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Thermal Energy Distribution System (TEDS) Startup and Commissioning

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ACRONYMS

DETAIL	Dynamic Energy Transport and Integration Laboratory
DOE	Department of Energy
ESL	Energy Systems Laboratory
INL	Idaho National Laboratory
MAGNET	Microreactor Agile Non-Nuclear Experimental Test
NIST	NuScale Integral System Test
RTDS	Real Time Digital Simulators

Thermal Energy Distribution System (TEDS) Startup and Commissioning

INTRODUCTION

Nuclear power plants operate most efficiently and economically when run at a constant power output. However, with the current dynamics of the electrical grid, including the introduction and growth of renewable energy sources (such as wind and solar), nuclear generation facilities across the U.S. are finding it difficult to maintain constant power output and provide for baseload generation capacities. As a result, many nuclear power plant operators are finding it hard to compete with other power generation sources, most notably natural gas [1]. Finding a solution to this intermittent demand dynamic could help U.S. nuclear power plants to economically compete with other generation sources, such as natural gas, wind, and solar.

A Dynamic Energy Transport and Integration Laboratory (DETAIL) is being constructed at Idaho National Laboratory's (INL's)Energy Systems Laboratory (ESL) to demonstrate an integrated system operation as part of supporting research and development needs for the Department of Energy's Office of Nuclear Energy Integrated Energy Systems Program. DETAIL will demonstrate real-time integration with the electrical grid, renewable energy inputs, thermal and electrical energy storage, and energy delivery to an end user. The Thermal Energy Distribution System (TEDS) has been constructed at ESL, as part of DETAIL, to demonstrate heat transfer components, distribution systems, instruments, and controls that can be monitored and controlled for integrated energy system operation, emulating the distribution of thermal energy to the generation of electrical power and/or use in producing non-electrical commodities (e.g., hydrogen).

As will be the case for other subsystems within DETAIL, TEDS is designed to operate either independently or as a part of an integrated system to demonstrate the operation of integrated components, develop and validate thermal energy transport models and control systems, and study thermal energy inertia and storage. Within the integrated system, TEDS will be connected to INL's Real Time Power & Energy Systems Innovation Laboratory test platform to develop and demonstrate monitoring and control systems and to investigate real-time, hardware-in-the-loop response characteristics relative to grid operations. The system can be used to characterize thermal energy inertia and thermal energy management relative to the interoperability of a nuclear plant, power generation, and industrial heat applications. Additionally, TEDS operation will provide data to validate computational models such as RELAP5, Modelica, and other transient physics-based models that can be used as we scale-up hybrid energy systems for demonstration with operating (fueled) nuclear plants. TEDS can also be used to support cyber-informed engineering of controls and hardware systems.

Note TEDS essentially acts as an intermediate loop that would connect a primary system (e.g., a pressurized water reactor or other reactor technology) to a thermal energy user. In its initial implementation, the physical emulation of the nuclear primary system will not be connected to TEDS. The system instead includes a programmable heater/temperature controller that can be used to emulate the heat input from a variety of primary systems either via pre-determined operational data sets or via virtual connection to primary system test facilities through communications protocol available in the laboratory. Such virtual communications and interconnected operation have previously been demonstrated with the "Real Time SuperLab" concept via Real Time Digital Simulators (RTDS) in the DETAIL facility. Virtual connection with facilities such as the NuScale Integral System Test (NIST) facility at Oregon State University is being assessed currently. Prior to establishing real-time connections, the TEDS programmable heater will be controlled to emulate steady-state operation and transient operation that might be anticipated in the primary system. Future laboratory additions to include the thermal integration of the Microreactor Agile Non-Nuclear Experimental Test Bed (MAGNET) that will be physically connected to TEDS via heat exchanger for integrated energy system operation. The TEDS was constructed in the DETAIL facility to test heat transfer components, distribution systems, instruments, and controls that can be monitored and controlled for hybrid generation of electrical power and/or non-electrical products. As is the case for other subsystems within DETAIL, TEDS is designed to operate as a part of an integrated system or independently to demonstrate the operation of TEDS unit components, to develop and validate thermal energy transport models and control systems, and to study thermal energy inertia and storage.

