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Liquid nitrogen historical and current usage of the central helium liquefier at SNS

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Abstract. The main cryogenic system for the Spallation Neutron Source (SNS) is comprised of a 4-K cold box, a 2-K cold box, six warm compressors, and ancillary support equipment. This system has been cold and operating with little disruption since 2005. Design and operation of liquid nitrogen (LN2) supplied from a single 20,000-gallon supply Dewar will be discussed. LN2 used to precool the 4-K cold box heat exchanger started to increase around 2011. LN2 Consumption during 2012 and 2013 was almost double the nominal usage rate. Studies of this data, plant parameter changes to respond to this information, and current interpretations are detailed in this paper. The usage rate of LN2 returned to normal in late 2013 and remained there until recent additional changes. Future study plans to understand potential causes of this including contamination migration within the 4-K cold box will also be addressed.

1. Introduction

The cryogenic system for the SNS Linear Accelerator (linac) is comprised of a 4-K cold box, a 2-K cold box, six warm compressors, eight helium gas storage tanks, a 20,000 gallon liquid nitrogen storage tank, a 7000 liter liquid helium storage Dewar and a transfer line distribution system. Approximately 120 grams per second of supercritical helium is supplied to the cryomodules in the primary supply passage of the transfer line. Flow then goes through a Joule Thomson valve where the pressure drops to approximately 40 millibar resulting in superfluid helium in the 23 cryomodules. The 4-K cold box also supplies a secondary helium flow to cool the fundamental power couplers resulting in approximately 6 g/s of liquefaction load and shield cooling in the temperature range of 30 K to 50 K [1].

This system has been cold and operating with little disruption since 2005. While individual cryomodules in the tunnel have been warmed to 300 K, the plant has never been outside of normal operating temperatures for an extended period. Even summer and winter accelerator maintenance periods require the cryogenic system to maintain the cryomodules in the linac at 4.5 K. The system is continuously monitored for impurities in the helium flow to detect either air from the sub-atmospherics sections of the linac or oil vapors from the warm compressors. These contaminants would freeze solid onto cold surfaces within the cryogenic system.

Liquid nitrogen is supplied from a 20,000 gallon storage Dewar to two points in the SNS cryogenic system. The majority of nitrogen flow is supplied to the nitrogen helium heat exchanger within the 4-K cold box. A small fraction of the system usage of LN2 goes to cool the motors of the cold

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compressors located inside the 2-K cold box. The saturated vapor exhaust from this liquid bath cooling is combined with the nitrogen vapor within the 4K cold box and vented to atmosphere.

Figure 1 shows the EPICS control screen for the LN2 cooling section of the SNS 4-K cold box. Nitrogen supply to the 4-K cold box comes from two locations, shown as “LN” and “VN” in figure 1. The total amount of LN2 supplied to the 4-K cold box is determined by the PV31409 valve position. The control loop that operates this valve attempts to regulate the high pressure helium temperature exhaust from heat exchanger (HX) 410-B as read by TD31310. The design of the LN2 circuit for the SNS cold box differs from both of Thomas Jefferson National Accelerator Facility’s (TJNAF) 4-K cold boxes. In those designs, HX 410-B LN2 flow is driven by the liquid head in the phase separator and then vapor is returned to the vapor space of the phase separator [2]. The advantage of the TJNAF 4-K cold boxes is a very steady and controllable level in the phase separator for PV31409 to regulate. The SNS design has a noisy phase separator level due to liquid flash in HX 410-B causing pressure oscillations in the recombined flow path through HX 410-A.

