MOCK-UP TO SIMULATE PIPE FREEZING IN SHUTDOWN COOLING ROOMS

M. A. Aamir, D. Creates and P. Bekeris
Ontario Power Generation, Pickering, Ontario, Canada

Abstract

In order to repair/replace isolation valves in the Shutdown Cooling (SDC) Rooms inside the Reactor Vault, three ice plugs are required to provide the necessary isolation. An attempt was made in 2001, but the ice plugs formed could not provide work protection for the replacement of the isolation valve as the jackets were not full and there was no Liquid Nitrogen (LN2) visible at the jacket vents.

The mock-up was carried out using new hoses and arrangement, which allowed LN2 to arrive at the freezing jackets 32 minutes from the start. Within 125 minutes of the first LN2 observed at the jacket, the first ice plug (10”) was called and the second ice plug (8”) was formed 78 minutes later, while maintaining the first ice plug. Both ice plugs were successfully called within 4 hours and 42 minutes from the first start of the LN2. This mock-up also measured the amount of LN2 required to maintain the two ice plugs being 20% lower than the OP&P limit of 250 kg/h.

1. Introduction

Liquid Nitrogen (LN2) is used to form ice plugs on system piping that does not have valves or other means of isolation for maintenance of line equipment. The Shutdown Cooling (SDC) System is a prime example of a system that requires ice plugs to isolate portions of the system to enable maintenance. In order to form the ice plugs in the SDC rooms, LN2 hoses are run from the penetration on the 100 m elevation (ground level) North side, through the vault and down to SDC rooms at elevations 92.5 and 87.7 on the South side.

An attempt was made in 2001, when the amount of LN2 hoses used were in excess of 350 feet in length. Due to the excessive length of LN2 hoses that were required to reach the SDC Rooms and the reduced LN2 flow, the LN2 “boiled off”, which caused the temperature of the ice plug to fluctuate between -190°C and -150°C and work protection could not be established.

Simple fluid flow calculations presented in Reference [1] showed that large size hoses with improved insulation can prevent the boil off, reduce the two-phase pressure drop and thus provide LN2 to the jackets over the required distance. A mock-up was set up to test the new hoses, proving the success of the engineering solution to a complicated problem.

2. Mockup Specification

Based on the recommendations presented in reference [1], new ¾” and 1½” hose assemblies were specified, while remaining within the realm of the registered system. Hence no modification was required. Two important features required in the specification were the pressure drop and insulation. The specification requires that the pressure drop at 70°F in the $1^1/_2$” hose must be less than 0.02 psi/ft and in the $^3/_4$” hose is less than 0.03 psi/ft at the flow rate of 10 gpm of water. Furthermore, the hose assemblies are required to include 1” to $1^1/_2$” thick insulation on the hose surface (depending on the hose size), the thermal conductivity of which should be less than 0.27 Btu-in/h ft^2 °F (0.039 W/mK) at an average insulation temperature of 24°C and a lower use temperature limit of -183°C.

Neoprene insulation is used to satisfy these requirements, and is a better insulator and weighs less than the silicone foam.

The assembly of the pipe freezing equipment was required to simulate the concurrent formation of ice plugs in 8” and 10” pipes in the SDC rooms at elevations of 87.7m and 92.5m respectively. The mock-up would be deemed a success by meeting the following requirements:

- LN2 visible at the vents during and after the formation of the ice-plug.
- Forming ice plugs successfully on the 8” and 10” test stands and maintaining them.
- Meeting the OP&P limits for LN2 input into containment of <250 kg/hr long term.

3. First Attempt: Successes and Failures

The mockup was setup to simulate the actual hydraulic conditions to form ice plugs in the SDC rooms as shown in Figure 1. The LN2 tanker was staged outside in the corridor at 100 m elevation.. The hoses ran through the doors, up the scaffold and down the stairs to the header located at 92.5 elevation. From the header, hoses ran to the 8” and 10” test stands at 92.5 m elevation and 87.7 m elevation respectively. The ventilation from the jackets was attached to the vents at 87.7 m via flexible hoses.

Liquid Nitrogen was turned on with a tanker pressure of 17 psig. In 25 minutes, the hoses were cooled down and the liquid nitrogen was visible at the vents of the freeze jacket. This was a huge engineering success to be able to get the liquid nitrogen to the jackets at a distance of greater 110 m (360 ft) in such a short time.

