

EVALUATION OF CONTAMINATION INSPECTION AND ANALYSIS METHODS THROUGH MODELING SYSTEM PERFORMANCE

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ABSTRACT

Contamination is usually identified as a risk on the risk register for sensitive space systems hardware. Despite detailed, time-consuming, and costly contamination control efforts during assembly, integration, and test of space systems, contaminants are still found during visual inspections of hardware. Improved methods are needed to gather information during systems integration to catch potential contamination issues earlier and manage contamination risks better. This research explores evaluation of contamination inspection and analysis methods to determine optical system sensitivity to minimum detectable molecular contamination levels based on IEST-STD-CC1246E non-volatile residue (NVR) cleanliness levels. Potential future degradation of the system is modeled given chosen modules representative of optical elements in an optical system, minimum detectable molecular contamination levels for a chosen inspection and analysis method, and determining the effect of contamination on the system. By modeling system performance based on when molecular contamination is detected during systems integration and at what cleanliness level, the decision maker can perform trades amongst different inspection and analysis methods and determine if a planned method is adequate to meet system requirements and manage contamination risk.

INTRODUCTION

Surface cleanliness requirements for molecular contamination are defined in terms of IEST-STD-CC1246E non-volatile residue (NVR) levels (ref. 1). Requirements are verified throughout the assembly, integration and test (AI&T) process through methods such as ASTM E1235 to gravimetrically determine NVR from spacecraft surfaces or witness surfaces (ref. 2). This gravimetric determination is usually followed with other analysis techniques such as Fourier transform infrared spectroscopy (FTIR) and/or gas chromatography–mass spectrometry (GC-MS). However, NVR analysis through solvent rinsing of surfaces can be time consuming and take several hours to days before results are reported. Throughout spacecraft AI&T and prior to rinsing or sampling surfaces with a solvent for NVR analysis, surfaces are visually inspected to IEST-STD-CC1246E viewing conditions and are considered “visually clean” if no particles or molecular films are present. Currently, no correlation exists between IEST NVR levels and visual inspections to determine a limit of detection. By the time an NVR molecular film has built up to a visual level, it may already be at a film thickness that could negatively impact the performance of the system. If a film is visually detected, a decision must be made: Should the

surface be cleaned, or should the part be reworked or replaced? This decision making process becomes more complex as the AI&T process matures into higher assemblies where the risk of cleaning and damaging a sensitive surface becomes much greater.

To catch problems earlier, different inspection and analysis methods may be employed throughout AI&T. Before a new method can be employed, the limit of detection should be quantified for both the newly proposed method and the existing method. To accomplish this, a systems modeling tool was created to allow for the evaluation of different inspection and analysis methods in terms of system performance to determine how much time savings (response time) and knowledge can be gained to assist the decision maker. The model allows for the comparison of one method to another, determines how soon a molecular contaminant film of a certain type on a given substrate can be detected, and how the presence of the film impacts the performance of the defined system. The modeling tool considers popular spacecraft surfaces that are sensitive to contamination: reflective surfaces, transmissive surfaces, and thermal control surfaces. Based on model results, the decision maker can determine if a particular inspection and analysis method will be adequate and how soon problems can be detected to allow for course-correction early in the AI&T process.

MODEL OVERVIEW

An overview of the system performance model is provided in the flowchart in Figure 1.

