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Thermal Energy Distribution System (TEDS) Operating Modes and Control Strategies

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ABSTRACT

The Thermal Energy Distribution System has been constructed at the Idaho National Laboratory for demonstrating the distribution of thermal energy to and from co-located systems sited in the Idaho National Laboratory's Dynamic Energy Transport and Integration Laboratory (DETAIL). DETAIL includes TEDS, a non-nuclear microreactor test bed, a high-temperature steam electrolysis unit, and a thermal energy storage system.

This report discusses the various operating modes and control strategies for enabling simultaneous, flexible, and efficient transfer of heat from thermal energy sources to end users.

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ACRONYMS

DETAIL	Dynamic Energy Transport and Integration Laboratory
FOR	Functional and Operational Requirements
HMI	Human-machine interface
HTR	Heater
HX	Heat exchanger
I&C	Instrumentation & Control
LI	Laboratory Instruction
MAG	See MAGNET
MAGNET	Microreactor AGile Non-nuclear Experimental Testbed
MAGNET HX	MAGNET heat exchanger
MOS	Mid-Size hot oil system
N-R HES	Nuclear-Renewable Hybrid Energy System
P&ID	Piping and instrumentation diagram
PLC	Programmable logic controller
PWR	Pressurized water reactor
SOEC	Solid oxide electrolysis cell
TEDS	Thermal energy distribution system
TES	Thermal energy storage
VFD	Variable frequency drive

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Thermal Energy Delivery System Operating Modes and Control Strategies

1. INTRODUCTION

The Thermal Energy Distribution System (TEDS) is a thermal hydraulic flow loop with a stand-alone dedicated control system to support test and demonstration operations for the Dynamic Energy Transport and Integration Laboratory (DETAIL) and Nuclear-Renewable Hybrid Energy System (N-R HES) applications. TEDS has been developed 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).

TEDS 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. The Microreactor Agile Non-nuclear Experimental Test Bed (MAGNET), also a part of DETAIL, mimics the energy input from a microreactor. Work is underway to interface MAGNET to TEDS, but the system currently includes a programmable heater that can be used to emulate the heat input from a variety of primary systems. A thermocline packed-bed thermal energy storage (TES) system is integrated to TEDS to either store heat when thermal energy is abundant or source heat later to a thermal energy user as a backup heat source. A solid-oxide electrolysis cell (SOEC) demonstration unit and an air-cooled chiller are integrated into TEDS to mimic thermal energy users.

1.1 Purpose

TEDS is designed to allow for modulation of the flow rate and temperature of the heat transfer medium and be able to divert thermal energy as required by heat customers. To meet this design objective, operating modes and control strategies have been identified and are presented in this document. The control strategy is developed with an operator in the loop. Control strategies for unattended operation of TEDS shall be developed during the future phases of the project.

The functional and operational requirements for TEDS were provided in FOR-415 [1] from which the control-system-specific requirements were identified and listed below:

1. The oil heating system shall allow for monitoring/control of heater electrical power level.
2. The system shall be designed to support unattended operation with remote alarm capability.
3. An appropriately sized oil circulation pump with a variable frequency drive shall provide flow through the system.
4. Valves shall be capable of remote control as described in Table 2.

2. SYSTEM DESCRIPTION

A piping and instrumentation diagram (P&ID) for TEDS is presented in Appendix A. The P&ID is a controlled drawing and is the most accurate source of currently installed TEDS instrumentation and valves.

The heat transfer medium selected for use in TEDS is a high-performance, highly stable synthetic heat transfer oil (Therminol 66). In the P&ID, the flow path starts from the Mid-Size Hot Oil System (MOS) pump (label #1). The flow can be split and heated at the pressurized water reactor (PWR) interface, which will be a heat exchanger, or go directly to the MOS heater system to have its temperature increased from 225 to 325°C (label #2). After the heat transfer fluid has been heated to the maximum operating temperature, it can be diverted to the thermal energy storage (TES) system for charging (label #3) or to the SOEC unit (label #4) or to the oil-to-air heat exchanger (label #5) before entering the suction side of the pump.

2.1 System Configuration

To demonstrate flexible and dynamic heat distribution, TEDS is configured with various thermal sources and loads.

2.1.1 Heat Sources

The following heat sources are available in the system:

- MOS heater (Source 1)
- MAGNET heat exchanger (Source 2)
- Fully charged TES tank (Source 3)

The MOS heater is a 200 kW oil heater system which supplements heat from the PWR heat exchanger interface. This heater will initially be the heat source for the loop and bring the oil temperature to its maximum 325°C operating temperature.

PWR heat exchanger and the MAGNET heat exchanger interface refer to the same interface providing thermal energy to the integrated energy system.

