Lithium Mass Flow Control for High Power Lorentz Force Accelerators

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Abstract. A lithium feeding system has been developed to measure and control propellant flow for 30-200 kW Lithium Lorentz Force Accelerators (LiLFAs). The new, mechanically actuated, liquid lithium feed system has been designed and tested as a central component of a campaign to obtain basic data and establish scaling laws and performance relations for these thrusters. Calibration data are presented which demonstrate reliable and controllable feed of liquid lithium to the vaporizer hollow cathode of the thruster at flow rates between 10 and 120 mg/s. The ability to thermally track the liquid lithium through the system by the use of external temperature measurements is demonstrated. In addition, recent developments are presented in the establishment and successful testing of a lithium handling facility and safety procedures allowing for the in-house loading of the feed system and the neutralization, cleaning and disposal of up to 300 g of lithium.

INTRODUCTION

The Lithium Lorentz Force Accelerator (LiLFA) is a high power electric propulsion option currently being considered by NASA for heavy payload orbit raising missions as well as for future cargo and human missions to Mars and the outer planets (Frisbee, 1996). Considered the next generation of the magnetoplasmadynamic thruster (MPDT), the LiLFA shares many of its features. As in the MPDT, propellant is ionized and accelerated through the direct application of a Lorentz ($\mathbf{J} \times \mathbf{B}$) body force arising from the interaction of an applied current and a self-induced and/or applied magnetic field. The MPDT and the LiLFA are unique among electric propulsion options in their the ability to process MW levels of power in a single, compact and simple device (thrust densities on the order of 10^5 N/m^2) while providing specific impulses (I_{sp}) from 1500 to 8000 seconds at thrust efficiencies exceeding 40%. High efficiencies (>30%) are typically reached only at high power (> 500 kW) lending to the consideration of steady-state MPDTs as a high-power propulsion option. The major limitations to the in-space application of steady-state MPDTs are the current lack of MW-level steady-state power in space and unacceptably low lifetimes due to erosion of the central cathode, which can be as high as 0.2μg/C. The LiLFA promises to overcome these deficiencies through the introduction of a multi-channel hollow cathode and by the use of lithium vapor as propellant. This combination allows efficient operation at power levels as low as 200 kW and significantly increased lifetimes. The demonstration of 50% efficiency at 0.5 MW with 500 hours of nearly erosion-free operation (Ageyev, 1993) has shown the validity of the LiLFA concept and placed it at the forefront of current high power propulsion research.

Recent work has been concerned with the design, construction, and successful testing of a new *mechanical liquid lithium* feed system to support basic studies and the development of scaling relations for LiLFAs. A *liquid* feed is required to allow the system to be compatible with LiLFAs employing vaporizer cathodes, such as the 30 kW Moscow Aviation Institute (MAI) thruster which will be employed during the present stage of an experimental LiLFA research program. A liquid system also has the advantage of not requiring expensive and fragile refractory metal construction and complicated heating and heat management schemes as are required for the vapor feed system previously developed by Princeton and Thermacore Inc. (Choueiri, 1996). A *mechanical* system is chosen, because it is believed that a mechanically driven system will provide better

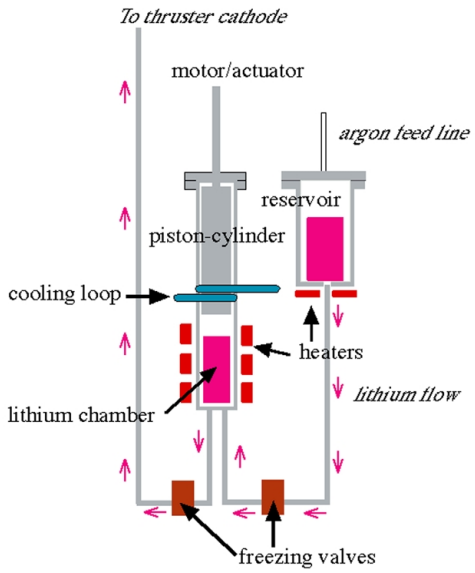

FIGURE 1. Schematic of the Mechanical Liquid Lithium Feed System Showing Path of Liquid Lithium Flow.

