Introduction

The examination of failed radioactive solid lithium lenses has not been permitted until recently. Since a method to examine failed lenses has been worked out [1], lenses 21, 20, 17, 18, and 16 have been disassembled and work has begun to understand why these lenses have failed. While the damage produced during the failure of these lenses is obvious, the initial conditions leading to failure are yet to be identified. A fair amount of metallurgical work has been and continues to be done, primarily by the Mechanical Support Department. The purpose of this Note is to document what was found during the lens unfilling and disassembly including the condition of the septum upon removal from the lens body.

The operation of collection lenses on the test station has been reviewed in detail and is to be reported in a separate pbar NOTE. A summary of the test station operation (pulse count at peak current) is provided for each of the unfilled lenses. It should be noted that the peak current corresponding to what is now nominal gradient (750 T/m) is about 500,000 amps. As will be seen, all lenses reported on in this Note where tested at gradients well above the nominal gradient. In some cases, the gradient at which lenses were tested appears to have been significantly higher than intended.

Finally, some effort was made to determine the tritium inventory of each lens in conjunction with the unfilling process. The results of these tritium measurements will be reported.

Lens 21

Lens 21 was filled in June 1993 with a reported preload of 2,060 psig[1]. It was tested in August 1993 for a total of 409,700 pulses at a maximum peak current of 626,675 amps. Figure 1 contains a summary of the number of pulses tested versus peak current. The desired and achieved gradients were 900 and 940 T/m, respectively.

[1] The preloads reported in this note were determined by strain gages externally mounted on the surface of the lens bodies. The apparent precision of reported preload pressures is misleading. Historically, the strain gage response was suspicious and is now thought to have very large errors, easily better than 30%. Starting with lens 27, a Dynisco pressure transducer has been used and the associated error is estimated to be about 5%.

Lens 21 was placed in service on June 27, 1995 replacing lens 18. It failed on July 12, 1995 with just 194,484 operational pulses. It appears that the short service life of Lens 21 may have been due to operation with high conductivity water in the cooling system[2]. It is probable that the water cooling system conductivity monitor began to malfunction while Lens 18 was in service. That there were subsequent, repeated attempts to revive lens 18, and that it was ultimately determined lens 18 failure was due to a septum breach reinforces the belief that Lens 21 was operated with high conductivity cooling water. The Lens 21 failure was preceded by an abrupt increase in conductivity and a rise in water system pressure which caused the water cooling lines to rupture.

