FRIB Lithium Stripper Thickness and Stability Measurements

Nuclear Engineering Division and Physics Division

About Argonne National Laboratory

Argonne is a U.S. Department of Energy laboratory managed by UChicago Argonne, LLC under contract DE-AC02-06CH11357. The Laboratory's main facility is outside Chicago, at 9700 South Cass Avenue, Argonne, Illinois 60439. For information about Argonne, see <http://www.anl.gov>.

Availability of This Report

This report is available, at no cost, at <http://www.osti.gov/bridge>. It is also available on paper to the U.S. Department of Energy and its contractors, for a processing fee, from:

U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831-0062
phone (865) 576-8401
fax (865) 576-5728
reports@adonis.osti.gov

Disclaimer

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor UChicago Argonne, LLC, nor any of their employees or officers, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of document authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof, Argonne National Laboratory, or UChicago Argonne, LLC.

FRIB Lithium Stripper Thickness and Stability Measurements

***Claude B. Reed, ‡Jerry Nolen, *Yoichi Momozaki, ‡James Specht, *David Chojnowski, and
*Ronald Lanham**

*Nuclear Engineering Division

‡Physics Division

Argonne National Laboratory

February 28, 2011

ABSTRACT

This report documents the results of a number of tests of the prototype liquid lithium thin film stripper for FRIB, in which 1) the thickness of a flowing film of liquid lithium was measured in real time, 2) the thickness distribution of the film was measured in real time, and 3) the stability of the films was determined based on both digital video recordings and digital signal recordings of Faraday cup current. The high-pressure liquid lithium system, capable of driving liquid lithium at up to 13.9 MPa (2000 psia) through a nozzle opening as large as 1 mm (40 mil) in diameter, is described. As part of the work reported here, the system was modified to facilitate convenient and efficient testing of design variations in nozzle and deflector geometry so that their effect on film thickness and film stability improvement could be determined. A previously developed electron beam based thickness measuring system was recalibrated for this specific geometry and used to measure the film thickness under a number of different flow conditions and deflector designs. A thin film ~9 mm in width flowing at a velocity of ~60 m/s was formed under several flow conditions and with several deflector designs. A deflector design was found that practically eliminates the puddle issue. The film stability is judged to be excellent; based upon a ~25 minute stable flow run during which time only a single breakup of the film occurred. That breakup event, which lasted only about 0.6 second, was most likely caused by an Ar gas bubble that became trapped in the high-pressure lithium line, during lithium transfer operations. The trapped gas issue will not be a problem for the FRIB stripper system because a pumped, closed loop system will be used, eliminating the need for lithium transfer operations. Based on thickness distribution measurements from the electron beam system, the expected central thickness (at halfway between center spot and bottom spot) is **$632 \pm 35 \mu\text{g}/\text{cm}^2$** ($\pm 5.5\%$ for 1 mm spot diameter). This corresponds to a physical thickness of the flowing lithium film of **$12.3 \pm 0.7 \mu\text{m}$** .

Table of Contents

ABSTRACT	i
List of Figures.....	iv
List of Tables	v
1 SUMMARY OF PRIOR WORK:.....	7
2 ISSUES TO BE RESOLVED IN THE PRESENT WORK	7
2.1 Improving Nozzle Design.....	8
2.2 Reducing Interference from the Puddle.....	9
2.2.1 Changing the deflector shape	9
2.2.2 Adding wick structures to the deflector	12
2.2.3 Improving the deflector surface finish	14
2.3 Deflector alignment	15
2.4 System operating conditions, parameters, and procedures	18
2.5 Film formation experiments	19
2.5.1 Results	19
2.6 Thickness measurement experiments	22
2.6.1 Results	23
3 SUMMARY AND CONCLUSIONS	38
Appendix A: Simulant experiments	39
Appendix B: Hardware and System Description.....	52

LIST OF FIGURES

Figure 1 – All stainless steel 3-piece nozzle.....	8
Figure 3 – First lithium film with Type-1 deflector 11-23-2010.....	10
Figure 2 – Pictures of old and Type-1 deflectors in operation	10
Figure 4 – New 4-way deflector	11
Figure 5 – Wick Structure Forces vs pore radius	13
Figure 6 – Wick structures attached to 4-way deflector	14
Figure 8 – Schematic showing the correct deflector location, looking from top	15
Figure 9 – Schematic showing the deflector location, looking from back	16
Figure 10 – Schematic showing laser image on dummy film	16
Figure 11 – Actual laser image during alignment process	17
Figure 11. System operating conditions and parameters.....	18
Figure 12 – The first formation of a sharp round jet issuing from the nozzle.....	20
Figure 13 – The first stable lithium film formation.....	21
Figure 14 – Films from different deflector designs, see text for explanation	22
Figure 16 – Temperature history of 01/24 run.	25
Figure 17 – Drive pressure history of 01/24 run.	25
Figure 18 – Emission current history of 01/24 run.....	26
Figure 19 – Faraday cup signal history of 01/24 run.....	26
Figure 20 – Temperature history of 02/04 run.	27
Figure 21 – Drive pressure history of 02/04 run.	27
Figure 22 – Vacuum history of 02/04 run.	28
Figure 23 – Emission current history of 02/04 run.....	28
Figure 24 – Faraday cup signal history of 02/04 run.....	29
Figure 25 – Film breakup, L & stable, R (02-04-2011)	30
Figure 26 – Film breakup, L & stable, R (02-04-2011)	31
Figure 27 – Oscilloscope raw data taken on 02/04 run for 10 sec at sampling rate of 12.5 kHz.....	31
Figure 28 – First spike in Figure 27.	32
Figure 29 – Second spike in Figure 27.	32
Figure 34 – E-beam locations viewed from the ion beam port.	33
Figure 35 – Actual beam positions on lithium film.....	33
Figure 36 – Histogram of film thickness data.	35
Figure 37 – Spatial thickness variation.....	36
Figure 38 – CASINO simulation comparing C and lithium transmission.....	37

Figure 39 – Simulant film testing setup.....	39
Figure 40 – All stainless and standard nozzles.....	40
Figure 41 – Details of the flow path in the standard nozzle.....	41
Figure 42 – Comparing jets from standard (above) and all-SS (below) nozzles.....	41
Figure 43 – Sapphire orificed nozzle and all stainless steel orifice-less nozzle.....	42
Figure 44 – Film formation maps with different nozzle sizes.....	44
Figure 45 – Details of the 7/16 inch nozzle (from AM Gatti website).....	45
Figure 46 – Old and new deflector designs.....	46
Figure 47 – Pictures of old and new deflectors in operation.....	46
Figure 48 – Type 1 deflector, front view.....	47
Figure 49 – First lithium film with Type-1 deflector 11-23-2010.....	47
Figure 51 – Observed optical interference and measured thickness variation.....	50
Figure 52 – Comparison of Sapphire and Stainless Steel Nozzle Materials.....	50
Figure 53 – All stainless, 3-piece nozzle.....	51

LIST OF TABLES

Table 1 – Operating conditions.....	18
Table 2 – Film thickness and variation.....	35

1 SUMMARY OF PRIOR WORK:

With prior DOE funding, a series of experiments was performed to investigate the feasibility of using a liquid lithium thin film for the stripper in high power heavy ion linacs. The main objective of the that work was to demonstrate the formation of a temporally stable liquid lithium thin film in a vacuum environment, simulating a stripper useful for high intensity heavy ions such as uranium in the energy range of ~ 10 -20 MeV/u. Because of the extreme technical difficulty of conducting a variety of developmental investigations using liquid lithium, it was decided to use lithium simulants as much as possible in various preliminary experiments to settle on a film formation scheme, to investigate the film stability, and to obtain the design parameters for a liquid lithium thin film system. Based on the results from those preliminary studies, a high-pressure liquid lithium system was constructed for further work. The lithium system was capable of driving liquid lithium at ~ 300 °C and up to 13.9 MPa (2000 psia) through a nozzle opening as large as 1 mm (40 mil) in diameter. This drive pressure corresponds to a lithium velocity of >200 m/s. A thin lithium film 9 mm in width flowing at a velocity of ~ 58 m/s was produced while the chamber pressure remained below 10^{-5} Torr in the area of the film. The behavior of the liquid lithium thin film was visually observed to check for its temporal stability. Based on those visual observations and drive pressures, the velocity, width, and length of the thin film were estimated. Its thickness was estimated to be roughly ≤ 13 μm .

2 ISSUES TO BE RESOLVED IN THE PRESENT WORK

The prior work established that a liquid lithium thin film would be feasible as an electron stripper for heavy ion beams, if a number of technical uncertainties could be eliminated. For example, the necessary charge state distributions require that the optimum thickness of a liquid lithium first stripper should be on the order of 10-20 micrometers, for uranium beam energies in the 10-20 MeV/u range. Rather than just an estimate, this thickness must be measured and confirmed to be in the right range. To provide consistent stripping characteristics, the shape, especially the thickness and thickness distribution, of the film must be kept constant and stable for a long time ($> \sim$ hours). This long-term stability was demonstrated in the prior work with lithium simulants, water and Fluorinert, but was not firmly demonstrated in the prior work with liquid lithium. (See Appendix A for a description of the simulant work done here for FRIB.) The width and the length of the film need to be larger than the size of an ion beam whose diameter is typically ~ 1 mm or less; this requirement was previously demonstrated with liquid lithium. Also, to avoid excessive vaporization of the liquid lithium, the mass flow rate of the flowing lithium sheet must be high enough to remove the thermal energy deposited in the film from an ion beam without a significant temperature rise; based on earlier windowless lithium target tests¹, this requirement seems to be achievable, but confirmatory tests are needed.

