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APPLYING CONTAMINATION MODELING TO SPACECRAFT PROPULSION SYSTEM DESIGNS AND OPERATIONS

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Abstract

Molecular and particulate contaminants generated from the operations of a propulsion system may impinge on spacecraft critical surfaces. Plume depositions or clouds may hinder the spacecraft and instruments from performing normal operations.

Firing thrusters will generate both molecular and particulate contaminants. How to minimize the contamination impact from the plume becomes very critical for a successful mission. The resulting effect from either molecular or particulate contamination of the thruster firing is very distinct. This paper will discuss the interconnection between the functions of spacecraft contamination modeling and propulsion system implementation. The paper will address an innovative contamination engineering approach implemented from the spacecraft concept design, manufacturing, integration and test (I&T), launch, to on-orbit operations. This paper will also summarize the implementation on several successful missions. Despite other contamination sources, only molecular contamination will be considered here.

Introduction

One potential source of concern facing the instruments of orbiting spacecraft is the effect of molecular contaminant interaction with sensitive thermal control and optics surfaces. Typically, the sources of these on-orbit contaminants can be categorized into five general areas; 1) Material outgassing (water, hydrocarbons, silicones) from materials of construction; 2) Spacecraft and Multiple-Layer Insulation (MLI) venting; 3) Fluid leakage from pressurized vessels (e.g. cryogen tanks), dumps, and lubricant loss; 4) Exhaust material generated through thruster firings; and 5) Extravehicular activity. [1] Once released, contaminants can propagate to the receiving surfaces through direct line-of-sight transport (direct flux), reflections with spacecraft surfaces, and scattering through self-scattering or with the local ambient atmosphere (return flux). The efficiency of these transport mechanisms is a complicated function of spacecraft geometry, mission/flight operations, and environmental effects.

In the past, the purpose of computer modeling was concentrated in the assessment of contamination damage during the late design phase, I&T, and on-orbit operation. The impact of modeling on the mission was limited to minor

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design changes (such as vent locations), verification (for meeting contamination requirements), and on-orbit operation (such as operational constraints imposed to avoid contamination).

Due to increased sensitivity of spacecraft components to contamination effects, contamination engineering has begun to play a more notable role in overall spacecraft development. By influencing the early design, cost savings will be very significant since many inefficient contamination avoidance remedies established late in the design cycle can be eliminated. This represents the most effective direction of future contamination modeling efforts. Therefore, at an early mission phase, it is crucial to apply modeling techniques to achieve a better spacecraft propulsion system. A better design provides more favorable environments for spacecraft operations without sacrificing propulsion capability. Modeling also generates useful information for contamination engineers to assess the impact resulting from plume effluents. This information aids contamination engineers in designing protective methods to mitigate plume influences. In addition, parametric modeling allows propulsion engineers to optimize propulsion system designs and operations.

Resolutions resulting from a contamination engineering study may include the following options: 1) Propellants can be selected to minimize contaminant generation; 2) Thruster locations can be optimized to avoid direct impingement on surfaces; 3) Modes of thruster firings can be arranged to curtail excess contaminants; 4) Sensitive surfaces can be placed facing away from the backflow region; 5) Protective plume shields or deployable doors can be installed to reduce plume hazards during the thruster firing; and 6) Affected surfaces can be prepared to be less contamination sensitive. An effective contamination engineering approach is to apply one option or combination of options for sensible spacecraft propulsion system designs and operations.

In recent years, improved contamination modeling techniques have been used extensively by contamination sensitive projects to improve spacecraft and instrument design during the early stages. One good example is the detailed modeling effort for the Tropical Rainfall Measuring Mission (TRMM). Modeling efforts for this mission resulted in several design changes especially in the propulsion system. How contamination modeling aided TRMM propulsion system designs and operations will be discussed in later sections.