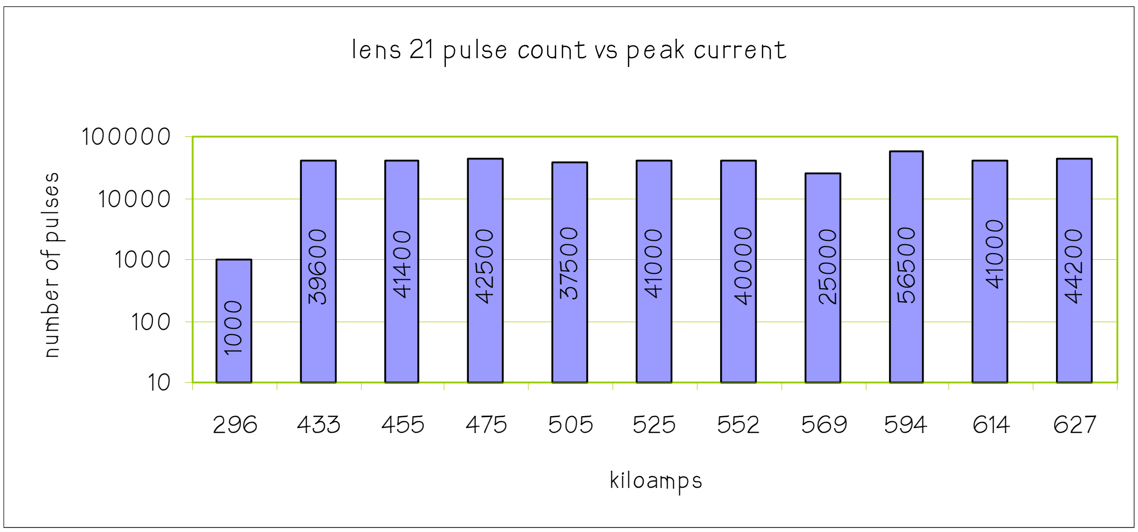

Figure 1

Lens 21 was the first operating lens to be disassembled and was completed over the period June 5 to June 18, 2001. Before beginning the unfilling process on lens 21, low conductivity water was pumped through the cooling water circuit to verify that a lithium/water cooling system septum breach had occurred. A total of 51 grams of lithium was removed during three attempts in Phase

[2] The lens cooling water system is designed so that when high conductivity water is sensed, the lens power supply and lens cooling water systems are tripped off while argon gas is introduced to purge water from the lens cooling water jacket in the lens septum. Conductivity cell systems are not inherently fail safe devices; if a cell stops responding correctly, the collection lens conductivity interlock protection features can be rendered inoperable.

1[3] and 12 liters of hydrogen gas were produced during Phase 2. Only about 1/2 to 2/3 of the hydrogen gas produced in Phase 3 was burned which yielded about 1 mCi of tritium. Total tritium produced in phase 2 is estimated to be 1.5 to 2 mCi. Damage in the inner conductor was extensive near its center. The inner conductor appeared to be burned through circumferentially (dark crescent shape in photo) and some long longitudinal cracks were found along the length of the inner tube.

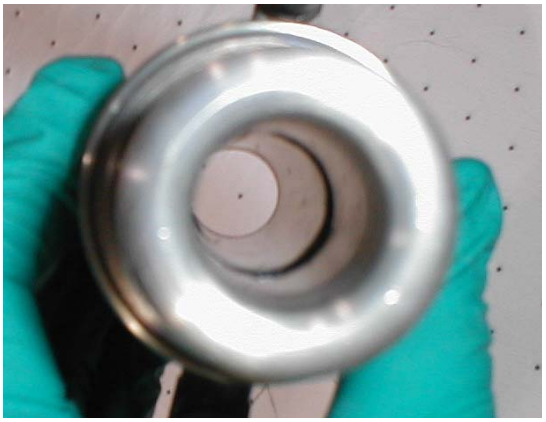

Photo 1 - Lens 21 damage near center of lens

Photo 2 – Lens 21 inner titanium tube sections

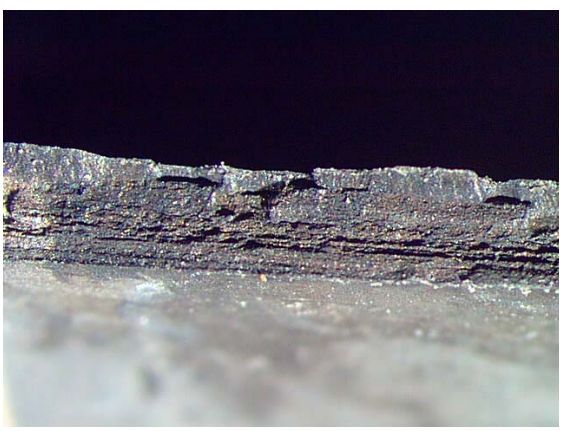

Photo 3 – edge view of Lens 21 crack

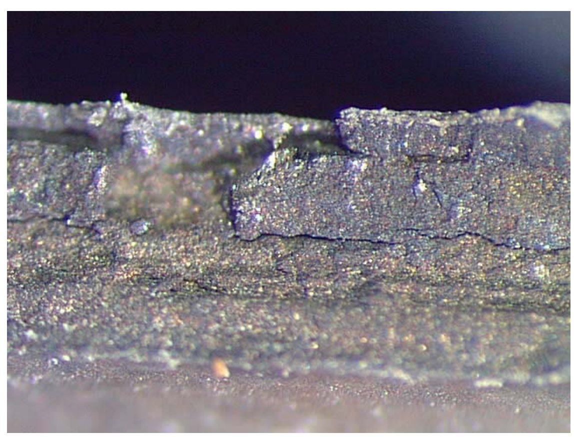

Photo 4 – edge view of Lens 21 crack

[3]In Phase 1, lithium is melted and removed by applying pressurized argon gas to force the metal from the lens body. In Phase 2, any remaining lithium metal is removed by reaction with water. In Phase 3, the resulting hydrogen gas collected from the lithium/water reaction in Phase 2 is consumed and the resulting water vapor is collected for analysis.

