XENON LOADING DEVICE FOR MUSES-C ION ENGINE SYSTEM

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Abstract

The Institute of Space and Astronautical Science (ISAS) is planning to launch a space probe in 2002 for an asteroid sample return mission as MUSES-C. One of the primary objectives of this mission is to verify electric propulsion applicability to interplanetary exploration. As the electric propulsion, we employed a new technique of microwave discharge ion engine system. The MUSES-C ion engine system will consume about 70 kg xenon propellant during its round-trip mission of 4 years. Since xenon is one of the rarest in the earth (about 0.09 ppm by volume in the atmosphere), it becomes quite expensive propellant. So, a method of xenon filling up to the spacecraft propellant tank will be a key technique to save the cost of MUSES-C project. In this paper we are comparing five loading methods from the viewpoint of minimum cost in total. We finally assessed the liquefaction method becomes a suitable method of xenon propellant loading device for MUSES-C ion engine system. This method needs neither any special facility nor device. We demonstrated the liquefaction method using two small pressurized xenon bottles before the loading device have been fabricated. After the device fabricated, we have demonstrated a dry-run using trifluoromethane (CCH_3, R23) coolant instead of precious xenon. The result of this demonstration is quite sufficient. We will contract with a Xenon supplier of an open tenderer in this fall.

Introduction

The Institute of Space and Astronautical Science (ISAS) is planning to launch a 480 kg weight space probe in July 2002 for an asteroid sample return mission called MUSES-C. After 20 months, MUSES-C will arrive at the asteroid "1989ML". Onboard cameras will take asteroid pictures and scientific instruments will observe asteroid characteristics. Asteroid surface samples will be collected into a sample container of MUSES-C. Both Japan and NASA JPL will deliver a small separable vehicle(s) of 1 kg weight for asteroid surface science investigations. Following a two-month stay around the asteroid, MUSES-C will depart for Earth return. In both the transfer and return phases, high efficiency ion engine is utilized as the main engine.

The mission will conclude in July 2006, when the reentry capsule separates from MUSES-C main body, it enters the earth atmosphere. Then the asteroid sample will be retrieved on the ground. MUSES-C spacecraft touching on the asteroid is illustrated in artist's conceptual Figure 1. A high gain antenna is mounted on the top panel. A pair of solar paddles are equipped on the side panels. Four ion engine thruster heads with gimbals are installed on the left hand side panel. The board shape equipment on the right hand panel is a thermal louver. A sample capture horn is equipped on the bottom panel. A NASA JPL separable micro vehicle and a target for rendezvous maneuver are dropped on the asteroid surface in figure 1.

One of the primary objectives of this mission is to verify electric propulsion applicability to interplanetary exploration. As the electric propulsion, we employed a new technique of microwave discharge ion engine system[1), 2), 3)]. Other primary objectives of this mission are to acquire and verify the following technologies, an

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autonomous navigation and guidance to a small target in deep space, rendezvous with an asteroid and sampling of its surface materials, and reentry to the earth's atmosphere with quite high speed.

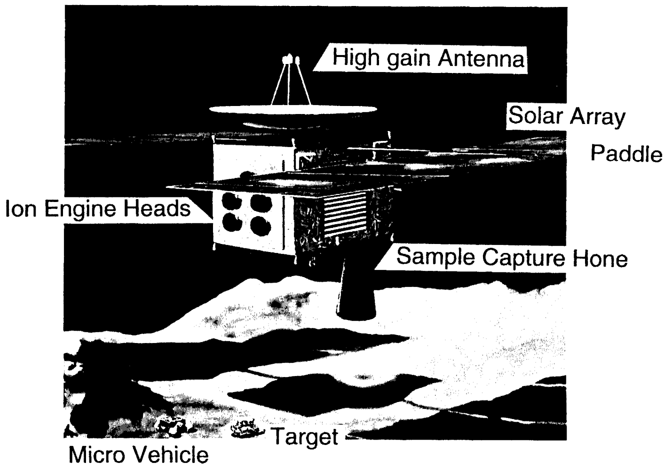

Figure 1 MUSES-C artist's conceptual drawing.

In order to operate the ion engines during the four years round trip, the ion engine system requires about 70 kg xenon propellant. The specific impulse of the ion engine system is about 2700 sec. We compared five loading methods and have assessed the liquefaction method will become a suitable method for MUSES-C ion engine system. A demonstration result of the liquefaction method using two pressurized xenon bottles has reported $^{4)}$.

