Introduction

The potential hazards associated with operation of a failed collection lens postulated in 1983 are documented in Reference 1. Interlocks recommended by Reference 1 and described in Reference 2 were in use for many years. Extensive operating experience with approximately 30 lenses over the past 21 years has allowed us to reconsider the plausibility of postulated hazards. With the benefit of this additional insight, the interlock system has been modified. Major changes to the system include:

- Addition of interlocks to prevent collection lens power supply operation in the event of loss of cooling water flow to the collection lens
- removal of the argon purge system

There were a number of local interlocks on the collection lens cooling water system designed to protect the cooling water system pump; these included a flow switch, reservoir tank level switch, and pump motor overload protection. A fault in any of these three devices caused the pump to trip off which resulted in a loss of lens cooling water flow. The lens power supply was not directly inhibited by any of these faults; power supply operation was eventually inhibited by related interlocks such as lens cooling water flow or pump discharge pressure. In the new interlock scheme, the paddle switch is eliminated; two existing flow turbines in the lens cooling water supply and return lines will continue to inhibit power supply operation in the event of loss of cooling water flow. The reservoir tank level interlock function has been changed to inhibit power supply operation; the loss of level no longer trips off the collection lens water pump. A thermocouple has been added to the pump motor to provide early detection of pump motor overheating; an associated interlock inhibits the collection lens high voltage power supply in the event of pump motor overheating. The motor current overload protection remains to trip off the pump in the event of a pump motor over current condition.

As indicated in Reference 1, the critical action to be taken in the event of a failed lithium lens is to inhibit operation of the lithium lens pulsed power supply. In the absence of cooling water flow, resistive heating in the collection lens resulting from power supply operation increases lithium temperature and allows the possibility of a number of chemical reactions with air and water.

Continued application of cooling water reduces the likelihood of high temperature lithium/air/water reactions. Operating experience has shown that continued application of cooling water to failed lenses is not harmful. The only noteworthy effect is that the cooling water system becomes contaminated with lithium hydroxide, a condition which is relatively simple to correct.

An argon gas purge system had been in use as recommended by Reference 1. When activated, the purge system introduced argon gas and removed cooling water from the lens. The purpose of the system was to prevent mixing of very hot lithium (produced in a lens which lost cooling water but continued to receive current pulses) with water and air. The system rarely acted as intended. In some cases, lenses had been operated after failure without activating the purge system due to a faulty conductivity monitoring system. In other cases, lenses failed shortly after unintended purge system operation had occurred; the purge system could be activated by certain power failure scenarios or by a conductivity monitoring system fault. These otherwise healthy lenses are thought to have been damaged, indirectly, by the purge system because these lenses lost cooling water during operation. More recently, with correctly functioning, closely monitored conductivity systems, lens failures have been detected well before the argon purge systems could act. For these reasons, the argon gas purge system has been deactivated.

<u>Operating and Engineering Experience Notes</u>

Nearly two decades of collection lens operating experience have accrued since the target station became operational. The following are important points considered for the interlock system reconfiguration:

1. A correctly functioning conductivity monitoring system is necessary and sufficient to detect mechanical failures in the lithium containment structures. In recent years, the conductivity monitoring system detected a number of lens failures including lenses 22, 24, 25, 26 and 29. In some cases, the conductivity system has been sufficiently sensitive to allow one to identify lens failures before the interlock system initiated a trip. Conditions noted during failure of these lens are described here:

