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Upgrade of Core Conduction Cooldown Test Facility Control System

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Nuclear Energy and Fuel Cycle Division

UPGRADE OF CORE CONDUCTION COOLDOWN TEST FACILITY CONTROL SYSTEM

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ABBREVIATIONS

AGR	Advanced Gas Reactor Fuel Development and Qualification (Program)
AGR-1	first AGR program irradiation experiment
AGR-2	second AGR program irradiation experiment
AGR-5/6/7	fifth, sixth, and seventh AGR program irradiation experiment
AOV	automated operation valve
CCCTF	Core Conduction Cooldown Test Facility
EVAC	furnace evacuation (automated routine)
GUI	Graphical User Interface
IFEL	Irradiated Fuels Examination Laboratory
NI	National Instruments
ORNL	Oak Ridge National Laboratory
PIE	post-irradiation examination
TRISO	tristructural isotropic (coated particles)
VI	Virtual Instrument (NI LabVIEW file format)

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1. INTRODUCTION

The Core Conduction Cooldown Test Facility (CCCTF), located in the Oak Ridge National Laboratory (ORNL) Irradiated Fuels Examination Laboratory (IFEL), is a critical capability utilized by the Advanced Gas Reactor Fuel Development and Qualification (AGR) Program for safety testing of tristructural isotropic (TRISO)-coated particles and fuel compacts (Baldwin et al. 2014, Morris et al. 2014, Morris et al. 2016, Hunn et al. 2018). During a safety test, AGR fuel is exposed to accident-level temperatures (typically 1600–1800°C) while maintaining a He atmosphere. Throughout the test, He sweep gas is monitored for ^{85}Kr fission gas released from the fuel through liquid nitrogen-cooled charcoal traps monitored with NaI detectors. Additionally, the facility collects condensable fission products on a deposition cup, which is water-cooled throughout the test. Utilizing an airlock, which isolates the internal portion of the furnace through thermal shutters and a pneumatic gate valve, the deposition cups can be removed from the furnace at temperature and replaced to obtain time-resolved release behavior. With these two collection methods, the system can help determine quantities of radioactive fission products released from the fuel and can detect TRISO failures. This system has been used to perform 36 safety tests of fuel from the AGR program's first (AGR-1) and second (AGR-2) irradiation experiments (Demkowicz et al. 2015; Stempien et al. 2021) and will be heavily utilized throughout the AGR-5/6/7 post-irradiation examination (PIE) campaign to complete the safety tests planned as part of that effort.

The CCCTF was designed and installed at ORNL in the 1990s for high-temperature gas-cooled reactor accident simulation. It is located within a modular hot cell housed in the IFEL facility. In 2008 and 2009, modifications were made to the CCCTF in preparation for AGR safety testing. A new airlock was designed and installed to better support periodic exchange of the fission product deposition cups while maintaining the fuel at safety test temperature, and modifications were made to add routines to the existing user interface software for computer-controlled automation of the He sweep gas flow and liquid nitrogen supply to the ^{85}Kr cold traps. However, the furnace control hardware and software remained essentially unchanged.

At the conclusion of the AGR-1 and AGR-2 PIE campaigns, continued use of the CCCTF was in question because of the gradual obsolescence of the hardware and software used to control the furnace and ancillary systems that make up the CCCTF. Therefore, an effort was undertaken to replace all the obsolete components with new hardware and update the software to increase system reliability and ensure this capability's maintenance for future research and fuel qualification efforts. The modifications included creating a new National Instruments (NI) LabVIEW-based control system with a graphical user interface (GUI).

2. DESCRIPTION OF NEW CCCTF CONTROL SYSTEM

Because numerous previous reports and articles detail the functionality and purpose of the CCCTF, and the upgrade of the control system does not add or remove functionality, a detailed description of the CCCTF is not included here. The control system maintains four aspects of the overall operation of the CCCTF: gas flow, pneumatic valve actuation, temperature control, and cold finger motor control. The previous control system consisted of an analogue control cabinet (Figure 1a) used for monitoring furnace output and temperature readings as well as motor control for cold finger actuation. The cabinet was accompanied by a desktop computer, on which user inputs were used to control the furnace heating profile, liquid nitrogen valve actuation for temperature control of the ^{85}Kr traps, He sweep gas flow rate, and pneumatic valve actuation. The updated control system aims to simplify and consolidate the previous apparatus into one cabinet/computer combination that houses all the aforementioned systems and capabilities (Figure 1b). Apart from the cold finger motor control, all data monitoring, user input, and system control are handled by a LabVIEW program developed and customized by ORNL staff.