MUSES-C consist of the following sub-systems; Power subsystem, Communication subsystem, Data Handling subsystem, Propulsion subsystem, Navigation and Guidance subsystem, Structure and Thermal control subsystem, Reentry capsule subsystem, Scientific instruments, and fuel. A pair of the solar array paddles generate 1.4 kW electric power at 1 A.U.. A parabolic high gain antenna receives commands and transmits telemeters by X-band wave. The bi-propellant thrusters execute midcourse maneuvers and mono-propellant thrusters control the attitude of the spacecraft. All of the cruising phase between the earth and the asteroid "1989ML", the spacecraft will be propelled by the microwave discharge ion thruster system. The ion engine will generate thrust for about 800 days between 1 kW maximum to 250 W minimum electric power. The power level will depends on the distance from the sun. A single unit of the ion engine is rated at 350 W electric power so that three units are operated at the maximum electrical power.

Ion Engine System

Ion engine system is consists of the following components; a thruster control unit, three power processing units, four microwave supply units, a propellant supply unit, four ion thruster assemblies (one head for redundant) and a wire harness. The dry weight of the ion engine system is 70 kg at present time. The propellant management unit (PMU) consists of a xenon tank (Xe tank), heater, a fill drain valve , a main valve, isolation valves, pressure gauges (P), regulation valves, latching valves , flow restricters , a plenum tank, and a service valve. Filters are assembled in valves. Figure 2 shows a block diagram of the propellant management unit for ion engine system. ITH means ion thruster head and NEUT means neutralizer in Figure 2, respectively.

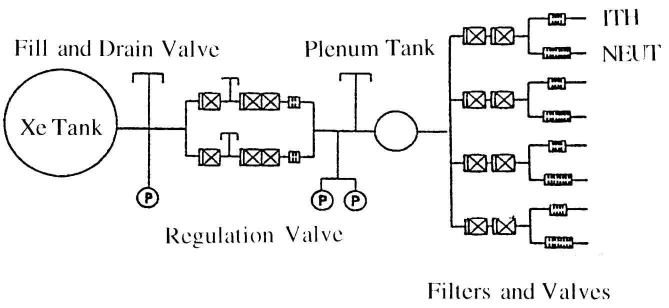

Figure 2 The Propellant Management Unit of the ion engine.

Propellant Xenon

The noble gases such as xenon, krypton and argon, have been primarily selected as the propellants for ion engines. Propellant requirements also include high atomic weight, low ionization potential, easiness of handling and storage, and low contamination potential. In the three noble gases, xenon is the heaviest and has the lowest ionization potential. In addition, xenon has the highest boiling point and the highest density. Xenon is currently the propellant of choice for ion engine systems world-wide. Xenon has a unique property of critical temperature of 17 ℃ (290 K) or critical pressure of about 6 MPa (60 kg/cm^2). It means that xenon suddenly changes to liquid phase from gas phase when the temperature moves slightly down. Figure 3 shows this unique property of xenon density versus pressure relation at various temperatures.

On the other hand, it is well known that the existence of an optimum density of propellant that minimizes the propellant tank weight [3]. The value of optimum density for xenon is about 1.4 g/cc . In Japan, xenon vendors (usually having a liquid oxygen and/or liquid nitrogen plant) bottle xenon gas below 1.23 g/cc of density at room temperature. Because filling pressure (or density) is limited by Japanese "High Pressure Gas Safety Law" (hereafter call the law) and/or, MITI (Ministry of International Trade and Industries) Ordinance of "General High Pressure Gas Safety Regulations", "Container Safety Regulations" (hereafter call the regulations) and so on. The MUSES-C ion engine system will consume about 70 kg xenon propellant during its round-trip mission of 4 years. Since xenon is one of the rarest in the earth (about 0.09 ppm by volume in the atmosphere), it becomes quite an expensive propellant. So, xenon loading method for the spacecraft propellant tank will be a key technique to save the cost of MUSES-C project.

