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A CRYOGENIC SYSTEM FOR STABLE ARGON LIQUEFACTION

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A CRYOGENIC SYSTEM FOR STABLE ARGON LIQUEFACTION

By

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A capstone project submitted for Graduation with University Honors

May 7th, 2026

University Honors

University of California, Riverside

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ABSTRACT

Liquid argon (LAr) has wide applications in nuclear and particle physics, particularly in dark matter research, where it enables the detection of ionization and scintillation signals while minimizing radioactive background. Doping liquid argon with xenon can enhance ionization and increase photon yield, lowering the energy threshold and improving signal strength. This amplification of light output enhances detector sensitivity, increasing the likelihood of detecting weak interactions, such as those from potential dark matter candidates. However, the system presents challenges due to the narrow liquefaction temperature range and the potential for xenon to separate from argon or to form ice, which can introduce instabilities.

This paper discusses a cryogenic system designed to increase liquid argon production while maintaining a stable liquefied state to address these challenges. This research involves developing a stable, functional cryogenic condenser to ensure a continuous supply of high-purity liquid argon, optimizing storage conditions, and refining the argon-xenon doping process. Through this research, I aim to advance the capabilities of liquid argon detectors for experiments such as DarkSide-LowMass and contribute to future applications in medical, engineering, and scientific research, including aerospace applications in satellites and rocketry.

Preliminary testing has demonstrated successful nitrogen condensation and partial argon liquefaction. Ongoing work will address the challenges associated with stabilizing the system and continue investigating scalable xenon doping for applications in experiments such as DarkSide-LowMass. This research will contribute to the development of next-generation liquid argon detectors, broader cryogenic engineering, and particle physics research.

ACKNOWLEDGEMENTS

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I would also like to express my gratitude to the two postdoctoral fellows, Michela Lai and Iftikhar Ahmad, who guided me throughout the experimental work. Although Michela has since left the group and is now a professor at Queen's University, her contributions to the project were instrumental, particularly in establishing the system during its early stages. Iftikhar, who has recently joined the team, brings valuable experience in experimental research and continues to support the project's development.

I would also like to thank Alejandro Turnbull and Mark Gergawy for being excellent lab partners throughout this project. Their valuable suggestions and constructive feedback played an important role in advancing the work.

Lastly, I would like to express my appreciation to the University Honors program for providing me with these opportunities and for guiding me throughout my undergraduate journey. The capstone project has greatly enriched my experience at the University of California, Riverside, offering unique opportunities for research and professional growth.

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INTRODUCTION

Dark matter accounts for approximately 85% of the total mass of the universe, yet its nature remains one of the biggest fundamental questions in modern physics - What is dark matter?

The history of dark matter discovery can be dated back to the 1930s with Fritz Zwicky's observation of galaxy cluster motions, but cemented by the 1970s galaxy rotation studies by Vera Rubin.¹ While many more studies aim to address this, no direct detection has confirmed its existence. The current cosmological model was developed in the 1990s and 2000s, based on measurements of the Cosmic Microwave Background (CMB) that confirm that dark matter accounts for approximately 27% of the universe's mass-energy density. This finding also aligned with the previous estimation of the dark matter mass portion by calculating the missing mass in the galaxy cluster.

In modern times, scientists have turned their attention to advanced technologies, such as liquid argon detectors, to understand this substance better. One of the leading dark matter candidates is the Weakly Interacting Massive Particle (WIMPs)². WIMPs are hypothetical particles that, while presumed to have mass, interact with ordinary matter primarily through the weak force and gravity, making their detection extremely challenging. As such, a highly sensitive detector with extremely low background noise is required to detect the faint signal produced from the interaction of ordinary particles with WIMPs.

A modern dark matter detector was designed to measure two primary signals generated

¹ Bertone, Gianfranco, and Dan Hooper. "History of Dark Matter." *Reviews of Modern Physics*, vol. 90, no. 4, 15 Oct. 2018, <https://doi.org/10.1103/revmodphys.90.045002>.

² Bertone, Gianfranco, and Tim M. P. Tait. "A New Era in the Search for Dark Matter." *Nature*, vol. 562, no. 7725, Oct. 2018, pp. 51–56, www.nature.com/articles/s41586-018-0542-z, <https://doi.org/10.1038/s41586-018-0542-z>.

by particle interactions: ionization and scintillation. Ionization is the production of free electrons when a particle interacts with atoms, where scintillation is the emission of photons as atoms return to the ground state. Different particles generally exhibit distinct combinations of ionization and scintillation signatures.

A Time Projection Chamber (TPC) is widely used for such detection. When an incoming particle interaction produces both scintillation light and ionization electrons, the light is then detected, and electrons are drifted toward a readout plane. By measuring these signals, scientists can infer the type of interaction particle based on its signal signature.

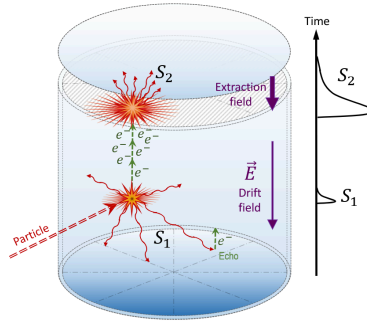


Figure i illustrates the TPC working principle.

Liquid argon (LAr) time projection chambers (TPCs) are detector systems that utilize the unique properties of argon. Argon provides a low-background noise in detection due to its chemical inertness and radiopurity, as well as its high scintillation yield, enabling effective event discrimination. This capability has been demonstrated in the DarkSide-50 experiment,³ one of the first projects to use liquid argon as a medium for dark matter detection.

However, limitations in sensitivity remain in regular LAr detectors for low-energy events, especially for dark matter candidates. Xenon doping is used to address this downside: a small

³ Agnes, P, et al. "DarkSide-50 532-Day Dark Matter Search with Low-Radioactivity Argon." *Physical Review*, vol. 98, no. 10, 16 Nov. 2018, <https://doi.org/10.1103/physrevd.98.102006>. Accessed 25 Oct. 2023.

concentration of xenon is introduced into the system, which modifies the scintillation process by increasing photon yield and shifting the emission spectrum. This will lower the detection energy threshold and increase the sensitivity to potential dark matter interactions by enabling the detection of faint signals from particle interactions.