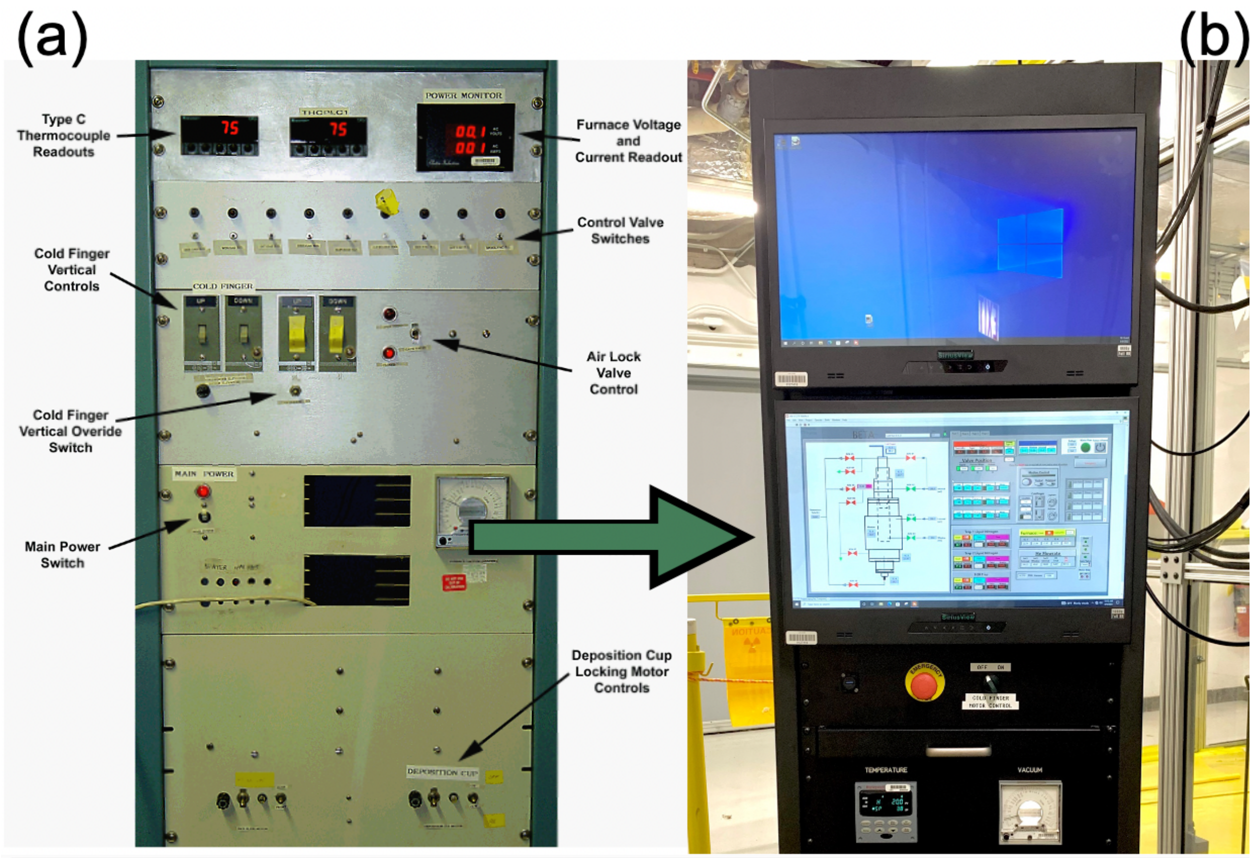

Figure 1. Former CCCTF control cabinet (a), which was analyzed and simplified, and features and functions transferred to a new control cabinet (b), which houses the ability to read signals from and send control signals to the CCCTF system components.

2.1 DESCRIPTION OF CCCTF CONTROL SYSTEM FUNCTIONALITY

The CCCTF control system controls/monitors the following:

1. The furnace temperature and ramp profile.
2. The temperature of the three liquid nitrogen–cooled traps: moisture collector, ^{85}Kr Trap 1, and ^{85}Kr Trap 2. This is done by an on/off air-actuated pneumatic valve system controlling liquid nitrogen flow.
3. The He gas flow rate through the furnace internal region during the cold finger operation by setting an external mass flow controller.
4. The He gas flow rate through the region containing the heating elements.
5. The He gas flow rate through the view port (window) region.
6. The up/down operation of the cold finger in coordination with the airlock operation.
7. The airlock (gate) valve operation as well as the evacuation and purging of this region.
8. The deposition cup drive motor.
9. The flow rate of the sum of the outputs from the furnace is monitored and compared to the sum of the inputs for leak or clog detection.
10. The furnace pressure is monitored for leak detection and trap plugging, as well as to prevent backflow into the furnace.
11. The water leak detectors are monitored for a leak signal.
12. The furnace power circuit is monitored for a shutdown condition.
13. The furnace body temperatures are monitored for an over temperature condition.
14. The furnace water flow valves are controlled.
15. The chiller water flow valves are controlled.
16. The valve sequence for furnace evacuation is controlled.
17. The valve sequence for furnace purging is controlled.

The following data are recorded:

1. Furnace temperature—two thermocouples.
2. Furnace body temperatures—four thermocouples.
3. Trap temperatures—six thermocouples.
4. Cold finger temperature—one thermocouple.
5. Flow rates—four flow/controllers.
6. Furnace pressure—one pressure gauge.
7. Furnace power control signal.

Inputs for system:

1. Operator inputs.
2. Signal from moisture detectors.
3. Signal from vacuum gauge.
4. Signal from pressure gauge.
5. Seven 4–20 mA signal inputs from the furnace thermocouples.
6. Two switched inputs from the gate valve.
7. Three location switches from the cold finger.
8. Six type K thermocouples.
9. Four 0–10 V flow indicators.

Outputs for system:

1. Control signal to furnace power supply.
2. Three 120 VAC signals to trap table.
3. Ten 120 VAC signals to the furnace valves.
4. 120 VAC signal to cold finger motor.
5. 120 VAC signal to cold finger lift.
6. 120 VAC control signal to furnace fans.
7. 120 VAC signal to chiller valves.
8. 120 VAC signal to furnace valves.
9. 120 VAC signal to gate valve.

Displays and data collection:

1. Window displays of the furnace temperature.
2. He gas flows.
3. Furnace pressure.
4. Trap temperatures—control and core.

The operation of the cold finger involves command signals sent to and received from:

1. Up/down and rotational motors.
2. The airlock gas purge system.
3. The upper, middle, and lower interlock switches.
4. The gate valve.
5. The manually operated thermal shutters.
6. Manipulation of the internal He flowrates to the furnace.