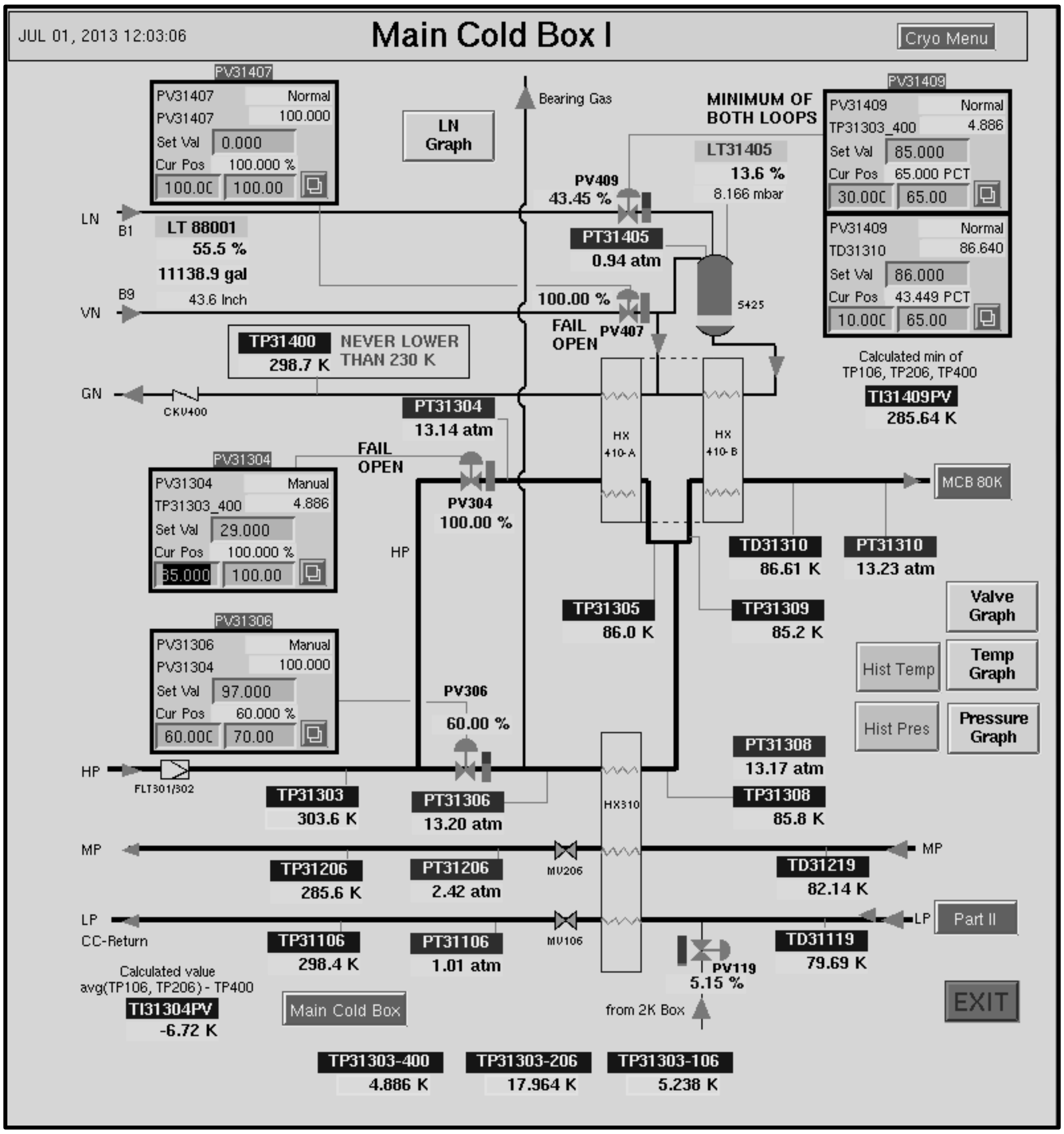

Figure 1. SNS 4K cold box warm end EPICS graphic

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The high pressure helium entering the cold box has two different paths available for cooling. Helium flow that goes through the PV31306 control valve is cooled first by the returning cold helium medium and low pressure circuits inside HX 310 before being cooled by the nitrogen HX 410-B, which is designed to extract the latent heat from the LN2, boiling it from saturated liquid to saturated vapor inside a counter-flow heat exchanger. The flow through PV31306 represents between 88 and 92 percent of the total high pressure helium flow through the warm end of the 4-K cold box.

Helium flow that goes through the PV31304 control valve is cooled first by the nitrogen vapor in HX 410-A, including the nitrogen vapor return from the motor cooling LN2 circuit inside the 2-K cold box, before rejoining the main high pressure flow and being cooled by the two phase nitrogen flow in HX 410-B. HX 410-A is designed to extract the sensible heat from the cold nitrogen flow, taking saturated nitrogen vapor and raising the temperature to just below room temperature. The flow through PV31304 represents between 8 and 12 percent of the total high pressure helium flow through the warm end of the 4 K cold box. The appropriate amount of flow split between PV31304 and PV31306 will be discussed later in this paper.

