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Hydrogen Moderator System Functional System Description

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SPALLATION NEUTRON SOURCE

Argonne National Laboratory • Brookhaven National Laboratory • Thomas Jefferson National Accelerator Facility • Lawrence Berkeley National Laboratory • Los Alamos National Laboratory • Oak Ridge National Laboratory

SNS

Hydrogen Moderator System
Functional System Description

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1. Introduction

The purpose of this document is to provide a general description of the Hydrogen Moderator System and basic information pertaining to the operation and control of the system. Those responsible for the operation and maintenance of the SNS Moderator System are required to be experienced in the fundamentals of operating machinery of like complexity. A complete set of operating procedures containing a sufficient level of detail in a step-by-step format is planned and will be provided to enable a qualified person to operate the system.

2. System Description

The SNS Hydrogen Moderator System is a series of three cryogenic loops comprised of a circulator, accumulator, helium heat exchanger, load (moderator), and interconnecting cryogenic transfer lines. The equipment is contained in two modules designed to maintain the necessary cryogenic temperatures and also to contain the hydrogen in the event of a leak. These modules are the Heat Exchanger and Pump Modules. All valves designed to control the flow of ambient hydrogen and helium are grouped in a rack that is referred to as the Gas Management System. These major components are located in the hydrogen utility room (HUR), which is designed to conform to Class I, Group B, Division 2 hazardous location as defined by National Electric Code. All transfer lines connecting the moderators in the core vessel to the Pump Module are co-axial, vacuum-jacketed with a separate helium guard to maintain the cryogenic temperature and to contain the hydrogen in the event of a leak. All vacuum-jacketed transfer lines will be evacuated with a portable vacuum pump and then sealed. The vacuum pressure will be continuously monitored and alarmed through the control system to ensure system integrity. Other equipment includes pressure relief devices, circulator drive control, pressure control instrumentation, hydrogen/helium gas supply systems, and a helium purged vent system. The hydrogen supply cylinders are located at the compressor building with a ¼" line connecting them to the Gas Management System. The instrumentation racks that house the controls for the loops are contained in the adjacent prep area. Local controls for the helium refrigeration system are located at the cold box on the high-bay floor and in the compressor building. The SNS control network links all instrument systems electronically.

The SNS Hydrogen Moderator Control System is designed to provide interlocks to protect personnel and equipment and will provide closed loop control to maintain certain critical loop parameters (see P&ID, 106020000F8E8700A001). Pressure in each loop will be controlled by filling the loop with pressurized hydrogen from standard bottles and maintaining control of the pressure with a helium backpressure, bellows accumulator (AC-6X00, "X" denoting the loop number). The flow of hydrogen in each loop will be controlled with a variable speed circulator (P-6X00) and monitored using a Venturi tube based flow measurement device (FT-6X01). Hydrogen and helium purge gas will be introduced and evacuated from the loops though a Gas Management System and a dedicated system designed to vent hydrogen safely to the atmosphere. A heat exchanger for each loop is connected to a common 7.5kW, 17K helium refrigerator. All portions of the hydrogen piping system are protected from over-pressurization by pressure relief valves and safety class rated rupture discs. The control systems for each sub-component as well as the overall control system will employee SNS standard hardware and software such as Allen-Bradley Contrologix programmable logic controllers (PLC) and EPICS display screens.

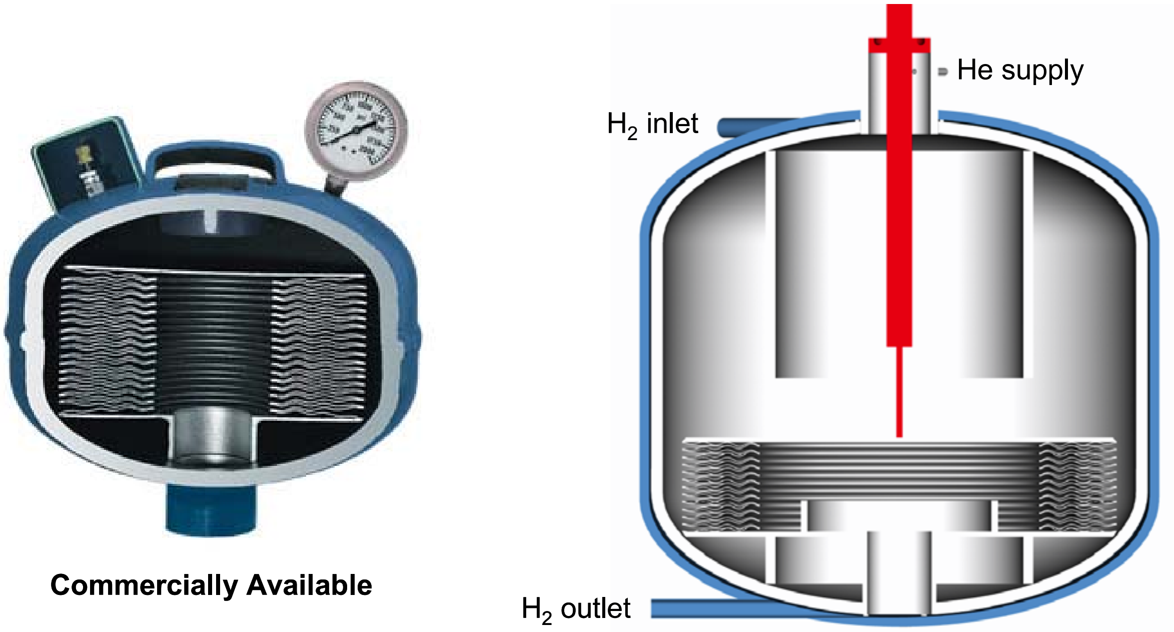
3. General Control Philosophy

The goal of the Hydrogen Moderator System is to safely and reliably provide stable 20 K hydrogen to the three cryogenic moderators within the inner reflector plug. The general control philosophy has been to accomplish this goal in as simple a manner as is possible while maintaining strict safety requirements. This system has been fundamentally based upon many years of successful operation at other spallation neutron sources namely LANL's Lujan Center and Rutherford Appleton's ISIS. The hydrogen system is a circulating, non-recycling, closed loop system filled from pressurized cylinders of UHP hydrogen. As in the case of ISIS, all hydrogen moderator vessels and transfer lines are double contained using a helium inert blanket. The

Hydrogen Moderator System operates at supercritical conditions at all times thus eliminating phase change effects. The base pressure of the system is maintained at 14 bar providing a 1 bar margin above the critical pressure. While ISIS was originally designed to operate at supercritical pressure it rarely does and the Lujan Center only operates at supercritical pressure during beam operation and cool down.

