S-AA-M-31

Cryogenic Target Handling System Operations Manual Volume IV–CTHS Description

Chapter 13: High-Pressure DT Fill Process

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Chapter 13
High-Pressure DT Fill Process

13.1 INTRODUCTION

The OMEGA laser at the University of Rochester's Laboratory for Laser Energetics (UR/LLE) will conduct direct-drive laser-implosion campaigns on ICF targets, which contain cryogenic solid deuterium–tritium (DT) ice layers. These campaigns are an important step in the U.S. effort to achieve ignition of DT and energy gain, using targets containing cryogenic solid-DT fuel, on the National Ignition Facility (NIF) at the Lawrence Livermore National Laboratory (LLNL).

The High-Pressure DT Fill Process requires the integration of the TFS, the DTHPS, the FTS Permeation Cell, and the TRS. The integration of the TFS, DTHPS, and FTS can be seen in Fig. 13.1-1. This chapter describes the integration and operation of this equipment. The process integration into the TRS can be seen in Fig. 13.1-2.

Safety during the high-pressure DT fill is achieved through the combination of containment systems, monitoring, and a sequence of seven "Fill States." Figure 13.1-3 illustrates the state concept. The control system transitions to the appropriate fill state as the DT fill progresses. The fill state reflects the tritium location, pressure, and temperature.

The process conditions are checked before the control system transitions to a new fill state. This ensures that the process condition and fill state are synchronized. The control system enables the devices that are required for the next fill state and disables devices that are not needed; this helps ensure that the process stays within the fill-state boundaries. The control system monitors the containment system integrity and takes the appropriate action, based on the tritium location, pressure, and temperature, if a breach is detected. In addition to release monitoring, the tritium inventory is monitored via assays throughout the fill process.

The primary objective of the fill state sequencer is to track the location of the tritium inventory during the fill process. For example, in the scenario where the TFS containment system is compromised, it is undesirable to return the tritium that is in the permeation cell to the TFS. In other scenarios, the containment failure may be upstream of the tritium; in this case, the process is placed on hold.

The state sequencer is designed to reduce the number of unnecessary aborts. There are 119 detectable scenarios; 45 of these scenarios will execute a pause and 6 scenarios will return DT to the getters. Tritium in the permeation cell will not be getter, thus leaving the permeated targets in tact.

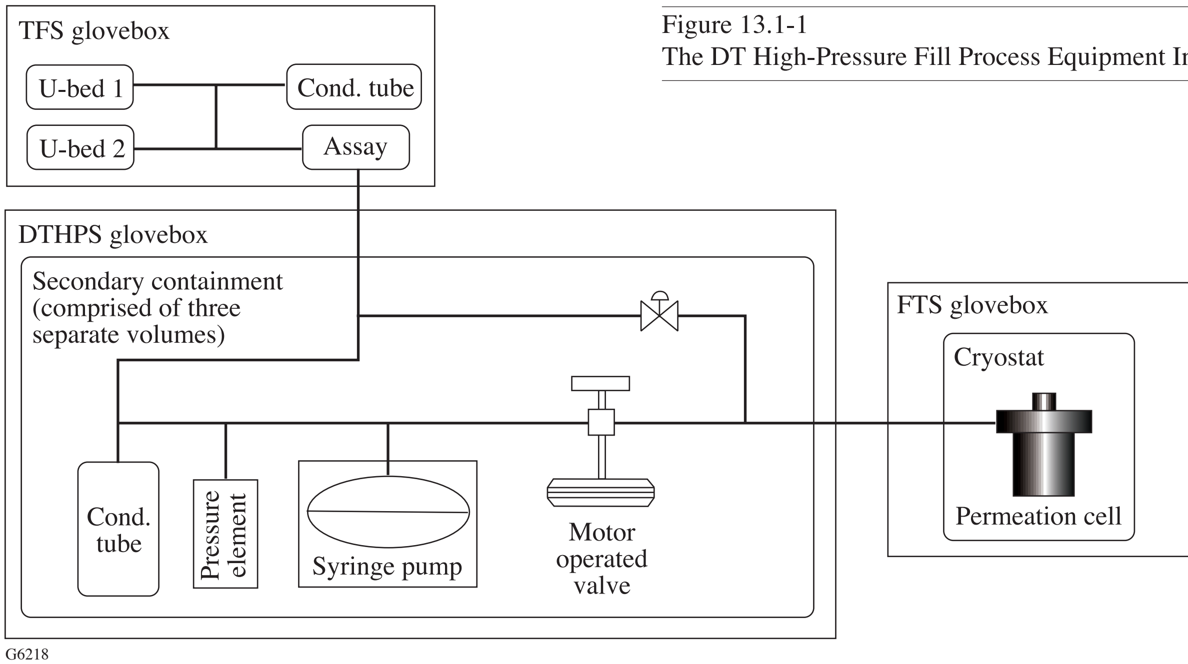

Figure 13.1-1
The DT High-Pressure Fill Process Equipment Integration.

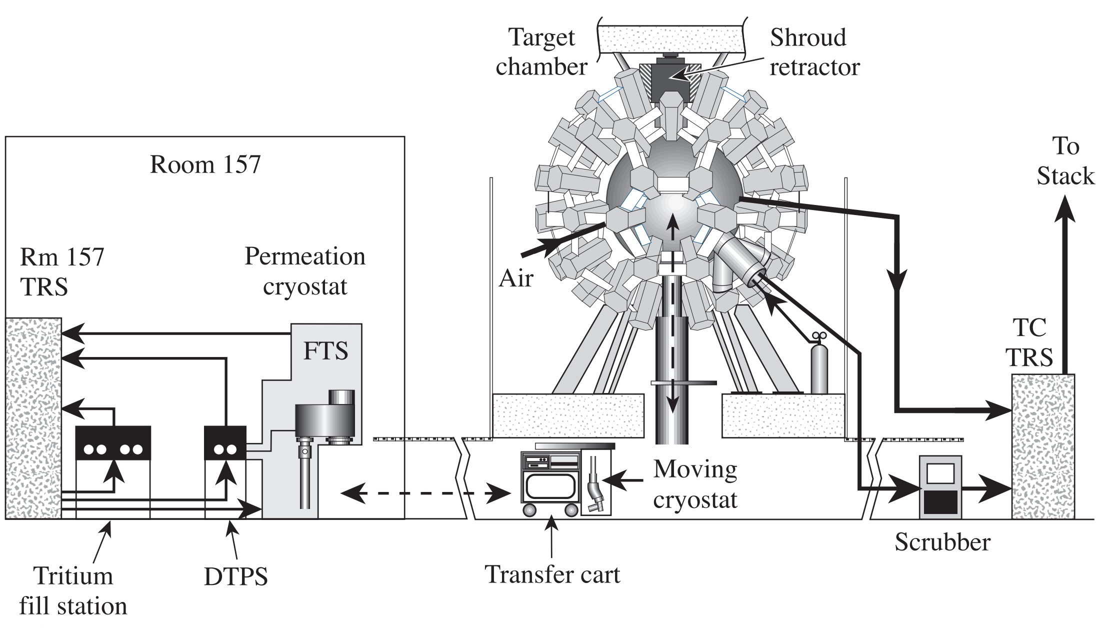

Figure 13.1-2
High-Pressure Fill Process Equipment Integration into the Tritium Recovery System.