LN2 is required for the SNS cold box to minimize the number of required turbines, to provide cooling for the liquefaction load imbalance caused by the coupler cooling in the linac, and to recover some of the HX losses given the finite size of the heat exchangers in the 4-K cold box [3].

Oil removal and contamination removal from the SNS cryogenic system is accomplished by three oil coalesce vessels external to the 4-K cold box, an 80-K carbon bed external to the 4-K cold box, a final filter external to the 4-K cold box, and dual 80-K carbon beds internal to the 4-K cold box downstream of the Nitrogen heat exchanger. This purification configuration is shown in figure 2.

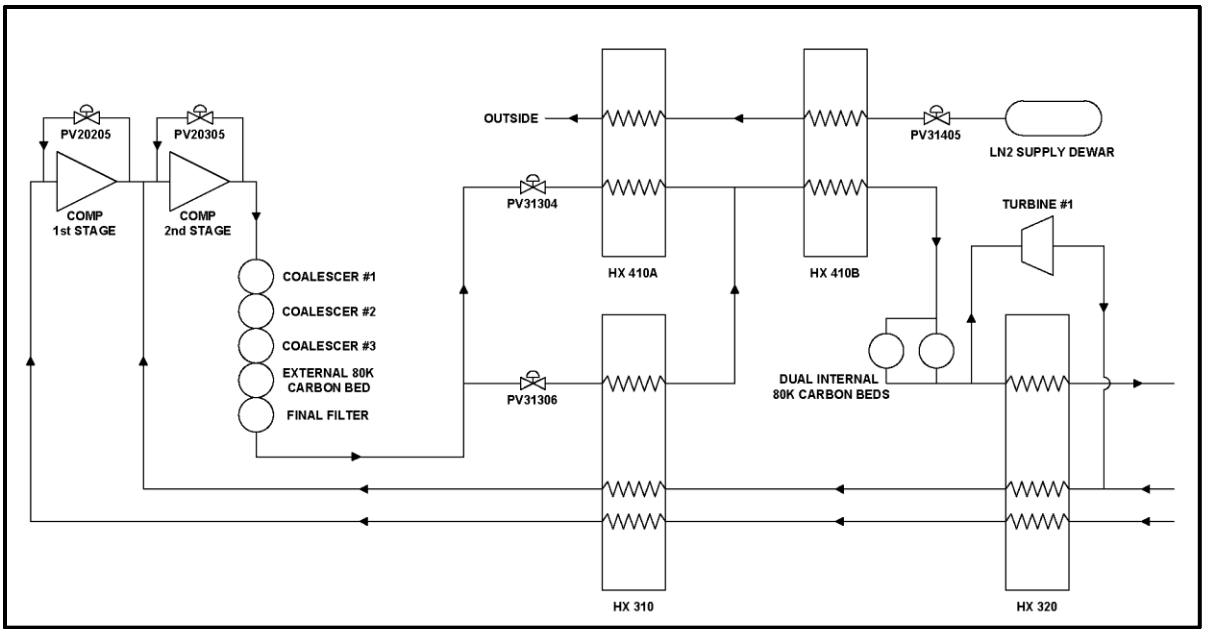

Figure 2. SNS 4K cold box warm end contamination removal scheme

2. LN2 Consumption Studies

At the beginning of 2013, it was discovered that the SNS cryogenic system was using more LN2 than the normal usage of about 3000 gallons per day. There is no flow meter available for tracking the amount of LN2 used in the system. Instead, the volume change of the LN2 storage Dewar over time is recorded and archived to determine a usage rate. Since the Dewar is filled almost daily, the calculation to determine usage rate is accomplished by taking one Dewar level point right after the fill and then one point right before the next fill to give the largest time baseline. Since the Dewar correlation between level and volume is not linear, the level readout in inches at each point is converted to a liquid volume. The difference between these two points produces the gallons per hour rate of LN2 consumption.

