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DIII-D CRYOGENICS CONTROL SYSTEM STATUS

by

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ABSTRACT

The DIII-D cryogenics system provides liquid helium for various auxiliary systems at the DIII-D tokamak facility. The system described here executes control and supervision of the cryogenics plant and associated load systems which include four neutral beam injectors, superconducting magnets, and an in-vessel tokamak cryocondensation pump. The recent addition of this divertor cryopump represented a major increase in the scope of the control system and greater need for reliable and automatic operation. The pump must be precooled, cooled and regenerated in a relatively short period of time under automatic control. Since the pump is located in the tokamak primary vacuum, coordination with the machine vacuum control system and consideration for the requirements of physics operations and vessel wall conditioning are required. A programmable logic controller is the central element in the cryogenics control system and exercises direct or supervisory control over the liquefier, gas management and loads. In the time since the control system was built during 1989, additions and improvements have been made to simplify operation and support upgrades. Cryogenics system capacity has been upgraded by the purchase of a new 150 L/hr helium liquefier, a second 400 hp helium compressor and additional gas storage. The new liquefier incorporates a controller of its own which exchanges information with the cryogenics control system. This independent controller relieved the main system of liquefier process control tasks but necessitates much finer control of the system high and low pressures. The control system upgrades and automation will be discussed with emphasis on the divertor cryocondensation pump control.

INTRODUCTION

The DIII-D tokamak fusion research program is carried out by General Atomics (GA) under contract to the U.S. Department of Energy (DOE). The cryogenics system provides liquid helium and nitrogen for neutral beam injectors and electron cyclotron resonant heating (ECRH) gyrotron magnets for the DIII-D tokamak. The system has been expanded with the addition of equipment to support a new in-vessel divertor cryocondensation pump and the capability to support new anticipated loads such as a pellet injector. The cryogenics system was first automated during 1988 and 1989 [1] with a large programmable logic controller (PLC) and work has continued with upgrades which have increased the reliability and flexibility of the system. The system is now

easier to operate and the ability to accommodate new requirements is enhanced.

CONTROL SYSTEM OVERVIEW

The cryosystem is operated by a programmable controller with approximately 1500 input and output (I/O) signals. Inputs and outputs are distributed between four locations. The first location is the cryogenics control room where the PLC is located and a color graphics operator interface is provided. The PC-based operator interface gives access to setpoints and alarm information, shows status in tabular and piping and instrumentation diagram (P&I) formats, and logs operating parameters. A telephone modem provides off-site access via compatible operator interface equipment and software. An automatic dialer controlled by the PLC is used to notify personnel of problems during all hours that the cryosystem is running. Other I/O locations are in the restricted DIII-D machine area and are fiberoptically isolated from the control room. Several pneumatic controllers are also used to control cryogen flow to the four neutral beam injector systems. Other pneumatic controllers have been replaced with control loops programmed in the PLC.

ADVANCED DIVERTOR CRYOPUMP CONTROLS

The in-vessel divertor cryocondensation pump provides an important capability to the DIII-D advanced divertor program. The program charter is to provide density and impurity control for rf current drive and transport studies and to facilitate a divertor engineering test program [2]. The in-vessel and ex-vessel components of the cryopump have been described elsewhere [3-5]. Operational performance is also presented elsewhere in these proceedings [6]. The flow of cryogens through the divertor pump ring is controlled by valves in the ex-vessel cryostat and from the pneumatically operated distribution box. The simplified P&I diagram of Fig. 1 shows the valves used to precool and maintain low temperature in transfer lines, pump, subcoolers, and heat exchanger. Each isolated segment of piping is sufficiently instrumented to enable control of the process. The instruments used are silicon diodes, vapor pressure thermometers, thermocouples, and pressure transmitters. Two compensated Pitot tube-type flowmeters are used to measure heat exchanger primary and secondary flow.

FIG. 1. Divertor cryopump P&I diagram.

