Preventing Premature Death in the M&S Lifecycle: Lessons Learned from Resurrection and Modernization of a Space System Contamination Model

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ABSTRACT

Models and simulations (M&S) are often developed to meet specific needs and unique requirements for a particular situation. Once the M&S is implemented for a specific case and questions are answered, the M&S may go dormant until a similar need arises again at a later time, perhaps months to years later. Possible modification of the M&S may be required, and issues may arise if the M&S is not well documented, captured, or available. This can severely limit the useful life of the M&S and hinder future development or enhancements. This situation occurred with an M&S tool that had been developed to determine the impact to space system performance due to the presence of molecular contaminant films accumulating on key spacecraft surfaces. The challenges and issues encountered when resurrecting, executing, and modernizing the tool will be presented as a case study. To stay ahead of tomorrow's challenges, resources to create M&S tools must be utilized efficiently. Lessons learned from this case study will aid M&S developers and users in planning for proper maintenance, transfer, and capture of key M&S tools and knowledge to avoid increased cost, increased development time, and wasted resources for projects relying on M&S.

ABOUT THE AUTHORS

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INTRODUCTION

The reliance on modeling and simulation (M&S) tools is increasing with the challenge to manage projects cost effectively. For example, model-based systems engineering (MBSE) has emerged as a model-focused approach to reduce product rework and replace the traditional document-centric method of requirements development and verification (Kennedy, Sobek, & Kennedy, 2014). Prototypes based on M&S products during the system architecture design phase can significantly reduce risk in the completed system (INCOSE, 2010).

M&S tools are usually developed to meet a specific project need, and as such, are under the pressure of project schedule constraints to meet required milestones and deadlines. This creates two issues: M&S tools that are designed around highly specific applications which may limit future use, and an end to M&S tool development efforts and capability once a specific project has reached completion. As such, very little effort may be spent on planning for the future capture, maintenance, transfer, and possible expansion of M&S tools. This can result in M&S tools being completely lost over time, resulting in a loss of knowledge and capability. A selling point used when new projects are bid is the utilization and build off of legacy and existing M&S tools to save development cost. However, when M&S tools are lost, additional cost is required for developers to re-learn or recreate previous tools, resulting in a step backwards before forward progress can be made. Customers desire forward progress, rather than spending valuable funding and resources for suppliers of M&S products to re-learn the past.

The above scenario occurred with an M&S tool that had been developed many years ago to model the impact of molecular contaminant film accumulation on space system surfaces and the resulting impact to mission performance. The tool was dangerously close to being lost over time, and the following case study reveals the challenges encountered and process required to resurrect and modernize the tool. Lessons learned are presented to aid M&S developers in understanding the importance of planning for tools later in the project lifecycle so that M&S knowledge and capability is not lost for future opportunities.

THE CASE STUDY

For decades the spacecraft community has battled the issue of molecular contamination as an on-orbit degradation effect. Sources of molecular contamination include assembly process residues (e.g. oils, lubricants, etc.), cleaning agents and residues, fingerprints and other handling residues, and materials outgassing. Materials outgassing occurs under vacuum or elevated temperature when volatile molecules are released from an organic material. These released molecules are then free to re-distribute and condense onto sensitive spacecraft surfaces such as optics, solar panels, and thermal control surfaces such as blankets and radiators. These molecules can build up into layers, forming a molecular contaminant film. An example of a molecular contaminant film outgassed from spacecraft materials and condensed on a cryogenically cooled scavenger plate in a thermal vacuum test chamber is shown in Figure 1.