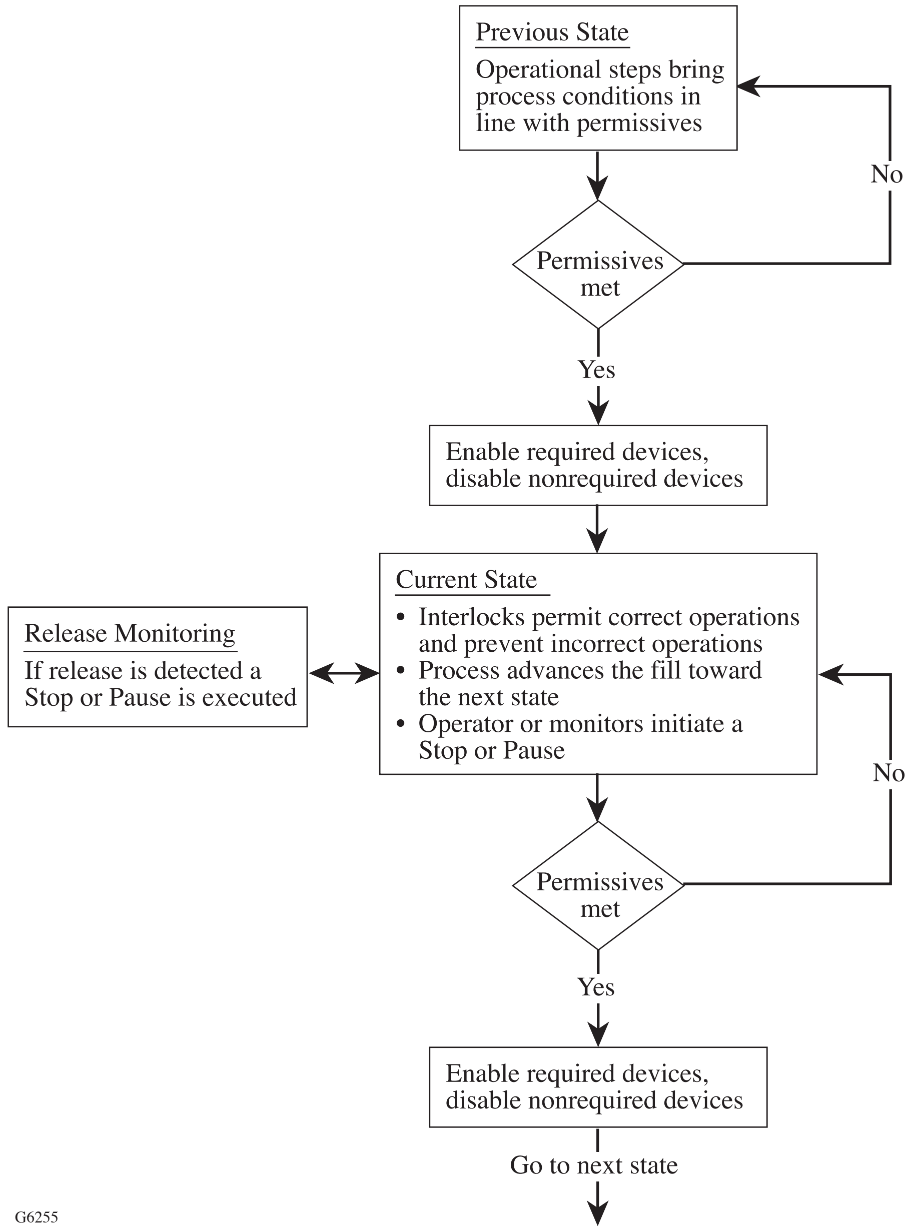

Figure 13.1-3
The fill-state control diagram.

13.2 THE TRITIUM FILL PROCESS

The high-pressure fill process is divided into an initialize state and seven different fill states. The room-temperature fill process is divided into an initialize state and one fill state. The state machine begins in the ready state and will transition to either the high-pressure fill or the room-temperature-fill initialize state. If a release scenario is detected, the state machine will transition to the stop state or the pause state.

When the Initialize State has been established, the control system allows the operator to proceed with the room-temperature fill process. Tritium does not leave the TFS for this type of fill; therefore, the fill-state sequencer is not required (the DT location is not tracked). The room-temperature fill interlocks will execute a stop and return the tritium to the U-bed (in all cases). The room-temperature fill is covered in Chap. 5. The following are the seven fill states for cryogenic fills:

Fill State 1. Tritium **is condensed** from the U-bed to the TFS cold finger.
Fill State 2. Tritium **is expanded** from the TFS cold finger to the assay volume.
Fill State 3. Tritium **is condensed** into the DTHPS condensation tube.
Fill State 4. Tritium **is expanded** from the condensation tube to the permeation cell (medium-pressure ramp). Residual tritium is returned to the cold U-bed.
Fill State 5. The syringe pump diaphragm **is compressing** tritium into the permeation cell (high-pressure ramp). Residual tritium is returned to the cold U-bed.
Fill State 6. Tritium is being **cooled** to the liquid state in the permeation cell, and the DTHPS is being cleaned up and evacuated. The redidual tritium from the high-pressure ramp is being returned to the cold U-bed.
Fill State 7. Tritium-filled targets are cold in the permeation cell, and the tritium is **returned** to the cold U-bed.

A fill-state sequencer state machine has been developed in the PCC controls to manage each fill state and the associated interlocks and permissives. The following sections describe the sequencer states.

13.2.1 Ready State

This is a standby state. When a fill is started, the state machine will go from ready to initialize. The process starts with the entire inventory of DT on one of the two U-beds in the TFS. (Bed 2 is used in this discussion).

13.2.2 Initialize State

Fill preparations such as leak checks, evacuations, and temperature changes are completed in this state. In addition, all report data are initialized. Separate initialize states are provided for room-temperature fills and the high-pressure fills.

13.2.3 Fill State1: Transfer DT from the U-bed to the TFS Condensation Cell

The entire tritium inventory is transferred from the U-bed (via heating) to the TFS condensation cell (via condensation) (Fig. 13.2-1).

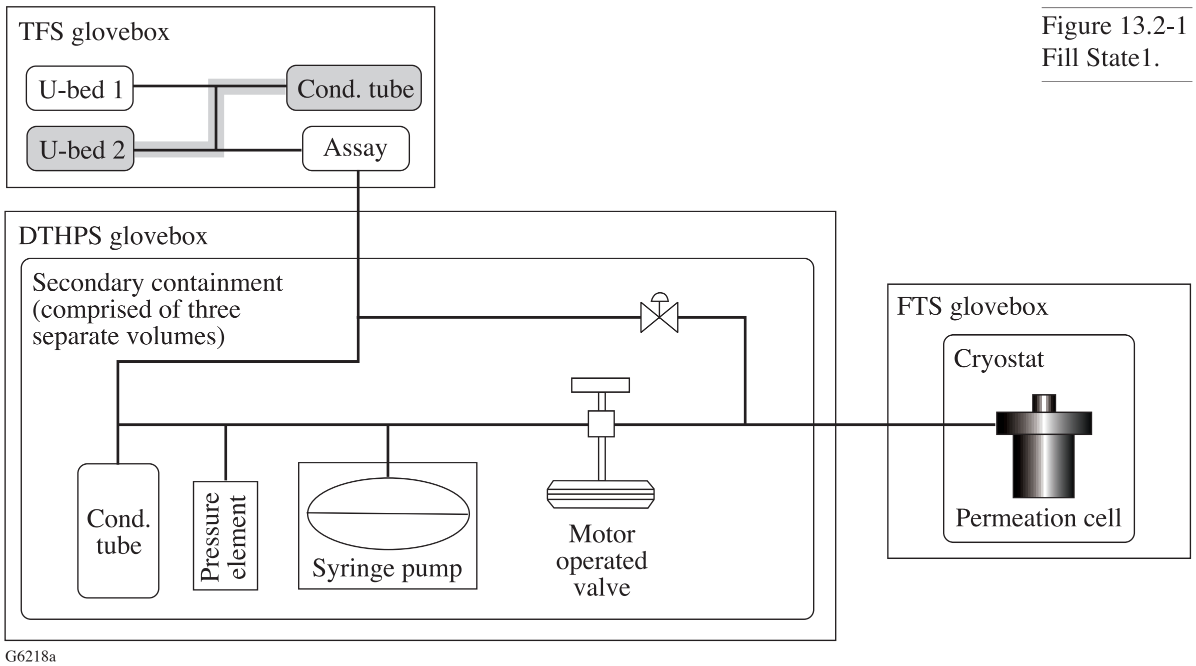

Figure 13.2-1
Fill State1.

