Opposed-Cavity Solar Thermal Thruster Made of Single Crystal Tungsten*†

Hironori Sahara
Japan Science and Technology Corporation (JST)
7-44-1, Jindaiji-Higashi-Machi, Chofu, Tokyo, 182-8522, Japan
Tel: +81-422-40-3188 / Fax: +81-422-40-3142
sahamail@nal.go.jp
Morio Shimizu
National Aerospace Laboratory of Japan (NAL), Japan
Tadayuki Fujii
National Institute for Materials Science (NIMS), Japan
Ken-ichi Okamoto, Shigehiko Takaoka
Allied Material Corporation, Japan
Yoshihiro Nakamura
Hosei University, Japan

IEPC-01-214

This paper shows promising preliminary experimental results of heating test in relation to a solar thermal propulsion (STP) thruster with a pair of cavities aligned in back-to-back position, so-called the opposed-cavity STP thruster. It was made of stainless steel, or made of single crystal tungsten that is an ideal material in respect of its high material strength and an absolute impossibility of recrystallization embrittlement under high temperature conditions. Besides, the opposed-concentrator, which consists of a pair of face-to-face concentrators, was prepared for the opposed-cavity STP thruster. Combining with them led the thruster temperature to 1,400K even in not-so-good vacuum and solar concentration condition under solar power density of 800W/m^2. In addition, a TERC-type secondary concentrator was designed and examined in order to more highly concentrate solar power at the focus. Furthermore, new-designed main concentrators are under manufacture now in order to obtain more effective heating in the thruster cavity chamber.

Introduction

The Solar Thermal Propulsion (STP) is considered as a promising high performance upper stage capability of transferring payloads from LEO to higher orbits such as GEO, or station keeping and attitude control of spacecraft very efficiently. STP is a typical thermal propulsion with high Isp (500-1,000sec) in an appropriate thrust magnitude range and provides possibly much less space pollution than conventional chemical propulsion, so that USAF or NASA have devoted themselves to develop STP as one of the most promising propulsions for orbit transfer vehicles (OTV), doubling the GEO mission payload capability [1-3]. One of the most important investigation items with respect to STP is a thruster made of refractory metals such as tungsten, rhenium, tantalum and molybdenum, or advanced high temperature ceramics because of the high propellant temperature (up to 3,000K) involved [1,4]. Recently, USAF has been developing the Integrated Solar Upper Stage (ISUS) of a solar orbit transfer vehicle (SOTV) centered in AFRL [2,5]. The SOTV adopted an inflatable type of solar concentrator and tungsten alloy thruster so far, but the tungsten becomes brittle due to recrystallization under high temperature conditions. Hence, rhenium is considered as the most ideal material for STP thrusters. In fact, Phillips Laboratory (PL) investigated a whole rhenium pipes thruster very intensively. Nevertheless, rhenium

* Presented as Paper IEPC-01-214 at the 27th International Electric Propulsion Conference, Pasadena, CA, 15-19 October, 2001.

is considerably higher cost than the other refractory materials, and establishment of STP manufacturing technologies using rhenium is difficult. On the other hand, NAL started a preliminary STP investigation several years ago [6-10]. Actually, technologies of rhenium have been infant in Japan, so it was difficult to choose suitable materials for STP thruster. Fortunately, the National Institute for Materials Science (NIMS) patented and developed single crystal molybdenum (SC-Mo) and single crystal tungsten (SC-W). These are ideal materials in respect of their high material strength and an absolute impossibility of the high temperature recrystallization embrittlement [11-13]. The previous paper reported fabrication and promising experimental results of a very-small-sized STP thruster made of SC-W with W-CVD coating. Also, we reported design and fabrication of an opposed-cavity STP thruster made of SC-W with W-CVD coating [14]. This paper shows promising preliminary experimental results of an opposed-cavity STP thruster made of stainless steel. Furthermore, a TERC-type secondary concentrator was designed and examined in order to more highly concentrate solar power at the focus.