- A. Lens 22 - The interlock system initiated a purge caused by high conductivity several hours after the lens power supply turned off. Subsequent examination of the lens septum revealed small cracks in a weld that allowed lithium/water contact. The system purge served no useful function in this failure because the lens power supply would have failed to turn on thereby preventing further lens operation.
- B. Lens 24 – Target station personnel noted increased conductivity readings in the cooling water system while lens 24 continued to operate for one to two days after onset of the initial failure. The conductivity increased was very gradually and never did reach the trip point before the lens was removed service. The purge system served no useful function in this failure.
- C. Lens 25 – An erroneous conductivity indication, probably due to an instrumentation cable fault, initiated a system purge while the lens operated for pbar production. After restarting the water cooling system, the lens operated for about 15 hours until a genuine conductivity indication inhibited the high voltage power supply and initiated a system purge. In the case of lens 25, the first purge may have been responsible for the eventual failure of the lens. Even though the interlock system inhibited the power supply, the loss of cooling water to the lens could have resulted in high stresses in the titanium septum due to substantial residual heat in the lens body and the transformer. Since the genuine conductivity excursion inhibited the power supply, the functional value of the second purge is not obvious. Continued operation of the cooling water system would reduce the lens/transformer temperatures while lithium hydroxide and hydrogen gas entered the cooling water system. Target station personnel had to drain and refill the cooling water system in this case; the purge system served no useful function in this failure.
- D. Lens 29 – Lens 29 failed on the test stand. The test station operator noted that cooling water conductivity increased above the nominal levels (well below the power supply inhibit and purge system trip level) which lead to the conclusion that the lens had failed. The test station purge system served no useful function in this case.

- E. Lens 26 – Lens 26 failed on the test stand which at the time did not have a functional purge system. The conductivity interlock inhibited the high voltage power supply which was sufficient to prevent the more severe consequences of lithium lens failures described in Reference 1.

2. An incorrectly functioning conductivity monitoring system probably existed during the failures of lenses 17, 18, 20, and 21 in the period starting 1992 and continuing into October 1995 [5]. These lenses have all been unfilled and disassembled. Severe damage, including burning of the inner conductor tube was found (in all but lens 20) indicating that significant tube damage was caused by continued pulsed operation after the mechanical failure. Water lines ruptured on lenses 17 and 18 which resulted in the ejection of cooling water from the septum. If these lenses received current pulses after the water lines ruptured, excess heating would boil away any residual water at temperatures below lithium's melting temperature. Lens 20 contained no lithium; target station personnel believe that flowing cooling water removed all the lithium over several months when the water systems continued to run over an extended shutdown period. The consequence beyond the failure of the lens was limited to simple draining and refilling the collection lens water system.

3. One lens has failed as described in the second scenario described in Reference 1. An alternate cooling water system (which did not include a conductivity monitoring system) provided non-LCW cooling water to Lens 27. The lens received current pulses and beam pulses after mechanical failure for hundreds of cycles without a water cooling system. The water cooling lines had ruptured, probably due to the pressure increase caused by hydrogen gas generation resulting from the lithium/water reaction. Additional lens heating caused by continued power supply operation simply boiled off any residual cooling water, again with no other permanent damage to the target station. One positive aspect of the unfortunate experience with lens 27 was to demonstrate that a purge system was not required to prevent severe damage to the target station as was suggested by Reference

1. Target station personnel implemented specific corrective actions to ensure that the experience with lens 27 is not repeated.

4. Conductivity detections systems are not inherently fail safe [6]. The interlock trip points for the system need to be set for a rather narrow range of operation so that open circuits or short circuits in the system will inhibit the collection lens high voltage power supply. The collection lens water system has been modified to permit in-situ testing of the conductivity cells with a standard solution so that proper conductivity cell response can be verified as necessary.

5. Like lens 25, lenses 17 and 18 failed shortly after the gas system purges. During the service lives of lenses 17 and 18, power outages could activate the purge system through faulty interlock system logic. Target station personnel suspected that those lens failures may have been related to the purges. Loss of cooling water in a hot lens (one which has been receiving current and beam pulses) probably leads to higher than intended stresses in the collection lens inner conducting tube which can ultimately weaken or crack the tube.

6. Operational experience suggests that it very important to inhibit the lens current pulse and proton beam immediately when any cooling water system parameter goes out of tolerance. In addition, cooling water should flow to provide as much lens cooling as possible after removal of the heat loads. The reduction of lens temperature to reasonable levels after removal of heat loads serves to reduce corresponding stress levels in the septum inner conducting tube. Engineering calculations show that high lens temperatures in the absence of water cooling can lead to either prompt or premature failure of the inner conducting tube. Initiation of a gas system purge defeats lens body cooling and is therefore ill-advised.

7. The transformer water cooling system is important. In the absence of transformer water cooling, the transformer heat removal is limited to radiation cooling (which is very inefficient) and to conduction cooling through the lens body. Transformer water cooling

serves to reduce lens body temperature during operation by 10 to 15 C (at 5E12 ppp every 2.4 seconds.)

