Management of Lithium Propellant for Magnetoplasmadynamic Thrusters

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Procedures and guidelines are presented for the safe preparation, delivery, mass flow calibration, and neutralization of lithium propellant during electric thruster ground testing. Lithium is a promising propellant for electromagnetic plasma thrusters, particularly magnetoplasmadynamic (MPD) thrusters. Preparation is conducted in an argon-filled glovebox under positive pressure, where solid lithium is melted into a reservoir. A liquid lithium feeding procedure is described that minimizes gas entrapment and enables flow tracking via localized temperature measurements. Mass-flow calibration is performed by displacing gas-free lithium with a motorized piston into a beaker on a balance. Calibration results were within 2% of theoretical predictions. The vacuum chamber is lined with disposable aluminum foil to facilitate post-test cleanup, and neutralization is achieved by injecting water into the chamber. A survey of relevant chemical reactions and their rates allowed prediction of the maximum condensed lithium film that can be neutralized after a specified wait period. Finally, disassembled feed-system components are cleaned by soaking in water under a ventilation hood.

Nomenclature

$\dot{m}_{\mathrm{Li}}$ = mass flow rate of lithium
c_{cal} = mass-flow calibration coefficient
ρ_{Li} = density of lithium
u_{pis} = piston velocity setting
A_{pis} = measured piston head area
T = temperature of liquid lithium in piston

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I. Introduction

The lithium magnetoplasmadynamic thruster (MPDT) can process megawatt-level power and achieve thrust densities on the order of 10^5 N/m^2, positioning it as a leading candidate for nuclear electric propulsion of heavy cargo or piloted interplanetary missions. NASA has expressed renewed interest in lithium MPDTs and is developing a megawatt-class ground-test facility especially for testing electric thrusters with lithium propellant.[1]

Pure lithium has several properties that make it attractive for plasma propulsion. Its first ionization energy is relatively low (5.4 eV), whereas its second ionization energy is comparatively high (75.6 eV). This combination reduces the energy cost of single ionization and minimizes frozen-flow losses to double ionization. Lithium has also been shown to lower the work function of tungsten hollow cathode surfaces, thereby reducing cathode operating temperatures.[2] In ground test facilities, lithium vapor or plasma can be efficiently pumped from a vacuum chamber using a room-temperature cold trap. However, the same single valence electron responsible for its favorable ionization properties also makes lithium highly reactive. Lithium reacts with water and atmospheric gases, complicating handling and limiting the range of compatible materials for thruster, feed-system, and facility design. Because lithium readily forms stable ionic compounds, and because many of its reactions are strongly exothermic, a thorough understanding of its interactions with air constituents is essential for safe handling.

At elevated temperature, liquid lithium is corrosive to many materials. Prolonged exposure corrodes aluminum, copper, polymers, and glass - materials common in gloveboxes and vacuum chambers.[3] Corrosion-resistant engineered materials like 316 stainless steel and Inconel survive short-term exposures to liquid lithium of single days below 600°C. For prolonged exposure or very high temperatures, pure iron or refractory metals (tungsten, molybdenum) are preferred.

Armed with this background in lithium chemistry and compatibility, we compile, update, and establish guidelines for safe handling and preparation of lithium for electric thruster ground tests. While prior publications mention equipment and safety precautions, a complete procedure for lithium preparation and neutralization has not been formalized.[4–7] We also discuss implications for the design and calibration of lithium feed systems and demonstrate implementation in calibrating a liquid-lithium feeding system for our 30 kW lithium MPDT.

II. Lithium Reactions with Air

Lithium reacts with oxygen and water like other alkali metals, and also with nitrogen and carbon dioxide. Even at room temperature, lithium rapidly tarnishes in air. In oxygen, lithium combusts according to Eq. (1):

$$4\,\mathrm{Li}_{(s)} + \mathrm{O}_{2(g)} \longrightarrow 2\,\mathrm{Li_2O}_{(s)} + 1191.6\mathrm{kJ} \tag{1}$$

Uniquely among alkali metals, lithium also combusts in nitrogen to form lithium nitride:

$$6\,\mathrm{Li}_{(s)} + \mathrm{N}_{2(g)} \longrightarrow 2\,\mathrm{Li_3N}_{(s)} + 329.9\mathrm{kJ} \tag{2}$$