The challenge with introducing xenon is the difference in thermodynamic properties, specifically the freezing temperature. LAr temperature ranges between 87 K and 83 K, where xenon freezes at 161 K. This means that without special methods, xenon will concentrate in the system and freeze into a solid, which then creates a non-uniform response from the detector. Furthermore, Dark matter detection requires long-term continuous production and maintenance of high-purity xenon-doped argon, as any instability in temperature, flow, or contamination can significantly degrade the performance and possibly damage the system. Therefore, designing a reliable cryogenic system that enables stable liquid argon production is vital for the detector's capability.

This research project aims to address the challenges of achieving such a system by designing and experimenting with a condenser capable of producing liquid argon while supporting xenon doping, and by addressing thermal instability, heat transfer, and scalability in subsequent work. The end goal of the project is to provide a foundation for next-generation liquid argon detection, including future experiments such as DarkSide-LowMass and other particle physics experiments that require an LAr detector.

Background and Literature Review

The project is heavily built upon two pieces of research, the Darkside – 50 project and Dr. Bernard's study on the thermodynamic stability of xenon-doped liquid argon.⁴

⁴ Bernard, E. P., et al. "Thermodynamic Stability of Xenon-Doped Liquid Argon Detectors." *Physical Review C*, vol. 108, no. 4, 20 Oct. 2023, <https://doi.org/10.1103/physrevc.108.045503>. Accessed 18 Feb. 2025.

One of the main challenges of my project is the use of xenon doping. Xenon has a freezing point around 161 K, while liquid argon remains at around 83~87 K, well below the freezing point of xenon. Therefore, it is important to prevent this freezing from happening by spreading xenon atoms at an atomic level. The experiment conducted by Dr. Bernard successfully achieved a xenon concentration of up to 1% by volume. However, his experiment only produced this substance at a small scale, which wouldn't satisfy the demand for larger-scale experiments. This project will build on this to develop a method for large-scale production of xenon-doped argon, providing the possibility of using high-concentration xenon-doped argon for DarkSide projects such as DarkSide Low Mass, as well as other particle physics research evolving the use of xenon-doped liquid argon.

In addition, the project will aim to develop long-term stability for the xenon-argon mixture, which is one of the biggest challenges it will face. Since xenon has a significantly higher freezing point than argon, it is important to ensure the distribution of xenon is uniform within the argon; however, this is difficult to achieve because there is no direct method for controlling atomic-scale distribution, so it must be done in other ways through a carefully designed and controlled thermodynamic cycle. Through this, long-term storage of this xenon-argon mixture can be achieved, thus opening the door to other research utilizing this substance.

Method and Approach

This project relies heavily on lab-based experiments to design and construct a unique condensing system; the amount of research review from other researchers will be minimal, and much of the missing information will be obtained from the experimental test runs. As a result, performing test runs is essential for collecting key data, such as thermal conductivity. Without

sufficient data and calculations, simulations cannot be performed because the condenser uses many custom-made components whose thermal performance is initially unknown. To obtain this data, a typical test procedure involves starting a condensation run and recording temperature, pressure, flow rate, and time. This data is then used to calculate parameters such as thermal conductivity, which determines how well a material transfers heat energy and is an important value for computer simulations. As a final step, once sufficient data is gathered, a computer simulation can model the thermodynamic cycle of the system, helping evaluate performance, improving the design, and serving as a guide for further research. Since the condenser operates in a sealed environment, simulations are essential for understanding its internal behavior. This insight will enable precise control over the condensation process — for example, by adjusting gas flow rates to optimize xenon doping and liquid argon production.

Although the project does not involve human subjects or any IRB requirements, I must complete all safety training under E&HS guidelines because the majority of my work will be conducted in the lab. These lab safety requirements apply to library research and include Hazardous Materials and Waste Management, Fire Extinguishers, Cryogen Safety, Compressed Gas Safety, PPE training, and Laboratory Safety Fundamentals.

SYSTEM SETUP

The condensing system discussed in this paper can be broken down into four subcategories: condenser, cryostat, purification systems, and gas mixing cell. A full system P&ID is below for reference.

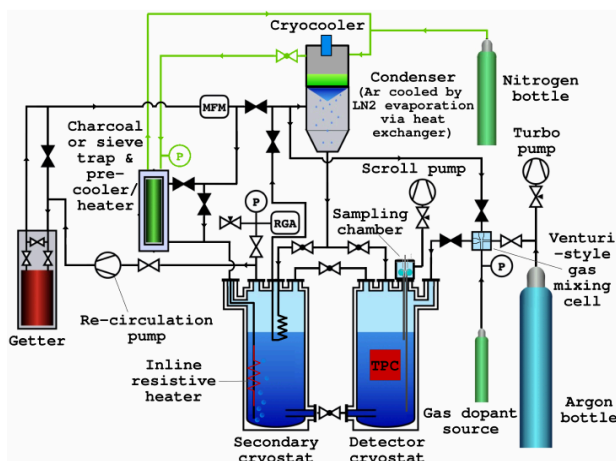


Figure 1 shows the full system P&ID

The condenser system consists of the cryocooler and heat exchanger. The top section of this system contains nitrogen in both liquid and gas phases. Using a PT-90 pulse tube cryocooler, which provides 90 W of cooling power at 77 K, nitrogen gas will be condensed into liquid nitrogen and then fed through a chicken feeder into the heat exchanger, where it will be mixed with argon. The heated nitrogen vapors will leave the heat exchanger and return to the condensing chamber after going through two pre-coolers. Before entering the condensing chamber, the gas will also pass through a flow meter to measure the flow rate. The condenser is also referred to as the Universal Condenser, which can operate in two modes: one uses the PT-90 cryocooler to provide cooling power, and the other uses liquid nitrogen to augment cooling.