Within 10 minutes of first liquid at the freezing jacket, it was obvious that too much liquid was being sent to the jacket. Later calculations showed that the flow of liquid nitrogen, which was 6 L/minute during the cooldown of hoses jumped to 27 L/minute during the initial plug formation phase, once all the vapor was flushed out of the system. Attempts were made to control the flow of the liquid nitrogen by reducing the tanker pressure to 15 psig and closing down the control valves at the two headers to less than one turn open. These attempts reduced the liquid nitrogen to a controlled flow of 8 L/min. But the initial uncontrolled flow led to the choking of the vent and the liquid nitrogen started to spill on the floor and created a hazard. There were also concerns that if continued, it would be even more difficult to control the flow of LN2 to the 10” ice plug once the 8” ice plug was started. 67 minutes from the start, the LN2 supply was turned off. The thermocouples recorded temperatures of -103 °C and -162 °C on the top and bottom ends of the pipe under the jacket, when the LN2 supply was stopped.

4. Second Attempt: A Success Story

In order to get the control over the LN2 flow, the mockup assembly was simplified to add some resistance to the flow. The simplified assembly for the second attempt is shown in Figure 2. ¾" hoses were used to connect the Volvo tank to the header, which also connects TK1. This offers simple control and switch over capability from the tanker to TK1, if required. Single hoses were run from the header at 92.5 m elevation to the freeze jackets at 92.5 m and 87.7 m elevations. A ¾" y-connector was used to connect the 1½" hose to the two inlet ports of the jacket. This configuration allows single valve control of LN2 to the freeze jackets and simplifies the control.

Liquid Nitrogen was turned on again with a tanker pressure of 17 psig. In 32 minutes, the hoses were cooled down and the liquid nitrogen droplets were visible at the vents of the freeze jacket. This met the first success criteria mentioned in section 2. An average flow rate of 3.66 L/min of LN2 was observed during the initial cool down phase. Within 125 minutes of the first LN2 observed, the 10" ice plug was called on the basis of the measured temperature of the pipe under the jackets being below -180 °C. An average LN2 flow rate of 6.3 L/min was used to form the ice plug.

The 10" ice plug was maintained for 47 minutes before starting flow to the 8" freeze jacket. The second ice plug was formed in 78 minutes. An average consumption rate of LN2 to form the 8" ice plug, while maintaining the 10" ice plug, was 8.4 L/min. It is a great victory for team work that both ice plugs were called within 4 hours and 42 minutes of the first start of the LN2 as compared to more than 24 hours in both of the previous attempts in 2000 and 2001.

Both ice plugs were maintained for 72 minutes using the LN2 tanker with an average LN2 consumption rate of 4.4 L/min or 214 kg/hr (calculated at atmospheric pressure with a LN2 density of 803 kg/m3). The supply was switched to the small tanker, TK1 and the two plugs were maintained using TK1 for 100 minutes. The average LN2 consumption rate using TK1 to maintain 8" and 10" ice plugs was 4.5 L/min or 217 kg/hr (calculated at atmospheric pressure with a LN2 density of 803 kg/m3). Following are some of the pictures of the successful mockup.

5. LN2 Consumption

The LN2 consumption varies during the ice plug formation and is also different when maintaining the ice plug. When the LN2 flow is first started, it is vaporized to cool down the hoses and the N2 gas provides enough resistance to flow. Since the only place the gas can escape is from the jacket vents, a flow is established.

Once the hoses are cooled down, the heat gained by LN2 decreases considerably and LN2 manages to reach the freezing jacket in the liquid phase. Some of the liquid which enters the jacket is entrained in the vapor emitting from the jacket and droplets of LN2 become visible at the vent. This is the start of the ice plug formation stage.

Once the ice plug is called, LN2 is still required to maintain the ice plugs and keep the freezing jacket full. This is done by manually throttling the upstream valve to decrease the flow of LN2 to the jackets.

5.1 During Cool Down of Hoses

During cool down of the hoses and freeze jackets in the 1st attempt, 145 L of LN2 was consumed in 25 minutes at an average rate of 5.8 L/min. In the second attempt 117 L of LN2 was consumed in 32 minutes at an average rate of 3.66 L/min. The amount of hoses to be cooled was less in the second attempt and therefore less LN2 is consumed. Figure 11 shows the variation of consumption rate with time for the second attempt, which almost increases exponentially with time, and stops when the jacket is full and the valve is throttled. At the start a lot of vapor is generated, which develops a back pressure and provides enough resistance to flow. As the vapor generation decreases within the cooled down hoses upstream, the back pressure decreases and the consumption rate increases.

5.2 10" Ice Plug Formation

Figure 12 shows the LN2 consumption rate while forming the 10" Ice Plug. Once the lines are cooled down, LN2 is visible at the vents and the control valve at the second header is throttled back to prevent wastage of LN2. During the formation of the ice plug, the LN2 consumption rate continues to be constant around 230 kg/hr between 28 and 82 minutes of 10" ice plug formation shown in Figure 12.