Contamination Concerns of Thrusters

Most, if not all, spacecraft employ some kind of attitude control system (ACS) for achieving proper pointing direction and a reaction control system (RCS) for altitude maintenance. Many times thrusters are employed for these purposes. The basic function of any thruster is to expel gas for generating momentum through the production of thrust. Thrusters come in many sizes and types, too numerous to discuss here. However, for purposes of molecular transport modeling, they can often be considered to fall in one of two categories: chemical and cold gases. Although varieties of electric propulsion are increasingly being considered to fulfill this task, their use will not be discussed here.

Chemical Thrusters

The chemical thruster relies on a chemical reaction to generate the gas discharge. The propellant source can either be solid or liquid. The most common liquid propellant in use today is hydrazine. It is employed either on its own (monopropellant, N_2H_4) or with a liquid oxidizer (bipropellant as MMH or UDMH).

Monopropellant hydrazine systems are most commonly used for unmanned satellites. Monopropellant hydrazine, when exposed to a catalyst contained within the thruster, produces high temperature gases by disassociation into hydrogen, nitrogen, and ammonia. Usually, the purity of N_2H_4 is classified according to MIL-P-26536.[2] For instance, "monopropellant grade" hydrazine allows certain trace levels of impurities such as water ($[H_2O] = 1\%$ by weight) and aniline ($[C_6H_7N] = 0.5\%$ by weight). The system can be made cleaner through the choice of a higher purity fuel (i.e. "high purity hydrazine grade").

In addition, catalyzation is often not complete, leaving about $[N_2H_4] = 1\%$ by weight in the exhaust, along with a certain amount of undecomposed ammonia ($[NH_3] = 20\text{-}35\%$ by weight). Depending on the spacecraft application, any or all of these species may be considered contaminants. Generally, monopropellant systems are cleaner than bipropellant systems.

Bipropellant hydrazine systems are used in the Shuttle Orbiter as its primary on-orbit maneuvering system. Bipropellant hydrazine systems use an oxidizer, which allows increased thrust during the combustion process. While advantageous in performance, bipropellant thrusters generally produce more condensable contaminants than the cleaner "burning" monopropellant systems. The main bipropellant thruster contaminant is MMH-nitrate.

Cold Gas Thrusters

The cold gas system consists simply of a storage bottle of inert gas, usually nitrogen or argon. The gas is expanded through a nozzle to provide propulsion. No chemical reaction is employed. Because of the lower thrust potential of these systems, they tend to be used only for attitude correction. Unless a spacecraft employs extremely cold critical surfaces, condensation of these gases is not a direct problem due to the relatively high gas vapor pressure. However, large quantities of gas released into the local environment of the spacecraft can produce temporary increases in local density. The increased local density can enhance molecular scattering effects from other non-thruster sources as well as obstruct instrument observation.

Molecular Contamination Modeling Tools

A complete modeling effort is an iterative process consisting of model setup, data acquisition, model execution, result analysis, and contamination assessment. The mathematics required for modeling the transport of molecular contaminants can be extremely tedious, especially for complicated spacecraft geometries and complex environments. A typical modeling case can require about a dozen inputs as shown in Table 1. Basically these inputs describe detailed geometry of the model, molecular kinetics, operational conditions, and environments.

Several software tools exist to "automate" the analysis of molecular transport environments. A list of these programs with their capabilities and restriction is shown in Table 2. These programs are available through the Public Domain as the result of development efforts under contract with National Aeronautics and Space Administration (NASA). Program selection for actual modeling depends on the nature of the contamination problem to be solved.

The Shuttle/Payload Contamination Evaluation Program (SPACE II) [3] was created by Martin Marietta Aerospace under contract with NASA's Johnson Space Center (JSC). The package was primarily developed for use as a contamination modeling tool for Space Shuttle projects, but is generic enough that it can be applied to any spacecraft project.

Molecular Flux (MOLFLUX) [4] was developed by Lockheed using the SPACE II code as a basis to predict molecular flow conditions. MOLFLUX was designed to serve as a contamination modeling tool for Space Station projects. The advantages of SPACE II and MOLFLUX are short run times and easy to use.

