

Development of Long-life Lightweight Arcjets

IEPC-2013-292

*Presented at the 33rd International Electric Propulsion Conference,
The George Washington University, Washington, D.C., USA
October 6–10, 2013*

Daisuke Nakata*

Muroran Institute of Technology, 27-1, Mizumoto-cho, Muroran-shi, Hokkaido 050-8585, Japan

Kiyoshi Kinefuchi†

Japan Aerospace Exploration Agency, 2-1-1, Sengen, Tsukuba-shi, Ibaraki 305-8505, Japan

Masahiro Kinoshita‡

The University of Tokyo, 7-3-1, Hongo, Bunkyo-ku, Tokyo 113-8656, Japan

Satoshi Hosoda§

Japan Aerospace Exploration Agency, 3-1-1, Yoshinodai, Chuoku, Sagamihara-shi, Kanagawa 252-5210, Japan

Hirokazu Tahara¶

Osaka Institute of Technology, 5-16-1, Omiya Asahi-Ku, Osaka 535-8585, Japan

and

Hitoshi Kuninaka||

Japan Aerospace Exploration Agency, 3-1-1, Yoshinodai, Chuoku, Sagamihara-shi, Kanagawa 252-5210, Japan

Abstract: With ultra light-weight solar panel, it is anticipated that arcjets enables us fast and efficient interplanetary cargo transportation. Next generation arcjets should have lighter-weight design and prolonged lifetime. In this paper, some solutions are proposed. It is shown that the radiator mass can be drastically reduced by the effective use of propellant as a coolant at the lower temperature region on the radiator. Resulting thruster weight of 1.5 kg including the radiator is possible assuming 2.1 kW of anode heat load at 150 A of the discharge current. For the lifetime issue, replaceable cathode system is proposed. The trade-off study is necessary between the total lifetime and the system weight.

*Research Assistant Professor, Aerospace Plane Research Center, E-mail: nakata@mmm.muroran-it.ac.jp

†Research Engineer, Space Transportation System Research and Development Center, E-mail: kinefuchikiyoshi@jaxa.jp

‡Graduate Student, Department of Aeronautics and Astronautics, E-mail: kinoshita@ep.isas.jaxa.jp

§Research Engineer, JAXA Space Exploration Center, E-mail: hosoda.satoshi@jaxa.jp

¶Professor, Department of Mechanical Engineering, E-mail: tahara@med.oit.ac.jp

||Professor, JAXA Space Exploration Center, E-mail: kuninaka@isas.jaxa.jp

Nomenclature

A	= referential area
A_0	= universal Richardson constant
A_c	= cathode emission area
c_p	= specific heat
d	= diameter of the cooling tube
dT_{mean}	= log mean temperature difference
E	= Young's modulus
e	= charge of electron
h	= heat transfer coefficient
J	= discharge current
k	= Boltzmann constant
\dot{m}	= mass flow rate
Pr	= Prandtl number
Q_{anode}	= heat load to the anode
$Q_{cathode}$	= heat load to the cathode
Q_{conv}	= convection heat
Q_{rad}	= radiation heat
Re	= Reynolds number
r_{in}	= inner radius of the cylinder
r_{out}	= outer radius of the cylinder
T	= temperature
T_0	= background temperature
t_1	= inlet propellant temperature
T_1	= inlet pipe temperature
t_2	= outlet propellant temperature
T_2	= outlet pipe temperature
T_c	= cathode surface temperature
T_e	= electron temperature
V	= discharge voltage
V_a	= anode sheath fall voltage
V_{conv}	= equivalent voltage drop due to the convection
α	= thermal linear expansion coefficient
ε	= emissivity
η	= efficiency
λ	= thermal conduction coefficient
λ_R	= correlation factor for the Richardson constant
ν	= Poisson's ratio
ϕ	= work function
σ_{ste}	= Stefan-Boltzmann constant
σ_θ	= stress in θ direction
σ_z	= stress in z direction

I. Introduction

Nowadays available electricity on the orbit is drastically increasing to the tens of kW level. Orbit raising by powerful electric propulsion has been already realized.¹ Powerful interplanetary cargo mission is also anticipated in the near future. Specific mass (kg/kW) of electric propulsion system has not been considered to be an important parameter because generally the specific mass of solar panel is much larger. However, the state of art technology such as thin-film solar array² or stretched lense array (SLA)³ realizes ultra-lightweight power source less than 3.0 kg/kW of the specific weight. In this situation, the specific mass of the EP system is considered to be a significant parameter as well as the efficiency. Arcjets are advantageous in this point, compensating the disadvantage in their poor efficiency compared to Hall effect thrusters (HETs) and ion thrusters. Table.1 shows simple performance comparison between arcjets and HETs. Already the commercial arcjets such as MR-510 has very small specific system weight (0.61 kg/kW + 3.4 kg/kW for head and PPU),⁴ but further reduction of the total system weight is required for next generation arcjets. If the specific system weight becomes less than 1.0 kg/kWe, arcjets with ultra-light solar array will become a promising candidate to realize various unique interplanetary missions.

Authors have continued research and development activity of long-life, light-weight arcjet as a competitive candidate for interplanetary cargo mission in ISAS/JAXA since 2011.⁵ Especially optimum thermal design is the key issue to minimize the weight of thruster head. As for the lifetime, it seems difficult to prolong single cathode lifetime to the required duration necessary for interplanetary cargo mission (several thousand hours). The replaceable cathode system is suggested in this paper.

Table 1. Performance comparison between Hall thrusters and conventional/next generation arcjets.