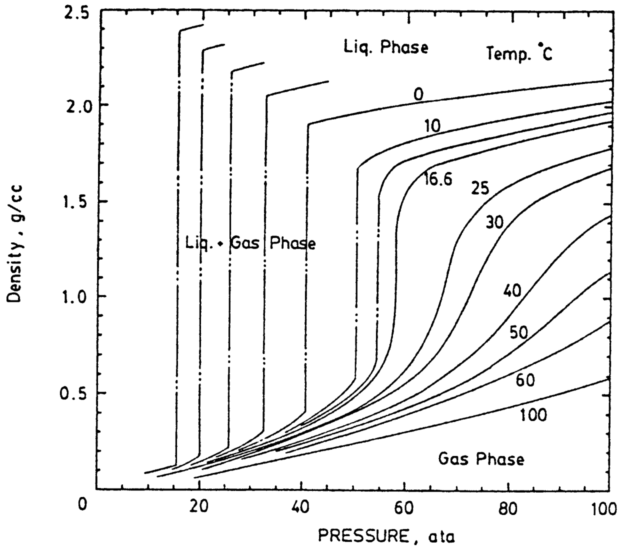

Figure 3. Xenon density versus pressure in various temperatures.

Trade-off of Loading Methods

We have compared five loading methods from the viewpoint of minimum cost in total. Five loading methods were 1) blow-down method, 2) compression method, 3) solidification method, 4) warm up method and 5) liquefaction method. As a result, we selected the liquefaction method for the MUSES-C xenon propellant loading device.

Table 1 shows results of a trade-off for loading methods. Horizontal column shows 5 methods and vertical columns show trade-off items.

The first item is about the satellite tank. The tank has been already fixed of its basic design (i.e., spherical bottle of 48 litter in volume, made by Titanium alloy). So, temperature for loading operation is a difference in each method. It is necessary that a special loading permit (for high pressure gas) is given from the local government before xenon can be loaded into the satellite tank. An easiness to obtain a primary bottle(s) is shown in secondary column. All difficulty or easiness will be reflected in cost. Though the risk will not reflected in total cost of each method, we have to consider it from a view point of system management. The third column shows a secondary bottle or facility. In case of the compression method, a compressor will be attached in the filling pipe line. A reciprocating type compressor has a leak problem and a diaphragm type compressor has a very high cost problem. In case of solidification method, a secondary bottle is contained in a container which is filled by liquid nitrogen coolant. This is an excellent method but it is a high cost facility. The liquefaction method needs a secondary tank with a bath tab. The secondary bottle or facility needs permission of the law from the local government. The fourth column shows operation temperature of secondary tank. The solidification method

Table 1 Trade-off Matrix of Five Loading Methods.

Items	Blow-down	Compression	Solidification	Warm-up	Liquefaction
Satellite Tank	Fixed Design: Spherical bottle, 50 litter Volume, Titanium alloy, 1.5 of Safety Factor, Special loading permit				
Easiness to obtain primary bottle	Impossible	Easy	Easy	Easy	Easy
Secondary Bottle or Facility	N/A	Compressor Leak/Cost	Special	N/A	Special
Operational Temp.	Room	Room	Very Low (Liq. Nitrogen)	Max. 40	Room
Complexion	Simple	Normal	Complexion	Simple	Simple
Reality of System	Unreal	Unreal	Excellent	Good	Very Good

is operated at exceptionally low temperature. The fifth column is a complexion of loading system. The sixth column is a reality of loading method or is an appraisal.

We finally assessed the liquefaction method becomes a suitable method for MUSES-C ion engine system. Actually, we have made a loading facility using this method including a secondary bottle (it corresponds to bottle A below) which meets with the law.

Liquefaction method

Liquefaction method may become a suitable way. This method needs not any special facility nor device. Only cool water or ambient atmosphere is necessary. This method is similar to the warm up method since these methods use just the temperature difference between two bottles. Figure 3 shows a schematic drawing of the liquefaction method. First, one provides two nominal (density of 1.2 g/cc xenon) bottles, and sets those bottles into fill line. One puts one bottle (bottle A) into a cool tub (10 ℃ for example), and opens a valve of the other bottle (bottle B) of room temperature. Then some xenon moves into bottle A, and bottle A contains heavy density xenon. As the next step, the bottle A is connected with a satellite tank. Consequently, xenon moves into the satellite tank. This is a simple and cheap way. We can easily provide each device that meets with the law, such as primary bottles, pipe, valves, tub(s), all commercially available. The only negative point is the remaining xenon in the bottle B. We still believe that it is allowable. This method can keep satellite tank in room temperature. We need to receive permission of the law for a secondary bottle from the local government.