2.2 LABVIEW PROGRAM DESCRIPTION

The CCCTF control program uses NI LabVIEW software to receive and send signals from and to the system's hardware. The main program consists of six control virtual instrument (VI) files, each of which contains multiple sub-VIs, or subroutines. The six control VIs and their functionality are as follows:

1. CCCTF Control VI—this VI is the central hub for the program, it monitors and controls the flow of all the other VIs in the program.
2. Data Acquisition VI—receives all the data from external devices and inputs.
3. Data Management VI—performs all computational analysis on the information acquired by the Data Acquisition VI and, after the analysis, activates safety protocols if required.
4. System Output VI—generates all output signals required to run the system.
5. Display VI—displays the data on the GUI.
6. Event Monitoring VI—executes the desired commands when the user activates a control, button, drop-down box, or any other input on the GUI.

2.3 LABVIEW PROGRAM FUNCTIONALITY

The CCCTF LabVIEW control program is designed and laid out logically and intuitively such that the interface is familiar to former users, and new users can quickly learn basic function and operation. Several routines that were housed in separate programs in the previous setup were consolidated into a single multifunctional program. The functionality and operation of the program as well as automated subroutines are discussed in the following subsections.

2.3.1 User Interface and Operation

The main control screen (Figure 2) consists of three panels: (1) a schematic of the CCCTF furnace as well as valves that can be actuated, (2) a panel for user input and control, and (3) a panel for indicators and readings. The user input and control panel in the upper right corner of the screen contains multiple pages for secondary and tertiary functions, which are discussed in Section 2.3.2.

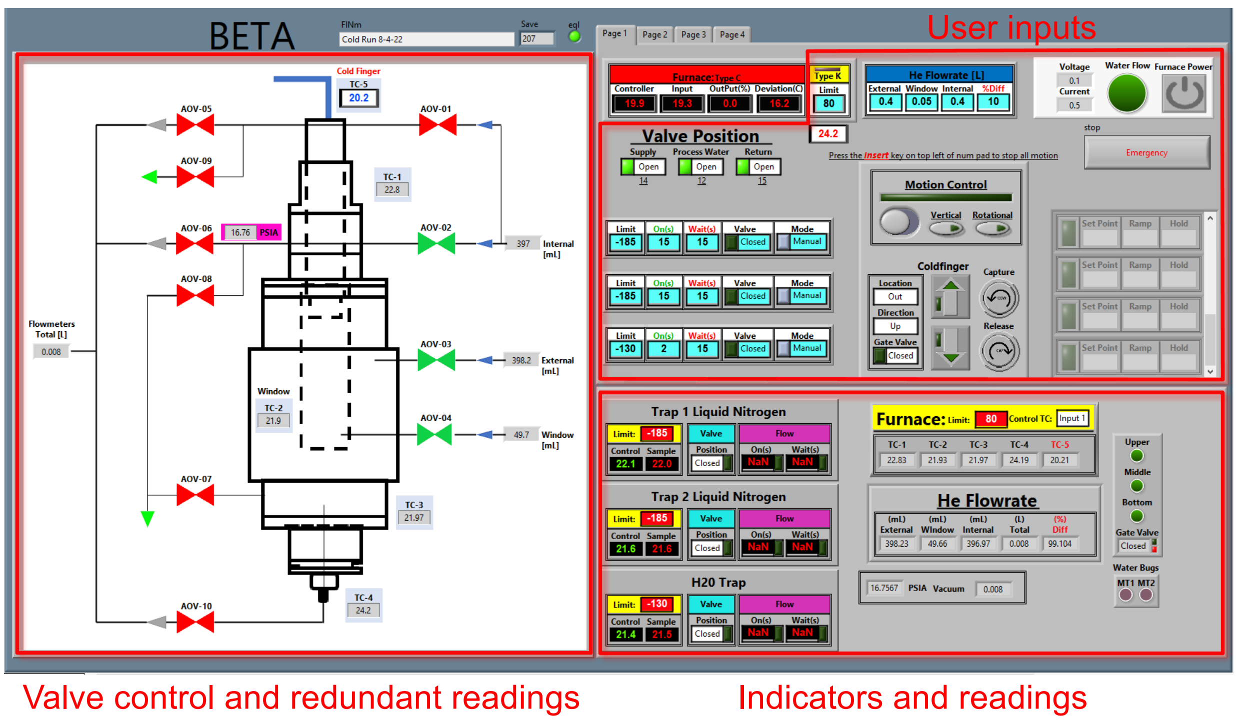

Figure 2. Main control screen for the CCCTF.

The main (Page 1) user input and control panel (Figure 3) houses:

