Sputtering Yield of Carbon-Carbon Composite Due to Xenon Ion Bombardment in Ion Engines*

Masakatsu NAKANO,1) Satoshi HOSODA,2) and Kazutaka NISHIYAMA2)
1) Tokyo Metropolitan College of Industrial Technology, Tokyo 116–0003, Japan
2) Japan Aerospace Exploration Agency, Kanagawa 252–5210, Japan

The angular and energy dependence of the sputtering yield of a carbon-carbon composite due to xenon ion bombardment was investigated. Instead of assuming surfaces to be flat, a simple carbon fiber distribution model was introduced to account for the carbon-carbon composite surface structure observed using a scanning electron microscope. Yamamura’s semi-empirical sputtering formula, which accounted for 14% xenon adsorption, was used to calculate the sputtering yield of the carbon fiber surface. The proposed model provided fairly good estimates of the angular and energy dependence of the sputtering yield for the carbon-carbon composite. A comparative analysis of sputtering yield models demonstrated that the proposed model most accurately predicted both the accelerator and decelerator grid mass changes in the μ10 PM ion engine endurance test. In this paper, we present sputtering yield data over a range of xenon incidence energies from 0 to 2 keV and angles of incidence from 0 (normal incidence) to 90°.

Key Words: Sputtering, Xenon Ion Bombardment, Carbon-Carbon Composite, Angular and Energy Dependence, Ion Engine

Nomenclature

A1–6: polynomial coefficient
E: incidence energy
Eth: threshold energy of sputtering at normal incidence
f: adjustable parameter
fs: Sigmund parameter
sn: Lindhard-Scharff-Schiott (LSS) elastic stopping cross-section
w: working fraction
Y: sputtering yield
Y1: sputtering yield of graphite
Y2: sputtering yield of graphite with Xe adsorption
Y: averaged sputtering yield
φ: LSS reduced energy
ρ: density
θ: incidence angle
θopt: incidence angle at maximum sputtering yield

Subscripts and superscripts
C: carbon
C/C: carbon/carbon composite

1. Introduction

1.1. Background

Electrostatic electric propulsion such as ion engines can offer high specific impulse by exhausting high-velocity ions using charged plate electrodes,1) henceforth, referred to as grids. Molybdenum is widely used as the grid material in ion engines. In the μ10 ion engines on the Hayabusa explorer, carbon/carbon composite (C/C) was adopted for the first time because of its low thermal expansion and low sputtering yield properties.2)

Though the use of C/C extended the lifetime of the ion engines, the time and cost of life qualification increased dramatically; two 18,000 h and 20,000 h qualification experiments had to be performed during the development of the μ10 ion engine, thus, attesting to the need for quick and cost effective means of life qualification. To address this requirement, the JAXA Ion Engine Development Initiatives (JIEDI) project was started, and a numerical tool called JIEDI was developed to assess the ion acceleration grid erosion of ion engines at a low qualification cost.3–5)

Using the JIEDI tool, life qualification of the ion acceleration grid system can be shortened to within a few days. However, its accuracy and precision depends on the sputtering yield of C/C. The lack of a standard sputtering yield model for C/C has resulted in an urgent need to develop a practical sputtering yield model for C/C to prepare for the increasing use of C/C grids in ion engines and future innovative gridded electric thrusters.

1.2. Sputtering of ion engine grids

Sputtering particles generated from charge-exchange and elastic collisions continuously bombard the grid surface of the ion engine. These particles have a broad range of energies and incidence angles. The maximum energy of the incident sputtering particles in the μ10 ion engine is approximately 1,850 eV for singly charged xenon ion bombardment. It is approximately 3,700 eV for doubly charged xenon ion bombardment, which is included in around 5–12% of the mainstream ion beams.6) The incidence angles of the sputtering particles range widely between 0°
model (PM) of the accelerator and decelerator grid surfaces in the prototype (normal incidence to the grid surface) and 90°.

Figure 1 shows a plot of average incident angles on the accelerator and decelerator grid surfaces in the prototype model (PM) of the \( \mu \)10 ion engine.\(^7\) The average values for the angle are between 30°–70° incidence, with the high energy particles having high incidence angles. Because the sputtering yield is roughly proportional to the incident energy, improving the accuracy and consistency of the sputtering yield in the case of high incidence angles is important for the accurate and high-precision assessment of ion engine grid erosion.