The Hydrogen Moderator System operates in a constant mass mode. Once the system has been filled with hydrogen and cooled down to operating temperature, the isolation valve is shut. Beam heating results in an increase in average temperature and thus hydrogen expansion. Gas expansion is accommodated by a helium backed cryogenic bellows allowing for an adjustment in the system volume. Metal bellows have historically been implemented in various systems as accumulators for not only thermal expansion but also pulsation dampers. As can be seen in Figure 1, commercial suppliers of accumulators have been located. The additional volume provided by the accumulator will drastically reduce the pressure rise in the system. The normal operating pressures of the system accounting for a 1 bar pressure rise across the circulators are 14/15 bar with no beam and 15/16 with full power beam. As hydrogen is incompressible at 20 K, this variation in pressure does not affect the density and therefore does not affect the neutronic performance of the moderators.

The system is further simplified in that no compensation heater is utilized in either the hydrogen or helium stream to respond to beam trips. Operating experience at the Lujan Center has indicated that compensation heaters can periodically cause an inadvertent venting of small quantities of gas resulting from a temperature overshoot. In many cases, however, without a compensation heater the hydrogen temperature could drop significantly and as a result unnecessarily prolong beam trip recovery. The design approach selected was to employ a warm gas bypass system on the helium circuit to isolate the refrigeration system from beam trips. This bypass, however, occurs downstream of the Heat Exchanger Module and therefore does not affect the helium supply temperature to the load heat exchangers. The heat exchangers were designed, however, for a temperature difference between the helium inlet and hydrogen exit of only 0.5 K, which should not contribute significantly to recovery time.



Commercially Available

SNS Conceptual Design

Figure 1. Commercially Available Accumulators

4. Safety Requirements

A safety requirement of the Hydrogen Moderator System is to provide at least two barriers between the hydrogen and atmospheric air. The helium barrier is monitored for pressure rise or fall indicating cooling water or hydrogen leaks into the blanket, or helium leaks either external to the transfer line or inward to the insulating vacuum. It is important to note, however, that before hydrogen could enter the helium blanket, the insulating vacuum would first be spoiled and would initiate an inevitable vent of the system due to rapid boiling and thermal expansion of the hydrogen. With the exception of the hydrogen cylinder manifold that is located outside at the Compressor building, all components that are located external to the Hydrogen Utility Room (HUR) are at least double contained by an inert blanket. Consequently the cryogenic transfer lines are triple contained, as they are also vacuum jacketed. The entire hydrogen system, including vacuum and helium layers, is protected against excessive positive pressures by relief valves and rupture discs that exhaust into a dedicated vent system, which is inerted with weeping helium gas. The hydrogen loops are protected by two sets of safety class rated rupture disks RD-6X01 and RD-6X05 set at 19 bar and pressure relief valves PRV-6X02 and PRV-6X03 that are set at 18 bar. One set is located upstream of the heat exchangers while the other is downstream to provide pressure relief in the event of a frozen obstruction in a heat exchanger. The vacuum and helium layers are protected by rupture disks set at 2 bar.

Some other measures that have been taken to protect the hydrogen system include those that have been incorporated into HUR. The room will be equipped to contain the more sensitive operational equipment and provides a clean working environment for servicing it. The HUR, which meets standard safety requirements, is designated as a Class I, Group B, Division 2, hazardous location in accordance with the National Electric Code (NEC). The HUR is force ventilated and constantly monitored for traces of hydrogen to maintain the room below the lower flammability limit in the event of a hydrogen release. Access to the room is restricted to authorized personnel only.

5. Control Instrumentation

Process instrumentation for the three loops will be connected to the EPICS system via local Allen-Bradley programmable logic controllers (PLC) and associated networks. Allen-Bradley components were selected as the SNS Project-wide standard. Control of the loops is maintained by the PLC system. Process instrumentation includes loop temperatures, pressures, and valve actuation signals. Parameters such as speed, motor currents and voltages, and speed set point related to the circulator operations will be monitored and generated by the PLC. The helium refrigeration vendor will provide the control system for the 20 K helium refrigerator and key operational parameters will be available to the main SNS data acquisition and control system. Various safety interlocks will be programmed into the PLC's to ensure safe operation.

5.1. Software Validation/QA

Knowledgeable personnel will subject all computer programs designed to control system hardware to review and validation. Existing ORNL QA procedures will be followed to maintain proper documentation of control software. The Moderator System Engineer will maintain record copies of the latest version of software and any modifications to a software system will be reviewed to determine effect and interaction with other systems. Computer simulation will be performed if it is deemed to be warranted or possible. Once a change is made, a test of the system will be designed and performed to verify proper operational functionality prior to returning the moderator system to normal operation.

5.2. Calibration and Maintenance

In an attempt to simplify calibration and maintenance activities, temperature and pressure transducers are being standardized with main subsystem vendors. A calibration schedule for system instrumentation will be developed based on operational experience and manufacturer's recommendation. Procedures will be developed and maintained on file by the Moderator System Engineer. Coordination with Target Operations will be maintained to schedule calibration and record findings.

6. System Integration

As in the case of most, the Hydrogen Moderator System is a collection of various subsystems. Most are often constructed by outside vendors complete with their own independent control systems and are then integrated into a complete system. As such, the Hydrogen Moderator System consists of three major subsystems: the helium refrigeration system (which includes the Heat Exchanger Module), the Pump Module, and the Gas Management System. To ensure that all of the subsystem controls are adequately integrated into the Moderator System control, the subcontractor selected by the refrigeration vendor to develop the control system interface using EPICS will be contracted with to provide EPICS interfaces for all of the other subsystems. As the refrigeration system represents by far the most complicated control system, this approach seems appropriate. This measure will guarantee a consistent look and feel to the operator interface at each of the remote control room locations.