After 82 minutes the temperatures measured were -179 °C and -132 °C at the bottom and the top ends of the pipe under the freeze jackets. At this time, the circumferential frost line was significantly visible on the pipe near the freeze jacket end which hosted the vents predicting that ice plug might had established at this end .This is a normal phenomenon, where the ice plug first forms near the vents and the grows axially. Once this happens the boiling of the LN2 in the freeze jacket dramatically decreases, producing less resistance to the LN2 path and therefore, results in an increase of the consumption rate. This is the time when the control valve is throttled the second time to minimize the LN2 wastage, which shows as a decrease in the consumption rate towards the end. The 10" ice plug is called 125 minutes from the start of the ice plug formation and 157 minutes from the start of LN2 flow.

5.3 8" Ice Plug Formation, while maintaining 10" Ice-Plug

There was a 47 minutes lag between the time when 10" ice plug was called and LN2 was started to the 8" freeze jacket. 392 L of LN2 was consumed during this time at a rate of 400 kg/hr. This was because the valve on the line providing LN2 to the 10" ice plug was not throttled enough. But it was throttled further before LN2 was started to the 8" freeze jackets.

Figure 13 shows the LN2 consumption rate which was nearly constant at approximately 400 kg/hr during the formation of 8" ice plug, while maintaining the 10" ice plug. There were no means available to measure the LN2 flow exclusively to the 8" ice plug, which was called 78 minutes from the start of LN2 to the 8" freeze jacket and 282 minutes (4 hours 42 minutes) from the first start of the LN2 flow.

5.4 Maintenance of 8" and 10" Ice Plugs

The 8" and 10" ice plugs are first maintained by the Volvo tanker as the flow from the tanker is continued following the formation of ice plug. Figure 14 shows the LN2 consumption rate while maintaining the ice plugs using the Volvo tanker.

Both 8" and 10" valves are throttled to provide just enough LN2 to the ice plugs. When that happens in the manual control (or a simple proportional controller), the valves are first throttled back (0-37 minutes) to decrease the LN2 flow rate. The valves were then open a bit to increase the flow rate (~37-45 minutes) and then throttled back to give a steady state flow rate (45-72 minutes). An average consumption rate during this period when ice plugs are maintained using Volvo is 214 kg/hr, while the end point (steady state flow) in Figure 14 is at 216 kg/hr.

After using the Volvo tanker to maintain the 10” and 8” ice plugs for 72 minutes, the supply is switched to the TK1. There is 2 minute overlapping period. Figure 15 shows the LN2 consumption rate while maintaining the ice plugs using TK1.

The initial higher rate of consumption is attributed to the switch over affect. Following that, the consumption rate is approximately steady. If the 1^{st} data point is taken into account, then the average consumption rate using TK1 is 217 kg/hr.

If the first data point is ignored, then the steady state flow required to maintain the two ice plugs comes out to be 194 kg/hr, whereas the last two data points are at 159 kg/hr and 175 kg/hr. Therefore it has been shown that the LN2 flow rate into the containment will be lower than the OP&P limit of 250 kg/hr.

6. Conclusions

The soft solution of new hoses with neoprene insulation proved technically that LN2 can be delivered to multiple freezing jackets at a distance of greater than 350 ft from the source, with large margins to spare. The LN2 was available at the freezing jacket in 32 minutes from the start and an 8” and 10” ice plugs were established in less than 4.5 hours. Not only that, the other requirement that the amount of LN2 required to maintain the two ice plugs be acceptable from OP&P stand point, is shown being approximately 20% lower than the limit.

7. References

[1] Aamir, M. A. *et al*, “Application of the Simple Analytical Approach to Calculate Pressure Drop in Liquid Nitrogen Two Phase Flow over Large Distances Using Hoses”, 29th Annual Conference of the Canadian Nuclear Society, June 2008.