The TES system used in TEDS is a single packed-bed thermocline tank filled with alumina beads to store heat. The thermocline tank is capable of operating in either a charging or discharging mode. During charging mode, the tank will behave as a heat sink. This will allow the hot oil to transfer its heat to the alumina beads until an equilibrium temperature has been reached and the system has reached its storage capacity. Similarly, during discharging mode, the TES acts as a heat source. This will cause the cooler oil to flow from the bottom to the top of the tank, thereby absorbing heat from the alumina beads and increasing the fluid temperature. This will continue until the outlet temperature at the top of the tank reaches 325°C and starts to decrease until a cutoff temperature is reached. This cutoff temperature will vary based on testing performed with the TES.

2.1.2 Heat Loads

The following heat loads are available in the system:

- Discharged TES Tank (Load 1)
- SOEC Stack (Future Load) (Load 2)
- Air-cooled Heat Exchanger (Load 3)

The TES tank serves both as a heat source, when fully charged, and a heat sink when it is discharged. An oil-to-air heat exchanger, or an air-cooled chiller acts as a heat sink for the loop. This heat exchanger has an air blower to remove the heat. The chiller serves as the default load during system startup. The SOEC unit serves as a heat load which uses heat from the thermal flow loop for generating steam to produce hydrogen. Work is being done currently to integrate SOEC stack into TEDS.

2.1.3 I&C Design

To monitor system parameters, a combination of flow sensors, pressure sensors, and thermocouples has been incorporated into the system design. (Refer to the appendix in [2] for a list of TEDS instrumentation).

The instrumentation layout uses thermocouples before and after a component to observe temperature changes, as well as pressure transmitters on the high-temperature side to monitor pressure drop and system conditions. Flowmeters are preferentially placed on the cold legs of the loop to reduce exposure to the higher system temperatures. Flowmeters were positioned downstream of valves to provide researchers with accurate flowrates and allow operators to monitor for leaks from the valves. Instrumentation shown around the TES tank is used to provide bulk fluid properties and is connected to piping surrounding the tank.TEDS flow loop is currently controlled by National Instrument's LabVIEW software. This will be replaced by a programmable logic controller (PLC) based control system with a human machine interface (HMI) interface. The PLC will acquire instrumentation data with input modules, process control logic, communicate with the actuators equipped on the valves to control their positions, control heater power, adjust pump motor speed with a variable frequency drive (VFD) via PLC output modules, and have built-in alarms to prevent damage to the flow loop and personnel.

2.2 Control Parameters

The operator shall be able to control the flow rate and temperature of the heat transfer medium, from the HMI. This is possible by control of the following devices:

- MOS Heater (HTR-001) Control
  - Operator shall enter the desired heater temperature (setpoint) on the HMI.
  - The set point is communicated with the local heater control panel.
  - The local heater controller (separate from the TEDS controller) adjusts the power of the heater to meet the desired oil temperature setpoint.
- MOS Pump (P-001) VFD Control
  - Operator shall enter a desired flow rate (setpoint) on the HMI, which is converted to a pump P-001's motor speed by VFD-001.
  - PLC shall use the flow rate from FM-001 as the actual flow rate in the loop. The difference between the actual and desired flow rate shall be fed into a proportional-integral-derivative (PID) control algorithm to calculate the motor speed and maintain the desired flow rate in the loop.
  - VFD adjusts the pump motor speed to reflect the flow rate setpoint.
- Valve Control
  - Operator shall transfer heat between heat sources and loads by adjusting valve positions in the corresponding piping legs. Pneumatic valve positions are commanded from the HMI while manual valves are adjusted in the field.
  - Pneumatic valve position ranges from 0% - 100%.
    - 0%: valve fully closed.
    - 100%: valve fully open.
    - 0% $< x <$100%: variable position.

2.3 Control Modes

One of the primary objectives of TEDS listed in [1] is for the control system to support unattended operation. The current phase of the project does not support a fully automated control system. The control strategy presented in this document is devised with an 'operator-in-the-loop' approach. This shall evolve into fully automated control during future phases of the project.

The control system shall be mostly operated in the manual mode, in which the control system waits for operator input. Automatic (AUTO) control shall be engaged by the operator for automatically sequencing valve positions. Operator inputs are required by the control system to change from a current operating mode to another. The operator shall initiate auto valve sequencing to enable a mode transition. Manual/Auto control mode shall be used during the following system operations:

- Startup
- Normal
- Shutdown

The description of control during each operation is provided in Sections 3 to 5.

2.4 System Operating Modes

The system configuration was described in Section 2. To allow for the flexible and dynamic operation of TEDS, several operating modes have been identified. Operator input is required to select a particular mode or transition to another mode.

The operator shall have the capability to choose either a single heat source/load or a combination of heat sources/loads from the HMI. Operating modes for TEDS are defined as shown in Table 1.