Figure 1. Condensed Molecular Contaminant Film (NASA/Elaine Seasly)

Performance degradation of the system may be experienced once a molecular contaminant layer film layer forms on sensitive surfaces. "Molecular contamination is known as one of the most serious problems for satellites, which typically include optical components and solar panels that are sensitive to contamination, which results in degraded performance" (Yokozawa, Baba, Miyazaki, & Kimoto, 2012). Optical surfaces can experience throughput loss from incoming light being absorbed, scattered, or re-emitted at the film interface. The amount of throughput loss for optical components depends on the chemistry of the contaminant film. As stated by Yokozawa et al., "Changes in the optical properties are, of course, related to the thickness of condensed outgas. The spectral absorbance properties, however, vary with the contaminant" (Yokozawa et al., 2012). Thermal control surfaces may experience changes in solar absorptance and/or emissivity which, in turn, impacts the ability to control spacecraft heating and cooling. Solar arrays may experience a reduction in power due to molecular films absorbing light and obscuring the solar array surface, which may reduce the ability to charge on-board batteries.

Contamination control emerged as a discipline to proactively reduce the risk of systems experiencing such performance degradation. Contamination control involves deriving system requirements, selecting materials, system design considerations, integration and test methodologies, and system performance verification to control contamination to acceptable levels for a system. "Effective contamination control is essential for the success of most aerospace programs because the presence of contamination, even in small quantities, can degrade the performance of sensitive spacecraft hardware" (Rampini, Grizzaffi, & Lobascio, 2003). As such, contamination control engineers rely on M&S tools to predict system performance degradation due to the presence of various contaminants so that acceptable requirements can be set for materials selection and system designs. These tools may range from complex computation fluid dynamics (CFD) for molecular transport to simple mass allocation budget spreadsheets for materials outgassing that track hundreds of materials in the supply chain. As stated by Villahermosa, "Contamination control engineers often have to operate in the grey area between rigorous analysis and gross estimation to make decisions that are compatible with budget and schedule" (Villahermosa & Joseph, 2004).

Traditionally, molecular contamination requirements are set based on the maximum allowed concentration of non-volatile residue (NVR) allowed on a surface or in fluids as defined by IEST-STD-CC1246 (IEST, 2013). This requirement is set for the total molecular contaminant film deposited, regardless of the film chemistry as hundreds of materials can outgas and contribute to the condensed film. To account for the most probable chemistry of the film and model the effects, Arnold Engineering Development Center (AEDC) created the modeling program "STACK" (Palmer, Williams, Budde, & Bertrand, 1994). This model replaced the previous modeling program "Calculation of Reflectance and Transmittance," or "CALCRT." CALCRT allowed the user to input the complex refractive index properties (*n* and *k* values) of molecular films to calculate the impact on transmission and reflection of optical components (Wood et al., 2007). STACK expanded on this further all allowed the user to model a "stack" of contaminant films of different chemistry to determine changes in transmission, reflection, and emission properties of the underlying substrate for spacecraft surfaces.

STACK was originally developed in 1994. Since that time, the tool had been transferred throughout organizations and changed hands several times as users utilized the tool for various projects. Recently, Contamination Control Engineers (CCEs) at NASA Langley sought the tool for instrument performance modeling as part of research efforts evaluating new contamination inspection and analysis techniques. The desire was to utilize tools that had already been developed and funded by the government, with the idea this would save overall time and effort. The following sections detail the challenges encountered and efforts required to overcome the challenges to utilize this legacy tool.

Challenges Encountered

Challenge #1: Locating the source code. The search for the contamination modeling M&S tool originally began by searching for the previous tool, CALCRT. In the 2000s, NASA had created the Spacecraft Contamination and Materials Outgassing Effects Knowledgebase (SCMOEK). The SCMOEK was part of the Space Environments Effects (SEE) program, which "collected, developed, and disseminated the SEE-related technologies required to design, manufacture and operate more reliable, cost-effective spacecraft for the government and commercial sectors" (NASA, n.d.-b). In 2007, NASA added CALCRT to the SCMOEK database as part of the SEE program. Originally, the SCMOEK could be accessed online, but security issues and hacking resulted in access being restricted and users having to obtain CDs (and later DVDs) to access the database (Wood et al., 2007). The executable program of CALCRT could be downloaded from these discs.