6.1. Helium Refrigeration System and Heat Exchanger Module

The Helium Refrigeration System is capable of producing 7.5 kW of cryogenic cooling at a helium supply temperature of 16.5 K. The scope of the refrigeration system contract includes the load heat exchangers located in the Heat Exchanger Module. The Heat Exchanger Module is designed to provide the necessary containment and vacuum environment to house the three cryogenic helium-to-hydrogen heat exchanger units and the requisite isolation valves, flow control valves, and temperature transmitters. The control system is designed to control the flow of cryogenic helium (FCV-6X03) to each heat exchanger to provide sufficient cooling of the hydrogen to maintain a discharge temperature of 17.5 K as indicated on TT-6X03. Each helium loop is protected from over-pressurization by a relief valve set at 10.3 bar (PRV-6X01). If for any reason a loop should become inoperable, that loop can be isolated from the refrigeration system supply header by closing SV-6X05. The module is protected from over-pressurization by rupture disk RD-6001 that is set to relieve at 2 bar. Pressure transmitter PT-6014 is for monitoring the vacuum in the module.

The refrigeration system is isolated from the effects of a beam trip through the use of a warm helium gas bypass. A needle valve is used to bypass a small stream of warm gas around the expansion turbine to compensate for the loss of beam heating thus maintaining a stable helium return temperature to the cold box heat exchanger.

6.2. Pump Module

The hydrogen circulator is capable of 1 to 5 L/s of flow in each of the loops at an operating pressure drop of 1 bar. The rotor of the circulator is designed to levitate to provide for frictionless operation and is capable of speeds ranging from 1,000 to 60,000 rpm. During cool-down and warm-up, the flow-rate will be automatically adjusted in response to changes in fluid density. At steady state the circulator will provide a nominal 1 L/s. The circulators are monitored for abnormally high current or winding temperature, or excess vibration. Any of these would indicate impending failure and would initiate a controlled shutdown during which the faulty unit could be replaced.

The Pump Module provides the structure and environment to house the cryogenic circulators, accumulators, and interconnecting piping. The hydrogen cryogenic transfer lines that carry the hydrogen to and from the moderators are terminated at the Pump Module. Pressure, flow, and temperature transmitters are also included. Piping from the hydrogen supply, helium purge, and vents that are part of the Gas Management System enter the Pump Module via a system of feed-throughs. Remotely controlled air operated valves designed to provide interconnection of the loops are also included in the Pump Module. Internal process piping is protected from over-pressurization through pressure relief valves (PRV-6X03 & PRV-6X02) set at 18 bar and safety class rated rupture disks (RD-6X05 & RD-6X01) set to 19 bar. Both safety devices discharge to a dedicated helium-purged vent system. The accumulator helium datum pressure supply lines also use a feed-through to penetrate the wall of the Pump Module. Following is a detailed description of the accumulator and circulator controls:

Accumulator

The accumulator is designed to compensate for pressure changes in the closed loop system resulting from variations in the thermal loading caused by beam trips. It is anticipated that a considerable number of the pressure changes will be caused by beam trips. It is estimated that the SNS system will experience up to 50 beam trips per day during normal operation. This number could be much higher during commissioning. The accumulator allows the hydrogen inventory to expand and contract thus operating in a constant mass mode. The accumulator consists of a double walled pressure vessel, an edge welded bellows assembly, and a linear variable differential transformer (LVDT) for monitoring of the bellows position (Figure 1). The LVDT signal (ZT-6X01) will be connected to the data acquisition system via a signal-conditioning module for data recording. Each helium datum pressure system will be independently controlled via an electrically activated pressure control valve (PCV-6X03) and an electrically activated isolation valve (SV-6X04) tied to the Target building helium supply. Pressure transmitter PT-6X04 will be used to monitor the helium datum pressure. As in most cases throughout the moderator system, the PLC will control pressures by adjusting a pressure control valve position based on a control set point input by the operator and a pressure transmitter signal as feedback. Pressure relief lines will be provided on each system designed to vent the datum pressure to the vent system. Each vent line is controlled with a solenoid valve (SV-6X07). The datum lines are tied to the vent system through control valve (PCV-6005). In the event of a hydrogen leak into the helium datum system, the combined gases will be released into the vent system. Each helium datum line will be evacuated prior to initial filling with a portable vacuum pump via HV-6X06.

Circulator

The air-cooled circulator is equipped with a magnetically levitated rotor to provide variable shaft speeds up to 60,000 rpm. It is designed for remote control operation via the controller provided by Barber-Nichols and Revolve. The levitation control system is designed to detect and shutdown the unit if a vibration that exceeds a predetermined value is detected. The unit is also equipped with an internal over temperature protection circuit. Circulator operating set points will be input to the Barber-Nichols controller via the PLC and EPICS user interface. An external user interlock that will be connected to the PLC will provide interlocking with other facility parameters. Circulator inlet and outlet pressures and temperatures are monitored (PT-6X01, PT-6X02, TT-6X01, TT-6X02) by the PLC. The pump differential pressure is calculated by subtracting PT-6X01 from PT-6X02. Transmitter TT-6X06 monitors circulator stator temperature. The flow of hydrogen will be monitored by a Venturi tube (FT-6X01) based measuring system with the pressure drop converted to flow by a microprocessor provided by the vendor.

6.3. Gas Management System

The transfer of hydrogen and helium gas in and out of the three loops and the Design Validation and Training Module (DVTM) is handled through a group of remote operated valves in an equipment and instrumentation rack located in the HUR. Also included in this rack are pressure control valves, pressure relief valves and rupture disks intended to provide over-pressurization protection for the piping. All valves in the Gas Management System will be air operated. Solenoid operated valves control the flow of air to the valve operators. This is intended to avoid having potential spark producing equipment unnecessarily located in the hydrogen utility room. Also this will allow maintaining control of the Gas Management System in the event of a shutdown of electrical power in the HUR. Purge Vacuum pump VACP-6001 will also be located on this equipment rack.