The heat exchanger is attached below the nitrogen condensing chamber. This is the place where cooling power is provided to argon and most of the system, where nitrogen will provide a constant cooling power to the hot argon gas. The heat exchanger includes cooling fingers to increase heat-transfer area and a chicken feeder to control the LN2 feed rate.

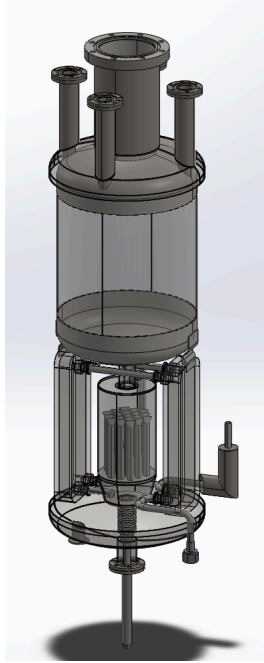


Figure 2a shows the condenser model, which is covered by a vacuum jacket.

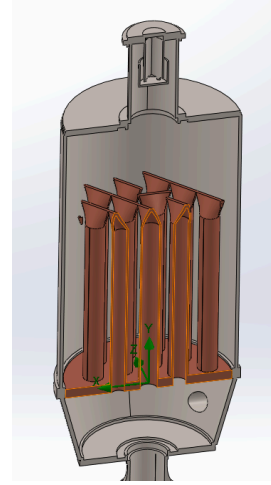


Figure 2b shows the heat exchanger structure, where LN2 enters from the top.

The Cryostats are two storage tanks that store liquid argon and maintain it in the liquid phase; the two are named Pampa and Timon. Since the cooling power to the argon volume came only from the heat exchanger, even a well-insulated cryostat will cause the liquid to boil due to heat leaks from the atmosphere. Because of this, a recirculation system was installed to allow argon vapor to be recondensed in a heat exchanger, with the option of passing through a purification system. In addition, condensed liquid argon will be used as a cooling fluid to provide some cooling power in the secondary cryostat, as shown in **Figure 1**.

The purification system, while not currently tested, is a critical component for the setup. Electronegative impurities, contaminants that attract free electrons, such as oxygen, can absorb drifting electrons, which weakens the ionization signals. Other impurities, such as nitrogen, can absorb excitation energy and dissipate it through non-radiative processes, thereby suppressing scintillation and reducing the detector's ability to distinguish signal from background events and

degrading its energy resolution. Since the condenser construction and assembly will be exposed to the atmosphere, it will not be possible to remove contamination before condensing starts. For this purpose, the two purification devices, Getter and Charcoal Trap, will be used. Since xenon will also be purified by the system, a bypass option is available to prevent loss of xenon concentration during operation.



Figure 3a shows the Getter assembly.

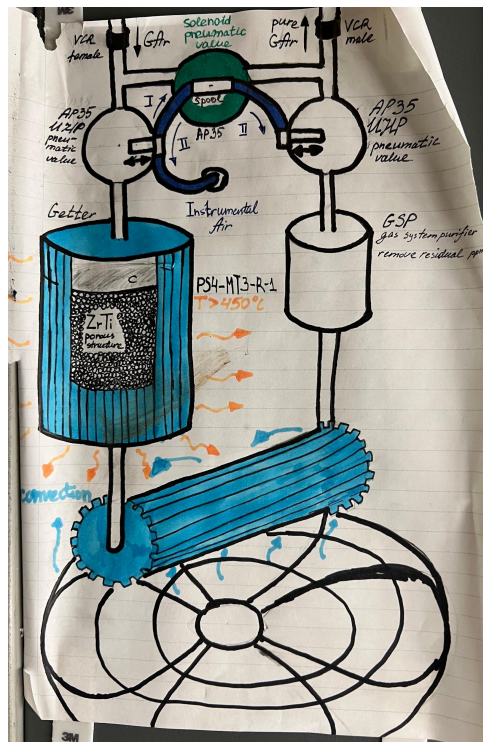


Figure 3b shows the system drawing of the Getter.

Once the system purifies the argon to the desired level, xenon can be introduced, where it will first mix with argon gas in the Venturi-style gas mixer, which pre-mixes the xenon-argon gas before it arrives at the cryostats. However, one system not shown on the P&ID is the xenon recovery system, which recovers xenon after the system is shot down. This was needed because of the high cost of xenon, and recovery will reduce the cost and extend the amount of trial run by reusing xenon.

SYSTEM DEVELOPMENT AND EXPERIMENTAL RESULTS

The development of the cryogenic system follows an iterative process informed by experimental testing and refinements. The initial design of the system adopted a vacuum-insulated cup mounted on the cold head, with the intention of minimizing heat transfer with the environment. Copper wires and thermal grease were added between the copper plate and the cold head to enable heat transfer, while the space was evacuated to prevent heat transfer. However, this configuration has a few issues. The vacuum port is attached to the bottom of the cup, inside the condenser, making it impossible to repump during operation. At the same time, the cold from the liquid nitrogen can also damage this vacuum seal. The second issue with this design is that the welded tube on the copper plate created stress concentration; notably, the copper plate is already thin. This design led to the later failure due to increasing pressure inside the cup. In addition, the copper used in this experiment isn't oxygen-free; oxygen was removed from the copper at low temperature and liquefied. This concentrated liquid oxygen then oxidized the copper, further affecting its heat-transfer performance (**Figure 4a**).



Figure 4a shows the copper wires on the cold head (left) and the damaged cup (right). Oxidation can be seen on the copper plates.