Lens 20

Lens 20 was filled in August 1993 with a reported preload of 2554 psig. It was tested in October 1995 for a total of 408,615 pulses at a maximum peak current of 626,675 amps. Figure 2 contains a summary of the number of pulses tested versus peak current. The desired and achieved gradients were 900 and 940 T/m, respectively.

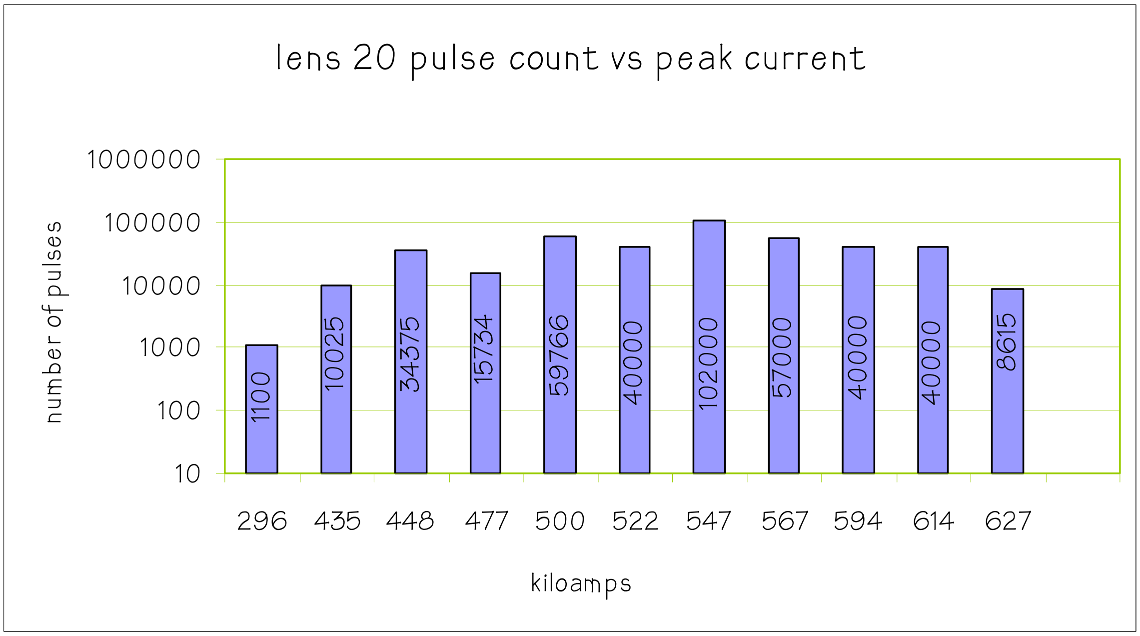

Figure 2

Lens 20 was placed in service on July 12, 1995 replacing lens 21. Like its predecessor, Lens 20 was placed in service and operated with high conductivity water in the water cooling system. Lens 20 was operated for less than a month accumulating about 299,000 pulses when a planned, extended scheduled shutdown began. Lens 20 was replaced in October 1995 when, during target station startup, it was discovered that it had failed. The failed conductivity monitor was discovered and replaced at this time as well.

Lens 20 was disassembled over the period July 5 to July 10, 2001. While attempting to remove lithium from Lens 20 during the Phase 1 process, it was discovered that there was no lithium contained in the lens body at all. It appears that the lens had failed sometime in July after the planned shutdown had begun. It is probable that the lithium gradually reacted with cooling system water during the extended shutdown. Visual examination showed a thin, straight axial crack in the inner conductor tube wall. There was no evidence of severe burning or arcing in this lens.

For obvious reasons, no tritium measurement data is available for this lens.