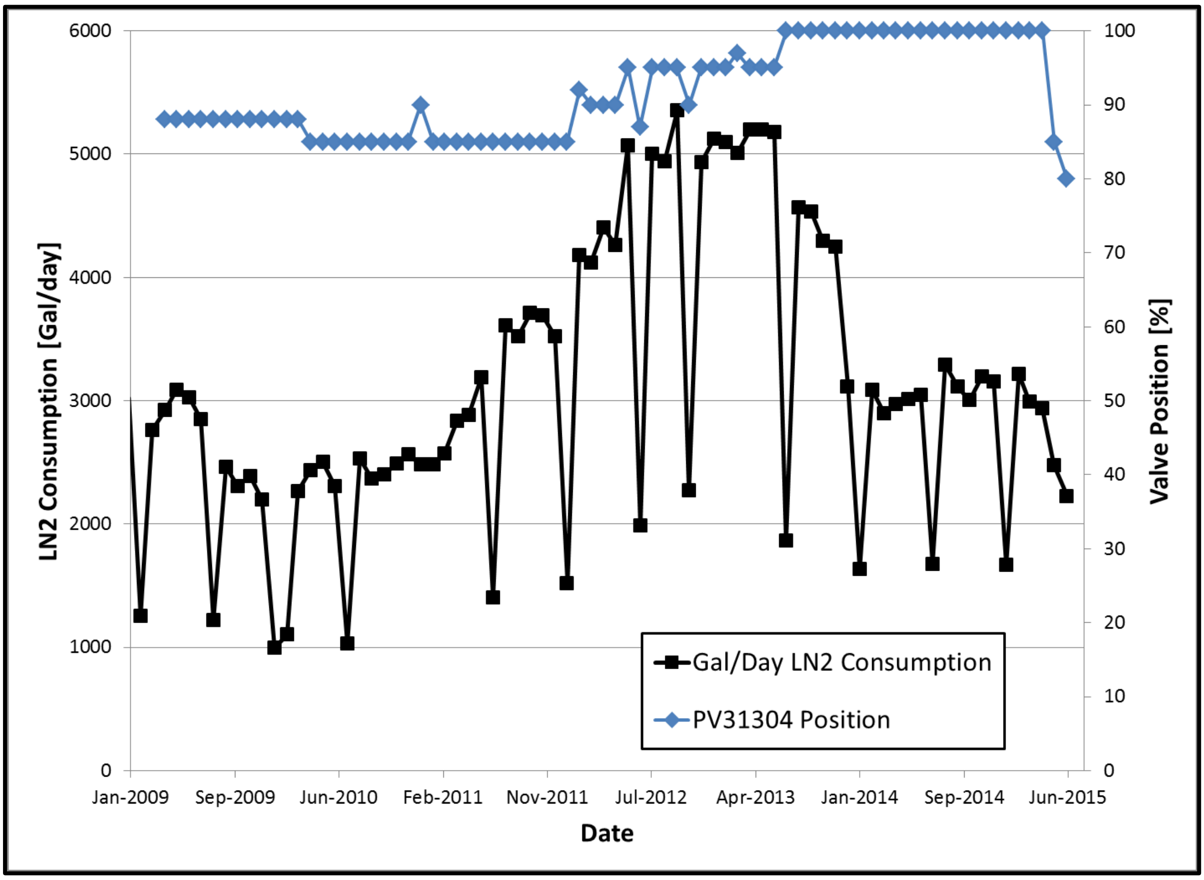

Figure 3. LN2 historical usage and PV31304 valve

Historical data going back to 2009 is collected and the results are displayed in figure 3. This rate does not represent a continuous spectrum of LN2 usage. The data in figure 3 was collected by looking at data surrounding one fill cycle during the first week of every month. This assumes that daily usage of LN2 remains relatively unchanged when compared to trending over several years.

It appears that there are three distinct phases in the LN2 usage rate as documented in figure 3 from 2009 till 2013. Prior to the start of 2011, the usage appears to be stable at around 3000 gallons per day. Periods on this figure where the usage rate is between 1000 and 2000 gallons per day correspond to periods of 4 K operation in the linac.