Table 1 Molecular Contamination Modeling Inputs

INPUTS	SOURCE
Viewfactors	Geometric Model (TRASYS or VIEW)
Critical Surfaces	Engineering Assessment
Emission Rates	Experimentation or Database
Reemission Rates	Experimentation or Database
Species & Characteristics	Experimentation & Calculation
Temperatures	Thermal Engineers
Source Distribution Functions	Calculation, or in case of thrusters, provided
Atmospheric Parameters	Atmospheric Models (e.g. MSIS) & Calculation
Collisional Mechanics	Calculation
Orbital Characteristics	Mission Specified
Attitude Parameters	Mission Specified

Table 2 Molecular Contamination Modeling Tools

Tools	Capabilities	Restrictions
SPACE II	• Models direct and return flux transport. • Considers outgassing surfaces and plume expansions by vents, leaks, and thrusters. • Permits multiple contaminant sources. • Accounts for multiple reflection. • Short run times. • Small memory requirements. • Internal database of material properties. • User friendly - Command Language Format.	• 300 node (or surface) geometry limit (Has been modified to 1000 nodes). • Steady-state predictions only. • No accounting for the reemission of deposited mass (i.e. deposited mass is permanently affixed). • Single Ambient-Contaminant and Contaminant- Contaminant collisions. • Unattenuated environment. • Ambient is considered a single molecular species.
MOLFLUX	• Similar to SPACE II	• Similar to SPACE II
CAP	• Models transient contaminant transport. • Accounts for reemission. • Considers outgassing surfaces and plume expansions by vents, leaks, and thrusters. • Permits multiple contaminant sources. • Small memory requirements. • Readily accessible code allows tailoring to specific spacecraft application.	• Direct flux predictions only. • Requires quantitative values for emission and reemission rate constants and the amount of volatile material in the system. This may require additional outgassing rate measurements. • Long run times are typical.
ISEM	• Models direct and return flux transport. • Considers an attenuated contaminant density field. • Accounts for surface reemissions. • Multi-molecular collisions. • Considers multiple ambient species. • Accounts for the shadowing effects caused by physical obstructions. • Considers surfaces, vents, thrusters, and through diffuse leakage.	• Steady-state predictions only. • Long run-times are common. • Large memory requirements. • No user interface – code is essentially augmented with user-written subroutines and recompiled for each case. • Model size limited only by system memory.
DSMC	• Most accurate way to model transport since it simulates gas flow almost at the molecular level. • Provides transient predictions of contaminant deposition. • Can account for reemission. • Essentially performs direct and return flux simultaneously.	• Requires many parameters and time consuming to determine. • Generally prohibitive long run times. • Usually iterative requiring specialized knowledge and significant user interaction. • Requires extensive pre & post processing.

The Contamination Analysis Program (CAP) [5] was developed for NASA by the Applied Mechanics Technology Section of the Jet Propulsion Laboratory (JPL) as a more sophisticated analytical tool for generic spacecraft applications. CAP is capable of solving large multinodal contamination problem in the free molecular flow environment. CAP is especially useful to determine molecular transport within instrument enclosures.

The Integrated Spacecraft Environment Model (ISEM) [6] software package was developed by Science and Engineering Associates, Inc. under contract with NASA's Marshall Space Flight Center (MSFC). Although originally designed to model Space Station environments, this program is completely generic and will model any spacecraft application.

Direct Simulation Monte Carlo (DSMC)[7] is a method developed for the general simulation of rarefied gas flows. This is one of the few contamination transport programs not specifically developed for modeling the contaminant transport of spacecraft environments. The method is a departure from the 'continuum' type techniques of the models previously discussed, where the flowfield is determined by its macroscopic (or overt) behavior. DSMC, on the other hand, is more accurately described as a 'particle' (or microscopic) simulator. In this technique, the macroscopic flowfield is developed on the interactions of millions of individual simulated particles that behave as molecules do. This difference often makes DSMC technique more capable than macroscopic models. Although at present DSMC computational requirements have not yet reached the level for routine satellite contamination transport modeling, it shows significant prospects for the future of contamination transport modeling.