¹ "A 20 kW beam-on-target test of a high-power liquid lithium target for RIA," **Reed, C. B.**, et.al., Nuclear Physics A, Volume 746, pp161-165, 27 December 2004.

2.1 Improving Nozzle Design

The direct film formation method used here relies on the quality of the initially formed round jet as a necessary, but not sufficient, condition for producing a stable film flow. When a temporally stable jet is formed, the spatial length of the jet strongly depends on the amplitude of any initial disturbance and the size of the liquid jet; in other words, it depends on the physical dimensions of the nozzle, the surface finish of the nozzle interior, any externally induced pressure fluctuations in the fluid, and any mechanical vibrations, etc. Especially, the quantities such as surface finish, pressure fluctuation, and vibration in a real system are extremely hard to determine *a priori*. Therefore, nozzle design work with water, as reported in detail in Appendix A, was continued as an important element of improving film uniformity and stability.

Based on the results of the nozzle design observations and film uniformity observations, it was decided to use an appropriately sized, 3-piece nozzle. Because of the incompatibility of sapphire with molten Li, the orifice must be made of a material that is known to be compatible with Li. Although stainless steel is not an ideal material for making an orifice (it is not as hard as sapphire), it was decided to make a 3-piece nozzle with a stainless steel orifice that conforms to the same shape as the standard nozzle, see Figure 1. We also requested the manufacturer to polish the stainless steel orifice of the nozzle as well as his technology would permit.

Figure 1 – All stainless steel 3-piece nozzle

2.2 Reducing Interference from the Puddle

Perhaps the major obstacle to producing a stable lithium film in the prior work was interference by a puddle of lithium that formed just above the striking point of the round jet on the deflector. Over time, the puddle would grow in volume, because of the high surface tension and low density of lithium (compared to, say, water or Fluorinert, that were used in the simulant testing). When large enough, the puddle would hang down far enough to touch the incoming round jet, destroying the film formation mechanism. Ridding the deflector of this puddle was the second thrust of the present work. The following two main strategies were pursued in trying to eliminate the puddle:

- Changing the deflector shape
- Adding wick structures to the deflector

2.2.1 Changing the deflector shape

A new deflector design, Type-1, with a cutout to facilitate liquid draining was fabricated and tested with water. This new design was made to promote draining of liquid from the face of the deflector to the edges of the cutout, minimizing the formation of a puddle near the impaction point.

Water experiments showed that this modification was effective in minimizing the size of the puddle on the deflector and shifting the dripping points away from the film, Figure 2. The Type-1 deflector design was installed in the lithium system as the first deflector and was used from 11-16-2010 through 11-23-2011 (for details on the lithium system and other hardware and systems, see Appendix B). The film produced by that deflector is shown in Figure 3. Based on the deflector water test results, another, further improved, 4-way deflector with multiple cutouts and highly polished surfaces was fabricated, Figure 4. The 4-way deflector was used in lithium testing beginning 1-24-2011. The optimum radius of the deflector cutout, which must be determined via lithium testing, was not fully explored.

Figure 2 – Pictures of old and Type-1 deflectors in operation

Figure 3 – First lithium film with Type-1 deflector 11-23-2010

Figure 4 – New 4-way deflector

2.2.2 Adding wick structures to the deflector

After observing the results of the first series of Li film formation experiments with the Type-I deflector, draining of the puddle definitely improved, but further improvement was needed. It was hypothesized that a wick structure might work to help remove the puddle from the deflector. Several papers on heat pipes were reviewed to understand the parameters that govern the choice of the wick material. Two similarities were found between the physics/fluid mechanics of an alkali metal (Li) heat pipe and how a wick structure might work to help remove the puddle from the deflector:

1. In a heat pipe, the lithium (in its liquid state) is transported by capillary forces via a wick structure. The capillary forces can be either assisted by, or work against, gravity (depending on the orientation of the wick structure with respect to gravity); so capillary forces could help drain the puddle, and
2. The ambient pressure in both cases is just the vapor pressure of Li.

The one dissimilarity between the heat pipe case and stripper case is that in the heat pipe case, the lithium enters the wick structure as the result of vapor condensation and leaves the wick structure at the other end by the reverse process; this is of course driven by a temperature difference from one end of the wick structure to the other. In the stripper case, there is no temperature difference to deplete the lithium at one end; the only mechanism for depletion of the lithium will be the formation and dripping of lithium drops from the bottom end of the wick structure. The concern was whether this idea really buys anything, since the lithium must have the potential to leave the bottom end of our wick structure at a rate greater than it builds up at the origin of the film; otherwise there will be no capillary driving force, only gravity.

In a paper by Dunn & Reay², at the bottom of page 191, the following equation for maximum mass flow rate in a wick is given:

An expression for the maximum mass flow rate $\dot{m}_{max}$ may be obtained by neglecting the vapour pressure loss equation (5) and substituting equations (2), (3), (7) into equation (1)

$$\dot{m}_{max} = \left(\frac{\rho_l \sigma}{\mu_l} \right) \left(\frac{KA}{l} \right) \left(\frac{2}{r_e} - \frac{\rho_l g l}{\sigma} \sin \phi \right).$$

If one takes gravity to be aligned parallel to the wick structure, then the sin function becomes -1.

Also, if one factors out the $(2/r_e)$ term, then the terms inside the last parentheses become $\left(1 + \left[\frac{\rho_l g l r_e}{2\sigma} \right] \right)$

The dimensionless grouping on the right is a Bond number; a ratio of the gravitational forces on the lithium to the surface tension forces. An inverse Bond number of 2 would mean that the surface tension force is twice as large as the gravitational force. There are two length

² "The Heat Pipe" by Dunn & Reay, Physics in Technology 4 187, 1973

scales, “ l ” is the length of the wick structure in the direction of g and “ r_e ” is the pore radius of the wick structure.

Using lithium properties, and taking the length of the wick structure “ l ” to be 5 cm, the inverse Bond No. vs the Pore radius can be plotted as in Figure 5 below. The red oval is the area of wick pore radius where a significant benefit from capillary force draining of the puddle can be obtained. The lower end of the pore radius is probably limited by wettability and probably also by the interdependence of the wick structure parameter group factors (KA/lr_e) that contain “ r_e ” both explicitly and implicitly in K , the wick permeability.

Figure 5 – Wick Structure Forces vs pore radius

Based on these ideas, two wick structures were fabricated and attached to the new 4-way deflector on the cutout with the largest radius of curvature, as shown in Figure 6. A wire was added to the bottom of each wick to give the lithium droplets a preferential collection point, from which to depart the wick structure.

Figure 6 – Wick structures attached to 4-way deflector

The wick structures were comprised of three layers of stainless steel mesh.

2.2.3 *Improving the deflector surface finish*

It was observed in water testing that the quality of the edge of the deflector from which the film departs is very important in determining the quality of the resulting film. An imperfection in the edge of the deflector directly translates into an imperfection of the same order of magnitude in the smoothness, and thus the uniformity in film thickness, of the resultant film. Therefore, to include this feature to some extent in the Type-1 deflector, yet take delivery on a schedule that would support the timely acquisition of water test results, the Type-1 deflector was fabricated from a pre-polished piece of stainless steel stock. Regarding the new 4-way deflector, to provide the best edge possible, with known fabrication techniques, a 1 μin diamond polish surface finish (1 microinch = 1/39.37 micrometer) was specified on the front face and the 4 back cut surfaces, see Figure 4 and Figure 6.

2.3 Deflector alignment

The location of the deflector is one of the most critical values that needed to be carefully adjusted. Since the ion beam coming from the ion beam port and the e-beam coming from the e-beam port would intersect and this beam intersection point needs to exist in the lithium film formed below the deflector, the front face of the deflector must be adjusted such that it exists vertically above the intersection point (see Figure 7).

Figure 7 – Schematic showing the correct deflector location, looking from top

Figure 8 – Schematic showing the deflector location, looking from back

This was done by adjusting the deflector horizontal distance, X_d . To check the alignment of the deflector, a laser alignment device was used. Before installing the e-beam line to the chamber, this alignment device was mounted at the e-beam port. The laser alignment device was made such that the laser beam was perpendicular to the flange face and located at the center of the flange. If X_d is too large, the laser image would have appeared on the right side of the dummy film that was made of a translucent film, when viewed from the ion-out port (back side). If X_d is too small, the image would have appeared on the left side of the dummy film (see Figure 8 and Figure 9).

Figure 9 – Schematic showing laser image on dummy film

Figure 10 shows the actual laser image at the end of the alignment process. The laser image appears very near the centerline of the film, indicating the alignment is correct. Due to the ability to move the e-beam and its uncertainty of the location, we have concluded that this is sufficiently correct.

Figure 10 – Actual laser image during alignment process

2.4 System operating conditions, parameters, and procedures

Based on the previous experiments at ANL, it was found that the orifice diameter of ~ 0.5 mm was a good size to form a nice film with the thickness of ~ 10 μm . Also, to form a stable lithium thin film, a lithium jet needed to be issued at $> \sim 100$ psia. The angle of incidence was 52 degrees and the relative position of the jet impaction point with respect to the deflector edge must be adjustable to an accuracy of ~ 0.1 mm. Other important conditions and parameters are shown in Figure 11.