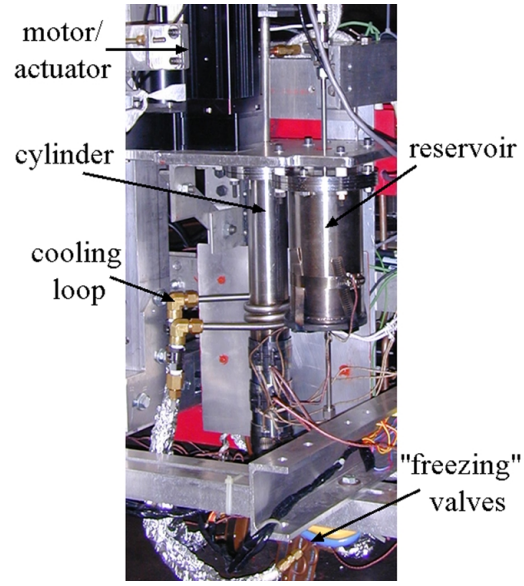

FIGURE 2. Photograph of Mechanical Liquid Lithium Feed System in Testing Facility. Reservoir Height is Approximately 15 cm.

mass flow accuracy and control than previous pressure driven systems used by groups at Los Alamos (argon pressure driven bellows) (Fradkin, 1973) and, more recently, at MAI (oil pressure driven piston) (Kim, 1995). A mechanical design is also shown to significantly simplify the flow rate determination without requiring detailed thermal balances and post-analysis as required by the above mentioned Princeton-Thermacore open heat pipe vaporizer design (Emsellem, 1999) and earlier pressurized vaporizer/sonic orifice systems tested by Electro-Optical Systems, Inc. (Nelson, 1967).

First, overall system design and operating principles are presented with a focus on key design issues such as valve design and lithium loading. The results of a recent calibration campaign are then discussed, during which the system design and operation are verified and controllable and measurable mass flow rates are demonstrated. Finally, a brief overview of lithium safety and handling in support of the on-going lithium research program is presented.

MECHANICAL LIQUID LITHIUM FEED SYSTEM DESIGN

The mechanical liquid lithium feed system is designed to deliver liquid lithium at flow rates of 10 to 120 mg/s to the vaporizer cathode of the 30 kW Moscow Aviation Institute LiLFA. A schematic of the feed system is shown in Fig. 1 , with arrows indicating the path of liquid lithium flow. A photograph of the system installed in the testing facility in shown alongside the schematic (Fig. 2). The key components and operation of the system will be the subject of the following paragraphs.

Reservoir Loading

The reservoir, shown in Fig. 1 and in the photograph in Fig. 2 , allows for the contamination-free loading of a solid lithium ingot into the system. The reservoir is loaded in the Lithium Handling Facility (LiHF), a 0.5 m^3 stainless steel glove box, under a positive argon atmosphere. An interior volume of 880 cm^3 allows the loading of a maximum of 470 g of solid lithium, this corresponds to the maximum amount of lithium the testing facility can safely handle between cleanings. In testing to date, the maximum amount of lithium

loaded has been 300 g. The reservoir flange is then sealed by an O-ring and four equally spaced hex bolts providing a leak-tight environment to 583 kPa. The leak-tight reservoir is then transferred from the handling facility to the testing chamber, a 1.5 m diameter by 6.4 m steel vacuum chamber. The upper argon feed line allows for a steady flow of argon to protect the lithium from contamination during the attachment of the reservoir to the rest of the feed system and during the initial stages of the pump down.

Heating and Power Requirements

Prior to operating the thruster, the system is brought to 523-623°K ($\approx$ 250-350°C) and the liquid lithium is gravity-fed into the feed lines and the section of the piston-cylinder assembly below the piston, referred to as the lithium chamber (see Fig. 1). The piston-cylinder assembly consists of a 35.6 cm long stainless steel cylinder with an inner diameter of 46.8 mm and a 20.3 cm long solid stainless steel piston of 46.5 mm outer diameter. With the piston in the fully retracted position, against the top flange of the cylinder, the lithium chamber is capable of holding approximately 133 g of liquid lithium. Feed system heating is accomplished through the use of a combination of commercially available heaters with power control provided by three separately controllable Variacs which maintain the system temperature above the melting point of lithium (453°K). The reservoir is heated from the bottom by a 500 W disk heater and the lithium chamber is heated by a band heater requiring 613 W. The thruster and reservoir lines are heated by 6.35 mm wide, Samox insulated, constant Watt/cm heating tape wired in parallel on a single Variac-controlled circuit. During start-up both lines are heated requiring 800 W of power to achieve steady state. Once filling of the chamber has been completed, the reservoir and reservoir line heating are discontinued. The thruster line operating alone on the line circuit requires 650 W. Total power requirements of the unoptimized system are therefore 1.9 kW during the start-up phase and 1.3 kW during thruster operation. System heat up time, including lithium melting and filling of the chamber, at the power levels mentioned is 3.5 hours.

