Rocket-borne Lithium ejection system for neutral wind measurement

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Chemical tracer releases represent the most widely used technique for in situ neutral wind measurements in the thermosphere/ionosphere region. Different chemicals have been used for this purpose, but lithium releases in particular provide some unique capabilities due to the strong resonant emissions that are produced when lithium is illuminated by sunlight. The majority of the lithium releases from sounding rockets were carried out in the 1960’s and 1970’s, but there has been recent renewed interest in the use of lithium vapor releases to extend neutral wind measurements into the F region and for daytime wind profile measurements in the E region. The rocket-borne Lithium Ejection System (LES) is a chemical release device that has been developed for the Japanese space research program. Since lithium vapor acts as a neutral tracer, the winds are obtained by tracking the motion of the clouds or trails optically from the ground using the bright red emission that is characteristic of the chemical. Lithium is a solid at room temperature, so that a gas release requires rapid vaporization of the metal to make the cloud at the intended altitude. The release canister is designed to produce a high-heat chemical reaction without gaseous products. Appropriate mixtures of thermite are employed as the heat source. In early experiments, lithium pellets were mixed directly into the thermite. However, since lithium is an active chemical, the use of lithium-thermite mixtures creates potential hazards when used in a rocket-borne device. Moreover, the pyrotechnic devices used to ignite the thermite also have to be considered in the payload canister design to assure that the safety standards for sounding rockets are satisfied. The design of the LES, described in this paper, was based on the safety requirements and the reliability in storing and handling of the materials. The LES design is also flexible in that the lithium tracer material can be replaced with other chemicals without difficulties. This paper introduces the design of the LES and the method for controlling the thermite burn.

Key words: Chemical payload, thermite reaction, neutral wind observation.

1. Introduction

The basic electrodynamic parameters in the thermosphere/ionosphere system include the electric fields, the plasma densities, and the neutral winds. The neutral winds are often the primary drivers for the plasma motions, but there is also a significant feedback from the ionization to the neutrals that alters the neutral dynamics. Obtaining the neutral wind measurement in the E and F region that are required to understand the strongly coupled system in those regions has been a challenge since the early days of ionospheric physics. A variety of metal vapor releases have been used in sounding rocket experiments during the last five decades as tracers of the neutral or ion motions in the thermosphere and ionosphere, including sodium, lithium, barium, and strontium (see, Davis, 1979; Larsen, 2002, for comprehensive reviews). Some of the earliest releases involved the use of lithium vapor as a neutral tracer (e.g., Derblom et al., 1966). The lithium canister in the early experiments had a mixture of thermite, usually iron oxide and aluminum, and lithium flakes or pellets. The thermite was ignited with a pyrotechnic device and burned at a sufficiently high temperature to vaporize the lithium. The burn rate was controlled to some extent by changing the particle mesh size, i.e., the particle size in the mixture, and also by changing the composition of the thermite.

Both sodium and lithium trail releases were used in the early days of sounding rocket experiments in the 1960’s. Both types of releases require solar illumination to make them visible. The resonant emission from lithium is much brighter than that from sodium, which actually made the lithium trails less useful for E-region wind measurements since the detailed structure in the trail was difficult to discern in the trails. The lithium and sodium releases were quickly replaced by aluminum vapor release techniques for E-region wind measurements, especially trimethyl aluminum (TMA) techniques. The TMA is a liquid, which makes it possible to control the release rates more precisely and to eliminate the high-temperature thermite burn, which makes the TMA more compatible with other instrumentation on the same payload. The time when the measurements could be made with lithium or sodium was limited to brief periods around dusk or dawn twilight when the trails were illuminated but the ground-based camera sites were in darkness. TMA is chemiluminescent, which makes it possible to carry out experiments at any time during the night, independent of the solar depression angle.

The lithium trail technique saw a renewed interest in the 1970’s as a technique for measuring daytime E-region winds (e.g., Bedinger, 1973; Hind and Lloyd, 1974). The lithium line is sufficiently bright so that the trails could be detected in daylight conditions with the improved narrow-
band filters. Successful experiments were carried out by groups in the U.S.A., Australia, and India.

There has been renewed interest in the lithium release technique in the last few years as a way to extend thermospheric wind profile measurements to F-region altitudes and for daytime measurements. The Lithium Ejection System (LES) described here is an updated payload canister design created to support the space research program in Japan.