7. Modes of Operation

There are several external factors that will impact the Hydrogen Moderator System's modes of operation. The proton beam, for example, will be interrupted nominally 50 times per day. Each beam trip will result in temperature and pressure transients throughout the system. The target is replaced four times annually at which time the system will need to be shutdown and backfilled with helium. Every three years, a major outage will occur when the inner reflector plug, which includes the moderator assemblies, is replaced. Not only will the system require shutting down at this time, but also the transfer lines to the core vessel will be severed. The following describe the normal operational modes of the Hydrogen Moderator System:

7.1. Standby

In this mode, the process piping is evacuated and backfilled with helium to prevent moisture buildup. All electrics will be off and secured in a safe state using an approved lock-out/tag-out procedure to prevent personnel injury and equipment damage. The hydrogen supply will be isolated at the source by closing SV-6003.

7.2. Purge

Prior to startup, a series of helium fills and evacuations will be preformed to purge the piping of any moisture and unwanted gases before introduction of hydrogen to the loop. The hydrogen lines will be purged with helium by opening SV-6008 and setting the pressure to 1.2 bar using PCV-6008. Once the helium pressure is set, valves SV-6X01 will be opened to introduce helium to each loop. After 1.2 bar is indicated on PT-6X01, the helium source will be isolated and the helium released to the helium-purged vent through valves SV-6X03. The lines will then be evacuated to 10^{-2} torr using the purge vacuum pump VACP-6001 and the entire process repeated twice.

After each loop is purged with helium three times, the loops will be conditioned with hydrogen by opening SV-6001 and SV-6003 and setting the pressure to 1.2 bar using PCV-6003. Once the hydrogen pressure is set, valves SV-6X01 will be opened to introduce the hydrogen in each loop. After 1.2 bar is indicated on PT-6X01, the hydrogen source will be isolated and the hydrogen released to the helium-purged vent through valves SV-6X03. The lines will then be evacuated to 10^{-2} torr using the purge vacuum pump VACP-6001 and the entire process repeated twice. A control system interlock ensures that the entire circulating loop has been evacuated before hydrogen is allowed into the system. This is accomplished by interlocking the opening of SV-6001 to a vacuum pressure reading at PT-6001, PT-6002, PT-6003, PT-6X01, and PT-6X02.

7.3. Startup / Cool-down

Once the system has been adequately purged, the helium pressure on the accumulators AC-6X00 is adjusted to 15 bar with the helium supply regulator PCV-6X03 using PT-6X03 as feedback. Hydrogen is then introduced to the loop through the Gas Management System. The pressure is gradually increased to 14 bar with the hydrogen supply regulator, PCV-6003 using PT-6003 as feedback. The circulators will then be engaged and ramped up to max speed to provide approximately 5 L/s flow initially. The refrigerator is activated and helium flow thru the heat exchangers HX-6X00 is established. As the system cools, hydrogen and helium gas is continually added to maintain 14 and 15-bar pressure in each system respectively. The pressure drop across the circulators will increase with increasing density of the hydrogen and consequently the sustainable flow rate will drop to approximately 1 L/s. The speed of the circulator will be kept essentially constant thereafter into steady state. Monitoring and trending output from temperature sensors throughout the loop and pressure sensors on hydrogen and helium supply manifolds can be used to determine when the system has reached steady state. Once the system has reached thermal equilibrium, the hydrogen and helium supplies will be isolated using SV-6X01 and SV-6X04 thus transitioning into steady state operation.

7.4. Steady State

During steady state conditions, the mass of hydrogen in each loop will be held constant as the loop is passively controlled. The cryogenic accumulators are designed to allow for the expansion and contraction of the hydrogen inventory as it responds to varying heat loads. As a result, the system pressure is allowed to vary from 14/15 bar with no beam to 15/16 bar with full beam power. The flow and temperature of the helium being delivered from the refrigerator to the Heat Exchanger Module is held constant to within +/- 0.5 K. The distribution of this helium flow between the three heat exchangers, however, requires control valve FCV-6X03 actuations within the Heat Exchanger Module to provide adequate flow to each circuit to maintain the desired hydrogen supply temperatures TT-6X03. The speed of the circulators is kept essentially constant throughout steady state operation.

7.4.1. Beam Trip Response

During a beam trip, the pressure will decrease as a result of the loss of heat load. The helium flow and temperature conditions from the refrigerator, however, will not change. As the temperature difference between the helium inlet and hydrogen exit is only 0.5 K, the hydrogen temperature could at most drop 0.5 K, which is within the allowed operating range. The refrigerator will isolate the effects of a beam trip by utilizing the warm gas bypass to warm the helium prior to its return into the cold box heat exchanger. Upon resumption of the beam, the pressure will gradually climb back within its normal range as the average temperature approaches 20 K.

7.5. Shutdown / Warm-up

Each loop is provided with controls to provide for the safe handling of the hydrogen loop inventory during system warm-up and shutdown. During normal warm-up of the inventory, hydrogen will be vented via SV-6X02 and PCV-6004. The pressure regulator will be set to 14 bar to ensure that the hydrogen remains in a supercritical state throughout the warm up process. Helium will be vented simultaneously via SV-6X07 and PCV-6005 with a pressure setting of 15 bar. During normal shutdown, the refrigerator will actually be used to warm up the circulating hydrogen loop. Warm helium gas from the compressor discharge will bypass the cold box heat exchanger and expansion turbine thereby flowing directly to the Heat Exchanger Module to warm the circulating hydrogen loop. This helium will then return to the cold box where it will be additionally warmed by the 7.5 kW commissioning heater before entering the main cold box heat exchanger. Upon exiting the main heat exchanger, the helium will then flow through an ambient vaporizer before returning to the compressor suction. Using this process, both the cold box and hydrogen loop will be warmed simultaneously. As the circulating loop warms, hydrogen and helium gas will be vented slowly through the helium purged vent system. The pressure drop across the circulators will decrease with the density and consequently the sustainable flow rate will increase to approximately 5 L/s as the system approaches ambient temperature. Once the hydrogen loop has reached ambient temperature, the circulators will be shutdown and the pressure slowly let up using PCV-6004. When the pressure of the hydrogen system is at atmosphere, the vent system will be isolated using SV-6X02 and the evacuation will continue by using the purge vacuum system VACP-6001 via valve SV-6006 to completely remove the hydrogen inventory. The purge vacuum pump is protected from excessive pressure by an isolation valve SV-6006 using PT-6003 as feedback. After the hydrogen has been removed from the loop and a rough vacuum of 10^{-2} torr has been established, the purge vacuum pump is isolated using SV-6006. Helium pressure will be adjusted using PCV-6008 and then be introduced to the loop via SV-6008.