1. Temperature readings for the furnace, as well as indication of the current percentage output from the temperature controller and the deviation (in °C) from the present set point. Also included is a single temperature limit input (default is 80°C) for the five thermocouples monitoring important locations around the furnace and within the cold finger (these thermocouples are denoted TC-1–TC-5 and are displayed in the lower panel).
2. A section for input of He flow rates that are used to send signals to mass flow controllers.
3. An on/off button for a contactor within the furnace power supply. This button becomes active or inactive based on (1) the position of furnace cooling water valves, (2) the status of cooling water flowmeters (indication for water flow status is located adjacent to the power button), (3) whether any of the five thermocouples are above the user defined limit, and (4) whether the water leak detection monitors are tripped.
4. Furnace water cooling valve control (default is all valves open).
5. A digital emergency stop button which sends "FALSE" or off signals to liquid nitrogen pneumatic valves and the cold finger motor controls.
6. A section for user inputs for control of the liquid nitrogen pneumatic valves for the purpose of maintaining ^{85}Kr and moisture trap temperatures. Manual operation of these valves is offered here. The automated functionality and operation of this system is detailed in a following subsection.
7. Control of the cold finger motion and actuation of the gate valve. Redundant on/off switches are included to engage or disengage the ability to operate the cold finger. Digital momentary switches are used to move the cold finger up and down and to operate the rotation motor for capture or release of sample deposition cups. Within the cell, the cold finger's position is monitored and limited with roller switches. Cold finger motion is activated or deactivated based on which switch is engaged and when, in order to maintain a pure He environment within the furnace and to mitigate collision of the cold finger with important components.
8. Input for a furnace temperature profile program including set points, ramp rates, and hold times.

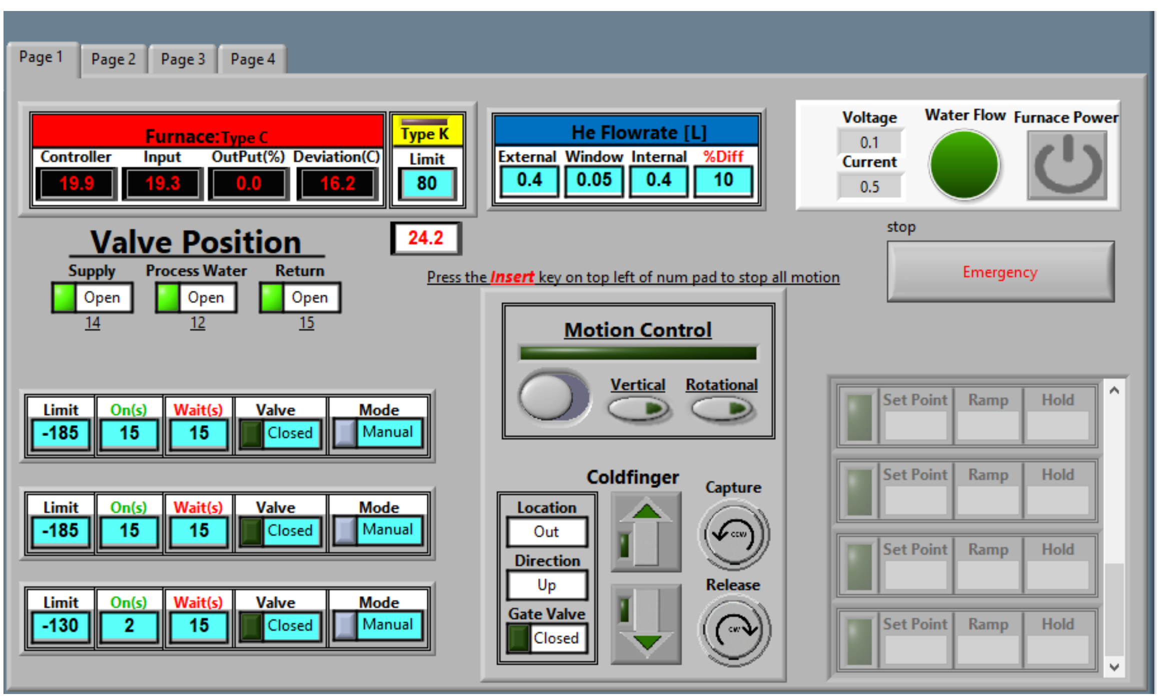

Figure 3. User input and control panel of the main program screen.

The indicators and readings panel (Figure 4) consists of the following:

1. A section monitoring the automated control of the liquid nitrogen pneumatic valves for the purpose of maintaining ^{85}Kr and moisture trap temperatures.
2. Readings for TC-1–TC-5, which are placed strategically around the furnace to maintain safe operation and to protect temperature sensitive components.
3. Readings for He flow rates from mass flow controllers: one for the internal compartment of the furnace (inside Ta container where the test specimen is loaded), one for the external compartment of the furnace (outside Ta container where the graphite heating elements reside), and one corresponding to flow past the window to the exterior compartment of the furnace. One other mass flow controller is monitored and is located on the exhaust of the furnace (total) and is used as an indication of whether the input flow is equal to the output flow. This is useful to determine whether there is a leak or blockage. The percent difference between the sum of the three input flows and the exhaust (total) is also calculated and displayed here.
4. A section for indication of in-cell cold finger limit switches used for determining and controlling cold finger motor control based on the location of the cold finger. This section also houses indicators for the status of the gate valve.
5. The status of the water leak detectors.