2. System Requirements

Producing the tracer cloud requires a high temperature chemical heat source to vaporize the tracer metals. Thermite is usually selected as the heat source because of the exothermic properties of the reaction. The composition and reaction properties should be optimized for the design of the chemical release device. The thermite mixture for the LES was developed by using the composition to control the burn rate and the reaction products temperature. An important difference between the LES canister design and that used in earlier experiments is that the lithium is loaded into the canister separately rather than being mixed with the thermite. This both enhances the ground safety for handling and storing the canisters throughout the rocket launch operation and produces flexibility in replacing the lithium with other chemical tracers.

The system described here was flown successfully in Japan on the flight of sounding rocket S-520 in August 2007. Three lithium releases were carried out during the flight, and lithium gas was successfully released at altitudes from 150 km to 250 km.

The thermite used in the payload canister has to produce sufficient heat to vaporize all of the lithium. The thermite reaction is usually initiated by a pyrotechnic device and hot ferric liquid is generated by the chemical reaction (Frolov and Pivkina, 1997; Duraes et al., 2007). The temperature of the chemical products usually reaches 2300 K and is enough to produce a rapid phase change from the solid to the gas phase. Gaseous lithium is ejected from the payload through a nozzle without delay.

For this device, a Safe and Arming Device (SAD) was used to prevent the hazardous situation caused by unexpected firing of the pyrotechnic device. The SAD uses a pressure switch that is activated at low pressure to switch the electronics from the safe mode to the arming mode. Based on this concept, the LES cannot work when it is on the ground at surface pressure. The design details are shown in Fig. 1.

Based on the discussion above, the system requirements are as follows:
1) 0.12 kg of Lithium in the gas phase is released in 15 seconds.
2) LES is ignited by the pyrotechnic device activated with the onboard sequencer.
3) Ejection delay of the lithium gas is within 5 seconds.
4) Igniter should be equipped with the Safe and Arming Device (SAD).
5) LES should be kept in the safe mode before the launch even if the pyro activated by improper operation.

3. Chemical Heat Source: Thermite

Thermite is loaded in the LES as the chemical heat source to vaporize the lithium. The thermite is currently categorized as non-explosive, although the burning characteristics show a rapid reaction and high temperatures. Thermite is well known as a mixture of ferric oxide (FO) and aluminum (Al) and usually reacts without gaseous products according to the reaction (Nagata, 2003).

$$\text{Fe}_2\text{O}_3 + 2\text{Al} \rightarrow \text{Al}_2\text{O}_3 + 2\text{Fe}. \quad (1)$$

Generally, this reaction generates high temperature products, including liquid phase iron. The mixture should be handled with care. Thermite initiation requires making hot spot by a chemical reaction because of the high melting temperature of aluminum, 933 K. The liquid phase of Al is active chemically for the oxidation reaction and combines with oxygen atoms from FO (Plantier et al., 2005). As the heat of the chemical reaction from the Al oxidation is accumulated in the condensed phase products, their temperature will increase to values up to 3000 K. The temperature of the reaction products is enough to vaporize the solid phase lithium since the boiling temperature for the latter is 1603 K. Thus, the condition for lithium vaporization is satisfied by the liquid phase of iron which exists in a wide temperature range from 1808 to 3073 K.

The burn rate of the thermite can be controlled by altering the ratio of FO and Al in the mixture. For the LES design, the burning characteristics of the thermite were estimated, as described in the following section.

3.1 Assessment of the thermite burn characteristics

3.1.1 Composition for the test For the composition design of the thermite, the mixture ratio between FO and Al and the particle diameter of Al were employed as parameters. MMR was defined as the metal mass ratio of the mixture. For example, $\text{MMR} = 2.0$ means the composition of the sample whose composition is $\text{FO}/\text{Al} = 10.0/2.0$ in mass ratio. The mass ratio of 10.0 for FO was constant for all samples. Since the particle diameter has an impact on the burn rate of the thermite, three different Al particle diameters, 10, 25 and 45 µm, were used for this test. Moreover,
alloy of Al and Mg (MgAl), known as magnalium, was also added as a metal component. The latter material is widely used in pyrotechnics. MgAl particles are ignited at lower temperature than Al particles because MgAl has a lower melting temperature, 723 K. It is expected that MgAl improves the ignition characteristics of thermite composed of FO/Al. The MgAl particle size was 45 µm in diameter. The thermite sample composition is listed in Table 2. For example, the F300 and M200MA sample corresponds to FO/Al (10 µm)/MgAl = 10/3/0 and FO/Al (25 µm)/MgAl = 10/1/1 in mass ratio, respectively.