13.2.4 Fill State2: Transfer DT from the TFS Condensation Cell to the Assay Volume

The DT is expanded (via warming of the condensation cell) into the assay volume. The entire tritium inventory is then assayed (Fig. 13.2-2).

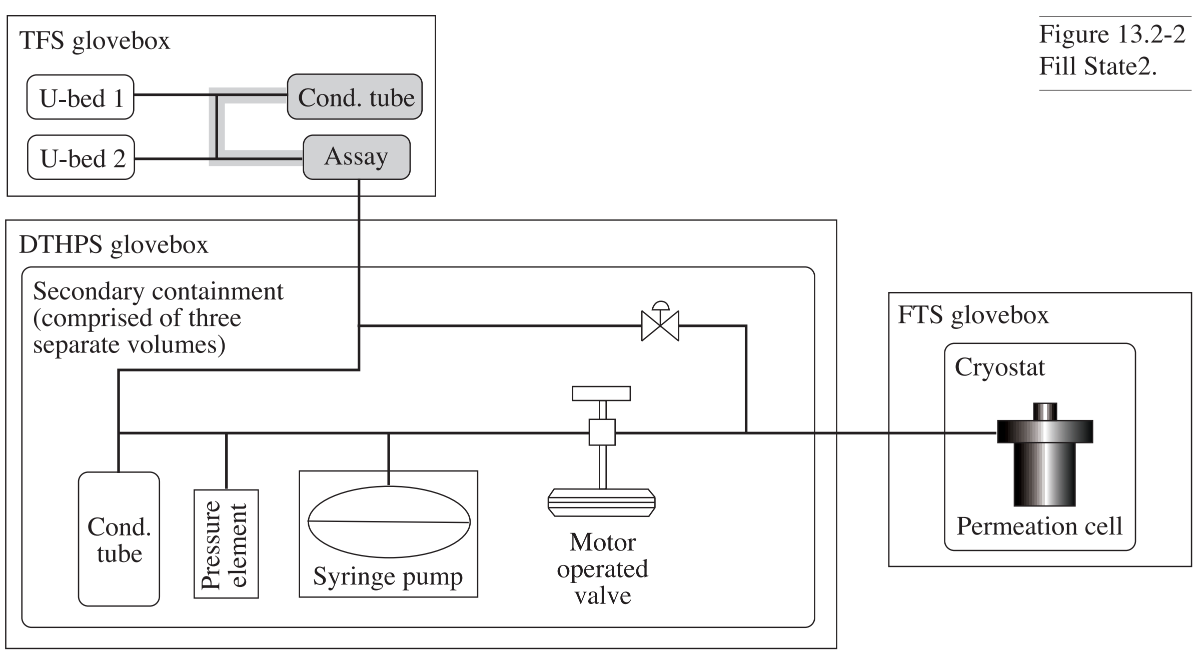

Figure 13.2-2
Fill State2.

13.2.5 Fill State3: Transfer DT from the TFS Assay Volume to the DTHPS Condensation Cell

A portion of the DT is then transferred to the DTHPS condensation cell (Fig. 13.2-3). The unused portion of the DT inventory is assayed and then returned to the cold U-bed.

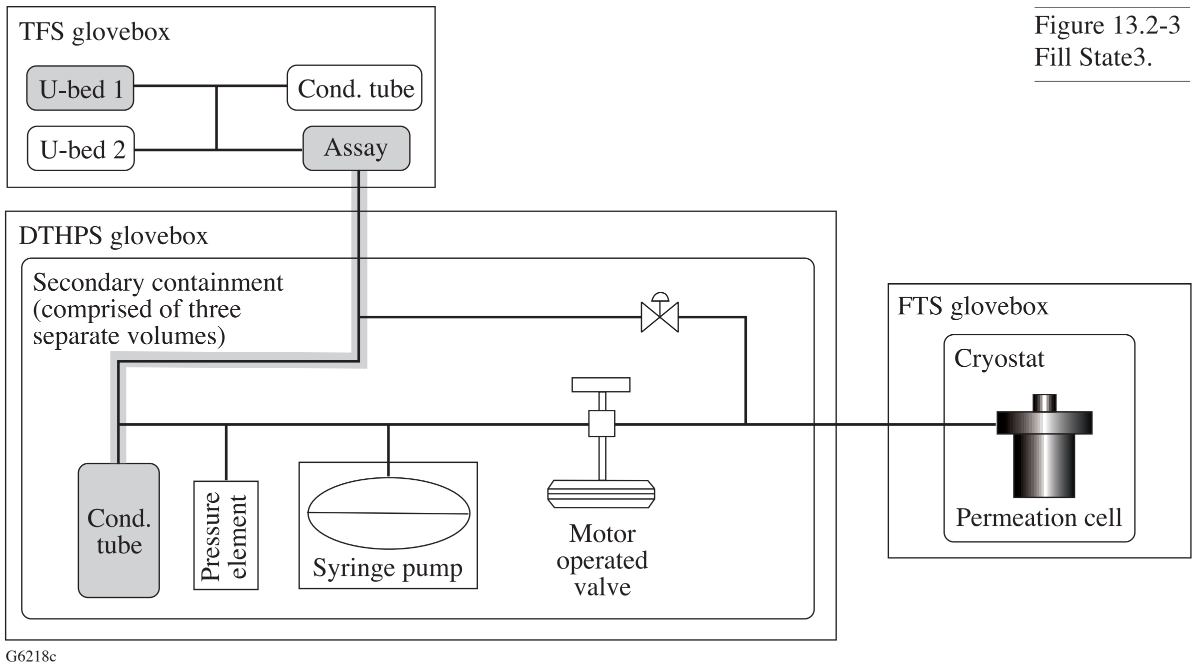

Figure 13.2-3
Fill State3.

13.2.6 Fill State4: Medium-Pressure Ramp

The DT is transferred to the permeation cell, and the pressure is steadily increased to ~200 atm by slowly increasing the temperature. A valve is closed to isolate the condensation tube from the permeation cell, and the unused portion of the DT is assayed and then returned to the U-bed (Fig. 13.2-4).

