JOURNAL OF SPACECRAFT AND ROCKETS
Vol. 43, No. 3, May–June 2006

N-Nitrosodimethylamine Release from Fuel Oxidizer Reaction Product Contaminated Extravehicular Activity Suits

William Schmidl* and Ron Mikatarian†
The Boeing Company, Houston, Texas 77059
Chiu-Wing Lam‡
Wyle Laboratories, Houston, Texas 77058
Bill West§
Hamilton Sundstrand, Houston, Texas 77058
Vanessa Buchanan¶ and Louis Dee¶
Honeywell Technology Solutions, Las Cruces, New Mexico 88004
David Baker**
NASA White Sands Test Facility, Las Cruces, New Mexico 88004
and
Steve Koontz††
NASA Johnson Space Center, Houston, Texas 77058

Before extravehicular activity (EVA) on the Russian segment (RS) of the International Space Station (ISS), the docking compartment (DC1) must be depressurized, because it is used as an airlock. It is preferred to use the U.S. control moment gyros (CMGs) instead of attitude-control thruster firings to compensate for disturbances and to maintain the ISS vehicle attitude. However, when the DC1 is depressurized, the CMGs' margin of momentum is insufficient to compensate for the disturbance and the service module (SM) attitude-control thrusters' need to fire to desaturate the CMGs. The SM roll-control thruster firings induce fuel–oxidizer reaction products (FORP) contamination on the adjacent SM surfaces around the thrusters. One of the components present in FORP is the potent carcinogen *N*-nitrosodimethylamine (NDMA). Because the EVA crewmembers often enter the area surrounding the thrusters for tasks on the aft end of the SM and when translating to other areas of the RS, the presence of FORP contamination is a concern. FORP contamination of the SM surfaces is discussed, along with the potential release of NDMA in a humid environment from crew EVA suits, whether they happen to be contaminated with FORP, the toxicological risk associated with the NDMA release, and the implementation of flight rules to mitigate the hazard.

I. Introduction

THE U.S. control moment gyros (CMGs) maintain the vehicle attitude of the International Space Station (ISS) by compensating for disturbances. However, when the docking compartment (DC1) of the ISS, the location of the Russian airlock, is depressurized for extravehicular activities (EVAs), the service module (SM) attitude control thrusters have to fire because the CMGs have an insufficient margin of momentum to compensate for the disturbance and must be desaturated.

The ISS propellant is unsymmetrical dimethylhydrazine (UDMH), and the oxidizer is nitrogen tetroxide (N_2O_4). Thruster firings produce fuel–oxidizer reaction products (FORP) that can contaminate adjacent surfaces around the thrusters. For EVAs on the aft end of the SM of the Russian segment, there is a concern that when EVA crewmembers translate around the FORP-contaminated area they could inadvertently brush against the FORP and transfer some of it to their suits.

FORP is composed of both volatile and nonvolatile components. How fast the volatile components leave varies. One of the components present in FORP that represents the greatest toxicological concern to the crew is the potent carcinogen *N*-nitrosodimethylamine (NDMA). NDMA is volatile; it poses an inhalation concern if it is introduced into the ISS atmosphere. In addition, when other components in the dried FORP, such as dimethylammonium nitrite and nitrate, are reintroduced into a humid environment such as the ISS cabin, NDMA can be formed. So the concern is that when FORP (on the suit) is brought back into the humid environment of the ISS cabin, it can release NDMA into the atmosphere and the crew can be exposed.

II. Background

Discoloration around the SM zenith roll thrusters was observed during the ISS Flight 5A Orbiter flyaround of the ISS, as shown in the image in Fig. 1. In the image, the pitch thrusters are closest to the aft end of the SM (right-hand side of the image). The roll thrusters are to the left of the pitch thrusters and elevated above the surface of the SM. The discoloration (brown color) can be seen clearly close to the roll thrusters in the inset zoomed image. The EVA handrails can also be seen in the inset image close to the roll thrusters and on either side of the pitch thrusters.

Contamination has also been observed around the SM nadir roll thrusters. Figure 2 shows the relative position and direction of the SM attitude control thrusters. It can be seen that the roll thrusters'

Received 24 January 2005; revision received 20 September 2005; accepted for publication 21 September 2005.

*Engineer/Scientist, M/C HB3-20 77059, Boeing ISS Environments, 13100 Space Center Boulevard. Member AIAA.
†ISS Environments Lead, M/C HB3-20 77059, Boeing ISS Environments, 13100 Space Center Boulevard.
‡Senior Scientist/Toxicologist, Toxicology Department.
§ISS EVA Increment Management, EVA Office, Johnson Space Center.
¶Scientist, NASA White Sands Test Facility, 12600 NASA Road.
**Projects Director, 12600 NASA Road.
††NASA System Manager for ISS Environments, Engineering.

plume centerline is directed 47 deg away from the normal to the surface (lower diagram), whereas the pitch and yaw thrusters' plume centerline is directed 13 deg away from the normal to the surface (top diagram). In addition, the pitch and yaw thrusters are recessed below the SM surface, whereas the roll thrusters are elevated above the surface to provide the roll-control component. So the plumes from the roll thrusters are more likely to contaminate the adjacent SM surfaces than the plumes from either the

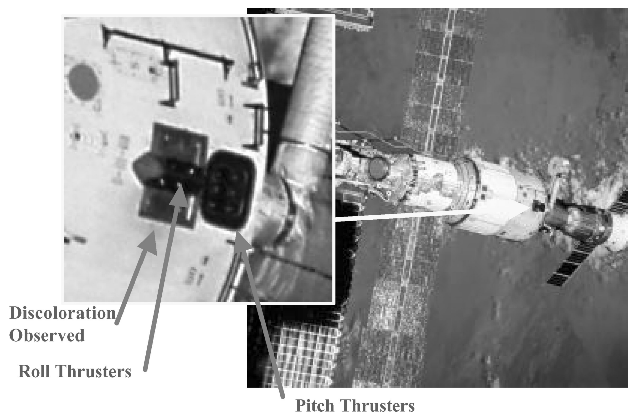

Fig. 1 Observations of surface discoloration near the SM zenith roll thrusters during the Flight 5A mission. The inset image shows an enlarged image of the zenith roll and pitch thrusters. Discoloration is visible near the roll thrusters.