While in the first few runs, the system showed significant losses in heat transfer efficiency, mainly due to the gas in the vacuum cup, a somewhat successful run was achieved in the last run, with the temperature in the nitrogen chamber dropping below the cryogenic limit (below 123K). However, this increase in heat transfer was later found due to a leak in the vacuum cup. The leak was likely due to the failure of a valve attached to the end of the vacuum line, which, during operation, is within the nitrogen chamber. While not at the fitting, which uses a VCR type that creates a good vacuum seal at the operating temperature, it is likely that the cold damages the seal around the valve handle, allowing gas or fluid to enter the cup. When the condensed liquid filled the gap between the cold head and the bottom of the cup, it created contact and allowed higher heat transfer than the copper wires. However, due to nitrogen accumulation, when the cryocooler turned off, the liquid quickly vaporized, creating high pressure inside the cup, which eventually caused plastic deformation to the bottom plate and permanently damaged the structure. Cracks were formed after deformation and allowed pressure to be released(**Figure 4e**).



Figure 4b shows the cup-cryocooler assembly taken out of the condenser.

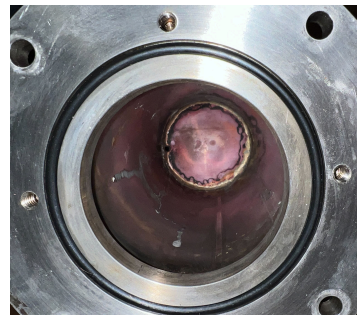


Figure 4c shows oxidation of copper on the inside, evidence of leaking on the cup



Figure 4d shows oxidation at the bottom of the cup due to low temperature.



Figure 4e shows the leak point, marked with a red circle.

The failure of the vacuum cup can be attributed to two factors: first, a design flaw in the placement of the vacuum port; second, the material's strength is insufficient for such operations, especially given that copper and steel become brittle at lower temperatures. A later version of the cup, with higher strength, oxygen-free copper, and an accessible vacuum outlet, was made. Aside from the improvement made to the vacuum cup, the lesson learned from this incident was also applied to improve the safety mechanism across the rest of the system, namely the condenser and cryostats. Additional pressure relief valves were added to all chambers, along with additional pressure gauges for monitoring. The operating procedures were also modified to close the system by installing a relief port.

While the system becomes safer and an improved vacuum cup is developed, the issue of achieving solid contact for maximum heat transfer remains the same as in the previous version. To address this, an attempt to use Indium wire (a soft metal that can be deformed easily) was made, but it was unsuccessful, likely due to thermal shrinkage. Different methods using thermal grease and copper wires were also used, but none succeeded. In the end, the cup was removed from the system, and had a cold head having direct contact with the nitrogen volume.

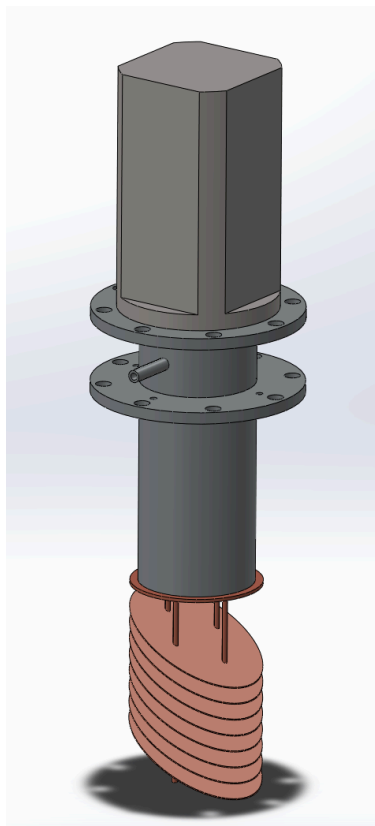


Figure 5a shows the model of the second cup version with an external vacuum port. Additional copper plates were added to the bottom to increase heat transfer.



Figure 5b shows the cup after use. The copper plates on the bottom were removed.

The nitrogen is condensed by inserting the cold head directly into the condenser using an adapter flange. The first test was conducted with gas only, yielding significantly better performance than in previous runs, with the temperature stabilized around 77 K. However, while the system proved capable of condensation, the process of condensing from gas can take up to two weeks to accumulate a significant amount of liquid nitrogen, stabilizing the system and providing enough cooling power to the heat exchanger. The second test of nitrogen condensing was done by directly introducing liquid nitrogen into the system. This method was not only to initialize the system faster but also to inspect the system's heat loss, as the cold head would be sufficient to maintain nitrogen in a liquid state. The result shows that the vacuum jacket around

the system is well capable of insulating heat from entering the system; however, some areas of the nitrogen recirculation loop exposed directly to the environment have ice forming on the line.

The recirculation loop that allows the nitrogen vapor to be recondensed was made using a $\frac{3}{8}$ " tube, which has no thermal insulation. This line has been identified as the largest heat-loss area so far, where ice forms as the cold vapor gas exits the heat exchanger. However, this heat loss does not affect the system's performance in any significant way. Later, a layer of foam was added for extra thermal insulation.



Figure 6a shows the ice forming on the nitrogen recirculation line, where ice starts from the end of the vacuum jacket and stops before the flow meter.

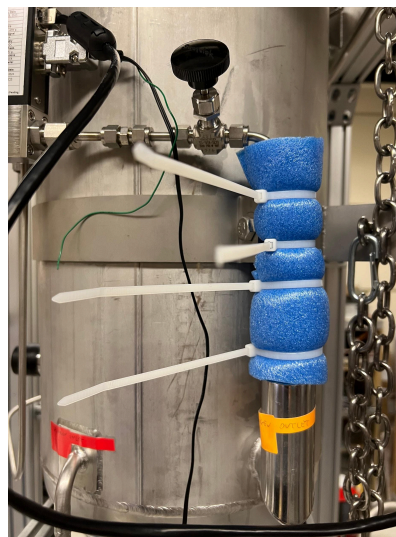


Figure 6b shows the recirculation line with foam insulation added to reduce heat transfer and a control valve for flow-rate adjustment.

During condenser testing, an issue with the support frame was identified. The condenser's dry mass was marked as 75 kg, and it was lifted by a frame made from 1010 aluminum extrusion. The condenser is attached to one side of the frame with two 1010 extrusions connected to it. This structure, over time, has slowly deformed and bent due to the moment introduced by the condenser, primarily in the main vertical extrusion and brackets, posing a risk of damaging the equipment if the structure fails and falls to the ground. A redesigned structure

was made using 2020 aluminum extrusion, with additional support on the bottom of the condenser to counter the moments. Experiments were continued after this work was done.