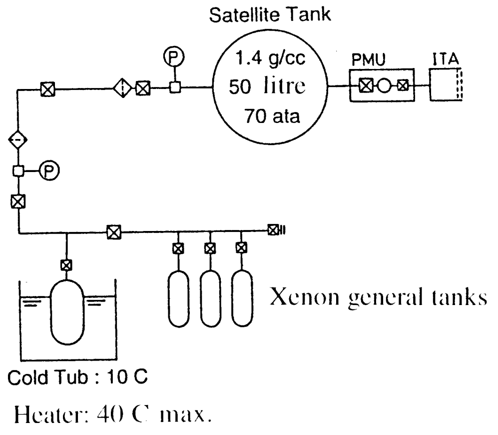

Figure 3 Schematic drawing of the liquefaction method.

Demonstration

We have demonstrated the liquefaction method using two pressurized xenon bottles. As a result, xenon gas was successfully transferred from bottle B to bottle A. The mass of transferred xenon was 830 grams. It moved from 1940 grams of initial value in the bottle B. The transfer efficiency was 43% in this demonstration. In other words, the bottle A contained gas phase xenon of 1.7 g/cc of density that rose from an initial value of 0.9 g/cc.

The demonstration configuration is shown in Figure 4.

Step 1 : connect a primary bottle (B) and secondary bottle (A) by pipe.

Step 2 : set the bottle A in the tub, and cool down by water.

Step 3 : open a valve between the bottles. Then xenon moves to bottle A from bottle B.

Figure 5 shows this results of the demonstration in Xenon density vs. pressure .

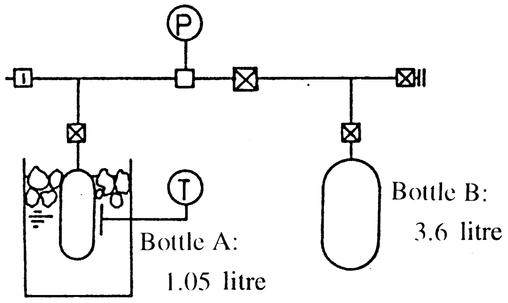

Figure 4 The demonstration configuration.

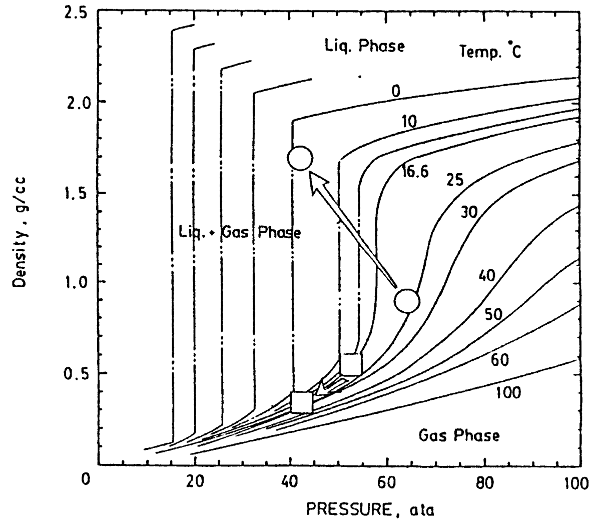

Figure 5 Results of the demonstration in Xenon density vs. pressure.

Manufacturing the Loading device

We have selected a liquefuction method for the loading device. Then we have manufactured the xenon loading device shown in figure 6. This device consists of a stainless steel frame and base, an operation panel, a liquefaction tank which settled in a temperature controlled tub, and a vacuum subsystem.

The loading device has folk-lift guide rails and wheels for total weight of 1,030 kg without three xenon general tanks. Sizes of the device is 1.8 m in width, 1.6 m in height and 1.3 m in depth.

A liquefaction tank has made by stainless steel of 130 kg of weight. Dimensions of the tank are 320 mm in diameter and 560 mm in length. The tank volume is 26.5 litre and 33 kg weight capacity of xenon. The tank endures 22.5 MPa of maximum pressure. Of cause the tank or device is in conformity with the low.

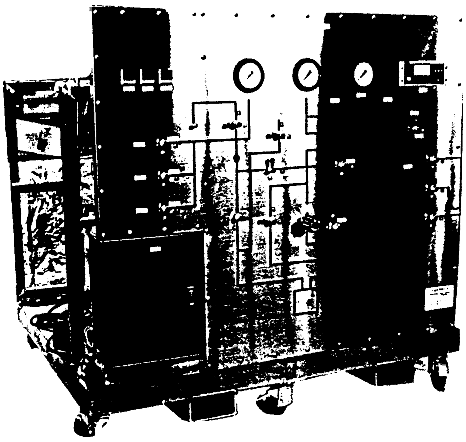

Figure 6 The xenon loading device.