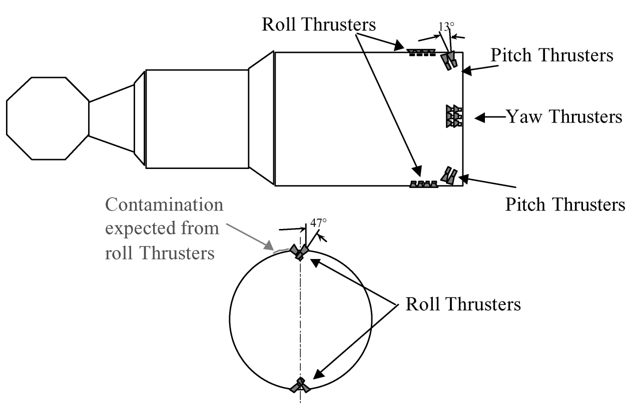

Fig. 2 Service module attitude-control thrusters' position and direction. The pitch and yaw thrusters point away from the vehicle surface at 13 deg from the normal to the surface; the roll thrusters point 47 deg from the normal to the surface. Contamination from the roll thrusters is expected on the adjacent SM surfaces.

pitch or yaw thrusters. The ISS external contamination team has concluded that the discoloration is plume contamination due to thruster firings. In such areas, it must be assumed that FORP is present.

The image in Fig. 1 was acquired before shields, gasdynamic protection devices (GZUs), were installed on the thrusters in January 2002 during an EVA. Rocket and Space Corporation Energia of Russia has designed the GZUs to constrain the thruster plume and limit contamination of the surrounding surfaces. Figure 3a shows the GZU for one of the roll thrusters prior to flight. It fits over the top of the roll thrusters. The handle on top of the GZU is used during installation and is not used for translating during EVAs, as it becomes contaminated. The brackets on the sides of the GZU are used to install the GZU on fittings that were preinstalled on the SM surface prior to flight. Figure 3b shows an image of roll thrusters prior to installation of the GZU. Figure 3c shows the other side of the roll thrusters (right-hand side of the image) and the corresponding pitch thrusters (left-hand side of the image). It should be noted that the GZUs used for the pitch and yaw thrusters are different from the ones used for the roll thrusters because they are recessed below the SM surface.

Images of the SM nadir attitude control thrusters have been taken from the DC1 window at regular intervals and the Russian Kromka experiment. Figure 4 shows one of these images. Kromka is an experiment to measure how well the GZUs are performing and to test how well some material samples will perform in space.[1] The Kromka experiment is the material tray visible in the middle of the image. It has several small material samples mounted on it. In front of the Kromka, the pitch thrusters with their GZUs installed can be seen. In front of the pitch thrusters are the roll thrusters with their GZUs installed. It can be seen that the GZUs are heavily contaminated compared to the preflight GZU image in Fig. 3a. Figure 5 shows a diagram of the nadir side of the SM and the relative positions of the

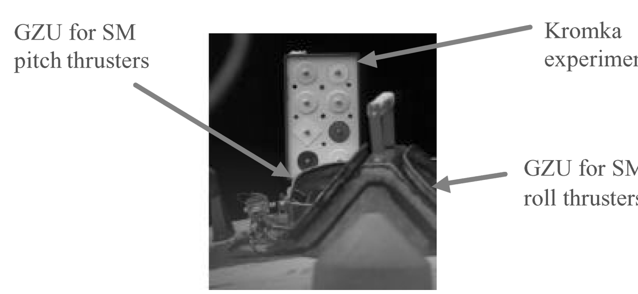

Fig. 4 Image taken from DC1 window. Kromka is visible in the middle of the image. The GZUs on the pitch and roll thrusters are also visible in the image.

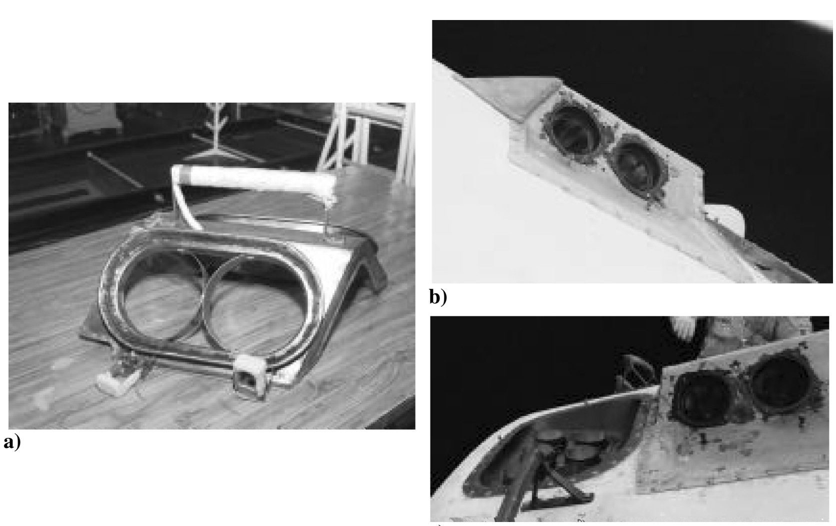

Fig. 3 GZUs designed by Rocket and Space Corporation Energia: a) GZU for the SM roll thrusters before flight and installation, b) SM roll thrusters before installation of the GZU, and c) SM roll thrusters (right-hand side of the image) and pitch thrusters (left-hand side of the image) before installation of the GZU.