Opposed-Cavity STP Thruster Made of SC-W

Since we had a patent of SC-Mo and SC-W, sufficient knowledge and experience of the very-small-sized STP thruster made of SC-Mo or SC-W, there were no very serious problems to make an opposed-cavity STP thruster with SC-W. The opposed-cavity STP thruster has an advantage that it enables an orbiter to kick at both apogee and perigee in an orbit [14]. The shape of the thruster is shown in Fig. 1.

Fig. 1. Opposed-cavity STP thruster made of SC-W before W-CVD coating.

It has the two same size cavities as the very-small-sized STP thruster, aligned in back-to-back position. The cavity and the cavity chamber diameters of the thruster are 4mm and 8mm, respectively, and its designed propellant temperature is over 3,200K, which corresponds to 950sec of Isp and 0.1N class thruster for hydrogen with a suitable solar concentrator set. The thruster weighs only about 100grams. Propellant is supplied through two pipes attached the cavity ports. These elements are jointed with screw for high mechanical strength and sealed with W-CVD coating, since tungsten has the lowest vapor pressure under high temperature and vacuum condition of all metals. The thruster is supported mainly with the two propellant supply pipes. This means a part of heat energy conducted away from the thruster through the support pipes is regenerated with cold propellant gas. The temperatures of propellant in a plenum chamber and outer chamber surface were measured by Re-5%W/Re-26%W thermocouples (up to about 2,600K) of 0.25mm in diameter. Since a multi layer insulation (MLI) has very high performance only in much higher vacuum condition like in space than that in a vacuum chamber mentioned later, the thruster was surrounded with sheets of carbon felt to insulate thermally instead of MLI, as shown in Fig. 2.

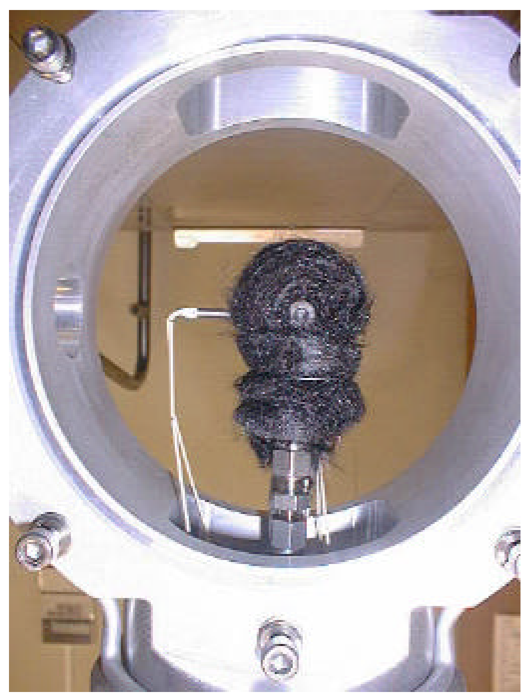


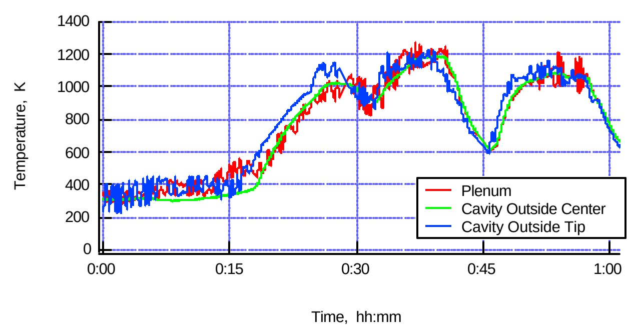
Fig. 2. Thruster surrounded with sheets of carbon felt in a vacuum chamber.