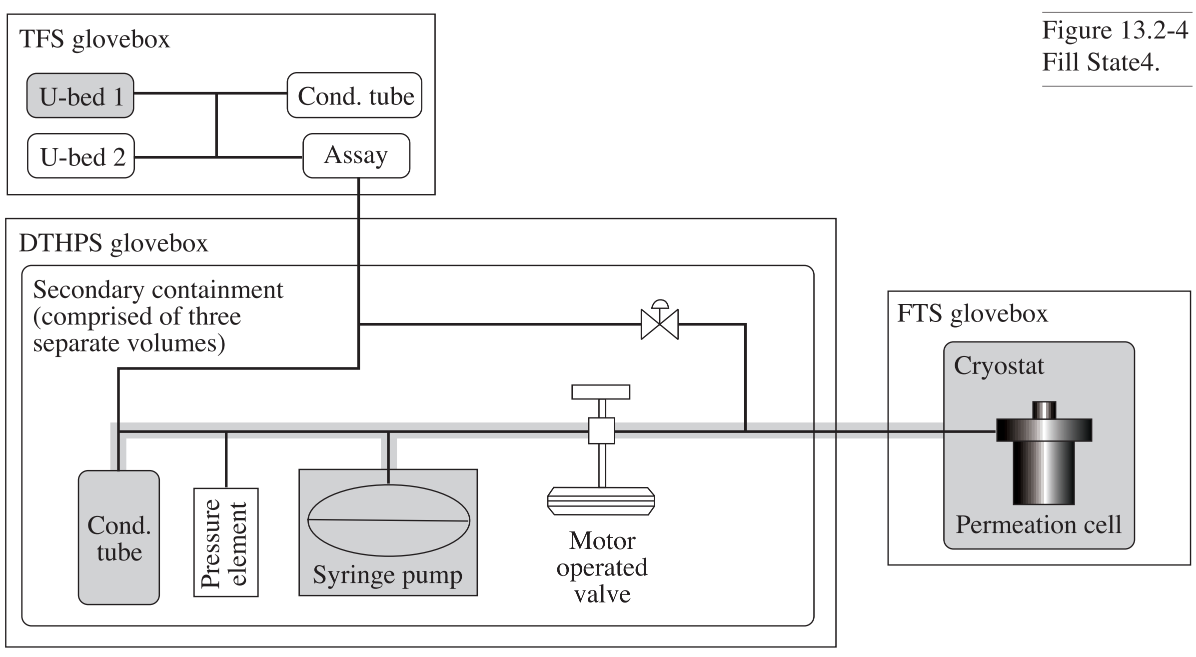

Figure 13.2-4
Fill State4.

13.2.7 Fill State5: High-Pressure Ramp

The pressure in the permeation cell is increased to ~1000 atm via the syringe pump. After the high-pressure ramp is completed, a valve is closed to isolate the permeation cell from the DTHPS (Fig. 13.2-5).

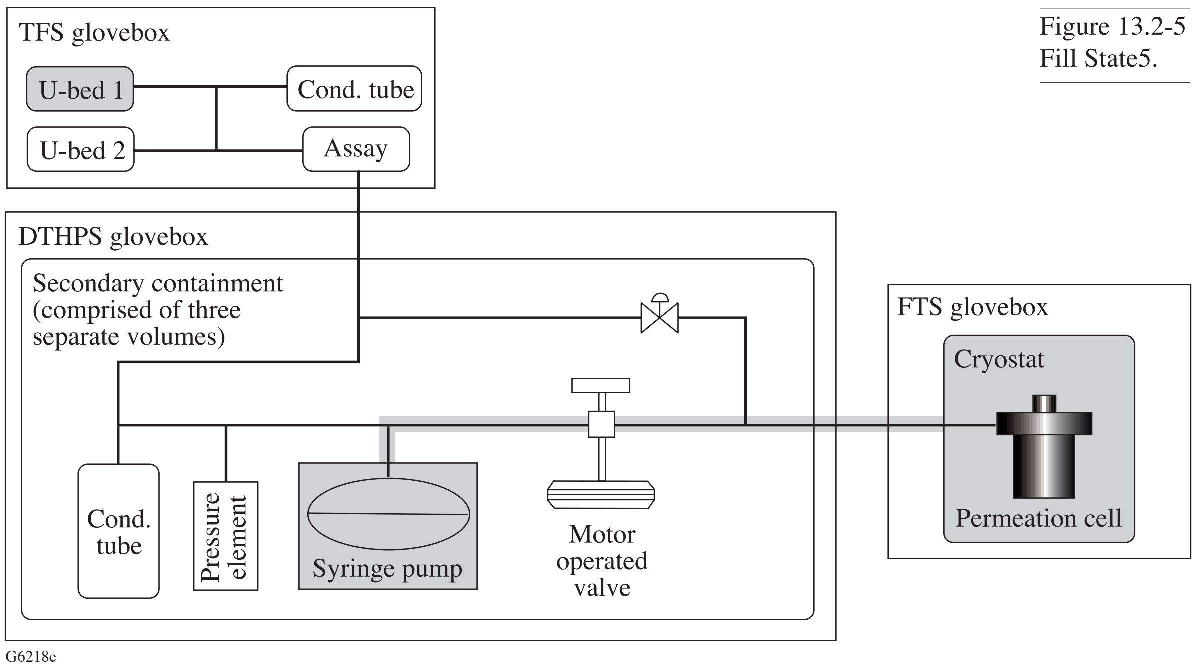

Figure 13.2-5
Fill State5.

13.2.8 Fill State6: Target Cooling

The permeation cell is cooled to ~20 K. After cooling has been initiated, the syringe pump is retracted and the unused DT is assay and returned to the cold U-bed (Fig. 13.2-6).

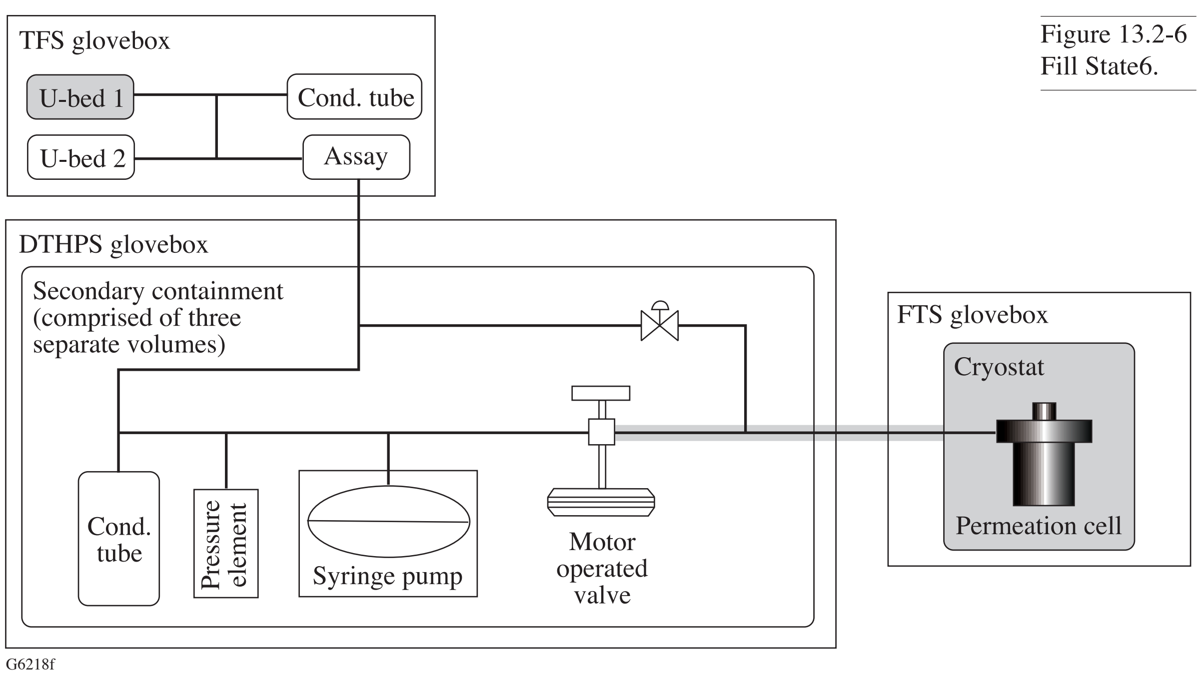

Figure 13.2-6
Fill State6.

13.2.9 Fill State7: Extract DT from the Permeation Cell

After the targets have been cooled to ~20 K, the majority of the DT is extracted to the TFS assay volume (which is initially at vacuum). The DT is assayed and then returned to the cold U-bed (Fig. 13.2-7). The residual DT in the permeation cell is then extracted using the TFS Normetex pump (pumped into the assay volume). The residual DT is assayed and returned to the cold U-bed.

The inventory in now back in the cold U-bed, the entire system is evacuated, and the Fill-State Sequencer is placed in the standby state.