Table 1 Results of prepared FORP composition ions

Ionic species	Ammonium, %/wt[a]	Methylammonium, %/wt	Dimethylammonium, %/wt	Nitrate, %/wt	Nitrite, %/wt
CY 2003 residue (10%)[b]	0.05	1.1	7.9	36	0.08
CY 2004	0.6	2	20	9	20
CY 2004 residue (14%)[b]	0.3	1.7	13	48	0.6

[a]Weight percent. [b]Ionic species were analyzed after UFORP was subjected to vacuum for 5 days.

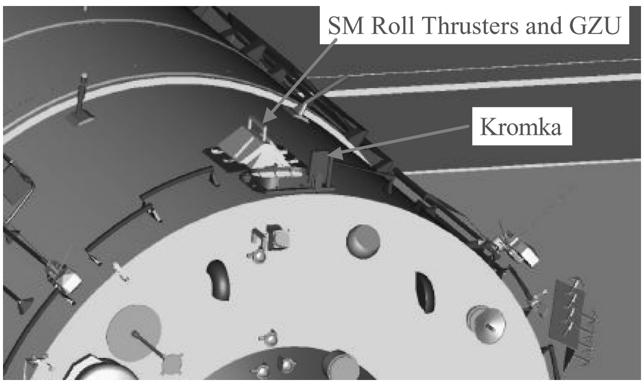

Fig. 5 Nadir side of service module. The Kromka experiment is visible near the SM pitch thrusters.

Kromka experiment and the thrusters. The Kromka experiment is visible near the SM pitch thrusters. EVA handrails that may be used by the crew can be seen on either side of the pitch thrusters.

III. Extravehicular Activity Constraints

Because of the presence of FORP on the SM surfaces adjacent to the roll thrusters and the potential for FORP contamination of the EVA crew, additional EVA constraints were required to be implemented in these areas. The constraints were initially established through a nonconformance report that discussed the removal of the Kromka 1-0 experiment and installation of the Kromka 1-1 experiment and in subsequent ISS program safety review panel discussions. The constraints were later confirmed in the protocol from a joint U.S./Russian FORP technical interchange meeting held in Houston, Texas, 15–26 April 2002.[2]

The EVA constraints were initially developed because the Kromka experiment is in close proximity to the SM thrusters, as can be seen in Fig. 5, and the EVA crewmembers would need to enter that area. The constraints included establishing a 1-m keep-out zone (KOZ) around the thrusters for 2.5 h after the last SM thrusters fired before the EVA crewmembers could enter the area, procedures for inspecting the EVA suits before ingress back into the airlock, and procedures for wiping the gloves and suit with towels that are jettisoned to retrograde. Also, once inside the ISS, the EVA gloves are bagged to mitigate any potential risk from FORP. Because EVAs are generally very time-constrained, the ISS program approved a test program at the NASA White Sands Test Facility (WSTF) to obtain FORP test data that could be used to determine whether those EVA constraints could be relaxed.

IV. NASA White Sands Test Facility Laboratory Tests

A. Introduction

A test program was set up at the NASA White Sands Test Facility to obtain the data that would be needed to determine the EVA constraints that would be required to mitigate the risk of an EVA crewmember inadvertently contacting a FORP-contaminated surface and bringing the FORP back into the humid ISS cabin. The program included tests to determine the evaporation rate of FORP on the zenith (25°C, hot) and nadir (−40°C, cold) sides of the ISS, the evaporation rate of NDMA within the FORP on the zenith and nadir sides of the ISS, the potential quantity of NDMA that would be released in a humid pressurized environment from the dried FORP, and the rate at which NDMA reforms when dried FORP is introduced into a humid environment. The techniques used to perform the study are discussed in detail in Ref. 3.

Two groups of tests were performed. The first group was performed during calendar year 2003. Results from this group are designated "CY 2003." Results from these tests included 100-h evaporation rate data for FORP for the zenith and nadir cases, NDMA evaporation rate data for the corresponding zenith and nadir cases, and NDMA formation rate data. Based on these results, the time to remain outside the keep-out zone (KOZ) after the last SM thrusters fired was reduced from 2.5 to 2 h.

Additional tests were requested by the ISS program to determine whether the time outside of the KOZ could be further reduced from 2 to 1 h. This was the series of tests performed during early calendar year 2004 and designated "CY 2004." Results from these tests included 1- to 6-h evaporation rate data for FORP for the zenith and nadir cases, NDMA evaporation rate data for the corresponding zenith and nadir cases, and NDMA formation rate data.