The transfer line that connects the heat exchanger and cryostats was a vacuum-jacketed flex line. At the start of the argon condensing test, the line was not connected to Timon to facilitate observation of liquid or gas exiting the line. The first test resulted in argon vapor exiting the heat exchanger, which confirmed successful gas flow through the system. However, issues with the line's vacuum jacket were found: an earlier modification to install flanges to heat the line exit had damaged the jacket, causing a heat leak that resulted in ice formation (**Figure 7b**). This leak was later fixed with epoxy (**Figure 7a**) and could be vacuumed down to below 0.1 mBar, which provides sufficient thermal insulation, while the line still requires periodic vacuuming to maintain the pressure. Icing was not spotted after the patch. Notably, a type of foam insulation (commonly referred to as 'pool noodle') was chosen as additional thermal insulation, as the air between each layer of foam provides excellent heat insulation.



Figure 7a shows the transfer line with epoxy applied around the flange on both sides.

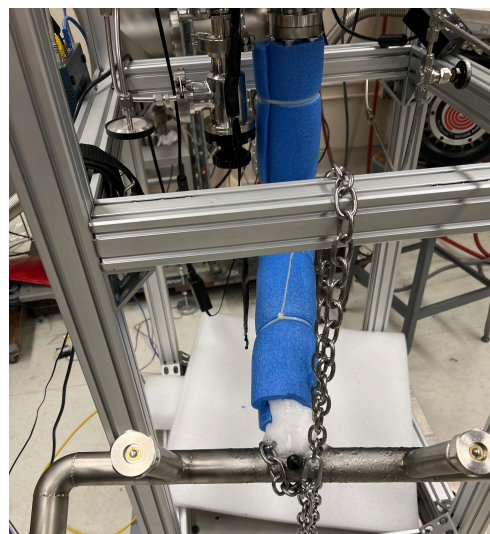


Figure 7b shows the non-vacuumed transfer line running, where ice formed in the exposed area.

The argon condensing test was conducted after the condenser consistently maintained liquid nitrogen. In the first test, argon vapor was detected at the transfer line outlet; later testing had the transfer line connected to the cryostat Timon. A few tests were conducted with liquid argon present in Timon to speed up the process and assess stability. However, while some tests have shown indications of condensation (LAr preserves for a longer time), the results of the experiments had several issues that cause LAr to boil off, including ice forming at the condenser outlet and nitrogen freezing, which reduces cooling power. As seen in **Figure 8**, one of the recent test runs. The temperature of the liquid nitrogen quickly dropped to 66 K in about 2 hours, near the freezing temperature of nitrogen under these conditions. The previous test, which ran longer, also shows a further drop in temperature to below 60 K, indicating that nitrogen freezes. The likely location of solid nitrogen is on the cold head, which will block heat transfer and reduce cooling power to the system.

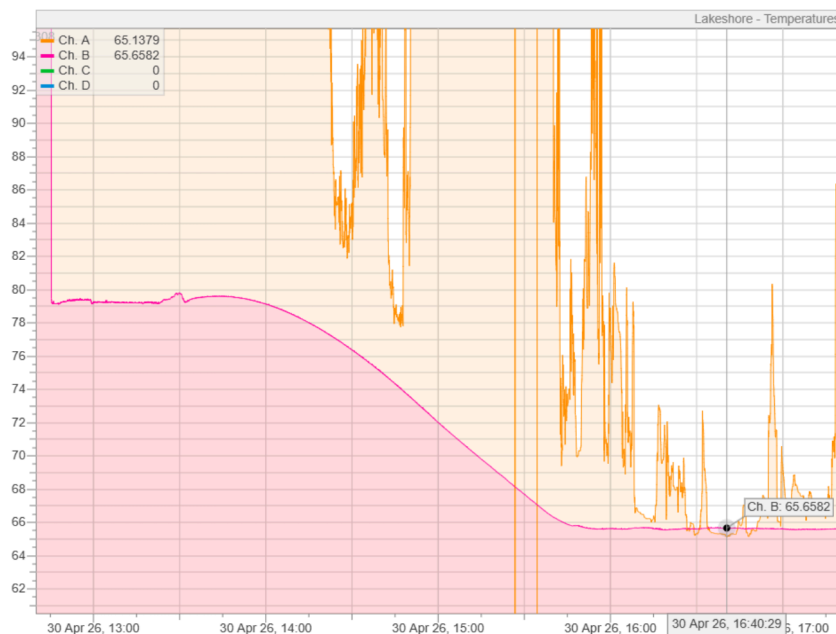


Figure 8 Nitrogen temperature profile measured by Lakeshore 336. Channel B is the temperature in liquid nitrogen, and channel A is the temperature on the cold head. The vertical axis is temperature in Kelvin, and the horizontal axis is time in calendar date.

The main issue causing the freezing is the lack of active temperature control in the nitrogen loop. The cryocooler model is a PT-90 pulse tube cryocooler, with a heat extraction of 90 W at 77 K, where the cooling power decreases as the temperature lowers (**Figure 9**). However, the cryocooler lacks integrated temperature control; during operation, it extracts heat at the maximum possible rate, so that when the condenser cannot remove enough heat, nitrogen will freeze and prevent heat extraction from argon.

A 25-ohm resistor heater was added to address this issue. The heat is connected to the Lakeshore 336 temperature controller. This controller uses an internal PID loop to maintain the temperature at a set point (**Figure 10**). The heater is attached to the bottom of the cold head and will provide additional heat to the cold head when the chamber temperature drops below the set point. This method prevents excessive cooling and reduces the likelihood of nitrogen solidification at the cold head, thereby maintaining maximum cooling power.