"Freezing" Valves and Seals

Due to the moderately high temperatures involved and the corrosive nature of lithium, standard valves and seals cannot be used to control the flow of lithium through the feed lines or to prevent lithium from leaking along the piston. Lithium reacts with most valve seal materials, including teflon, requiring expensive all-metal valves. The reliability and lifetime of these valves when exposed to lithium and numerous thermal cycles is, at best, uncertain. As an alternative, it was decided to take advantage of the thermal properties of the lithium itself and employ thermal or "freezing" valves and seals.

To prevent liquid lithium from leaking into the gap between the piston and cylinder wall, several turns of 3/8 inch stainless steel tubing are spot welded to the cylinder approximately 5 cm above the top of the lithium chamber, as is shown in Figs. 1 and 2 . Chilled water provided to the loop creates an actively cooled ring just above the lithium chamber. Tests of the system confirm that, under normal operating conditions, lithium does not leak between the piston and cylinder. This concept of a cooling loop seal was first employed at the Moscow Aviation Institute with an oil actuated feed system, also with good success, (Kim, 1995) and has been modified and adopted here. This idea of thermal seals is extended to the design of valves for the lines to the reservoir and thruster. Once steady state is achieved, the line to the reservoir is closed using a water-cooled "freezing" valve to prevent lithium backflow into the reservoir during thruster operation. In this first iteration, with simplicity of construction and operation taking precedent over efficiency, the valves consist simply of solid copper blocks approximately 8 x 3.5 x 3.5 cm into which 6 turns of 1/8 inch copper tubing supplying chilled water have been pressed. The valves are clamped directly to the lithium feed lines by means of hose clamps. When actively heated, sufficient power is brought to the lines to overcome the effects of the valves and the lithium temperature is maintained above 473°K (200°C). However, when heating is discontinued, the effect of the active cooling is such that a solid lithium plug is formed at the valve location after less than 30 minutes. In addition to reducing the time required to "freeze" the lithium in the line, the active cooling also ensures that the plug will remain even in the event that heat is transferred back to the valve location through the lithium. The schematic in Fig. 3 shows the "freezing" valve concept and operation. Of the 1.3 kW of steady-state power provided to the system during operation, an estimated 230 W on average is removed by the freezing valves and cylinder cooling loop operating on chilled water ($\approx$ 293°K) at flow rates of 2-3 g/s.

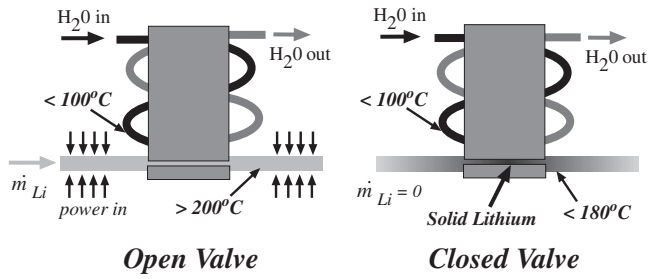

FIGURE 3. Schematic of "Freezing" Valve Operation with Continuous Water Flow.

Mechanical Liquid Lithium Feeding

Once the reservoir line has been closed, the system is ready for thruster operation. The motor/actuator system consists of a stepper motor/rodless actuator manufactured by Industrial Devices Corporation with a SmartStep^{TM} controller. The system is capable of driving the piston a distance of 15.24 cm at velocities as low as 1 μm/s, pushing the lithium out of the chamber, into the thruster feed line, and up to the vaporizer multi-channel hollow cathode. Piston position and velocity are controlled and monitored in real time by the SmartStep^{TM} controller. Position resolution is within $\pm$ 0.25 mm and velocity can be specified to within $\pm 1\mu$m/s. A thermocouple well, machined through the center of the piston, allows for the placement of a thermocouple approximately 6 mm from the chamber end of the piston to monitor lithium temperature during loading and feeding.

SYSTEM CALIBRATION

The goals of the initial calibration campaign were: to obtain a proof of concept for the "freezing" valves and cooling loop seal under operating conditions; to demonstrate the ability to determine lithium location and state based upon exterior thermocouple readings; to demonstrate mechanical feed of the liquid lithium; and, most importantly, to develop the relation between piston speed and lithium mass flow. Each of these goals has been successfully met.