1.3. Sputtering yield of carbon

There are several known allotropes and compounds of carbon, such as graphite, diamond, pyrographite, and C/C, whose sputtering yields vary widely. Large amounts of experimental data are available for the normal incidences of graphite, diamond, and pyrographite,\(^8\)\(^–\)\(^15\) that can be used to derive some empirical formula by curve-fitting, and this approach is widely used in engineering applications. In contrast, only small amounts of experimental data are available to derive an empirical formula for the angular dependence of sputtering.

Numerical analysis using Monte-Carlo and molecular dynamic (MD) simulations has been conducted by many researchers.\(^16\)\(^,\)\(^17\) The Monte-Carlo simulation accurately predicted the sputtering yield, the distribution of the sputtered particles, and their energies at high-incidence energies where a two-body approximation is considered adequate. However, it did not yield accurate results for low-incidence energies where multiple-collision effects dominate. In contrast, the MD simulation accounted for multiple collisions and was suitable for low-incidence energies; however, a gap remains between the simulated and experimental results.

1.4. Semi-empirical formula

As mentioned above, constructing a sputtering yield model only from experiments or simulations has certain limitations. The most practical method is a semi-empirical approach that involves using some analytical formula from a theory and determining its coefficients by curve-fitting experimental data. Yamamura’s sputtering yield formula is a well-known semi-empirical formula in the field of electric propulsion,\(^18\)\(^,\)\(^19\) and it has been used widely to evaluate the erosion of molybdenum grids of ion engines.\(^20\)\(^–\)\(^22\) In the case of sputtering carbon by xenon bombardment, Yamamura’s formula is not accurate at and below the threshold energy of 160.84 eV because it does not account for sputtering. However, experimental evidence indicates that the amount of sputtering cannot be neglected.\(^10\)\(^,\)\(^11\)

Understanding this discrepancy is an urgent problem in the development of the JIEDI tool for developing practical sputtering yield models for C/C. Kenmotsu et al. have suggested that adsorption of xenon atoms at the carbon surface enhances the sputtering yield. They proposed a correction to Yamamura’s semi-empirical formula, which yielded results in fairly good agreement to those obtained by experiments.\(^23\)

1.5. Angular dependence

As is evident from Fig. 1, the most common angles of incidence range between 30°–70°. However, sufficient experiments have not been conducted in order to construct an oblique sputtering yield model for C/C. The incidence energies and angles covered by the experiments are shown in Table 1.

In the JIEDI project, numerical studies were conducted using the Monte Carlo atomic collision in amorphous target (ACAT) code\(^10\) and MD simulations to develop an oblique sputtering yield model for C/C. However, these simulations assumed graphite and diamond surfaces that differed from those of C/C. Figure 2 shows a comparison between the sputtering yields obtained from simulations and experiments at 200 eV as a function of incidence angles.\(^5\) The discrepancies between the simulations and experiments were evident, and an order of magnitude difference was observed between the simulations. It should be noted that there is little agreement in the 30°–70° incidence range, where high accuracy and consistency are required most.

1.6. Surface structure of C/C

Experimental data show that the dependence of the sputtering yield of C/C on incidence angles is smaller than that of graphite and pyrographite, which can be attributed to the difference in their surface structure.\(^12\) Therefore, the incorporation of a C/C surface structure is important during
the modeling process, and the sputtering yield obtained by assuming the surface to be flat is not adequate.

As the sputtering progresses, the local sputtering yield varies because the shape of the carbon fibers changes gradually due to erosion. However, it is reported that the average sputtering yield remains nearly constant13) because the carbon fibers are distributed randomly in the horizontal and vertical directions. Thus, incorporating the time-independent common structure of the C/C surface in the sputtering yield model will be sufficient for engineering applications.

1.7. Objectives

The objectives of this study were 1) to clarify the surface structure of the C/C composite, and 2) to construct a sputtering yield model that included this structure in order to achieve higher accuracy and consistency, especially at incidence angles between 30–70° over a range of incidence energies from 0–2,000 eV.

2. Grid Surface

2.1. Surface observation

The surface of a C/C grid was observed using a scanning electron microscope (SEM, JSM-6510A). This grid was made by Toyo Tanso Co., Ltd. and was tested for 18,000 h as the accelerator grid of the μ10 EM ion engine. Figure 3 shows the photographs of the grid surface taken by SEM.