Enthalpies of reaction are calculated at 298 K and 1 atm, as our focus is safe handling at room temperature. Despite the potential to release large amounts of energy, lithium reactions with oxygen and nitrogen proceed negligibly at room temperature. The reaction with water is rapid at room temperature whether water is liquid or vapor:[8]

$$2\,\mathrm{Li}_{(s)} + 2\,\mathrm{H_2O}_{(l)} \longrightarrow 2\,\mathrm{LiOH}_{(s)} + \mathrm{H}_{2(g)} + 403.4\mathrm{kJ} \tag{3}$$

$$2\,\mathrm{Li}_{(s)} + 2\,\mathrm{H_2O}_{(g)} \longrightarrow 2\,\mathrm{LiOH}_{(s)} + \mathrm{H}_{2(g)} + 491.4\mathrm{kJ} \tag{4}$$

These reactions with water produce lithium hydroxide and hydrogen gas. Because water also reacts exothermically with the oxides and nitrides of lithium, it is the dominant concern for lithium contamination.

$$\mathrm{Li_2O}_{(s)} + \mathrm{H_2O}_{(g)} \longrightarrow 2\,\mathrm{LiOH}_{(s)} + 137.4\mathrm{kJ} \tag{5}$$

$$\mathrm{Li_3N}_{(s)} + 3\,\mathrm{H_2O}_{(g)} \longrightarrow 3\,\mathrm{LiOH}_{(s)} + \mathrm{NH}_{3(g)} + 618.5\mathrm{kJ} \tag{6}$$

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With sufficient water to absorb the heat released, the global sum of these reactions leads to aqueous lithium hydroxide and roughly 77.7 L of hydrogen per gram of lithium reacted at room temperature and pressure. This informs the neutralization and handling procedures discussed below.

Lithium hydroxide exposed to water vapor forms the monohydrate:

$$\mathrm{LiOH}_{(s)} + \mathrm{H_2O}_{(g)} \longrightarrow \mathrm{LiOH \cdot H_2O}_{(s)} + 121\mathrm{kJ} \tag{7}$$

The monohydrate converts the initial black hydroxide coating to a thicker, flaky white layer. Prolonged exposure in humid air thus transforms a dark gray/black surface into lithium hydroxide monohydrate with admixed lithium carbonate.

At room temperature, carbon dioxide does not react with metallic lithium but does react with lithium hydroxide and oxide. In sufficient quantity, carbon dioxide partially converts hydroxide/oxide coatings to carbonate. Due to the low molecular weight of lithium hydroxide, Eq. (10) has been exploited in the design of mass-efficient carbon dioxide scrubbers:[9]

$$\mathrm{Li_2O}_{(s)} + \mathrm{CO_2}_{(g)} \longrightarrow \mathrm{Li_2CO_3}_{(s)} + 224.9\mathrm{kJ} \tag{8}$$

$$2\,\mathrm{LiOH}_{(s)} + \mathrm{CO_2}_{(g)} + 32\mathrm{kJ} \longrightarrow \mathrm{Li_2CO_3}_{(s)} + \mathrm{H_2O}_{(g)} \tag{9}$$

$$2\,\mathrm{LiOH \cdot H_2O}_{(s)} + \mathrm{CO_2}_{(g)} \longrightarrow \mathrm{Li_2CO_3}_{(s)} + 3\mathrm{H_2O}_{(g)} + 89.5\mathrm{kJ} \tag{10}$$

Lithium carbonate is of particular concern because its poor water solubility limits the efficacy of water-based cleaning. It can, however, be dissolved in weak acids such as acetic or citric acid. Pure lithium carbonate is a white crystalline solid.

III. Materials and Methods

Lithium is prepared in a glovebox, transferred to the vacuum chamber, and heated under vacuum prior to test firing. After a test, deposited lithium is neutralized and removed, and contaminated hardware is promptly cleaned. We also summarize personal protective equipment (PPE) choices and their rationale.