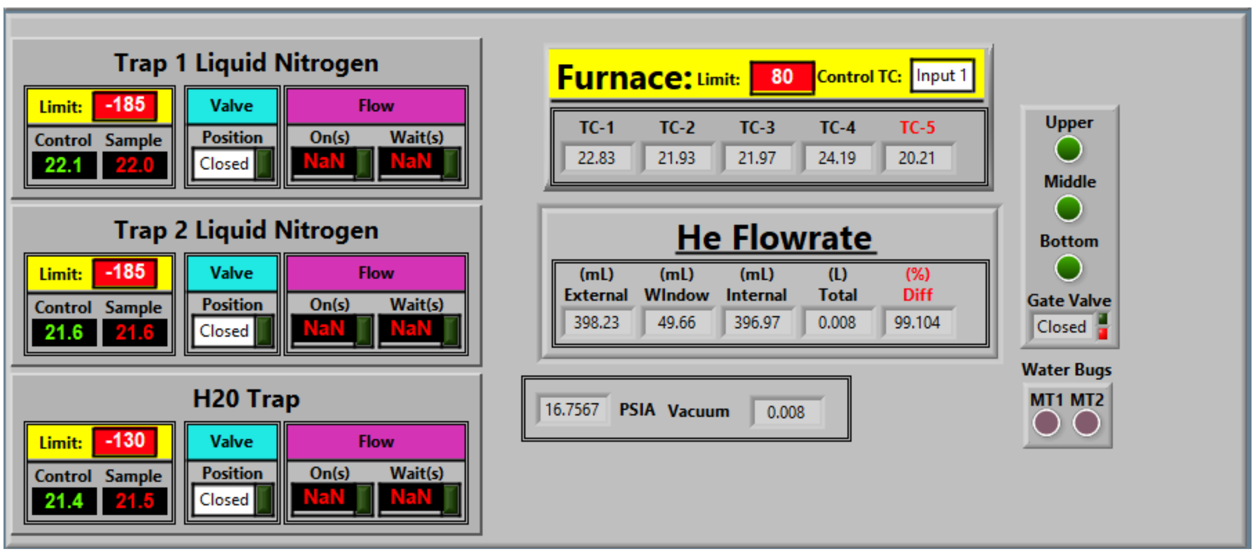

Figure 4. Indicators and readings panel on the main program screen.

The valve control and redundant readings panel (Figure 5) remains visible on the left side of the program regardless of which page the user chooses on the right side of the screen. The schematic format is helpful for visualization of valve and component locations with respect to flow paths and furnace compartments. The following items are included:

1. Click-to-actuate valve buttons for which the actual valve status is indicated and updated continuously.
2. Redundant temperature readings (thermocouples TC-1–TC-5).
3. Flow controller readings.
4. An internal compartment pressure gauge reading.

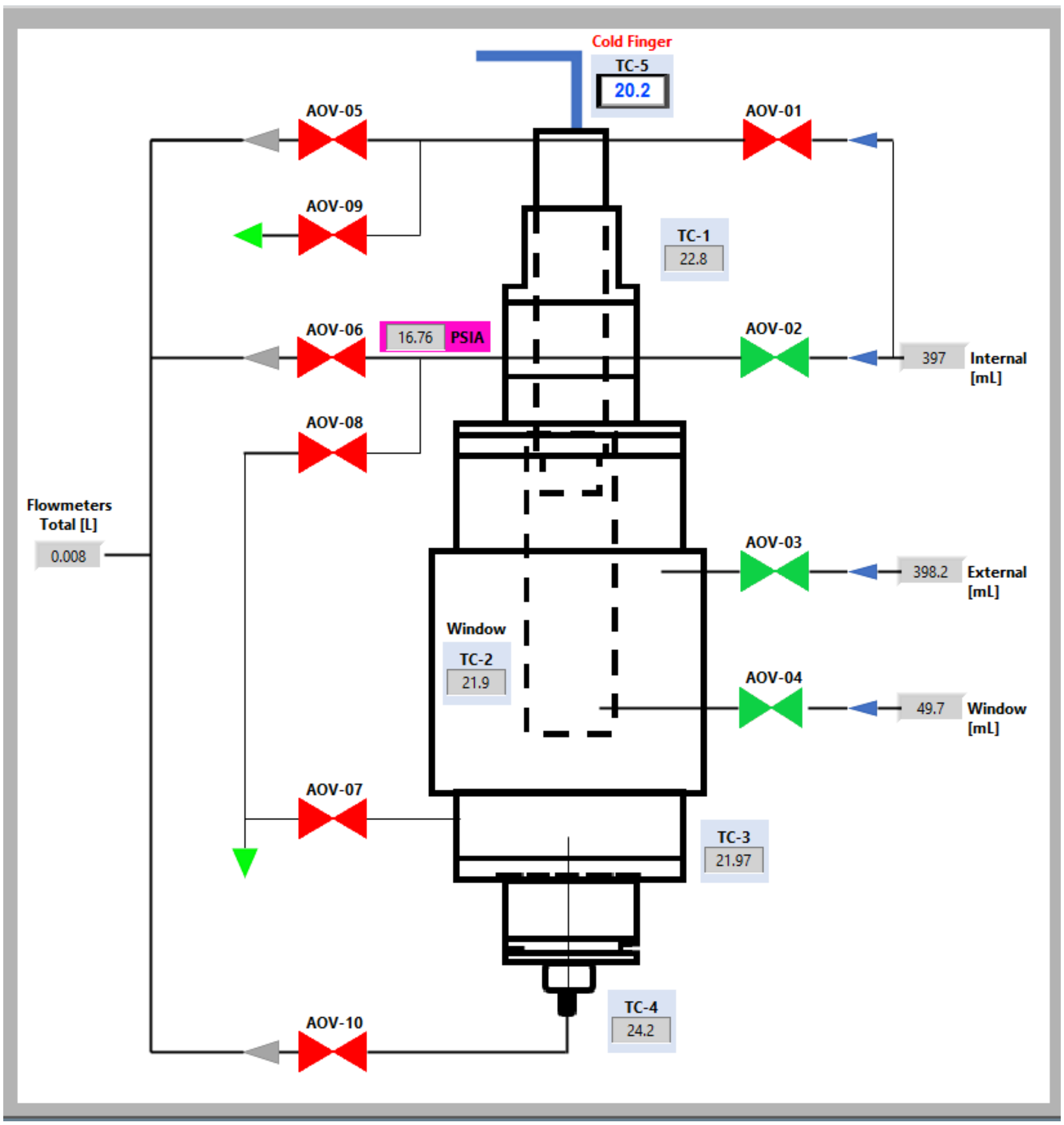

Figure 5. Valve control and redundant readings.