The primary objectives for TEDS are as follows:

- Provide a flowing test bed that will allow flow rate and temperature modulation and will enable performance analysis and demonstration of:
    - Energy storage in charging and discharging modes;
    - Energy storage function in the context of overall (integrated) system operation strategy;
    - Valves, flanges, instrumentation, and other associated components (such as gaskets, seals, and filler materials) under steady-state and cycling modes;
    - And distribution of thermal energy to and from various co-located systems in DETAIL, further providing information on the dynamic operation and characteristic time constants associated with moving thermal energy between systems of different sizes and heat requirements.
- Provide a connection to the INL digital real-time simulator test platform and to the high-temperature steam electrolysis system to develop and demonstrate monitoring and control systems and to investigate real-time, hardware-in-the-loop response characteristics relative to grid operations. The system can be used to characterize thermal energy inertia and thermal energy management relative to the interoperability of a nuclear plant, power generation, and industrial heat applications.
- Produce operational data that will be used to validate computational models such as RELAP, Modelica, and other transient physics-based models that can be used to support scale-up of integrated energy systems.
- Demonstrate transport/transmission characteristics and performance in a flexible and dynamic manner, such that the envisioned operational modes can be tested, and performance verified.
- Provide a testbed upon which to test both standard regional grid operations but also provide the ability to experimentally simulate the buildout of potential future grids that may include excessive renewable (solar and wind) penetration.
- Provide an opportunity to experimentally demonstrate grid stressors that otherwise may not be simulated and see how such stressors may impact the generators in one-way feedback.
- Support unattended operation and provide a platform for demonstrating safe shutdown procedures.
- Provide a test/demonstration platform to support cyber-informed engineering of controls and hardware systems.

This report serves as a summary of the startup and commissioning testing for TEDS. For a more detailed description of TEDS design considerations and parameters, see the design basis report [1].

OPERATION MODE DEFINITIONS

Mode definitions were set during Modelica modeling of TEDS. For a more detailed description, see the INL report describing the Modelica model for TEDS [2]. Mode 1 simulates the heat generation source operating in standard operational mode with zero-energy storage. This mode is akin to currently operating generators accommodating a standard load following mode. Mode 2 simulates a full charging scenario where the thermal generator is sending its heat to the thermal storage unit entirely. Mode 3 simulates a full discharge scenario. For this the thermal generator is turned off, and the thermal storage unit is the sole unit providing heat to the balance of plant or ancillary process. Mode 4 is a combination of Modes 1 and 2 where the thermal generator is providing a portion of its heat to thermal storage and a portion to the heat load. Typically, this operational unit provides heat to the load first and then dumps excess heat into the thermal storage unit for use later. Mode 5 involves a combination of Modes 1 and 3 where both the thermal generator and thermal storage tank are providing heat to the load. Table 1 provides a summary of operating modes, whether the heat source is going to the load, and whether the system is in charging or discharging status.

Table 1. Operating Mode Summary

Mode	Heat Source to Load	Charging (Heat Source to Thermocline)	Discharging (Thermocline to Load)
1	Yes	No	No
2	No	Yes	No
3	No	No	Yes
4	Yes	Yes	No
5	Yes	No	Yes

TEST PLAN

1. Fill and vent the system
    a. Fill by gravity to the extent possible
    b. Start MOS pump at low speed to fill remainder of system
    c. Vent all high points until no air is discharged
2. Heat up to 200°F
3. Shift to "charge" mode and let all thermocline thermocouples come to equilibrium
4. Shut system off and characterize ambient cool down of thermocline
5. Commission chiller according to manufacturer's instructions
6. Shift to "charge" mode (Mode 2) and heat thermocline to 150°C
7. Shift to "discharge" mode (Mode 3) until thermocline cools down to 100°C
8. Shift to "charge" mode (Mode 2) and heat thermocline to 200°C
9. Shift to "discharge" mode (Mode 3) until thermocline cools down to 100°C
10. Shift to "charge" mode (Mode 2) and heat thermocline to 225°C
11. Shift to "discharge" mode (Mode 3) until thermocline cools down to 100°C
12. Shift to "charge" mode (Mode 2) and heat thermocline to 250°C