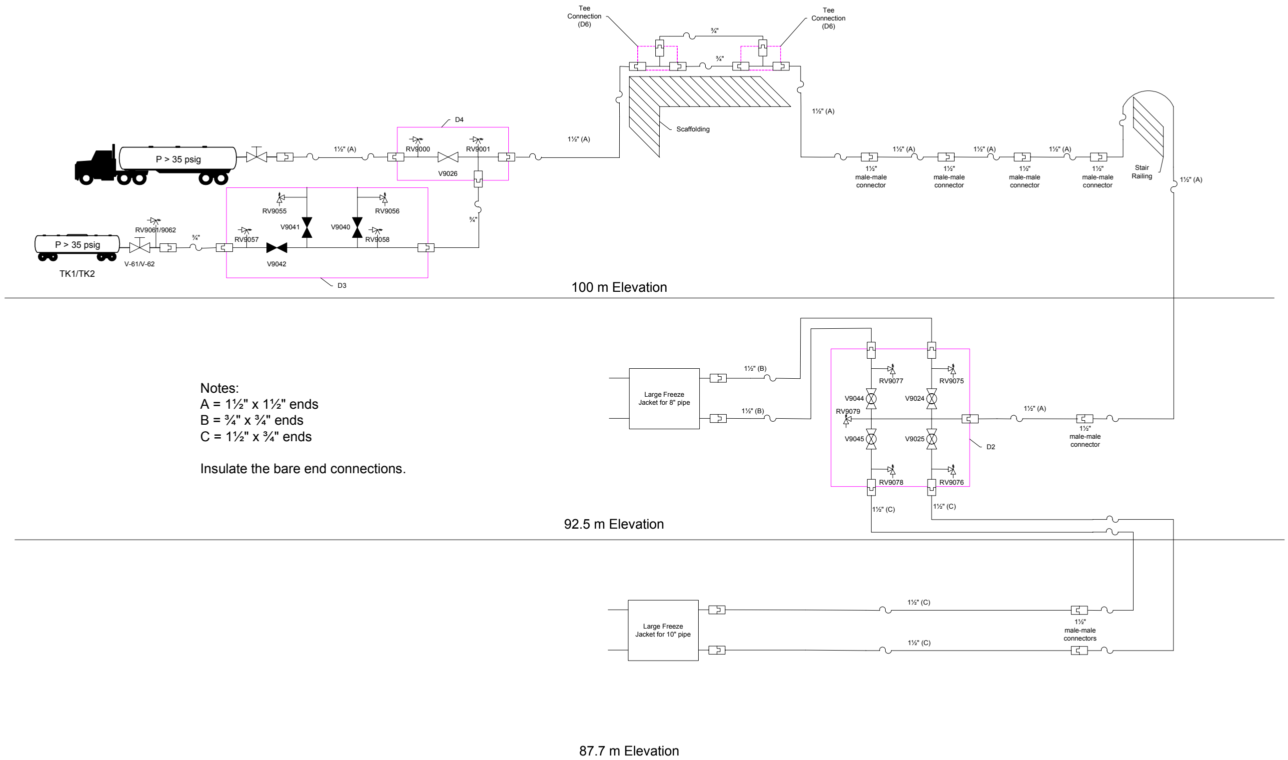

Figure 1: Mockup Assembly for the 1st Attempt

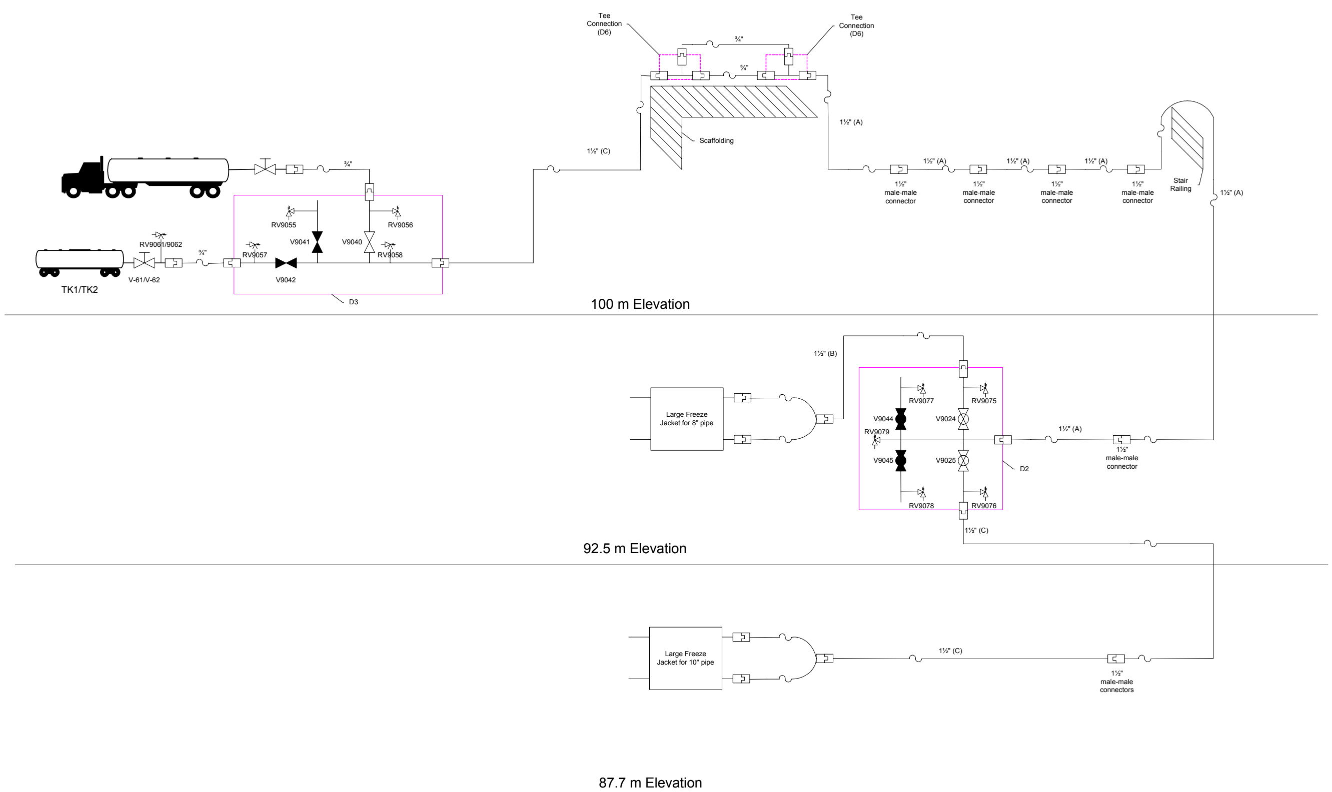

Figure 2: Simplified Mockup Assembly for the 2nd Attempt

