GA–A25825

IMPROVEMENTS OF THE DIII-D CRYOSYSTEM FROM ANALYSIS OF FAILURE MODES AND EFFECTS

by
P.S. MAUZEY, P.M. ANDERSON, and H.H. YIP

JUNE 2007

GENERAL ATOMICS

DISCLAIMER

GA–A25825

IMPROVEMENTS OF THE DIII-D CRYOSYSTEM FROM ANALYSIS OF FAILURE MODES AND EFFECTS

by
P.S. MAUZEY, P.M. ANDERSON, and H.H. YIP

This is a preprint of a paper presented at the 22nd IEEE/Symposium on Fusion Energy, Albuquerque, New Mexico on June 17-21, 2007 and to be published in the *Proceedings.*

Work supported by
the U.S. Department of Energy
under DE-FC02-04ER54698

GENERAL ATOMICS PROJECT 30200
JUNE 2007

GENERAL ATOMICS

Improvements of the DIII-D Cryosystem from Analysis of Failure Modes and Their Effects

P.S. Mauzey, P.M. Anderson, and H.H. Yip
General Atomics, P.O. Box 85608, San Diego, California 92186-5608, USA

***Abstract*— The cryogenic system at General Atomics' DIII-D Tokamak fusion facility provides cryopumping for the fusion vessel and neutral beams, cooling for the superconducting magnets for electron cyclotron heating, and cooling for the deuterium pellet injector. The operation of the fusion facility requires a reliable cryosystem, since upsets can result in significant downtime. A failure modes and effects analysis of the cryosystem was performed to identify and evaluate potential failures. This paper describes the methodology used for identifying the potential failures, based on likelihood of occurrence and consequence to operations. This paper further describes the analysis developed to understand these failure modes, and the improvements and testing to reduce the likelihood and the consequences of these failures. This failure analysis focused on maintaining the helium liquefier operation by providing reliable backup power and cooling for the helium compressors, and resulted in several recommendations which improved the liquifier's availability.**

Keywords: cryosystem, failure analysis

I. DESCRIPTION OF THE CRYOSYSTEM AT DIII-D

The cryosystem at General Atomics' DIII-D Tokamak fusion facility provides cryopumping for the fusion vessel and neutral beamlines, cooling for superconducting magnets for electron cyclotron heating, and cooling for the deuterium pellet injector. The cryosystem includes both helium and nitrogen. This analysis focused on the helium portion of the cryosystem.

The closed loop helium cryosystem (Fig. 1) compresses helium gas to 220 psig and cools the gas back down to near room temperature using water-cooled heat exchangers. The helium gas is then liquefied using expansion turbines and a J-T valve, stored at 4.6 K and 6 psig, and distributed for cryopumping in the tokamak vessel and neutral beamlines and cryocooling the deuterium pellet injector. Cold two-phase helium leaving the vessel cryopumps is used to cool high pressure (220 psig) helium gas to provide additional liquid helium for the storage dewar. The cold two-phase helium returning from the four neutral beamline cryopanels passes through a heat exchanger to cool high-pressure helium gas from the helium compressors to provide additional liquid helium. The cryosystem also supplies liquid nitrogen as a thermal shield for the liquid helium cryopumps and superconducting magnets.

Major components for the liquefaction and distribution of helium include four helium gas storage tanks, two Sullair helium compressors, one Sulzer helium liquefier, one liquid helium storage dewar, two distribution boxes for the three vessel cryopumps and four neutral beamline cryopanels, six cryostats with valves and heat exchangers for the vessel cryopumps and neutral beamline cryopanels, and a Koch expansion engine to liquefy high pressure helium gas cooled by two-phase helium returning from the neutral beamlines.

The control system for the cryosystem is PLC-based, with one central processor and ten sub-processors (PLC drops) distributed throughout the DIII-D facility. Control is performed automatically using ladder logic and manually through an operator's station in the cryo control room. The operator's station consists of a PC-based graphical user's interface with 28 pages of control screens.

II. METHODOLOGY FOR IDENTIFICATION OF THE MOST LIKELY AND SIGNIFICANT FAILURES OF THE CRYOSYSTEM

The operation of the fusion facility requires the cryosystem to perform reliably, since upsets can result in significant downtime. The cryosystem is a mature process plant that has been expanded and upgraded over the past twenty-five years. The majority of effort in the last five years has focused on improvements to instrumentation and control [1]. Older instrumentation has been upgraded to communicate with the cryo PLC so that control of the various subsystems of the cryosystem is now integrated. This has resulted in the ability of the cryo PLC to automatically correct upsets when a change in one subsystem affects other areas of the cryosystem. The main benefit in integrating control has been to create a reliable cryosystem.