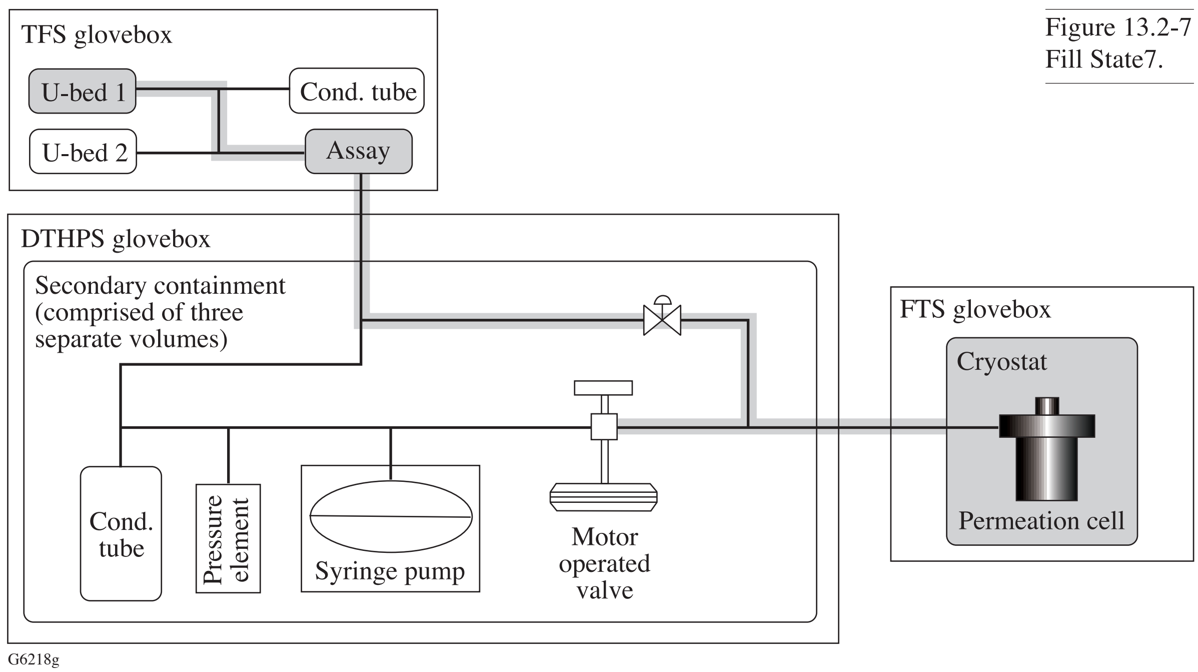

Figure 13.2-7
Fill State7.

13.3 SENSORS FOR CONTAINMENT SYSTEM INTEGRITY

Seventeen (17) sensors are used to monitor the integrity of the tritium containment system. These sensors include the following:

13.3.1 DT Monitors (6)

The tritium levels are monitored in the six areas below. The control system will take action if tritium is detected in any of these areas.

1. TFS glovebox
2. DTHPS secondary containment
3. DTHPS glovebox
4. FTS glovebox
5. Cryostat
6. Room 157

13.3.2 Pressure Sensors (3)

The pressure sensors are used to detect leakage into containment volumes.

1. **Syringe pump DT side:** This pressure sensor detects leakage from the syringe pump DT side diaphram.

2. **Syringe pump oil side:** This pressure sensor detects leakage from the syringe pump oil side diaphram.

3. **FTS Cryostat:** This pressure sensor detects leakage into the cryostat secondary containment volume.

13.3.3 Containment System Failures (6)

Containment system failure is a flag that is set if the system integrity is compromised. Any one of the following scenarios is considered a containment system failure:

- High moisture level
- Pump failure
- Loss of normal circulation in the DTHPS glovebox clean-up system
- Temperature of the U-bed deviates from normal
- TRS failure

The following process volumes have a containment system failure flag:

1. TFS glovebox
2. DTHPS glovebox
3. DTHPS secondary containment
4. FTS glovebox
5. TRS for the cryostat and rack inserter
6. Room ventilation

13.3.4 Other (2)

The following inputs are also monitored:

1. **Operator Stop Command:** The operator can request a stop if a failure is detected.

2. **Heartbeat Bit Failure:** The PLC communication is monitored, and the control system will take action if a failure is detected.

13.4 STOPS1–4

Four PLC-controlled stops and one pause (hold) are defined for the High-Pressure Fill Process. The stop (or hold) executed depends on the fill state (where the DT is located) and the type of release scenario detected (where the failure has been detected). The stops and the pause are discussed in the following subsections. The four stops are defined as follows:

1. **Stop1:** TFS only – The TFS is isolated from the DTHPS, and the DT in the TFS is gettered back to the U-bed.

2. **Stop2:** TFS and DTHPS – The DTHPS is isolated from the FTS permeation cell, and the DT in the TFS and DTHPS is gettered back to the U-bed.

3. **Stop3:** TFS, DTHPS, and Permeation Cell – DT in the entire system is returned to the U-bed.

4. **Stop4:** TFS and Permeation Cell – Syringe pump and condensation cell are isolated. The DT in the permeation cell and TFS is gettered back to the U-bed.

It is not desirable to transport DT into a zone where a failure has been detected. For example, if the system has DT in the DTHPS (> fill state 2) and a failure is detected in the TFS, the TFS is isolated and the DT remains in the DTHPS.

13.4.1 Stop1

If a failure is detected in the TFS containment system, the TFS is isolated from the DTHPS and the DT is gettered back to the U-bed (Fig. 13.4-1). The DT in the DTHPS and permeation cell is not transferred back to the TFS problem area.

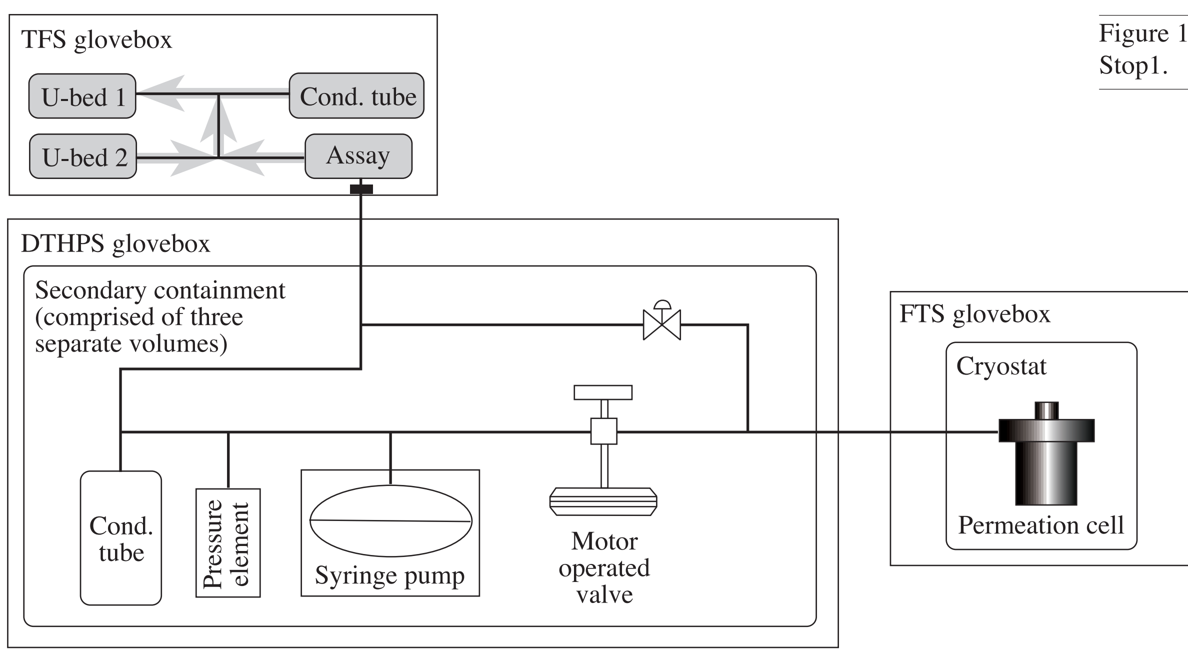

Figure 13.4-1
Stop1.