Sometime during the beginning of 2011, the daily LN2 usage started to climb in a somewhat linear manner from 3000 gallons a day to over 5000 gallons a day around the middle of 2012. After this time, the LN2 usage rate appears to be relatively constant up to studies period in 2013. Both the CHL high pressure on this floating discharge pressure system and the 2-K cold box flowrate were relatively constant during the period between 2009 and 2015. While SNS has sufficient storage capacity to meet a 5000 gallon a day usage rate, this leaves the facility susceptible to small disruptions in LN2 delivery.

In the middle of 2009, a LINDE gas analyzer was installed in the CHL compressor high pressure helium stream which monitors the helium stream for contamination. This analyzer has the capability to look for gaseous Nitrogen, gaseous water, hydrocarbons and aerosolized oil. Operation of this analyzer was cycled between the inlet and outlet of the CHL carbon bed at 3 month intervals. During periods of analysis on the inlet of the carbon bed, nitrogen levels remain relatively constant around 10 ppm, while both water and liquid oil levels were consistently lower than 2 ppm. The aerosolized oil levels were also around 50 ppb. When this analyzer was switched to sampling off the outlet of the carbon bed, all contamination levels were off-scale low. Only one minor spike in nitrogen contamination was observed in January 2012. This spike is related to depressurizing the system to fix the helium to air leak on the CHL high pressure header. No other abnormal system contamination levels have been observed during the service life of the analyzer. It has been noted that this style of LINDE gas analyzer is susceptible to providing false negative reading of oil contamination levels [4].