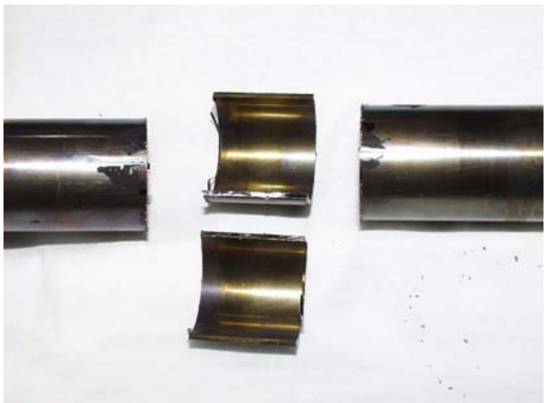

Photo 5- Lens 20 tube sections

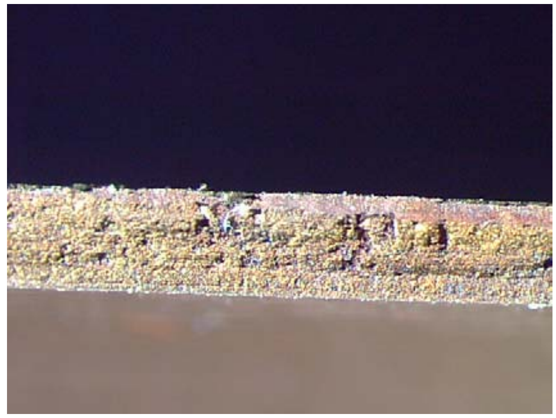

Photo 6. Edge view of Lens 20 crack

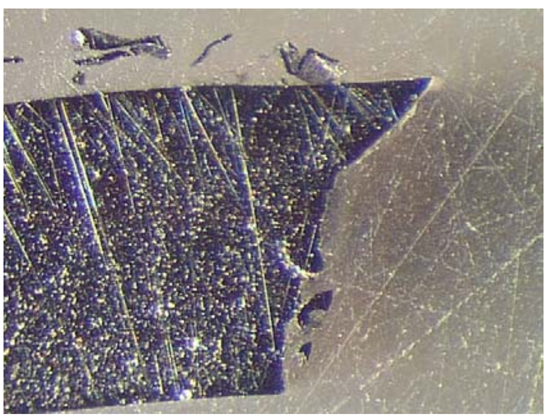

Photo 7 – cross section of Lens 20 crack

Lens 17

Lens 17 was filled in April 1990 with a reported preload of 2340 psig. It was installed on the test station on three different occasions for pulse testing in July 1990, March 1991, and October 1992. A total of 1,131,200 pulses at a maximum peak current of 609,263 amps were spent on the collection lens test station. Figure 3 contains a summary of the number of pulses tested versus peak current. The desired and achieved gradients at the test station were 914 and 805 T/m, respectively.

Lens 17 was placed in service on October 1992 replacing lens 16. Lens 17 was removed from service on April 7, 1994 with 5,146,125 pulses, probably due to a general interlock failure which would have included loss of cooling water flow, cooling water supply pressure, and possibly conductivity. The Lens 17 failure was probably fairly violent since the cooling water lines where found broken and bent when the lens was removed from the vault. When Lens 17 was to be put in its coffin, the badly bent water lines prevented the coffin lid from being installed. The water lines were simply broken off so that the coffin lid could be fitted in place.

