# Refillable Electric Propulsion
# with in-situ produced fuels in Space

*Prepared for the 35th International Electric Propulsion Conference*
*Georgia Institute of Technology • Atlanta, Georgia • USA*
*October 8 – 12, 2017*

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**Abstract: Alternative propellant has been researched to replace rare gases. In-situ producible propellant will largely be welcomed when we try to explore new place, such as the moon and the Mars. One of potential in-situ alternative propellants is methane, and discussion on this propellant gas are given in this paper to use it for a EP, Hall thruster. While there are some possible problems on methane, it still has potential for alternatives on the Mars or on future exploration based on the Mars.**

## I.Introduction

All of space exploration in history departed from the earth. Probes with chemical or electric propulsion and launchers by any nations contained fuel processed on the earth, especially for electric propulsion Xe has been used. Nowadays, plans for manned-mission to the Mars or Lunar surface are progressing in the world. In the future, there will be satellites of new generation which is originated from those space body and launched with in-situ propellant. It would cut cost to launch something from the earth if those satellites are totally produced on the other planet, and it would also take benefit to leave the gravitational area because those planets have less gravity or larger orbiting energy than the earth. Moreover, we'll have another ISS on the orbit and the station also needs a propulsion system to keep its orbit. For those usage, it is important problem which kind of gases we can have on the place when we begin next exploration based on the other planets. At the point of in-situ propellant, an American company, Busek, proposed a Hall thruster system with carbon dioxide propellant and its application on their Mars airplane concept[1]. Since plenty of $CO_2$ is included in the atmosphere of Mars, that can be available by producing on Mars bases or by air-breathing unit during flight.

Another potential gas is methane. This also can be produced on the Mars, by Sabatier reaction using an atmosphere or from living-things' wastes. Actually, methane is in the scope of propellant for chemical rockets. SpaceX has discussed to use it for their next generation rocket engine, Raptor, with liquid oxygen as an oxidizer[2]. Methane can be produced for such usage on the Mars and it is expected to use this propellant for satellites too. Since methane plasma itself has been researched in the other field such as plasma processing, fundamental characteristics like ionization or excitation are clarified. From this point, it can be a good choice of propellant for electric propulsion.

## II.Using methane as propellant of Hall thruster

In this section, necessary consideration to use methane in electric propulsion, Hall thruster, will be given.

### A. Choice of Hall thruster

A big anxiety of using methane is accumulation of particles on the thruster body. It is known that methane plasma is used to generate carbon layers on a material surface in the field of plasma processing[3]. However, such a deposition should be avoided because any change of wall or grid geometry alters its characteristics of thrusters. If it is considered to operate ion engines with methane, deposited carbon on the wall or the grid system would lead to operation failure in several thousands of hours. Therefore, it seems using methane plasma for ion thruster is not a realistic way.

On the other hand, there are some advantageous technology to reduce carbon deposition on the wall, while Hall thrusters also have annular discharge chamber. One of them is technology, which has been largely used for magnetic layer type thrusters since its advent, called “Magnetic Shielding[4].” The noble point of this technology is on its extremely low erosion rate, which is smaller than that of conventional thrusters without this technology by a factor of 1000. Three main features are realized by unique magnetic field design in this technology; reduction of the electron energy loss, a shift of ionization region by relatively high electron temperature, and repulsion of ions from the discharge wall. Therefore, this type of Hall thrusters can be used with methane without the undesirable carbon deposition. Another possible concept to be used is anode-layer type Hall thrusters[5]. This type of Hall thruster has originally short discharge channel because of high electron temperature by metallic walls biased to the same potential as its cathode. Since it also limits interference between methane and the wall, anode layer type Hall thruster can be another candidate of thruster with methane propellant.