B. Preparation of FORP

For each group of tests, a batch of FORP was generated using a permeation technique developed at the NASA WSTF.[2] In this technique, separate UDMH and NO_2 gas streams are concentrated in a small controlled area. The batch of FORP needed for the tests was prepared over a period of a couple of weeks. For the formation test, a sample of FORP from each batch was evaporated in a vacuum for 5 days at 25°C to generate a sample of dried FORP. Because the FORP was prepared over a long duration, the composition of the two batches of FORP varied. The composition of the FORP batches used in the tests is shown in Table 1. For the CY 2003 FORP, only the composition of the evaporated sample was measured. When comparing the two evaporated samples, it can be seen that the CY 2004 FORP has a higher concentration of dimethylammonium, nitrates, and nitrites (7.9 vs 13%, 36 vs 48%, and 0.08 vs 0.6%, respectively) than the CY 2003 FORP. The higher concentration of dimethylammonium, nitrates, and nitrites in the CY 2004 FORP likely explains why it has more mass remaining after the 5-day evaporation than the CY 2003 FORP (14 vs 10%).

The nitrite levels of the CY 2004 FORP before evaporation and after evaporation, 20% of the initial mass and 0.6% of the 14% mass remaining, indicate that the nitrite concentration is decreasing. A lower nitrite level significantly decreases the NDMA formation rate. This was seen in the results that will be discussed later.

The concentration of dimethylammonium ion is also higher in the CY 2004 dried FORP than in the CY 2003 FORP (13 vs 7.9%). The higher concentration of dimethylammonium and nitrites indicates that a higher NDMA formation rate would be expected for the CY 2004 FORP than for the CY 2003 FORP. This was seen in the results to be presented later.

C. Measurement Technique

The technique used to measure the evaporation rate for FORP and NDMA and the NDMA formation rate is discussed in detail in Ref. 3.

1. Evaporation Test

The FORP evaporation rate was determined by measuring the difference between the initial weight of FORP on a slide before it was put in a vacuum chamber and the final weight of FORP on the preweighed slide after it was removed from the vacuum chamber. To determine the initial weight of FORP placed on the slide, an empty syringe was weighed; then ∼0.200 ml of FORP was put into the capped syringe and the syringe was reweighed. This was necessary because of the presence of NDMA in the FORP. The weight of the preweighed slide, and the difference in weight of the syringe with and without the FORP is the weight of the initial FORP and slide. The weight of the FORP could then be determined.

The evaporation test was performed in a vacuum chamber at 10^{-3} Torr. Earlier tests performed by Dee et al.[2] of WSTF showed that more FORP and NDMA would be removed for tests performed at 10^{-6} torr. So the results from these tests are more conservative than would be expected in-orbit.

After the samples were removed from the vacuum chamber, they were allowed to warm up to room temperature in a desiccator before being reweighed.

The NDMA evaporation rate was measured using gas chromatography–mass spectroscopy (GC-MS). The NDMA concentration in the initial sample was measured before the evaporation test. After the evaporation test, the FORP remaining was rinsed from the slide and the GC-MS test was performed again on the sample to determine the NDMA concentration present.

2. NDMA Formation Test

The NDMA formation test was performed using a solid phase microextraction (SPME) test. The NDMA formation rate was measured by sampling the headspace above the sample at selected time intervals to determine the NDMA concentration present.

D. Test Results

1. NDMA Evaporation Rate

The test results in Fig. 6 show that the concentration of NDMA relative to the initial mass of FORP decreases rapidly. The test results are for simulating the nadir (−40°C, cold) case in which the ISS nadir thruster and surrounding surfaces are away from the sun. With reference to Fig. 6, the light squares are from the CY 2004 tests and the dark squares are from the CY 2003 tests. It can be seen that the CY 2004 FORP starts (time = 0) with a higher concentration of NDMA than the CY 2003 FORP. However, by the time it reaches the 2- and 4-h data points, the concentration of NDMA relative to the initial amount of FORP is comparable and the CY 2004 and CY 2003 data points overlap.

The results in Fig. 7 are for the zenith (25°C, hot) case. As expected, it can be seen that the NDMA concentration drops more

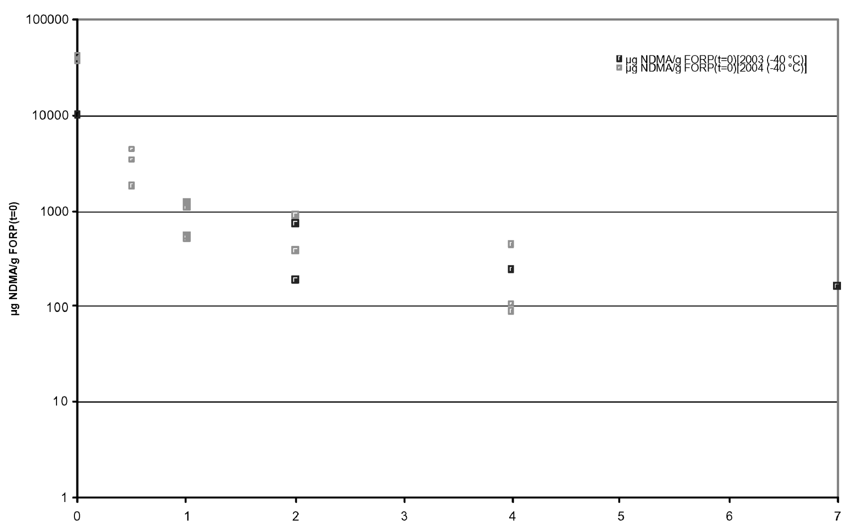

Fig. 6 Concentration of NDMA relative to the initial mass of FORP (micrograms of NDMA/grams of FORP) for the −40°C case (nadir, cold case) decreases rapidly with time.