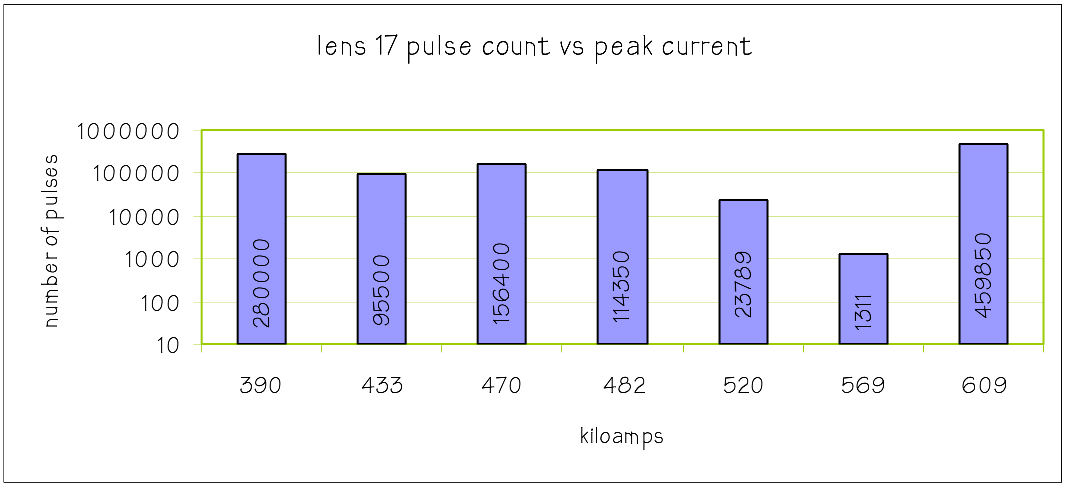

Figure 3

Lens 17 was disassembled over the period October 3 to October 31, 2001. Before Lens 17 could be unfilled, the end flanges had to be removed so that the broken water lines could be repaired to prevent lithium metal or water leaks out of the water cooling lines. A total of 23 grams of lithium was removed during four attempts in Phase 1. Seven to eight liters of hydrogen gas were produced during Phase 2. Upon disassembly, an unknown compound was found plugging one of the fill ports. This compound probably formed because the lens water cooling passages had not been dried out before the lens was put into storage. The presence of this compound prevented establishing water flow through the lens body and as a consequence, there was still some lithium metal present when the lens body was disassembled. The hydrogen gas burned in Phase 3 yielded about 7.7 mCi of tritium. Photos of the intact inner conducting tube and some tube sections are included below. Additional metallurgical examinations are being planned for the inner conducting tube of Lens 17.

Photo 8 – Lens 17 inner tube removed from septum **Photo 9 – another view Lens 17 inner tube**

Photo 10 – Lens 17 inner tube after sectioning

LENS 18

Lens 18 was filled October 7, 1990 with a reported preload of 2345 psig. It was installed on the test station in February 1992. Lens 18 had a total of 407,300 pulses on the test station at a maximum peak current of 606,776 amps. This lens had an additional 80,000 pulses on the test stand prior to this period at relatively low gradient before a problem developed in the transformer which subsequently required the transformer to be repaired. Figure 4 contains a summary of the number of test pulses versus peak current. The desired and achieved gradients at the test station were 910 and 948 T/m, respectively.