Figure 11. System operating conditions and parameters.

Table 1 – Operating conditions

Operation parameters	
Li temperature	220 $^{\circ}\text{C}$
Drive pressure	80 - 200 psi
Estimated Li velocity	46 - 73 m/s
Angle of incidence	52 ± 0.2 $^{\circ}$
Nozzle size	9/16 in
Orifice opening size	20 mils
Deflector type	Type 1 & 2

To minimize the possibility of plugging at the nozzle, extra care was taken to keep lithium as clean as possible in the system. Unlike the previous experiments, the use of readily available stainless steel filters was employed. The system was baked for a few days at up to 300 °C under vacuum for outgassing. The ultimate vacuum pressure of low 10^{-7} Torr range was obtained.

A typical experiment started by heating the system to around 220 °C. After all temperatures along the system were stabilized and the nozzle temperatures exceeded the melting point of lithium (181 °C), the pressure vessel was pressurized with Ar gas to a desired value. Then the valve 602 was opened. The lithium nozzle assembly was empty at the time because liquid lithium drains after an experiment. The nozzle heater usually was unable to effectively heat up the assembly and the nozzle assembly seemed to be colder than the melting point of the lithium. Once the valve 602 opens, the lithium just partly fills the nozzle and seems to freeze in the nozzle assembly. However, when a good thermal contact was obtained between the nozzle heater and the surrounding assembly due to this frozen lithium, the heater was enabled to effectively heat up the assembly. This could be observed by a rapid drop of the nozzle heater temperature and much slower increase of the heater temperature when the heater duty cycle was brought to 100 %. When this temperature change was confirmed, the valve 602 was closed again. It usually took about 20-30 minutes for the assembly to completely heat up. When the entire nozzle assembly sufficiently heated up, the lithium started to melt in the nozzle assembly again and eventually the lithium started to drip from the nozzle opening.

Once the lithium dripping was confirmed, the valve 602 was opened again to initiate the lithium jet. The drive pressure was usually set above ~700 kPa (~100 psia), but below ~1400 kPa (~200 psia). The formation of the jet was visually confirmed through the viewports. After the jet flow was established, the position of the nozzle assembly was carefully adjusted to optimize the location of the impaction point with respect to the deflector edge to form the best looking film. The temperatures and pressures were recorded at a set interval, usually once per minute. Digital camcorders recorded visual images of the lithium film from the viewports during experiments. These recorded visual images as well as temperatures and pressures form the basis of the present work. The total runtime usually was ~25 minutes at the drive pressure of ~1050 kPa (~150 psia).

When the total runtime reached ~25 minutes, the lithium jet was stopped by closing the valve 602. The top view port valve was opened to see the level pins at the bottom of the lithium chamber. If the level in the collection chamber was close to the pre-determined full level, the run was terminated and a lithium transfer from the collection chamber to the lithium reservoir was needed.

2.5 Film formation experiments

Once the loop was assembled, a series of film formation experiments was performed as a part of the shakedown of the lithium system before installing the EMS. The Type-1 deflector was installed for the early runs.

2.5.1 Results

At first, the nozzle and the deflector were intentionally misaligned so that a formation of a good round jet could be visually confirmed (Figure 12). As seen in the figure, once the

good jet formation was confirmed, the nozzle and the deflector were aligned so that the round jet hit the edge of the deflector to produce a film. Formation of a stable film was visually confirmed (Figure 13). Visual observations confirmed that excess lithium on the deflector surface successfully drained from both edges of the cut of the deflector, making the film very stable. The first run was for approximately 30 minutes. The run was terminated as planned when the lithium in the reservoir became low. After transferring the lithium from the collection chamber to the reservoir vessel, the second run was carried out on the next day, successfully reproduced a high quality stable film formation. These repeated experiments indicated that the modified deflector design and the new improved nozzle were extremely effective in improving the lithium film quality and stability. The design changes also significantly improved repeatability of film formation.

Figure 12 – The first formation of a sharp round jet issuing from the nozzle.

Figure 13 – The first stable lithium film formation.

2.5.1.1 Effects of deflector shape

Figure 14 shows front and back views of the film issuing from three different deflector profiles. The image on the left is from the Type-1 deflector. The four images in the middle were taken with the 4-way deflector, using the reverse cutout³. The two images on the right were taken with the largest cutout on 4-way deflector and with the wick structures in place. As expected from the water experiments, an arc cutout facilitated pulling excess lithium accumulated on the deflector away from the impaction point, drastically improving the film quality. However, as the deflector surface wet with lithium, the puddle tended to extend toward the impaction point and after a few runs, the film quality started deteriorating. It appeared that lithium dripping from the deflector was not sufficient to remove the minimum amount of lithium accumulated in the puddle. Based on this observation from the Type-1 deflector, wick structures were investigated. Additional wick structures seemed to accelerate dripping of lithium, improving long term lithium film quality. It appears that this shape is the best among all shapes tried at ANL so far.

³ See the drawing G0592-0039-DB at the bottom of Figure 4; the reverse cutout is at the 12:00 o'clock position, in the front view of the deflector.

Figure 14 – Films from different deflector designs, see text for explanation

2.5.1.2 Effects of drive pressure

Figure 15 Film width changes for driving pressures (L to R) 210, 150, 105 psia

As expected from the water experiments, increasing the drive pressure increased the film size, but also lithium mist and droplet formation increased. However, reducing the drive pressure below ~100 psia deteriorated the appearance of the lithium film. One of the runs indicated that the increasing drive pressure didn't change the film thickness much.

2.6 Thickness measurement experiments

After performing the film forming experiments and confirming the proper operation of the lithium system, the EMS was installed on the lithium system. The new deflector with 4 different patterns and a highly polished surface was also installed. Although the cutout on the Type-1 deflector reduced the amount of lithium puddle and greatly improved the stability of the film, it was recognized that a further reduction of lithium accumulation on the deflector

surface was necessary. It was decided to add a wick structure at each edge of one of the cutouts to facilitate the lithium draining.

2.6.1 Results

A total of 5 runs were carried out from 01/24 to 02/04. The first run was performed on 01/24. In this run, the objectives were to obtain the first good film thickness measurement and observe the effects of the drive pressure on the film. The cutout with 2 wick structures was chosen. The vacuum was about 1×10^{-6} Torr when the system temperatures were at around 230 °C and the drive pressure was set at 150 psia. A very nice, stable film was formed. The wick structures were not draining well at the beginning due to lack of wetting, but as lithium flowed and wetted the wicks, they wet well and started effectively draining excess lithium from the deflector. Once the stable film was formed, the gate valve was opened and the Faraday cup positioned at a distance of 300 mm from the film. Also, the gate valve to the e-gun was opened and the e-gun was turned on. Beam signals were obtained at the cup, but they were intermittent. The emission current at the gun was raised to 50 μ A, but unlike a 1 MeV e-beam on the thick lithium target, no visible beam spot was observed on the film. The film was very stable all the time and the drive pressure was varied from 100 to 200 psia to observe the effects of the pressure.

To investigate the intermittent signal at the cup, the Faraday cup and its support were removed from the lithium system. A dedicated braided ground sleeve was put over the signal wires.

The second and third runs were performed on 01/27. The objective of the 2nd run was to duplicate the 1st run, but with the improved Faraday cup with the new ground. It was confirmed that the installation of the ground sleeve to the Faraday cup wires improved the signal quality. The objectives of the 3rd run were to observe the effects of the lithium incident angle to the deflector. The incident angle was varied by moving the deflector in vertical direction, while changing the angle of the nozzle assembly.

To investigate the effects of deflector shape, an attempt was made to turn the deflector, however, due probably to lithium splash accumulating on the deflector shaft, it was impossible to rotate the deflector from outside using the rotary feedthrough via the flexshaft connected to the deflector support shaft. The system was cooled and opened on 01/28 to directly rotate the shaft by hand. The new deflector profile was successfully aligned to investigate the effects of deflector shape.

The forth run was performed on 01/30. This run was very similar to the 3rd run except the deflector shape.

The fifth run was performed on 02/04. The objectives were to obtain the best and long stability data and investigate the spatial thickness variation while moving the e-beam on the film. The cutout with the 2 wick structures was selected for obtaining the best film. To align the deflector, again the chamber was cooled and opened and the deflector was directly rotated by hand.

Some of the representative figures for history of parameters are shown below. Figure 16 shows the temperature history of the 01/24 run. The temperatures were measured in the nozzle assembly, representing the lithium jet temperature.

Figure 17 shows the drive pressure history of the same run (01/24), indicating that the drive pressure was varied in the range of 100-200 psia. Figure 18 shows the emission current from the e-gun. During the run, the emission current was increased to 50 μA to check whether an electron beam bombardment on a thin lithium film would produce an illumination or not (It didn't at $\leq 50 \mu\text{A}$, 30 keV). Figure 19 shows the signal received at the Faraday cup. The current received at the Faraday cup was measured via a picoammeter that also acted as an amplifier-converter to output an analog voltage signal proportional to the input current. It must be noted that the full scale of the picoammeter always corresponded to the output voltage of 2 V. Therefore, to convert the voltage signal back to the current at the cup, the range setting of the picoammeter is needed.