Table 1. TEDS Operating Modes

Mode	Flow Path		Description
	Source(s)	Load(s)	
Mode 0	MOS Heater or MAGNET HX or both	None	Bypass loop
Mode 1	MOS Heater or MAGNET HX or both	TES	TES in charge mode
Mode 2	MOS Heater or MAGNET HX or both	SOEC	Single load
Mode 3	MOS Heater or MAGNET HX or both	Chiller	Single load
Mode 4	MOS Heater or MAGNET HX or both	TES + SOEC	2 loads; TES in charge mode
Mode 5	MOS Heater or MAGNET HX or both	TES + Chiller	2 loads; TES in charge mode
Mode 6	TES	SOEC	TES in discharge mode
Mode 7	TES	Chiller	TES in discharge mode

The description of each mode in Table 1 is provided below:

- **Mode 0**
  - A bypass line involving no loads.
  - Not a standard operating mode.
  - Used 1) when the system is being heated up and the heat-up time must be reduced and 2) when heat removal is not needed.
- **Mode 1**
  - Standard operating mode.
  - Simulates a full charging scenario where the thermal generator is sending its heat to the thermal storage unit (thermocline tank) entirely.
- **Mode 2**
  - Standard operating mode with a SOEC stack as heat load for H_2 energy production.
  - All of the generated heat is diverted to the load.
  - Simulates generators accommodating a load following mode.
  - Zero-energy storage.
- **Mode 3**
  - Same as Mode 2 but the load here is an air-cooled chiller.
  - All of the generated heat is diverted to the load.
  - Simulates the heat source accommodating a load following mode.
  - Zero-energy storage.
- **Mode 4**
  - Combination of Modes 2 and 3.
  - Standard operating mode where the thermal generator is providing a portion of its heat to thermal storage and a portion to SOEC stack (heat load).

- Normal operation - heat source provides heat to the load first and then dumps excess heat into the thermal storage unit for use later.
- **Mode 5**
  - Same as Mode 4 but the load here is an air-cooled chiller.
- **Mode 6**
  - Standard operating mode with TES tank in discharge mode.
  - TES is discharging to the SOEC stack (load) for H_2 energy production.
  - Thermal generator is turned off/unavailable, and the thermal storage unit is the sole unit providing heat to the balance of plant or ancillary processes.
- **Mode 7**
  - Same as Mode 6 but the load here is an air-cooled chiller.

2.4.1 Valve Positions and Operating Modes

To accommodate the operating modes in Table 1, positions of pneumatic valves and manual valves shall be adjusted as shown in Table 2.

Table 2. Valve Positions and TEDS Operating Modes

Heat Source				**Manual Valves (MAGNET)**			**TES Charging**		**TES Discharging**				**Manual Valves (SOEC)**		
	Pnm. Valve #	**1**	**2**	**M1**	**M2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**M3**	**M4**	**10**
	Mode (Load)	**PV-002**	**PV-004**	**HV-003**	**HV-005**	**PV-006**	**PV-049**	**PV-050**	**PV-051**	**PV-052**	**PV-008**	**PV-009**	**HV-010**	**HV-011**	**PV-012**
a. MOS HTR	**Mode 0 (No Load)**	Open	Open	Closed	Closed	Open	Closed	Closed	Closed	Closed	Closed	Open	Closed	Closed	Closed
b. MAG HX		Open	Closed	Open	Open	Open	Closed	Closed	Closed	Closed	Closed	Open	Closed	Closed	Closed
c. MOS + MAG		Open	Variable	Open	Open	Open	Closed	Closed	Closed	Closed	Closed	Open	Closed	Closed	Closed
a. MOS HTR	**Mode 1 (TES Charge)**	Open	Open	Closed	Closed	Closed	Open	Closed	Closed	Open	Open	Open	Closed	Closed	Closed
b. MAG HX		Open	Closed	Open	Open	Closed	Open	Closed	Closed	Open	Open	Open	Closed	Closed	Closed
c. MOS + MAG		Open	Variable	Open	Open	Closed	Open	Closed	Closed	Open	Open	Open	Closed	Closed	Closed
a. MOS HTR	**Mode 2 (SOEC)**	Open	Open	Closed	Closed	Open	Closed	Closed	Closed	Closed	Closed	Closed	Open	Open	Closed
b. MAG HX		Open	Closed	Open	Open	Open	Closed	Closed	Closed	Closed	Closed	Closed	Open	Open	Closed
c. MOS + MAG		Open	Variable	Open	Open	Open	Closed	Closed	Closed	Closed	Closed	Closed	Open	Open	Closed
a. MOS HTR	**Mode 3 (Chiller)**	Open	Open	Closed	Closed	Open	Closed	Closed	Closed	Closed	Open	Closed	Closed	Closed	Open
b. MAG HX		Open	Closed	Open	Open	Open	Closed	Closed	Closed	Closed	Open	Closed	Closed	Closed	Open
c. MOS + MAG		Open	Variable	Open	Open	Open	Closed	Closed	Closed	Closed	Open	Closed	Closed	Closed	Open
a. MOS HTR	**Mode 4 (TES + SOEC)**	Open	Open	Closed	Closed	Closed	Open	Closed	Closed	Open	Open	Closed	Open	Open	Closed
b. MAG HX		Open	Closed	Open	Open	Closed	Open	Closed	Closed	Open	Open	Closed	Open	Open	Closed
c. MOS + MAG		Open	Variable	Open	Open	Closed	Open	Closed	Closed	Open	Open	Closed	Open	Open	Closed
a. MOS HTR	**Mode 5 (TES + Chiller)**	Open	Open	Closed	Closed	Closed	Open	Closed	Closed	Open	Closed	Closed	Closed	Closed	Open
b. MAG HX		Open	Closed	Open	Open	Closed	Open	Closed	Closed	Open	Closed	Closed	Closed	Closed	Open
c. MOS + MAG		Open	Variable	Open	Open	Closed	Open	Closed	Closed	Open	Closed	Closed	Closed	Closed	Open