Similar molecular modeling tools, such as MTK and EWB, have been widely used with success in the aerospace industry. In addition, plume contamination transport models using macroscopic techniques have been derived from the work of Simons, Boynton, & Chirivella in a form similar to that used in CONTAM. [8]

All of these modeling tools have been extensively applied in current spacecraft design. Most of contamination modeling has been performed to either verify or justify current designs. However, model verification using either ground test or on-orbit flight data has been lacking. In order to improve the accuracy of the modeling, a validation program consisting of ground laboratory experiments, in concert with a flight monitor validation project should be pursued.

Case Studies

TRMM

The TRMM spacecraft, a dedicated mission to measure tropical rainfall, was launched from Tanegashima Space Center on November 27, 1997. Five instruments onboard the spacecraft included the Visible/Infrared Scanner (VIRS), TRMM Microwave Imager (TMI), Precipitation Radar (PR), Clouds and Earth's Radiant Energy System (CERES), and Lightning Imaging Sensor (LIS). In order to achieve their scientific objectives, the instrument exterior cleanliness criterion was established at Level A requirement prescribed in MIL-STD-1246. [9] Per this requirement, contamination levels on the exterior surfaces of instruments were not permitted to exceed 100Å at any time during the mission. This requirement formed the total external contamination budget for the instruments since it represented the mission limit for all condensable contaminants from all sources (vents, thrusters, outgassing, etc.).

TRMM's low altitude (350 km) and three-year operational period made the situation particularly troublesome since they exposed the spacecraft and its components to an environment that is very accommodating for molecular transport mechanisms. This high density climate has two consequences that effect the level of contamination experienced by the spacecraft. First, a dense ambient atmosphere induces drag forces on the spacecraft which must be counterbalanced by an increased number of maneuvers performed by the spacecraft to maintain a stable orbit. Second, a dense atmospheric environment is conducive to the prevailing transport phenomenon governing contamination of the spacecraft, return flux. These two outcomes served to transform the normally benign decomposition products of the spacecraft's twelve 5-pound monopropellant-grade hydrazine thrusters into a source of potential concern. In response to this potential contamination concern, a task was initiated to investigate the on-orbit contamination environment created by TRMM and assess the impact of this environment on various contamination sensitive components of the spacecraft. [10]

ISEM was used to simulate the mass transport environment induced around TRMM during thruster operations. ISEM was chosen because of its capability to track individual molecular species, its consideration of multiple ambient-contaminant collisions and species dependent scattering mechanisms, and its proper accounting of surface and ram shadowing effects on molecular transport mechanisms.

Plume distribution functions formed one of the critical inputs to this study. These equations can be determined either through experimental or predictive methods. Usually plume characterization is extremely difficult to do from experimentation so in most situations purely analytical methods must be employed. The plume distribution profile for this study was derived from a simple Simons-type free-flow model and assumed 77% ammonia dissociation. The profile was found to be consistent with the profiles of 5-lb thrusters used on other projects (Galileo and Altair).

The thruster analysis examined the role of thruster effluent on 27 contamination critical surfaces. Working in conjunction with the propulsion engineers, a thruster arrangement was found that minimized contaminant effects. Two recommendations provided below were found to significantly reduce instrument contamination levels:

(a) Changing from Monopropellant Grade to High Purity Grade monopropellant hydrazine, as specified in MIL-P-26536, will decrease the aniline component of the plume exhaust by a factor of 100. This reduction should result in a comparable 100-fold reduction in the deposition incurred by the instruments (approximately).

(b) Commanding the CERES sensor head to adopt a more favorable viewing orientation during all drag make-up maneuvers will reduce the amount of condensable material entering its apertures from 64 Å to less than 4 Å.

