THE DIII-D CRYOGENIC SYSTEM UPGRADE

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ABSTRACT

The original DIII-D cryogenic system was commissioned in 1981 and was used to cool the cryopanel arrays for three hydrogen neutral beam injectors. Since then, new demands for liquid helium have arisen including: a fourth neutral beam injector, ten superconducting magnets for the electron cyclotron heating gyrotrons, and more recently, the advanced divertor cryopump which resides inside the tokamak vacuum vessel. The original cryosystem could not meet these demands. Consequently, the cryosystem was upgraded in several phases to increase capacity, improve reliability, and reduce maintenance. The majority of the original system has been replaced with superior equipment. The capacity now exists to support present as well as future demands for liquid helium at DIII-D including a hydrogen pellet injector, which is being constructed by Oak Ridge National Laboratory. Upgrades to the cryosystem include: a recently commissioned 150 ℓ /hr helium liquefier, two 55 g/sec helium screw compressors, a fully automated 20-valve cryogen distribution box, a high efficiency helium wet expander, and the conversion of equipment from manual or pneumatic to programmable logic controller (PLC) control. The distribution box was designed and constructed for compactness due to limited space availability. Overall system efficiency was significantly improved by replacing the existing neutral beam reliquefier Joule-Thomson valve with a reciprocating wet expander. The implementation of a PLC-based automatic control system has resulted in increased efficiency and reliability. This paper will describe the cryosystem design with emphasis on newly added equipment. In addition, performance and operational experience will be discussed.

I. INTRODUCTION

The DIII-D cryosystem was commissioned in 1981 to supply liquid nitrogen (LN2) and liquid helium (LHe) to three neutral beam injector cryopanel arrays [1]. This system had an LHe production rate of 80 ℓ /hr and employed a Koch Process model 2800R liquefier with reciprocating expanders and five Koch Process model RS compressors. A single reliquefier consisting of a large heat exchanger and a Joule-Thomson valve was used to recover refrigeration from the two phase helium returning from the beamlines. Control of the system was largely manual and maintenance requirements were relatively high due to the liquefier's reciprocating expanders and the five compressors which required maintenance every 2000 hr.

Upgrades to the cryosystem have been performed as demands for liquid helium at DIII-D have increased (Table I). The common goal of these upgrades was to provide additional capacity, to increase the system reliability, and reduce maintenance requirements. In addition, upgrades of the control system have increased the system automation.

II. PRESENT CRYOSYSTEM CONFIGURATION

The present DIII-D cryosystem supplies LHe and LN2 to four neutral beam injector cryopanel arrays [2], ten electron cyclotron heating (ECH) superconducting magnets, the advanced divertor cryopump, and the GRECE diagnostic instrument. The recently commissioned advanced divertor cryopump resides inside the tokamak plasma containment vessel where it provides particle exhaust pumping [3]. A deuterium pellet injector system supplied by Oak Ridge National Laboratory will be installed and commissioned in 1994. Table II lists the cryogenic users and their respective heat loads on the cryosystem.

A flow diagram of the cryosystem is shown in Fig. 1. Two helium compressors operating at 16 bar supply up to 110 g/sec of room-temperature gas to the liquefier and the reliquefiers. The helium liquefier cools the high pressure gas using LN2 precooling followed by a series of expansions before finally discharging LHe into the 3800 ℓ dewar. The liquefier is equipped with a control valve

Table I
DIII-D Cryosystem Upgrade History

Year	Event
1981	Doublet III cryosystem commissioned to support three beamlines
1986	ECH superconducting magnets operational
1986	DIII-D upgrade, fourth beamline added
1987	Wet expander added to improve four beamline reliquefaction efficiency
1989	Large Sullair compressor added to replace smaller aging compressors; new cooling tower added
1992	Second Sullair compressor added to increase system capacity
1992	Manual distribution box replaced with 20-valve automated distribution box
1993	New liquefier commissioned to increase overall capacity in preparation for the advanced divertor cryopump and pellet injector
1993	Advanced divertor cryopump commissioned
1994	Commissioning of deuterium pellet injector planned

Table II
DIII-D Cryosystem Heat Loads and Cryogen Consumption

Device	LHe	LN2
Neutral beam injectors (4)	40 ℓ /hr + 80 W at 4.6K	320 ℓ /hr
Advanced divertor pump	25 ℓ /hr + 17 W at 4.6K	80 ℓ /hr
Pellet injector	20 ℓ /hr	none
ECH magnets (10)	10 ℓ /hr	≈ 3 ℓ /hr
GRECE diagnostic	0.2 ℓ /hr	0.5 ℓ /hr
Storage dewar	0.0 ℓ /hr + 0.5 W at 4.6K	0
Liquefier precool	0	110 ℓ /hr
Totals	95 ℓ/hr + 78 W at 4.6K	514 ℓ/hr

which maintains the dewar at 1.43 bar, allowing 4.6 K gas to vent to the compressor suction line while providing refrigeration as it passes through the low pressure side of the liquefier heat exchangers. The pressurized LHe in the dewar is force flowed to the distribution box at 4.6K. LHe is then supplied to the neutral beam injectors, advanced divertor cryopump, and pellet injector via the control valves on the distribution box. The helium gas storage tanks vary in pressure acting as a buffer to store excess gas or provide the system with make-up helium as needed.