A study was made to identify the most likely and significant failures of the helium cryosystem. The study considered several failure modes and estimated the likelihood of occurrence and the consequence to operation. In the present state of the cryosystem, failures occur more often due to the utilities supporting the cryosystem than due to the cryosystem itself. These utilities include the water to cool the helium compressors and liquefier, and electrical power for the helium compressors, water pumps, and instrumentation and control. Unexpected shutdown of the helium liquefier was identified as a serious consequence to operations, due to the time required to restore the liquefier to support operations. The electrical utilities backup generators were not intended to keep the liquefier running in the event of a power outage. This failure analysis assumed the liquefier would have to be restored in such an event. During nights or on weekends, the time required to restore the liquefier is about twelve hours. This includes the time for an operator to respond from off-site. Future improvements to the cryocontrol system may allow restoring the liquefier remotely from off-site, reducing the down time.

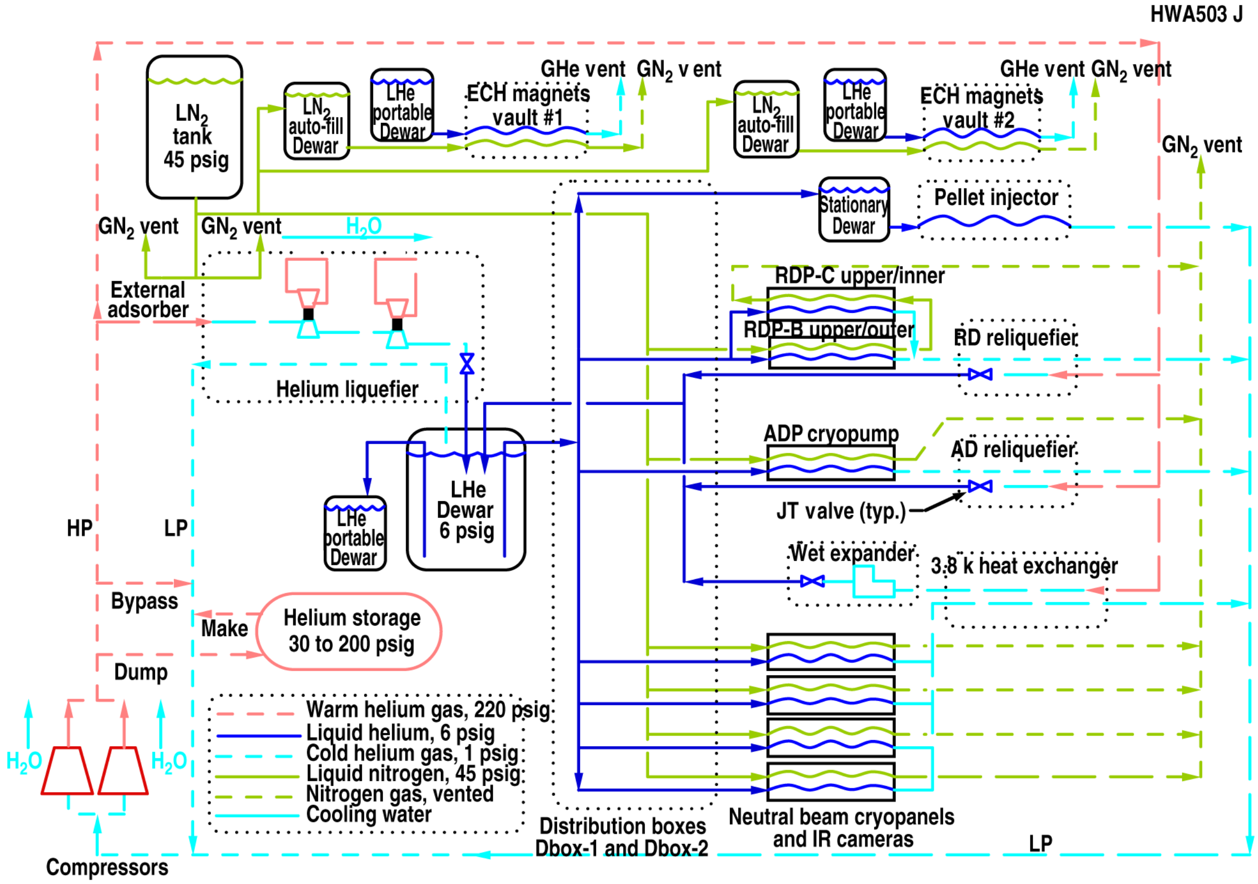

Figure 1. Cryosystem block diagram.