	Hall thruster ⁶	Arcjets(conventional) ^{7,8}	Arcjets(next generation)
Propellant	Xe	Ammonia	Hydrogen
Input Power, kW	5	26	15
Isp, sec	2000	800	1000
Efficiency η , %	50	30	30-40
Lifetime, hour	3000	1000	1000 x 4
Specific mass α_{EP} (head + PPU), kg/kW	2.0 + 2.0 = 4.0	0.4 + 1.6 = 2.0	0.2 + 0.8 = 1.0
$\eta / (\alpha_{EP} + \alpha_{pow})$, W/kg assuming $\alpha_{pow} = 3.0$ kg/kW	71	67	75-100

II. Thermal Design

A. Anode

The maximum operational temperature of the tungsten anode is considered to be less than 2100 K. The limiting factor is not the melting of the material, but is internal thermal stress. It is known that thoriated tungsten or W-4Re-0.35HfC alloy enhances its creep strength compared to the pure tungsten at higher temperature.⁹ The anode must have suitable area exposed to the outer space because the heat load is mainly disposed from this hottest part. The outer surface of the anode should be coated by high emissivity material such as TaC or ZrB₂. Axially-long cylinder configuration is preferable to have a sufficient radiation area without enhancing thermal stress. Since the available size of bulked tungsten alloy is limited, molybdenum is used as housing body. The temperature at the radiator end where the power cable is connected should be less than 350 K not to damage power processing unit.¹⁰

The heat load to the anode surface is almost proportional to the discharge current, not to the input power. One of the simple formulation on the anode heat load is as follows,¹¹

$$Q_{anode} = J(V_A + \frac{5kT_e}{2e} + \phi + V_{conv}) \quad (1)$$

Empirically the net anode heat loads run from 9 to 20 V times J , assuming $V_A = 0$ to 10 V, $kT_e/e = 1.4$ V, $\phi = 4.4$ V for copper and $V_{conv} = 2$ V.¹¹ This is the values for liquid-cooled copper anodes and V_A may be smaller in the case of radiation-cooled anode. As described in the next section, we used 14 V times J as Q_{anode} to the anode surface in our analysis based on experimental fact.

Most of heat load is disposed from the outer surface in accordance with Stefan-Boltzmann law

$$Q_{rad} = \sigma_{ste} A (T^4 - T_0^4) \quad (2)$$

Simple thermal stress formulation of the inner-hot, outer-cooled cylinder is shown in Eq.3. The largest tensile stress appears on the inner surface.

$$\sigma_\theta = \sigma_z = \frac{\alpha E}{1 - \nu} \left(\frac{1}{2 \ln(r_{out}/r_{in})} - \frac{r_{out}^2}{r_{out}^2 - r_{in}^2} \right) \quad (3)$$

Sufficient surface area is necessary to discharge the heat load via radiation, but larger diameter configuration is not preferable because the large temperature gradient along the radial direction causes terrific hoop stress. The large temperature gradient is allowed only along the axial direction. Therefore the thruster head generally has axially-long lateral surface. Historical 30 kWe arcjet designs have followed this rule.¹²¹³¹⁴

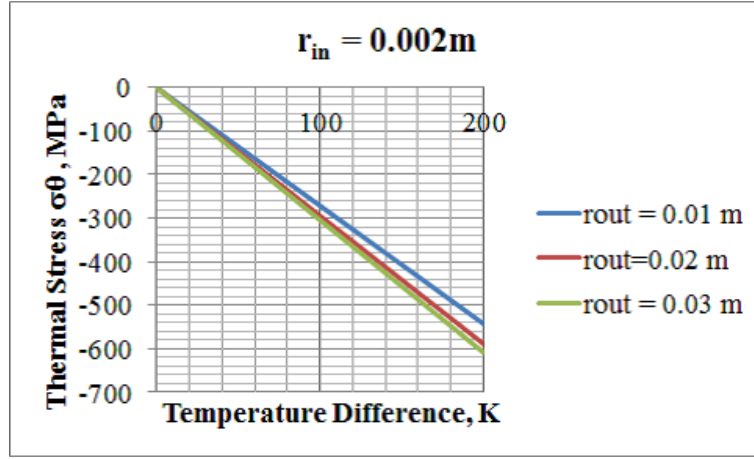


Figure 1. Thermal stress of inner-hot, outer-cold cylinder. If the yield stress is 300 MPa, allowable temperature difference between the outside and inside is about 100 K.

Material

As a material of radiation-cooled anode, only tungsten will be the possible choice because the arc attachment area becomes very high temperature. The physical property of the bulk tungsten strongly depends on its manufacturing process, especially in its of fracture strength. It is well known that the bulk tungsten is very brittle material at room temperature except for single crystal tungsten. Its fracture strength is drastically decreasing at higher temperature. According to the literature,¹⁵ the fracture strength of “pressed and sintered” tungsten is about 287 MPa at $T = 1650$ K, but it becomes only 65 MPa at $T = 2200$ K. It should be noted that there is a large deviation of the fracture strength. At $T = 2700$ K, it varies from 24.5 to 78.5 MPa among literatures.¹⁵ Several tens of MPa is considered to be a threshold of the cracking in this temperature range.