The above describes a normal shutdown in which both the hydrogen and helium systems are warmed simultaneously, as would be the case for a target change out. Should there be a need to warm up only the hydrogen system temporarily for repairs, the system can be warmed more rapidly while maintaining the cold box at cryogenic temperature to speed subsequent cool down. This is accomplished by the same procedure as above but utilizing the refrigeration system in a slightly different manner. During any warm up operation, the minimum allowed helium return temperature to the compressor limits the helium flow. In rapid warm up mode, the main cold box heat exchanger is bypassed entirely. In doing so, the maximum allowed helium flow is much greater as the 7.5 kW commissioning heater and the ambient vaporizer work together to warm the helium stream up before returning to the compressor suction.

8. Off-normal Conditions and Responses

This chapter addresses the single-point failure modes and effects analysis (FMEA) for each subsystem and how the control system is designed to mitigate the event. Only out-of-the-ordinary failure modes are contained in the FMEA. Typical common industrial failures have been considered but are not included. To determine the hazards for each discrete module, a systematic study was performed on each of the three moderator system modules to identify the potential hazards. These hazards include electrical, mechanical, thermal, high-pressure gas and cryogen. Each hazard is evaluated for its safety and health implications. Ways were examined to eliminate, control or mitigate each hazard. The purpose of this chapter is to describe how abnormal events will be handled. The following Off-normal conditions are in the order of decreasing probability.

8.1. Control System Failure

As described in Section 6, the Hydrogen Moderator System is a collection of subsystems with their own vendor supplied and designed control systems. These control systems rely on various sensors throughout the loop to interlock a variety of operating modes. During steady state operation, the impacts of a control system failure are minor as long as control can be re-established in a timely manner. The cryogenic bellows, for example, passively controls the pressure of the loop. Almost any control system failure would lead to a beam trip signal and as such the pressure would climb slowly as the system begins to warm. If control cannot be re-established or the system operation is neglected, passive pressure relief valves and rupture disks that vent to a helium purged manifold ultimately protect the entire system from over-pressurization.

8.2. Circulator Failure

Each hydrogen loop contains one circulator located in the Pump Module. The circulator has an associated speed controller that is in the local control room. The rotor of the circulator is designed to levitate to provide for frictionless operation. The control of this system requires the constant monitoring of position, speed, and motor current and thus requires numerous sensors to work continuously for reliable operation. The circulator controller does provide for an interface with a control computer to transfer critical information. The moderator control system will be designed to monitor for proper operation of the circulators. The circulator is also somewhat shock sensitive and it is felt that any unnecessary bumps could cause an inadvertent shutdown.

In the event of an inadvertent circulator shutdown, the beam will be tripped thus removing essentially the entire heat load from the system. The refrigerator will compensate for the loss of the beam load by utilizing warm gas bypass until flow can be re-established and the beam resumed. For prolonged loss of flow, the hydrogen loop affected will slowly warm due to heat in-leakage. The accumulator, however, can accommodate some degree of warming before requiring any pressure relief. With no operator intervention, a high loop pressure interlock will open the loop isolation valve SV-6X02 and begin relieving through the pressure regulator PCV-6004 while maintaining supercritical conditions.

If it is determined to be a faulty controller, the unit can be replaced without disturbing the hydrogen loops. This controller replacement can be quickly and easily accomplished. If the circulator requires replacement, however, all the hydrogen must be removed and backfilled with helium. Alternatively, the system can be operated in parallel flow mode in which the two remaining circulators are manifold together by opening SV-6010 – 13. In this mode, however, the flow rates in each loop will not necessarily be optimal, as they would be determined by frictional losses. It is important to note that each moderator average temperature can still be adjusted by varying the flow of helium to each individual loop via FCV-6X03.

8.3. Helium Refrigeration System Failures

Several complex components are needed to work as a system to provide the proper level of refrigeration needed to cool the hydrogen to 20 K. The refrigerator is being designed and built by the vendor to be capable of complete self-contained, stand-alone operation. The vendor's control system will be reviewed by Moderator System engineers and must be approved prior to installation of equipment. Computer links will be provided for operations monitoring of key equipment parameters.

In the event of a refrigerator failure, the beam will be tripped thus removing essentially the entire heat load from the system. No action will be required on the hydrogen system assuming the refrigerator can be restarted promptly. For prolonged loss of refrigeration capability, the hydrogen system will slowly warm due to heat in-leakage. The accumulators, however, can accommodate some degree of warming before requiring any pressure relief. With no operator intervention, eventually a high loop pressure interlock will open the loop isolation valve SV-6X02 and begin relieving through the pressure regulator PCV-6004 while maintaining supercritical conditions.

The Heat Exchanger Module consists of three separate helium-to-hydrogen heat exchangers, one control valve and isolation valve for each loop. Each loop also has a temperature sensor on the downstream side of the hydrogen circuit. This sensor is the control feedback to the helium refrigerator system for regulating the flow of helium to the heat exchanger. The control of the temperature of the hydrogen is the responsibility of the refrigerator contractor and will be a part of their control logic. The Heat Exchanger Module is equipped with dual temperature sensors so a failure of one will not require a shutdown. A failure of one of the control valves is considered the most likely and could be diagnosed by a drift in the hydrogen supply temperature. Although highly unlikely, a leak could develop between the helium and hydrogen sides of the heat exchanger. In this case as the pressure on the hydrogen side is higher than that of the helium, hydrogen would begin to leak into the refrigeration system. A hydrogen to helium leak would be detected by a hydrogen sensor located in the refrigeration system and ultimately by degraded refrigerator efficiency. Either of these failures, however, would require a complete shutdown for repairs.