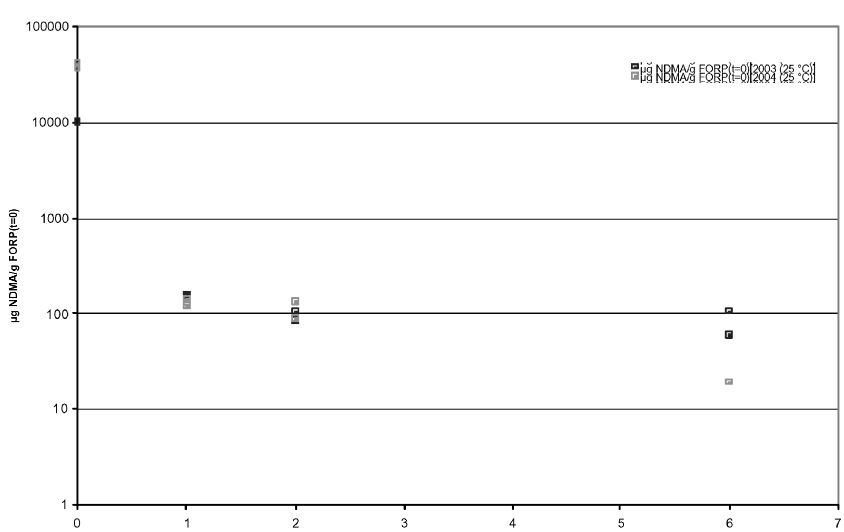

Fig. 7 Concentration of NDMA relative to the initial mass of FORP (micrograms of NDMA/grams of FORP) for the 25°C case (zenith, hot case) decreases rapidly with time. Within 1 h the concentration level has reached a plateau.

rapidly for the 25°C case than for the −40°C case. After 1 h the concentration has dropped approximately 2 orders of magnitude, compared with 1 order of magnitude for the −40°C case. It can also be seen that by 1 h the concentration drop has reached a plateau.

2. FORP Evaporation Rate

Figure 8 shows that the FORP volatilized rapidly to a stable mass that persisted over a longer period of time. The results show that within 1 h, the FORP reached a stable mass and that the CY 2004 FORP settled at a higher mass than the CY 2003 FORP. For CY 2004, the FORP remaining after 1 h was ∼36%. The results for CY 2003 FORP showed that 12–22% of the initial mass remained. The higher mass remaining was likely due to the higher concentration of nitrites and nitrates present in the CY 2004 FORP.

The results for the zenith (25°C, hot) case in Fig. 9 show that the FORP volatilized rapidly to a stable mass. The data showed that the CY 2004 FORP remaining after 1 h was 22% and that for CY 2003 FORP it was 10% to 11%. Again, the higher mass remaining was likely due to the higher concentrations of nitrites and nitrates.

3. FORP Formation Rate

Table 1 shows the nitrite levels of the CY 2004 FORP before evaporation and after evaporation; it was 20% of the initial mass, and 0.6% of the 14% mass remaining. These data indicate that the nitrite concentration in the FORP is decreasing. A lower nitrite level in the FORP would decrease the NDMA formation rate. This was observed in the results, because no NDMA formation was detected in the CY 2003 FORP when moisture was introduced into the sample of dried FORP. For the CY 2004 sample of dried FORP, the NDMA formation rate was negligible when moisture was introduced. It was determined that to form NDMA, nitrite had to be present in the sample. Both the CY 2003 and CY 2004 dried FORP samples were spiked with nitrite before the formation rate was measured. The nitrite introduced was 25% of the mass of nitrate present in the sample.

Table 1 also shows that the concentration of dimethylammonium was higher for the CY 2004 FORP than for the CY 2003 FORP sample (13 vs 7.9%). The higher concentration of dimethylammonium indicated that a higher NDMA formation rate would be expected for the CY 2004 FORP.

Figure 10 shows the NDMA formation rate that was measured. The plot shows the rates for both the CY 2003 FORP and CY 2004 FORP. The solid symbols indicate FORP where nitrite is added, and the open symbols are FORP with no nitrite added. It can be seen that when no nitrite was present the NDMA formation rate was very low. For the CY 2003 FORP, no NDMA formation was detected. For the CY 2004, a low rate of ∼100 μg of NDMA/g of FORP was measured.

The results in Fig. 10 also show that for the CY 2003 FORP, the NDMA formation rate was 1800 μg of NDMA/g of FORP present

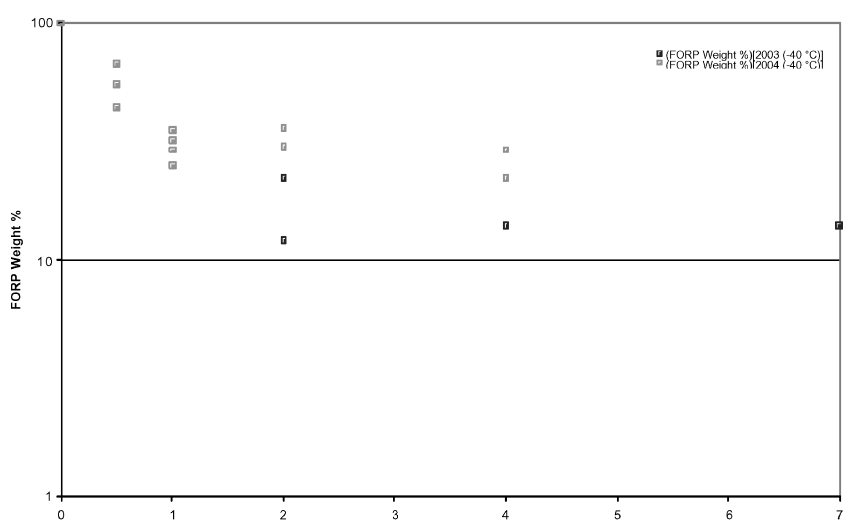

Fig. 8 FORP weight vs time for the −40°C case (nadir, cold case).