13.4.2 Stop2

If a containment failure is detected in the DTHPS containment system and DT has been transferred to the DTHPS, the permeation cell is isolated from the DTHPS and the DT is gettered back to the U-bed (Fig. 13.4-2). The DT in the permeation cell is not transferred through the DTHPS (problem area) to the TFS U-bed.

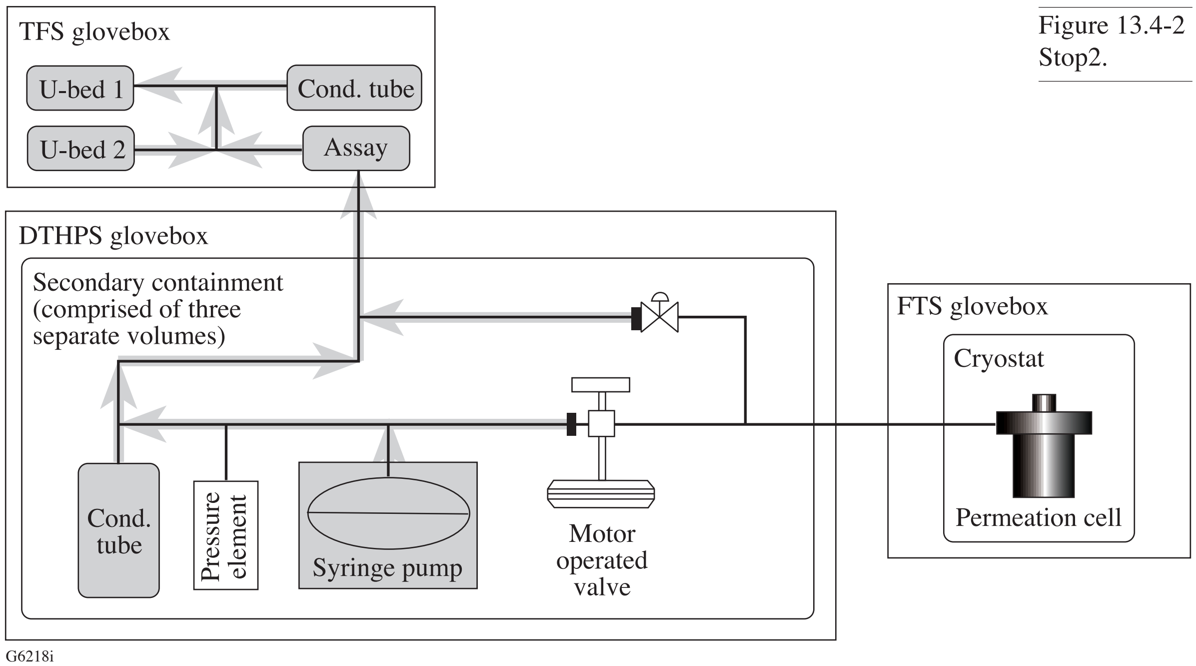

Figure 13.4-2
Stop2.

13.4.3 Stop3

If a containment failure is detected in the FTS containment system and DT has been transferred to the permeation cell, all of the DT is gettered back to the U-bed (Fig. 13.4-3).

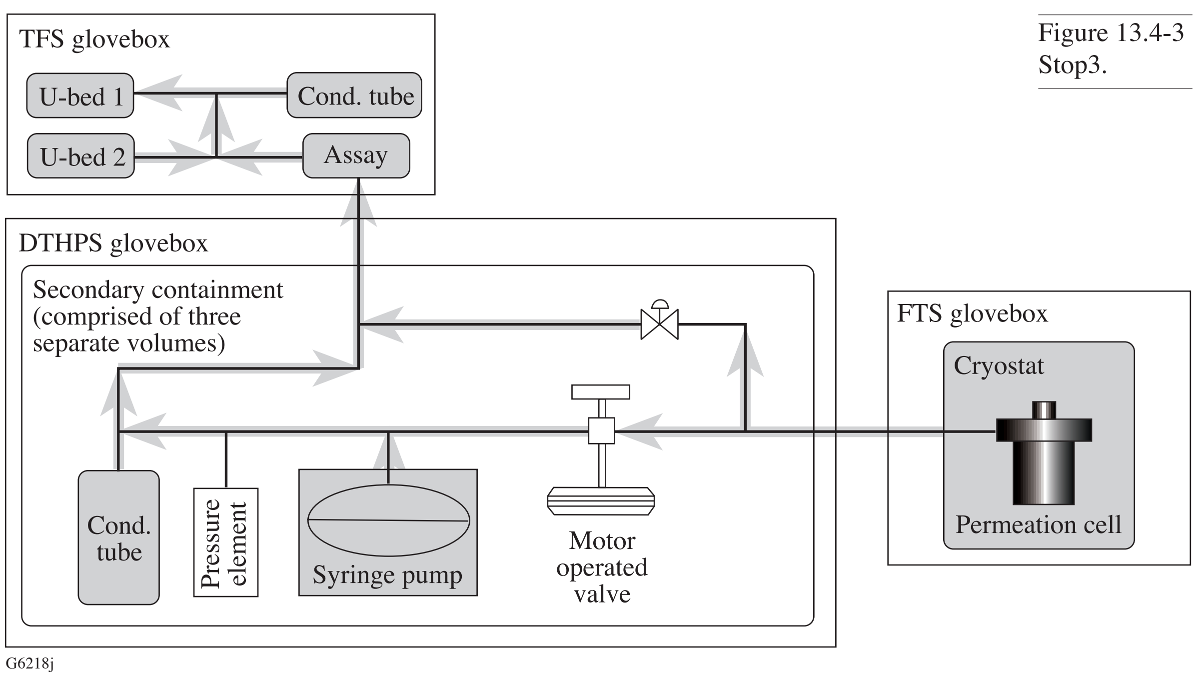

Figure 13.4-3
Stop3.

13.4.4 Stop4

If a containment failure is detected in the DTHPS or FTS containment system and DT is being extracted from the permeation cell (fill state 7), all the DT is gettered back to the U-bed (Fig. 13.4-4). The condensation tube and syringe pump, which is isolated in fill state 7, remain isolated.

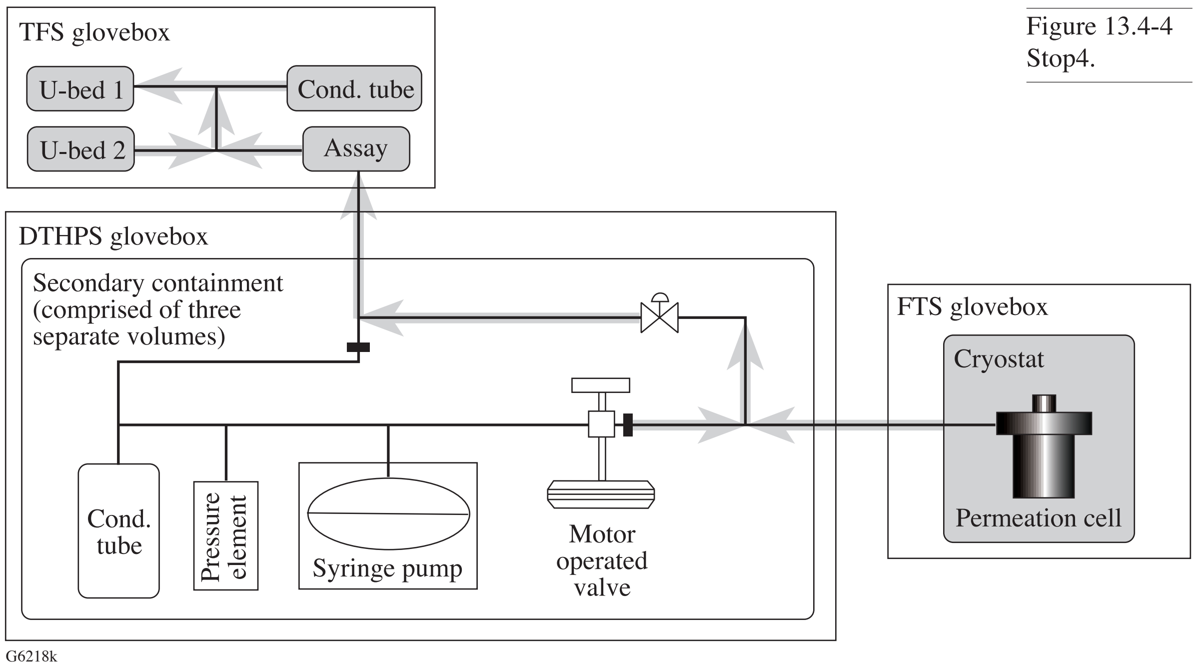

Figure 13.4-4
Stop4.