A. Test Facilities and Feed System

The lithium feed system is a lithium-sealed syringe pump, derived from the design discussed by Kodys et al. with subsequent refinements.[4,5] A schematic is shown in fig. 1 where the thermocouple locations are shown by orange stars. Lithium is loaded into a reservoir inside the glovebox. The reservoir is sealed, moved to the vacuum chamber, installed in the feed system, and heated to melt and transfer lithium toward a preheated piston. Once all lithium is molten, argon pressure is gently applied to fill the piston volume completely. A "freeze valve" (an actively cooled pipe section) is then brought below the melting point to solidify a plug of lithium that prevents backflow to the reservoir. With the freeze valve set, a translation stage drives the piston to volumetrically deliver lithium to the thruster.

"Piston" or "lithium piston" here refers to the whole assembly, whereas "piston head" refers specifically to the moving steel plug that displaces lithium from inside the "cylinder". The piston head is driven by a customized Zaber X-LRQ-SV2 motion stage controllable to micrometer-per-second speeds.

Feed system piping and the freeze valve are wrapped in aluminum foil to limit radiative cooling. The reservoir and cylinder are left unwrapped. The reservoir is not actively cooled. As lithium should never flow upward toward the argon port, the reservoir top is sealed with a Viton o-ring that would otherwise not survive lithium exposure.

The piston volume is unsealed except when filled with lithium. The piston head is a close fit in the cylinder with two guide rings near the bottom for centering. Lithium flowing into the piston passes around the piston and exits at the top. To prevent leakage, the piston region near the top of travel is cooled so that any lithium flowing past freezes and seals the piston.

Lithium sample preparation and reservoir loading are performed in a vacuum-sealed stainless-steel glovebox. A photo of our glovebox is shown in fig. 2. The glovebox is evacuated, purged, and backfilled with high-purity argon for lithium preparation. Maintaining a slight positive pressure of 0.1–0.2 psi ensures any

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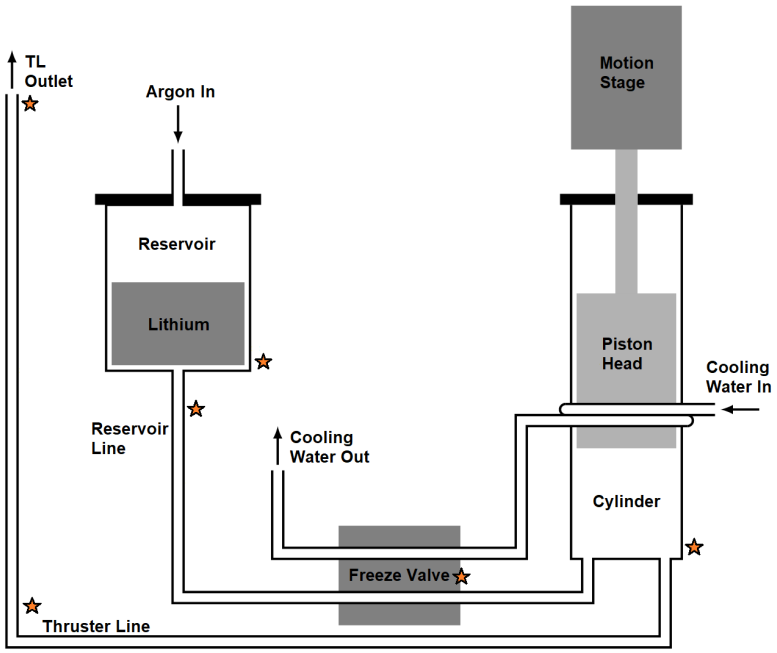


Figure 1. Lithium feed system schematic with thermocouple location shown by orange stars.[6]

small leaks drive argon outward, avoiding air ingress. A normally closed solenoid admits argon when pressure drops. An independently cycled airlock allows transfer of parts and tools without disturbing ongoing operations.

The Steady State Low Power (SSLP) facility vacuum chamber is a steel cylinder 1.5 m in diameter and 6.4 m long. Pumping is provided by a 48 in Consolidated Vacuum Corporation diffusion pump, a WSU 2000 Roots booster, and a Stokes Microvac 212H piston roughing pump. The roughing pump is operated with V-lube G instead of the nominal V-lube F to increase viscosity grade and operating temperature, aiding water removal. A 2 L condensate trap in the exhaust line prevents backflow of condensed water into the roughing pump. When hydrogen is pumped, the nitrogen is flowed through the roughing pump oil reservoir to prevent hydrogen entrapment and to dilute exhaust gases, reducing ignition risk. Provided hydrogen is not trapped in large pockets outside the exhaust pipe, it does not present a greater flammability hazard than hot vacuum pump oil vapor.