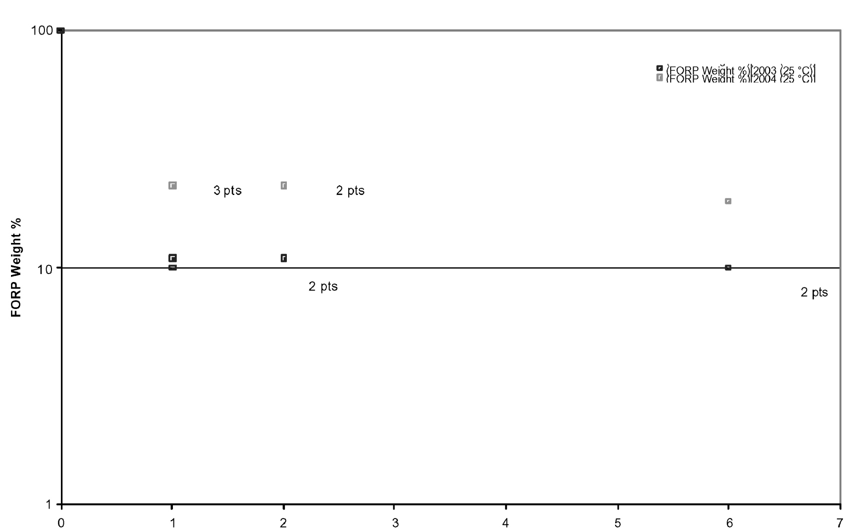

Fig. 9 FORP weight vs time for the 25°C case (zenith, hot case). FORP volatilized rapidly to a stable mass that persisted for a longer period of time.

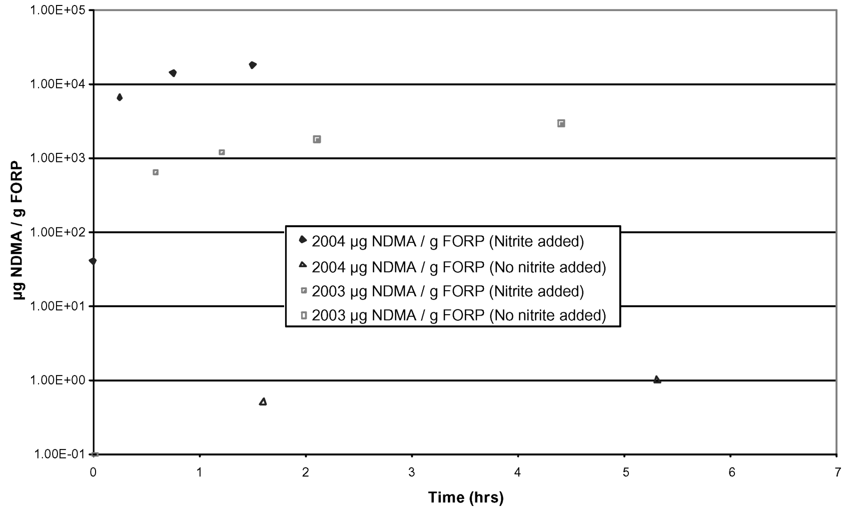

Fig. 10 NDMA concentration (micrograms of NDMA/grams of FORP) vs time measured during the NDMA formation test. It can be seen that the NDMA formed rapidly when nitrite was present. For the CY 2003 test, when no nitrite was present, no NDMA formation was detected.

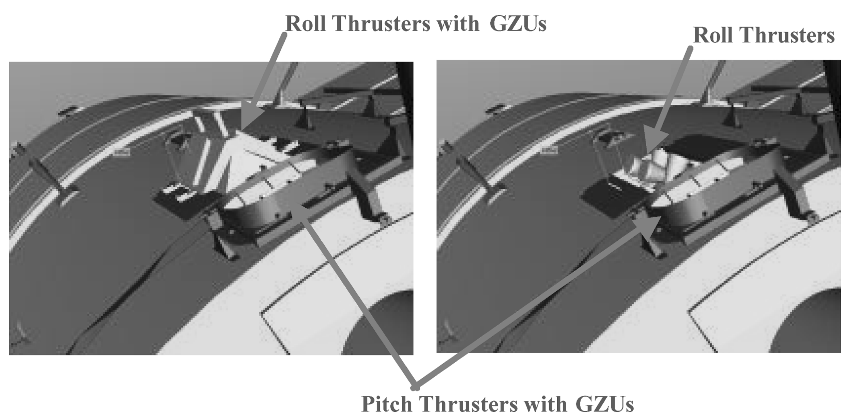

Fig. 11 Zenith side of service module (SM). Gas dynamic protection units (GZUs) constrain the thruster plume. The distance from the roll thruster to the closest SM surface outside the GZUs is ∼3.2 in. (∼8 cm).

after 2 h and that the formation rate for the CY 2004 FORP was higher, 18,400 μg of NDMA/g of FORP present after 2 h. One cause for the higher formation rate was the higher dimethylammonium concentration in the CY 2004 FORP. The mass of CY 2004 FORP remaining after the 5 days of evaporation was also higher. This might indicate that there were other components present in the FORP that could have resulted in a higher NDMA formation rate.

V. Methodology and Contamination Assessment

A methodology was developed to determine the FORP and NDMA remaining on the SM surface after the SM roll thrusters fire prior to an EVA and the subsequent release of NDMA in a humid environment due to inadvertent contact by an EVA crewmember with the SM surface in the vicinity of the SM roll thrusters contaminated with FORP.