13.4.5 Pause

In general, the system will pause if a containment failure is detected upstream of the current DT location. This will inhibit the system from transferring DT into a problem area. The system will also pause if a containment failure is detected in the TFS during the DT pressure ramp. This will inhibit the system from increasing the DT pressure.

13.5 CONTROL SYSTEM

The control requirements are aimed at achieving a balanced level of automation that incorporates safety interlocks for tritium containment system failures without restricting the operator's ability to navigate through anomalies that may occur during a fill.

The Fill-State Sequencer is the primary mechanism for providing safety, control, and flexibility. The Fill-State Sequencer steps through the seven fill states. Each fill state has a series of steps—some of them automated and some of them manual. The purpose of the Fill-State Sequencer is to:

- Provide safety interlocking for the additional equipment required for the fill process—TRS, DTHPS, and FTS.
- Structure and organize the fill process.

- Launch automated routines.
- Perform assays periodically throughout the fill process (logged into a database).
- Tracks and identify the current fill state. This is critical for proper operation of the tritium release scenario interlocks.

The Fill-State Sequencer has ~100 operations grouped into its seven states. A number of these operations are repeated or lend themselves to automation. The state machine's primary function is to enable the monitoring and interlocking that is required when DT is transferred out of the TFS. The state machine must be active when tritium is resident outside the TFS. The TFS interlocks remain active when the fill-state sequencer is off. The standard room-temperature fill procedures can be executed in this situation.

The key to this concept is a sequence of seven fill states that can only be entered when defined permissives are met; this ensures that the fill state and process conditions are compatible. Upon entering each fill state, certain required devices are enabled. Devices that are not required are disabled at each transition. This interlocking ensures that the operator keeps the process within the boundaries of the fill state. Figure 13.5-1 provides an overview of this concept.

Within each fill state, a sequence of manual operations and/or manually initiated automated sequences are executed. An operation is defined as a series of steps that achieves an objective within a fill state. The operator will be allowed to "pause" the process to correct or work around problems and can activate the appropriate "Stop" at any time. Presently, there are no interlocks defined within the fill-state operations, and there are no permissives defined between process operations. This allows the operator a certain amount of flexibility within each fill state.

The release scenario module monitors the process integrity and containment; if the containment system is compromised or a release is detected, the approriate stop (or pause) command for the current fill state will be executed.

13.5.1 Release Scenario Monitoring System

The command issued for each type of failure is dependent on the current fill state. Table 13.5-1 shows the defined actions for each type of failure. The 17 sensors used to monitor the containment system integrity are listed across the top. The command issued is listed in the left-hand column. The fill-state number is entered in the row of the command to be executed. For example, it can be seen that for a failure in the DTHPS secondary containment (12th sensor) that the system will issue the following commands:

- **Pause:** for fill states 1 and 2
- **Stop2:** for fill state 3
- **Stop3:** for fill states 0, 4, 5, and 6
- **Stop4:** for fill state 7

Figure 13.5-1
Fill-State Sequence overview.

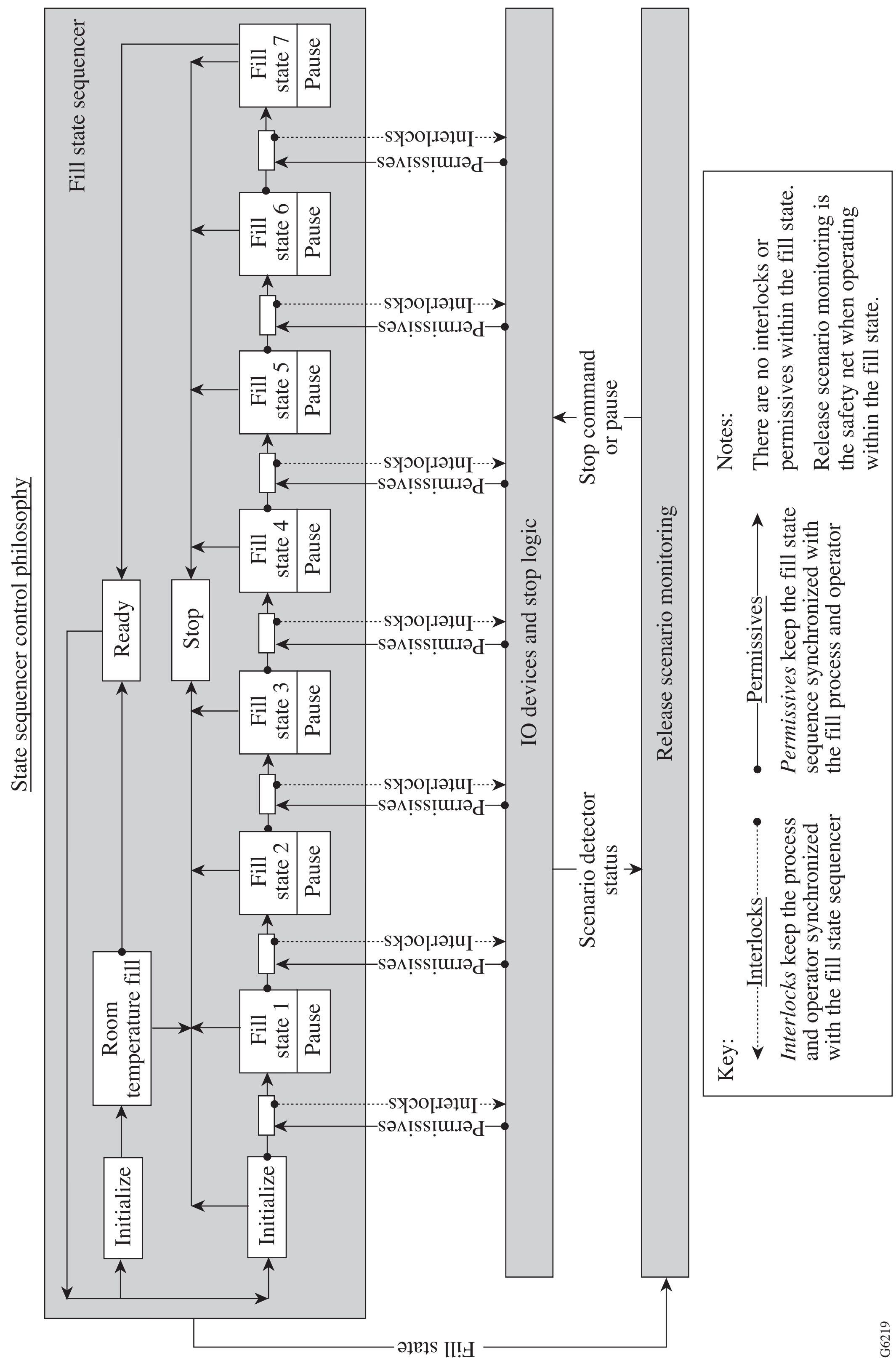

Table 13.5-1: Release Scenario Monitoring Command Table.