    NOTE: The strain gauges are rated only for 225°C and are not expected to survive at 250°C. The data from successive heat up and cool down to their maximum rated temperature will allow the experimental analysis team to extrapolate thermal ratcheting effects to full operational temperatures.
13. Shift to "discharge" mode (Mode 3) until thermocline cools down to 100°C
14. Shift to "charge" mode (Mode 2) and heat thermocline to 325°C

    On heatup to 325 °C, a valve was discovered out of position. When it was open, a system transient caused operators to shut the system down. A root cause analysis will prevent system start up for several weeks, but the data collected demonstrates TEDS operability. See Figure 4 for heatup and transient data.
15. After each heat up, inspect all bolted joints for leakage

16. Shift to “discharge” mode (Mode 3) until thermocline cools down to 50°C.

This test plan concludes the TEDS commissioning. The construction sub-contractor will install insulation pads over bolted connections and valves and will then turn the system over to INL. TEDS is considered fully operational and will be run to validate remaining operational modes to support modeling verification and validation work.

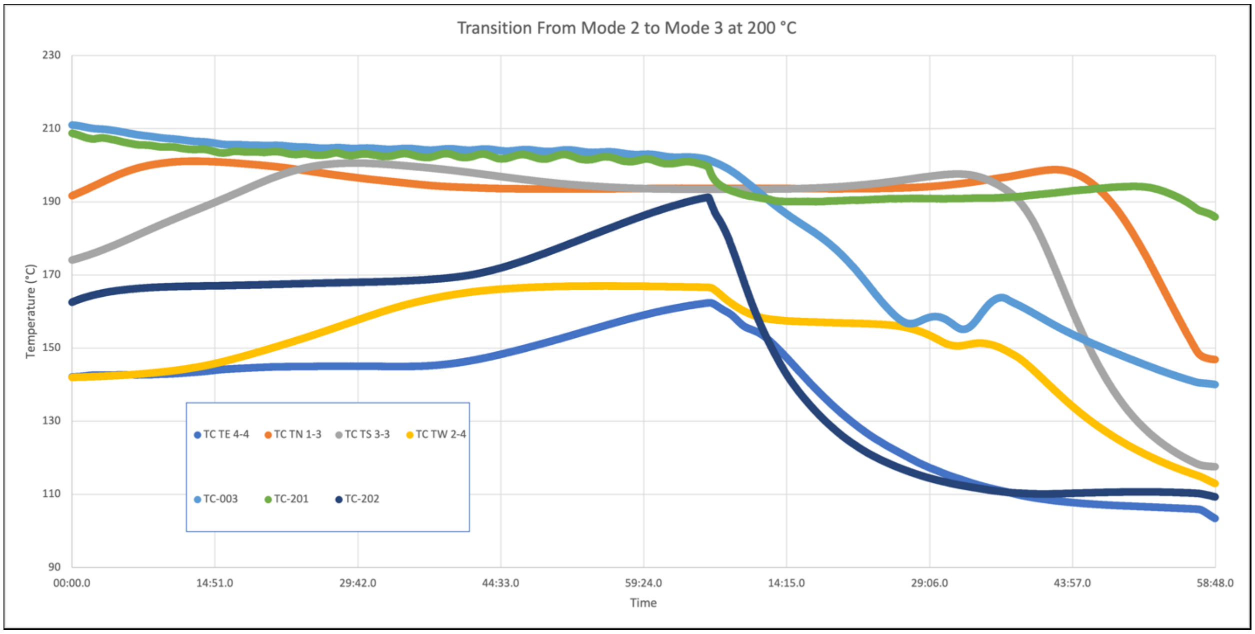

Figure 1. Temperature Data for Shift from Mode 2 to Mode 3.