B. Cathode

The heat input model to the cathode is relatively ambiguous compared to the case of the anode. It seems that $Q_{cathode}$ is independent from J or total input power. Hugel pointed that ($Q_{cathode}/J = 1-5$ W/A) from his experimental data.¹⁶ In this case, as the discharge current increases, $Q_{cathode}/J$ usually decreases. According to the experimental measurement by Tahara et. al.,¹⁷ the cathode tip temperature ($= 2000$ K) was

not changed against 90-150 A of the discharge current. This implies that $Q_{cathode}$ might not be affected by the discharge current. It seems that the arc discharge heats up the cathode tip until the sufficient amount of thermionic electrons are derived. At any rate, the cathode surface has to become high temperature regardless the input power. Even in the case of very small power arcjet, the cathode tip temperature will become more than 1000 K in order to emit sufficient electrons. The relationship between the discharge current and the cathode surface temperature is simply described by Richardson-Dashmann equation;

$$J = \lambda_R A_0 A_c T_c^2 \exp\left(\frac{\phi}{kT_c}\right) \quad (4)$$

where $A_0 = 1.20 \times 10^6 \text{ A/m}^2\text{K}^2$ and $\lambda_R = 0.5$. For sustainable operation, the arc attachment must be diffusive (not spotty). In the diffusive condition, experimentally observed current density is a few kA/cm^2 for $\text{ThO}_2\text{-W}$ cathode.¹¹ Figure.2 shows the relationship between the surface temperature and the required emission area for 150 A of the discharge current. If the cathode diameter is limited to several mm, more than 2400 K of the tip temperature is required.

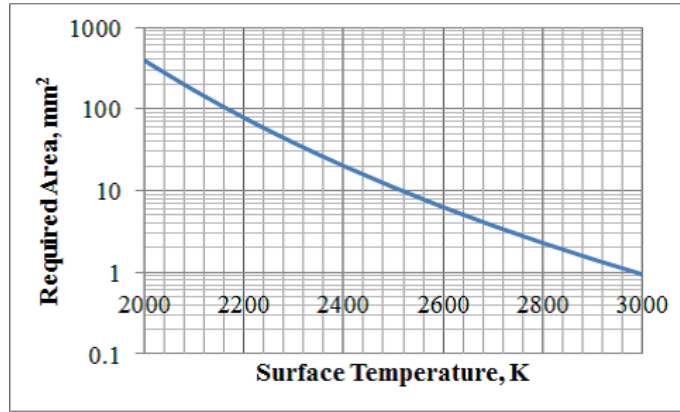


Figure 2. Required area for electron emission at $J = 150 \text{ A}$ operation.

Material

Thoriated tungsten ($\text{ThO}_2\text{-W}$) is widely used material because of its low work function and high melting point. $\text{La}_2\text{O}_3\text{-W}$ is alternative non-radio active candidate^{18,19,20}, but the long-term durability in steady-state operation is not well verified.

It is known that $\text{ThO}_2\text{-W}$ cathodes tend to have a very concentrated hot point on the tip of the cathode. On the other hand, $\text{La}_2\text{O}_3\text{-W}$ cathodes have its hottest region in wide area.¹⁹ Therefore, the temperature gradient along axial direction of the cathode tends to be smaller with $\text{La}_2\text{O}_3\text{-W}$ cathodes.

The advantageous point of $\text{ThO}_2\text{-W}$ cathodes is their high fracture strength. The fracture strength of $\text{ThO}_2\text{-W}$ is more than double of that of pure tungsten.¹⁵ For this reason, $\text{ThO}_2\text{-W}$ is sometimes used as an anode material.

C. Thermal Analysis Model

A thermal analysis model arcjet is shown in Fig.3. This model refers JAXA 15 kW water cooled arcjet (Fig.4)²¹ although the detail components such as screw bolts, seals or propellant injection ports are omitted. Throat diameter of the anode is 2 mm and the anode exit diameter is 22 mm. The conical-tip cathode diameter is 6 mm and the length including copper holder is totally 48 cm. Estimated total weight of the thruster head is 2612 g including radiators. The mass breakdown is shown in Table 2. Anode radiator is the heaviest part because large area is necessary to keep the acceptable temperature at the cable connection point.

FEM analysis was conducted by Patran2011/Nastran2012 platform. Figure 5 shows the thermal load and boundary conditions. It is confirmed that this scheme well worked to explain the temperature profile of actual radiation cooled thruster RAT-III²² within the error of 100 K. Thermal load to the anode body was

determined from our experimental fact as shown in Fig.6, the proportionality factor in Eq.1 is considered to be 14 V regardless of mass flow rate, now we assumed $J = 150$ A operation and $Q_{anode} = 2100$ W. As for the cathode, we assumed $Q_{cathode} = 150$ W based on 1W/A of heat load per discharge current. Both of radiation to the ambient space (3 K) from outer surface and inner enclosure radiation (e.g. cathode to insulator) were considered. Note that the setting of the internal enclosure radiation is very important although old-era thermal analysis omitted this procedure. Experimental fact showed that the most of heat load to the cathode tip is transferred to the inner insulator surface. In our case, the temperature rise of the cathode cooling water was a few degrees, which might not be corresponding to the total heat flux to the cathode tip. Figure 7 shows the resulting temperature profile. The highest temperature is 2300 K at the cathode tip, and the temperature of inner anode is about 2200 K. This is considered to be almost allowable upper limit. In other words, this design is almost optimum in terms of the weight. Figure 8 shows thermal stress (Mises stress) profile. The difference between the inner and outer surface of the anode is less than 50 K. Largest stress is recognized at the inner anode surface. Most of heat load was dissipated from anode and housing surface and only a little fraction of the heat was dissipated from anode radiator. Table.3 shows the heat flux at the connection point of the radiators. It is confirmed that only 160 W is disposed from anode radiator and 11 W is disposed from cathode radiator.