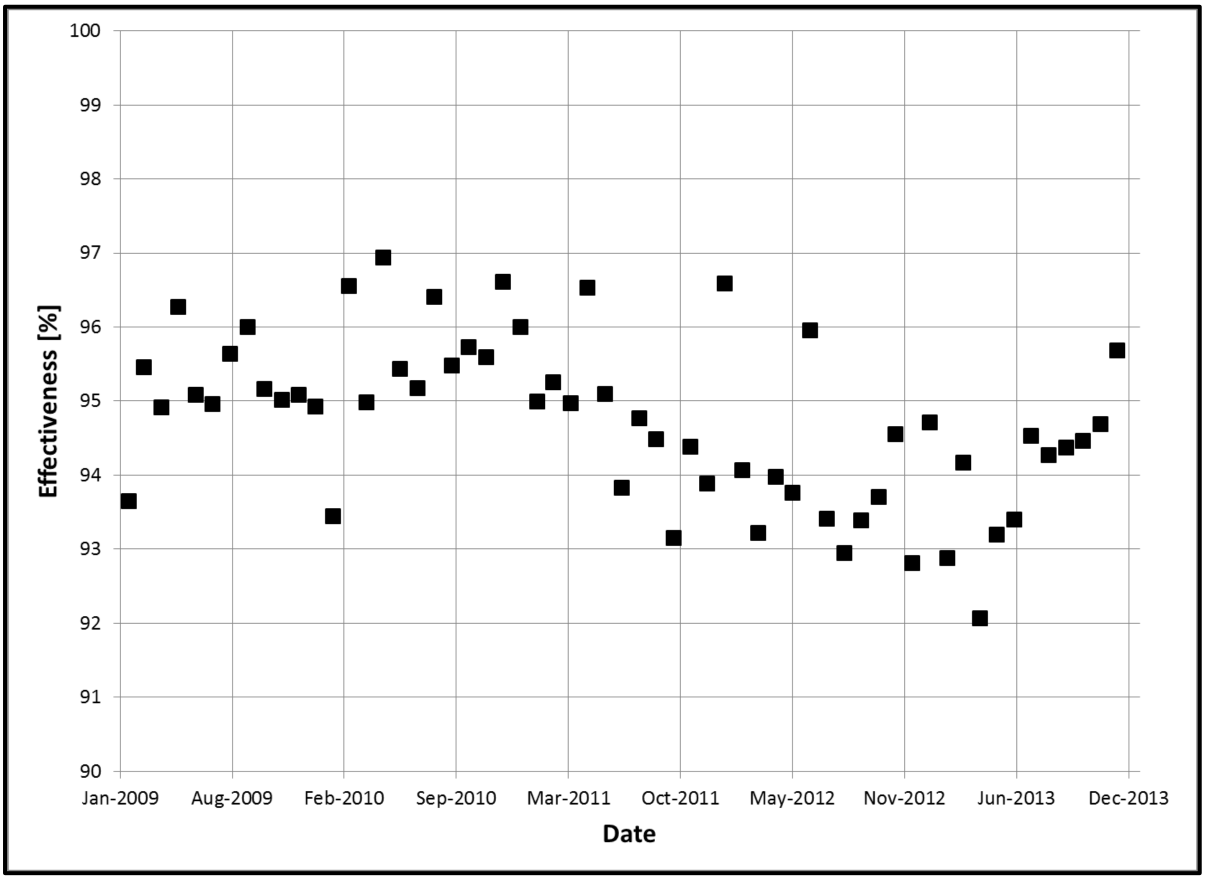

Figure 4. HX 310 effectiveness historical trending

A data mining and analysis effort was undertaken to determine if any heat exchanger in the CHL 4-K cold box was showing a decrease in performance. The SNS 4-K cold box heat exchangers have two low pressure streams, meaning the effectiveness for each flow has to be calculated separately, with the final effectiveness calculation for the heat exchanger encompassing both pressure streams. In order to calculate this effectiveness, a benchmark or ideal condition for the heat exchanger flow is established. The actual amount of heat transferred in watts is compared to ideal condition where the outlet temperature reaches this standard. For HX 310, the ideal temperature is assigned as the incoming high pressure helium stream as read by TP31303.

The effectiveness trending for the main warm end heat exchanger, HX 310 does show about a 2% decrease over the time period. The inflection points of the HX 310 efficiency plot shown in figure 4 seems to roughly correspond with the inflection points in the LN2 usage rate plot shown in figure 3 above. Again this data was collected around the first of every month going back to around the beginning of 2009. The effectiveness of the heat transfer inside the heat exchanger seems to start dropping from 95% around the beginning of 2011 and seems to stabilize around 93% around the end of 2012.

It is plausible that a decrease in effectiveness of 2-3% in HX 310 would account for the increase in LN2 usage rate. A 2% drop in HX effectiveness results in about 19 kW less heat transfer between the low/medium pressure circuits and the high pressure circuit. Since the latent and sensible heats of Nitrogen between saturation temperature and 273 K is 405.5 J/g, this would require an extra 48.7 g/s of LN2 to offset the loss in effectiveness. This equates to an additional 1489 gallons of LN2 a day. If instead there is a 3% drop in heat exchanger effectiveness, this would require an extra 2234 gallons of LN2 a day. Similar performance degradation was not observed in any of the other heat exchangers in the SNS 4-K cold box. This possibly indicates that there is some level of contamination buildup not observed by the gas analyzer. Future testing will be conducted to determine the level of contamination required to produce this observed degradation in performance.

At the beginning of the 2013 summer maintenance down, a week long test was conducted to investigate the 4-K cold box consumption of LN2 while the linac remained at 2 K. This week long testing period was not intended to answer the questions of why the LN2 usage increased over the past few years, but rather to restore or reduce the LN2 usage rate.

A testing plan was developed that revolved around three different adjustments that could be made to the 4-K cold box: changing the PV31409 loop set point and monitoring the three platinum resistors downstream of TD31310, changing the turbine 2 inlet valve loop to control off the B-side exhaust diode, and varying the flow split through PV31304 and PV31306 to find an optimal flow split. After each adjustment was completed, the system was allowed to stabilize overnight and a LN2 usage measurement was taken. Immediately prior to the testing week, a usage data point was taken as a baseline and resulted in 218.0 gallons per hour.

The PV31409 loop has historically been regulating PV31310 to 81 K. There was some discrepancy between the read back of TD31310 and the three platinum resistors TP31312B, TP31316B and TP31318B on the 80 K adsorber which have historically been reading about 77 K. The goal of adjusting PV31409 was to see if there was a corresponding increase in TP31312B when TD31310 was elevated. The first adjustment was made to the PV31409 loop on Monday morning. The loop was changed to regulate to 82 K. Almost immediately, a response on the downstream platinum resistors was observed. The cycle of raising the PV31409 loop set point and monitoring the downstream temperature change repeated until TP31312B read close to 81 K.