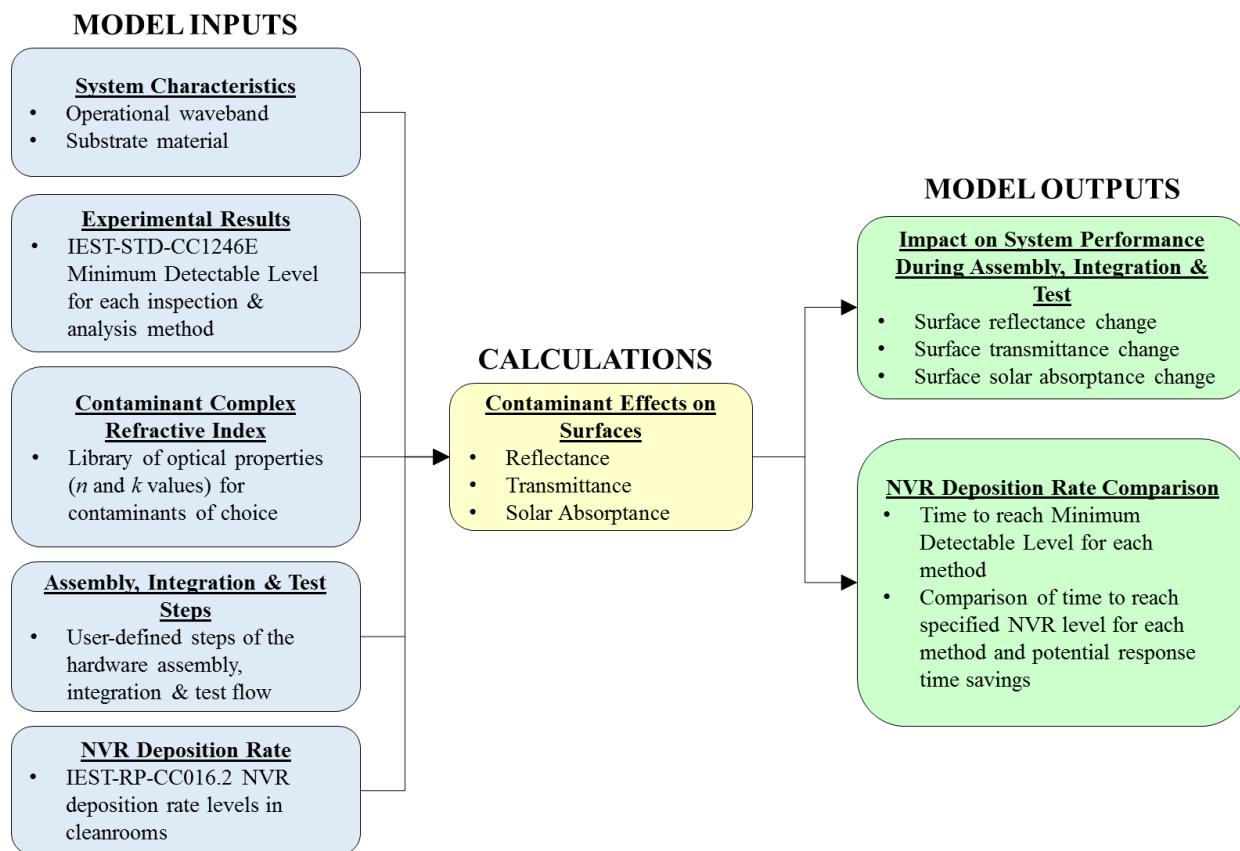


Figure 1: System Performance Model Flowchart

Model Inputs

First, the user defines the system's operational optical waveband or wavelength of interest and substrate material(s) upon which the contamination will be deposited. For example, the operational waveband for a longwave infrared (LWIR) sensor may be 8 - 12 microns. Substrate materials for contaminant deposition may include silicon wafers for environmental monitoring witness plates, optical glass for telescope windows or lenses, or gold for a reflective gold mirror. Second, experimental results for the minimum detectable NVR level as defined by IEST-STD-CC1246E (ref. 1) is input for each inspection and analysis method. In this experiment, NVR concentration levels for contaminants of interest are mixed per the IEST standard, and a fixed volume droplet is deposited on reflective and transmissive surfaces through a micropipette. Based on the droplet diameter and the concentration, the contaminant film thickness can be calculated, and the minimum detectable level is determined for the inspection method and input into the model. Third, a library of tables for the optical properties of the contaminant film (complex refractive index n and k values) for the contaminants of choice are input into the model. These optical constants may be obtained experimentally or from literature. Next, the user defines the steps of the hardware assembly, integration and test flow for the system of interest. This may be a subassembly such as an optical telescope, or an entire system such as a satellite. Finally, the NVR deposition rate values of interest from cleanroom environments per IEST-RP-CC016.2 (ref. 3) are input into the model.

Calculations

The presence of molecular contaminant films on surfaces can cause changes in reflectance, transmittance, and solar absorptance. Based on the user inputs in the previous section, the model calculates each of these effects using Equations 1 - 4 from Tribble (ref. 4).

Surface reflectance as a function of contaminant thickness is given by:

$$\rho^x(\lambda) = \rho(\lambda) \exp[-2\alpha_c(\lambda)x] \quad (1)$$

$$\alpha_c(\lambda) = \frac{4\pi k}{\lambda} \quad (2)$$

where:

$\rho(\lambda)$ is the substrate surface reflectance (no contaminant film present)

$\alpha_c(\lambda)$ is the absorption coefficient of the contaminant film

λ is the system operational wavelength

k is the extinction coefficient of the contaminant film

x is contaminant film thickness

Surface transmittance as a function of contaminant thickness is given by:

$$\tau^x(\lambda) = \tau(\lambda) \exp[-\alpha_c(\lambda)x] \quad (3)$$

where:

$\tau(\lambda)$ is the substrate surface transmittance (no contaminant film present)

$\alpha_c(\lambda)$, λ , and x are as above in Equations 1 and 2

Solar absorptance due to a contaminant film on a surface is given by:

$$\alpha_s^x = \frac{\int \{1 - \rho(\lambda) \exp[-2\alpha_c(\lambda)x]\} S(\lambda) d\lambda}{\int S(\lambda) d\lambda} \quad (4)$$

where:

α_s^x is the solar absorptance of the surface through a contaminant film

$S(\lambda)$ is the solar flux as a function of wavelength

$\alpha_c(\lambda)$, $\rho(\lambda)$, λ , and x are as above in Equations 1 and 2

Note that a factor of 2 in Equations 1 and 4 account for incoming energy passing through the contaminant film twice; before and after reflection at the surface.