The first step was to calculate how much FORP would be deposited on the adjacent SM surfaces by the thrusters firing prior to an EVA. To calculate the FORP remaining on the SM surface, the Russian plume model was used. The thruster firing times were obtained from the ISS Program's Guidance, Navigation, and Control group. The value of 45 s was used because it is the longest thruster firing time that has been recorded during the previous EVAs.

The next step was to calculate how much FORP would remain 1 h after the SM thrusters had fired. This was determined using the WSTF laboratory evaporation test data for the nadir case. The conservative value of 36% FORP remaining was used. Figure 11 shows a map of the distribution of FORP from the thruster remaining on the SM thruster based on the plume model and laboratory data. It can be seen that the FORP concentration drops rapidly with distance from the thrusters.

Next, to be conservative, it was assumed that all of the FORP in a 100-cm^2 area is transferred to the suit by an inadvertent swipe. Based on the amount of FORP transferred, the amount of NDMA that would be released from this FORP inside the cabin in the first 2 h was calculated using the rate of 400 μg of NDMA/g of FORP present. This value was obtained from the WSTF data based on the evaporation rate of NDMA for the zenith hot case. The amount of NDMA that would be formed from the dried FORP in the first 2 h was also calculated based on the more conservative CY 2004 rate, 18,400 μg of NDMA/g of FORP present.

Figure 11 shows that since the GZUs were installed, the closest point on the SM surface that can be touched is ∼3.2 in. (∼8 cm) from the edge of the thruster. The diagram is of the zenith side of the SM. The figure on the left shows the roll thrusters with the GZUs installed. The figure on the right shows the distance from the edge of the roll thruster to the closest SM surface outside of the GZUs. The roll thruster diameter is 1.8 in. The distance from the roll thruster centerline to the closest SM surface is ∼5 in. (12.7 cm).

Figure 12 shows the FORP predicted to remain after 1 h on the surface around the SM roll thruster after a 45-s roll thruster firing. The predicted concentrations of NDMA with distance from the SM thrusters that would be released by an inadvertent swipe into the DC1 and ISS compartments are shown in Tables 2 and 3. It can be seen that the concentration dropped off rapidly. Also, the closest point is at the GZU itself, which is defined as a "no touch" area by

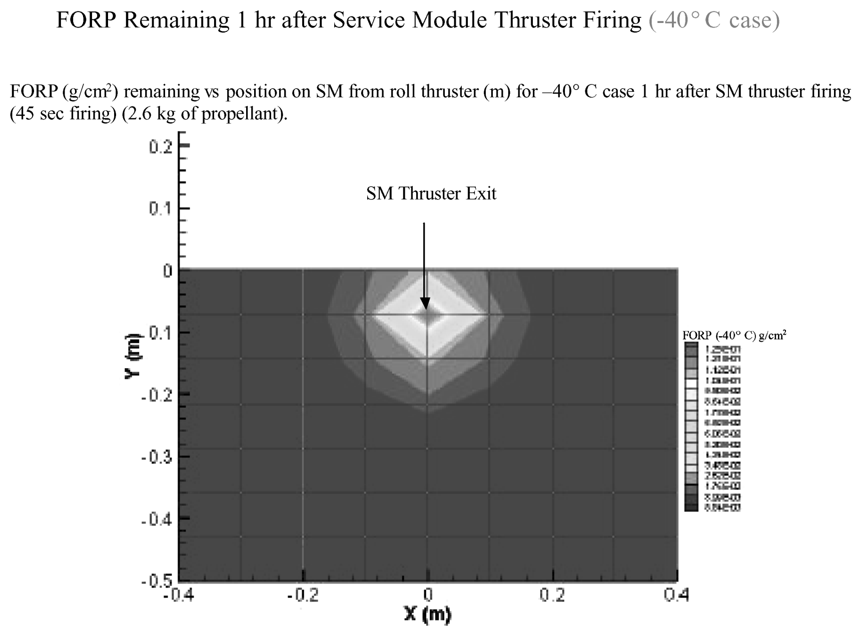

Fig. 12 Map of the FORP predicted to remain on the surface around the SM roll thruster 1 h after a 45-s roll thruster firing. It can be seen that the FORP concentration drops rapidly with distance from the thruster.

Table 2 NDMA concentration predicted to be released in the cabin for FORP transferred to the EVA suit 1 h after the roll thruster firing at different distances from the roll thruster for the −40°C case (nadir)

Distance from roll jet, m	FORP present, g/cm^2	NDMA released in pressurized environment	NDMA concentration, ppb	
			DC1[a]	ISS[b]
0.08[c]	1.96*E*–02	3.69*E*–02	965	34
0.15	6.22*E*–03	1.17*E*–02	306	11
0.23	2.96*E*–03	5.57*E*–03	146	5
0.30	1.72*E*–03	3.23*E*–03	84	3
0.37	1.11*E*–03	2.09*E*–03	55	2
0.44	7.77*E*–04	1.46*E*–03	38	1

[a]DC1 has a volume of 12.5 m^3. [b]ISS total volume 354 m^3. [c]At GZU.

Table 3 NDMA concentration predicted to be released in the cabin for FORP transferred to the EVA suit 1 h after the roll thruster firing at different distances from the roll thruster for the 25°C case (zenith)

Distance from roll jet, m	FORP present, g/cm^2	NDMA released in pressurized environment, g	NDMA concentration, ppb	
			DC1[a]	ISS[b]
0.08[c]	1.20*E*–02	2.25*E*–02	589	21
0.15	3.80*E*–03	7.15*E*–03	187	7
0.23	1.81*E*–03	3.40*E*–03	89	3
0.30	1.05*E*–03	1.97*E*–03	52	2
0.37	6.81*E*–04	1.28*E*–03	33	1
0.44	4.75*E*–04	8.93*E*–04	23	1

[a]DC1 has a volume of 12.5 m^3. [b]ISS total volume 354 m^3. [c]At GZU.

flight rule. These data were given to the JSC Toxicology Group for assessment.