2.3.2 Automated routines

The program supports and facilitates several automated routines—namely, evacuating the furnace, purging and pressurizing the furnace with He, testing the seal of the spool piece that acts as an air lock between the interior of the furnace and the open volume in the hot cell, and control over liquid nitrogen valves for the purpose of maintaining temperature within the ^{85}Kr and moisture traps. The functions discussed below for furnace evacuation (Section 2.3.2.1), furnace purging (Section 2.3.2.2), and spool seal testing (Section 2.3.2.3) are housed and operated on Page 2 of the user input and control panel (Figure 6). The liquid nitrogen input and control panel is on Page 1 (Figure 7) and is discussed in Section 2.3.2.4.

The automated furnace evacuation (EVAC) and He purge routines are executed after furnace rebuild and before starting a safety test. Before running these routines, the sweep gas line between the CCCTF furnace (inside the hot cell) and the trap table (outside the hot cell) is manually purged with helium and isolated by closing the inlet valve to the trap table and the three pneumatic automated operation valves (AOVs) through which He gas exits the furnace system (AOV-5, AOV-6, and AOV-10, as shown in Figure 5).

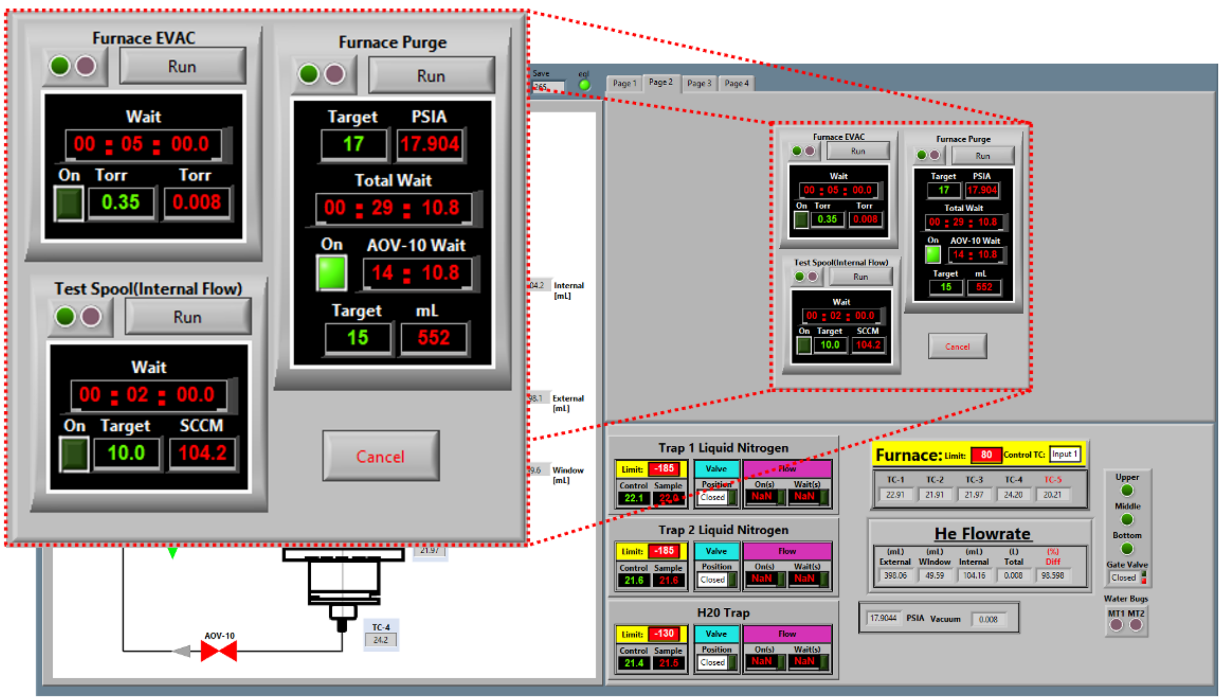

Figure 6. Page 2 of the user input and control panel, which houses several automated routines (inset).

2.3.2.1 Furnace EVAC mode

The evacuation mode (Figure 6) evacuates and vacuum leak tests the furnace by the following automated sequence:

1. A pop-up box is displayed to prompt the user to make sure the cold finger is out of the furnace, the gate valve is closed, and the trap table inlet valve is closed (this valve isolates the trap table from the CCCTF furnace system inside the hot cell).
2. All the pneumatic valves are closed (see Table 1).
3. After the valves have closed, the vacuum path is opened (see Table 2).
4. The vacuum gauge is monitored.
5. When pressure drops below a set limit (default is 0.35 Torr), a pop-up box tells the operator that the task is done. If the evacuation takes longer than a set wait period (default is 5 min), a pop-up box informs the operator of a problem, and the program terminates.

Table 1. Valve settings in preparation for evacuation

Valve [a]	Status	Result
AOV-1	Closed	No flow to Air lock compartment
AOV-2	Closed	No flow to furnace internal compartment
AOV-3	Closed	No flow to furnace external compartment
AOV-4	Closed	No flow past furnace window to external compartment
AOV-5	Closed	Exit path from Air lock closed
AOV-6	Closed	Exit path from internal compartment closed
AOV-7	Closed	External compartment and window vacuum path closed
AOV-8	Closed	Internal compartment vacuum path closed
AOV-9	Closed	Air lock compartment vacuum path closed
AOV-10	Closed	Exit path from external compartment and window closed
Gate Valve	Closed	Cold finger out of furnace and internal and air lock compartments isolated

[a] See Figure 5 for valve locations.