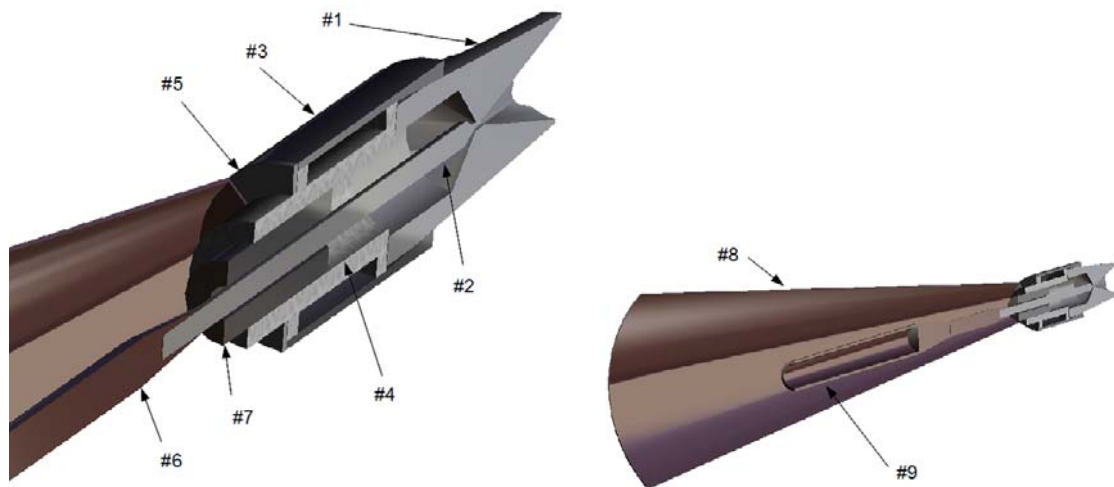


Figure 3. Cut view of the model case arcjet. (top: zoom view, bottom: whole view)

Table 2. Mass breakdown of the modelcase arcjet

#	Name	Material	Mass
#1	Anode	Tungsten	720
#2	Cathode	Thoriated Tungsten	70
#3	Housing	Molybdenum	219
#4	Insulator	Boron Nitride	88
#5	Base Plate	Molybdenum	14
#6	Cathode Base	Copper	137
#7	Cathode Sleeve	Molybdenum	84
#8	Anode Radiator	Copper	914
#9	Cathode Radiator	Copper	364
Total			2612

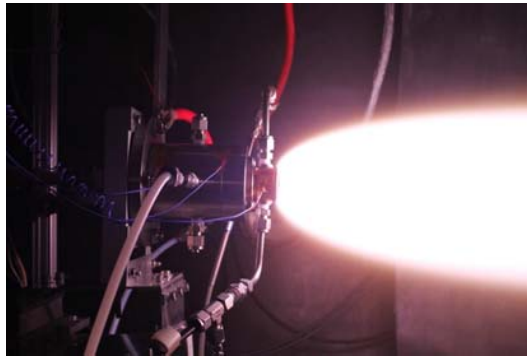


Figure 4. JAXA 15kW water cooled arcjet in operation

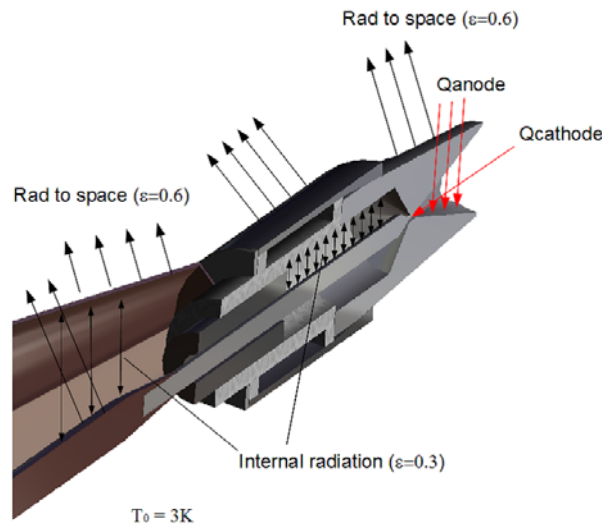


Figure 5. Thermal load and boundary conditions. $Q_{anode} = 2100 \text{ W}$ and $Q_{cathode} = 150 \text{ W}$ is assumed.

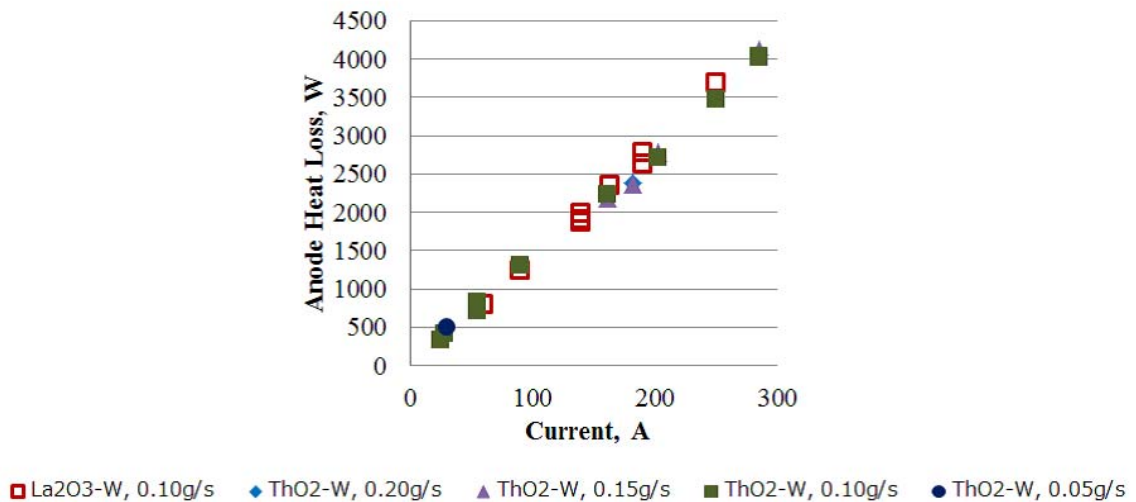


Figure 6. The relationship between the discharge current and the anode heat loss judging from the temperature rise of the cooling water. The slope is independent from the mass flow rate in the range of 0.05-0.2 g/s.