8.4. Remote Actuated Valve Failures

Remote actuated valves are located throughout the system. In the event of a failure, the valves are design to fail in a safe position. In most cases this is in the closed position. As remote actuated valves are not generally used during normal steady state operation, their failure would not be readily apparent nor would it require immediate attention. Their use is almost entirely limited to startup and shutdown applications. Should a isolation valve fail, for example, the loop that is affected would not be able to warm up in a normal manner. The pressure would continue to rise until the pressure relief valve would lift and allow the pressure to dissipate. While this is not preferred it does not constitute a hazard.

8.5. Accumulator Failures

Each accumulator has a separate helium supply line and bellows position monitor (LVDT). The most likely failure mode of the accumulator is a faulty LVDT. In the event of a failed LVDT, no operator intervention would be required, as it provides no feedback for control. Operations could continue and the unit could be replaced during a scheduled maintenance period. Although highly unlikely, a leak between the helium and hydrogen systems could develop in the bellows. The loop would be shut down, evacuated and the accumulator replaced.

8.6. Loss of Vacuum

The Hydrogen Moderator System has a static vacuum insulation system. The only failure mode would be a leak as no active components are involved. The vacuum system is constantly monitored and a slow leak would be detected before a thermal load would develop. This would give operators time to diagnose the problem and decide on a plan of action. As all pump out ports are accessible from within the HUR, a portable dry vacuum pumping station could be utilized to compensate for a slow leak. In the event of an unrecoverable vacuum leak, a controlled warm up could be initiated and the system vented in an orderly fashion.

9. Emergency Shutdown

A major hydrogen leak external to the process equipment in the HUR or a hazardous situation with the accelerator or target facilities will necessitate venting the hydrogen inventory and putting the facility in a safe mode. Complete elimination of all electrical sources to the HUR will also be necessary during such an emergency. Therefore, a PLC controlled interlock feature connected to hydrogen detection equipment in the HUR and core vessel designed to vent the inventory and shut down all electrical equipment is provided. Also, a SCRAM button will be provided in the prep area control station to manually activate the venting of the hydrogen at the operator discretion. Elimination of all electrical energy into the HUR will be done by disconnecting primary power to all circulator controllers and instrument signal conditioning equipment located in the HUR by use of a shunt trip. The HUR is provided with explosion proof lighting equipment so this interlock will not affect visibility.

To help facilitate rapid venting of the hydrogen inventory, valves SV-6X06 and SV-6X08 will be opened to spoil the insulating vacuum in the moderators and transfer lines with ambient helium. This will force the hydrogen to vent more rapidly through the combination of valves SV-6X03 and CKV-6002 to the helium purged vent system. Once the hydrogen pressure in the three loops is equal to the pressure in the helium purged vent system, SV-6X03 will be closed and the loops will be further evacuated through VACP-6001 via opening SV-6X01 and SV-6006. The hydrogen moderator control system and the accelerator control system will be linked to communicate their respective operational status.

Appendix A – Instrument Tabulation

Type	ISA	TAG	Element Discription	Element Interface
Valve Controller	SC	6014	Vessel Vacuum Isolation Valve Controller	Heat Exchanger
Solenoid Valve	SC	6014	Heat Exchanger Module Vacuum Isolation	Heat Exchanger
Automatic Valve	SV	6014	Heat Exchanger Module Vacuum Isolation	Heat Exchanger
Pressure Transmitter	PT	6014	Heat Exchanger Module Pressure	Heat Exchanger
Heat Exchanger	HX	6100	Loop 1 He/H2 Heat Exchanger	Heat Exchanger
Heat Exchanger	HX	6200	Loop 2 He/H2 Heat Exchanger	Heat Exchanger
Heat Exchanger	HX	6300	Loop 3 He/H2 Heat Exchanger	Heat Exchanger
Automatic Valve	SV	6106	Loop 1 He Supply Isolation Valve	Heat Exchanger
Automatic Valve	SV	6206	Loop 2 He Supply Isolation Valve	Heat Exchanger
Automatic Valve	SV	6306	Loop 3 He Supply Isolation Valve	Heat Exchanger
Flow Control Valve	FCV	6101	Loop 1 He Supply Control Valve	Heat Exchanger
Temp. Controller	TIC	6103	Loop 1 He Supply Temperature Control	Heat Exchanger
Flow Control Valve	FCV	6201	Loop 2 He Supply Control Valve	Heat Exchanger
Temp. Controller	TIC	6203	Loop 2 He Supply Temperature Control	Heat Exchanger
Flow Control Valve	FCV	6301	Loop 3 He Supply Control Valve	Heat Exchanger
Temp. Controller	TIC	6303	Loop 3 He Supply Temperature Control	Heat Exchanger
Temp. Transmitter	TT	6103	Loop 1 HX H2 Discharge Temp.	Heat Exchanger
Temp. Transmitter	TT	6203	Loop 2 HX H2 Discharge Temp.	Heat Exchanger
Temp. Transmitter	TT	6303	Loop 3 HX H2 Discharge Temp.	Heat Exchanger
Rupture Disc	RD	6001	Heat Exchanger Module Rupture Disc	Heat Exchanger
Relief Valve	PRV	6101	Loop 1 Cryogenic Helium Press. Relief	Heat Exchanger
Relief Valve	PRV	6201	Loop 2 Cryogenic Helium Press. Relief	Heat Exchanger
Relief Valve	PRV	6301	Loop 3 Cryogenic Helium Press. Relief	Heat Exchanger
Vacuum Pump	VACP	6001	Purge Vacuum Pump	Gas Management System
Automatic Valve	SV	6006	H2/He Vacuum Pump Inlet Valve	Gas Management System
Valve Controller	SC	6006	H2/He Vacuum Pump Inlet Valve Controller	Gas Management System
Automatic Valve	SV	6101	Loop 1 H2/He Supply Isolation Valve	Gas Management System
Valve Controller	SC	6101	Loop 1 H2/He Supply Isolation Valve Controller	Gas Management System
Automatic Valve	SV	6201	Loop 2 H2/He Supply Isolation Valve	Gas Management System
Valve Controller	SC	6201	Loop 2 H2/He Supply Isolation Valve Controller	Gas Management System
Automatic Valve	SV	6301	Loop 3 H2/He Supply Isolation Valve	Gas Management System
Valve Controller	SC	6301	Loop 3 H2/He Supply Isolation Valve Controller	Gas Management System
Automatic Valve	SV	6102	Loop 1 H2/He Controlled Vent Iso. Valve	Gas Management System
Valve Controller	SC	6102	Loop 1 H2/He Controlled Vent Iso. Valve Controller	Gas Management System
Automatic Valve	SV	6202	Loop 2 H2/He Controlled Vent Iso. Valve	Gas Management System
Valve Controller	SC	6202	Loop 2 H2/He Controlled Vent Iso. Valve Controller	Gas Management System
Automatic Valve	SV	6302	Loop 3 H2/He Controlled Vent Isolation Valve	Gas Management System
Valve Controller	SC	6302	Loop 3 H2/He Controlled Vent Iso. Valve Controller	Gas Management System
Automatic Valve	SV	6103	Loop 1 H2/He Emergency Vent Iso. Valve	Gas Management System
Valve Controller	SC	6103	Loop 1 H2/He Emergency Vent Iso. Valve Controller	Gas Management System
Automatic Valve	SV	6203	Loop 2 H2/He Emergency Vent Iso. Valve	Gas Management System
Valve Controller	SC	6203	Loop 2 H2/He Emergency Vent Iso. Valve Controller	Gas Management System
Automatic Valve	SV	6303	Loop 3 H2/He Emergency Vent Iso. Valve	Gas Management System
Valve Controller	SC	6303	Loop 3 H2/He Emergency Vent Iso. Valve Controller	Gas Management System
Check Valve	CKV	6007	Purge Vacuum Vent Check Valve	Gas Management System
Rupture Disc	RD	6101	Loop 1 Rupture Disc	Gas Management System