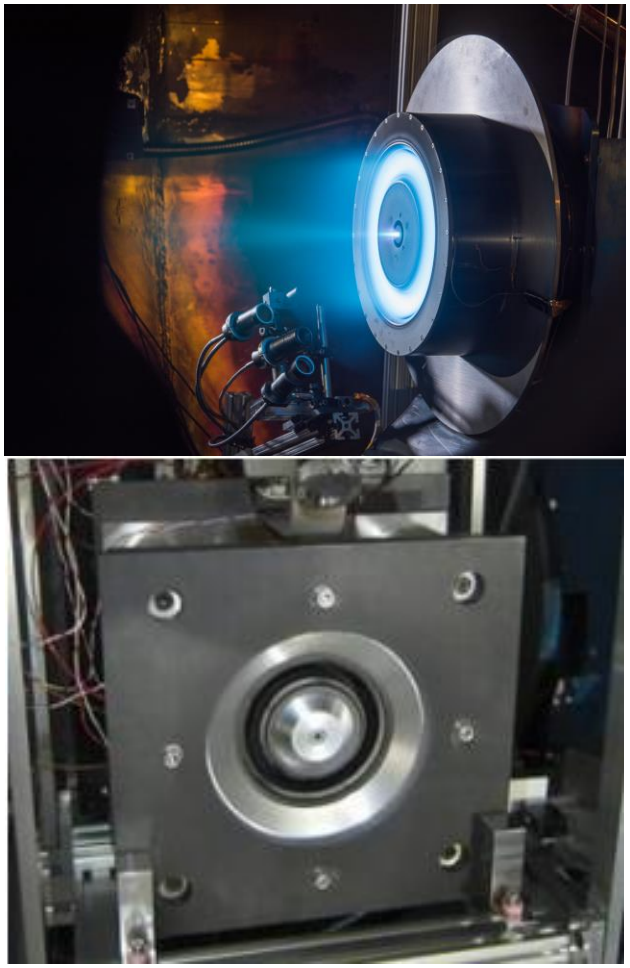

**Figure 1. Hall thrusters which can be candidates with methane propellant.** *(Upper)HERMeS thruster as an example of magnetically shielded Hall thruster (Image credit:NASA) (Lower) RAIJIN thruster, an anode-layer type Hall thruster*

### B. Substantial discussion about methane propellant

For practical consideration, it is necessary to discuss plasma with methane produced from collisional ionization. Dissociation should be considered if we use this molecular gas, which is not occurred in conventional gases like Xe or Ar.

From some literature, a single charged ion of methane is produced by collision with electron of 13 eV in temperature[7]. How far the ionization occurs is shown in Table1, which is the list of several ionization cross sections. While first ionization energy is not so different from conventional gases, the dissociation reaction is occurred at electron temperature of about 17 eV[8]. If dissociation is frequently occurred, produced ions will become light, and efficiency have a less value[9]. Those properties of reaction is strongly related to electron temperature and it should be controlled to suitable values. For the most efficient usage of propellant, increasing amount of single charged ions, $CH_4^+$, is profitable. However, dissociation from neutral particles is not the only problem, and it can occur from double charged ions. Double charged ions are also considered in the conventional thrusters by using correction factor to compensate its effect to efficiency and thrust. Double charged ions of methane dissociate to small fragments with releasing its kinetic energy, and that is observed experimentally when the electron energy set to the value of 55 eV[10]. This order of electron temperature, reaching several tens of eV, is also observed in some Hall thrusters[11,12], so this is a possible problem when methane is used as propellant.

In fact, there are possible ideas to control this temperature. One is to consider type of Hall thruster and its wall material. Some researchers have focused on characteristics of different wall materials which has different secondary emission property and affects temperature of discharge plasma[13,14]. General materials to be used is boron nitride, carbon and metals for the wall of Hall thruster, and its specification is summarized in Figure2. The suitable wall material will be different depending on thruster power or its application to a satellite.

For example, the power range over several kW class such as large satellites will need higher emission rate material to suppress temperature rise with increased discharge voltage. Conventional magnetic layer Hall thrusters will work well at this point of temperature control.

**Table 1. Ionization cross section of methane.** *The relative value of cross section is summarized about three species of ions. Those values are quoted from Ref. 10, and each value is relative portion to the value of the most fundamental species,* $CH_4^+$ *as 1.*

| ***E*/eV** | $\sigma_r[CH_3^+]$ | $\sigma_r[CH_2^+]$ | $\sigma_r[CH^+]$ |
|---|---|---|---|
| **30** | **0.792** | **0.114** | **0.0304** |
| **45** | **0.803** | **0.185** | **0.0897** |
| **60** | **0.835** | **0.205** | **0.1053** |
| **75** | **0.843** | **0.210** | **0.1120** |
| **100** | **0.854** | **0.210** | **0.1129** |

Considering small satellites, lower power Hall thrusters may be required on the Mars. Since demand for small satellites are gradually increasing concept on the earth, it will be launched around the Mars too. While electron energy will decrease along with discharge power, it can be compensated by the choice of Hall thrusters. For example, low electron emission structures like carbon velvet will decrease electron energy loss, or anode layer type Hall thrusters with the metallic wall also can improve low electron energy. Of course, while any choices of thruster is strongly related to specification of a satellite, orbit design or plan to satellites on the location should be discussed in advance.