Calibration Set-Up

The calibration set-up consists of the complete feed system in its firing configuration as described previously. Thermocouples are judiciously positioned at various locations on the exterior of the feed system to provide information regarding system temperature which, as will be shown, can be used to estimate lithium location and state. A liquid lithium dispenser section replaces the actual vaporizer multi-channel hollow cathode and allows for the collection of liquid lithium in a collection cup. A current of 10 A (300 W) is supplied to resistive Manganin heating wire on the section by a dedicated Variac independent of the feed system heating circuit. Just below the tip of the lithium dispenser section, the stainless steel collection cup sits on top of a digital balance with a resolution of 10 mg. The experimental set-up, consisting of the lithium dispenser section, the lithium collection cup, and the balance is shown in Fig. 4 . The aluminum foil under the cup protects the balance from any splattering of liquid lithium. During the calibration run, however, no splattering was observed and all lithium was collected in the cup. Testing facility pressure during the calibration was maintained below 7.3×10^{-3} Pa (5.5×10^{-5} Torr).

Thermal Tracking of Liquid Lithium Flow

One of the key results of the calibration campaign is the demonstration that properly placed, exterior thermocouples can be used to estimate lithium location within the feed system and to determine when

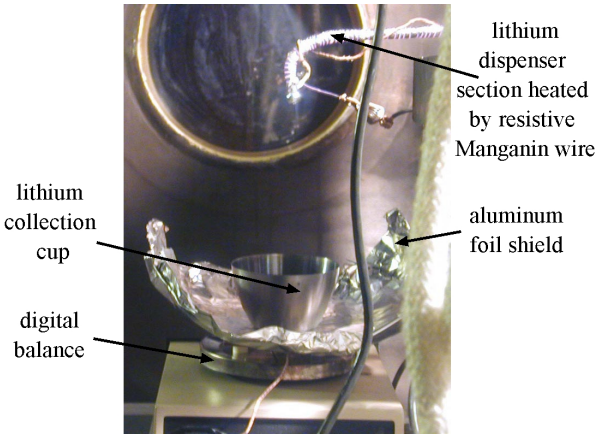

FIGURE 4. Lithium Dispenser Section and Collection Cup During Calibration Run.

melting is complete. As soon as melting begins the temperatures at various places in the feed system exhibit variations due to the motion of hot lithium inside the system. In the majority of the system, which is at temperatures above that of the lithium, the temperatures decrease suddenly as energy is transferred from the walls to the lithium. Conversely, the temperature of the piston, which is initially lower than the temperature of the molten lithium increases quickly as it comes into contact with the hot lithium. This is illustrated in Fig. 5 which shows the general trends of the cylinder (measurement at the base of the cylinder) and piston temperatures interrupted by large gradient temperature spikes or dips as the lithium arrives and fills the chamber. Likewise, the state and location of lithium in the reservoir and feed lines is apparent from a careful interpretation of the thermocouple readings, which can be done in real time.

Mass Flow Rate Measurements

Given the purely mechanical nature of the system, the lithium mass flow rate is a function solely of the piston velocity, the density of the liquid, and the inner diameter of the lithium chamber. Of these, the last is the most difficult to estimate given known irregularities in the cylinder diameter and the fact that lithium along the walls of the cylinder may reduce the effective diameter.

The goal of the calibration is therefore to establish the relation between piston velocity and lithium mass flow rate from which mass flow rate can be read during experimental runs. To this end, a calibration routine was written to drive the piston at velocities between 10 and 136 μm/s corresponding to the feeding of lithium at flow rates from 9.1 to 119.3 mg/s. Figure 6 shows the measured mass flow rate of lithium to the collection cup versus the piston speed. The slope of the calibration curve is determined from this data to be 812 ± 4 mg/mm. The smallness of the error bars in the measured flow rate data is due to the low piston velocities which allow for the collection of many data points, the high accuracy of the scale ($\pm$ 5 mg), and the high precision of the positioning system controller ($\pm 1 \mu$m/s). Fig. 6 also shows the comparison of the measured flow rate curve with the calculated flow rate (dotted line). The calculated mass flow rate was determined using an inner cylinder diameter of 46.8 mm. The discrepancy between the calculated and experimental curves can be traced to uncertainties in the inner diameter of the cylinder. From this comparison it can be seen that the effective diameter is slightly smaller than the measured value used in the calculations, as expected. Lithium density was taken as 0.512 g/cm^3 with fluctuations due to temperature variations determine to introduce less than 1% error.