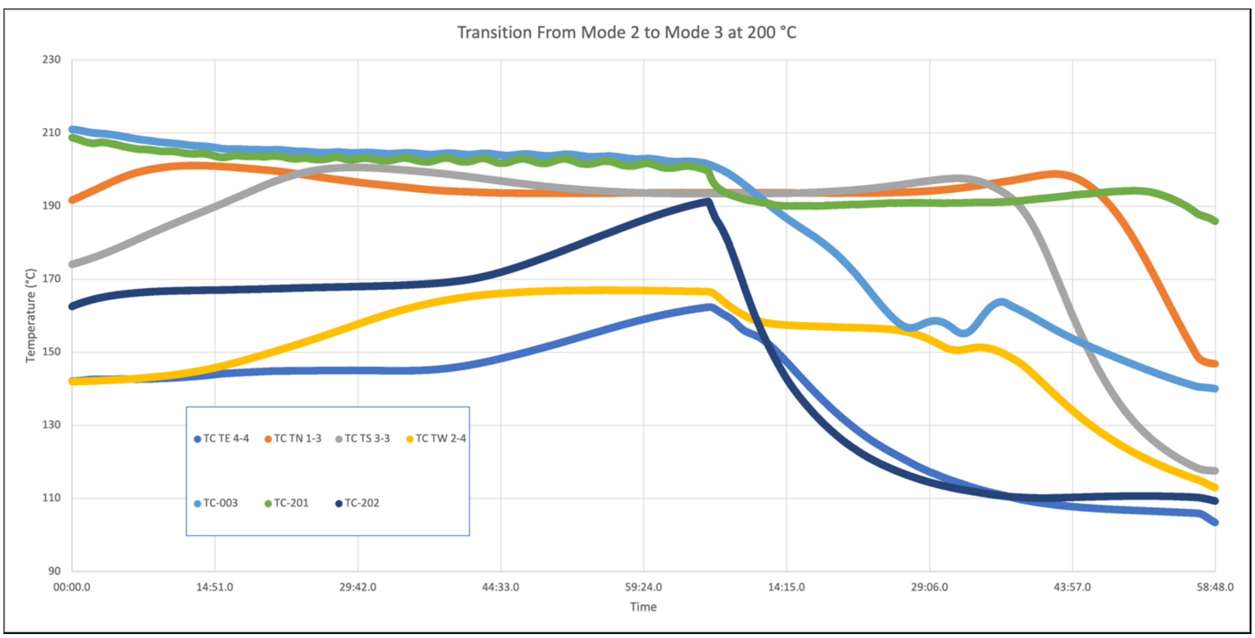

Figure 2. Temperature Data for Shift from Mode 3 to Mode 1.