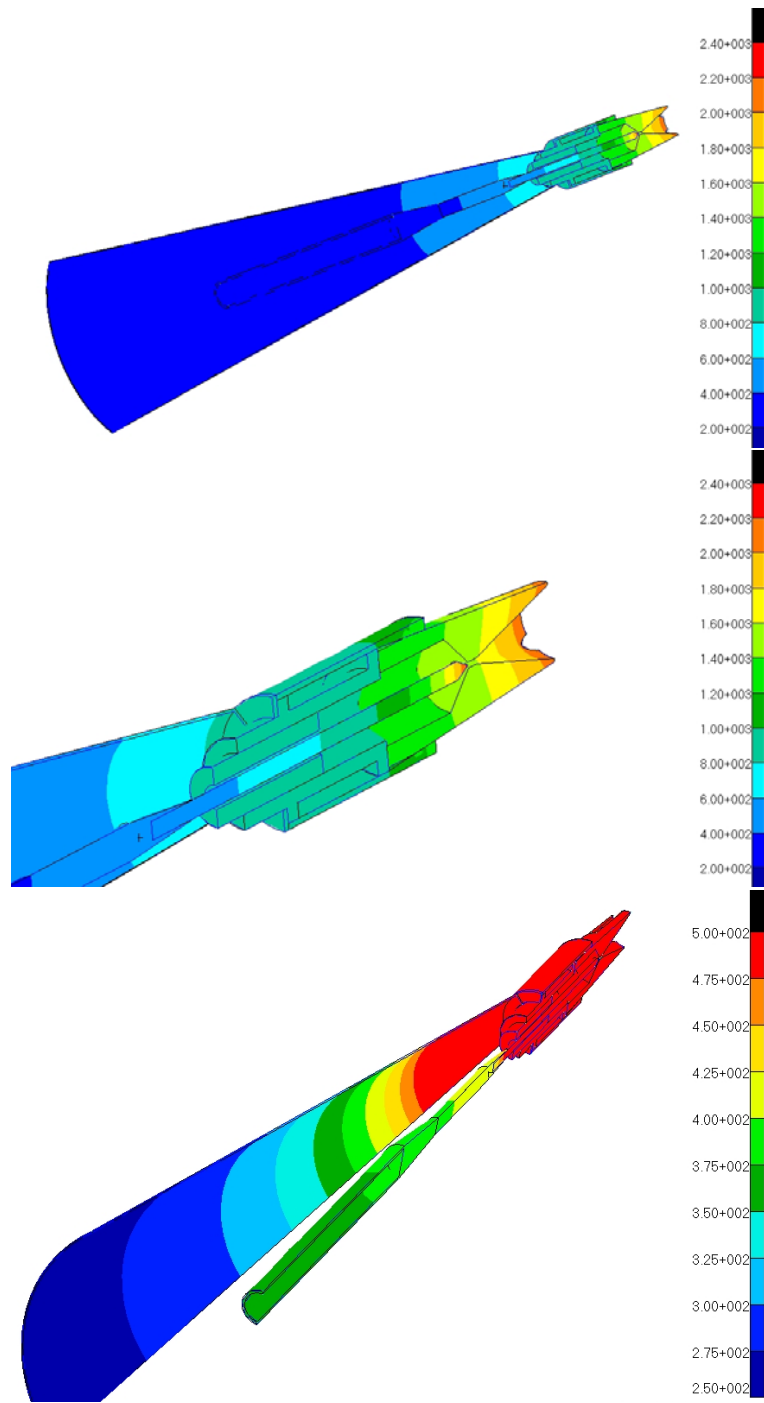


Figure 7. Temperature profile of the model case arcjet (top: whole view, middle: discharge chamber, bottom: radiator) Note that different color map is used for each figures.