The chamber uses a dedicated cooling water system delivering 10–20°C water to the vessel walls, baffles, thruster stand, feed system components, and the thruster's applied field solenoid. Cooling pipes on the cylindrical interior surface of the vacuum chamber pump lithium vapor by freezing it onto the walls. To facilitate cleanup, the majority of the interior surface is covered with disposable aluminum foil so that deposited lithium can be removed more easily.

Two General Monitors S104 hydrogen detectors are installed with a General Monitors DC110 controller. One detector is mounted above the vacuum chamber near the ceiling; the other is mounted at floor level near the top of the diffusion pump and above the roughing pumps in the basement. Detectors are calibrated with 2% hydrogen; 50% of the lower explosive limit of hydrogen in air.

B. Lithium Cleaning and PPE

Solid lithium is difficult to ignite and can be handled at room temperature and pressure, but risk factors persist. After feed-system or thruster operation, lithium and byproducts must be removed to minimize hazard and prevent corrosion.

If lithium were to ignite outside containment, a Class D metal fire extinguisher may be used with caution. A lithium fire in air burns extremely hot and can release ammonia, nitrogen dioxide, and reactive lithium-containing particulates. Such ignition during transfer is unlikely because pure lithium typically requires temperatures above 175°C to ignite in air.

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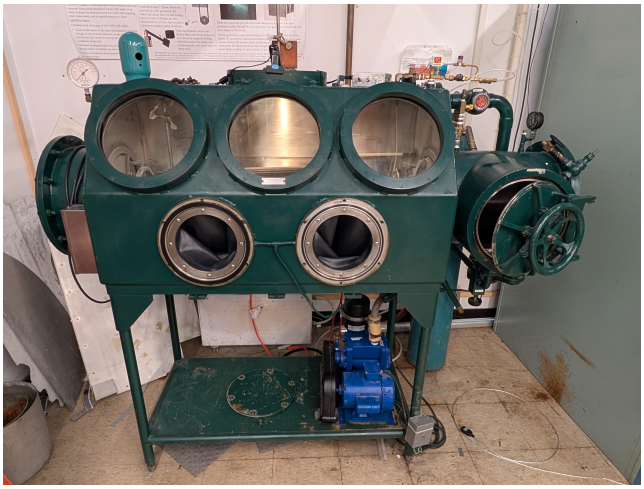


Figure 2. Photo of the steel glovebox used for lithium preparation. The airlock is pictured open.

When using the glovebox, base PPE includes flame-retardant lab coats, splash goggles, and nitrile gloves. During reservoir transfer, the carrier wears heat-resistant gloves over the nitrile gloves. If the lithium begins warming noticeably, the reservoir is placed in the glovebox airlock for secondary containment.

When removing lithium products from the chamber immediately after opening, we use TyChem 2000 coveralls and full-face air-purifying respirators. Coveralls with hoods and attached socks replace the lab coat; disposable boots or dedicated cleanable shoes provide traction. Wrist and neck seams are taped to nitrile gloves and APR, respectively. With the chamber open and ventilated, and no liquid water introduced, the dominant hazard is exposure to lithium hydroxide - especially flaky lithium hydroxide monohydrate, which HEPA cartridges address effectively. Supplied air respirators or self-contained breathing apparatus are too cumbersome for chamber entry under these conditions with limited benefit because the chamber is already ventilated.

Feed system parts contaminated with lithium are cleaned by immersion in a water bath under a ventilation duct. Our parts fit in a 16 gallon galvanized steel tub. If more than 10 g of lithium remains in the piston or reservoir, the bath is moved outdoors when practical to vent hydrogen directly. Operators wear thick chemical-resistant nitrile over-gloves and face shields when initially submerging parts. Once the reaction abates, the resulting lithium hydroxide solution can be handled without a face shield.

Due to the piston being sealed by lithium around the piston head, lithium can sometimes be trapped inside the thin gap between the piston head and cylinder wall such that the water from the water bath cannot contact it. In this scenario, an oil-filled hydraulic piston is used to pressurize and force the piston head out of the cylinder after the majority of the lithium has already been reacted and dissolved.