### 3.1.2 Measurement of burn rate and reaction temperature

For the burn rate measurement, each sample was loaded and pressed in an acrylic tube with dimensions 19 mmφ inner diameter and 50 mm in length. The thickness of the tube was 3 mm. Eight grams of each sample in Table 2 was loaded in the case with a pressure of 15 MPa. The sample density for this condition was approximately 1.7 g/cm³. In order to detect the combustion front and measure the burn rate, a K-type thermocouple with a wire diameter of 200 µm was embedded in a sample at three locations. The burn rate was calculated by using the distance between the sensors and the time of the signals from each of the sensors. The temperature of the reaction products was measured directly with C-type thermocouples, which is W-Re alloy. The wire diameter was 100 µm. The junction bead was embedded in the center of the samples. The burn
Fig. 4. Burning rate characteristics (2).

Fig. 5. Burning temperature.

3.1.3 Results Figure 2 shows the profiles of the signal from the thermocouples through the burn test. The voltage rose immediately when the reaction front reached the thermocouple bead. For this experiment, the arrival time of the reaction front was defined as the time when the voltage level exceeded 1.0 mV.

The burn rate of the thermite is shown in Fig. 3. The burn rate of the sample F200MA at MMR = 2.0 showed the minimum value of 7.9 mm/s. At the other extreme, F338 at MMR = 3.38, which is the stoichiometric composition, increased the burn rate to 58.2 mm/s. It was found that burn rate changes widely, even by a small modification of thermite composition.

The burn rate data was used to estimate the relation between the particle diameter and the burn rate. As Fig. 4 indicates, the sample containing fine Al showed the highest value, approximately 18.4 mm/s, and the burn rate decreased with increasing Al particle diameter. On the other hand, the sample containing MgAl showed a trend on convex. It is suggested that the sample with the file Al particles may have a wide range of burn rates, which could be controlled by the mass ratio of MgAl in the thermite composition.

The temperature of the reaction products is shown as a function of the Al particle diameter in Fig. 5. The temperature of the Al based sample dropped from 2064 K to 1726 K with increasing particle diameter. However, the trend of the samples with MgAl was different as shown in Fig. 5, and the maximum value was 1889 K for the particle diameter of 25 µm. In both cases, the results showed that the temperature exceeded the boiling temperature of lithium, 1600 K, for any composition. From the results shown in Figs. 3, 4 and 5, the composition of MMR = 2.0 with 10 µm of Al has the potential to control the burn rate and the products temperature with a small composition change.

For LES design, the composition which was MMR = 2.0 with MgAl addition was selected as a candidate considering the system requirements.

4. Design of Safe and Arm Device (SAD)

The payload initiated by pyrotechnics should be equipped with Safe and Arming Device (SAD). Before the rocket launch, the SAD would usually be switched from safe mode to arming mode electrically or mechanically. Therefore, the SAD for the LES was designed to prevent an accidental activation of the LES, which would lead to the ejection of hot lithium gas and liquid metal around the launch site.

The SAD employed in S-520 rocket flight used a mechanical system without electronics. The mechanism is shown in Fig. 6. The SAD has a free volume with trapped air which works as a power source. When the LES is at surface pressure, the pressure of the trapped air in the chamber is equal to the ambient. After launch, the ambient pressure decreases gradually with increasing rocket altitude. The differential pressure between the trapped air and the ambient will be caused by exposure to space. In the SAD, the fire protection wall, in the form of the mechanical pyro-shutter, will then slide from the initial position to the arming position. After that, the path of the hot gas by the pyrotechnics can be connected. This system therefore maintains the safe mode at all times before the launch.

The static and dynamical friction of the mechanical pyro-
shutter should be estimated in detail since the power source is limited to the differential pressure. The initial pressure in the chamber was defined as 760 torr and the ambient pressure at the apogee was given as 75 torr from other rocket experimental data. Considering these values and the shutter diameter, 20 mmφ, the minimum expected resistance was estimated to be 2.92 kgf since the differential pressure was 685 torr (=0.931 kgf/cm²). If the static friction is smaller than the dynamic one, the valve will move to the arming side. For the mechanical design, the static friction of this part was defined up to 2.65 kgf considering the design margin.

As for the dynamical friction, the value was also estimated based on the expected condition. Prerequisites for the calculation of the dynamical friction are as follows:

- (A) Initial volume of the chamber: \( V_1 = 15.45 \text{ ml} \).
- (B) Final volume of the chamber after the shutter slide: \( V_2 = 21.73 \text{ ml} \).
- (C) Pressure: 760 torr.
- (D) Ambient pressure at apex: 75 torr.