Figure 3(a) shows the downstream edge of the grid hole and Fig. 3(b) shows the magnification of the region surrounded by the black box in Fig. 3(a). In each figure, piles of carbon fibers (around 10 μm in diameter and several hundred μm in length) are visible, distributed randomly with spaces between the carbon fibers. These spaces result in a low-density C/C composite; 1.7 g/cm³ for BBM,24) and 1.6 g/cm³ for EM1, EM2, and PM24,25) grids, in contrast to 2.26 g/cm³ for pure graphite.

As shown in Fig. 3, the surface of each carbon fiber was smooth and there were no regions where blocks of carbon fibers were chipped away. Thus, we selected the simple approach detailed below.

2.2. Sputtering yield modeling strategy

From SEM observations, the sputtering yield of the C/C composite was modeled using the following steps.

1) A semi-empirical formula for carbon sputtering was developed using Yamamura’s formula with the Kenmotsu correction.

2) Next, all the sputtering on the carbon fiber surface using the sputtering yield of carbon developed in the above step was averaged.

3. Modeling

3.1. Carbon sputtering yield

To model the angular dependence of the sputtering yield of carbon, Yamamura’s formula was modified. Yamamura’s formula is a semi-empirical formula based on a linear cascade theory with fitting parameters obtained from experiments. It is widely used by electric propulsion researchers for molybdenum. However, for carbon, it offers significantly low sputtering yield values in the lower incidence energy regions. This problem was solved by Kenmotsu et al.23) using the experimental fact that 14% of Xe is adsorbed in the surface of carbon,8) which lowers the threshold energy of sputtering.

The formula proposed by Kenmotsu is given as follows:

\[
\text{sputtering yield} = \text{formula} \times \text{factor}
\]
was not underestimated; thus, we used this limit in the following analysis. Hereinafter, we refer to this sputtering yield model as the Yamamura-Kenmotsu (YK) model.

### 3.2. C/C sputtering yield

The C/C sputtering yield was obtained by integrating the sputtering contribution from each carbon fiber. Because adjacent fibers block some of the incoming sputtering particles and work as the source of the redeposition of sputtered carbon atoms, the sputtering yield of carbon fibers depends on the arrangement of adjacent carbon fibers. To provide the safe-side prediction model for the lifetime of the ion engine grid, the arrangement of the most severe sputtering is chosen, which can be given by neglecting all adjacent fibers.

Assuming that carbon fibers are infinitely long cylinders located horizontally on the C/C surface, as shown in Fig. 5, and the effect of adjacent fibers can be neglected, the averaged sputtering yield can be obtained

\[
\tilde{Y}(E, \theta) = \frac{\int_{\theta_{\min}}^{\theta_{\max}} \int_{0}^{2\pi} Y(E, \theta') \cos \theta' d\psi d\phi}{\int_{\theta_{\min}}^{\theta_{\max}} \int_{0}^{2\pi} \cos \theta' d\psi d\phi}
\]

where \(\theta'\) is the angle of incidence measured from the fiber surface normal, which can be calculated using

\[
\theta' = \cos^{-1}(\sin \theta \cos \phi \cos \psi + \cos \theta \sin \psi).
\]

The integration ranges of \(\phi\) and \(\psi\) in Eq. (9) are within the range where the cosine of \(\theta'\) is positive.

Because the sputtering yield of carbon \(Y(E, \theta')\) is given by the YK model, Eq. (9) can be easily evaluated using numerical integration. The sputtering yields calculated from Eq. (9) and their curve fitting coefficients are tabulated in the Appendix.
As seen in the SEM images, there are many spaces between the carbon fibers, where sputtering yield is assumed to be given by the YK model. The C/C surface at the beginning-of-life of the operation is not uniform and fluffy as a result of the cutting and drilling process. However, the fiber/matrix structure inside the C/C composite is the same and uniform, which appears after sputtering erodes away the upper layer of the C/C surface as seen in the SEM images in Fig. 3. Thus, the C/C sputtering yield can be written as

\[ Y_{C/C}(E, \theta) = w \times Y(E, \theta) + (1 - w) \times Y(E, \theta) \]  

(11)

using the working fraction on the C/C surface \( w \), which can be estimated using SEM images or the ratio of the densities between C/C and graphite as

\[ w = \left( \frac{\rho_{C/C}}{\rho_C} \right)^{2/3} \]  

(12)

Using Eq. (12), the fraction \( w \) is 0.794 for a density of 1.6 g/cm\(^3\) and 0.827 for 1.7 g/cm\(^3\). Hereafter, the sputtering yield model described by Eq. (11) is referred to as the C/C model.