TES (Discharge)	**Mode 6 (SOEC)**	Open	Closed	Closed	Closed	Closed	Closed	Open	Open	Closed	Closed	Closed	Open	Open	Closed
TES (Discharge)	**Mode 7 (Chiller)**	Open	Closed	Closed	Closed	Closed	Closed	Open	Open	Closed	Open	Closed	Closed	Closed	Open

Table 2 Notes:

- Manual valves: M1 – M4; pneumatic valves: #1 to #10
- Manual valves are adjusted in the field while pneumatic valves are controlled remotely. Currently, the PLC does not receive valve positions of any manual valves. Adding limit switches to manual valves or even replacing manual valves with pneumatic valves is being considered for future enhancements.
- Manual valves of the air-cooled HX (chiller) are not shown in this table. Chiller interface valves HV-042, HV-043, HV-046 and HV-047 are designed to be in the OPEN position after the pre-operational valve lineup. These valves are left open even if the chiller is not selected as a load for TEDS.
- Rows a, b and c for Modes 0-5 indicate the three source options available for each load. This is possible by controlling one pneumatic valve and two manual valves as shown in Table 3.

Table 3. Heat Source Valve Positions

Source	PV-004 (pneumatic)	HV-003 (manual)	HV-005 (manual)
MOS Heater	Open	Closed	Closed
MAGNET HX	Closed	Open	Open
MOS Heater + MAGNET HX	Intermediate	Open	Open

2.4.2 Valve Sequencing

To align valves in the flow loop for a particular operating mode, the operator shall choose to either:

- Manually open/close the pneumatic valves in sequence in accordance with Section 5. E[3].
- Engage AUTO valve sequencing from the HMI.

If the valve sequence is performed manually, the steps in reference [3] must be manipulated to accommodate each mode.

AUTO Valve Sequence

Before initiating the AUTO valve sequence (see Table 4), the operator shall perform the following steps on the HMI:

- Operator selects the heat source(s).
- Operator selects the heat load(s).
- Operator performs manual valve adjustment in field and enters valve position on the HMI.
- Operator selects AUTO valve sequence.

Table 4. PLC AUTO Sequence Logic

Steps	Process	Notes
1.	PLC enters AUTO control mode.	
2.	PLC processes heat source input(s) from the HMI.	
3.	PLC processes heat load input(s) from the HMI.	
4.	PLC verifies the position of manual valves[1] for source and load, by comparing the current position to the expected position. If there is a mismatch, operator shall be notified by a warning/alarm.	Current valve position shall either be manually entered or verified with limit switches.

<table>
<tr><td>5.</td><td colspan="2">PLC opens PV-002 (P-001 suction isolation), if not open already.</td></tr>
<tr><td>6.</td><td colspan="2">5-second delay (changeable based on operating experience or experimental needs)</td></tr>
<tr><td>7.</td><td>PLC sets PV-004 (HTR-001 inlet isolation) position based on source selection.
[For STARTUP operation, PV-004 position is set to open (100%) by default].</td><td>PV-004 valve position decides the heat source.
Fully closed (0%): MAGNET HX
Fully open (100%): MOS heater
Variable position (0% < x <100%): MOS heater + MAGNET HX</td></tr>
<tr><td>8.</td><td colspan="2">5-second delay (changeable based on operating experience or experimental needs)</td></tr>
<tr><td rowspan="3">9.</td><td>PLC identifies the operating mode (in Table 2).</td><td rowspan="3">Setting up flow loop.</td></tr>
<tr><td>Sets the position of pneumatic valves #3 to #10.</td></tr>
<tr><td>Follows a 5-second delay between each actuation (changeable based on operating experience or experimental needs).</td></tr>
<tr><td>10.</td><td colspan="2">If chiller is selected as a load, it is turned ON after completing the valve sequence for that mode.</td></tr>
<tr><td>11.</td><td colspan="2">PLC exits out of the automated sequence and enters manual control mode.</td></tr>
</table>