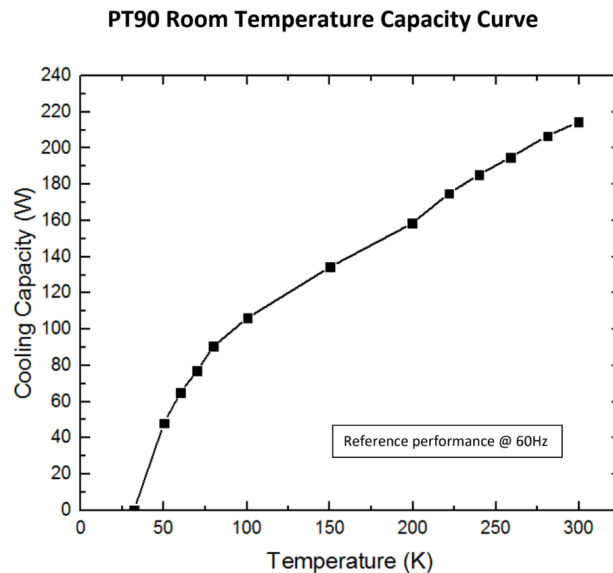


Figure 9: Cooling capacity curve provided by Cryomech

The Heater was also tested before being installed on the cold head, which yielded positive feedback. The test was conducted at room temperature, with a setpoint of 310K (37 °C).

Two temperature probes were attached to the surface of the heater: one integrated into the Lake Shore for feedback, and the other was an independent temperature probe for reference. The test results are successful, with the controllers actively adjusting power output, as shown in **Figure 10**. However, melting at the solder joint occurs at 100% power output, 50 W. It is speculative that the heat accumulated around the joint caused this failure. A similar failure also occurred in the condenser, where an open circuit was detected, likely due to solder-joint instability, and a mechanical failure occurred. The problem needs further investigation, and additional testing of the heating element hardware will also be needed to gain a better understanding.

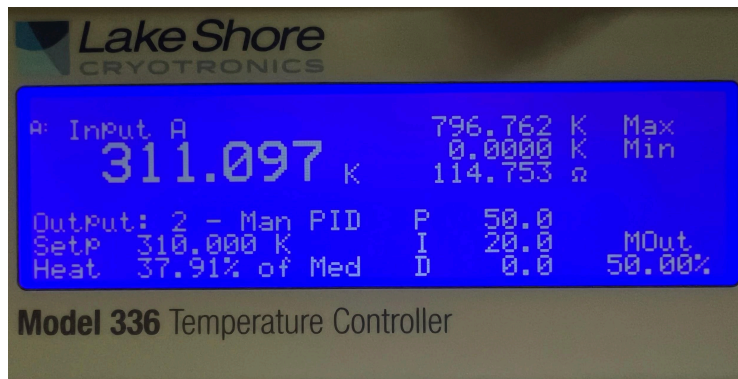


Figure 10 image of the lakeshore 336 temperature controller interface. It shows the heater test at a set point of 310K.

Since the internal space lacks sensors to measure the situation directly, simulations around the heat exchanger were performed to estimate the heat-transfer state. In the following section, two simulation examples will be presented, with conditions simulating the start and running conditions for each system, as well as a third condition with a lower argon flow rate.

The first two simulation setups have nitrogen flowing in at 75 K and argon entering at 333 K. The nitrogen flow rate was set to 3 sccm (standard cubic centimeters per minute), while the argon flow rate was set to half that of nitrogen. A vacuum jacket was modeled by representing the surrounding environment as a low-pressure region (0.01 Pa) to approximate the

behavior of vacuum insulation. All initial values were obtained from experimental runs to ensure consistency with the actual system performance.

One important goal of the simulation was to determine the heat flux, which is the heat transfer rate per unit area of a surface. While the cylinder section on the cold finger uses Fourier's law, which gives a theoretical value of 12 kW, the total heat transfer rate at balance is limited to 90 W by the cryocooler.

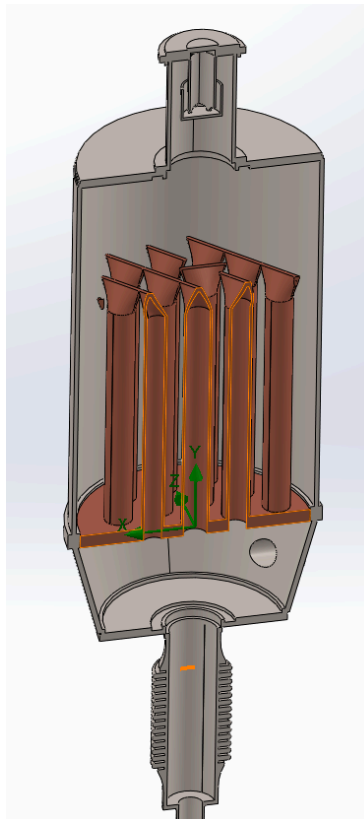


Figure 11 shows a model of a heat exchanger, with nitrogen at the top and argon at the bottom. The gray color is Stainless Steel, and red is Copper.

In the first condition, the wall temperature was set to 293 K. The simulation indicates that heat transfer is dominated by the cooling of the solid structure (steel shell and copper heat exchanger), with approximately 1.259 W conducted through the stainless steel shell, compared to significantly smaller heat transfer between the fluid streams (**Figure 12a, 12b**). The net heat

transfer from the argon to the liquid nitrogen is approximately 0.019 W, indicating that only a very small fraction of thermal energy is effectively removed from the argon stream with walls at room temperature.

The second simulation sets the wall temperatures to 83 K to assess the heat exchanger's performance after cooling down in temperature. Under running conditions (**Figure 12c**), the simulation shows that argon is cooled to approximately 75 K while nitrogen is heated to approximately 100 K, while indicating effective energy exchange once the system reaches cryogenic equilibrium, but the liquid nitrogen flow rate is too low at the set conditions which causes overheating.