In preliminary experiments, we used the STP thruster made of stainless steel (SUS310) instead of that made of SC-W, because the manufacturing cost of the former was less than 1/10 of the latter. Though melting point of stainless steel is much lower (about 1,700K) than tungsten, it was sufficient for the preliminary experiments and it was a meaningful result even if the thruster was melted by solar heating. The thruster was installed in the small vacuum chamber with two hemispherical quartz windows through which concentrated solar rays were both applied. The chamber was vacuumed with an oil-sealed rotary pump, and the vacuum chamber pressure was maintained at about 0.3kPa, while the heated propellant was injected from the nozzle at 1-2SLM gas flow rate and about 0.2MPa maximum plenum chamber pressure. The vacuum chamber was fixed on an automatic sun tracking system, so that both of the thruster cavity ports could be adjusted to the corresponding focal points of a pair of concentrators aligned in face-to-face position. Each concentrator consists of a ready-made paraboloidal antenna with 1m effective aperture diameter covered by a sheet of 50-micron-thick polyester film with aluminum vapor deposition (or, aluminized polyester film) so as to have high reflectance. For the use of a concentrator, the film is stuck to the antenna surface by evacuating a room between the antenna and the polyester film [14].

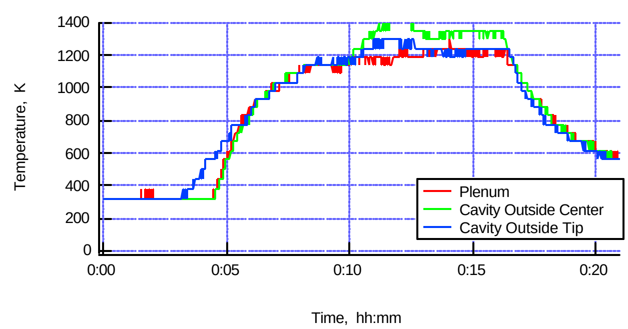
Fig. 3. Experimental apparatus combined thruster and concentrators on automatic sun tracking system.

Preliminary Heating Test Results

Though the sky of spring and summer is not clearer because of thin cloud or haze than that of fall and winter in Japan, the sun during the following experiments provided 800W/m^2 of solar ray. In Fig. 4(a), there was a passage of a cloud on the way, but temperature rose up to 1,000K for initial 10 minutes heated by one of the opposed-concentrators, and then rose to be saturated at 1,250K in another 10 minutes after that. Since the temperature did not rise as expected, we surrounded the thruster by carbon felt much carefully. Because the concentrated light heated the thruster so that it might look up as shown in Fig. 5(a), we uncovered the undersurface of the cavity chamber tip. Also, the concentrators were re-covered with the new sheet of polyester film with aluminum vapor deposition at the following time. Similar to the previous time, the two concentrators heated the thruster cavity chambers for initial 5 minutes and the following period. Then, one of the measured temperatures rose up to 1,400K at the outside center of cavity chambers. In addition, the saturation time became shorter to about 10 minutes, as shown in Fig. 4(b).



(a) Original insulation.



(b)Modified insulation.

Fig. 4. Preliminary heating test results.

Discussion

We had obtained higher temperature, 2,300K with a small-sized STP thruster, and 2,000K with a very-small-sized STP thruster. Particularly, the opposed-cavity STP thruster has the same sized cavities and cavity chambers as the very-small-sized STP thruster, whose cavity and cavity chamber diameters are 4mm and 8mm, respectively. Accordingly, we had expected similar result in respect to temperature. Nevertheless, the best result in previous section is 1,400K, which is much lower than the target temperature. One of the causes of it may be that the degree of vacuum in the vacuum chamber was not so good that the loss by heat transfer became remarkable. In order to cope with this, we are applying a turbo molecular pump (TMP).