8. Some existing collection lens water cooling system interlocks protect the water system pump and can initiate a loss of cooling water flow to the collection lens. These interlocks should never initiate a loss of cooling water condition to protect the cooling water system pump at the expense of a collection lens.
9. No beryllium window failure has ever occurred in a collection lens over the operating history of the target station.

Collection Lens Interlock System

Interlocks associated with the collection lens, are described individually in the remainder of this note. A summary of the interlocks, including the old and new trip points and functions, is included in Table 1.

Transformer cooling water flow

Transformer water cooling is a relatively new development which came in to use early in 2001. It has been found that transformer cooling helps to significantly reduce lens operating temperature. The pulsed magnet water cooling system provides transformer cooling water flow at this time. In the future, the collection lens water cooling system may provide cooling water for both the collection lens and the transformer since excess capacity exists on the lens cooling water system. The flow turbine interlocked inhibits the collection lens high voltage supply.

Collection Lens Water Supply Temperature

Chill water regulation for the lens cooling water system required repair in the summer of 2003; prior to that time, lens cooling water temperature could run as low as 10 C. The minimum supply temperature regulation is typically set at greater than 20 C during normal operation to prevent the formation of condensation, especially during periods of high relative humidity. The low temperature trip point guards against reduced preload which is known to occur as a result of reduced lens temperature and inhibits power supply operation if condensation may exist on the lens body.

Collection Lens Water Return Temperature

This device interlock is similar in function to the collection lens water supply temperature. The low temperature trip point inhibits power supply operation if condensation may exist on the lens body.

Transformer Cooling Water Supply Temperature

Transformer cooling water presently comes from the pulsed magnet water system. The collection lens water system may eventually provide cooing water to the transformer. This device interlock inhibits the collection lens power supply. The low temperature trip point guards against the formation of condensation on the transformer.

Transformer Cooling Water Return Temperature

This device interlock is similar in function to the transformer cooling water supply temperature. The low temperature trip point guards against the formation of condensation on the transformer.

Collection Lens Supply Cooling Water Flow

The cooling water flow rate has been increased to approximately 3 gpm as a result of better understanding of the cooling water system and its upgrades. The water flow turbine inhibits the collection lens power supply. The minimum cooling water flow interlock trip point guarantees sufficient cooling for the anticipated increases in beam intensity and pulse repetition rate.

Collection Lens Return Cooling Water Flow

This interlock is necessary to ensure cooling water flow is available in the return path from the lens. This interlock also inhibits the collection lens power supply in the event of a cooling water system failure. The minimum trip level is set to match that of the supply flow turbine.

Collection Lens Cooling Water Supply Pressure

This interlock inhibits the lens high voltage supply in the event of loss of cooling water supply pressure to the lens.

Collection Lens Cooling Water Return Pressure

This interlock inhibits the lens high voltage supply in the event of loss of cooling water return pressure from the lens.

Nitrogen Bottle Pressure Interlock

This interlock, related to the purge system is no longer be required.

Collection Lens Water Pump Inlet Pressure

The purpose of this interlock is to provide early warning for the cooling water pump cavitation which could lead to pump damage and eventual loss of cooling water to the lens. The interlock also functions in the event of a system water leak resulting from a substantial reservoir tank level decrease. The interlock inhibits only the collection lens high voltage power supply. The cooling water pump continues to operate to ensure adequate lens cooling before complete loss of cooling water flow, especially during lens operation.

Collection Lens Argon Gas Bottle Pressure

This interlock, related to the purge system, is longer required.

Collection Lens Return Conductivity

Collection lens return conductivity is the major protection feature in the collection lens cooling water system to detect mechanical failure of the collection lens. This very sensitive parameter provides indication of a septum failure and the failure of the beryllium window described in Reference 1. This interlock inhibits the collection lens high voltage supply. The low conductivity alarm set point, 0.045 umho/cm, provides protection against a defective cell or a cell which no longer contains water; the theoretical minimum conductivity is 0.054 umho/cm. Any reading below this level is indication that the cell is either defective or that water is no longer flowing through the cell. The conductivity interlock interrupts the high voltage power supply directly and independently of the remainder of the interlock chain.