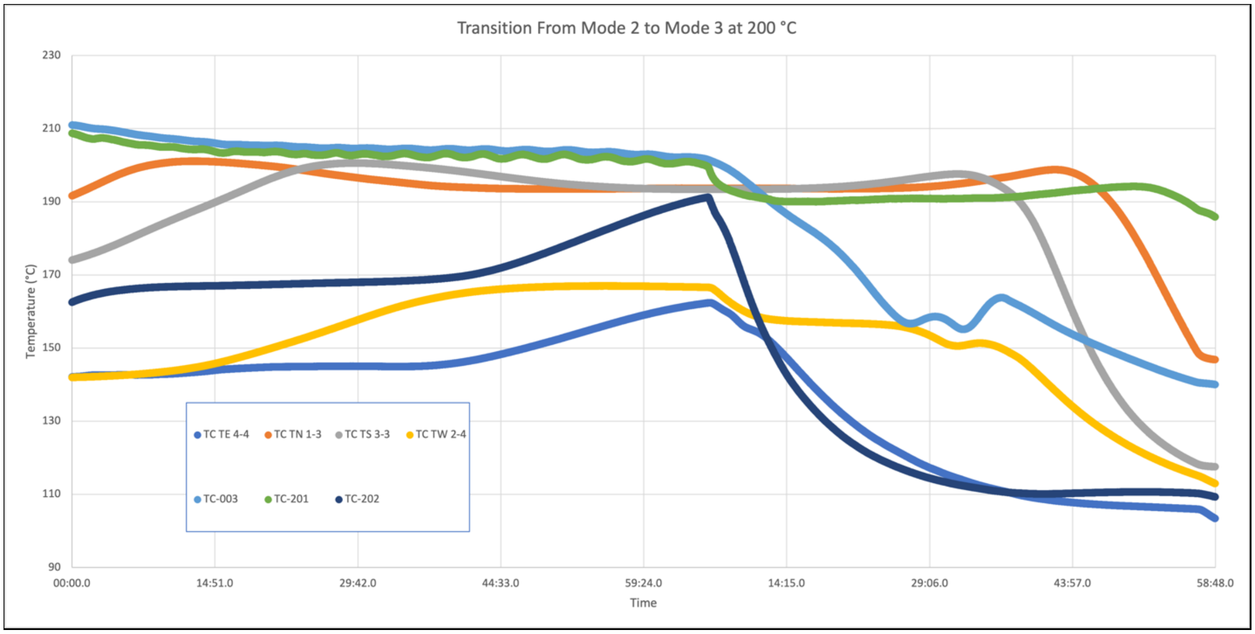

Figure 3. Temperature Data for Thermocline Heatup (Mode 2).

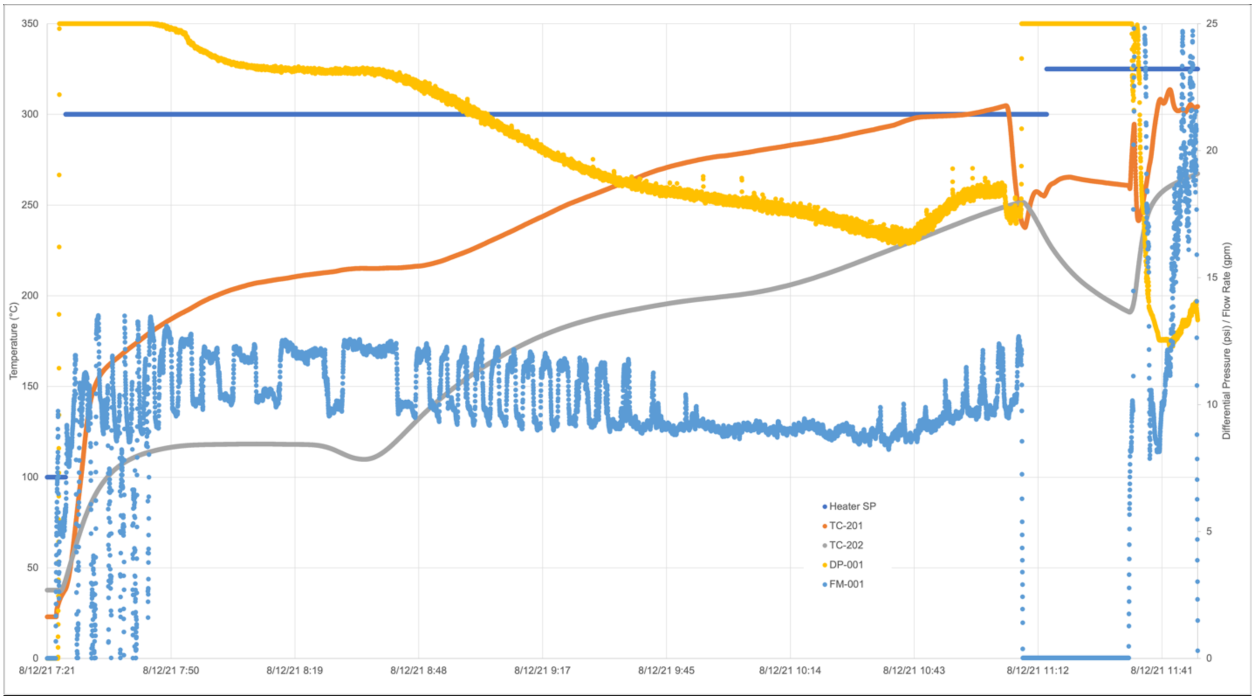

Figure 4. Temperature Data for Thermocline Heatup (Mode 2).

REFERENCES

1. Stoots, Carl, Alexander Duenas, Piyush Sabharwall, James O'Brien, Jun Soo Yoo, and Shannon Bragg-Sitton. 2018. "Thermal Energy Delivery System Design Basis Report." INL/EXT-18-51351, Idaho National Laboratory. https://doi.org/10.2172/1756571.
2. Frick, Konor L., Shannon Bragg-Sitton, and Christian Rabiti. 2020. "Development of the INL Thermal Energy Distribution System (TEDS) in the Modelica Ecosystem for Validation and Verification." INL/EXT-20-59195, Idaho National Laboratory. https://doi.org/10.2172/1668777.