Model Outputs

The impact on system performance during the assembly, integration and test cycle is determined for a given surface and contaminant film. The change in surface reflectance is calculated for surfaces such as mirrors, witness plates, or multilayer insulation. Changes in surface transmittance is calculated for optical surfaces such as windows and lenses, or the glass coverslide of a solar cell. Finally, changes in solar absorptance is calculated for radiator surfaces. Through these outputs, the user can not only determine the relative impact of each contaminant on the system, but also the relative impact of one inspection and analysis technique as compared to another because results are based on the minimum detectable level for each method and each contaminant type.

To determine the impact on response time between inspection and analysis techniques, the model provides a comparison of NVR deposition rates based on IEST-RP-CC016.2 levels. For example, consider the scenario of a witness plate exposed to a cleanroom environment. If a silicone is detected through a method such as portable Raman spectroscopy, the NVR class can be determined from the witness plate exposure time and the experimental results of the minimum detectable level for silicone on a silicon wafer witness plate. The user can then calculate the amount of time it would take to detect the same silicone through a different inspection technique, such as visual inspection. By comparing the detection times for a given NVR deposition rate between portable Raman spectroscopy and visual inspection, the user can determine the response time and amount of time saved using one technique over the other.

Currently, the system performance model does not account for mixtures of multiple contaminants or layers of multiple contaminants deposited on top of each other on a substrate. Future iterations of the model may be able to take these combinatory effects of contaminants into account. The model is a trade study tool that provides an evaluation of individual contamination effects on a system and the minimum detection level of inspection and analysis techniques. The intent is to determine how different contaminants identified at different points in the assembly, integration and test flow can impact system performance, and assist the user in mitigating the effects of contamination on the system.

EXAMPLE MODEL USE AND OUTPUT

Consider the AI&T process flow for an optical sensor instrument integrated onto a satellite as shown in Figure 2. The process begins with piece part optics and support structures received at the component level which are then integrated into a telescope assembly. The telescope proceeds through testing and is integrated into the instrument. The instrument goes through functional testing, environmental testing, and calibration before assembly, integration and testing at the satellite level prior to launch.

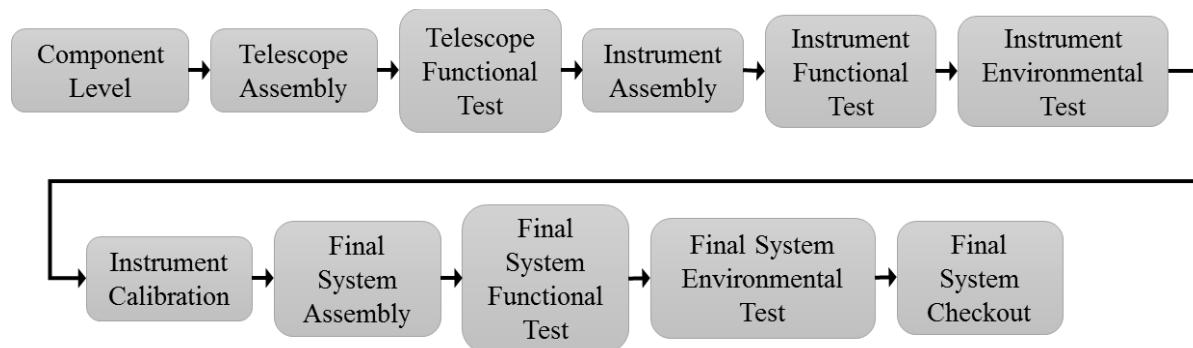


Figure 2: Example Satellite Optical Sensor Instrument AI&T Flow

Surface Reflectance and Transmittance Changes

The optical system built in Figure 2 may contain both reflective and transmissive optics and operate in the LWIR at 8 microns. A decision maker may be considering two methods for monitoring molecular film contamination buildup throughout the AI&T process: Method A and Method B. For comparison, let us consider a silicone film building up on the reflective and transmissive optics. Let us say from experimentation the minimum level of detection for silicone for Method A is Level A (1 mg/0.1 L) and Method B is Level A/5 (200 μ g/0.1 L) per IEST-STD-CC124E for both reflective and transmissive optics. Consider the silicone as a single droplet of diameter 0.1 cm and volume 0.05 ml on the optical surface. Assuming the density of a representative silicone as 1.0 g/cm³, the resulting minimum detectable film thickness for Method A is 0.637 microns and for Method B is 0.127 microns. Folding these values into Equations 1 – 3 results in the values in Table 1.