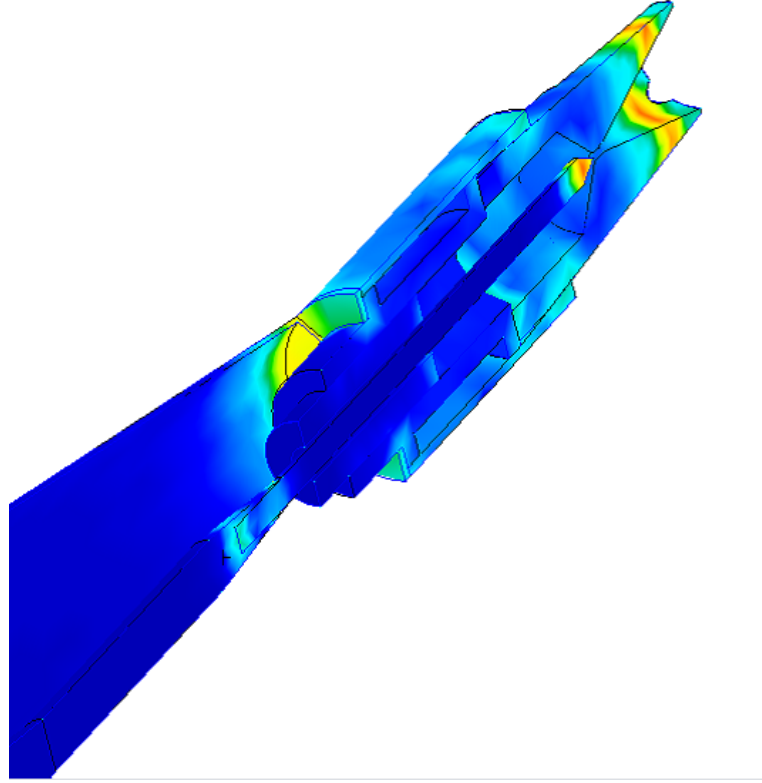


Figure 8. Mises stress profile of the model case arcjet (arbitrary unit)

Table 3. Heat flux and temperature at the connection face to the radiators

	Anode	Cathode
Heat flux, W/m ²	160	11
Temperature, K	860	425

D. Weight reduction by propellant cooling

Anode radiator is the heaviest part although it only discharges 160 W of the heat load. One might think the convection cooling by the propellant at the tail part of the radiator will be effective, but there are little literature available pointing out the possibility quantitatively. Fig.9 shows that Q_{conv} per area becomes larger than Q_{rad} when the surface temperature is less than 600 K where we assumed typical forced convection of gases ($h=10\text{W/m-K}$) or liquid fluids ($h=100\text{W/m-K}$).

Of course, it is known that the performance enhancement by regenerative cooling is hardly realized²³ in this level of high power arcjets because the gas enthalpy is negligible compared to the input electrical power. Also, it is not possible to realize the anode nozzle cooling by the propellant flow because the mass flow rate necessary for the cooling is typically much larger than that for designated thrust generation.

In this study, we compared 3 candidates of propellant, hydrogen, nitrogen and gas ammonia at a tank pressure of 0.3 MPaA. Physical properties are summarized in Table.4. At first, required temperature rise of the propellant ($t_2 - t_1$) was calculated. If t_2 is larger than the temperature of the radiator connection point, it is impossible to alternate whole radiator by propellant cooling. According to the simple parallel flow heat exchanger model, the required length of the coolant passage was calculated as shown in Table.5 and Table.6. Convection area was calculated by Eq.7. Heat transfer coefficient is calculated by Dittus-Boelter's equation (Eq.9). The coolant passage assumed here is 3 mm in the outer diam and 1.6 mm (1/16") in the inner

diam. It is easy to alternate cathode radiator by the convection cooling of any propellant, but GN₂ and gas ammonia are not suitable to alternate the anode radiator completely. It will be possible to alternate the half of the anode radiator by N₂ or ammonia convection cooling. Note that if one assume the use of the phase change of ammonia, the cooling capability is drastically increasing. However, many problem exist such as thermal spike etc. Since only hydrogen is the promising candidate to alternate whole cathode and anode radiator system due to its high specific heat and high heat transfer coefficient, the mass reduction in this case is calculated as shown in Table.8. Even if the weight increment of the propellant passage (orifices or manifolds) is taken into consideration, the specific mass will become less than 0.1 kg/kW assuming 15 kW of the input power.

$$Q_{conv} = AhdT_{mean} \quad (5)$$

$$dT_{mean} = \frac{((T_2 - t_2) - (T_1 - t_1))}{\ln((T_2 - t_2)/(T_1 - t_1))} \quad (6)$$

$$t_2 = 300 + Q_{conv}/(c_p * \dot{m}) \quad (7)$$

$$h = \frac{\lambda}{d} 0.023 R_c^{0.8} Pr^{0.4} \quad (8)$$

$$(9)$$

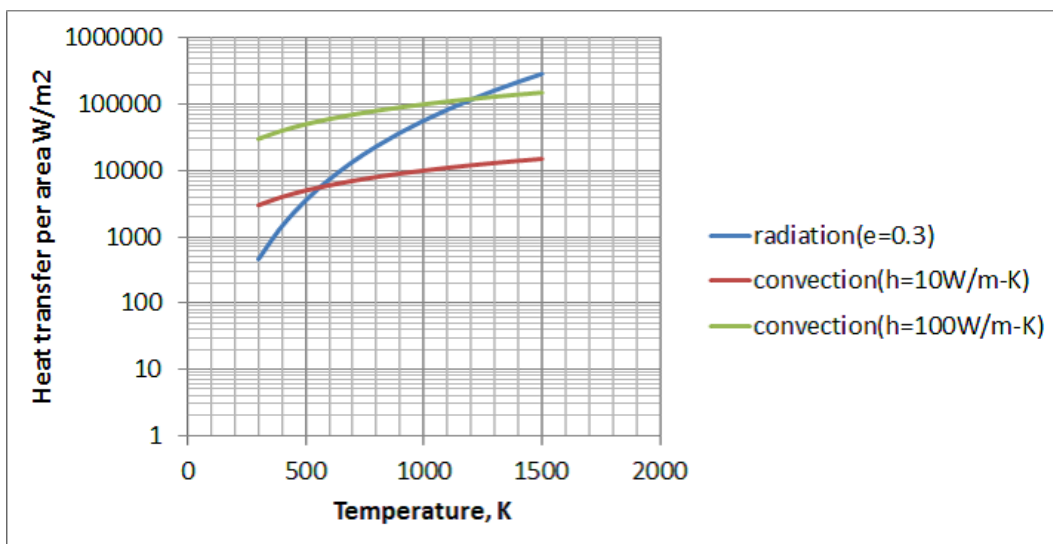


Figure 9. Heat rejection per area by radiation and convection cooling.