Eventually the SCMOEK was moved to the secure site Materials And Processes Technical Information System (MAPTIS) (NASA, n.d.-a). However, when the SCMOEK was searched for CALCRT in MAPTIS, no executable program files were found. The executable files may have been lost in the transfer from older DVDs to the online MAPTIS system. Through e-mail communications with the MAPTIS curator, the NASA official responsible for the SEE Program, and a network of NASA CCEs, the original authors were contacted and the executable programs for CALCRT and STACK were located. CALCRT was DOS-based and required accessing a gaming website to obtain a DOS emulator. The CALCRT program was able to run, but source code could not be accessed. STACK, on the other hand, was an improvement over CALCRT with additional functionality allowing more contaminants to be modeled. Both the executable and source files of the STACK program were sent by the original author on a DVD via postal mail. Had the original STACK authors not had these files available, the CALCRT and STACK programs may have fallen into obscurity. With the program finally in hand, the next challenge was encountered in executing the code for the M&S tool.

Challenge #2: Executing the code. STACK was written in the Interactive Data Language (IDL) which is currently supported and licensed for use by Harris Geospatial Solutions. Users of STACK must obtain an IDL license and know how to run an IDL program. This includes creating an IDL workspace, becoming proficient in using IDL commands, and knowing how to compile IDL programs. This put STACK in a realm above the skills of the CCE that required the tool for contamination research, and required the help of a programmer to determine how to resurrect STACK onto an IDL environment, obtain the required licenses, learn the STACK runtime environment, compile and run the code, and determine the output of the code. Approximately six weeks of effort were required to test and run the code before actual contamination analysis trials could begin.

Challenge #3: Limited documentation. Documentation received with the STACK executable files on the DVD was limited to a single page MS Word file. The note contained a date, a brief description of the purpose of the program, and a statement that the instructions for the program appear in the comments at the beginning of the main program "Stack.pro." These instructions were a single paragraph describing the program, the user inputs for substrates, contaminant films, and incoming light properties. The remainder of the documentation was in the form of comments throughout the source code. As part of the six week effort described above, a large portion of time had to be dedicated to determining the form and format of the input file for STACK to run, as no documentation was provided. Additionally, there was no documentation explaining the algorithms used.

Challenge #4: Interfacing with the tool. For STACK, the data is input as a set of virtual punch cards in the form of a WordPerfect file. The data is delineated in columns, and the user is required to find a method of determining the correct column for input data. For optical material data, the input data is in the form of wavenumber, index of refraction, and coefficient of extinction. Most index of refraction data available from published sources is tabulated by wavelength, rather than the units of wavenumber required by STACK. The index of refraction data was converted to wavenumber in MS Excel, transported to MS Word, formatted to the required column format, and output to a WordPerfect file in order to be input into STACK. During this input file data manipulation it was discovered that some of the STACK data fields require the lead integer to be followed by a decimal point with no trailing zero. The user has to perform a "find and replace" to change any data fields to remove trailing decimal places.

STACK output is in the form of plots or raw data files of wavenumber vs. reflectivity. The STACK plot routines provide data as white text on a black background as shown in Figure 2. Plots from subsequent trial runs plot over each other in the STACK output. Data files were imported into MS Excel to plot the analysis results of various film thicknesses against each other as shown in Figure 3. CCEs often need to perform multiple trials such as this to vary contaminant film thickness to determine acceptable contamination requirement levels.