IV. Results and Discussion

Operating the 30 kW lithium thruster requires accurate feed rates of order 10 mg/s. Based on multiple trials, we developed an operating procedure that yields reliable mass flow calibration. Post-test, lithium deposited on vacuum chamber surfaces must be safely neutralized.

A. Mass Flow Calibration

The vertically oriented piston acts as a syringe pump that volumetrically displaces liquid lithium into the thruster line. The ideal relation for finding the mass flow rate of lithium is

$$\dot{m}_{\mathrm{Li}} = c_{\mathrm{cal}}\, \rho_{\mathrm{Li}}\, u_{\mathrm{pis}}\, A_{\mathrm{pis}}\,, \tag{11}$$

where c_{cal} is the calibration factor, u_{pis} the piston velocity, and A_{pis} the piston-face area. Although the cylinder bore exceeds A_{pis}, lithium outside the piston diameter flows around the piston and freezes; the displaced volume is therefore $u_{\mathrm{pis}} A_{\mathrm{pis}}$.

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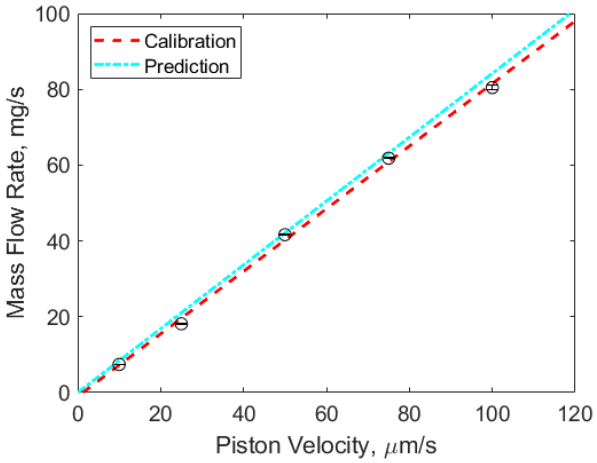


Figure 3. Mass flow rate versus piston velocity setting.

Lithium density depends on temperature. An empirical relation from Jeppson et al.[3] is

$$\rho_{\mathrm{Li}} = 0.515 - (1.01 \times 10^{-4})(T - 200) \quad \mathrm{g/cm^3}\,, \tag{12}$$

with T in °C. Over 250—500°C, Eq. (12) implies a 5% density decrease; any temperature drift during a calibration introduces bias if unaccounted for.

Fig. 3 shows the calibration. The cyan dash–dot line is the ideal prediction with $c_{\mathrm{cal}} = 1$. Measured points in black with a dashed red linear fit yield $c_{\mathrm{cal}} = 0.9802$, i.e., measured flow was 2% below the ideal. Error bars reflect propagated timing and balance measurement errors.

If the entire deviation from the ideal prediction were due to temperature error via Eq. (12), the implied lithium temperature would be 464°C. Because the true liquid temperature must exceed the measured maximum thruster line temperature (> 420°C), some bias likely arises from temperature underestimation when using an external cylinder measurement. Residual error could also stem from the piston area term A_{pis} if the piston moves laterally within its tolerance or the face is not perfectly flat/circular. In practice, using a consistently located piston temperature for density evaluation and treating c_{cal} as an empirical correction is effective. Future work may measure liquid temperature more directly to distinguish constant versus time-varying temperature bias.

B. Feed-System Operation and Thermal Signatures

Lithium motion is tracked via rapid local temperature changes as lithium enters regions of different temperature. We observed heating rates of 1–3 K/s on 0.375 in outer diameter pipe sections. Lithium freezing can also be detected: during cooldown, plateaus near the melting temperature appear when lithium comprises a significant fraction of the local thermal mass - latent heat release delays further cooling.

Because feed system temperatures evolve over tens of minutes, operation must proceed even more slowly. A representative temperature history from a mass flow rate calibration is shown in Fig. 4. From test start to pumping lithium through the thruster line required ∼3.5 h. The first temperature rise is offset from zero because piston positioning and venting steps precede the heater operation.