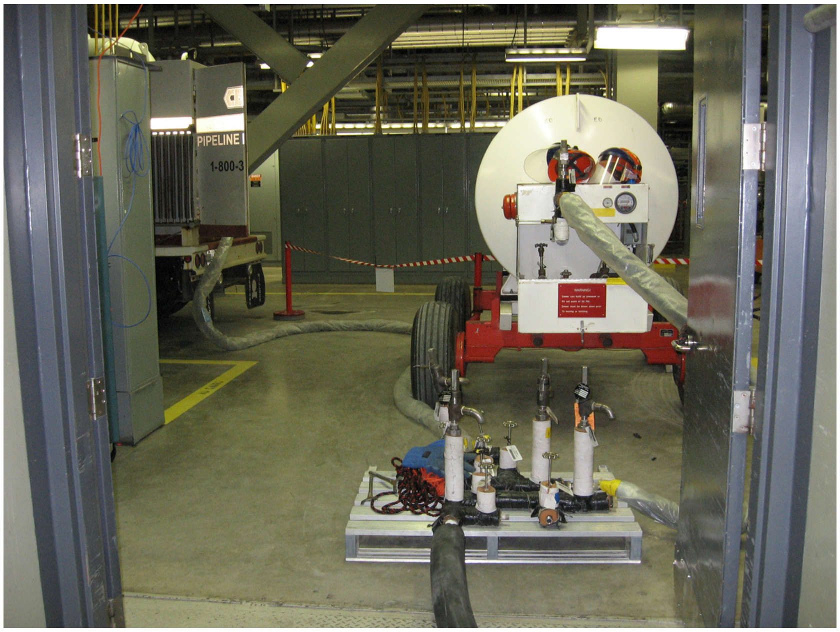

Figure 3: Tanker and TK1 staged outside R-102

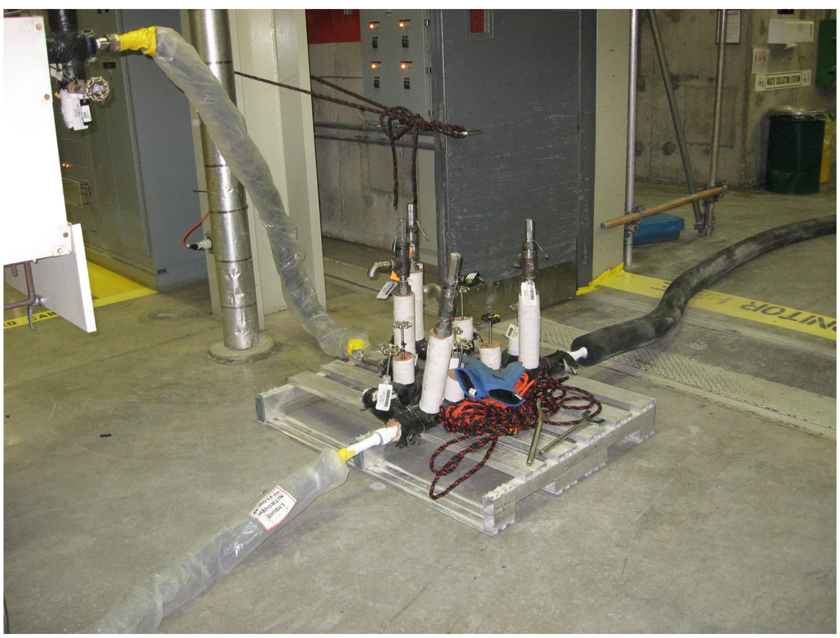

Figure 4: Tanker and TK1 Connected to a Single Header in the Simplified Arrangement