Type	ISA	TAG	Element Discription	Element Interface
Rupture Disc	RD	6201	Loop 2 Rupture Disc	Gas Management System
Rupture Disc	RD	6301	Loop 3 Rupture Disc	Gas Management System
Relief Valve	PRV	6102	Loop 1 Pressure Relief	Gas Management System
Relief Valve	PRV	6202	Loop 2 Pressure Relief	Gas Management System
Relief Valve	PRV	6302	Loop 3 Pressure Relief	Gas Management System
Pressure Transmitter	PT	6004	Loop Pressure Let-Down Pressure	Gas Management System
Pressure Controller	PIC	6004	Loop Pressure Let-Down Valve Pressure Controller	Gas Management System
Check Valve	CKV	6004	Loop Pressure Let-Down Check Valve	Gas Management System
Control Valve	PCV	6004	Loop Pressure Let-Down Control Valve	Gas Management System
Automatic Valve	SV	6001	H2 Supply Bottles Header ON/OFF Valve	H2 Supply Manifold
Valve Controller	SC	6001	H2 Supply Bottles Header ON/OFF Valve Controller	H2 Supply Manifold
Pressure Transmitter	PIT	6001	H2 Supply Bottles Header Press. Ind. Trans.	H2 Supply Manifold
Automatic Valve	SV	6002	H2 Header Vent Valve	H2 Supply Manifold
Valve Controller	SC	6002	H2 Header Vent Valve Controller	H2 Supply Manifold
Pressure Transmitter	PT	6001	H2 Supply Header Pre Regulator Pressure	H2 Supply Manifold
Automatic Valve	SV	6003	H2 Supply Header 1st ON/OFF Valve	H2 Supply Manifold
Valve Controller	SC	6003	H2 Supply Header 1st ON/OFF Valve Controller	H2 Supply Manifold
Flow Orifice	FO	6001	H2 Supply Header Flow Restriction Orifice	H2 Supply Manifold
Filter	FLT	6001	H2 Supply Header Particle Filter	H2 Supply Manifold
Check Valve	CKV	6001	H2 Supply Header Check Valve.	H2 Supply Manifold
Pressure Transmitter	PT	6002	H2 Supply Pre Reg. Header Press. Trans.	H2 Supply Manifold
Control Valve	PCV	6003	H2 Header Pressure Control Valve	H2 Supply Manifold
Pressure Controller	PIC	6003	H2 Header Pressure Controller	H2 Supply Manifold
Pressure Transmitter	PT	6003	H2 Supply Post Reg. Header Press. Trans.	H2 Supply Manifold
Automatic Valve	SV	6005	DVTM H2 Supply Header Valve	H2 Supply Manifold
Valve Controller	SC	6005	DVTM H2 Supply Header Valve Controller	H2 Supply Manifold
Automatic Valve	SV	6006	H2 Supply Header Vacuum Valve	H2 Supply Manifold
Valve Controller	SC	6006	H2 Supply Header Vacuum Valve Controller	H2 Supply Manifold
Hand Valve	HV	6106	Loop 1 Acc. He Back-Press. Evacuation Port	Accumulator Datum
Hand Valve	HV	6206	Loop 2 Acc. He Back-Press. Evacuation Port	Accumulator Datum
Hand Valve	HV	6306	Loop 3 Acc. He Back-Press. Evacuation Port	Accumulator Datum
Rupture Disc	RD	6102	Loop 1 Acc.He Back-Press. Rupture Disc	Accumulator Datum
Rupture Disc	RD	6202	Loop 2 Acc. He Back-Press. Rupture Disc	Accumulator Datum
Rupture Disc	RD	6302	Loop 3 Acc. He Back-Press. Rupture Disc	Accumulator Datum
Check Valve	CKV	6005	He Back-Press. Letdown Check Vakve	Accumulator Datum
Control Valve	PCV	6005	He Back-Press. Letdown Control Vakve	Accumulator Datum
Pressure Controller	PIC	6005	He Back-Press. Letdown Control Vakve Controller	Accumulator Datum
Automatic Valve	SV	6107	Loop 1 Acc. He Back-Press. Letdown Valve	Accumulator Datum
Valve Controller	SC	6107	Loop 1 Acc. He Back-Press. Letdown Valve Controller	Accumulator Datum
Automatic Valve	SV	6207	Loop 2 Acc. He Back-Press. Letdown Valve	Accumulator Datum
Valve Controller	SC	6207	Loop 2 Acc. He Back-Press. Letdown Valve Controller	Accumulator Datum
Automatic Valve	SV	6307	Loop 3 Acc. He Back-Press. Letdown Valve	Accumulator Datum
Valve Controller	SC	6307	Loop 3 Acc. He Back-Press. Letdown Valve Controller	Accumulator Datum
Automatic Valve	SV	6104	Loop 1 Acc. He Back-Press. Isolation Valve	Accumulator Datum
Valve Controller	SC	6104	Loop 1 Acc. He Back-Press. Isolation Valve Controller	Accumulator Datum
Automatic Valve	SV	6204	Loop 2 Acc. He Back-Press. Isolation Valve	Accumulator Datum
Valve Controller	SC	6204	Loop 2 Acc. He Back-Press. Isolation Valve Controller	Accumulator Datum
Automatic Valve	SV	6304	Loop 3 Acc. He Back-Press. Isolation Valve	Accumulator Datum