Appendix A

TEDS As-Built Process and Instrumentation Diagram (P&ID)

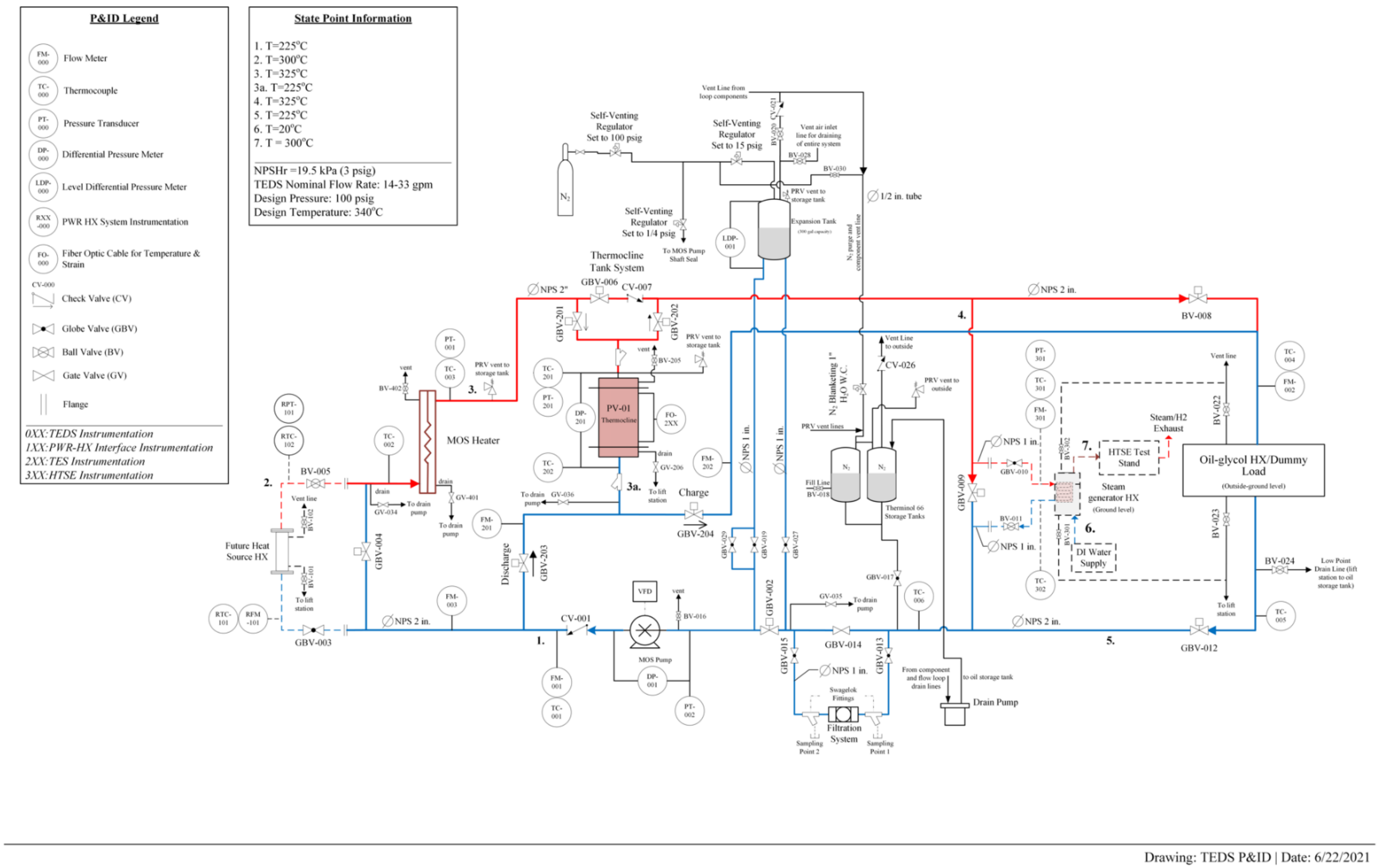

Figure A. TEDS As-Built Process and Instrumentation Diagram (P&ID).