Figure 20 shows the temperature history of the 02/04 run. Figure 21 shows the drive pressure history of the same run (02/04). During the run, the drive pressure was maintained constant at 150 psia to measure the stability data. Figure 22 shows the vacuum in the vacuum chamber, indicating several pressure spikes. After a run, when the lithium was transferred back to the pressure vessel, low pressure Ar gas ($\sim 1\text{-}2$ psig) was introduced into the vacuum chamber and the lithium collection vessel to push the collected lithium back to the pressure vessel. During this transfer process, a very small amount of this low pressure Ar could get trapped in the lithium nozzle assembly and these small Ar gas bubbles could be pushed out through the nozzle during a run and could produce these pressure spikes. Figure 23 shows the emission current from the e-gun. Figure 24 shows the signal received at the Faraday cup. This time, extensive Faraday cup current data were recorded by the oscilloscope at high sampling rates. These data were recorded by the oscilloscope and used to evaluate the film thickness and its stability.

FRIB Lithium Stripper Thickness and Stability Measurements
February 28, 2011

Figure 16 – Temperature history of 01/24 run.

Figure 17 – Drive pressure history of 01/24 run.

Figure 18 – Emission current history of 01/24 run.

Figure 19 – Faraday cup signal history of 01/24 run.

FRIB Lithium Stripper Thickness and Stability Measurements
February 28, 2011

Figure 20 – Temperature history of 02/04 run.

Figure 21 – Drive pressure history of 02/04 run.

Figure 22 – Vacuum history of 02/04 run.

Figure 23 – Emission current history of 02/04 run.

Figure 24 – Faraday cup signal history of 02/04 run.

2.6.1.1 Stability

After inspecting recorded digital movies, it was concluded that the film stability has greatly improved over the film produced in the previous experiments in 2005. The visually observable film disruption due to interference with the lithium puddle on the deflector in the previous experiments was virtually eliminated. Only once in the 02/04 run, a subtle, momentarily unstable film behavior was visually observed, Figure 25 and Figure 26. The breakup lasted for about 2/3 sec.

Figure 25 – Film breakup, L & stable, R (02-04-2011)

As mentioned previously, after a run, when the lithium was transferred back to the pressure vessel, low pressure Ar gas (~1-2 psig) was introduced into the vacuum chamber and the lithium collection vessel to push the collected lithium back to the pressure vessel. During this transfer process, a very small amount of this low pressure Ar could get trapped in the lithium nozzle assembly and these small Ar gas bubbles could be pushed out through the nozzle during a run and produce an unstable round jet. This, of course, would break the round jet and the resulting film. If this is the reason for the film breakup,

then it will not be a problem in the FRIB system, because that system will be a continuously flowing, pumped system.

Figure 26 – Film breakup, L & stable, R (02-04-2011)

Figure 27 – Oscilloscope raw data taken on 02/04 run for 10 sec at sampling rate of 12.5 kHz.

Figure 28 – First spike in Figure 27.

Figure 29 – Second spike in Figure 27.

The oscilloscope data recordings from the Faraday cup current were also used to investigate the film stability. For example, Figure 27 shows the raw data taken on 02/04 at 12.5 kHz for 10 seconds. The amplitude corresponds to the transmitted electron

current through the film. Most data are concentrated around 1 (volt), indicating that the film thickness didn't vary over a 10 second period. However, there are a few sharp spikes in the signal. Figure 28 shows the first spike in Figure 27. The range of the full time width in the figure is 20 ms. The signal started increasing from 1.01 V at -4.90952 sec, reaching its maximum of 1.83 V at -4.90856 sec. The spike then showed a somewhat exponential decay and came back to 1.03 V at -4.90184 sec. The second spike presented in Figure 29 shows very similar behavior. In other oscilloscope raw data, similarly, most data are concentrated around an average value of the readings, indicating that the film thickness didn't vary during each recording period (the longest was 400 seconds).

Figure 30 – E-beam locations viewed from the ion beam port.

Figure 31 – Actual beam positions on lithium film.

The oscilloscope data were taken at various locations (see Figure 30) for 10 seconds at 12.5 kHz to see the stability of the film at high temporal resolution as well as the spatial thickness variation. Each of these files contains 125 thousands data points. One set of data (T0029) was taken at the center of the film but for a longer period of time of 400 seconds with lower sampling rate of 3.125 kHz, containing 1.25 million data points, to see the long-term stability of the film. To analyze this very large amount of raw data (for example, the longest, 400 seconds raw data file taken at 3.125 kHz contains 1.25 million data points), a histogram was produced for each data file. Figure 32 shows 4 such histograms (T0024-center, T0025-top, T0025-bottom, T0029-center). This figure indicates that the film thickness at various locations is very uniform with a small thickness variation. Those sharp spikes in the Faraday cup signals appear in the histogram as data away from the average thickness. As shown in the histogram, those spikes appear very infrequently.

The spikes do not correlate with any visible phenomena; if their time scale were related to a hole in the film, then the following analysis would hold. First, looking at a few of the rise times of the spikes, they are about 1 ms in duration (different days, different datasets, different sampling rates). The decay time scale is about another 6 ms.

1) So, assume that a hole in the film is actually a long, narrow, rectangular opening (a thin slit) in the film that is moving at the film speed of ~ 60 m/s. Assume the width of the hole (or slit) is very small, but adequately large to allow enough e-beam to pass through the film to momentarily peg out the picoammeter. Also assume that the hole moves past the beam with the long side flowing vertically down. So, the length of the rectangular slit is equal to the width of a spike multiplied by the speed of the film, $(0.001 + 0.006) \text{ sec} \times 60. \text{ m/sec} = 420 \text{ mm}$.

It does not seem credible that a 420 mm long slit would exist in the film without one of two things happening: 1) the film would rip apart, or 2) we would see the slit.

2) One could postulate that the rise of the spike correlates with the arrival of the long narrow rectangular opening in the film, and that the decay part of the spike is an inherent time constant of the electronics when they decay from saturation. Taking this model, the length of the rectangular slit is equal to the rise time of a spike multiplied by the speed of the film, $0.001 \text{ sec} \times 60. \text{ m/sec} = 60 \text{ mm}$.

Same lack of credibility argument applies for the 60 mm slit length.

3) One could also argue that the slit is oriented at 90 degrees to the above model, i.e. that the width of the slit, in the direction of film travel is very narrow, but adequately large to allow enough e-beam to pass through the slit in the film to momentarily peg out the picoammeter (same idea as above, but rotated 90 degrees). In this case, the rise time of the spike would be related to the length of time that it takes for the slit to move past the 1 mm diameter beam spot. This leads to a calculation of the speed of the slit as it passes by the e-beam, thus: $\text{slit speed} = 1 \text{ mm} / 1 \text{ ms} = 1 \text{ m/s}$.

Knowing that the film speed is around 60 m/s, it does not seem credible that a slit, or hole in the film could move at a speed 60 times slower than the bulk fluid velocity.

We believe that since none of these explanations seem credible, we can rule the spikes to be noise at this point, and say that the issue must be investigated further with different instrumentation.

Figure 32 – Histogram of film thickness data.

2.6.1.2 Thickness

From the Figure 32 histogram, various thickness values are obtained at different locations on the film produced on 02/04. The driving pressure was 150 psia (see Figure 21) and corresponding lithium velocity was estimated to be 64 m/s. Those values are shown in Table 2. The center and full width at half maximum (FWHM) values were evaluated around each peak. Data below 0.1% occurrence were not used to evaluate these values. Because the e-beam was intercepted at 45 degrees by the lithium film, the actual lithium film thickness is $\sin(45^\circ) \times$. The variation was defined as the ratio of FWHM to the center thickness value.

	T0024	T0025	T0026	T0029
Position	Center	Top	Bottom	Center
Relative vertical distance (mm)	0	3.33	-3.7	0
Centroid ($C_{eq} \mu\text{g}/\text{cm}^2$)	610.0	1261	355.6	586.9
FWHM ($C_{eq} \mu\text{g}/\text{cm}^2$)	14.76	28.09	8.793	18.16
Actual thickness ($C_{eq} \mu\text{g}/\text{cm}^2$)	431.3	891.7	251.4	415.0
Variation (based on FWHM)	0.024	0.022	0.025	0.031

Table 2 – Film thickness and variation.

2.6.1.3 Spatial thickness variations

The film has lower gradient between center and bottom than between center and top (see Table 2 and Figure 33). This is consistent with the fringe pattern in the water films. Since these notations were arbitrarily determined, the “film thickness” will be given as the film thickness observed halfway between the center and bottom positions.

Figure 33 – Spatial thickness variation.

To calculate the true thickness, an electron simulation code, CASINO was used. The code was run to calculate the transmission values over 0-1500 $\mu\text{g}/\text{cm}^2$ for carbon and lithium. Comparing these 2 sets of numbers for the same transmission, the conversion from the carbon equivalent thickness to the lithium equivalent thickness was carried out. For the values obtained in the 02/04 run, the center thickness at 45 deg. (carbon equivalent) was 600 $\mu\text{g}/\text{cm}^2$ and the bottom thickness at 45 deg. (3.7 mm lower) was 356 $\mu\text{g}/\text{cm}^2$. The center lithium thickness is 1075 $\mu\text{g}/\text{cm}^2$; correcting for 45 degree angle: 760 $\mu\text{g}/\text{cm}^2$. The bottom lithium thickness is 710 $\mu\text{g}/\text{cm}^2$; correcting for 45 degree angle: 502 $\mu\text{g}/\text{cm}^2$ (see Figure 34).

Figure 34 – CASINO simulation comparing C and lithium transmission.