Finally, it is worth noting that the total weight of the collection cup is linearly related to the piston position, thus to the volume change in the cylinder, and that this relation is constant irrespective of changes in piston velocity over the range of 10 to 136 μm/s.

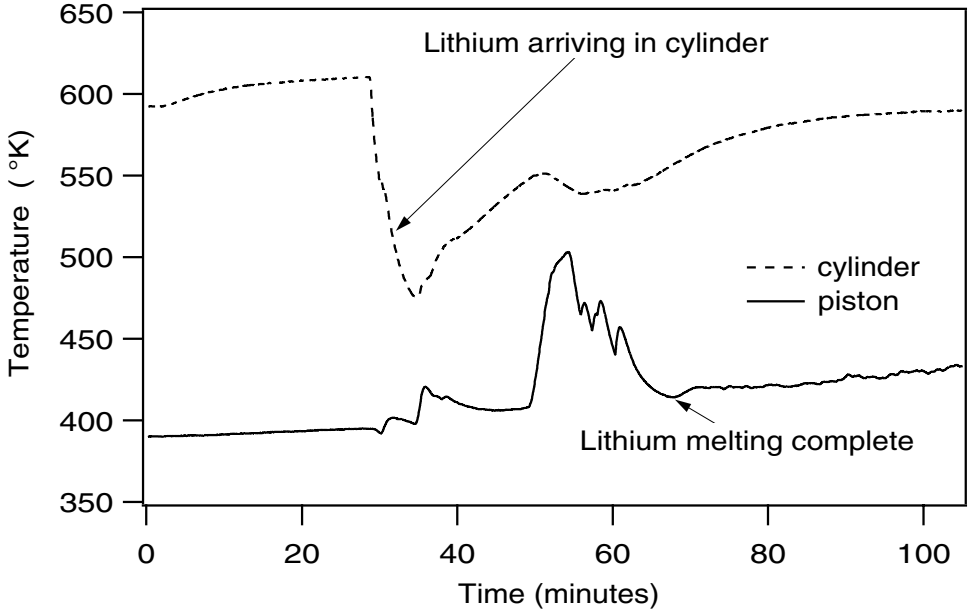

FIGURE 5. Variations in Piston and Cylinder Temperature with Lithium Movement Through System. The Sudden Drop in the Cylinder Temperature Signals the Arrival of the Colder Molten Lithium in the Chamber. Once Melting is Complete, Both Temperatures Resume Their Steady Increase.

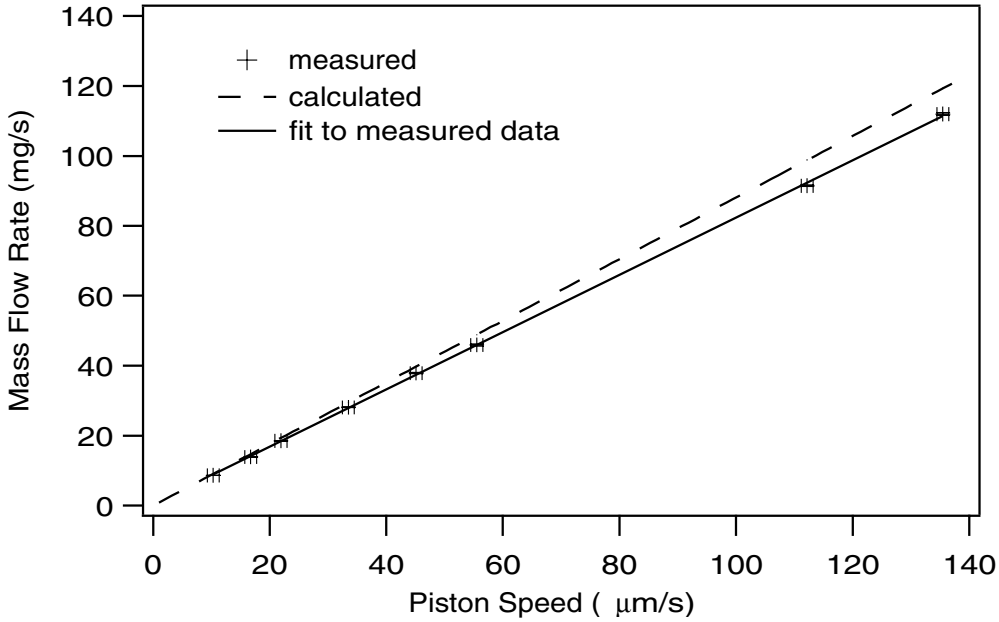

FIGURE 6. Measured Mass Flow Rate Versus Piston Speed. Also Shown is the Calculated Curve Where the Inner Cylinder Diameter was Taken to be 46.8 mm.