The pressure of the chamber after the shutter slide is completed, \( P_2 \), was estimated to be 540 torr (0.734 kgf/cm²) based on the relationship \( P_1 V_1 = P_2 V_2 \). The thrust surface of the switch was pressed with a force of 2.30 kgf by the trapped air.

5. Ground Test

The ground fire test should be conducted to estimate the ejection characteristics. The specifications for the LES, including the ejection delay and the duration, are character-
ized by the ground test data and are referred to the time-line of events for the rocket launch. Before the ground test, the LES canisters were subjected to vibration testing with parameters defined by the flight environment of the rocket.

The best way to understand the properties of the LES is to measure the temperature profiles of the nozzle surface and the canister. Type-K thermocouples are appropriate for this objective. As shown in Fig. 7, the thermocouple, T1, was fixed to the top of the nozzle surface and the temperature profile was obtained through the test as shown in Fig. 8.

5.1 Lithium gas ejection delay

The onset of lithium ejection was calculated with the profile of T1 because the temperature gradient changed through the lithium ejection. The lithium gas launch is caused by the contact with the hot thermite reaction products. Therefore, the ejection delay is fundamentally involved in the mechanical design of the LES.

As shown in Fig. 9, the temperature profile showed two inflexion points. These inflexion points usually involve the change of state of the heat input value from the hot products. Therefore, the temperature profile shows the LES gas ejection characteristics. The first temperature gradient was calculated between from X + 9.0 to 11.0 s for each test. Then the lithium gas launch time was also estimated with the initial temperature, 20 degC. Considering the heat conduction to the nozzle material, the gas launch time should be earlier than the calculated results. The data were compensated with the constant, \( \eta = 0.85 \). The delay and the duration could be also estimated by the VTR capture data, which had a recording rate of 30 fps. The data from the temperature measurements were compared with the data of the optical method and the results are listed in Table 3.

Although the accuracy of the optical data was dominant over the temperature measurement, the error of the analytical results from the thermocouple was within 10%. Finally, the average ejection delay was obtained to be X + 5.5 s with an accuracy of 1.1 s.

6. Lithium Imagers for Ground Observation

In order to observe 670.8 nm Lithium emission, a special Lithium imager was designed. The imager was developed to have wide field of view (FOV = 110°) and wide aperture (F/3.5) by using a band pass filter (BPF) of 20 nm bandwidths as well as image-side telecentric optics. BPFs are manufactured by interference coating technique. Usually, the coating technique was applied for BPF to obtain large transmittance parameter at a wavelength \( \lambda \) for main light beam perpendicular to BPF surface, it has a character of shifting the larger transmittance parameters at the shorter wavelength \( \lambda - \Delta \lambda \) for oblique light beams. In case of the image-side telecentric optics, whole of the main beams can be designed absolutely in parallel at image-side of the lens, so that we can obtain optimum optic design with wide FOV and narrow wavelength width when a BPF is set at between the telecentric lens and an image sensor.

Depending on FOV and aperture, oblique beam components are usually existed. In case of telecentric lens, the oblique light beams can be uniformed and followed within a certain fixed angle \( \theta \) and be flattened for whole of the image. Thus we can design it so as to fulfill a condition that the wavelength shift \( \Delta \lambda \) is to be in an appropriate range for all of the oblique beam components within the angle \( \theta \). The angle \( \theta \) can be determined by FOV and aperture of the lens used, and the \( \theta \) and the transmittance width in wavelength for BPF are in a trade-off relationship. We developed two Lithium imagers: one for F-region imaging is designed to be wide FOV (FOV = 110°, F/3.5, \( \Delta \lambda = 20 \) nm, \( \theta = 11° \)) because of the rapid diffusion of the Lithium cloud in F-region (Fig. 10); the other for daytime imaging is designed to be narrow band pass condition (FOV = 50°, F/6, \( \Delta \lambda = 2 \) nm, \( \theta = 3° \)) so as to obtain high S/N in daytime.

As for the imaging devices, commercial-use digital cameras of Canon EOS Kiss Digital N and EOS X4 are used. Precise triangulation is necessary for measuring the neutral wind in thermosphere. These low-cost cameras with large CMOS devices of over 2000 \times 3000 pixels are significant for high spatial resolution. In a S-520 rocket experiment in 2007 in evening sky, these cameras were used under a condition of ISO = 800 to 1600 and their exposure time of 4 s

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Fig. 10. A schematic diagram of telecentric optics design of the Lithium imager for F-region imaging (FOV=110°, F/3.5, \( \Delta \lambda = 20 \) nm, \( \theta = 11° \)), where main light beams passing through a band pass filter (BPF) are uniformed absolutely in parallel in the image-side of lens.