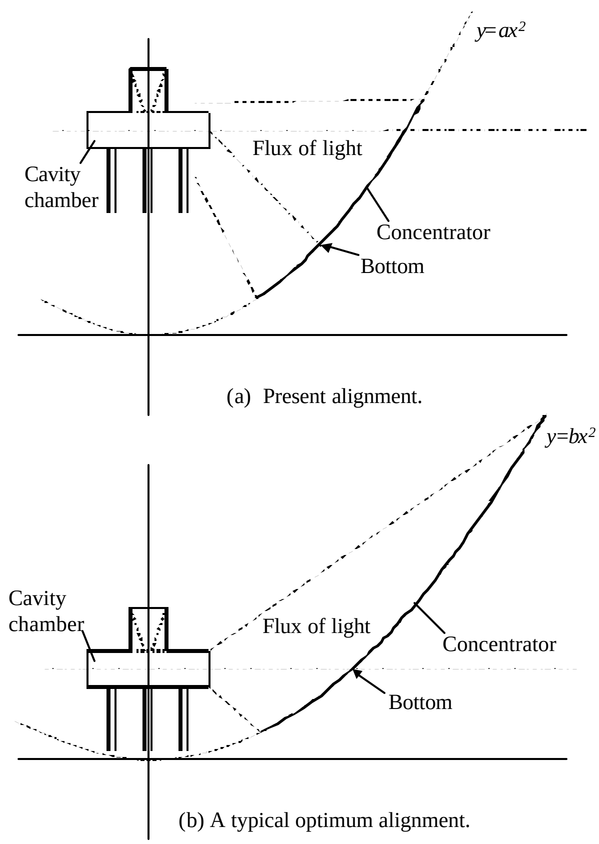


Fig. 5. Alignments between thruster and concentrator.

However, it is considered that the most influential cause may be diameter of concentrated solar image. Since the ready-made paraboloidal antenna was used for the concentrator, the minimum diameter of solar focal image was about 20mm in the full-width-at-half-maximum (FWHM) with assumption that distribution of light was formed Gaussian at the focus. Namely, the diameter of concentrated solar image was much larger than outer diameter of the thruster, 8mm. Hence, considerable amount of the concentrated solar power was useless for thruster heating. Of course, much more expensive and precise paraboloidal mirror may make power loss considerably smaller. However, that is an unavoidable thing as long as an inexpensive ready-made paraboloidal antenna is used for the shape of a paraboloidal concentrator. In addition, for heating entire of cavity and/or cavity chamber tip, flux of concentrated light should input within the entire surface of them. Nevertheless, present alignment is not good as shown in Fig. 5(a). In order to acquire optimal alignment, we should design and manufacture a new concentrator so that a bottom of the concentrator may be in agreement with the center axis of the thruster cavity as shown in Fig. 5(b).

TERC Design and Setup

We thought of the first application of TERC (Tailored Edge-Ray Concentrator, shown in Fig. 6) that used super-gloss aluminum for the reflective side of cone form in order to more highly concentrate solar power at the focus. We designed it so as to be contained in the vacuum chamber behind the hemispherical quartz windows so that diameter of the concentrated solar image might be 9.2mm. Because solar power density increases and illumination loss decreases at the focus as the result of increase of concentration ratio by applying the TERC, it is expected that the thruster temperature rise higher.