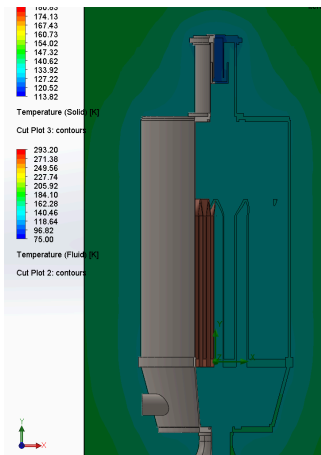


Figure 12a shows the simulated temperature profile of the heat exchanger, where the temperature reaches equilibrium in both volumes.

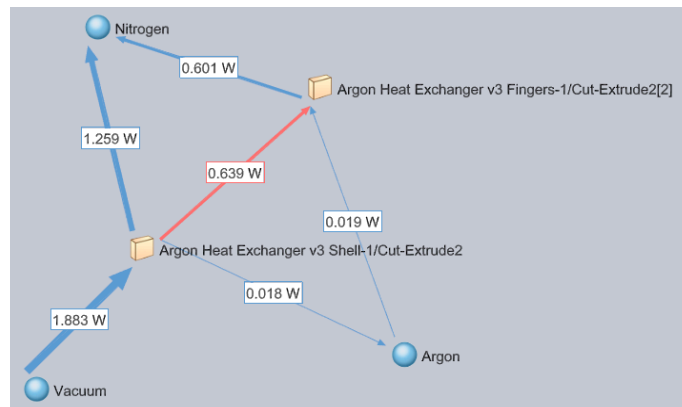


Figure 12b shows the heat flux plot with a solid initial temperature of 190 K to simulate the start condition. The red line is conduction, and the blue line is convection.

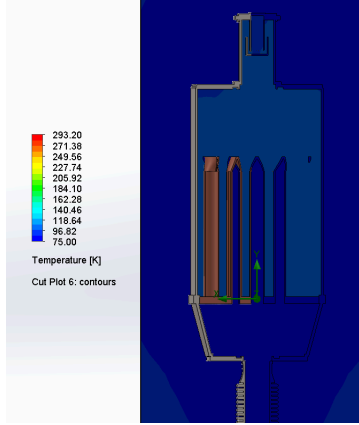


Figure 12c shows the temperature profile under running conditions.

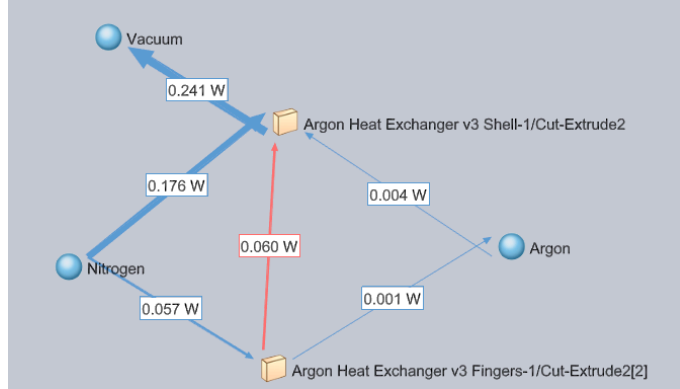


Figure 12d shows the heat-flux map for the running condition with a solid initial state at 83 K. The red line is conduction, and the blue line is convection.

The third condition sets the argon flow rate to 5 times less than nitrogen (0.6 sccm), while keeping the rest the same as in the running condition (**Figure 13**). This configuration is close to the actual system. While the majority of heat transfer still occurs from the environment to the heat exchanger, a significantly higher heat extraction from argon occurs at over 55 W. The result of their run indicates that the flow rate in this system significantly affects performance. While maintaining the flow rate of nitrogen, increasing the flow rate of argon means that as fresh hot argon flows in, it introduces more total heat per time that needs to be extracted to achieve the same result than low argon flow rate. In contrast, low argon flow rate allows longer condensing time and reduces the stress on the heat exchanger.

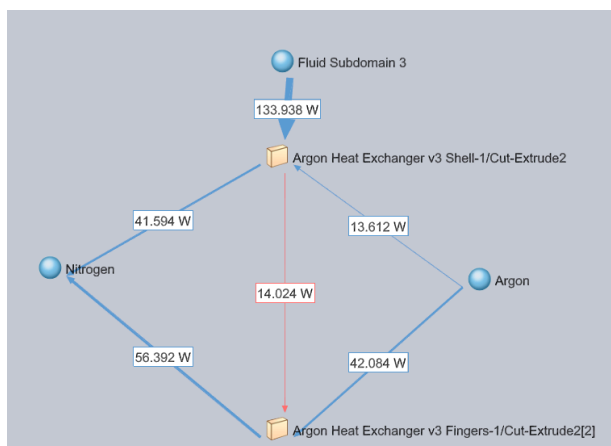


Figure 13 shows the reference run with the default environment, where fluid subdomain 3 is the vacuum jacket. The red line is conduction, and the blue line is convection.

One misleading factor in the simulation is that heat transfer is dominated by the vacuum region. The cause of this phenomenon is the infinite volume of the vacuum region, which acts as a massive heat sink or heat source depending on temperature, which it naturally attracts energy flow toward or away from it, with no change in the total energy of that region. In the actual system, the heat transfer between vacuum jackets to the heat exchanger is expected to be minimal.

The start condition simulation shows that more heat was transferred into the nitrogen volume than was removed from the argon, indicating that the additional heat originated from the heat exchanger itself. These results suggest that the heat exchanger becomes significantly more efficient once the body reaches 77 K and below, while the vacuum jacket minimizes heat leaks to the external environment. However, some previous simulations indicate that argon may locally approach or reach freezing conditions near the cold-finger tips under low-flow conditions. While this does not pose a risk of failure, it requires further monitoring and investigation. The simulation will also be refined as more experimental data are collected, with additional simulation conditions introduced to improve understanding of system behavior.

The experimental and simulation results provided important insight into the system's performance. More importantly, they revealed several challenges associated with the current testing configuration. Although nitrogen condensation was successfully achieved, stable argon liquefaction remains a challenge at this stage.