After nearly two years on-orbit, the TRMM spacecraft and its instrument complement continue to function nominally. No degradation of any optical component or thermal control surface has been reported.

Other Examples

Many recent NASA Goddard Space Flight Center (GSFC) space and earth programs have had particular concerns about thruster operations. The scenarios have shown considerable variety. These following examples consider thruster-related issues in 1999.

GOES N-Q

An article survey and analytical effort was conducted to estimate the effect of stationkeeping operations on the Solar X-Ray Imager (SXI) instrument. In the current design, four 10 N bipropellant (MMH/N_2O_4) thrusters are oriented perpendicular to SXI, and there were concerns about monomethylhydrazinium nitrate ($MMH\text{-}HNO_3$) deposits accumulating across the SXI aperture. Analytical results indicated only low levels of thruster contaminant deposition should be expected. The plume model was partially validated through comparisons with ground-based experiments. [11,12]

GRACE

The impact of separation maneuvers on payload deposition was analyzed to define restrictive zones for thruster firing. During this period, the Breeze upper stage vehicle will fire 1.3 kgf and 40 kgf $UDMH/N_2O_4$ thrusters at the GRACE satellites. [13] Project personnel were interested in deposition on instrument apertures and solar arrays. Model results were found to scale closely with ground-based experimental data. [14]

Triana

Project personnel analyzed the contamination potential of aniline and ammonia from N_2H_4 thrusters on instrument apertures. [15] Thruster heat fluxes on a variety of instrument boom configurations were also rapidly modeled to determine an acceptable design. [16]

Deep Space 4

Project personnel were interested in understanding impact of sustained ion engine operations on contamination of the Champollion sample-gathering instrument for a comet lander mission.

Earth Orbiter-1

This spacecraft features an experimental pulsed plasma thruster (PPT) that uses Teflon® for fuel. NASA Glenn Research Center (GRC) vacuum chamber testing demonstrated no noticeable buildup of Teflon® related deposits or fluorine-induced damage on spacecraft mockup containing characteristic optical or thermal control surfaces. [17]

Another activity associated with this involvement has been to begin validation of a kinetic-based description for rocket plumes by comparison with ground tests and flight data with promising results. [11,12,18] The early success of this model with bipropellant thrusters appears to stem from a few physical observations. First, little thermal scattering occurs within the plume core relative to its expansion into high vacuum. Second is due to the natural inclusion of species separation effects expected within the plume expansion for this description. Third, it appears that surface-mediated chemical reactions may explain the presence of certain deposition products. The significance of this process is the assumption that the plume transports reactants to surfaces rather than deposition products. Continuation of this validation effort is currently underway.

Conclusions

Currently there are numerous computational modeling tools available for contamination modeling purposes. Each modeling tool has its own distinct capabilities and restrictions. Contamination engineers usually select a specific modeling tool based upon the problems to be solved. These modeling tools allow contamination engineers to predict contaminant deposition on critical surfaces from various sources, including thrusters. Spacecraft contamination modeling has sufficient fidelity to provide inputs to propulsion system implementation through many mission phases. However, it is most cost effective to implement any design changes at the early mission phase.

Through the modeling effort, an effective contamination engineering approach can protect sensitive thermal control and optics surfaces from thruster operations. As a result, spacecraft operations have been improved without sacrificing propulsion capability. In particular, contamination modeling work has generated useful information for propulsion system designs such as the TRMM spacecraft. After nearly two years on-orbit, TRMM flight data indicate that the spacecraft and its instrument complement continue to function nominally. There is no contamination induced degradation of any optical component or thermal control surface. Contamination modeling has also been successfully applied in answering many other propulsion related contamination problems.

In contamination modeling development, model verification has always been a weak point. The verification process should include the review of existing models and verification data. Then, ground testing, and more importantly, flight monitors should be developed specifically to validate models. The aerospace community should go forward with monitor development and flight, and post-flight data evaluation/comparison.

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