4. Evaluation of Sputtering Yield Models

4.1. Carbon sputtering yield

The sputtering yields calculated using the YK model were compared to those measured for graphite and pyrographite at 300, 400, 600, and 1,000 eV.\(^{11,14,15}\) For the experiments, Tartz et al. used a microbalance\(^{14,15}\) and Kolasinski et al. employed a quartz crystal microbalance (QCM).\(^{11}\)

4.2. C/C sputtering yield

The sputtering yields computed by the C/C model were compared to those obtained using the YK model and the data from the measurements.\(^{12-14}\) The working fraction \( w \) was assumed to be 0.8 for a density of 1.6 g/cm\(^3\). The sensitivity of the C/C model to the working fraction was studied changing the working fraction to 0.5 and 1.0. For the experiments, Tartz et al. used a microbalance\(^{14,15}\) and Williams et al. employed a QCM.\(^{13}\) The sputtering yields obtained from ACAT and MD simulations at 200 eV are shown for reference.

4.3. Grid erosion analysis

To assess the impact of the different sputtering yield models on the accuracy of grid erosion analysis, the accelerator and decelerator grid mass changes of the \( \mu \)10 PM ion engine were evaluated using the JIEDI tool. Because there is no mass measurement for the C/C composite over 20,000 h of operation except for the \( \mu \)10 PM ion engine, this is the one and only comparison using actual ion engine testing data. The JIEDI tool is a numerical software for the life qualification of ion engine optics, which can analyze the wear of the grid system caused by ion and neutral sputtering within a reasonable computation time.\(^{3-5}\)

Four sputtering yield models were used: 1) CSU model, 2) MD model, 3) YK model, and 4) C/C model (\( w = 0.8 \)). The CSU model was based on the measurements\(^{13}\) by Williams et al. at Colorado State University (CSU), and the MD model used a database setup by Muramoto’s MD simulations. Because the range of incidence energy is limited between 200–1,000 eV in the CSU experiments and 100–500 eV in the MD simulations, values outside of these energy ranges were extrapolated by linear fitting. Both the CSU and MD models are built-in in the JIEDI tool.

The grid and operating parameters\(^{25}\) used in the analysis are listed in Table 2. To reproduce the ion beam current profile of the \( \mu \)10 ion engine, five ion beam currents were selected to calculate the overall grid mass changes.

5. Results and Discussion

5.1. Carbon sputtering yield

Figure 6 shows a comparison of the sputtering yields of carbon at 300, 400, 600, and 1,000 eV, respectively. For all the incidence energies, the calculated sputtering yields agreed well from 0° to 30° incidence. Although there are some differences for incidence angles above 30° at 300 eV, the similarities in the angular dependence between the calculations and experiments are high at 400 eV, 600 eV, and 1,000 eV.

5.2. C/C sputtering yield

Figure 7 shows a comparison of C/C sputtering yields. At 200 eV, both the ACAT and MD results showed discrepancies from the experimental data—underestimation of the sputtering yield for low incidence and substantial overestimation for high incidence. The YK model predicted adequately at normal incidence, with an underestimation factor of 2–3. However, the calculated sputtering yield was higher than those obtained from experiments at 35°–65° incidence. In contrast, the C/C models resulted in the same angular dependence and agreed quantitatively well with experiments.

At 400 eV, 1,000 eV, and 1,400 eV, the YK model showed an abrupt increase at 45°–75° incidence, while the C/C models showed a similar increasing trend as compared to the sputtering yields measured experimentally. Considering that the average incidence angles in the \( \mu \)10 ion engine are between 30°–70°, the C/C models are superior to the YK model.

Comparing the results for the different working fractions, the C/C model with the working fraction of 0.5 showed overestimation at 45°–75° incidence at 200, 1,000, 1,400 eV, and the C/C model with the working fraction of 1.0 showed underestimation at 400, 1,000, and 1,400 eV.

The C/C model with the working fraction of 0.8 predicted
produced the accelerator grid mass change, and the decelerator grid erosion became so large that direct impingement no longer occurs. Almost constant in the accelerator grid and it has a bending accuracy than other models was developed. Quantitative agreement with experimental data was best for this C/C sputtering yield model developed for a graphite surface. The YK model underestimated the grid erosion. In contrast, the YK model overestimated both grid erosions. The MD model underestimated both grid erosions by a factor of around 2 or more. Table 3 summarizes the results of comparisons of the sputtering models with experiments.