Before heating, the feed system is vented to the chamber and left open. The argon feed line vents to the chamber via a dedicated line. The piston volume remains unsealed until contacted by liquid lithium. The thruster line is left open either to the balance for calibration or through the thruster. Keeping the argon line vented allows any gases liberated during melting to escape from either end of the lithium column.

The piston is positioned so that the combined volume of the piston cavity and any pipe volume that molten lithium can occupy downstream of the reservoir is less than the loaded liquid lithium volume. We include the lowest horizontal sections of the thruster, the entire reservoir line, and add a 20% safety factor. The lithium column between the freeze valve and the advancing front must be bubble-free. Gas bubbles increase compressibility degrading response and accuracy and, in the worst case, can retain enough pressure to drive lithium flow through the thruster line without piston motion.

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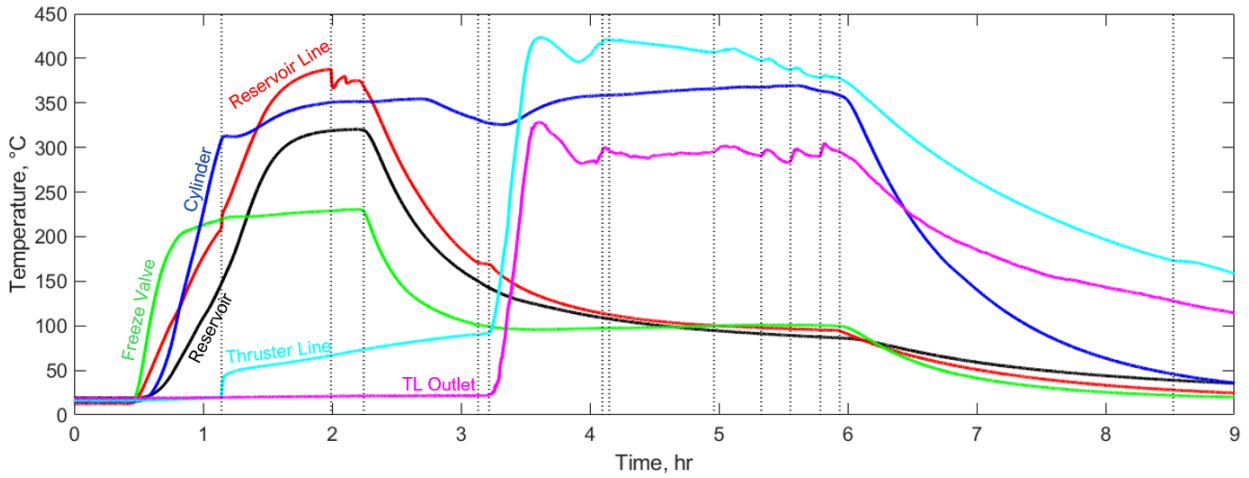


Figure 4. Temperature history during feed system mass flow calibration.

Lithium is then melted and transferred from reservoir to piston. Patience is essential: slow melting promotes a uniform, bubble-free slug. The reservoir, reservoir line, and piston are brought above 250°C; the actively cooled freeze valve is held above 200°C at its thermocouple. During a 30 min wait period, small melting events are typically observed - these are gravity-assisted flows of lithium out of the reservoir. In the trace of Fig. 4, this begins at 1.1 h.

Nonuniform melting is common when oxide/hydroxide tarnish is present. Glovebox tests with lightly tarnished pellets showed that lithium reaction products can inhibit coalescence and that intact surface films can retain the pellets' form while the interior melts. For tarnished stock, scraping or pre-melting to separate clean lithium is recommended. We melted lithium in the glovebox with varying degrees of tarnish and found that melting and pouring off the liquid lithium into an ingot mold or directly into the reservoir was an effective way to remove thin films of tarnish, regardless of lithium form factor.

After lithium melting is complete, the argon vent is closed and argon pressure is increased gradually to a maximum of 20 psia, pushing lithium into the piston. In the record of fig. 4, pressure-assisted flow in the reservoir line is detected at 2 h. Flow ceases once lithium freezes around the piston and in the thruster line, sealing the liquid. Without venting argon, reservoir and reservoir-line heaters are then turned off so those sections cool below the melt while the piston cavity remains hot. The freeze valve is heated gently to 100°C to avoid freezing the lithium inside the piston cavity. A temperature stagnation in the reservoir line at 3.1 h indicates local freezing 55 min after heater shutdown.