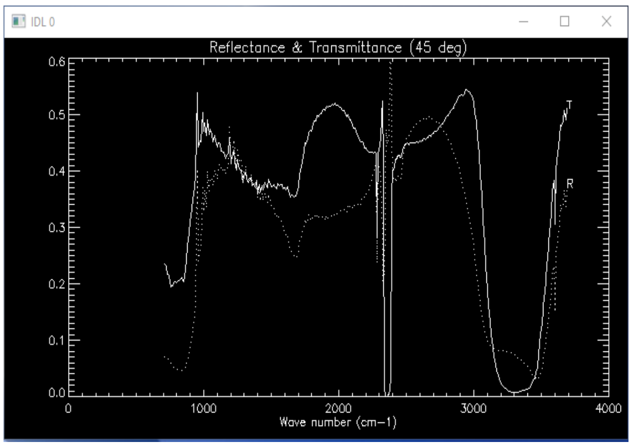

Figure 2. STACK Output for a Water Film over CO2 on a Germanium Substrate at 20K

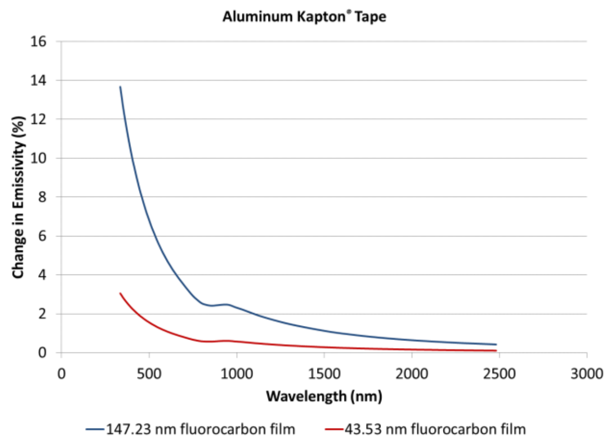

Figure 3. STACK Results for Multiple Film Thicknesses of Fluorocarbon Film on Aluminum Kapton® Tape Substrate

Challenge #5: Verifying results. STACK has the ability to input reflectivity data from either discrete data points or a curve fit. However, there is no documentation that explains to the user any trade-offs in accuracy. No set of "canned" data is provided with known outputs to let the user know if the program is running properly. Without this data, even if the user is successful in getting the model to run, there may be uncertainty as to whether the output is reasonable or realistic. In order to verify the results of STACK prior to detailed analysis runs, the program was verified to be running properly by modeling polished aluminum, a common reflectance material standard. The results of bare polished aluminum reflectivity calculated by STACK were compared to and verified against data from an optical reference standard ("Optical Reference Laboratory Reflectance Standards," n.d.) as shown in Figure 4. A good fit was obtained, which allowed the user to proceed with more complex analysis in STACK.

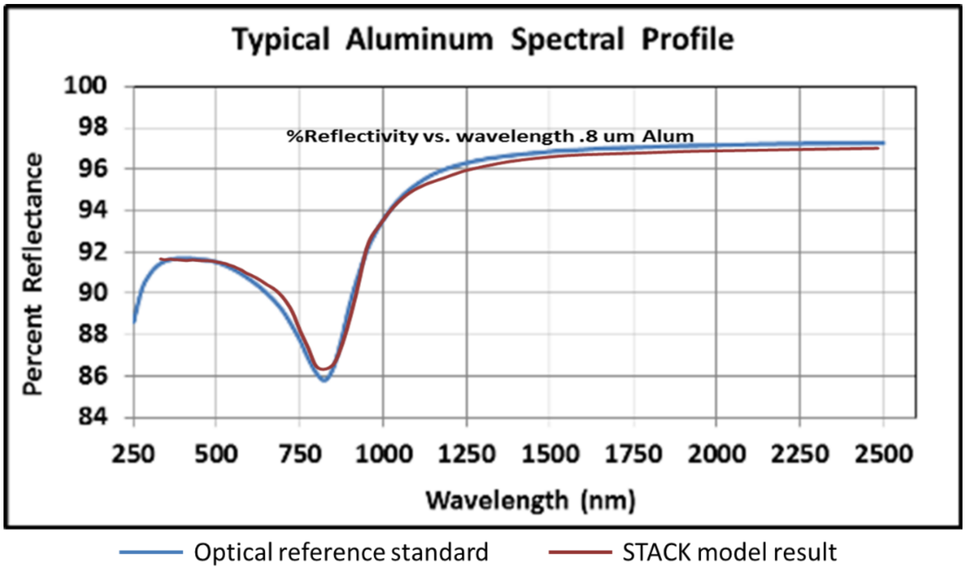

Figure 4. STACK Results for Bare Polished Aluminum Substrate as Compared to an Optical Reference Standard