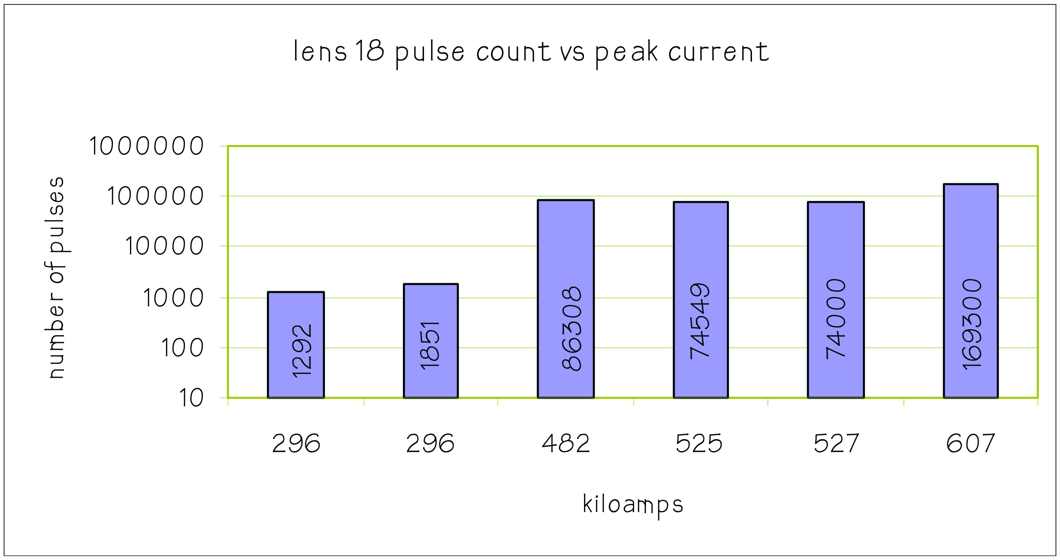

Figure 4

Lens 18 was placed in service on April 28, 1994 replacing lens 17. It was removed from service on June 25, 1995 with 7,870,738 operating pulses probably due to tripped interlocks which would have included loss of cooling water flow, cooling water supply pressure. As with lenses 17 and 21, the water lines were found to be broken on lens 18. There was an unsuccessful attempt to restore lens 18 to service by repairing its water lines which had been broken in the original failure.

Lens 18 was disassembled over the period November 19 to December 5, 2001. One attempt was made to unfill Lens 18 with Phase 1 and only 1 cc of lithium was removed. Forty liters of hydrogen gas were produced during Phase 2. The hydrogen gas burned in Phase 3 yielded about 26 mCi of tritium. Damage to Lens 18 was rather unique. In this case the downstream end of the inner conducting tube (not the welded end) was burned off entirely. There was no evidence of any cracks. Photos of the inner conducting tube removed from the septum assembly and some tube sections are included below. Additional metallurgical examinations are being planned for the inner conducting tube of Lens 18.

Photo 11 – Lens 18 inner conducting tube removed from septum

Photo 12 – Same as Photo 11 except ring reversed

Photo 13 – Lens 18 inner conducting tube after sectioning

Lens 16

Lens 16 was filled February 9, 1990 with a reported preload of 2,560 psig. It was installed on the test station on five different occasions including March 1990, May 1990, July 1990, December 1990, and April 1991. Lens 16 had a total of 1,467,361 pulses on the test station at a maximum peak current of 599,314 amps. Figure 5 contains a summary of the number of test pulses versus peak current. The desired and achieved gradients at the test station were 900 and 936 T/m, respectively.

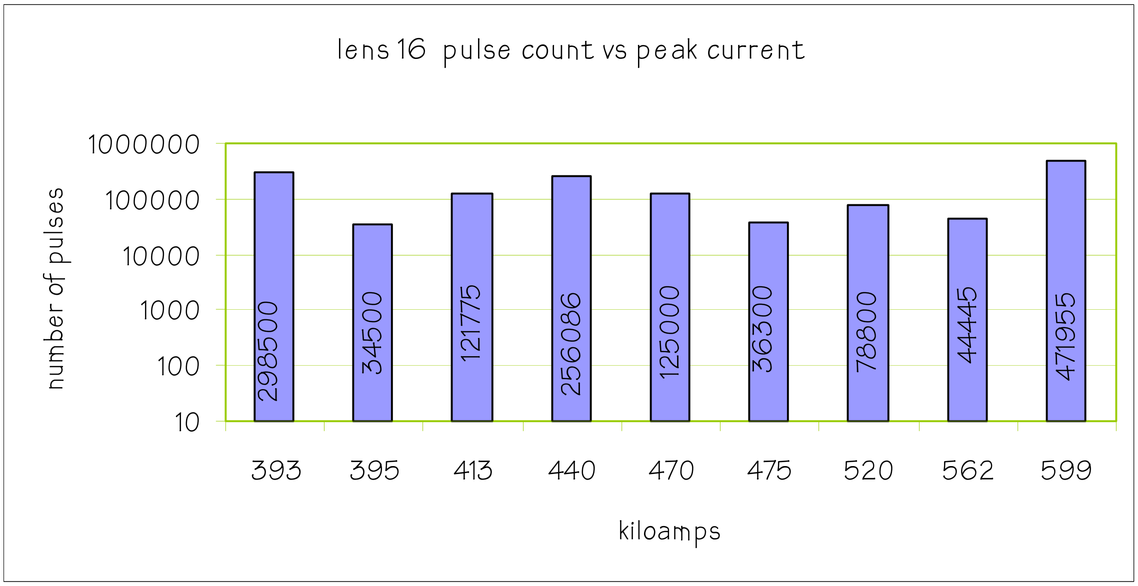

Figure 5

Lens 16 was placed in service on December 19, 1991 replacing lens 13. Lens 16 was removed from service on October 12, 1992 with an estimated 3,200,000 operating pulses due to an internal water leak, i.e., water was reportedly leaking from somewhere within the lens body.