FUTURE WORK AND SYSTEM INTEGRATION

In the system, there are two cryostats; previously, tests were conducted with only one cryostat, Timon, because the flange of cryostat Pumba was not manufactured until recently. The next step in the test sequence is to integrate both cryostats into the system, as this will provide direct cooling power to the liquid argon in the cryostats, which is currently missing. Adding cooling power should greatly improve the performance and stability of argon condensation.

The gas panels in the current test were not being used since the reconstruction of the support frame. While not deemed necessary for the test, a temporary recirculating line was added to allow the recooling of argon vapor. However, as additional systems are added to the setup, including a getter, a charcoal trap, and a venturi gas mixer, the gas panel must be integrated to control argon flow. As a result, the panel is also undergoing modifications to accommodate these systems and potential future adoptions.

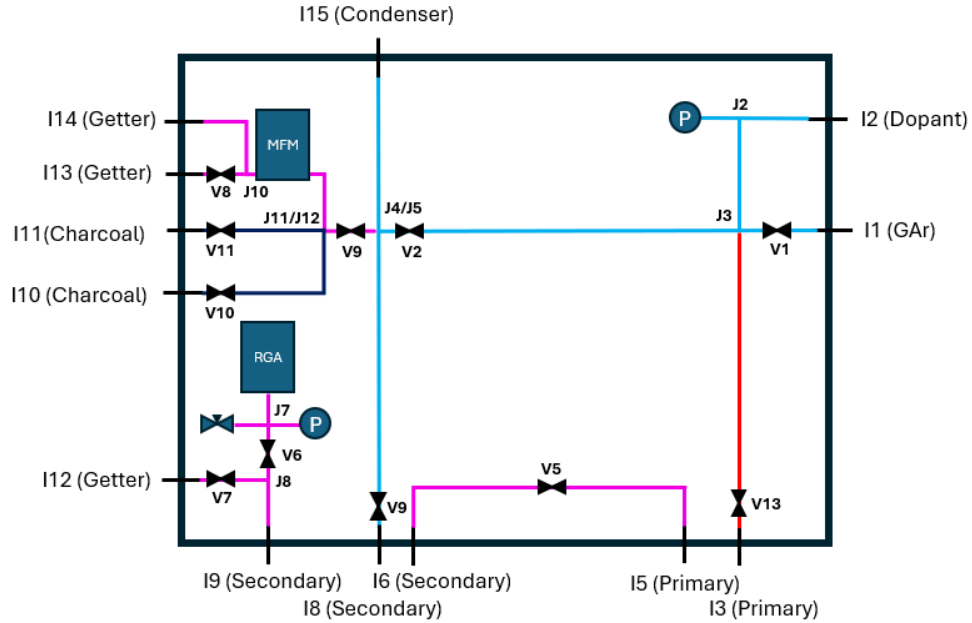


Figure 14 shows the most up-to-date P&ID for the gas panel.

A primary focus of the future work is the integration of argon purification systems, which is critical to system performance, as contamination in pure argon can induce noise and interfere with the detection of weaker signals from particle interactions. The Getter and Charcoal Trap are used for such an application. The Getter will be implemented to improve system stability and gas purity. When argon flows through the Getter system, the impurities will slowly be purified over time, leaving only argon. This system will also be critical to the thermal stability of the argon volume, as argon gas exits the Getter at 40 °C and reenters the heat exchanger, introducing heat and balancing the heat exchange rate, which prevents argon from freezing inside the heat exchanger.

Upon completion of the Getter, the charcoal trap is another purification system installed in the system, where the argon gas goes through the charcoal. In this system, argon passes

through a small heat exchanger with nitrogen to be cooled and, in the meantime, through charcoal to remove any contamination, which serves as a pre-cooler.

One important feature of this system was the xenon-dopant process; while the test continues, a recovery system for xenon must be developed to reduce costs, given the high price of xenon. Recovered xenon can then be reused for additional tests, enabling more experimental runs without a substantial increase in cost. The xenon dopant test can be initiated with high-purity argon once this recovery system is implemented. While it's likely to require many trials before success, this system will extend that limit, allowing more tests to be run.

Following successful system-level validation, TPC tests with both xenon-doped argon and pure argon will be conducted to collect performance data. The test can be performed in the cryostat Pumba, which offers extra space and a larger feed-through, allowing it to accommodate much larger devices. These tests can help determine the signal yield at different xenon concentrations, as well as quickly and easily attempt other types of dopants.

CONCLUSION

The progress completed during this project has yielded valuable data and knowledge on the design, construction, and experimentation of the cryogenic condenser system for the production of liquid argon, with future capability for the xenon doping process. The system demonstrated the capability and functionality of the pulse tube cryocooler, heat exchanger, vacuum insulation, and recirculation loop, which generally met design expectations and demonstrated that the system is capable of operation near 77 K. Simulations on the heat exchanger have also been done that allow researchers to gain more insight into the performance of the heat transfer, which will help with the optimization of flow in the future. While significant

progress has been made, further work is required to achieve stable large-scale argon condensation and xenon doping.

One important takeaway is the vacuum cup's failure, which reveals a potential failure mode. The failure occurred during the system's heating up, causing cryogenic liquid to boil and turn the vacuum cup into a pressure vessel, which in turn caused the plate to bulge outward and crack. As such, similar systems, including the nitrogen chamber, argon chamber, and cryostats, were also reevaluated to refine their operating procedure to reduce risks at the system level, as well as ensure an oxygen free environment from design. This is also to be evaluated on more systems as progress is made. Many systems have also been temporarily removed during the condenser reconstruction, and some, including the Gas Panel, are also undergoing upgrades. By building on what has been achieved, the system integration will be fast and will allow more time for testing and optimization.

Overall, this work contributes to the development of cryogenic technologies for next-generation particle physics experiments, particularly those involving liquid argon detectors. In addition to its scientific impact, the project represents a multidisciplinary effort combining physics, engineering, and manufacturing, providing a strong foundation for future system development and experimental research.

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