Table 2. Valve settings for evacuation

Valve [a]	Status	Result
AOV-1	Closed	No flow to Air lock compartment
AOV-2	Closed	No flow to furnace internal compartment
AOV-3	Closed	No flow to furnace external compartment
AOV-4	Closed	No flow past furnace window to external compartment
AOV-5	Closed	Exit path from Air lock closed
AOV-6	Closed	Exit path from internal compartment closed
AOV-7	Open	External compartment and window vacuum path opened
AOV-8	Open	Internal compartment vacuum path opened
AOV-9	Closed	Air lock compartment vacuum path closed
AOV-10	Closed	Exit path from external compartment and window closed
Gate Valve	Closed	Cold finger out of furnace and internal and air lock compartments isolated

[a] See Figure 5 for valve locations.

2.3.2.2 Furnace PURGE mode

The purge mode is performed directly after the EVAC mode successfully completes an evacuation cycle. It fills the furnace with He, and tests the ability of the furnace to hold pressure (Figure 6). Note that the trap table inlet valve remains closed for this function.

1. The purge segment of the task sets the valves as shown in Table 3.

Table 3. Valve settings for purging and pressurizing with He

Valve [a]	Status	Result
AOV-1	Closed	No flow to Air lock compartment
AOV-2	Open	Flow to furnace internal compartment
AOV-3	Open	Flow to furnace external compartment
AOV-4	Open	Flow past furnace window to external compartment
AOV-5	Closed	Exit path from Air lock closed
AOV-6	Closed	Exit path from internal compartment closed
AOV-7	Closed	External compartment and window vacuum path closed
AOV-8	Closed	Internal compartment vacuum path closed
AOV-9	Closed	Air lock compartment vacuum path closed
AOV-10	Closed	Exit path from external compartment and window closed
Gate Valve	Closed	Cold finger out of furnace and internal and air lock compartments isolated

[a] See Figure 5 for valve locations.

2. When the internal compartment pressure gauge reads a set limit (default is 17 psia), AOV-6 is opened to pressurize the sweep gas line between the CCCTF furnace and the trap table. Since the external portion of the furnace consists of a larger volume and thus takes longer to pressurize, a delay of 15 min occurs before opening AOV-10 to prevent backflow into this portion of the furnace. After a total wait time of 30 min, the sum of the flows indicated by the three inlet flowmeters is totaled, and it should be less than a set limit (default is 15 mL). This indicates that the furnace and sweep gas line are sufficiently gas tight. A pop-up box indicates pass or fail, and the screen shows the sum, as well as indicators: green for good or red for too high. The operator then clicks OKAY, and operation reverts to nominal without changing any valves.

At this point, the trap table inlet valve is opened and normal flow through the system is resumed.

2.3.2.3 Test Spool Seal mode

To test the cold finger seal, the cold finger is physically moved by the operator to a position above the furnace airlock by use of the in-cell manipulators. Subsequently, the following program is initiated (Figure 6).

The valves are set as shown in Table 4.

Table 4. Valve settings prior to spool piece seal test

Valve [a]	Status	Result
AOV-1	Closed	No flow to Air lock compartment
AOV-2	Open	Flow to furnace internal compartment
AOV-3	Open	Flow to furnace external compartment
AOV-4	Open	Flow past furnace window to external compartment
AOV-5	Closed	Exit path from Air lock closed
AOV-6	Open	Exit path from internal compartment open
AOV-7	Closed	External compartment and window vacuum path closed
AOV-8	Closed	Internal compartment vacuum path closed
AOV-9	Closed	Air lock compartment vacuum path closed
AOV-10	Open	Exit path from external compartment and window open
Gate Valve	Closed	Cold finger out of furnace and internal and air lock compartments isolated

[a] See Figure 5 for valve locations.

The operator then uses the down switch on the control panel/computer to carefully jog the cold finger into the airlock. Once in the airlock, the cold finger moves down to the middle interlock and stops via the software-controlled interlock.

The ***Test Spool Seal*** button is then clicked on to begin the test. There is no more movement of the cold finger. The cold finger seal test is as follows:

1. Valve AOV-2 is closed.
2. Valve AOV-1 is then opened.
3. The internal flowmeter is monitored for 2 min.
4. After 2 min, the flowmeter reading should be less than 10 mL. A pop-up box displays the internal flowmeter readings: green if less than 10 mL and red if greater than 10 mL. The operator then clicks OKAY.
5. Valve AOV-2 is opened.
6. Valve AOV-1 is closed.
7. The system then returns “Test Successful” and reverts to normal operation.

2.3.2.4 Liquid Nitrogen-Cooled Trap Temperature Control

The CCCTF's trap table system consists of a moisture trap (H_2O trap, for capturing water from the gas stream so that lines do not clog with ice) and two charcoal traps designed to capture, detect, and monitor ^{85}Kr fission gas released from test specimens and entrained in the He sweep gas. The moisture trap must be cooled to freeze and collect water but maintained at a temperature above the freezing point of ^{85}Kr such that it passes to the main traps. The temperature of the main traps must be reliably maintained to capture all ^{85}Kr in the gas stream (He gas passes through the ^{85}Kr traps and is routed back into the hot cell). This cooling is executed by pulsing liquid nitrogen flow into the center of each trap. The internal trap temperature and exhaust temperature of the liquid nitrogen flow loop are monitored. When the trap control temperature exceeds a threshold temperature, a valve is opened for a user-defined amount of time to let liquid nitrogen into the trap jacket. This fills the trap jacket with liquid nitrogen. The operation is complicated by the fact that a vapor pocket can form in the system, which may insulate the control thermocouple from the liquid. To remedy this, a pause with the valve closed is implemented for a short period of time so that the system can equilibrate. For each trap, the user inputs the control threshold temperature, as well as the on and off times for this routine (Figure 7). When the set point is reached, the program remains in standby mode until the temperature rises above the user-defined threshold.