The corresponding spatial thickness change in 3.7 mm is $258 \mu\text{g}/\text{cm}^2$, or $35 \mu\text{g}/\text{cm}^2$ per 0.5 mm (the expected beam spot radius). The expected central thickness (at halfway between center spot and bottom spot) is $632 \pm 35 \mu\text{g}/\text{cm}^2$ ($\pm 5.5\%$ for 1 mm spot diameter).

Since the gradient is non-linear (flatter as moving away from the impaction point), the uniformity is probably even better near the bottom spot position where the thickness is $502 \mu\text{g}/\text{cm}^2$. The lithium temperature was 220°C (see Figure 20) and its corresponding density was $513 \text{ kg}/\text{m}^3$. Using this density value, $760 \mu\text{g}/\text{cm}^2$ of lithium corresponds to $14.8 \mu\text{m}$, $502 \mu\text{g}/\text{cm}^2$ of lithium corresponds to $9.78 \mu\text{m}$, and $632 \pm 35 \mu\text{g}/\text{cm}^2$ of lithium corresponds to $12.3 \pm 0.7 \mu\text{m}$.

3 SUMMARY AND CONCLUSIONS

A number of tests were conducted on the prototype FRIB liquid lithium thin film stripper system, in which 1) the thickness of a flowing film of liquid lithium was measured in real time, 2) the thickness distribution of the film was measured in real time, and 3) the stability of the films was determined based on both digital video recordings and digital signal recordings of Faraday cup current. The system was modified to facilitate convenient and efficient testing of design variations in nozzle and deflector geometry so that their effect on film thickness and film stability improvement could be determined. A previously developed electron beam based thickness measuring system was recalibrated for this specific geometry and used to measure the film thickness under a number of different flow conditions and deflector designs. A thin film ~9 mm in width, flowing at a velocity of ~60 m/s was formed under several flow conditions and with several deflector designs. A deflector design was found that practically eliminates the puddle issue. The resulting film stability is judged to be excellent; based upon a ~25 minute stable flow run during which time only a single breakup of the film occurred. That breakup event, which lasted only about 0.6 second, was most likely caused by an Ar gas bubble that became trapped in the high-pressure lithium line, during lithium transfer operations. The trapped gas issue will not be a problem for the FRIB stripper system because a pumped, closed loop system will be used, eliminating the need for lithium transfer operations. Based on thickness distribution measurements from the electron beam system, the expected central thickness (at halfway between center spot and bottom spot) was $632 \pm 35 \mu\text{g}/\text{cm}^2$ ($\pm 5.5\%$ for 1 mm spot diameter). This corresponds to a physical thickness of the flowing lithium film of $12.3 \pm 0.7 \mu\text{m}$.

Appendix A: Simulant experiments

Introduction and Prior Work

Earlier DOE funded tests using water as the stimulant helped determine various parameters. The optimum angle of the jet with respect to the deflector was found to be about 45 degrees. It was also found that the best films were produced when the distance from the end of the nozzle to the deflector was as short as possible and when the impaction point of the round jet was about one jet diameter up from the edge of the deflector. The face of the deflector needed to be highly polished with a thin back cut edge.

Prior DOE funded experiments in lithium revealed that the quality of the lithium film produced was not satisfactory. Observations showed that puddle formation on the deflector near the impaction point periodically disturbed the thin film. In addition, dripping lithium from the puddle on the deflector interfered with and disrupted the lithium film. Also, the lithium nozzle design had not optimized to form the best possible smooth round jet. Key design parameters needed further investigation to fully understand the following issues:

1. optimization of the nozzle design.
2. puddle formation and droplet interference, and
3. film uniformity

To better understand how these parameters influence film formation and behavior, water experiments simulating the formation of lithium films were made. Figure 35 shows the water stimulant setup.

Figure 35 – Simulant film testing setup.

Nozzle design

The standard nozzle produced by the manufacturer (AM Gatti) for water service has a sapphire orifice with a larger opening in the nozzle body downstream of the orifice (Figure 36). Sapphire is used for water because it can be highly polished and resists wear from high-pressure water. However, sapphire is not compatible with molten lithium, so it cannot be used in the lithium stripper system.

The lithium nozzle used in the prior DOE funded thin film system was made from one piece of stainless steel. This one-piece nozzle did not exactly conform to the shape of the manufacturer's standard, sapphire-orificed, nozzle (Figure 36) that has 3 sections along the flow path, each section with a different diameter (Figure 37). In addition, the manufacturer cannot polish the edge of the orifice in the one-piece design as well as the sapphire orifice can be polished in the three-piece nozzle (Figure 39). The present water experiments confirmed that these differences apparently have an impact on the quality of the round jet issuing from each nozzle (see Figure 38), although the quality of the jet seems to be very insensitive to the inner diameter at exit, ID_e , as long as it is reasonably larger than the inner diameter of the orifice, ID_o , by ~ 0.1 mm for water. This number may be different for lithium since the surface tension of lithium is much larger than that of water. It was found that this quality deterioration is more pronounced at lower drive pressures.

Figure 36 – All stainless and standard nozzles

Figure 37 – Details of the flow path in the standard nozzle

20 mil Al₂O₃
File:100-265

10 psi

20 mil SS
File:100-275

Figure 38 – Comparing jets from standard (above) and all-SS (below) nozzles

It was observed during previous DOE funded water experiments that nozzles with larger orifice openings (ID_o) did not produce good films. Many water experiments were performed in the work reported here using sapphire-orificed nozzles and the quality of the films was checked (see Figure 40). The value of the inner diameter at inlet, ID_i , is directly related to the size of the nozzle (see Figure 41). The size of the nozzle is given as the size of the thread and the head of the nozzle body that can have variety of orifices (hence different orifice openings, ID_o) with different inner diameter at exit, ID_e to form a “family” of nozzles. Therefore, within that “family”, there can be different ID_o and ID_e , while they have the same ID_i .

Figure 39 – Sapphire orificed nozzle and all stainless steel orifice-less nozzle

Results (Figure 40) show that apparently the larger nozzle (hence larger inner diameter at inlet, ID_i) can produce good quality films with larger orifice openings, ID_o . For example, it was impossible to form a good quality film using the 30 mil opening orifice in the 7/16 inch nozzle, but a limited number of results from the 9/16 nozzle indicates a good quality film can be produced using even a 60 mil opening orifice. From these film formation maps, it was decided to use a larger nozzle (9/16 inch) instead of the nozzle used last time (3/8 inch), in the DOE funded work.

A summary of nozzles that were tested in water is given in the table below.

Nozzle Family	Nozzle size Size of thread Mfgr #	Orifice diameter (inches) ID_o	Inner diameter at exit (inches) ID_e	Tested?	Orifice Material
3024	3/8" - 24 tpi	0.010	0.041	Y	Sap
		0.016	0.040	Y	Sap
		0.020	0.040	Y	Sap
		0.020	0.020	*Y	SS
		0.038	0.055	Y	Sap
		0.040	0.055	Y	Sap
		0.039	0.039	Y	SS
		0.055		N	Sap
3076	7/16" - 20 tpi	0.010	0.040	Y	Sap
		0.014	0.040	Y	Sap
		0.017	0.040	Y	Sap
		0.020	0.040	Y	Sap
		0.020	0.055	Y	SS
		0.022	0.055	Y	Sap
		0.025	0.055	Y	Sap
		0.026	0.055	Y	Sap
		0.028	0.055	Y	Sap
		0.030	0.055	Y	Sap
		0.032	0.055	Y	Sap
		0.033	0.055	Y	Sap
		0.035	0.055	Y	Sap
		0.036	0.055	Y	Sap
		0.037	0.055	Y	Sap
		0.039	0.055	Y	Sap
		0.040	0.055	Y	Sap
		0.060	0.067	N	Sap
3349	9/16" - 18 tpi	0.020	0.055	Y	Sap
		0.020	0.055	**Y	SS
		0.040	0.055	Y	Sap
		0.060	0.073	Y	Sap
*Used in Li - previous work			**Used in this Li work		

This investigation was suspended to concentrate resources on construction of the lithium loop system; it should be continued and completed with all stainless steel nozzles that conform to the same shape as the standard nozzle, to check the validity of the map for stainless steel nozzles. Also a wider variety of the nozzles should be used to better develop this map.

Figure 40 – Film formation maps with different nozzle sizes

Figure 41 – Details of the 7/16 inch nozzle (from AM Gatti website)

Deflector design

A new deflector design, Type-1, with a cutout to facilitate liquid draining was fabricated and tested with water. This new design was made to promote draining of liquid from the face of the deflector to the edges of the cutout, minimizing the formation of a puddle near the impaction point. Figure 42 & Figure 43 compare the old deflector and the new deflector designs.

Water experiments showed that this modification was effective in minimizing the size of the puddle on the deflector and shifting the dripping points away from the film (see Figure 43). The Type-1 deflector design, Figure 44, was installed in the lithium system as the first deflector; and was used from 11-16-2010 through 11-23-2011. The film produced by that deflector is shown in Figure 45. Based on the deflector water test results, another, further improved, 4-way deflector with multiple cutouts and highly polished surfaces was fabricated, Figure 46. The 4-way deflector was used in lithium testing beginning 1-24-2011. The optimum radius of the deflector cutout, which must be determined via lithium testing, was not fully explored.

Figure 42 – Old and new deflector designs.

Figure 43 – Pictures of old and new deflectors in operation.