At 3.2 h, thruster line heaters are turned on. After both thruster line thermocouples exceed 250°C, we wait 30 min and begin the experiment. For mass flow calibration, lithium is dispensed onto a balance while the piston velocity is stepped. Because they are separated with a section of zero flow, each flow event is detected by temperature increases in both the thruster line and the outlet, consistent with lithium exiting at a hotter temperature than that measured at both the thruster line and the piston exterior.

After data acquisition, all heaters are turned off. Approximately 2.6 h later (8.5 h total), lithium freezing in the thruster line is inferred from a temperature lag near the melting point.

C. Lithium Neutralization

During test firing, thin lithium films deposit on chamber surfaces. To remove the flammability hazard of residual lithium and to avoid hydrogen entrapment, we neutralize lithium films under low vacuum by injecting water. At reduced pressure, injected water boils, reacts with lithium, and the resulting hydrogen is pumped out at low pressure, avoiding entrapment.

An estimate of the water vapor reaction rate at 50 Torr and room temperature was inferred from Irvine and Lund, giving 9.06×10^{-6} cm/min.[10] A 1 cm-thick lithium slab attacked from both sides at this rate would require about 10 weeks for full conversion to lithium hydroxide monohydrate. A 1 μm lithium film attacked from one side, however, should react within 15 minutes. Therefore, water vapor neutralization is

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appropriate for distributed thin films produced during thruster firing, but large chunks require mechanical removal, using a chisel or paint scraper if necessary, before any wet cleanup. A quantity of water that fills the vacuum chamber to the saturated vapor pressure is injected into the vacuum chamber and allowed to react 30 minutes. After that, the remaining hydrogen and water vapor are pumped out and the process is repeated until a total amount of water equal to eight times the stoichiometric equivalent according to Eq. (4) has been processed. That is a safety factor of four and enough water for the lithium hydroxide to hydrate.

Ammonia generation is an important consideration. If small quantities of water contact lithium in the presence of nitrogen, ammonia is produced according to Eq. (6). Even part-per-million concentrations of ammonia gas can irritate eyes and lungs. In water immersion baths, ammonia dissolves readily, but spraying water onto metallic lithium in air is less controlled. Thus, as much dry lithium as possible is first removed mechanically from the chamber. If wet cleaning is necessary due to stubborn residue, operators apply water from maximum standoff with ample excess water to limit temperature rise and utilize respirator filters rated for trace ammonia exposure.

Concerns about clogging narrow passages such as hollow cathode channels with insoluble carbonate are addressed by a vacuum-drying step. The equilibrium associated with Eq. (7) is $\sim$2 Torr, meaning that higher water pressures favor monohydrate formation. Reaction (9) is endothermic and less effective for carbon dioxide absorption than reaction (10).[9] During neutralization, we dry the reacted lithium film under medium vacuum before venting to air: the piston pump and Roots blower bring the chamber well below 2 Torr, typically $<$ 200 mTorr, indicating little residual water and dehydrating lithium hydroxide monohydrate in situ. Subsequent venting with air thus reduces carbonate formation.

V. Conclusion

We have compiled and demonstrated procedures for the safe preparation, handling, neutralization, and delivery of lithium propellant for electric thruster ground tests. The guidelines integrate lithium chemistry, materials compatibility, and operational experience to support future lithium thruster research.

Key outcomes include a predictive basis for scheduling lithium neutralization by water vapor, informing cleanup timelines and operator safety, demonstration of liquid lithium feed system calibration within 2% of the ideal volumetric prediction, and practical identification of pitfalls in gas venting, thermal detection of lithium motion, and piston heating that inform subsequent design choices.

Lithium's low first ionization energy and compatibility with MPDTs make it uniquely attractive for high-power plasma propulsion, yet its reactivity imposes stringent safety and engineering constraints. The procedures reported here aim to make lithium-based electric propulsion research more accessible and reproducible while maintaining rigorous safety practices. Future work will refine neutralization timelines for higher test cadence, and improve liquid-temperature diagnostics to ensure thruster firing with a steady and known mass flow rate.

Acknowledgments

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