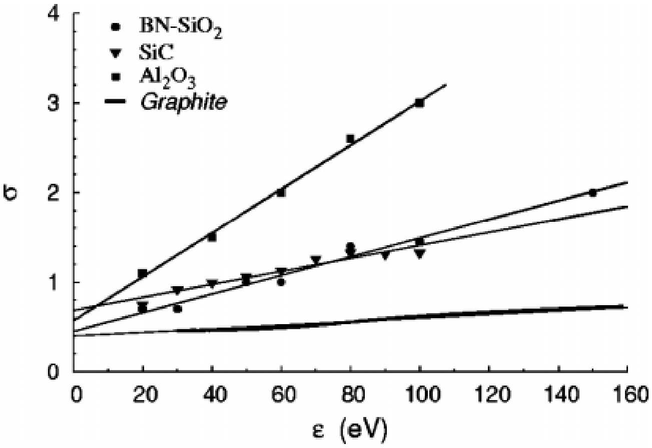

**Fig. 2. Secondary electron emission yield on several materials[13].** *Representative materials are summarized in this table. Boron nitride, Aluminum oxides and graphite are listed from some literatures. The range of electron energy in this table is up to 100 eV.*

## References

[1] Szabo, J. J., and Hruby, J. J., “Breakthrough Concepts for Mars Exploration with In-Situ Propellants,” Concepts and Approaches for Mars Exploration, Vol. 1679. 2012.

[2] Markusic, T., “SpaceX Propulsion,” Proc. of the 46th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, July. 2010.

[3] Von Keudell, A., and Möller., W., “A combined plasma ‑ surface model for the deposition of C: H films from a methane plasma,” Journal of applied physics Vol.75, No. 12,pp. 7718-7727, 1994.

[3] Mikellides, I. G., Katz, I., Hofer, R R., Goebel, D. M., De Grys, K., and Mathers, A., “Magnetic shielding of the channel walls in a Hall plasma accelerator,” Physics of Plasmas Vol. 18, No. 3, 033501, 2011.

[5] Semenkin, A. V., Zakharenkov, L. E., and Solodukhin, A. E., “Feasibility of high power multi-mode EPS development based on the thruster with anode layer,” IEPC paper 2011-064, 2011.

[6] Yamamoto, N., Miyasaka, T., Komurasaki, K., Koizumi, H., Schoenherr, T., Tahara, H., Takegahara, H., Aoyagi, J., Nakano, M., Funaki, I., Watanabe, H., Ohkawa, Y., Kakami, A., Takao, Y., Yokota, S., Ozaki, T., and Osuga, H., “Developments of Robust Anode-layer Intelligent Thruster for Japan IN-space propulsion system,” 33rd International Electric Propulsion Conference, IEPC-2013-244, Washington, DC, USA. 2013.

[6] Collin, J. E., and Delwiche, J., “Ionization of methane and its electronic energy levels,” Canadian Journal of Chemistry Vol. 45, No. 16, pp.1875-1882, 1967.

[8] Danko, M., et al. "Electron impact excitation of methane: determination of appearance energies for dissociation products." Journal of Physics B: Atomic, Molecular and Optical Physics 46.4 (2013): 045203.

[9] Goebel, D. M., and Katz, I., “Fundamentals of electric propulsion: ion and Hall thrusters,” Vol. 1. John Wiley & Sons, 2008.

[10] Ward, M. D., King, S. J., and Price, S. D., “Electron ionization of methane: The dissociation of the methane monocation and dication,” The Journal of chemical physics 134.2 (2011): 024308.

[11] Hofer, Richard R., et al. "Magnetic shielding of a laboratory Hall thruster. II. Experiments." Journal of Applied Physics 115.4 (2014): 043304.

[12] Keidar, M., I. D. Boyd, and I. I. Beilis. "Plasma flow and plasma–wall transition in Hall thruster channel." Physics of Plasmas 8.12 (2001): 5315-5322.

[13] Barral, S., et al. "Wall material effects in stationary plasma thrusters. II. Near-wall and in-wall conductivity." Physics of Plasmas 10.10 (2003): 4137-4152.

[14] Raitses, Y., et al. "Measurements of secondary electron emission effects in the Hall thruster discharge." Physics of Plasmas 13.1 (2006): 014502.