VI. Toxicological Assessment

The quantity of FORP present and NDMA released into the ISS from an inadvertent swipe by an EVA crewmember of the contaminated area around the SM roll thrusters was calculated and provided to the NASA JSC toxicology group for assessment. These data are shown in Tables 2 and 3.

Acute toxicity has not been reported at concentrations below 10 ppm. Therefore, it can be concluded that at concentrations below 1 ppm, it is very unlikely that NDMA will produce any acute toxic reactions. Therefore, the NASA JSC Toxicology Group concluded that for the concentration levels expected, it is unlikely that NDMA will produce acute toxicity.

The NASA JSC Toxicology Group also found that the highest calculated cancer risk from the projected NDMA concentrations is less than 8.46×10^{-5} (−40°C, distance 0.08 m from the thrusters). The NASA Toxicology Group, with the concurrence of the National Research Council Spacecraft Maximum Allowable Concentrations (SMAC) Subcommittee, accepts a cancer risk of 1/10,000 (i.e., 10^{-4}) in deriving SMACs for carcinogenic compounds, such as benzene.

VII. Flight Rule Development

Owing to the presence of FORP on the SM surfaces adjacent to the roll thrusters observed in Flight 5A and subsequent imaging and the potential for FORP contamination of the EVA crew, additional EVA constraints were required to be implemented in those areas. These EVA constraints were initially implemented through the nonconformance report described earlier. The constraints included establishing a 1-m keep-out zone (KOZ) around the thrusters for a period of time after the last SM thrusters fired before the EVA crewmembers could enter the area, procedures for inspecting the EVA suits before ingress back into the airlock, and procedures for wiping the gloves and suit with towels that are jettisoned to retrograde. Also, once inside the ISS, the EVA gloves are bagged to mitigate any potential risk from FORP.

Based on the results of the NASA CY 2003 and CY 2004 WSTF tests, subsequent analyses, and the NASA JSC Toxicology Group assessment of the risk, it was determined that the constraints could be reduced and the time to remain outside the 1-m KOZ could be reduced to 1 h. The procedures for inspecting the EVA suits and clean-up procedures were retained. The reduction in KOZ time is a significant time savings for EVA planning.

VIII. Conclusions

Prior to an EVA on the Russian segment, the DC1 must be depressurized, because it is used as an airlock. When the DC1 is depressurized, the CMGs' margin of momentum is insufficient to compensate for the disturbance and the service module attitude control thrusters need to fire to desaturate the CMGs. The thruster firings result in FORP contamination of the adjacent SM surfaces.

The FORP contamination of the SM surfaces, the release of NDMA in a humid environment from crew EVA suits if they happen to be contaminated with FORP, and the toxicological risk associated with the NDMA release were calculated. It was determined that the FORP and NDMA evaporate rapidly and that their concentration drops off rapidly with distance from the thrusters. The FORP remaining after 1 h for the nadir (cold side) case was found to be 36% of the initial mass. For the zenith (hot side) case the FORP remaining after 1 h was 22% of the initial mass.

The NASA JSC Toxicology Group found that the highest calculated cancer risk from the projected NDMA concentrations is less than 8.46×10^{-5} (-40°C, distance 0.08 m from the thrusters). The NASA JSC Toxicology Group, with the concurrence of the National Research Council Spacecraft Maximum Allowable Concentrations (SMAC) Subcommittee, accepts a cancer risk of 1/10,000 (i.e., 10^{-4}) in deriving SMACs on carcinogenic compounds, such as benzene.

Based on the results of the NASA CY 2003 and CY 2004 WSTF tests, subsequent analyses, and the NASA JSC Toxicology Group assessment of the risk, the time to remain outside the 1-m Keep-Out Zone (KOZ) could be reduced to 1 h. This is a significant savings for EVA planning.

Acknowledgments

The authors gratefully acknowledge the ISS Program office for supporting this study and the NASA White Sands Test Facility (WSTF) and its personnel for conducting the study.

References

[1]Naumov, S. F., Gerasimov, Y. I., Sokolova, S. P., Rebrov, S. G., Gerasimova, T. I., Kalistratova, O. V., Prokofyev, M. A., Grigorevsky, A. V., Prosvirikov, V. M., Buryak, A. K., and Chernik, V. N., "Influence Orientation Thrusters Fuel/Oxidizer Reaction Products on Thermo-Optic Properties of Spacecraft Thermal Control Coatings," *9th International Symposium on Materials in a Space Environment*, European Space Research and Technology Centre, Noordwijk, The Netherlands, 2003, pp. 661–666.

[2]Dee, L. A., Davidson, V. D., and Baker, D. L., "Laboratory Preparation and Characterization of UDMH/NO_2 Reaction Products," Protocol External Contamination Technical Interchange Meeting Fuel/Oxidizer Reaction Products (FORP) Plume Induced Contamination, NASA Johnson Space Center, 2002, Appendix E, pp. 1–22.

[3]Buchanan, V. D., and Dee, L. A., "Evaporation Rate Study and NDMA Formation from UDMH/NO_2 Reaction Product," White Sands Test Facility, Investigative Rept. WSTF-IR-0188-001-03, White Sands, NM, Aug. 2003.

J. Kleiman
Guest Editor