No in-vessel instrumentation is provided due to problems associated with thermal and electrical isolation, vacuum compatibility, and high temperature baking procedures. The absence of in-vessel instrumentation presented a challenge in design of protection interlocks and coordination of the pump operation with the tokamak systems. The cryostat sensors and valves are connected to PLC I/O modules located near the cryostat and are electrically isolated with a fiberoptic communication link (Fig. 2). Proportional control algorithms are executed within the PLC to operate the valves listed in Table I.

DIVERTOR PUMP CONTROL MODES

Different operating modes have been defined to automate pump operation. These modes, listed in Table II,

FIG. 2. Divertor cryostat I&C overview.

Table I
Divertor Pump Control Loops
(TT = Si Diode, TC = Thermocouple)

Description	Action	Device	Input	Setpoint
LN2 precool	on/off	V90112	TC9003	90K/120K
LHe inlet precool	on/off	V90119	TT9012	6K/10K
JT to dewar precool	on/off	V9008	TT9011	6K/14K
HX high pres. precool	on/off	V9007	(TT9009- TT9005)	2K/6K
LN2 panel inlet valve	prop/integral	V90110	TC9002	100K
LHe panel inlet valve	prop/integral	V90111	FM9003	5 g/sec
HX bypass valve	prop/integral	V90131	FM9003	5 g/sec
JT valve	prop/integral	V90108	TT9009	7K

Table II
Divertor Pump Control Modes

Title	Purpose	Preconditions
LN2 precool	Transfer line cooldown	none
LHe line precool	Transfer line cooldown	none
LN2 panel cooldown	Operate pump nitrogen shield	DIII-D machine temperature
LHe panel cooldown	Operate in-vessel pump	LN2 panel cold + DIII-D temp.
glow cleaning defrost	Defrost pump during glow cleaning	Heat exchanger cold
Heat exchanger cooldown	HX cooldown	LHe panel cold
LHe shutdown	Terminate LHe system flow	none
LN2 shutdown	Terminate LN2 system flow	none
Emergency shutdown	Isolate divertor cryosystem	none

are invoked by the cryosystem operator using the graphical operator interface. Precool modes can be selected at any time, and upon completion of their sequence, maintain precooled conditions indefinitely. The cooldown and operating modes, which introduce cryogenics into the vessel pump, are interlocked with the DIII-D vessel conditioning control system (vacuum control). The interlocks insure that the cryopump components have cooled sufficiently after baking and that the vessel pressure is low enough to allow pumping. The DIII-D vacuum vessel is periodically baked up to 400° Celsius using inductive heating. Following baking, the vessel is generally cooled by the flow of air through the corrugated walls. The cooldown rate is controlled by the vessel conditioning PLC with a system of valves and a heat exchanger. Due to the good thermal isolation of the divertor pump, and the fact that it is also inductively heated during baking, the pump components must be allowed additional time to cool before cryogen flow starts. Since the pump temperature is not measured, this additional time was determined by analysis and forms the basis of the cooldown interlock. An interlock acting in the reverse is also used

to prevent operation of the machine baking system unless the pump in-vessel components have been determined to have warmed sufficiently after cryogen flow has stopped. Currently the interlock requires that the vessel pressure be raised to 0.02 mbar in helium gas for a period of 30 min to warm the pump by conduction. The 30 min warmup time was derived analytically because of the lack of in-vessel temperature measurement.

LN2 and LHe line precool modes are provided to cool the flexible transfer line between the distribution box (d-box) and cryostat, a distance of 26 m. Nitrogen precool mode opens the divertor pump LN2 d-box valve and flows LN2 to the cryostat radiation shield and subcooler using valve V90112 and sensor TC9003 (GN2 vent temperature). This mode does not allow any significant flow and in practice the LN2 panel cooldown mode, described below, is used as a combined precool and in-vessel cooldown procedure. The LHe line precool mode opens the d-box helium valves (cold gas and liquid) and enables on/off controllers for valves V90119 and V9098. V90119 cools the liquid line to the subcooler and V9098 allows cold gas to cool lines up to the heat exchanger Joule-Thomson (JT) valve, V90108. The JT valve is closed at this time.