From these results, we conclude that the C/C sputtering model provides the most accurate predictions for grid erosion as compared to other models, and is suitable for grid erosion analysis of ion engines.

6. Summary

A sputtering model of carbon/carbon composite for an ion engine grid that can calculate the sputtering yield with higher accuracy than other models was developed.

From SEM observations, carbon fibers around 10 μm in diameter and several hundred microns in length were found to be distributed randomly on the C/C surface. The averaging of the sputtering on the fiber surface was done using the sputtering yield model developed for a graphite surface. The quantitative agreement with experimental data was best for this C/C sputtering yield model as compared with other sputtering models. Grid erosion analysis using this C/C model provided more accurate predictions than using built-in sputtering yield models in the JIEDI tool.
Acknowledgments

This study was supported by JSPS KAKENHI Grant Number 24560981.

References

1) Jahn, R. G.: *Physics of Electric Propulsion*, McGraw-Hill, New York, 1968.
2) Hosoda, S. and Kuninaka, H.: The Homeward Journey of Asteroid Exploration: "Hayabusa" Powered by the Ion Engines, *J. Plasma Fusion Res.*, 86 (2010), pp. 282–293 (in Japanese).
3) Kuninaka, H.: Research and Development of JIE(IA) (JAXA Ion Engine Development Initiatives) Tool for Numerical Evaluation of Ion Engine Grid Lifetime, JAXA-SP-06-019, 2007, pp. 5–9 (in Japanese).
4) Funaki, I., Watanabe, H., Nakano, M., Kajimura, Y., Miyasaka, T., Nakayama, Y., Hyakutake, T., Wada, M., Kenmotsu, T., Muramoto, T., and Kuninaka, H.: JAXA’s Ion Engine Development Initiatives, JAXA-RM-11-02, 2012 (in Japanese).
5) Satori, S., Kuninaka, H., and Otaki, M.: Beam Diagnostics of a Microwave Discharge Ion Engine, *J.pn. Soc. Aeronaut. Space Sci.*, 46 (1998), pp. 406–412 (in Japanese).
6) Nakano, M., Muramoto, T., Kenmotsu, T., Hyakutake, T., Kajimura, Y., and Funaki, I.: Embedding of Differential Sputtering Yield Model in JIEDI Code and Its Evaluation, Proceedings of Space Transportation Symposium, FY2010, 2011 (in Japanese).
7) Doerner, R. P., Whyte, D. G., and Goebel, D. M.: Sputtering Yield Measurements during Low Energy Xenon Plasma Bombardment, *J. Appl. Phys.*, 93 (2003), pp. 5816–5823.
8) Funaki, I., Kuninaka, H., Toki, K., Shimizu, Y., Nishiyama, K., and Horiiuchi, Y.: Verification Tests of Carbon-Carbon Composite Grids for Microwave Discharge Ion Thruster, *J. Prop. Power*, 18 (2002), pp. 169–175.
9) Blandino, J. J., Goodwina, D. G., and Garner, C. E.: Low Energy Sputter Yield Measurements for Diamond, Carbon-Carbon Composite, and Molybdenum Subject to Xenon Ion Bombardment, *Diamond and Related Materials*, 9 (2000), pp. 1992–2001.
10) Kolasiński, R. D., Polk, J. E., Goebel, D., and Johnson, L. K.: Carbon Sputtering Yield Measurements at Grazing Incidence, *Appl. Surface Sci.*, 254 (2008), pp. 2506–2515.
11) Delschew, R., Tartz, M., Plicht, V., Hartmann, E., Neumann, H., Leiter, H. J., and Esch, J.: Sputter Characteristics of Carbon-Carbon Compound Material, IEPC-01-118, 2001.
12) Williams, J. D., Johnson, M. L., and Williams, D. D.: Differential Sputtering Behavior of Pyrolytically Graphite and Carbon-Carbon Composite under Xenon Bombardment, AIAA Paper 2004-3788, 40th AIAA/ASME/SAE/AESS Joint Propulsion Conference and Exhibit, Fort Lauderdale, 2004.
13) Jahn, R. G.: *Physics of Electric Propulsion*, McGraw-Hill, New York, 1968.
14) Tartz, M., Neumann, H., Leiter, H., and Esch, J.: Pyrolytic Graphite and Carbon-Carbon Sputter Behaviour under Xenon Ion Incidence, IEPC 2005–143, 2005.
15) Tartz, M. and Neumann, H.: Sputter Yields of Carbon Materials under Xenon Ion Incidence, *Plasma Process. Polym.*, 4 (2007), pp. 633–636.
16) Yamamura, Y. and Mizuno, Y.: Low-Energy Sputtering with the Monte Carlo Program ACAT, IPPM-AM-40, Inst. Plasma Physics, Nagoya Univ., 1985.
17) Muramoto, T., Kenmotsu, T., Hyakutake, T., and Nishida, M.: MD Simulation of Carbon Sputtering under Low-energy Xe Ion Bombardment, JAXA-RR-09-004, 2009, pp. 21–25 (in Japanese).
18) Yamamura, Y. and Tawara, H.: Energy Dependence of Ion-Induced Sputtering Yields from Monatomic Solids at Normal Incidence, *Atomic Data and Nuclear Data Tables*, 62 (1996), pp. 149–253.
19) Yamamura, Y., Itikawa, Y., and Itoh, N.: Angular Dependence of Sputtering Yields of Monatomic Solids, Inst. Plasma Physics, IPPM-AM-26, 1983.
20) Boyd, I. D. and Crofton, M. W.: Grid Erosion Analysis of the T5 Ion Thruster, AIAA Paper 2001-3781, 2001.
21) Gruber, J. R.: Low-Energy Sputter Erosion of Various Materials in a T5 Ion Thruster, IEPC-01-307, 2001.
22) Farnell, C. C.: Numerical Simulation of HiPEP Ion Optics, AIAA Paper 2004-3818, 2004.
23) Kenmotsu, T., Wada, M., Hyakutake, T., Muramoto, T., and Nishida, M.: Enhanced Sputtering Yields of Carbon Due to Accumulation of Low-energy Xe Ions, Nucl. Instrum. Meth. B, 267 (2009), pp. 1717–1720.
24) Funaki, I., Kuninaka, H., Toki, K., Shimizu, Y., Nishiyama, K., and Horiiuchi, Y.: Verification Tests of Carbon-Carbon Composite Grids for Microwave Discharge Ion Thruster, *J. Prop. Power*, 18 (2002), pp. 169–175.
25) Toyoda, Y.: Study on Microwave Discharge Ion Thruster, Master’s Thesis, The University of Tokyo, 2009 (in Japanese).
26) Nakano, M.: Sensitivity Analysis for Effect of Doubly Charged Ions on Ion Acceleration Grid Erosion, *J.pn. Soc. Aeronaut. Space Sci.*, 55 (2012), pp. 364–372.