LITHIUM SAFETY AND HANDLING

An extensive review of lithium handling and safety procedures identified the major hazards areas of lithium thruster operation to be: the handling of the pure lithium metal at room temperature during loading and transfer of the reservoir; the cleaning and disposal of lithium reaction products in the feed system and the testing facility; and the release of potentially hazardous gases, especially hydrogen, during facility venting and cleaning.

The hazards of lithium operation can be divided into two classes: fire or explosion hazards due to the high reactivity of lithium and the production of hydrogen during reactions with water; and health hazards due to the corrosive and toxic nature of the stable end products of lithium reactions. The first of these concerns is addressed through the *controlled reaction* of the lithium and lithium compounds under a *controlled environment*. The basic reaction of lithium with water is: $Li + H_2O \Rightarrow LiOH \cdot H_2O + 1/2H_2 + 508$ kJ/mole. The explosion and fire hazard of the hydrogen gas is controlled by means of isolated, well vented facilities and proper detection. The heat is eliminated by means of a circulating water bath and by controlling the reaction speed. The reaction product, a corrosive lithium hydroxide solution, is handled with nitrile gloves and collected for proper disposal.

Alcohol neutralization is used in the contaminated testing facility by introducing ethanol vapor into the chamber prior to venting. Alcohol, rather than water, is chosen as it slows the reaction making it less violent than the water reaction while also producing LiOH. Reaction gases are eliminated prior to opening the facility by (*i*) pumping of the facility after neutralization and (*ii*) venting the facility to the outside via a filtered fan. To protect operators from any remaining hazardous gases, and also from inhalation of corrosive and toxic dust from the lithium reaction products, self-contained breathing apparatus (SCBA) gear is worn by operators during tank inspection and cleaning (wipe down with damp cloths).

Small lithium-contaminated components, including all feed system components, which may still contain pure lithium are cleaned using a circulating water bath under a positive pressure argon environment in the Lithium Handling Facility (LiHF). The facility consists of an extensively re-conditioned 0.5 m^3, stainless steel Blickmann glove box. The baseline facility pressure is less than 6.7 Pa (50 mTorr). To facilitate the cleaning of the feed system, two water feedthroughs were added to the main chamber and connected inside to a 20-liter capacity stainless steel water tray. A positive argon pressure of 6.7 to 20.0 kPa (50-150 Torr) above atmosphere establishes and ensures a continuous water flow during the reaction. In addition, during the initial stages of the cleaning the argon atmosphere is continually circulated to remove hydrogen. A photograph of the glove box facility is shown in Fig. 7 . The open ante-chamber and extended gloves are seen in the foreground. Also note the water inlet to the upper left of the main chamber and the 50-gallon drum for collection of lithium hydroxide solution in the bottom right corner of the photograph. Figure 8 shows a schematic of the interior of the LiHF during the controlled cleaning process. Both the argon atmosphere and water circulation are shown. Hydrogen bubbles indicate the presence of pure lithium in the component being cleaned.

To date, the largest amount of lithium handled, during a single reaction, in the LiHF has been 100 g. During the entire reaction the water temperature was easily maintained below 323°K (50°C), a maximum 25 degree temperature increase. During most of the process only a 2 to 5 degree increase was observed. The cleaning of 100 g of pure lithium took approximately 40 minutes to complete and demonstrates the establishment of an in-house ability to dispose of this amount of lithium safely and effectively.

CONCLUSIONS

A new *mechanical liquid lithium* feed system and lithium handling facility have been designed, implemented and tested in support of an experimental LiLFA program currently underway. The goals of the experimental program include the characterization of the basic processes of LiLFAs and the development of performance scaling relations in support of NASA's interest in these devices for energetic (high Δv), high thrust orbit raising and planetary missions.