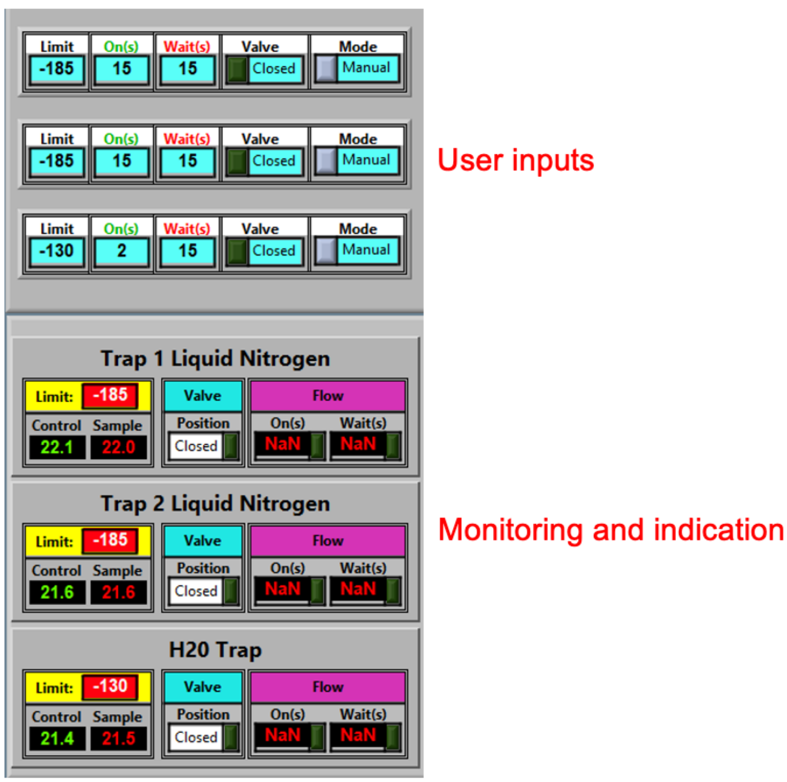

Figure 7. Liquid nitrogen valve control inputs and monitoring on the main user interface screen.

3. SUMMARY

The CCCTF control apparatus was updated to leverage advances in modern hardware and computational capabilities. Compared with the outgoing setup, the new system was consolidated and simplified. By using modern computational tools such as the LabVIEW software, user inputs and control are simplified such that even novice users can successfully operate the CCCTF. In addition, future upgrades and modifications to the control apparatus and system capabilities will be relatively simple and efficient.

4. REFERENCES

Baldwin, Charles A., John D. Hunn, Robert N. Morris, Fred C. Montgomery, Chinthaka M. Silva, and Paul A. Demkowicz. 2014. "First Elevated Temperature Performance Testing of Coated Particle Fuel Compacts from the AGR-1 Irradiation Experiment." *Nuclear Engineering Design* 271: 131–141.

Demkowicz, Paul A., John D. Hunn, Robert N. Morris, Isabella J. van Rooyen, Tyler J. Gerczak, Jason M. Harp, and Scott A. Ploger. 2015. *AGR-1 Post Irradiation Examination Final Report*. INL/EXT-15-36407, Revision 0. Idaho Falls: Idaho National Laboratory.

Hunn, John D., Robert N. Morris, Fred C. Montgomery, Tyler J. Gerczak, Darren J. Skitt, Charles A. Baldwin, John A. Dyer, Grant W. Helmreich, Brian D. Eckhart, Zachary M. Burns, Paul A. Demkowicz, and John D. Stempien. 2018. "Post-Irradiation Examination and Safety Testing of US AGR-2 Irradiation Test Compacts." *Proc. 9th International Topical Meeting on High Temperature Reactor Technology (HTR-2018)*. Warsaw, October 8–10, 2018.

Morris, Robert N., Paul A. Demkowicz, John D. Hunn, Charles A. Baldwin, and Edward L. Reber. 2014. "Performance of AGR-1 High Temperature Reactor Fuel During Post-Irradiation Heating Tests." *Proc. 7th International Topical Meeting on High Temperature Reactor Technology (HTR-2014)*. Weihai, October 27–31, 2014. Also published in *Nucl. Eng. Des.* 306: 24–35.

Morris, Robert N., John D. Hunn, Charles A. Baldwin, Fred C. Montgomery, Tyler J. Gerczak, and Paul A. Demkowicz. 2016. "Initial Results from Safety Testing of US AGR-2 Irradiation Test Fuel." *Proc. 8th International Topical Meeting on High Temperature Reactor Technology (HTR-2016)*. Las Vegas, November 6–10, 2016. Also published in *Nucl. Eng. Design* 329: 124–133.

Stempien, John D., John D. Hunn, Robert N. Morris, Tyler. J. Gerczak, and Paul A. Demkowicz. 2021. *AGR-2 TRISO Fuel Post-Irradiation Examination Final Report*. INL/EXT-21-64279, Revision 0. Idaho Falls: Idaho National Laboratory.