Figure 44 – Type 1 deflector, front view

Figure 45 – First lithium film with Type-1 deflector 11-23-2010

Figure 46 - 4-way deflector

Film Uniformity

It was observed in water testing that the quality of the edge of the deflector from which the film departs is very important in determining the quality of the resulting film. An imperfection in the edge of the deflector directly translates into an imperfection of the same order of magnitude in the smoothness, and thus the uniformity in film thickness, of the resultant film. Therefore, to include this feature to some extent in the Type-1 deflector, yet take delivery on a schedule that would support the timely acquisition of water test results, the Type-1 deflector was fabricated from a pre-polished piece of stainless steel stock. To provide the best edge possible, with known fabrication techniques, a 1 μ in diamond polish surface finish (1 microinch = 1/39.37 micrometer) was specified on the front face and the 4 back cut surfaces of the 4-way deflector, see Figure 46.

A fringe pattern in the films in the Figure 43 images can be seen. In water tests performed with prior DOE funding, it was observed that some films produced by a 4 mil sapphire orifice nozzle contained interference patterns known as Newton's Rings. With some effort it was possible to obtain similar interference patterns in the 10 mil and 20 mil nozzles with both sapphire and stainless steel orifices. Measurement of the fringe spacing is an indication of the degree of the film's uniformity of thickness. Figure 47 presents an analysis of one film's fringe pattern. From the spacing between fringes, the variation in the film thickness in the horizontal dimension is calculated to be 5.7 μ m, while the vertical variation in film thickness is calculated as 8.6 μ m. If the edge is assumed to have zero thickness then the number of fringes between the center and the edge provides some reasonable estimate of the film's thickness. This assumption results in an estimated water film thickness of about 9 μ m.

Figure 48 presents a comparison of the fringes produced by sapphire and stainless steel orifice material in the same size nozzle, at the same pressure and with the same nozzle to target geometry. Both produce similar fringe number and spacing patterns, indicating similar film thickness and flatness characteristics. However, the fringe pattern produced by the SS nozzle appears to be less distinct, not as sharp. Since the fringe patterns are best observed using time exposure photography, as was the case for the photos in Figure 47 and Figure 48, we believe that the lack of sharpness in the fringe patterns of the SS nozzle is due to slight temporal variations in the film thickness of SS nozzle-produced films compared to the thickness of films produced by the nozzle with a sapphire orifice. Based on the results of the nozzle design observations and the film uniformity observations, it was decided to use an all stainless steel nozzle that conforms to the same shape as the standard nozzle, see Figure 49. We also requested the manufacturer to polish the SS orifice of the nozzle as well as his technology would permit.

The fringe patterns shown in Figure 47 and Figure 48 were created by shining the light from a helium neon laser onto the film, whereas in Figure 43, a sodium vapor lamp was used. The analysis of the fringes in the water work discussed above and the images in Figure 47 and Figure 48 were done under prior DOE funding.

Figure 47 – Observed optical interference and measured thickness variation.

Figure 48 – Comparison of Sapphire and Stainless Steel Nozzle Materials

Summary

The water experiments helped to resolve three main issues:

1. optimization of the nozzle design.
2. puddle formation and droplet interference, and
3. film uniformity

Several nozzle designs were eliminated, and a suitable nozzle design was found using these experiments. Based on the results of the nozzle design observations and film uniformity observations, it was decided to use an appropriately sized, 3-piece nozzle. Because of the incompatibility of sapphire with molten Li, the orifice must be made of a material that is known to be compatible with Li. Although stainless steel is not an ideal material for making an orifice (it is not as hard as sapphire), it was decided to make a 3-piece nozzle with a stainless steel orifice that conforms to the same shape as the standard nozzle, see Figure 49. We also requested the manufacturer to polish the stainless steel orifice of the nozzle as well as his technology would permit. A promising solution to the puddle and resulting droplet problems was found by changing the deflector design. But since the physical properties of water are quite different from those of lithium, the above issues may not be fully resolved in lithium service. However, the excellent quality of round jets and films produced during all the lithium testing reported here, which were based on the results obtained using water, demonstrate the effectiveness of this approach.

Figure 49 – All stainless, 3-piece nozzle

Appendix B: Hardware and System Description

Figure 4.1 is the lithium loop piping diagram. This figure shows all the major vessels, pumps, valves, and interconnecting pipes. In the following sections of this report, part numbers used in this figure will be referenced and discussed. From the color key on the diagram, the part numbers referenced are grouped in series that help identify the parts function.

a. Liquid Lithium Thin Film System

i. Major system components

1. The high pressure lithium reservoir (641) is an ASME coded vessel fabricated from type 304 stainless steel. It has an inside diameter of 18.25 cm, an overall length of 96.5 cm, and has a wall thickness of 1.8 cm with a net volume of 23 liters. It was designed to operate at an internal pressure up to 2000 psig and at temperatures up to 662 degrees F. It has two penetrations, one 0.5" OD in the top head and another 1" OD in the bottom head.

The top penetration is connected to the high pressure Ar gas used to push the lithium through the nozzle. The bottom penetration is used to supply lithium to the nozzle or return the lithium to the reservoir from the collection chamber (642).

2. The Vacuum chamber (642) is mounted on top of the collection chamber and is where the film is generated. This chamber was manufactured out of stainless steel by Nor-Cal and is shown in Figure 4.2. Two chambers were built, one for the e-gun system's initial setup and the second for the stripper loop.

There are many side ports on this chamber, each with a specific function. Each port is terminated in con-flat style vacuum flanges. Following is a list of the side port functions:

1. Lithium Nozzle assembly,	6. Main beam outlet
2. E-beam inlet	7. MCP system
3. Faraday cup	8. View ports
4. Vacuum system	9. Illumination port
5. Main beam inlet	

Standard copper conflat gaskets were used on these flanges except where molten lithium was expected. Molten lithium quickly dissolves copper if they are in contact, so in these locations special soft iron gaskets were used. Most ports were fitted with gate-type vacuum valves. These valves were fitted with Kel-Rez type seals to withstand higher than normal operating temperatures.

Figure 4.1 Lithium Stripper Loop Piping Diagram

Figure 4.2 Lithium Stripper Vacuum Vessel

3. High Pressure Piping is used to supply high purity argon gas to push the molten lithium through the nozzle. This consists of Ar gas and molten lithium lines.

The lines were constructed out of type 304 stainless steel seamless tube. 0.5" OD tube with a wall thickness of between 0.049" and 0.065" or 1"OD tube with wall thickness of 0.083" were used. Connections between various sections were either welded or used Swagelok VCR or Swagelok tube fittings made out of either type 304 or 316 stainless steel. All molten lines used VCR type fittings and bellows sealed valves.

All connections had to be vacuum tight and were checked with a helium mass spectrometer type leak detector.

ii. Film Production Components

It was decided to use as many commercially available parts as possible in order to take advantage of existing expertise and help keep costs down. The initial tests with water determined many of the requirements. We chose to work with A.M. Gatti Inc as they are a leader in high tech water nozzles and they were very willing to help with any special manufacturing, if needed.

1. Nozzle Assembly

The nozzle assembly consists of the nozzle holder and nozzle. Within the nozzle is the orifice. From the water tests we found that the larger the nozzle the better the film produced.

a. Nozzle Carrier

The nozzle screws into the carrier where a seal is made between the two pieces. Figure 4.3 is a drawing of the carrier. This type 316 stainless steel holder was slightly modified from a standard commercial part in order to allow a butt-weld with the connecting pipe.

Figure 4.3 Nozzle Carrier drawing

b. Nozzle

The largest standard nozzle produced by Gatti is 9/16". Although the figure shows a 7/16" nozzle, the 9/16" is very similar except for the slightly larger size. We had two special nozzles fabricated from type 17-4 stainless steel, a one-piece design and a three-piece. Gatti used special care to duplicate their sapphire design dimensions and finishes as much as possible. Both type nozzles had 0.020" dia. orifices and 0.055" dia. exit holes. Because of time constraints we never tested the new nozzles with water, although Gatti tested them at 200 psig and reported very nice jets produced. We chose to install the three-piece nozzle on the lithium loop. See Appendix A for more details on the nozzle.

c. Orifice

The orifice on the all stainless steel three-piece nozzle installed in the loop was made in the following manor. First, the orifice was fabricated in a disk of thin stainless steel followed by wire polishing the opening. These two steps are very critical and proprietary in order for the nozzle to make a good cohesive jet. They used the same procedure for polishing as they use for the standard sapphire nozzle. Sapphire is their material of choice as it is very hard and takes a very fine polish.

Starting with their standard model 3349 9/16" nozzle body, they inserted the orifice disk. A stainless steel retainer was then pressed in to capture the orifice disk and make a seal. In their standard nozzle, they use a plastic piece along with the retainer to make a better seal, but because of the temperature of the molten lithium and the chemical incompatibility between plastic and lithium, the plastic could not be used. We felt this would not be a problem as their standard nozzles operate at pressures up to 50,000 psig and we were planning on operating at less than 200 psig. The one-piece nozzle was fabricated differently. Gatti made a special nozzle body out of one piece of stainless with the orifice fashioned into the body. The exit hole was then drilled from the face side. Polishing was much harder to do and was done by hand. An advantage of this design is that there is no possible leak around the orifice. It was decided that the three-piece design had the best chance of producing the best film.

d. Nozzle heater

The nozzle carrier and nozzle are suspended in a vacuum and only supported from one side via a relatively long 3/4" dia. stainless steel lithium supply tube. This does not provide good thermal contact between the nozzle and any heated surface. In order to heat the lithium in this assembly, a heater-thermocouple assembly with an outer sheath made of type 304 stainless steel was inserted inside the 3/4" dia. supply tube nearly all the way to the nozzle. See figure 4.4 for a detailed drawing.