Dry Run Demonstration using Trifluoromethane

After manufactured the device, we have planned a dry run test of the device. The reason of high cost of xenon gas, we have traded off several gases instead of xenon. We compared the chemical and physical properties of several gases with xenon properties. The substitute gases we compared, were dioxidecarbon (CO_2), chlorotrifluoromethane ($CClF_3$), trifluoromethane (CHF_3) and hexafluoroethane (C_2F_6). Those gases are well known as a coolant gas. The properties of those gases are shown in table 2. We took notice of values of critical temperature and critical pressure. As a result of trade off, trifluoromethan was selected as a substitute gas for precious xenon. Our goal density of using trifluoromethane was over 0.673 g/cc which corresponds to 1.42 g/cc of xenon.

Using trifluoromethane, we have demonstrated a dry run test at high pressure test facility. We set a trifluoromethane general tank on the device as be xenon tank position. We have set a sampling bottle as simulated the MUSES-C satellite xenon tank. Though the volume of the satellite tank is 50 litre, we have loaded to the sampling tank of 0.3 litre.

The objectives of the dry run demonstration was, 1) to confirm the safety capability of the device, 2) to confirm the performance capability of liquefaction method loading device, 3) to confirm the loading procedure using the same device for true loading, and 4) to estimate a loading time of 70 kg xenon at the lauch site. Before the loading task, we have pumped down the gas pipe line and tank by a vacuum system and have baked a gas pipe lines by heaters. These preparation tasks were finished along the test procedure. Finally, we have loaded trifluoromethane into the sampling bottle of 0.93 g/cc in density at 6.2 MPa from the general tank in 8 hours.

As conclusive results, 1) we have confirmed the device is acceptable for safety loading, 2) we have confirmed the liquefaction method is useful for the MUSES-C xenon loading device, 3) we have checked a loading procedure. The dry run demonstration showed us that several points should be improved, for example, the device needs more powerful additional heater for saving a time, 4) we could

Table 2 Chemical and physical properties of several gases.

Name	Xenon	Dioxidecarbon	Chlorotrifluoromethane	Trifluoromethane	Hexafluoroethane
Chemical Symbol	Xe	CO_2	$CClF_3$	CHF_3	C_2F_6
Critical Temp. ℃	16.6	31.5	28.9	25.7	19.7
Critical Pressure, MPa	5.83	7.34	3.92	4.84	2.98
Critical Density, g/cc	1.11	0.47	0.58	0.53	0.62
Mol Number	131	44	104.5	70	138

estimate that the total loading time will be about a week to two weeks for full loading of 70 kg xenon gas into the MUSES-C satellite tank.

Finally, we are going to obtain the propellant xenon by an open tender method. Required specifications of xenon are shown as below:

1) Xenon purity
  Xenon: > 99.995%
  Krypton: < 35 ppm
  Oxgen: < 1 ppm
  Nitrogen: < 5ppm
  Monooxidecarbon, Dioxidecarbon: < 1 ppm
  Hydrocarbon: < 0.5 ppm
  Water: < -70 ℃ of Dew temperature
2) Xenon loading density in supply tank (bombe)
  1.225 g/cc < ρ < 1.234 g/cc
3) General tank
  Handbook JIS B 8241 is applied.
  Volume: 47.0 litre < v < 47.5 litre
4) Tank valve
  Handbook JIS B 8244 is applied.
  The valve with lupture disk is required, but not melt disk.

A xenon supplier will be selected on this December.

Conclusion

We have compared five loading methods from the viewpoint of minimum total cost. The liquefaction method has been selected for the MUSES-C xenon loading device. Before manufacturing the device, we demonstrated the liquefaction method using small two bottles. The demonstration has been finished in success. We used real xenon in this demonstration. As a result, xenon gas was successfully transferred to the bottle A from the bottle B. The mass of transferred xenon was 830 grams. It moved from 1940 grams of initial value in the bottle B. The transfer efficiency was 43 % in this demonstration. In other words, the bottle A contained gas phase xenon of 1.7 g/cc of density that rose from initial value of 0.9 g/cc.

Then we manufactured the loading device that was in conformity with the low and the regulations. Using the loading device, we have operated a dry run demonstration. Trifluoromethane has been selected instead of precious xenon propellant. The dry run has been successfully finished. We learned several improvement points through the dry run demonstration. The true xenon loading time will be estimated about a week or more.

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