Figure 5: Hoses Run Up the Scaffold to Simulate Containment Penetration

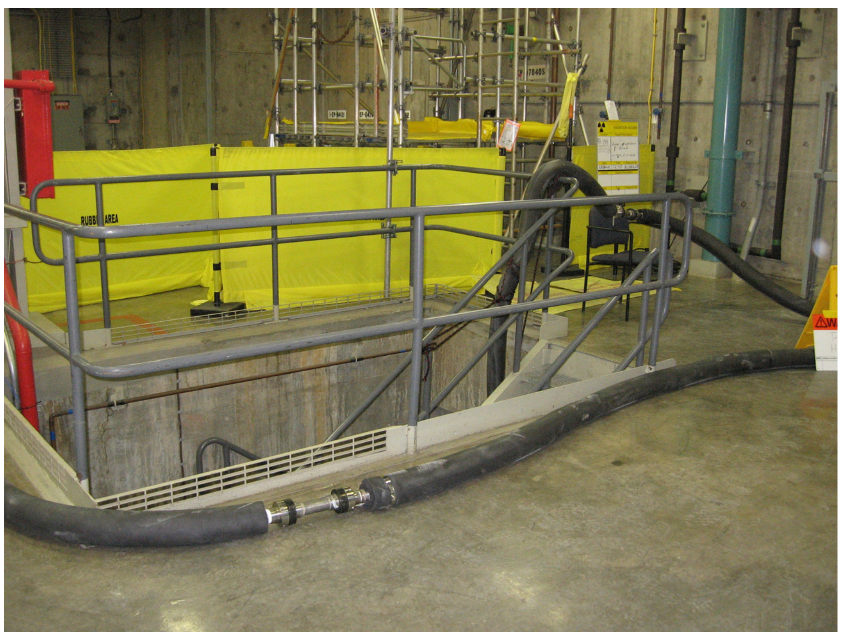

Figure 6: Hoses Run Up the Railing and Down the Stairs to Simulate the Vent Riser

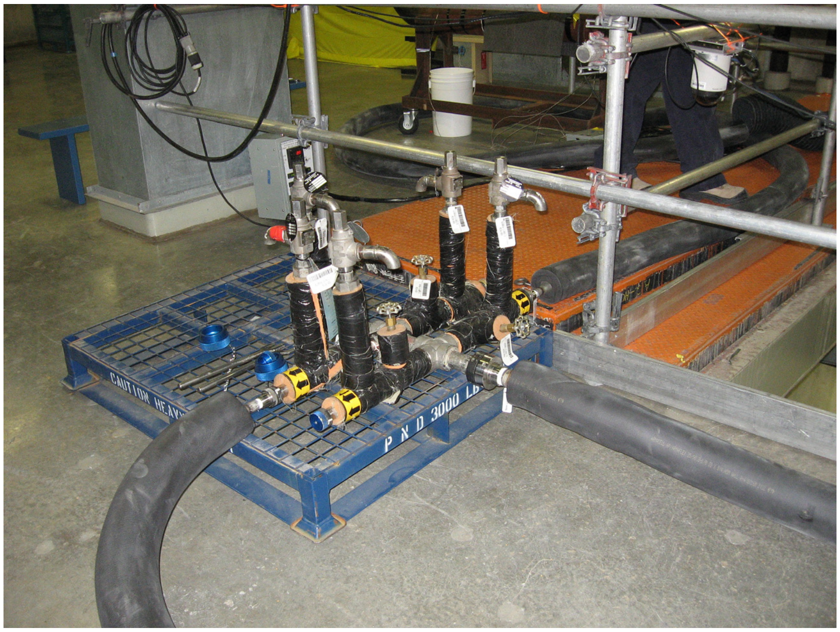

Figure 7: Header at 92.5 m Elevation, Supplying Single Hoses to both Freeze Jackets