Reservoir Tank Level

The reservoir tank has a low level detection float switch which inhibits the high voltage power supply. Cooling water flow is essential for a collection lens both during and immediately after shutdown to reduce the lens body temperature sufficiently to prevent high stress levels in the titanium septum. This interlock will inhibit the high voltage power supply in the event of a low reservoir tank water level. The pump will continue to provide cooling water flow as long as water is available in the reservoir tank.

Paddle Switch

This interlock is no longer used. The two flow turbines provide adequate, redundant protection.

Pump Motor Overload

This interlock stops the pump and initiates a loss of cooling water flow. A thermocouple attached to the cooling water pump motor will provide early warning of the overload condition and the associated interlock will inhibit the collection lens power supply.

References

1. Lithium Lens Catastrophe Theory, pbar note #373, G. Dugan, 4/24/83
2. Lithium Lens Interlocks, pbar note #443, J. Krider, 12/18/85
3. Letter to G. Lautenschlager et al, from T. Moreland, Modifications of AP0 Collection Lens Purge System, dated 9/20/1999
4. Lithium Lens 21, 20, 17, 18, and 16 Eulogies, pbar note #689, T. Leveling & J. Morgan, 6/13/03
6. The Relationship Between pH and Conductivity in a Lithium Contaminated, De-Ionized Water system, pbar note #674, A. Leveling, 6/7/02

A. Leveling
8/11/04

ACNET NAME	Description	Old Low trip level	Old High trip level	Former Action	New Low trip level	New High trip level	New Action
D:LNWM6	Transformer cooling water flow	1 gpm	3 gpm	Inhibit HV supply	1 gpm	3 gpm	Inhibit HV supply
D:LNTC7	Collection Lens water Supply temp	5 C	35 C	Inhibit HV supply	15 C	35 C	Inhibit HV supply
D:LNTC8	Collection Lens water Return temp	5 C	35 C	Inhibit HV supply	15 C	35 C	Inhibit HV supply
D:LNTC10	Transform cooling water supply temp	5 C	35 C	Inhibit HV supply	15 C	35 C	Inhibit HV supply
D:LNTC11	Transformer cooling water return temp	5 C	35 C	Inhibit HV supply	15 C	35 C	Inhibit HV supply
D:LNWM1	Collection Lens water supply flow	1.3 gpm	5 gpm	Inhibit HV supply	2.0 gpm	5 gpm	Inhibit HV supply
D:LNWM2	Collection Lens water return flow	1.3 gpm	5 gpm	Inhibit HV supply	2.0 gpm	5 gpm	Inhibit HV supply
D:LNWP1	Collection Lens water supply pressure	40 psig	bypassed	Inhibit HV supply	40 psig	bypassed	Inhibit HV supply
D:LNWP2	Collection Lens water return pressure	5 psig	100 psig	Inhibit HV supply	5 psig	100 psig	Inhibit HV supply
D:NIBOTP	Nitrogen bottle pressure	80 psig	120 psig	Inhibit HV supply	80 psig	120 psig	Purge system removed
D:LNWP5	Collection Lens Water Pump inlet pressu	1.5 psig	30 psig	Inhibit HV supply	4.0 psig	20 psig	Inhibit HV supply
D:LNBOTP	Collection Lens Argon Gas Bottle pressu	10 psig	50 psig	Inhibit HV supply	10 psig	50 psig	Purge system removed
D:LNWN1	Collection Lens Return Water conductivit	0 umho/cm	1.2 umho/cm	Inhibit HV supply and Initiate purge	0.045 umho/cm	1.2 umho/cm	Inhibit HV supply
On Fault	Reservoir Tank Level	Low	NA	Stop pump/Initiate LOCA	Low	OK	Inhibit HV supply
On Fault	Flow switch	Low	NA	Stop pump/Initiate LOCA	Low	OK	Inhibit HV supply
On Fault	Pump motor overload	NA	Hi	Stop pump/Initiate LOCA	OK	Hi	Inhibit HV supply Add interlocked thermocouple to pump motor to inhibit supply before motor overload trip
On Fault	Loss of nitrogen gas bottle pressure			Initiates LOCA & purge			Purge system removed
On Fault	Solenoid valve fails			Initiates LOCA & purge			Purge system removed

Table 1 – Old and New Lithium Lens System Interlocks