Table 4. Physical properties of propellants as a coolant of the arcjet.

	GH ₂	NH ₃ (gas)	GN ₂
Specific Heat, J/g-K	14.6	2.65	1.08
Thermal Conductivity ($T = 300$ K),	0.186	0.026	0.028
Prandtl Number ($T = 300$ K)	0.69	0.72	0.92

Table 5. Required temperature rise and heat exchange area for convective cooling as an alternative of the cathode radiator.

	GH ₂	NH ₃ (gas)	GN ₂
\dot{m}	0.1 g/s		
$Q_{cathode}$	11 W		
dT, K	7.5	41	102
A, cm ²	0.42	3.6	11
Tube Length, cm	0.8	7	23

Table 6. Required temperature rise and heat exchange area for convective cooling as an alternative of the anode radiator.

	GH ₂	NH ₃ (gas)	GN ₂
\dot{m}	0.1 g/s		
Q_{anode}	160 W		
dT, K	110	603	1478
A, cm ²	2.65	-	-
Tube Length, cm	5.3	-	-

Table 7. Required temperature rise and heat exchange area for convective cooling as an alternative of anode/cathode radiator by gas hydrogen.

	GH ₂
\dot{m} for cathode	0.02 g/s
\dot{m} for anode	0.08 g/s
$Q_{cathode}$	11 W
Q_{anode}	160 W
dT in the cathode path, K	37.7
dT in the anode path, K	137
A (cathode path) , cm ²	1.8
A (anode path) , cm ²	3.3
Tube Length (cathode path), cm	3.6
Tube Length (anode path), cm	6.6

Table 8. Modified mass breakdown with propellant cooling approach.

Initial total mass	2612 g
Reduction of anode radiator	914 g
Reduction of cathode radiator	364 g
New total mass	1334 g

III. Lifetime Issue

It is said that the life-limiting issues of arcjets are mainly three points: 1) Cathode erosion, 2) Constrictor closure, 3) Insulator degradation.⁹ Constrictor closure is one of the biggest problem for relatively low-power arcjets, but is not a severe problem for 15 kW arcjet because the closure rate is negligible to the original throat diameter (2-3 mm). Insulator degradation is resolved by minimizing the contact area between the high temperature regions of cathode and insulator. The cathode erosion is identified as the major life limiter. The operational characteristics of arcjets are strongly affected by the gap distance between anode and cathode. The definition of the end of life (EOF) is usually about 1000-1500 hours, where the operational point departs from the designated operation point. Many fundamental studies are conducted in 1980s, but it seems difficult to prolong the lifetime drastically. Here we propose the use of cathode replacement system. As shown in Fig.10 it resembles the revolver of the gun. The key issues of the replaceable cathode system are as follows; 1) reliable cable connection to the cathode, 2) gas seals 3) robust actuator design. As for the first issue, commercial high power connectors are available (ex. Multi-Contact EBB14/EBS14). For the second problem, multiple piston seals will be used taking care of the long-term durability. In the current design, the temperature inside the cathode sleeve is 800 K. Therefore, the length of the cathode sleeve should be prolonged to have an adequate temperature for piston seals. For the third point, actuators should not be located just behind the thruster head because there is severe heat load or electromagnetic interference. Drive force should be transmitted mechanically (gears, rack-and-pinion and so on) from actuators located at a distance.

Apparently the application of this system results in the increase of the total weight. Our design requires 500 g for the cathode revolver and 300 g per space cathode (including cathode radiator) as an increment of the thruster mass. In order to keep an advantage of light-weight arcjet, the number of the spare cathodes should be less than 4. Therefore, the effort to prolong the single cathode lifetime is still important. The use of hollow cathode is studied in our group.²¹ Although this is just a proposal, several thousands hours of operation time necessary for typical interplanetary mission to the Mars will be achieved by the coupling of long life cathode (1500 hours per cathode) and this replacement system with 4-5 spare cathodes.

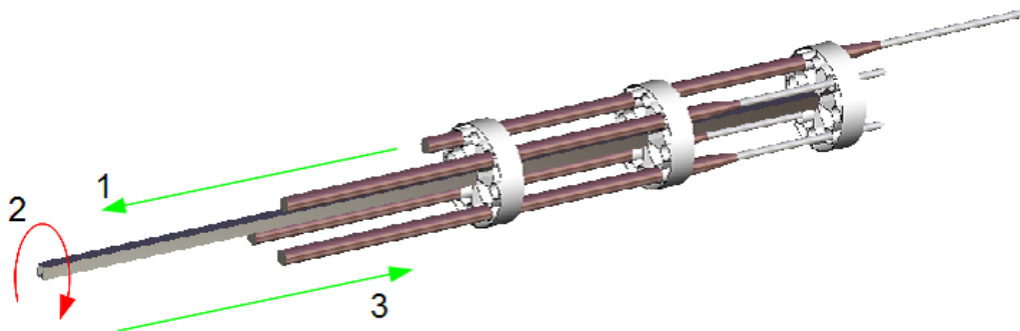


Figure 10. Cathode Replacement System.

IV. Summary

Authors have continued research and development activity of long-life, light-weight arcjet pursuing a competitive candidate for interplanetary cargo mission in ISAS/JAXA since 2011. Analytical survey was mainly described in this paper and the following conclusion is obtained.