A decision maker building up a system sensitive to silicone contamination will want to know as soon as possible if silicone films are present. The results in Table 1 let the decision maker know how sensitive their system is to silicone contamination, and the earliest detection level for each method. Method B allows the decision maker to detect silicone contamination earlier and the results of the model allow them to determine the potential hit to performance. If Method A is solely relied upon, the resulting impact to performance by the time the silicone NVR has built up to IEST-STD-CC1246E Level A may be too much for the system to withstand. Additionally, if the silicone has not built up to this minimum detection level until later in the AI&T flow, such as at final system assembly, the ability to clean and remove the contamination may not be possible. Method B alerts the decision maker earlier that an issue has occurred and allows for mitigation activities to be employed.

Table 1: Example Comparison of Reflectance and Transmittance Changes due to Silicone Contamination for Different Inspection Methods

| Inspection Method | Reflectance Change | Transmittance Change |
|-------------------|--------------------|----------------------|
| Method A | 21.3% | 11.3% |
| Method B | 4.67% | 2.36% |

NVR Deposition Rate Comparison

NVR rate deposition levels for cleanroom environments are defined by IEST-RP-CC016.2, “The Rate of Deposition for Nonvolatile Residue in Cleanrooms.” Assuming the source of silicone is from the AI&T cleanroom environment, a comparison can be made for the amount of time it takes the silicone NVR to build up to the minimum detectable level for each inspection method. Two NVR Rate Levels per IEST-RP-CC016.2 were chosen for comparison: Level 5 (middle level) and Level 10 (high level). Results are shown in Table 2 for the Method A and Method B inspection levels. For an NVR Rate Level 5, Method B can detect the silicone film in 14.7 days, while it would take 73.7 days for Method A to detect a silicone. For an NVR Rate Level 10, Method B can detect within 12.7 seconds while Method A would take 63.6 seconds. Depending on the level of control and deposition of silicone NVR in the AI&T cleanroom environment, the decision maker can determine if it is worth employing a new inspection method. For a higher NVR rate level, the decision maker may not want to incur additional cost of bringing on a new inspection method to save approximately 51 seconds of response time. However, the decision maker with a mid-level NVR rate level cleanroom, 59 days of response time to detect the presence of a silicone may be significant.

Table 2: Example Comparison of NVR Deposition Rates due to Silicone Contamination for Different Inspection Methods

| IEST-RP-CC016.2 | Method A | Method B |
|--|---------------------------------------|---------------------------------------|
| NVR Rate Level 5 (1×10^{-4} nm/s) | 6.37×10^6 sec (73.7 days) | 1.27×10^6 sec (14.7 days) |
| NVR Rate Level 10 (10 nm/s) | 63.6 sec | 12.7 sec |

FUTURE WORK AND CONCLUSIONS

The above examples provide a generic illustration of the use and output of the system performance model for an optical system comprised of reflective and transmissive optics. Future work will entail experimentally collecting minimum detectable NVR levels for different surfaces and different contaminant types for two inspection methods of interest: visual inspection (current method) and portable Raman spectroscopy (proposed new method). The experimental results will be folded into the system performance model described above for various spaceflight projects currently in the design phase, and will consider instrument optics, radiator surfaces, and environmental monitoring witness plates. The process can be repeated for any new inspection methods that may be considered for future use. In this way, project managers, contamination

control engineers, and decision makers can determine the most effective inspection method to employ for monitoring contamination for the system of interest during AI&T.

REFERENCES

1. Product Cleanliness Levels – Applications, Requirements, and Determination. IEST-STD-CC1246E, Institute of Environmental Sciences and Technology, February 2013.
2. Standard Test Method for Gravimetric Determination of Nonvolatile Residue (NVR) in Environmentally Controlled Areas for Spacecraft. ASTM Designation: E1235-12, American Society for Testing and Materials, November 2012.
3. The Rate of Deposition of Nonvolatile Residue in Cleanrooms. IEST-RP-CC016.2, Institute of Environmental Sciences and Technology, Contamination Control Division Recommended Practice 016.2, November 2002.
4. Tribble, A. C., “Fundamentals of Contamination Control,” SPIE Press, Bellingham, Wash., 2000.