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Fig. 11. An example of the neutral wind profile in thermosphere observed on 2007 Sep. 2 at midlatitude (31 deg.N in geographic) under the evening sky condition derived from the Lithium release experiment by using the JAXA S-520-23 sounding rocket. What is the dashed line between 160 km and 225 km?
to 30 s. Since the 670.8 nm Lithium emission by resonance scattering mechanism is at the reddest end of the human visible light, these CMOS devices are used by removing infrared cut filters.

7. Summary of Wind Measurement by S-520-23 Rocket

The S-520-23 sounding rocket was launched at Uchinoura Space Center (USC) of JAXA, at 19:20 LT on 2007 Sep. 2. By the LES canisters onboard the rocket, 3 Lithium releases were successfully operated at 232 km, 193 km, and 144 km, respectively. 4 ground observation sites (Shionomisaki, Miyazaki, Uchinoura, and Amami) were set at about 400 km apart from the Lithium release points. Owing to good weather condition, 3 red clouds illuminating by resonance scattering of Lithium were successfully observed at the 4 ground sites. By the special Lithium imager with a 20 nm BPF, high S/N images of the Lithium clouds were taken for more than 40 minutes after the release. The red clouds could be visible for a few minutes by naked eyes, for about 10 minutes by cameras without BPF.

As a result of precise triangulation, we obtained a neutral wind profile in wide altitude range from 115 km up to 400 km only by the 3 Lithium releases (Fig. 11). Being

Fig. 12. Example images of the Lithium clouds released by the S-520-23 LES. Images were photographed at Miyazaki. Images were recorded at (a) 4 s, (b) 20 s, (c) 44 s, (d) 76 s, and (e) 342 s after the release time of the first Lithium cloud (19:26:13 LT on Sep. 2, 2007). The rocket was at (a) 231 km, (b) 215 km, (c) 187 km, and (d) 141 km altitude at the time of observations. For images (a) to (d), camera condition was ISO = 800 and 4 s exposure, whereas, ISO = 1600 and 30 s for image (e). Note that a horizontal structure on the Lithium clouds is a tropospheric cloud probably created by airplane passage.
helped by vertical diffusion of gaseous Lithium in thermosphere, the 3 red clouds were finally merged into one long tracer in the sky (Fig. 12(e)). At the conjunction region of two Lithium clouds at near 200 km altitude, some difficulties were found in deriving process; however, a neutral wind profile with a stable NW-ward wind above 200 km as well as two considerably large wind shear structures at 116 km and 197 km altitudes was analyzed (Yokoyama, 2009; Yamamoto et al., 2010). Note that error range was within 5 m/s for the E-region profile below 170 km, whereas 35 m/s for the F-region above 200 km altitude because of rapid diffusion of the clouds. At each release 125 g Lithium was released. Microprocess of the Lithium releases was also studied in detail by using an impedance probe onboard the rocket (Uemoto et al., 2010).

For deriving the F-region wind profile, a central line of the illuminating clouds was carefully analyzed on the successive images by using light curve of the clouds on an image processing software. Then, by using background star field in the evening sky, a triangulation procedure established by meteor train studies (Yamamoto et al., 2003, 2005) were applied for Lithium tracers. Moreover, we should comment here that the velocity of the rocket motion could affect on the initial motion of the released clouds especially in F-region measurement. Thus, in the process of measuring wind profile in the F-region, we need to use long-time-tracking data more than 10 minutes because we need to wait for a certain merging or stabilizing time between the released Lithium particles and the ambient atmosphere species by their microscopic collision process.

Here, it was described briefly that the technical part of the ground observation for the Lithium release experiment in the E and F region. Scientific results of the S-520-23 rocket experiment (WIND campaign) for clarifying the interaction between the neutral and plasma atmosphere will be written in another paper in detail.

8. Summary

This paper is a guide for the design of a chemical payload. The key technology of the lithium release system is the burn rate and the reaction product temperature controlling of thermite in the canister. The burn rate of thermite relates to the mixture ratio between iron oxide and Al, and the particle diameter of Al also impacts the burn rate. The temperature of the reaction products is controlled by the mixture ratio of the thermite. Considering the ground safety of the handling through the loading and rocket launch operation, lithium or other chemicals should be loaded separately from the thermite. To avert the hazardous situation by the unexpected firing of pyrotechnics, the chemical payload should be equipped with the safety module to seal the ignition energy in itself independently. The LES design has the potential of providing flexibility in replacing lithium with other chemical tracers.

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References