Figure 8: Arrangement Ready to form Ice Plug on 10" Test Stand

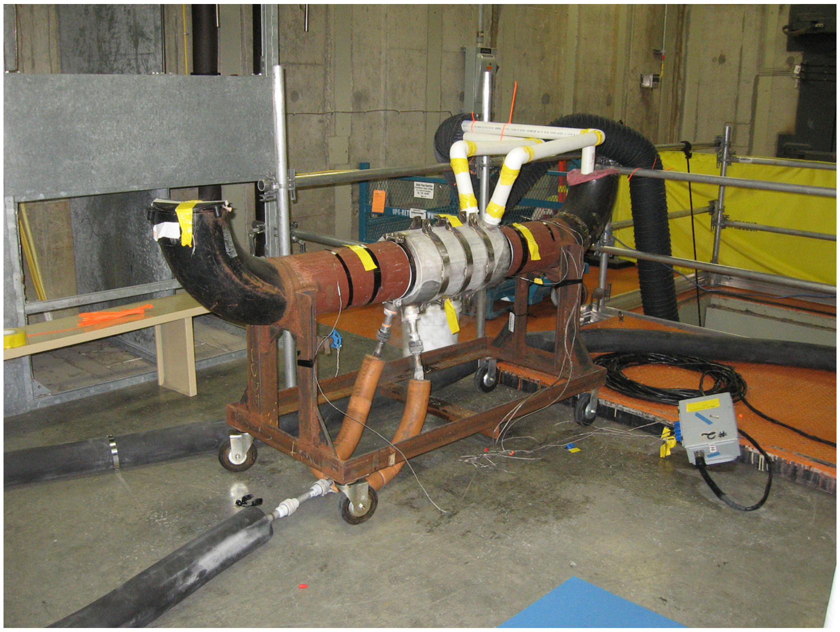

Figure 9: Arrangement Ready to form Ice Plug on 8” Test Stand

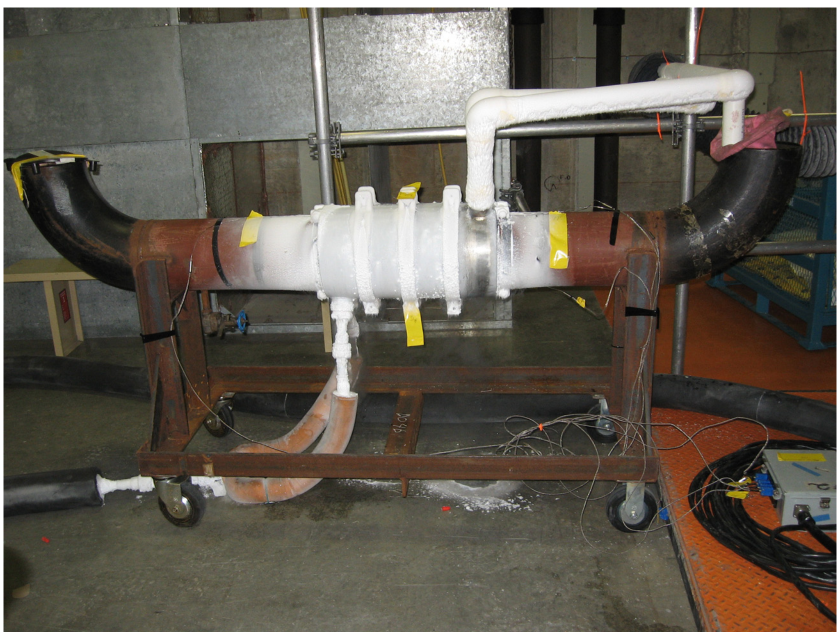

Figure 10: 8” Ice Plug Formed

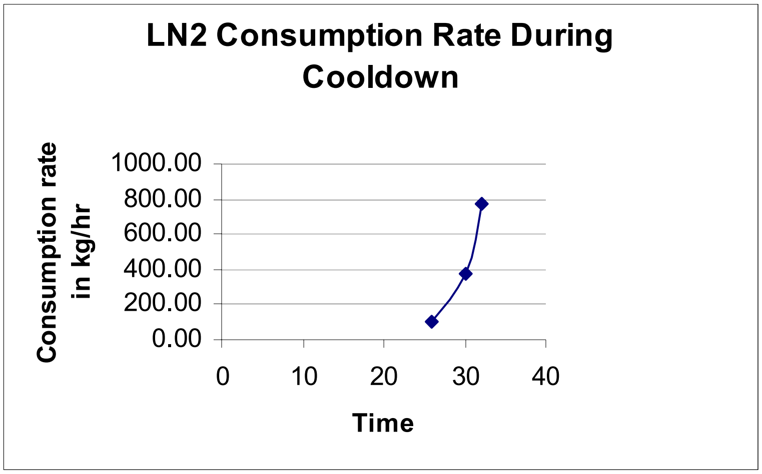

Figure 11: LN2 Consumption Rate During Cool down in the 2nd Attempt

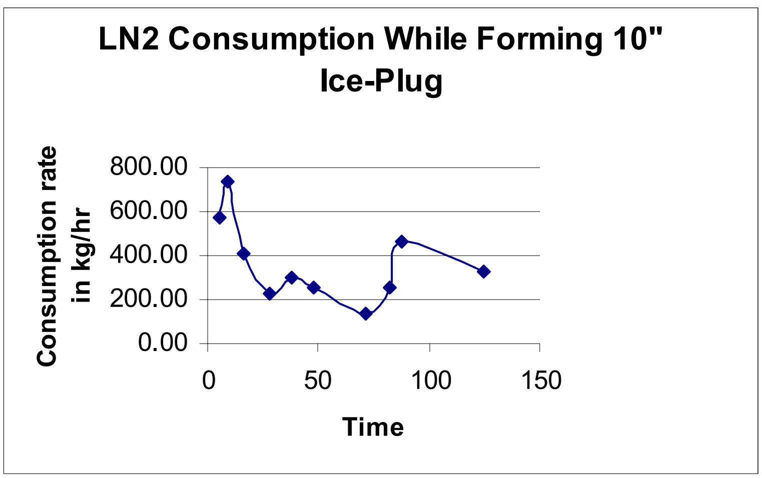