Table notes:

1. If the MAGNET interface is either fully or partially sourcing heat to the loop, manual valves at the MAGNET interface must be opened. See Table 3.
2. Similarly, to enable or disable SOEC or chiller load, the respective manual valves must be positioned as listed in Table 2. Chiller's manual valves are always left in the open position as it is the default load on startup.

2.5 Alarms and Warnings

The TEDS control system shall have the capability to annunciate alarms and warnings. There shall be a master alarm which is a combination of system alarms and PLC alarms as such:

- System alarm
  - When monitored parameters exceed set limits.
- PLC trouble alarm
  - Power supply failure
  - Processor failure
  - Data acquisition system failure (processor/io module/channel failure)

3. STARTUP OPERATION

3.1 Prerequisites

The pre-startup procedure for TEDS is defined in LI-970 [3]. Depending on whether the system was under maintenance or not prior to startup, the operator shall follow the appropriate sections in this reference to ensure a safe startup operation.

As part of getting the system ready, the operator performs a pre-operational valve lineup procedure [3]. This provides a baseline state for all the devices and valves in the system. After completing this procedure, the system will be in the following state as shown in Table 5.

Table 5. TEDS Pre-Startup State

Device	State
MOS Pump	OFF
MOS Heater	OFF
Air-cooled HX (Chiller)	OFF
Interface	**State**
MAGNET HX	DISABLED
TES	DISABLED
SOEC Stack	DISABLED
Air-cooled HX (Chiller)	DISABLED
HMI	**Mode/State**
Control Mode	Manual
System Alarms	None/Acknowledged
PLC Alarms	None/Acknowledged
System Parameters	**Value**
Temperature	N/A
Flow	0 GPM

3.2 Startup Procedure

The startup configuration of the system shall be defined as shown in Table 6.

Table 6. TEDS Startup Configuration

Heat Source	MOS Heater
Heat Load	Air-cooled HX
	Bypass Loop (No Load)
Control Mode	Manual

The control system shall be operated in manual mode, except when the operator initiates automated valve sequencing. The sequence of startup operations is provided in Table 7. The operator performs steps #1 to #5 from Section 5. E [3] in the field, followed by source and load selection on the HMI. For startup,

- MOS heater is the default heat source.
- MAGNET HX (heat source) will not be available to select.

For load selection, the operator shall have two options:

- Air-cooled chiller
- Bypass loop (no load)

The other loads shall not be available on the HMI until the system is initialized and meets set conditions (see 'System Parameters' section in Table 8). The operator shall commence AUTO valve sequencing from the HMI. Depending on the selection, the PLC then initiates an automated valve sequence (see

Section 2.4.2) for either:

- Mode 0a
- Mode 3a

A manual STOP shall be used to exit from the automatic control mode in the event of an alarm or unexpected conditions. When the valve sequence is complete, PLC enters the manual control mode. Valve sequencing shall also be performed manually from the HMI in accordance with Section E [3]. The operator shall continue with the remaining steps #13 to #17 in Section 5. E [3] to complete the startup procedure.

Table 7. Startup Procedure

No.	Step	Operator Action	Parameter
1.	VERIFY RV-038 set for 10 psig.	Field step	
2.	OPEN N2 bottle isolation valve.	Field step	
3.	OPEN HV-081 (RV-038 outlet isolation).	Field step	
4.	OPEN HV-019 (TK-003 isolation).	Field step	
5.	Select the default heat source.	HMI Input	MOS Heater
6.	Select the load.	HMI Input	Air-cooled HX or Bypass Loop
7.	Operator starts AUTO valve sequence on the HMI. [Note: Manual valves of the default source and load are already in the expected position since pre-operational valve line up.]	HMI Input	Mode 0a or 3a
8.	IF 'Bypass Loop' is selected, PLC initiates valve sequence for Mode 0a[4].	AUTO	Valve Position
9.	ELSE PLC initiates valve sequence for Mode 3a[4].	AUTO	Valve Position
10.	OPEN HV-014 (FLT-001 bypass isolation).	Field step	
11.	START P-001 with VFD-001 at 20 Hz.	HMI Input	VFD Frequency
12.	START HTR-001.	Field step	Select ENABLE position[1]
13.	VERIFY HTR-001 over-temperature trip set to 330°C or lower.	Field step	Local display value[2]
14.	SET HTR-001 set point to desired temperature.	HMI Input	Temp. setpoint and increment steps[3]
15.	WHEN temperature at TC-006 reaches 100°C i. OPEN HV-013 (FLT-001 inlet isolation).	Field step	
	ii. OPEN HV-015 (FLT-001 outlet isolation).	Field step	
	iii. CLOSE HV-014 (FLT-001 bypass isolation).	Field step	