Type	ISA	TAG	Element Discription	Element Interface
Valve Controller	SC	6304	Loop 3 Acc. He Back-Press. Isolation Valve Controller	Accumulator Datum
Control Valve	PCV	6103	Loop 1 Acc. He Back-Press. Control Valve	Accumulator Datum
Pressure Controller	PIC	6103	Loop 1 Acc. He Back-Press. Control Valve Controller	Accumulator Datum
Control Valve	PCV	6203	Loop 2 Acc. He Back-Press. Control Valve	Accumulator Datum
Pressure Controller	PIC	6203	Loop 2 Acc. He Back-Press. Control Valve Controller	Accumulator Datum
Control Valve	PCV	6303	Loop 3 Acc. He Back-Press. Control Valve	Accumulator Datum
Pressure Controller	PIC	6303	Loop 3 Acc. He Back-Press. Control Valve Controller	Accumulator Datum
Pressure Transmitter	PT	6103	Loop 1 Acc. He Back-Press. Pre-Valve	Accumulator Datum
Pressure Transmitter	PT	6203	Loop 2 Acc. He Back-Press. Pre-Valve	Accumulator Datum
Pressure Transmitter	PT	6303	Loop 3 Acc. He Back-Press. Pre-Valve	Accumulator Datum
Pressure Transmitter	PT	6104	Loop 1 Acc. He Back-Press.	Accumulator Datum
Pressure Transmitter	PT	6204	Loop 2 Acc. He Back-Press.	Accumulator Datum
Pressure Transmitter	PT	6304	Loop 3 Acc. He Back-Press.	Accumulator Datum
Hand Valve	HV	6103	Loop 1 He Transfer Line Blanket Manual Vent	Transfer Lines
Hand Valve	HV	6203	Loop 2 He Transfer Line Blanket Manual Vent	Transfer Lines
Hand Valve	HV	6303	Loop 3 He Transfer Line Blanket Manual Vent	Transfer Lines
Rupture Disc	RD	6103	Loop 1 He Transfer Line Blanket Rupture Disc	Transfer Lines
Rupture Disc	RD	6203	Loop 2 He Transfer Line Blanket Rupture Disc	Transfer Lines
Rupture Disc	RD	6303	Loop 3 He Transfer Line Blanket Rupture Disc	Transfer Lines
Rupture Disc	RD	6104	Loop 1 Transfer Line Vacuum Rupture Disc	Transfer Lines
Rupture Disc	RD	6204	Loop 2 Transfer Line Vacuum Rupture Disc	Transfer Lines
Rupture Disc	RD	6304	Loop 3 Transfer Line Vacuum Rupture Disc	Transfer Lines
Automatic Valve	SV	6106	Loop 1 He Blanket Supply Auto.Valve	Transfer Lines
Automatic Valve	SV	6206	Loop 2 He Blanket Supply Auto.Valve	Transfer Lines
Automatic Valve	SV	6306	Loop 3 He Blanket Supply Auto.Valve	Transfer Lines
Automatic Valve	SV	6108	Loop 1 He to Vacuum Auto.Valve	Transfer Lines
Automatic Valve	SV	6208	Loop 2 He to Vacuum Auto.Valve	Transfer Lines
Automatic Valve	SV	6308	Loop 3 He to Vacuum Auto.Valve	Transfer Lines
Automatic Valve	SV	6109	Loop 1 He Blanket Evacuation Valve	Transfer Lines
Automatic Valve	SV	6209	Loop 2 He Blanket Evacuation Valve	Transfer Lines
Automatic Valve	SV	6309	Loop 3 He Blanket Evacuation Valve	Transfer Lines
Automatic Valve	SV	6110	Loop 1 Vacuum Evacuation Valve	Transfer Lines
Automatic Valve	SV	6210	Loop 2 Vacuum Evacuation Valve	Transfer Lines
Automatic Valve	SV	6310	Loop 3 Vacuum Evacuation Valve	Transfer Lines
Control Valve	PCV	6005	Transfer Lines He Blanket Pres. Control Valve	Transfer Lines
Pressure Transmitter	PT	6005	Transfer Lines He Blanket Pres. Trans.	Transfer Lines
Pressure Transmitter	PT	6105	Loop 1 He Blanket Pressure Trans.	Transfer Lines
Pressure Transmitter	PT	6205	Loop 2 He Blanket Pressure Trans.	Transfer Lines
Pressure Transmitter	PT	6305	Loop 3 He Blanket Pressure Trans.	Transfer Lines
Pressure Transmitter	PT	6106	Loop 1 Vacuum Blanket Pressure Trans.	Transfer Lines
Pressure Transmitter	PT	6206	Loop 2 Vacuum Blanket Pressure Trans.	Transfer Lines
Pressure Transmitter	PT	6306	Loop 3 Vacuum Blanket Pressure Trans.	Transfer Lines
Control Valve	PCV	6017	Transfer Lines He Blanket Pres. Control Valve	Transfer Lines
Pressure Transmitter	PT	6017	Transfer Lines He Blanket Pres. Trans.	Transfer Lines
Automatic Valve	SV	6017	Transfer Lines He Blanket Isolation Valve	Transfer Lines
Rupture Disc	RD	6017	He Transfer Line Blanket Rupture Disc	Transfer Lines