Twelve failure modes were identified:

1. Transformer T-5 power outage (providing power to the cooling tower to support the cryo system).
2. Dunhill substation power outage (providing power to the cryosystem).
3. Boost pump P-29 failure (providing cooling water to the helium compressors).
4. Boost pump P-30 failure (providing cooling water to the helium compressors).
5. Pressure switch failure for boost pump discharge.
6. Pressure transducer failure for boost pump discharge.
7. Loss of cooling tower water.
8. Cryo PLC power failure.
9. Compressor room cryo PLC drop power failure.
10. Water/vacuum PLC power failure.
11. Loss of emergency city water for the helium compressors.
12. Electrical power outage of the 69 kV transmission line to the DIII-D facility (providing power to the cryo system and the cooling tower supporting the cryo system).

III. DEVELOPMENT OF ANALYSIS TO UNDERSTAND THE IDENTIFIED FAILURE MODES

This failure analysis required an understanding of the relationship between the identified failures and the resulting shutdown of the helium liquefier. To be able to understand this cause and effect relationship, a diagram was created to show the electrical power distribution to the helium compressors, the helium liquefier, the water system used to provide cooling to the cryosystem, and the cryo- and water-vacuum PLCs needed to control the compressors, liquefier and water cooling. The diagram was developed by a combination of taking information from the current as-built DIII-D electrical drawings and physically tracing equipment and instrumentation power sources.

Once the diagram was created, color was added to show the paths of electrical power (in green). Each failure mode that involved a loss of power was shown in red, thus identifying the equipment that was affected by the power failure.

The DIII-D facility has two backup emergency diesel generators and a UPS (uninterruptible power supply). Diesel generator No. 1 provides backup power for the cooling tower primary pump, the PLC drops for PLC control of the cooling tower, and the UPS. Diesel generator No. 2 provides backup power for the primary helium compressor, the compressor boost pumps, the liquefier control cabinet, and the cryo-PLC drop in the compressor room. These diesel generators will come on line in fifteen to thirty seconds after a power failure. The UPS provides backup power for the cryo PLC, the water/vacuum PLC and the other PLC drops. The UPS switches to battery backup in the event of a power failure to provide uninterrupted power to these users. Diesel generator No. 1 will come on line before the UPS batteries are depleted.

A matrix was created (Fig. 2) to show what equipment was affected due to each failure mode, and the status of the helium liquefier due to each failure mode. Because the diesel generators come on line in fifteen to thirty seconds, the status of equipment was shown before and after the generators come on line. Similarly, the emergency city water for the helium compressors does not open immediately, so the status of equipment was shown before and after emergency city water opened.

The failure analysis was presented to an internal review panel, which provided recommendations for the methodology for identifying failures. From these recommendations a flow chart was developed showing the electrical power and water supporting the cryosystem's helium compressors and helium liquefier.

IV. IMPROVEMENTS AND TESTING TO REDUCE THE LIKELIHOOD AND CONSEQUENCES OF THESE FAILURES

The failure analysis resulted in seventeen recommendations for improving the reliability of the cryosystem. These were presented to an internal review panel that included persons responsible for electrical, PLC, cryo, water and vacuum systems for DIII-D. The panel determined which recommendations should be implemented and provided additional recommendations. The panel decided to implement the following eleven improvements.

Improvements in electrical power reliability for the cryo control system:

- Provide an enclosure for the cryo PLC module in the helium compressor room, to prevent failures of the PLC from water spray or dripping condensate from overhead helium lines
- Install local UPSs using continuous battery power for the system PLCs, which are already backed up by the main UPS. These UPSs eliminate voltage fluctuations that cause PLC crashes when the main UPS switches to battery power.
- Provide UPS backup power to the cryo PLC controlling the upper vessel cryopumps and the 30 and 330 degree neutral beamlines. This was not related to the liquefier reliability, but was a result of the analysis.

Improvements in electrical power reliability for the cryo water system:

- Provide diesel generator backup power for the water/ vacuum PLC controlling the cooling tower.

Improvements to the reliability of helium compressor cooling boost pumps:

- Install a differential pressure transducer to control the helium compressor boost pump speed. Controlling the differential pressure across the compressor cooling water heat exchangers maintains a constant required flow rate of cooling water, eliminating cooling water flow fluctuations due to changing cooling water return pressure.
- Eliminate the low water pressure switches supplied with the helium compressors, which are redundant, and not as reliable as the added pressure transducer.
- At the startup of the helium compressors, test the two coolant boost pumps and the emergency city water. Running the backup pump and opening emergency city water before startup verifies the availability of backup cooling.

Improvements to the city water emergency backup for helium compressor cooling:

- Provide UPS backup power for the solenoid valve that actuates the emergency city water valve for the helium compressors.
- Install an accumulator and check valve for compressed air to the emergency city water pneumatic actuator, to enable the valve to operate in the event of a loss of compressed air.
- Double the cooling water flow interlocks to signal the PLC to open emergency city water, using a differential pressure transducer, with a pressure switch as a backup set at a lower pressure.
- Provide valve control and PLC logic to eliminate overflow of the cooling tower basin when emergency city water enters the cooling system. This was not related to the liquefier reliability, but was a result of the analysis.