16.	ADJUST VFD-001 to reach desired flow rate.	HMI Input	VFD Frequency

Table notes:

1. The enable/disable knob is on the heater controller panel.
2. Over-temperature trip setting is displayed on a local display on the door of the heater control panel.
3. Temperature setpoint/steps: The operator shall enter the temperature setpoint and step increments on the HMI. The default step increment is 0. PLC calculates the first setpoint based on the step and communicates it with the heater controller. The process variable is the heater outlet temperature, $T_{HTR\text{-}001,}$ which the PLC accesses from the heater controller. When $T_{HTR\text{-}001}$ reaches the first setpoint, the PLC automatically increments to the next step until $T_{HTR\text{-}001}$ indicates the desired setpoint.

3.3 Startup State Summary

The following table summarizes the state of the system upon completing the startup operation.

Table 8. TEDS Startup State Summary

Device	State	Condition
MOS Pump	ON	
MOS Heater	ON	
Air-cooled HX (Chiller)	ON	If operator selects this as a startup load.
	OFF	If not selected as a startup load.
Interface	**State**	**Condition**
MAGNET HX	DISABLED	
Air-cooled HX (Chiller)	ENABLED	If operator selects this as a startup load.
	DISABLED	If bypass loop is selected.
TES	DISABLED	
SOEC Stack	DISABLED	

HMI	Mode/State
Control Mode	Manual
System Alarms	None/Acknowledged
PLC Alarms	None/Acknowledged
System Parameters	**Value**
Temperature	> 100 ºC
Flow	As set

4. NORMAL OPERATION

The operator shall run the system in the normal state after the system has been initialized and meets set conditions. (See section ‘System Parameters in Table 8). This is for safely integrating loads such as TES tank and SOEC stack into the flow loop. During normal operations, the operator can choose to operate in any operating mode in Table 2.

The normal operating state shall have the following configuration as listed in Table 9.

Table 9. TEDS Normal Configuration

Heat Source(s)	MOS Heater
	MAGNET HX
	MOS Heater + MAGNET HX
	Charged TES Tank
Heat Load(s)	No Load
	Discharged TES Tank
	SOEC Stack
	Air-cooled HX
Control Mode	Manual

The operator shall select new source(s) and load(s) on the HMI. The manual valves are adjusted in the field and the operator enters the current valve position on the HMI. The operator shall choose to engage AUTO valve sequencing (see Section 2.4.2) or perform the valve sequence manually.

If AUTO sequencing is engaged, based on the new selection, the PLC identifies the new operating mode and determines the expected valve (both) positions for sources/loads exiting the previous mode and for sources/loads entering the new mode. PLC verifies if all conditions are met for the transition. If the pneumatic valve positions are not as expected, the PLC positions the valves to reflect the selected mode in Table 2. If there is a mismatch in the expected manual valve positions, the operator is issued a warning on the screen. In the event of an alarm or unexpected event before completing the AUTO sequence, the operator shall take control using the manual STOP from the HMI. Once complete, the PLC automatically transitions to the manual control mode.

4.1 Valve Control Criteria

This section identifies the limiting conditions, if any, for pneumatic valves to open or close during operating modes.

4.1.1 Valve #1: PV-002

	Valve Position		
	Open	**Closed**	**Variable**
When	Always	System OFF	N/A
Limiting temperature	None	None	N/A

4.1.2 Valve #2: PV-004

	Valve Position		
	Open	**Closed**	**Variable**
When	MOS heater is the	MAGNET HX is the only heat	MOS heater and

	only heat source	source TES in discharging mode	MAGNET HX are available.
Limiting temperature	None	None	None

4.1.3 Valve #3: PV-006

	Valve Position		
	Open	**Closed**	**Variable**
When	In bypass loop mode	TES is charging	N/A
	Chiller is in the loop	TES is charging + SOEC is in the loop	
	SOEC is in the loop	TES is charging + Chiller is in the loop	
		TES is discharging to SOEC	
		TES is discharging to the chiller	
Limiting temperature	None	TC-003 ≥ 325 ºC	N/A

4.1.4 Valve #4: PV-049

- Valves #4 and #7 (PV-052) are part of an interlock logic.
- IF TES is charging, both are open.
- ELSE, closed.