LN2 and LHe panel cooldown modes are the normal operating modes for the in-vessel system. The LN2 mode enables a proportional controller for valve V90110 using LN2 panel outlet temperature TC9002 for control. LHe panel cooldown enables the controller for V90111 which presently is adjusted for a nominal 5 g/sec helium mass flow as measured by FM9003 on the compressor suction after the heat exchanger. This mode also initially opens the return bypass valve V9099 until the start of the heat exchanger cooldown.

The helium panel cooldown sub-mode 'Glow Cleaning Defrost' operates between tokamak discharges when the vessel pressure is raised to approximately 0.02 mbar for initiation of glow discharge cleaning using helium gas. The mode is triggered automatically after the in-vessel LHe flow is established and the cryostat heat exchanger has been cooled. The LHe flow is diverted from the pump to a bypass line (V90131) allowing the pump to defrost during the glow initiation. Once the glow discharge current is established and the vessel pressure returns to the 10^{-5} mbar range, LHe flow is returned to the pump. During the defrost period V90131 is controlled to maintain the same flow through the heat exchanger as was present through the pump before the glow defrost mode started.

The heat exchanger (HX) is cooled by a separate mode which starts immediately following stable flow of LHe in the pump (completion of LHe panel cooldown). At this time the return bypass valve V9099 is closed, V90109 is opened, and an on/off controller for valve V9097 (HX high pressure side precool) is enabled. This controller attempts to bring HX high pressure outlet, TT9009, and low pressure inlet, TT9005, temperatures

to within 6K of each other. When this is completed and the temperatures are both less than 10K, the controller is disabled and V9098 (JT precool) is closed. A proportional controller is then enabled to keep HX high pressure outlet temperature at 7K by modulating the JT valve V90108.

At this point, the system is stable and proportional controllers are operating to adjust LN2 flow (V90110), LHe flow to pump (V90111) or bypass (V90131), and HX high pressure flow (V90108). Isolation valve V90109 is simply kept open during cryopump operation.

Shutdown modes are programmed to allow operators to easily begin defrost of the in-vessel LN2 and LHe components. In general, these modes stop cryogen flow at the d-box and position valves to allow liquid to boil off from the pump to the vent (LN2) or compressor suction (LHe). The emergency shutdown mode differs in that the entire cryostat, pump, and transfer line system is isolated from the remainder of the DIII-D cryogenics system.

MODIFICATIONS FOR NEW LIQUEFIER

During 1992, a new helium liquefier was specified and purchased for the DIII-D project. This unit was delivered in late 1992 and replaced the previous 80 ℓ /hr model with one having a capacity of 150 ℓ /hr. The old liquefier had been extensively modified for automatic control by the PLC. JT valve position and expansion engine speeds were important parameters that were controlled. The capability to put the liquefier in a standby mode and to control the liquefaction rate had also been implemented. These controls were invoked when gas storage pressure became low or Dewar level became too high. Consideration also had to be made for the load system (neutral beam injector cryopanel) status and available compressor capacity. The new liquefier came equipped with a complete control system capable of operating the unit automatically from cooldown to operation and warmup. The procurement specification required an external control input signal for make rate or capacity control to be supplied by the cryo control PLC. This 4 to 20 mA signal is generated in response to the same conditions that governed make rate on the old liquefier. The new liquefier internal controls use this signal to adjust turbine inlet pressure thereby controlling liquefier capacity. Overall, the elimination of the many interlocks and control loops used on the old liquefier have simplified the control system. Since the new liquefier uses turbine expanders, the manufacturer specified much finer control of the compressor discharge (HP) and suction (LP) pressures. This required extensive modification of the cryogenics gas management system (Fig. 3). Previously LP was controlled with a pneumatic split controller which made up or dumped gas to storage to maintain LP at 1.1 bar. HP was controlled by allowing the PLC to load and unload the 400 hp (300 kW) compressor slide valve with a 17 bar backup pressure control valve. This

FIG. 3. DIII-D cryosystem gas management.