Liquid nitrogen is supplied from a 40,000 ℓ bulk storage tank which is telemonitored and filled by an outside supplier. LN2 is used to cool radiation shielding in the neutral beam injectors, advanced divertor cryopump, ECH magnets, and for various diagnostics. The liquefier uses liquid nitrogen to precool the incoming gaseous helium to 77K. All nitrogen boil-off is vented to the atmosphere.

LHe is fed to each of the four beamlines at a flowrate of 140 ℓ /hr to ensure two-phase flow stability in the cryopanel. The returning two-phase helium is piped to

the primary side of the reliquefier heat exchanger where it is warmed to 290 K and then fed into the compressor suction line. A side stream of high pressure gas is taken from the compressor discharge and counterflowed in the secondary side of the reliquefier heat exchanger. The counterflow stream exits the heat exchanger as a gas at 12 bar and 7 K before passing through the wet expander. It leaves the wet expander and enters the LHe dewar as a two-phase mixture at 1.43 bar. The liquid phase is separated and remains in the dewar while the cold gas phase provides refrigeration as it passes through the low pressure side of the liquefier heat exchangers via the pressure controlled return valve. The advanced divertor cryopump helium flow circuit operates in a similar manner except that it utilizes a separate heat exchanger/Joule-Thomson valve reliquefier. Liquid helium is force flowed to the advanced divertor cryopump at a rate of 155 ℓ /hr.

Liquid helium from the main dewar is transferred into intermediate dewars for distribution to the ECH magnets and the GRECE diagnostic. Room temperature helium boiloff from the magnets is piped to the compressor suction line for recovery. The pellet injector will utilize a dedicated 500 ℓ dewar which will be batch-filled daily via a 60 m transferline connected to the distribution box. Helium boiloff from the pellet injector will also be recovered at room temperature.

All of the cryogenic users are located in areas which are inaccessible during plasma operations. Therefore, remote control of these systems is mandatory. The cryogenics production equipment is located outside of the DIII-D shield wall and is accessible during plasma operations. Fig. 2 shows the equipment arrangement.

FIG. 1. DIII-D cryosystem flow diagram (simplified). Dashed lines indicate LN2, solid lines LHe.

FIG. 2. Plan view showing the DIII-D cryosystem equipment arrangement.

III. SYSTEM UPGRADES

The cryosystem, as originally commissioned to support the operation of three neutral beam injectors, had limited excess capacity. Incremental improvements making use of available equipment and a restrictive cryosystem budget provided sufficient capacity when the fourth beamline and ten ECH magnets were added. However, the recent introduction of the advanced divertor cryopump and the planned addition of a pellet injector forced a major upgrade of the system. This major upgrade included a new 150 ℓ /hr liquefier, two large rotary screw compressors, an automated cryogen distribution box, increased gas storage capacity, and major additions and improvements in the PLC based control system. The main parameters of the upgraded cryosystem are shown in Table III. A detailed description of the control system can be found in [4,5].

A. Liquefier

The Sulzer model TCF 50 helium liquefier was commissioned in January 1993. The liquefier uses LN2 precooling, aluminum plate-fin heat exchangers, two dynamic gas bearing turbine expanders, and a PLC based control system which operates the liquefier automatically during cooldown, steady-state operation, and warmup. With a measured liquefaction rate of 170 ℓ /hr (versus 150 ℓ /hr performance specification), the new liquefier approximately doubles the output of the old unit.

To date the liquefier has logged over 5500 hr of operating time in the nine months since its installation with no major failures and has exceeded all of its performance specifications. System operation is stable and surplus capacity exists while supporting all connected users. Uninterrupted operation for long periods has been possible with the new liquefier. A large silica-gel adsorber

Table III
DIII-D Cryosystem Parameters

Liquefier (Sulzer TCF 50)

Liquefaction Capacity ¹	170 ℓ /hr
GHe flowrate at maximum liquefaction ¹	68 g/sec
LN2 Precool at maximum liquefaction	110 ℓ /hr

Compressors (Sullair model C20LA704-48-400HP)

Number	2
Maximum flow per compressor ²	55 g/sec
Total compressor flow	110 g/sec
Discharge pressure ²	16 bar
Inlet Pressure ²	1.1 bar
Power consumption at full flow ²	240 kW

Storage Capacity

Liquid helium dewar	3800 ℓ
Liquid nitrogen tank	40,000 ℓ
Gaseous helium volume	225 m ³
Gaseous helium tank pressure	2 to 16 bar

¹Measured-dewar at 1.43 bar, 4.6K, constant level

²Measured quantities

at 80K and a smaller adsorber at 20K have been useful in removing contamination from the helium stream. The new liquefier has operated for up to 12 weeks continuously without regeneration of the adsorbers with no decrease in performance. The old liquefier had a pair of small switchable adsorbers at 80K and no 20K adsorber. Historically it had to be shut down after three to four weeks of continuous operation due to diminished performance caused by impurity buildup in the liquefier.