	Valve Position		
	Open	**Closed**	**Variable**
When	TES is charging	TES is discharging	N/A
Limiting temperature	When TC-003 ≥ 325 ºC until TC-202/203 = TES equilibrium temperature*	None	N/A

**Note: Equilibrium temperature of TES tank dependent on the type of test and is set by the operator.*

4.1.5 Valve #5: PV-050

- Valves #5 and #6 (PV-051) are part of an interlock logic.
- Both are open if TES is discharging, closed otherwise.

	Valve Position		
	Open	**Closed**	**Variable**
When	TES Discharging	TES Charging	N/A
Limiting temperature	From 225 ºC ≤ TC-201 ≤ 325 ºC and	None	N/A

	Until TC-201 ≤ Cutoff Setpoint*		

**Note: Cutoff temperature for discharging is dependent on the type of test and is set by the operator.*

4.1.6 Valve #6: PV-051

- Valves #5 (PV-050) and #6 are part of an interlock system.
- IF TES is discharging, both are open.
- ELSE, closed.

	Valve Position		
	Open	**Closed**	**Variable**
When	TES is discharging	TES is charging	N/A
Limiting temperature	From 225 ºC ≤ TC-201 ≤ 325 ºC and Until TC-201 ≤ Cutoff Setpoint*	None	N/A

**Note: Cutoff temperature for discharging is dependent on the type of experiment and is set by the operator.*

4.1.7 Valve #7: PV-052

- Valves #4 (PV-049) and #7 are part of an interlock system.
- IF TES is charging, both are open.
- ELSE, closed.

	Valve Position		
	Open	**Closed**	**Variable**
When	TES is charging	TES is discharging	N/A
Limiting temperature	When TC-003 ≥ 325 ºC until TC-202 = TES equilibrium temperature*		None

**Note: Equilibrium temperature of TES tank is dependent on the type of experiment and is set by the operator.*

4.1.8 Valve #8: PV-008

	Valve Position		
	Open	**Closed**	**Variable**
When	Chiller is in the loop	Otherwise	N/A
Limiting temperature	None	TC-003 ≥ 325 ºC	None

4.1.9 Valve #9: PV-009

	Valve Position		
	Open	**Closed**	**Variable**
When	In bypass loop mode	Chiller in loop	N/A
	TES is charging	SOEC in loop	

		TES Charging + SOEC in loop	
Limiting temperature	None	TC-003 ≥ 325 ºC	None

4.1.10 Valve #10: PV-012

	Valve Position		
	Open	**Closed**	**Variable**
When	Chiller is in the loop	Otherwise	N/A
Limiting temperature	None	None	None

5. SHUTDOWN OPERATION

The shutdown configuration of the system shall be defined as shown in Table 10.

Table 10. TEDS Shutdown State

Device	**State**
MOS Pump	OFF
MOS Heater	OFF
Air-cooled HX (Chiller)	OFF
Interface	**State**
MAGNET HX	DISABLED
TES	DISABLED
SOEC Stack	DISABLED
Air-cooled HX (Chiller)	DISABLED
HMI	**Mode/State**
Control Mode	Manual
System Alarms	None/Acknowledged
PLC Alarms	None/Acknowledged
System Parameters	**Value**
Temperature	< 170 ºC
Flow	0 GPM

Prior to shut down, the system would have been running in any of the eight operating modes listed in Table 2. If the current operating mode is other than the TES discharge mode (Mode 7), the operator shall transition the system to operate in Mode 7 to shut down the system. The sequence of shutdown operations is provided in Table 11. The operator shall choose to perform the transition manually in sequence or engage the AUTO valve sequence (see Section 2.4.2). To engage AUTO sequencing, the operator selects:

- TES as the heat source and
- Chiller as the heat load.

When the operator initiates AUTO valve sequencing, PLC identifies the new operating mode and determines the expected valve (both) positions for sources/loads exiting the previous mode and for sources/loads entering the new mode. PLC verifies if all conditions are met for the transition. If the pneumatic valve positions are not as expected, the PLC positions the valves to reflect the selected mode in Table 2. If there is a mismatch in the expected manual valve positions, the operator is issued a warning on the screen. In the event of an alarm or unexpected event before completing the AUTO sequence, the operator shall take control using the manual STOP from the HMI. Once complete, the PLC automatically transitions to the manual control mode.

Table 11. Shutdown Procedure

No.	Step	Operator Action	Parameter
1.	STOP HTR-001	Field step	Select DISABLE position[1]
2.	IF the current mode is not Mode 7, transition from current mode to Mode 7 (TES discharge mode).	Manually perform the valve sequence or engage AUTO valve sequence.	
3.	ELSE WHEN all thermocouples cool down below 170°C, STOP Pump P-001	HMI Input	VFD Frequency
4.	CLOSE all pneumatic valves.	HMI Input	Valve position
5.	STOP Chiller CH-001.	Field step	

Table note:

1. The enable/disable knob is on the heater controller panel.

6. REFERENCES

[1] Stoots, Carl, 2018, “Thermal Energy Delivery System,” FOR-415, Idaho National Laboratory.