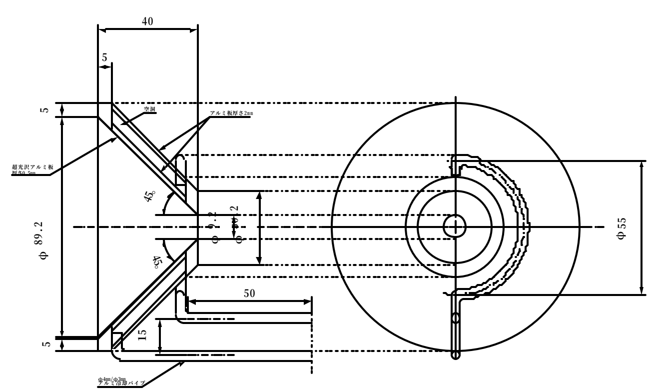
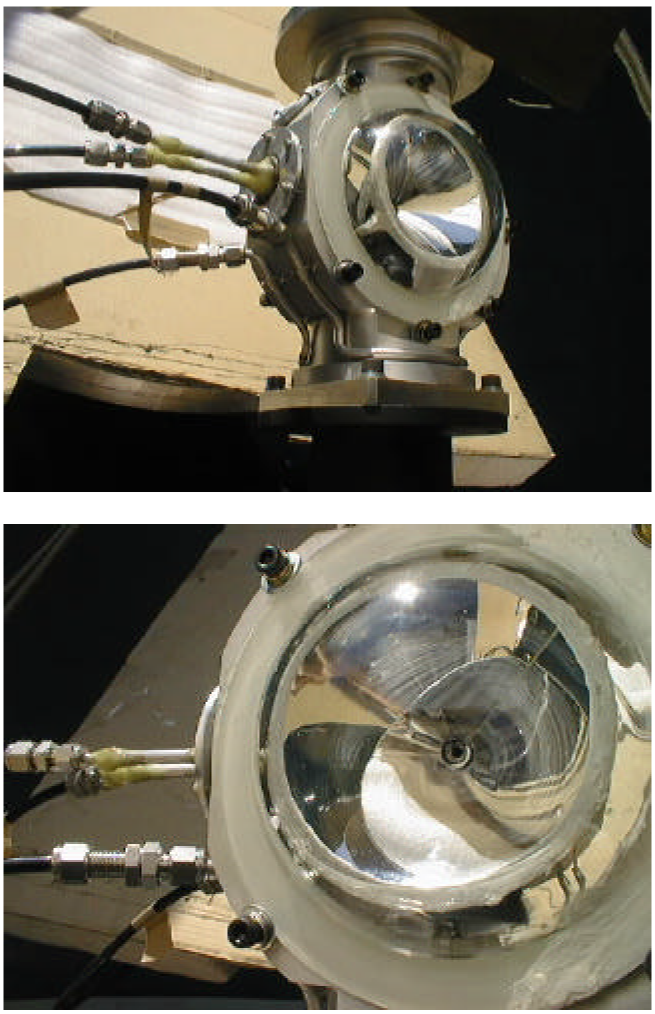


Fig. 6. Designed TERC.

In application of the TERCs, they are installed in the vacuum chamber as shown in Figs. 7, in which the thruster cavity ports are seen behind the exit of TERC. Although exit of the TERC is very close to the thruster cavity ports, they do not touched to each other. The smaller a gap between the TERC and the thruster cavity port, the less the concentrated light leaks through the gap. For assuring that the TERC and the thruster do not contact each other, we keep the gap in only 1mm in order not to enlarge the heat loss.



Figs. 7. TERC installed in the vacuum chamber.

Validity Check of TERC

In order to check the actual TERC effectiveness, we conducted experiments of TERC validity check. Because of difficulty to adjust alignment between the TERC and the main concentrator, we examined it by two ways, as follows.

By Heating Experiment

At first, a thermocouple was put directly behind the exit of TERC. Since the positions of the focus differed a little in the case with and without the TERC (we call the exit of the TERC a focus, too), we moved and adjusted it. In this way, the measured temperature was not stable comparatively due to very small heat capacity of the thermocouple. However, there was a clear difference between the case with and without the TERC. Namely, while the temperature rose only to 750K without the TERC in the condition of 600W/m^2 solar power (the whole sky was covered by thin clouds like a haze although it was fine weather), it rose up to 1,000K with the TERC. This result is comparatively good in taking heat loss under the atmosphere into consideration. Next, we conducted the experiment in the way that the concentrated solar power heated a tungsten sheet of 10mm x 10mm x 1mm and the thermocouple was attached to the solar side of the sheet. Because of much larger heat capacity of the sheet than the thermocouple, the heated temperature would be stable. As the result, the same differences as previously was obtained between the case with and without the TERC. In the above two ways, the validity of TERC was checked. Hence, we are planning to apply the TERC to the future experiment of thruster heating.