The heating element is rated at 500 watts @ 39 volts and the two thermocouples are type K. One thermocouple is used to control the heater power in order to maintain a given temperature. The second TC is used for temperature monitoring.

Operating condition:
350 °C @ 2000 PSI

Vincent J. Novick
Argonne National Laboratory
Nuclear Engineering Division
+1-630-252-1527
8/10/2010

Figure 4.4 Nozzle heater assembly

e. Nozzle adjustment system

An adjustable nozzle system allows a small amount of nozzle position adjustment. A drawing of this assembly is shown in figure 4.5. A flexible bellows allows movement of the nozzle assembly with respect to the mounting flange while maintaining the chamber vacuum. Four springs mounted on threaded rods along with standoffs and nuts allow either up/down, left/right, or in/out movement of the nozzle. This system is difficult to adjust because the liquid lithium feed pipe connects this assembly to the supply reservoir. This thick walled 0.5"OD stainless steel tube is quite rigid, especially when it is filled with solid lithium making adjustment difficult.

Figure 4.5 Nozzle and Adjustment Assembly

2. Deflector

The thin lithium film desired is produced by allowing a very fast moving non-turbulent jet of molten lithium metal to strike the edge of a deflector. The resultant film's quality depends on the shape and finish of the deflector as well as the quality of the jet itself. Two deflectors were fabricated out of type 304 stainless steel. The front face of these deflectors is highly polished. Special care was taken during their fabrication not to allow any rough edges where the film forms. Figure 4.6 is a drawing of the second deflector used in the final tests.

Figure 4.6 Deflector Drawing

The first deflector tested was similar to the above figure but only had one deflector cutout surface (the bottom cutout at the 6:00 position as shown on the drawing.) This is the same deflector as used in the earlier water stimulant experiments. The second deflector was then completed as shown in the figure, but with the addition of two wicks. These stainless steel mesh wicks were added one to each side of the deflector cutout on the right side of fig. 4.6 (3:00 position) and were about 3" long. Their purpose was to help direct the lithium on the top of the jet impingement point away from the film area where it could harmlessly drip to avoid disturbing the film. Figure 4.7 shows the actual deflector with wicks installed before being installed in the chamber. Note the highly polished mirror-like finish on the front face.

Figure 4.7: Lithium deflector with wicks installed.

3. Deflector Adjusting System

The deflector plate is mounted on a shaft supported by bearings permitting several types of adjustments. See figure 4.8 for a view of the top flange assembly. The shaft that supports the deflector is held in position by two linear actuators. By adjusting the length of the two support arms, the vertical position of the deflector can be changed or the deflector can be tipped forward or backward. The deflector shaft can also be rotated by means of an actuator. This causes the deflector to rotate and thus changes which portion of the deflector is creating the film. The second deflector had four different shapes to be tested.

4. Vacuum System

The stripper loop has several vacuum systems, both high and low pressure. The chamber high vacuum system consists of three high vacuum pumps. A 230 l/sec compound molecular turbo-pump (522), a 120 l/sec triode type ion-pump (523), and a small oil type diffusion pump (521). In this loop the turbo pump and the diffusion pump can each be isolated from the upper chamber with its own valve (504 and 532 respectively) while the ion pump can not. In order to keep the target chamber oil-free, the diffusion pump was not used. Also, the backing pump (423) for the turbo is an oil-free scroll type pump. A small 75 l/sec turbo pump (530) is mounted on the e-gun beam line and another 75 l/sec turbo (531) is mounted on the MCP. These pumps are also backed by a scroll pump (424). These two turbo pumps help maintain a good vacuum in their respective systems. An oil free roots type vacuum pump (421) with a pumping speed of 27 m³/h is used as the chamber low vacuum system. This pump is used to remove most of the argon cover gas from the chamber before the turbo is valved on to the chamber. Vacuum gauges are used to measure the pressures in the chamber and systems. Convectron gauges (411, 412, 413, 425, 426, and 511) are used between atmosphere and 1E-4 torr while Micro-ion gauges (424, 512, 533, and 534) are used for high vacuum measurements below 1E-4 torr. Also, the ion-pumps current draw is calibrated for reading its vacuum.

5. Heating System

Type-K thermocouples (TCs) are attached to the loop at various locations to monitor temperatures and some of them are used to control the heaters. A multiple zone heating system using ceramic band heaters controls the system temperature and temperature distribution and minimizes hot/cold spots, which could result from significant differences in metal mass from component to component. The heaters are grouped into 7 different zones for optimum heating as well as power distribution.

Each heating zone is controlled by a solid-state heater power control system. Each control system contains two independent temperature controllers while each controller has its own TC for temperature monitoring. One controller is to accurately control the temperature around the set point and another controller acts as a circuit breaker to turn off the power to the zone when the reading from the TC exceeds the over-temperature set point. This latter heater controller provides an extra over-temperature protection to the heater control system. All control TCs are sheathed, type-K and installed at the locations considered to represent the zone temperature. Each control TC is connected to an Athena series 16 programmable temperature controller, which controls the temperature of a zone by controlling the power to the heaters in that zone. Each over-temperature limiter TC is connected to an Omega high limit controller, which turns off the power to the heaters when the reading exceeded the set point. For controlling temperatures, 6 TC bundles are employed. Each TC bundle contains 4 Type-K TCs. The first of the 4 TCs provides an input to a temperature controller, the second provides separate input to another temperature controller for independent over temperature protection, and the third is a spare.

iii. Data Acquisition System

The fourth TC is connected to an Agilent 34970A data acquisition/switch unit for recording. Other various analog outputs including pressure readings from GP vacuum readers, MKS PDR-C-2C, Gamma Vacuum Ion pump power supply, emission current signal from the e-gun power supply, amplified signal from a Keithley 6485 picoammeter, and valve position signals are also collected by the Agilent 34970A.

A GP ionization gauge and a convection gauge are installed on the vacuum chamber to monitor the pressure in the vacuum chamber. There are several more gauges mounted at various locations on the system as well. These sensors are controlled by the GP vacuum readers. In addition, the ion pump power supply signal is also used to monitor the pressure in the vacuum chamber. Two MKS capacitance pressure gauges, controlled by the MKS PDR-C-2C reader, are installed on the high pressure Ar supply line to monitor the drive pressure.

The lithium valves (601 and 602) are electromechanically activated pneumatic valves and electric signals to control the valve control solenoids are monitored to obtain the valve position information.

The power supply for the e-gun has analog output proportional to the emission current from the e-gun. Also the e-beam received at the Faraday cup is read by the Keithley 6485 picoammeter. This ammeter amplifies the signal, which is subsequently monitored by a Tektronix DPO2024 digital oscilloscope and the DAS. The oscilloscope has much higher sampling rate (up to MHz range) than that of the DAS (~1 Hz) and is used to monitor and record the film stability data at a high temporal resolution.

A laptop PC collects various signals from the DAS via a General Purpose Interface Bus (GPIB) for display and storage. Data acquisition was controlled by a LabVIEW program.

b. Electron Beam Thickness Measurement System (EMS)

i. Major system components

The electron beam thickness measurement system is used to monitor and verify film stability and thickness. The system utilizes a low energy electron beam, and depends on the thickness-dependent scattering and absorption of electrons by the film to generate a real-time fast response film thickness gauge. For this purpose, a commercially available 30-kV electron gun (Kimball-Physics EMG-4214) has been purchased, and coupled to a 90° double-focusing bending magnet specifically designed for this application (see Figures 1, 2 and 4). To achieve a tightly focused beam, an electrostatic gridded lens was designed and built (see Figure 3). Electron detection is achieved with the use of a Faraday cup, which was designed and built in-house (see Figure 5). This Faraday cup is connected to a commercially available picoammeter, designed to measure very low currents. The current measured in the Faraday cup is proportional to the electrons striking the cup, with a higher current indicating a thinner film. In order to relate cup current to a film thickness, calibration with solid foils of a known thickness is required. A ladder assembly with thin carbon foils of known thickness (100-2000 $\mu\text{g}/\text{cm}^2$) was used to create a calibration curve relating cup current to lithium film thickness.

1. E-Beam Line: The electron beam line is shown below in Figure 1 and Figure 2. The major beam line components are indicated, and are further described below in more detail. The design of the beam line to include a bending magnet was done to reduce the chance of lithium vapor, mist, or splash reaching the electron gun during operation. The presence of the magnet also allows further adjustment of the beam by varying the magnet current. The Einzel lens is an electrostatic gridded lens operated at up to 15 kV, which allows further adjustment of beam focus. The bellows is a KF-Conflat conversion bellows which allows the electron gun beam line to be flexibly coupled to the chamber, and independently adjusted for alignment purposes. Not shown in Figure 1 is an electro-pneumatic gate valve, used to isolate the electron gun beam line from the lithium chamber. The electron gun and bending magnet have supports with integrated height adjustments to assist in beam line alignment.