B. Compressors

Compressed gaseous helium is provided by an identical pair of Sullair oil-flooded screw compressors. The compressors are single stage and may be operated independently. Each compressor produces a measured flow of 55 g/sec at a discharge pressure of 16 bar and a suction line pressure of 1.1 bar. The compressors are equipped with remotely controllable slide valves to reduce the compressor flow and power consumption as system gas requirements change. A dedicated water cooling tower provides cooling to both of the compressors.

Oil removal from the helium stream is critical since the screw compressors are oil flooded for sealing and cooling purposes. Oil removal is accomplished in three steps. First, oil is removed in the bulk separator module supplied by Sullair to approximately 200 ppm. Second, the helium stream passes through 3 stages of progressively finer coalescing filters where the oil contamination is further reduced to 1 ppm. Finally, the helium stream passes through a large activated carbon bed where the residual oil level is reduced to less than 20 ppb. The high pressure helium stream is continuously monitored for oil, nitrogen and water using a Sulzer model WF34D-3 multicomponent detector combined with a model SM34 pyrolyzer. Maintenance of two large Sullair

compressors is substantially less than that required for the smaller compressors which they replaced.

C. Gas Management System

The gas management system maintains constant pressure in the compressor discharge and suction piping while acting as a gas inventory control system. The helium gas storage pressure can vary between 2 and 16 bar, depending on the quantity of LHe which has been vaporized. The storage capacity was recently increased 50% by adding a 75 m³ tank to accommodate the maximum cryosystem liquid inventory during shutdown periods when it is fully vaporized. An upgrade of the gas management control system was required to prevent damage to the liquefier turbines due to rapid system pressure changes. The control system upgrades are discussed in [4].

D. Distribution Box

The distribution box enables the selection of cryogen flow to any combination of the users. It contains the piping, automatic valves, and transferline terminations which connect the LHe dewar and the LN2 storage tank to the users. It also contains the return piping and valves to operate the neutral beam and advanced divertor cryopump reliquefiers. The distribution box was recently redesigned and rebuilt at General Atomics (GA) to accommodate the advanced divertor cryopump system and the pellet injector. The design is relatively compact due to limited space. The existing manual valves were replaced with 20 pneumatically actuated cryovalves allowing fully automatic operation. Automation has allowed a variety of operational tasks to be performed by PLC control in addition to improving safety by providing a means of automatic shutdown of cryogen supply in case of emergency.

E. Neutral Beam Wet Expander

The original neutral beam reliquefier contained a heat exchanger, Joule-Thomson valve, the bayonet connections and various instrumentation. It was designed by Cryogenic Consultants Inc. of Allentown, PA and supported the operation of three beamlines. A fourth neutral beamline was added in 1986 as part of the DIII-D upgrade. This placed an additional heat load on the cryosystem and the net production rate with four beamlines was close to zero. This made operations complicated often forcing the shutdown of one or two beamlines over the weekend to re-establish liquid inventory.

A more efficient liquefaction process can be achieved using a so-called "wet-expander" in which the cold high pressure gas flowing in the secondary side of the heat exchanger performs mechanical work as it expands against a piston device [6]. The design and construction of a wet expander was undertaken soon after the fourth beamline was commissioned. The rotating machinery was supplied by Koch and modified and packaged by

GA. The wet expander is now used in place of the Joule-Thomson valve resulting in substantially increased overall efficiency. An overall net liquefaction rate of 20 to 30 l/hr was achieved while supporting four beamlines using the wet expander with the old liquefier.

F. Control System

Control and operation of the cryosystem has been largely automated using a PLC based control system. The goal of control system upgrades has been to improve reliability and facilitate one-shift operation. The operator initiates modes and monitors the system from a graphical display terminal located in the cryogenic control room. Engineers use IBM PC compatible terminals at home to emulate the graphical display by logging onto the system via a modem connection. An automatic dialing telephone system is used to call personnel at home or by pocket pager when system trouble arises during off hours.

IV. CONCLUSION

An overview of the upgraded DIII-D cryosystem has been presented. The system has been upgraded as demands for liquid helium have increased. New hardware has been selected and installed to increase production while satisfying the goals of increased automation, greater reliability and reduced maintenance. Major upgrades to the control system have allowed one-shift operation of the system and reduced the number of off-hours personnel call-ins. The present system has the capability to support all installed users as well as those planned for future installation.

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