Aside from small changes immediately after the loop adjustments, the valve position of PV31409 remained largely unchanged. This would suggest that these changes had a relatively minor effect on the LN2 usage rate. There was also very little response from the remainder of the plant in response to this increase in PV31409 loop regulating temperature. The only observed deviation from normal operating conditions was seen in the turbine 1 inlet valve, which regulates the turbine exhaust to 37 K. This valve opened slightly, presumably allowing more cooling to compensate for the elevated nitrogen exhaust temperature. With TD31310 now being regulated to 86 K and TP31312B now reading 81 K, the system was allowed to stabilize overnight and the following morning the usage rate was determined to be 215.5 gallons per hour.

Changing to the turbine 2 B-side exhaust diode did not occur since when a handheld meter was used to measure the B-side exhaust diode reading prior to making the swap, it was discovered that this backup diode was reading 23 K. With this diode being higher than both the current exhaust reading and the current inlet reading, it was decided to not make any change.

The flow split through PV31306 and PV31304 was then studied. The first night was spent with PV31304 at 100% open and PV31306 at 40%. The following night was spent with PV31304 at 80% open and PV31306 at 70%. Neither experiment yielded much improvement over the baseline. However, it was noticed during the slow transition between those two operating modes that the LN2 supply valve PV31409 appeared to have a minimum position when PV31304 was still at 100% and PV31306 was passing through 60%. The usage rate with this new optimum was 189.4 gallons per hour.

As seen in figure 2, the LN2 usage rate with these adjustments for the entire CHL system slowly decreased during the next 2-K operational period in the linac until usage appeared to return to the

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nominal system usage level of about 3000 gallons per day. This usage rate held steady until the next round of LN2 usage optimization studies in 2015.

3. Current LN2 Consumption Status

In March of this year, process parameters surrounding the LN2 cooling circuit have been analyzed. Two things stood out as not optimized: first the inlet valve to the first turbine in the 4-K cold box was only operating at about 70% and second the differential temperature between the high pressure helium inlet temperature and the medium pressure cold box outlet temperature was between 12 and 15 K. Ideally this differential temperature should be between 7.5 and 9 K [3].

In order to rectify both these issues, further adjustments were made to the PV31304 and PV31306 valve flow split. This time PV31306 was opened 100% while PV31304 was set to 85%. This change yielded a usage rate of 103.2 gallons per hour and a differential temperature of about 8.5 K. After a month of this mode of operation, further reduction in PV31304 position yielded further reduction in usage to 92.8 gallons per hour and a differential temperature of 7.5 K. The differential temperature and valve positions are shown in figure 5. While currently both valves are fixed, further development will occur to have PV31304 slowly regulate to maintain a differential temperature.