V. CONCLUSIONS

A failure modes and effects analysis performed on an existing complex system such as the DIII-D cryosystem has proven beneficial in improving reliability, and is recommended for other systems and utilities at DIII-D.

ACKNOWLEDGMENT

This work was supported by the U.S. Department of Energy under DE-FC02-04ER54698.

REFERENCE

[1] K.L. Holtrop, et al., "Improvements to the cryogenic control system on DIII-D," Proc. of the 20th IEEE/NPSS Symp. on Fusion Engineering, San Diego, California (Institute of Electrical and Electronic Engineers, Inc., Piscataway, New Jersey, 2003), p. 401.

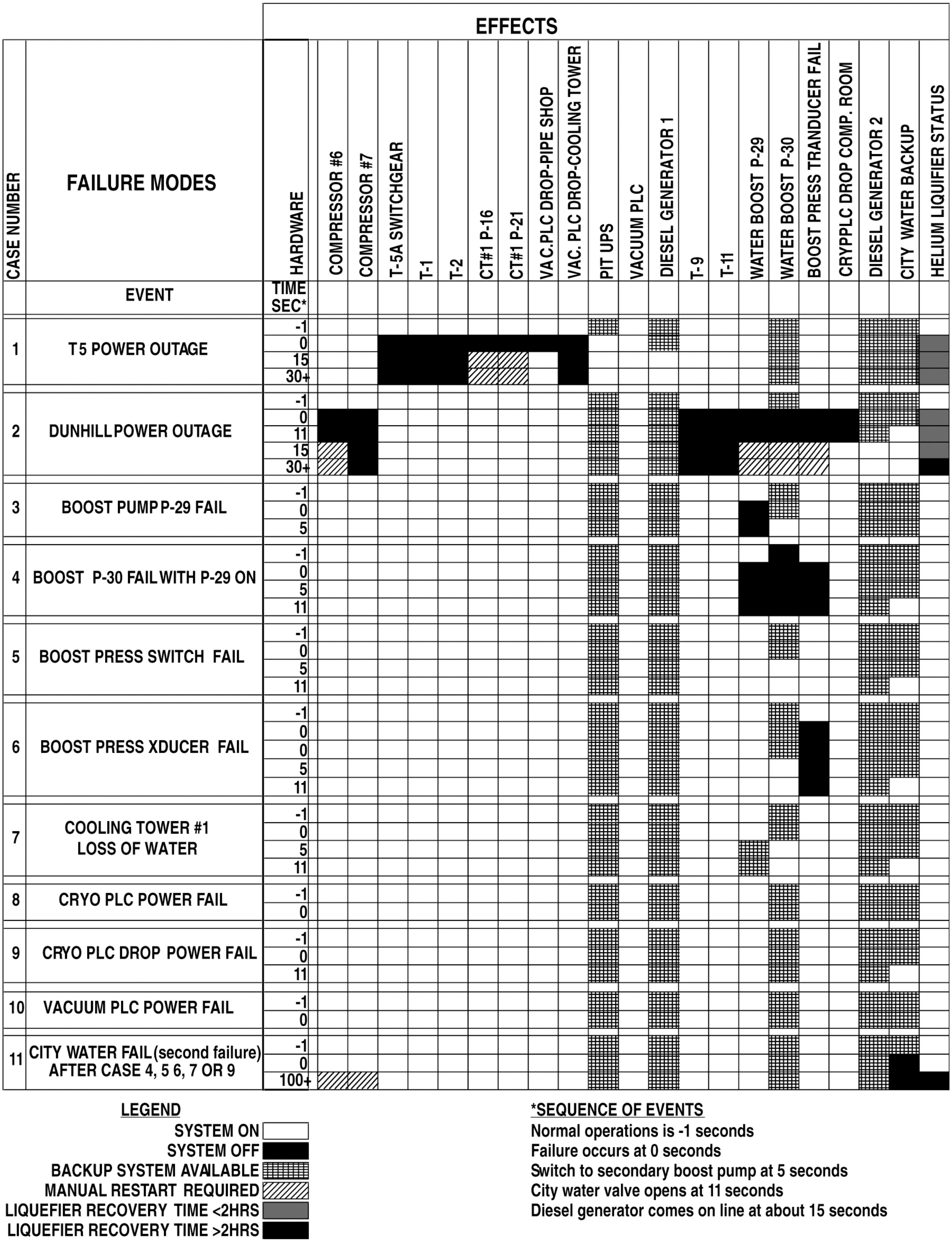

Figure 2. Failure mode and effects matrix for the cryosystem power and water.