method proved to be much too slow to control HP to the specifications of the new liquefier, especially during unstable operating scenarios such as neutral beam cryopanel regeneration. HP is now controlled by setting the pressure control valve to 16 bar through which there is a nominal flow to LP. Excess compressor capacity is needed to maintain this flow so the compressor slide valves, of which there are now two, are set for worst case needs. Usually this requires both 400 hp compressors to be at least partially loaded. The combined maximum compressor flow is 110 g/sec. LP is still controlled by operating the make up and dump valves to gas storage but control is now done by the PLC. In addition to the basic requirement of keeping LP at 1.1 bar, the LP control is now subject to conditions in the HP side of the system. The liquefier manufacturer emphasized that control of HP is of primary importance in avoiding damage to turbines and gave requirements for the maximum rate of change for HP. The cryogenics PLC satisfies this requirement by using the output of an HP derivative controller to modulate the action of the LP proportional/integral controller. In the case of falling HP pressure, this 'rate watchdog' will limit the amount of gas that the LP controller may return to storage even though LP may rise a few hundred mbar. With excessively rising HP pressure, the LP controller will be forced toward the dump to storage position even though LP may, in extreme cases, go sub-atmospheric. In practice, LP pressures lower than atmosphere are an invitation to system contamination and in fact have not occurred often or for periods longer than a few seconds.

OPERATING EXPERIENCE

Following installation and checkout of the divertor pump cryostat control components the system was operated manually for a period of time. This operation was accomplished by directly opening valves from the PLC executive software. Data and experience from

this testing was used to finalize the planning for interlocking and mode sequencing. The completion of the mode control and full interlocking programming is fairly recent. The in-vessel pump is now routinely operated in automatic mode and the pump is now appearing as a desirable element in many more physics experimental plans than was originally thought. It has been found that the pump can be regenerated and cooled within a few minutes between tokamak discharges, placing no limitation on the experimental cycle time. The next step for the cryopump control will be to implement operation of the pump modes from the central tokamak control computer. The new liquefier and gas management controls are also operating very satisfactorily. Further operating experience and more detailed analysis will provide data needed to improve utilization of compressor power while maintaining the integrity of the HP restrictions on the gas management system.

CONCLUSION

An overview of the existing DIII-D cryogenics control system has been presented. The interlocking and control philosophies for operation of the advanced divertor cryocondensation pump and new liquefier were discussed. The control system has achieved a high level of reliability and continues to contribute to the functionality of DIII-D systems. The needs of new experimental hardware are expected to be easily accommodated due to the considerable growth potential of the hardware base. Although the system is centralized within a large PLC, it has been simple to manage because of the inherent modularity of the cryogenics system.

REFERENCES

- [1] G.L. Campbell and J.J. Gilgallon, "DIII-D cryogenic control system upgrade," in *Proc. 13th Symp. on Fusion Engineering*, Knoxville, 1989.
- [2] M.A. Mahdavi, "The DIII-D collaborative advanced divertor program," unpublished.
- [3] J.P. Smith, C.B. Baxi, E.E. Reis, and D.L. Sevier, "A cryocondensation pump for the DIII-D advanced divertor program," in *Proc. 10th Top. Meeting on the Technology of Fusion Energy*, Boston, 1992.
- [4] E.E. Reis, I. Almajan, C.B. Baxi, M.M. Menon, M.J. Schaffer, D.L. Sevier, and J.P. Smith, "Design and analysis of the cryopump for the DIII-D advanced divertor," in *Proc. 17th Symp. on Fusion Technology*, Rome, 1992.
- [5] K.M. Schaubel, C.B. Baxi, G.L. Campbell, G.J. Laughon, M.A. Mahdavi, M.M. Menon, et al., "The development of an in-vessel cryopump system for the DIII-D tokamak," *Advances in Cryogenic Engineering*, vol. 39. New York: Plenum, 1993.
- [6] M.M. Menon, C.B. Baxi, G.L. Campbell, K.L. Holtrop, A.W. Hyatt, G.J. Laughon, et al., "Performance characteristics of the DIII-D advanced divertor cryopump, this symposium.

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