Fig. 8. TERC under the validity check experiment.

By Picture Analysis
For the purpose of measuring a diameter of concentrated solar image, we took pictures of it. In the case without the TERC, the solar image was focused on a metal plane for the purpose. On the other hand, in the case with the TERC, we took a picture of the thruster cavity chamber illuminated by the concentrated solar ray using a mirror. We took the solar image before or at or after the focus in that case, and took the solar image in various interval between the TERC and the main concentrator in this case. The distribution of light intensity within the solar image was assumed as forming the shape of Gaussian, and it was almost correct so far as the result of fitting. The measurement is under performance now, and just a part of the results is shown in Fig. 9. The narrowest FWHM at the focus in the case without the TERC was 18.1mm.

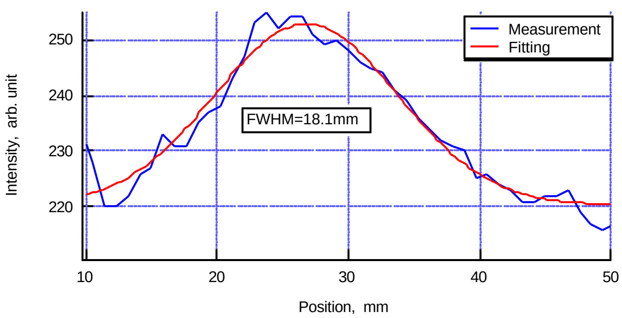


Fig. 9. Intensity distribution at focus without TERC.

New Concentrator Design

In order to acquire optimal alignment between the main concentrators and the thruster, we designed new main concentrators. The number of the points, which serve as an important point by the design, is two. One is diameter of concentrated solar image at the focal plane. According to the geometric optical relation, the diameter of concentrated solar image is about 1/100 of a focal length. Therefore, the focal length must be no more than 400mm in order that the diameter of concentrated solar image is less than 4mm, the diameter of the thruster cavity. On the other hand, the focal length is sufficient to be less than 800mm even if the diameter of concentrated solar image is more than 4mm, as long as it is less than 8mm, the diameter of the thruster cavity chamber. The other point is cone angle of reflective light form. Flux of reflective light should illuminate within entire surface of the thruster cavity or cavity camber tip. For this purpose, a bottom of a concentrator must be in agreement with the center axis of the thruster cavity, and the cone angle must be determined so that the axis bisects it almost equally, as shown in Fig. 5(b). According to the two points above, we designed two types of new main concentrators, as shown in Fig. 10. One has 600mm diameter with about 280mm focal length, the other has about 1200mm diameter with 480mm focal length. The concentrators are now under manufacture. With the use of the new 600mm concentrator, the TERC may be no necessary to use, while both of them may be used together. On the other hand, the new 1200mm concentrator will be combined with the TERC. Thus, we are planning to apply also the new concentrators to the future experiment of thruster heating.

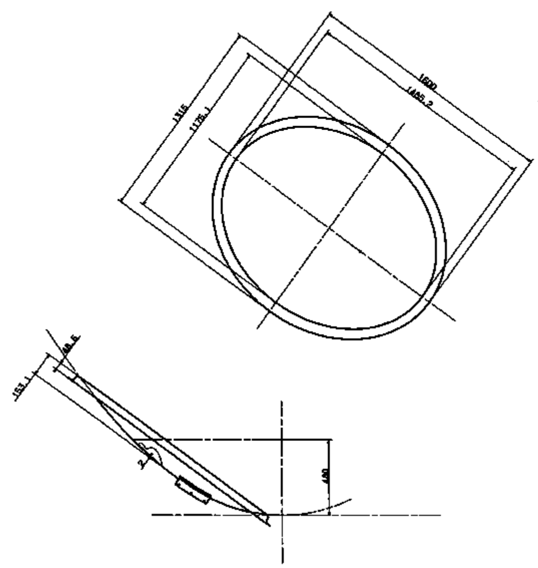


Fig. 10. New concentrators design.