Appendix

Table A1 contains the sputtering yields calculated using Eq. (9) for 0–90° incidence over a range of incidence energies between 0–2,000 eV. The curve-fitting coefficients $A_0$, $A_1$, $A_2$, $A_3$, $A_4$, and $A_6$ using a sixth-order polynomial

$$
\tilde{Y} = A_0 \cos \theta \cos \phi + A_3 \cos \theta \cos ^2 \phi + A_4 \cos \theta \cos ^3 \phi + A_2 \cos ^2 \theta + A_1 \cos \theta + A_0
$$

are also tabulated.

Y. Ohkawa
Associate Editor

Table A1. Sputtering yields and polynomial coefficients for Eq. (9).

| $\theta$ (°) | $0^\circ$ | $10^\circ$ | $20^\circ$ | $30^\circ$ | $40^\circ$ | $50^\circ$ | $60^\circ$ | $70^\circ$ | $80^\circ$ | $90^\circ$ |
|-------------|----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
| $A_0$       | 0.000    | 0.000     | 0.000     | 0.000     | 0.000     | 0.000     | 0.000     | 0.000     | 0.000     | 0.000     |
| $A_1$       | 0.000    | 0.000     | 0.000     | 0.000     | 0.000     | 0.000     | 0.000     | 0.000     | 0.000     | 0.000     |
| $A_2$       | 0.000    | 0.000     | 0.000     | 0.000     | 0.000     | 0.000     | 0.000     | 0.000     | 0.000     | 0.000     |
| $A_3$       | 0.000    | 0.000     | 0.000     | 0.000     | 0.000     | 0.000     | 0.000     | 0.000     | 0.000     | 0.000     |
| $A_4$       | 0.000    | 0.000     | 0.000     | 0.000     | 0.000     | 0.000     | 0.000     | 0.000     | 0.000     | 0.000     |
| $A_6$       | 0.000    | 0.000     | 0.000     | 0.000     | 0.000     | 0.000     | 0.000     | 0.000     | 0.000     | 0.000     |

©2015 JSASS 219