[2] Stoots, Carl, et al., 2018, “Thermal Energy Delivery System Design Basis Report,” INL/EXT-18-51351, Idaho National Laboratory, https://doi.org/10.2172/1756571.

[3] Idaho National Laboratory, 2023, “Thermal Energy Distribution System (TEDS) Operation,” LI-970.

7. APPENDIX A

TEDS Process and Instrumentation Diagram (P&ID)

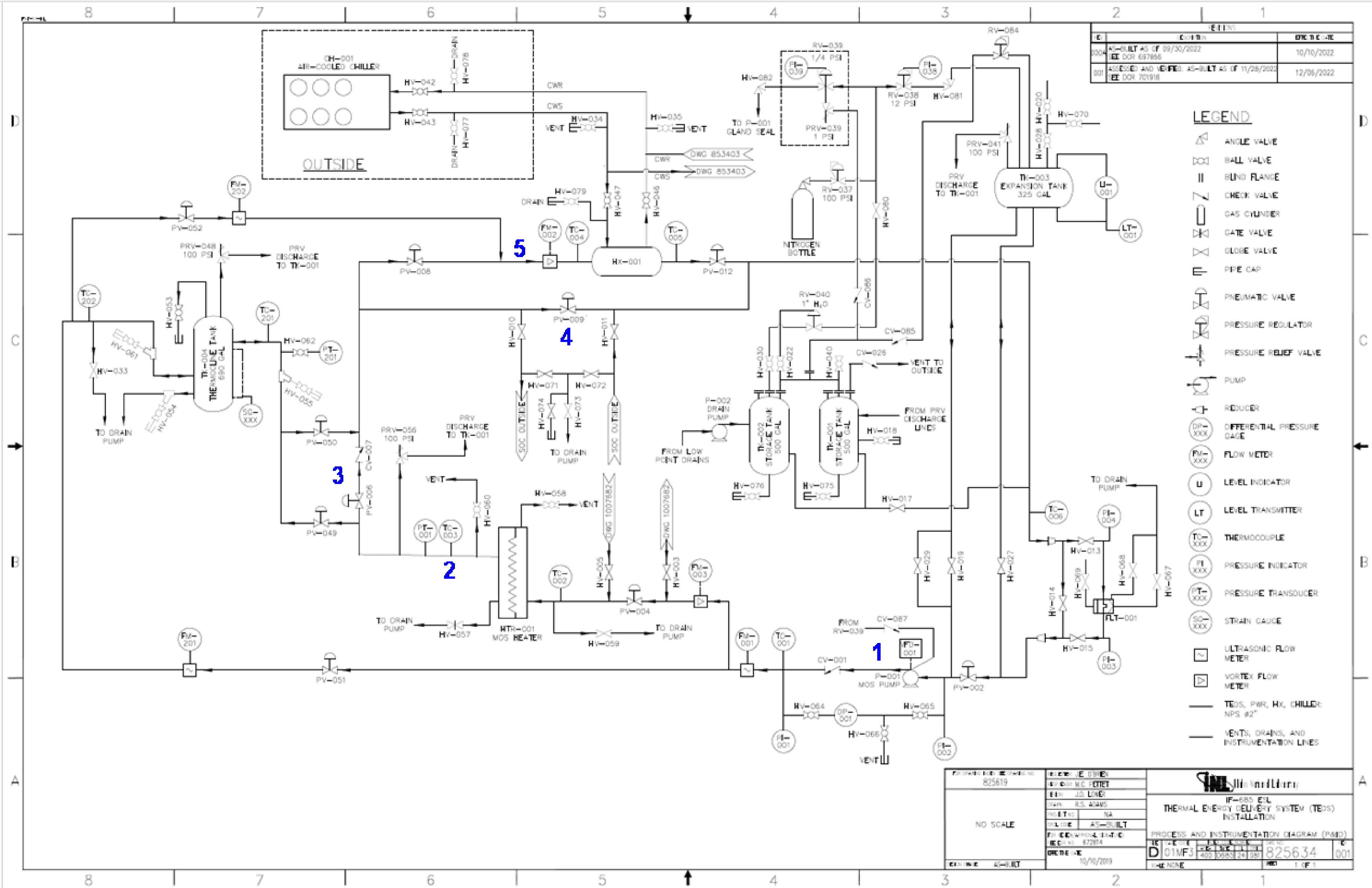

Figure 1. TEDS P&ID