	Sensors	Pause	Stop1	Stop2	Stop3[a]	Stop4	Sensor Tag
Tritium Monitors	TFS glovebox > XX		1,2,3,4,5,6,7				TMT-89-21/22
	DTHPS secondary containment > XX	1,2		3	0,4,5,6	7	TMT-89-41
	DTHPS glovebox > XX	1,2		3,4,5,6,7			TMT-89-11/12
	FTS glovebox > XX	1,2,3			0,4,5,6	7	TMT-89-31/32
	Cryostat > XX	1,2,3			0,4,5,6	7	TMT-86-04
	Room 157 > XX	0,1,2,3,4,5,6,7[b]			0,1,2,3,4,5,6[c]	7 [c]	TMT-??
Pressure Sensors	Diaphragm on DT side > XX	1,2,3		4,5,6,7			PT-2106
	Diaphragm on oil side > XX	1,2,3		4,5,6,7			PT-2170
	Cryostat outlet > XX	1,2,3			4,5,6,7		T/PT-4003
Containment System Failures	TFS glovebox	4,5	1,2,3,4,5,6,7				TFS glovebox
	DTHPS glovebox	1,2		3,4,56,7			DTHPS glovebox
	DTHPS secondary containment	1,2		3	0,4,5,6	7	DTHPS second containment
	FTS glovebox	1,2,3			0,4,5,6	7	FTS glovebox
	TRS cryostat and rack inserter	1,2,3			0,4,5,6	7	TRS cryostat and rack inserter
	Room ventilation	2,3,4,5,6,7					Room ventilation
Other	Heartbeat bits		1,2	3	0,4,5,6	7	
	Operator stop button		1,2	3	0,4,5,6	7	

[a]"0" state indicates the fill state sequencer is off. When the operator pushes the stop button in this condition, a Stop3 will be executed.

[b]A level of 2E-5 Ci/ml will cause the fill to pause.

[c]A level of 2E-4 will cause the system to issue a stop command.

A Stop3 will be invoked when a release scenario is detected and the state machine is off.

13.5.2 Fill-State Interlocks

It is imperative to keep the operator, the process, and the sequencer synchronized. The interlocks have been specified to ensure that the operations occur in the proper "state." Table 3.5-2 "Fill-State Sequence Interlocks" specifies the states in which the key equipment is allowed to operate; otherwise, these devices are disabled. These interlocks are only active when the state machine is running and are not enforced when the state machine is stopped.

Table 13.5-2: Fill-State Interlocks.

Device	States						
	1	2	3	4	5	6	7
U-bed heater	enabled						
TFS cold finger	enabled						
TFS condensation tube heater		enabled					
DTHPS cold finger			enabled	enabled			
DTHPS condensation tube heater				enabled			
Syringe pump forward					enabled		
Syringe pump reverse	enabled	enabled	enabled	enabled	enabled	enabled	enabled
Genesis temperature controller				enabled			
PV18	closed	closed					
MV-2150	closed	closed	closed				
PV53 and PV56	closed	closed	closed	closed	closed	closed	closed

"Enabled" means that the operator can turn the device on. The device is off when not enabled. A Stop1–4 will override any interlock and force the valves to the state required by the stop.

13.5.3 Fill-State Permissives

The fill-state interlocks discussed in Table 13.5-2 ensure that the operator is in phase with the Fill-State Sequencer. The fill-state permissives are used to ensure that the process conditions are compatible with the Fill-State Sequencer. These permissives are checked before entering a fill state; if the conditions are not met, the state cannot be entered. The conditions are not monitored after the fill state has been entered (many of the conditions will change within a fill state). Table 13.5-3 defines the permissives required for each fill state.

Table 13.5-3: Fill-State Permissives.

Device	**State Permissive Conditions**						
	1	**2**	**3**	**4**	**5**	**6**	**7**
DTHPS condensation tube heater					>290 K	>290 K	room temperature
Syringe pump position	retracted	retracted	retracted	retracted			retracted
PT-2151	<1 atm	<1 atm	<1 atm	<250 atm	<200 atm		low pressure
TFS cold finger temperature	<20 K		>290 K	>290 K	>290 K	>290 K	>290 K
DTHPS cold finger temperature	>290 K	>290 K		<20 K	>290 K	>290 K	room temperature
Permeation cell temperature	>290 K	>290 K	>290 K	>290 K	>290 K		<285 K
PV11, PV12				closed	closed	closed	closed
PV50				closed	closed	closed	closed
PV18	closed	closed		open	open	open	open
POV2151	closed	closed		closed	open	open	open
POV2153	closed	closed	closed	open	closed	closed	open
MV-2150	closed	closed	closed	open	open	closed	closed
POV2150	closed	closed	closed	closed	closed	closed	closed
PV19	closed	closed	closed	closed	closed	closed	closed

13.6 ASSAYS

Assays are essential for DT inventory control and for detecting leaks. An assay determines the quantity (moles) of gas in a known volume by measuring the pressure and temperature. The assays are listed in Table 13.6-1 and are required to determine the following:

- Initial reading (calibrate zero)
- Quantity of DT released into the process lines
- Ice-thickness
- DT leakage/lost during the fill
- Inventory requirements

Assay inventory calculations require a "pair" of assays; the first assay establishes the zero reading which is subtracted from the second assay.

Table 13.6-1: High-Pressure Fill Assays.

Number	State	Name	Purpose
1	1	Assay 1A	Zero reading for Assay 1B
2	2	Assay 1B	Amount of DT released in first heating of the U-bed
3	3	Assay 2	Determines amount of DT condensed in DTHPS condensation cell and amount gettered
4	3	Assay 3A	Zero reading for Assay 3B
5	5	Assay 3B	Determines amount of DT in DTHPS syringe pump and how much is gettered
6	5	Assay 4A	Zero reading for Assay 4B
7	6	Assay 4B	Measures the valve leakage during the high-pressure ramp cycle
8	6	Target Assay	Determines the quantity of DT within the target
9	6	Assay 5	Determines the DT in the permeation cell and how much DT is returned to the U-bed
10	6	Assay 6A	Zero reading for Target Assay 6B
11	7	Assay 6B	Measures leaks across the valves during the cooling process
12	7	Assay 7	Measures the amount of DT returned from the permeation cell–first extraction cycle
13	7	Assay 8A	Zero reading for Target Assay 8B
14	7	Assay 8B	Measures the amount of DT returned from the permeation cell–second extraction cycle

The assays are used to make the following calculations for the fill report:

1. **Fill State2**
   - Total DT Inventory = (Assay 1B–Assay 1A)

2. **Fill State3**
   - DT sent to DTHPS = (Assay 1B–Assay 1A) – Assay 2

3. **Fill State4**
   - DT returned to TFS = (Assay 3B–Assay 3A)
   - DT in the DTHPS = (Assay 1B–Assay 1A) – Assay 2 – (Assay 3B–Assay 3A)

4. **Fill State5**
   - DT leakage into the assay volume = Assay 4B–Assay 4A
   - DT in the FTS permeation cell = (Assay 1B–Assay 1A) – Assay 2 – (Assay 3B–Assay 3A) – (Assay 5–Assay 4A)

5. **Fill State6**
   - Cooling Recipe

6. **Fill State7**
   - DT leakage into assay volume = Assay 6B–Assay 6A
   - DT returned to the TFS first cycle = Assay 7–Assay 6A
   - DT returned to the TFS second cycle = Assay 8B–Assay 8A

7. **Summary**
   - DT lost = (Assay 1B–Assay 1A) – Assay 2 – (Assay 3B–Assay 3A) – (Assay5–Assay 4A) – (Assay 7–Assay 6A) – (Assay 8B–Assay 8A)