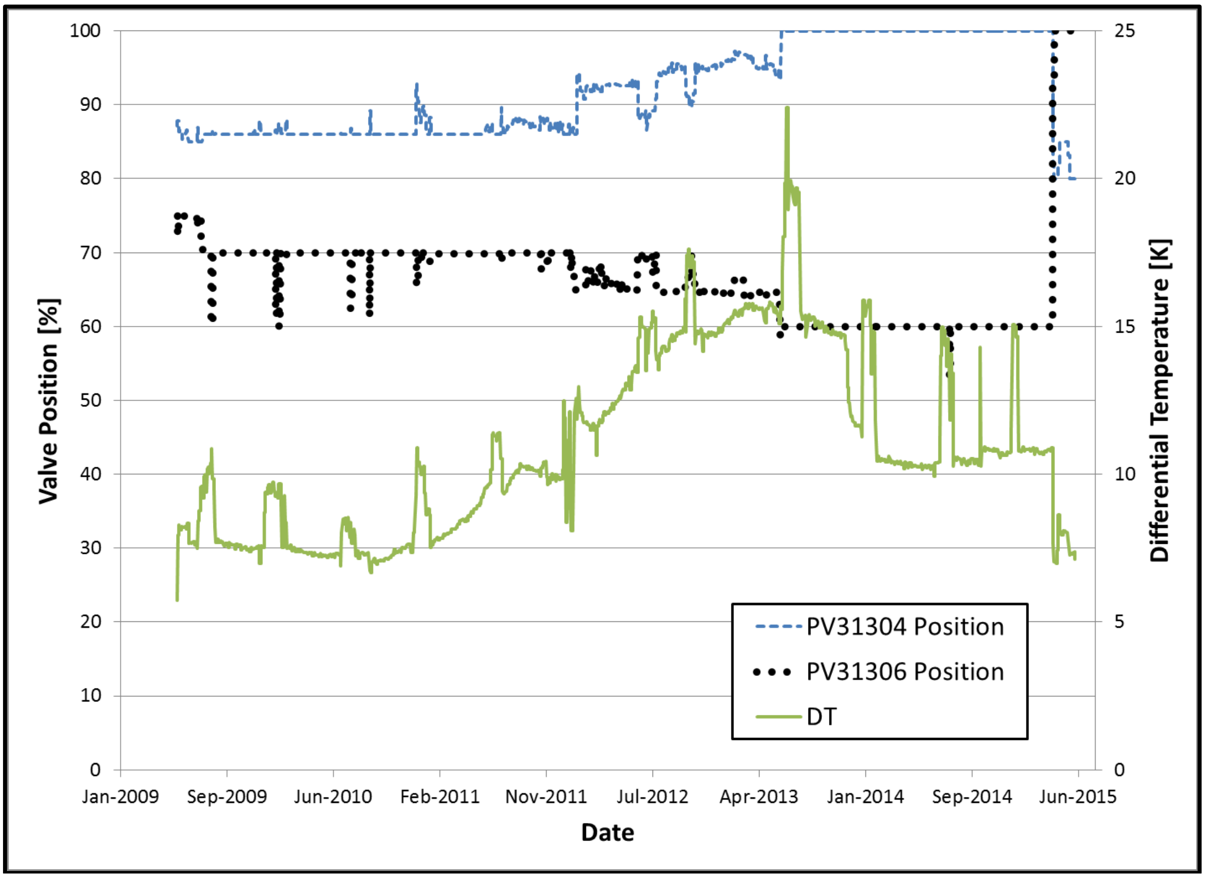

Figure 5. CHL 4-K cold box warm end differential temperature

This most recent change did also have the effect of increasing the flow through first turbine in the 4-K cold box. The inlet valve is now open about 85%. While normally this would increase the power consumption of a plant, the SNS compressors operate fully loaded with bypass flow to maintain medium and low pressure headers at the correct pressure. Therefore there is no consequence to shifting the cooling load from the nitrogen circuit to the first turbine since the same amount of compressor power is used in both scenarios. It should also be noted that this new mode of operation also produces an acceptable nitrogen exhaust temperature of 283 K.

4. Future Experiments

Given the critical nature of the 4-K cold box performance to the overall SNS linac performance and the budget and delivery realities of having excess LN2 consumption, a future experiment is being planned to study the possibility of having contamination migrate to various positions within a continuously cold LN2 cooled heat exchanger. The design of this test vessel to support this testing is underway. This vessel will incorporate a small LN2 Dewar, helium heat exchanger, and appropriate instrumentation. The goal of this vessel's design will be to inject impurities into the helium flow and monitor how the helium pressure drop changes over time.

5. Conclusion

The testing performed during the first week of the 2013 maintenance down successfully decreased the LN2 usage rate by 39%. This equates to a real savings of 2100 gallons of liquid nitrogen per day. The changes made to PV31304 and PV31306 in March of 2015 has reduced the LN2 consumption by another 32%. This equates to a real savings of another 1000 gallon of liquid nitrogen per day.

There does appear to be evidence that HX 310 has degraded, but the source of the HX 310 degradation is not obvious. One possible explanation for this performance degradation could be the result of contamination migration within the cryogenic system, but the online contamination monitoring did not record any increase since 2009. Additional monitoring of the performance of all components located inside the 4-K cold box will continue. It is intended that the future experimentation utilizing the custom Dewar, currently under design, will help determine the cause of the temporary increased nitrogen usage.

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