LESSONS LEARNED

The following lessons learned are provided as a guideline for M&S tool developers to avoid the pitfalls identified in this case study and reduce the risk of M&S tools experiencing a limited life. This list is not exhaustive, rather, it is intended as a reminder and to spark additional thoughts for preserving tool capability.

Lesson #1: When developing an M&S tool, choose a computing environment that is likely to be around for a long time. MS Excel and MATLAB are examples of computing software that are supported and will execute models created on earlier versions with very little effort. MS Excel operates on a Mackintosh as well as a PC, and is often a tool that non-programmer scientists and engineers use for displaying and publishing results. M&S tools can experience increased use and extended utilization if the tool is easy to implement on various systems and can be used by non-experts to perform analysis and confidently make decisions based on the results.

Lesson #2: Develop a flowchart. Potential future users need to understand the sequence of the logic that is being applied. A flowchart is also helpful when debugging code and is indispensable if the code has to be “ported” to another language or operating system. It is important for future users to understand not only the formulas used, but the sequence and reason the calculations are performed. Keep the perspective of potential future users in mind.

Lesson #3: Document the algorithms. After documenting the flowchart and before typing the first line of code, document the algorithms and the exact equations used to implement the flowchart. This will help future users in modifying the code and adding additional capabilities.

Lesson #4: Comment the code. There can never be too many comments. It is insufficient to just comment the date the code was written and the author. Again, keep future users in mind and provide comments that will help from a new user perspective.

Lesson #5: Spend quality time developing the graphical user interface (GUI). A new user that needs to run the M&S tool should be able to do so with ease. A good test is to have someone who is not involved in the code generation to attempt to use the tool by only following written documentation and the prompts in the GUI.

Lesson #6: Provide "canned" examples. Develop a user package with examples that the user can use to verify the code is operating properly. This increases the user's confidence that the tool can be relied upon to provide realistic results.

Lesson #7: Document the work. This is more than just comments in the source code. At the very minimum, documentation should include the above items plus an explanation of what the model was developed to do, any known limitations in the calculations, reference sources for input data or equations, the author of the code, and the date the code was written. M&S tools should also document changes with each new version.

FUTURE WORK

After STACK was recently resurrected to perform contamination analysis, plans were made to stabilize the tool an increase the capability so that non-programmers can easily utilize the tool for analysis. The goal of this future work is to modernize STACK for any contamination control engineer to employ in evaluating the possible effects of contamination on critical flight hardware. First, the source code will be analyzed and the aforementioned flowchart will be created, and the code will be commented to capture the underlying calculations. Second, the model will be ported to a more readily available platform that will interface with the tools CCEs use in their contamination analysis and requirements development processes. Third, a GUI will be developed to provide standardized input and output of data to and from STACK. A library of common thin film contaminants will be developed as sources of input for the tool, and the GUI will facilitate easy file transfer for CCEs to execute. Finally, a user manual will be developed to help future CCEs in learning and understanding the tool with the goal that more CCEs will adopt and use the tool.

CONCLUSIONS

Confidence in M&S tools is important, especially for users that may not have programming expertise but need to utilize the results from M&S tools in key decision making processes. As such, many users desire to utilize legacy tools with proven results as a starting point for creating new analysis capabilities. Legacy M&S tools can experience increased utilization and extended life if developers keep the perspective of future users in mind when creating and documenting M&S tools. The case study presented in this work is an example of potential knowledge that could have been lost from a legacy M&S tool that almost fell into obscurity. The lessons learned from this work are provided to help M&S developers in avoiding such pitfalls and create tools that enable use, enhancement, and expansion by future users.

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