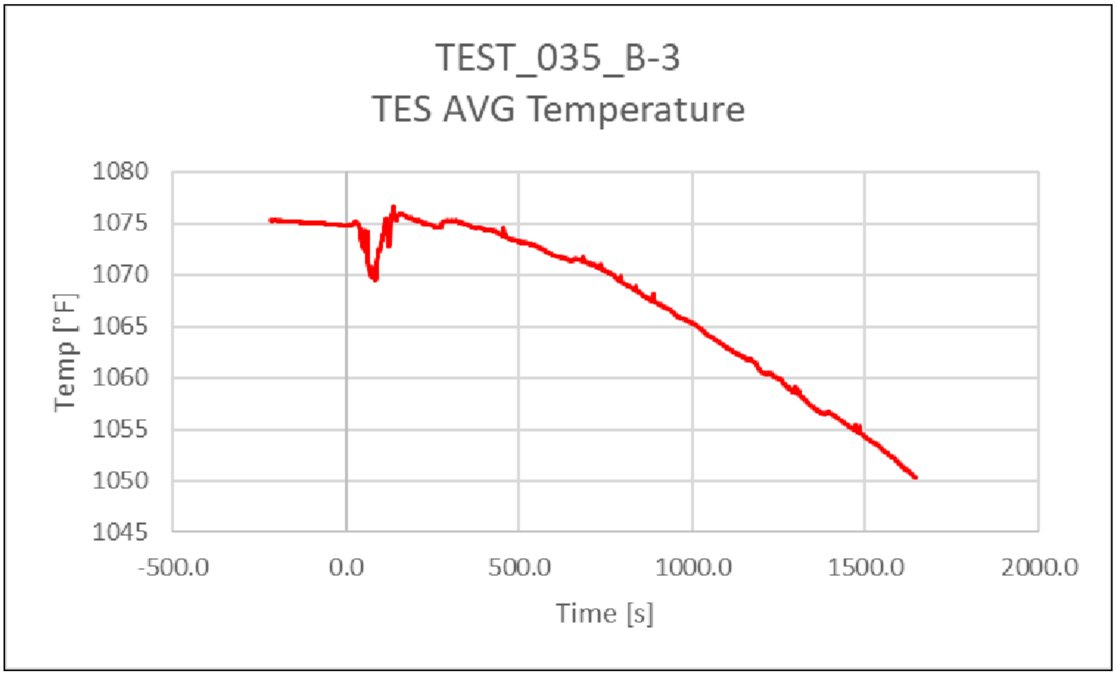

Figure 9 – Thermal Storage Average Temp During a System Test

CONCLUSION

To the author's knowledge, the Luna Test Rig developed by Peregrine Turbine Technologies, LLC represents the first integration of an sCO2 power cycle with a thermal energy storage (TES) medium and will be the first to produce 350 kW of power directly from stored thermal energy. The system tests prove TES design methods, control strategies, sCO2 component performance, heat exchanger performance, durability and overall viability of the sCO2 Brayton cycle for commercial applications. The luna test rig provides the needed steppingstone to the testing of the 1MWe Peregrine Turbine TES system as well as the biomass-fired system, both of which are slated as demonstrators to be fielded in real-world applications in 2025.

REFERENCES

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ACKNOWLEDGEMENTS

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