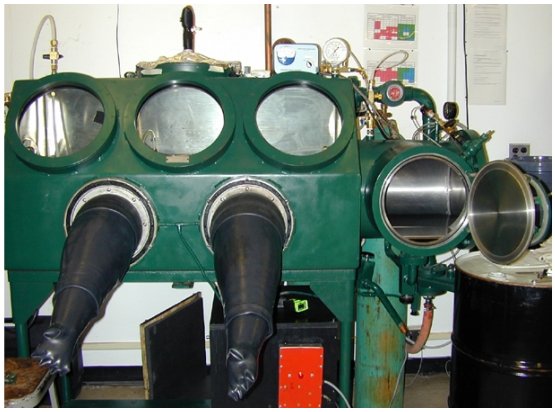

FIGURE 7. Photograph of Glove Box Facility with Gloves Extended and Open Ante-chamber.

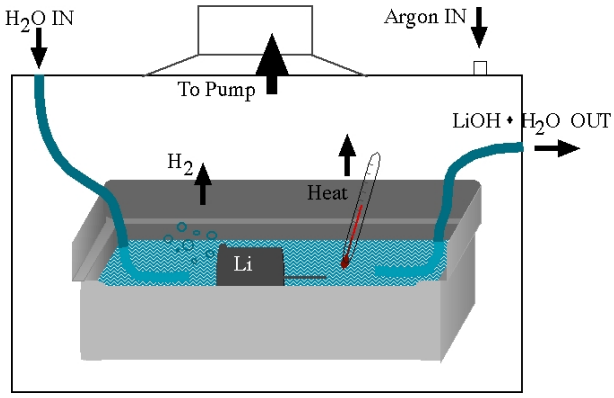

FIGURE 8. Schematic of the Glove Box Interior Showing Lithium-contaminated Component Cleaning Set-up.

Design validation, including proof of concept of a "freezing" valve for liquid lithium flow control and the ability to nonintrusively track lithium in the system, has been achieved. Calibration data are presented demonstrating the reliable and controllable real-time feeding of lithium at flow rates from 10 to 120 mg/s. A linear calibration curve has been obtained relating the lithium flow rate to piston velocity. This first iteration of a mechanically-actuated liquid system outperforms previous pressure-fed and vaporizer designs in mass flow rate accuracy, and ease of flow rate determination and control.

In addition, an operational lithium handling facility and procedures for the handling of lithium have been presented. The ability to safely transfer up to 300 g of pure lithium to the testing facility, to neutralize the lithium in the testing facility, to eliminate hydrogen gas, to clean reaction products from the testing facility, and to dispose of up to 100 g of pure lithium in a single reaction under a positive argon atmosphere and circulating water bath in the lithium handling facility have been demonstrated.

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REFERENCES

Ageyev, V.P. and Ostrovsky V.G., "High-current Stationary Plasma Accelerator of High Power," In 23rd *International Electric Propulsion Conference*, Seattle, WA, USA, 1993, IEPC-93-117.

Choueiri, E.Y. et al., " Lorentz Force Accelerator with an Open-ended Lithium Heat Pipe," In 32nd *Joint Propulsion Conference*, Lake Buena Vista, FL, USA, 1996, AIAA-96-2737.

Emsellem, G., Kodys, A.D., and Choueiri, E.Y., "Thermal Analysis of a Lorentz Force Accelerator with an Open Lithium Heat Pipe," In 26th *International Electric Propulsion Conference*, Kitakyushu, Japan, 1999, IEPC-99-166.

Fradkin, D.B. *Analysis of Acceleration Mechanisms and Performance of an Applied Field MPD Arc Jet*, PhD thesis, Princeton University, 1973.

Frisbee, R.H., and Hoffman, N.J., "SP-100 Nuclear Electric Propulsion for Mars Cargo Missions," In 32nd *Joint Propulsion Conference*, Lake Buena Vista, FL, USA, 1996, AIAA 96-3173.

Kim, V., Tikhonov, V., and Semenikhin S., "The Second Quarterly Report on Stages ## 3-4 of the Contract on the Research Studies No. NASW-4851 between RIAME MAI and JPL," Technical Report Contract NASW-4851, RIAME, MAI, Moscow, Russia, January 1995.

Nelson, S.T., Cann, G.L., and Harder, R.L., "High Specific Impulse Thermal Arc Jet Thruster Technology: Part II Performance of Hall Arc Jets with Lithium Propellant," Technical Report Technical Report AFAPL-TR-65-48 Part III, Electro-Optical Systems, Inc., Pasadena, CA, August 1967.