2. Electron Gun: The Electron Gun used for film measurement is a 30 kV commercially available unit from Kimball Physics, Inc., with a beam current range of 10 nA-100 μA . This unit is equipped with the standard refractory metal disc cathode, and is controlled by a Kimball-Physics EGPS-4212A power supply. In this application, the gun is typically operated at 30 kV, and 10 μA beam emission. A vacuum environment is required, with a minimum vacuum level of 1×10^{-6} Torr required to operate the gun. The gun is operated via the power supply control chassis, with numerous adjustments for controlling the beam. Beam control parameters include gun energy, source voltage and current, grid voltage, deflection in the X and Y directions, and internal focus. A schematic of the gun internal components is shown below in Figure 4.

Figure 1: Electron gun beam line major components.

Figure 2: Installed electron gun system.

Figure 3: Einzel lens showing internal components.

Figure 4: Kimball Physics EMG-4212 Electron Gun internal components

3. Faraday Cup Assembly: The faraday cup used to detect electrons is a custom designed unit built in-house. The cup has an input aperture diameter of 48 mm, and has an outer grounded shield for secondary particles, and has a biased suppression ring. The cup is constructed of 304 stainless steel, and utilizes ceramic standoffs to electrically isolate the suppression ring and the inner cup. Figure 5 shows detail of the Faraday cup.

Figure 5: Faraday cup details

The cup is mounted to a vacuum-tight linear actuator, which allows the cup to move relative to the lithium film. The cup has a storage ‘garage’, which is located behind a valve, which allows the cup to be isolated from the lithium chamber, and away from potential damage from the molten lithium when not in use. When the lithium film is produced, the valve is opened, and the cup is extended to the appropriate position for measurement of the electrons. The cup actuator has a hollow shaft, so the cup and ring signal wires can be routed internally and be protected from shorting. The cup assembly is shown below in Figure 6.

Figure 6: Faraday cup assembly

The cup utilizes a suppression ring to suppress secondary electrons, which is electrically isolated from the rest of the cup. The cup was tested with and without a 200 VDC potential applied to the suppression ring, and no difference in signal was found in our application. As a result, the suppression ring was grounded during all subsequent experiments. The actuator allows the cup to film distance to be varied from approximately 150 to 300 mm. A lower cup to film distance provides a higher current (more electrons intercepted), but places the cup closer to the Li, increasing the chance of shorting due to lithium splash. A greater distance between the cup and film results in a reduced current signal, but provides an increased buffer between the cup and the Li. Initially, the cup was set at 300 mm distance during testing. When an initial lithium film was produced, a very noisy and weak signal was measured, and eventually the cup signal approached zero. To remedy this, the cup had to be moved closer to the lithium film to regain signal. This phenomenon occurred several times during operation. The cause of this loss of signal is unknown and is currently under investigation.

Figure 7: Faraday cup assembly with garage before installation on chamber.

Figure 8: Faraday cup assembly mounted to lithium chamber

4. Data Acquisition: The data acquisition system for the EMS consists of both high sample rate and low sample rate data logging. The output signal generated by the Faraday cup is monitored with the picoammeter, which amplifies and converts the current signal to a DC

voltage, and sends it to the oscilloscope and Agilent DAQ system simultaneously. This is accomplished with a Keithley 6485 Picoammeter, which is a precision current measuring device, with range from 20 fA to 20 mA, and a sampling rate of up to 1 kHz. The unit incorporates an analog output feature, with a ± 2 VDC scaled output, which is useful in reducing induced signal noise, or when the output is split to several devices. In our setup, the Faraday cup is connected to the Picoammeter via low noise BNC cables. These cables incorporate graphite lubrication within the cable, to reduce the noise induced by the triboelectric effect. From the picoammeter, the amplified voltage signal is connected to both the oscilloscope and the Agilent DAQ chassis. The Oscilloscope is a Tektronix DPO2000 200 MHz 4-channel unit, with 1 GS/s sampling rate incorporating USB port data logging. Figure 9 illustrates the data acquisition system overall configuration for the electron gun thickness measuring system.

Figure 9: Electron gun system data acquisition block diagram

The Faraday cup generates a current proportional to the electrons that strike the cup, typically in the nA-μA range. The picoammeter converts this signal to an analog voltage signal, that is sent to both the oscilloscope and Agilent DAQ unit. The oscilloscope has the capability to record this signal at a high sample rate, for a relatively short period of time. The Agilent DAQ is a multichannel device that connects standard sensor inputs to the PC for trending and logging. The sample rates with this device and the PC are much slower than the oscilloscope, but it can record for much greater periods of time. These simultaneous data recordings provide both detailed waveform capture and long term trending information. The data can then be processed and analyzed for overall trends, and specific events can be investigated with the high sample rate data recorded by the oscilloscope.

ii. EMS Calibration:

1. Description: The EMS operates on the principle of thickness-dependent scattering and absorption of electrons by a thin foil or film. The number of electrons detected in the Faraday cup, and hence the current measured, are dependent on the thickness of the film the electron beam strikes. The system first needed to be calibrated with several foils of appropriate and known thickness. This was done by striking the foils one at a time with the electron beam, and measuring the current in the Faraday cup. With foils of known thickness, a calibration curve was developed from this procedure, and applied when used with the unknown thickness of Li. The calibration data is dependent on cup-to-film distance, however. So, a different calibration procedure must be performed for each cup-to-film distance. The foils used for the calibration procedure are commercially available from ACF-Metals with a density of 1.83 g/cm^3 and thickness ranging from $3.22\text{--}12.3 \text{ }\mu\text{m}$. Foils were mounted on a ladder-type assembly mounted to an actuator, to allow adjustment (Figure 10). Also mounted to the ladder assembly are phosphor targets, used to observe the beam, and optimize the focus. Figure 11 shows the beam illuminating the phosphor target during shakedown. The ladder assembly was positioned perpendicular to the electron beam, so that an accurate image of the beam spot dimensions would be visible on the phosphor target. In the actual lithium chamber, the electron beam is at 45° to the lithium film. This difference was accounted for in the calibration data, and was corrected by a simple geometric correction factor of $\sqrt{2}$. Figure 12 shows the vessel, identical to the actual lithium chamber, used during shakedown and calibration of the EMS.

Figure 10: Ladder assembly with carbon foils and phosphor targets

Figure11: Electron beam on phosphor target during EMS shakedown.

Figure 12: EMS system shakedown and calibration vessel

The calibration procedure results in values for current measured from the Faraday cup with a certain thickness of foil between the cup and the electron gun (i_f). The current in the Faraday cup is also measured without the foils present (i_{nf}). A transmission value is then calculated by dividing the current with the foil in place by the current without the foil:

$$\text{Transmission} = i_f / i_{nf}$$

These dimensionless transmission values are plotted versus foil thickness. This calibration curve is used to determine actual lithium film thickness from the Faraday cup signal recorded during experimental runs.

2. Results: Initially, calibrations were performed for 150 and 300 mm cup-to-foil distances in the calibration vessel. It was planned that these calibrations would be applicable for the system when relocated to the lithium vessel. During calibrations it was observed that the cup current, and therefore the calibration data, appeared to be dependent on beam position. It was originally believed that the electron beam could be scanned during operation, and the thickness gradient determined in real time during that movement. But, since it was believed that the calibration was position-dependent, the beam was typically not moved during operation. It is not well understood why the system exhibited such behavior, but it was agreed that there was a need to perform another calibration on the system as installed on the lithium vessel. The same ladder assembly with carbon foils was installed, but this time it was oriented horizontally through an available port at 90° from the beam. This also provided the benefit of allowing the position and focus of the beam to be checked and adjusted as necessary. These calibrations were performed at a cup-to-film distance of 300mm. Once a lithium film was created, the output signal from the faraday cup dropped to essentially zero while the electron gun was operating. When the cup was moved closer than 300 mm to the film, the signal returned. The cause for this behavior is not known, but as a result the cup to film distance was reduced during the run. Since the cup current is dependent on the cup-to-film distance, a calibration was necessary at the new distance. During the next several runs, the cup distance required to measure a current from the faraday cup was decreased several times. Each time the distance was changed, a new calibration was performed. The cup-to-film distance started at 300mm, was reduced to 239mm, 213.5mm, and finally 150mm. Many additional calibrations were performed in-situ, to be used with the data recorded at the various cup-to-film distances. Finally, after operating at 150 mm cup-to-film distance, and recording reliable cup signals, a run was performed where the beam was moved to 5 different positions, to investigate film thickness and stability throughout the film, and to test the hypothesis of calibration-beam position dependency. For this test, the beam deflection settings were recorded, and a calibration was performed for all five of these beam positions. Figure 13 shows calibration data for four of the five beam positions, as well as an additional set of calibration data, and a curve fit and resulting equation. Figure 14 contains the same data, but plotted on a logarithmic scale on the Y axis. The fifth location, “bottom” position, was eliminated from the plots due to possible errors in the data, caused by the beam striking the aluminum foil holder frame, and partially obstructing the electron beam. The data labeled as “Data on 2011-01-31” is a calibration data set taken on a different day, but using the same foils and with the beam at the center position. As observed from these plots, data repeatability is very good, suggesting that the calibration procedure is fairly independent of

beam position. Some variation in the data is expected, due to inconsistencies in the carbon foils or variations in the gun emission, which have both been observed during testing.

Figure 13: Calibration curve for 150 mm cup to foil distance.

Figure 14: Calibration curve for 150 mm cup to foil distance, log plot.

Nuclear Engineering Division

Physics Division

Argonne National Laboratory

9700 South Case Avenue

Argonne, IL 60439

www.anl.gov

Argonne National Laboratory is a U.S. Department of Energy
laboratory managed by UChicago Argonne, LLC