- As a result of the careful thermal design based on the result of water-cooled experiment, it was found radiator cooled 150 A class arcjet which has 1300 g of thruster head + 1300 g of radiators is possible.
- Reduction of the total weight is possible by the propellant cooling approach on a radiator. Especially gas hydrogen is the most promising candidate. In this case, resultant specific weight of 0.1 kg/kW is possible. Nitrogen or ammonia will reduce the radiator weight partially.
- Lifetime issue can be solved by using cathode replacement system, but the use of many spare cathodes

causes the unallowable system mass increment. Careful trade-off study is necessary between the total lifetime and the system weight. Efforts to prolong the lifetime of single cathode are also important.

References

- ¹Steven, A. F. and Julie, P. M., "Finding a way : Boeing's All Electric Propulsion Satellite," AIAA Paper 2013-4126, Jul. 2013.
- ²Osamu, M. and et. Al., "Outer Planetary Exploration using Solar Power Sail," JSASS-2013-1082, Mon. 2013.
- ³Brandhorst, H. W., Rodiek, J. A., O'Neill, M. J., and Eskenazi, M. I., "Ultralight, Compact, Deployable, High-Performance Solar Concentrator Array for Lunar Surface Power," AIAA Paper 2006-4104, Jun. 2006.
- ⁴Smith, R. D., Aadland, R. S., Roberts, C. R., and Lichtin, D. A., "Flight Qualification of the 2.2 kW MR-510 Hydrazine Arcjet System," IEPC paper 97-082.
- ⁵Nagao, N., Kinefuchi, K., Saito, Y., Okita, K., and Kuninaka, H., "Activities for High Power Electric Propulsion System in Japan," Proceedings of International Symposium on Space Science and Technology 2013-b-10, Jun. 2013.
- ⁶Ozaki, T. and et. al., "Development Status of 200mN class Xenon Hall Thruster of MELCO," IEPC paper 2005-064.
- ⁷Kriebel, M., M., "System Engineering, Design, Integration, and Qualification of Electric Propulsion Space Experiment," *Journal of Propulsion and Power*, Vol. 18, No. 4, 2002, pp. 731-739.
- ⁸Haag, T., W. and et. al., "Recent Testing of 30 kW Hydrogen Arcjet Thrusters," IEPC paper 93-1902.
- ⁹Linchon, P. and Sankovic, J. M., "Development and Demonstration of a 600-Second Mission-Average Isp Arcjet," *Journal of Propulsion and Power*, Vol. 12, No. 6, 1996, pp. 1018-1025.
- ¹⁰Cassady, R. J., "Qualification of a 26 kW Arcjet Flight Propulsion System," AIAA Paper 95-2505, 1995.
- ¹¹Bruno, C., *Nuclear Space Power and Propulsion Systems*, AIAA, 2008.
- ¹²Fife, J. M., Bromaghin, D. R., Chart, D. A., Hoskins, W. A., Vaughan, C. E., and Johnson, L. K., "Orbital Performance Measurements of Air Force Electric Propulsion Space Experiment Ammonia Arcjet," *Journal of Propulsion and Power*, Vol. 18, No. 4, 2002, pp. 749-753.
- ¹³Wallner, L. E. and Jr., J. C., "Arc-jet Thrustor for Space Propulsion," NASA TN D-2868, 1965.
- ¹⁴Deininger, W. D., Chopra, A., King, D. Q., and Pivrotto, T. J., "Thermal Design Improvements for 30kWe Arcjet Engines," IEPC Paper 88-073, 1988.
- ¹⁵Marmer, E. N., Gurvich, O. S., and Mal'tseva, L. F., *High Temperature Materials [in Russian]*, Metallurgiya, Moscow, 1967.
- ¹⁶Hugel, H. and et. al., "Phanomenologie und Energiebilanz von Lichtbogen-kathoden bei niedrigen Drucken und Hohen Stromstarken," *Beitrage aus der Plasmaphysik*, 1969, pp. 87-116.
- ¹⁷Tahara, H., Sakakibara, T., Onoe, K., and Yoshikawa, T., "Experimental and Numerical Studies of a 10 kW Water Cooled Arcjet Thruster," IEPC Paper 91-015, 1991.
- ¹⁸Nakata, D., Toki, K., Funaki, I., and Kuninaka, K., "Performance of ThO₂-W, Y₂O₃-W and La₂O₃-W cathodes in Quasi-Steady Magnetoplasmadynamic Thrusters," *Journal of Propulsion and Power*, Vol. 27, No. 4, 2011, pp. 912-915.
- ¹⁹Yamamoto, K., Tashiro, S., and Tanaka, M., "Numerical Analysis of Current Attachment at Thermionic Cathode for Gas Tungsten Arc at Atmospheric Pressure," *Transactions of JWRI*, Vol. 38, 2009.
- ²⁰Ushio, M., "Arc Discharge and Electrode Phenomena," *Pure & Appl. Chem.*, Vol. 60, No. 5, 1988, pp. 809-814.
- ²¹Kinoshita, M., Nakata, D., Kinefuchi, K., and Kuninaka, H., "Experimental Study to Hollow Cathode Application to DC Arcjet," IEPC Paper 2013-243, 2013.
- ²²Yoshikawa, T., Onoe, K., Yoshida, H., and Kotani, S., "Operating Characteristics of 1 kW hydrazine Arcjet Thruster," IEPC Paper 88-108, 1988.
- ²³Yamada, T., Shimizu, Y., Toki, K., and Kuriki, K., "Thrust Performance of a Regeneratively Cooled Low-Power Arcjet Thruster," *Journal of Propulsion and Power*, Vol. 8, No. 3, 1992, pp. 650-654.