Figure 12: LN2 Consumption Rate While Forming 10” Ice plug in the 2nd Attempt

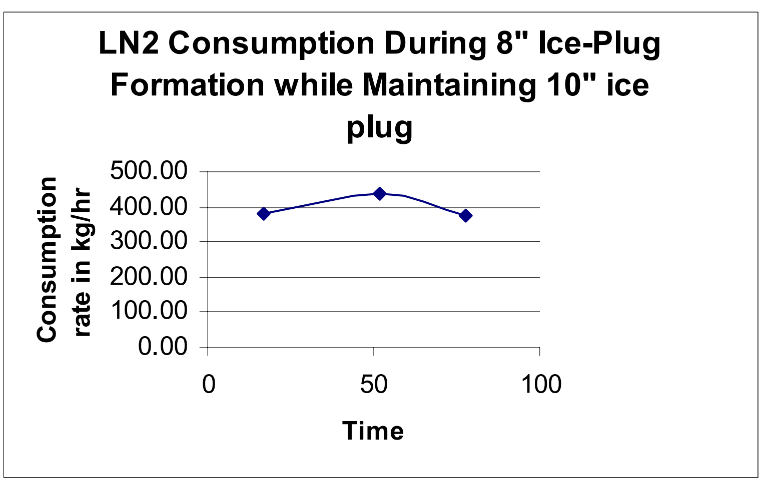

Figure 13: LN2 Consumption Rate While Forming 8” Ice plug and Maintaining 10” Ice Plug

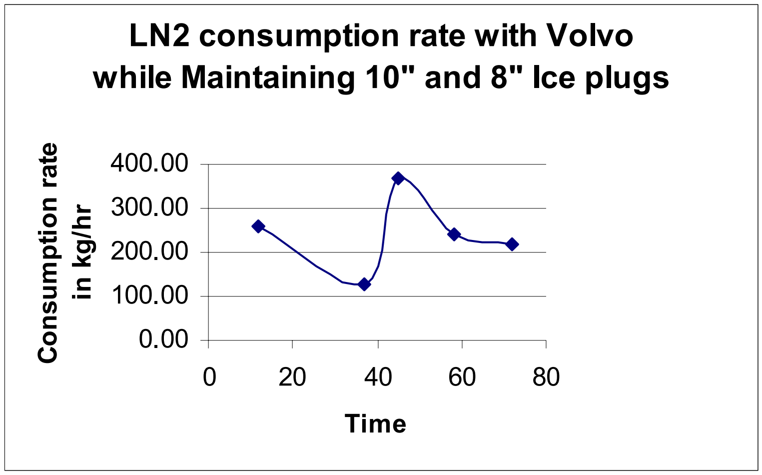

Figure 14: LN2 Consumption Rate to Maintain 10” and 8” Ice Plugs Using Volvo

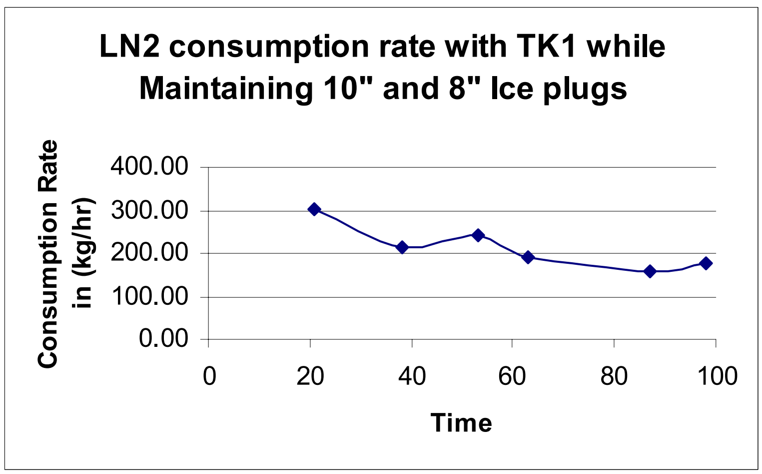

Figure 15: LN2 Consumption Rate to Maintain 10” and 8” Ice Plugs Using TK1