Summary

With the use of a technology of manufacturing SC-W by NIMS etc., we designed and fabricated an opposed-cavity STP thruster made of SC-W. In the preliminary experiments, we used an opposed-cavity STP thruster made of stainless steel. Combining it with an opposed-concentrator set, 1,400K at the outside center of cavity chamber was acquired under solar power density of 800W/m^2. To obtain higher temperature of the thruster, we designed a TERC-type secondary concentrator and new-designed main concentrators. As the result of

TERC validity check experiment, we confirmed that the TERC would contribute more effective heating. We are planning to apply the TERC and the main concentrators to the future experiment of thruster heating in order to get higher temperature of the thruster.

References

[1] Shoji, J. M., "Solar Rocket Component Study," AFRPL TR-84-057, AD-A154 186, 1985.

[2] Kudiya, C., "The Integrated Solar Upper Stage (ISUS) Engine Ground Demonstration (EGD)," AIAA Paper, AIAA-96-3043, 1996.

[3] Partch, R., "Solar Orbit Transfer Vehicle Space Experiment Conceptual Design," AIAA Paper, AIAA-99-2476, June 1999.

[4] For example, Workshop Proceedings, NASA Solar Thermal Propulsion Workshop, MSFC, NASA, Mar. 19-20, 1997.

[5] Kennedy, C. F., Jacox, M., "The Integrated Solar Upper Stage (ISUS) Program," AIAA Paper, AIAA-95-3628.

[6] Shimizu, M., et al., "Very Small Solar Thermal Thruster Made of Single Crystal Tungsten for Micro/Nanosatellites," 36th Joint Propulsion Conf. And Exhibit, AIAA-2000-3832, Huntsville, Alabama, Jul. 16-19, 2000.

[7] Shimizu, M., et al., "Solar Thermal Thruster Made of Single Crystal Molybdenum," 47th IAF, Beijing, China, Oct. 7-11, 1996, IAF-96-S.4.01, Acta Astronautica, Vol. 41, No. 1, pp. 23-28, 1997.

[8] Shimizu, M., et al., "JSUS Solar Thermal Thruster and Its Integration with Thermionic Power," Proc. STAIF-98, pp. 364-369, 1998.

[9] Shimizu, M. et al., "Single Crystal Mo Solar Thermal Thruster for Micro/nanosatellites," 49th IAF, IAF-98-S.6.01, Acta Astronautica, Vol. 44, No. 7, pp. 345-352, 1999.

[10] Itoh. K, et al., "Solar Thermal Rocket as an Apogee Engine For Japanese Launch Vehicles," 21th International Symposium on Space Technology and Science, Omiya, Japan (21th ISTS), May 24-31, 1998, ISTS-98-a-2-01.

[11] Fujii, T., "A New Technique for Preparation of Large-Scaled Mo and W single Crystals and Their Multilayer Crystals for Industrial Applications," Proc. Japan-Russia-Ukraine International Workshop on Energy Conversion Materials (ENECOM 95), Sendai, Japan, Jan. 1995.

[12] Okamoto, K., et al., "Effects of Dopants on the Secondary Grain Grouwth in Tungsten Sheet," Proc. Of 12th Plansee Seminar '89 in Austria, pp. 171-184.

[13] Hiraoka, Y., Fujii, T., "Welding and Joining of Single Crystals of BCC refractory Metals," Proc. Of 12th Plansee Seminar '89 in Austria, pp. 265-279, 1989.

[14] Sahara, H., et al., "Single and Opposed-Cavity Solar Thermal Thrusters Made of Single Crystal Tungsten," Proc. Of 3rd International Conference on Spacecraft Propulsion, pp. 195-201, Cannes, France, Oct. 10-13, 2000.