Lens 16 was disassembled over the period March 27 to April 4, 2002. Lens 16 was unfilled utilizing only Phase 2 and the nested tube arrangement in which 106 liters of hydrogen gas were produced. The total gas production versus time the pump was running is plotted in Figure 6. Lens 16 provided a unique opportunity to measure the total tritium associated with the lens both in gaseous and aqueous forms. The lithium was completely intact in this lens since the septum was not destroyed. The total tritium recovered from hydrogen gas was 17.7 mCi while the total tritium recovered in the Phase 2 tank water was 0.7 mCi. The total estimated proton beam intensity on target over the Lens 16 operating life was 6.4E18 protons. A total of 18.4 mCi was collected from this lens. In References 1 and 2 the predicted total tritium was 4 and 0.9 Curies. The total tritium measured is a factor of 50 times less than predicted.

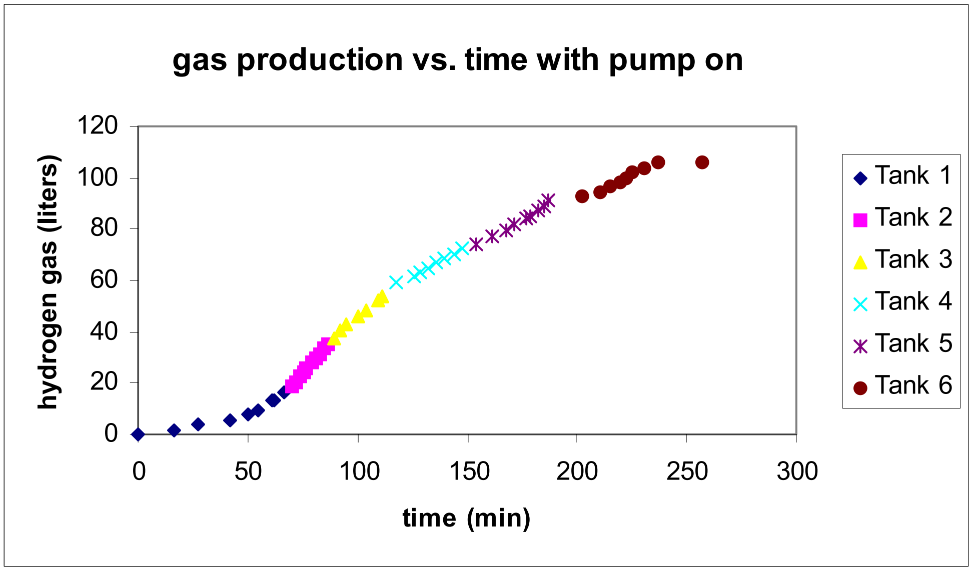

Figure 6

As expected, there was no evidence of damage in the Lens 16 inner conducting tube. A photo of the inner conducting tube removed from the septum assembly showing marks for intended tube sections are included below.

Photo 14 – Lens 16 inner tube removed from septum prior to sectioning

Metallurgical examinations are being planned for the inner conducting tube of Lens 16 to look for evidence of onset of cracking, pitting, or other evidence of fatigue.

As a result of the success of the alternate method for unfilling Lens 16, a new procedure was written which should eventually appear as a pbar note [2].

Reference

1. A Practical Method for Unfilling a Solid Lens, pbar Note 664, A. Leveling, 6/4/01
2. Revised Unfilling Procedure for Solid Lithium Lenses, draft pbar Note xxx, A. Leveling, 6/3/03
3. Test Station Power Supply Evaluation, draft pbar Note xxx. A. Leveling, 6/1/03