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Development of the Spacecraft Materials Selector Expert System

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Abstract

A specific knowledge base to evaluate the on-orbit performance of selected materials on spacecraft is being developed under contract to the NASA SEE program. An artificial intelligence software package, the Boeing Expert System Tool (BEST), contains an inference engine used to operate knowledge bases constructed to selectively recall and distribute information about materials performance in space applications. This same system is used to make estimates of the environmental exposures expected for a given space flight. The performance capabilities of the Spacecraft Materials Selector (SMS) knowledge base are described in this paper. A case history for a planned flight experiment on ISS is shown as an example of the use of the SMS, and capabilities and limitations of the knowledge base are discussed.

Introduction

Institutions need to retain valuable information even as experienced individuals leave an organization. Modern electronic systems are capable enough to retain large quantities of information that can mitigate the loss of experience. The expert system discussed in this paper is being developed to capture materials performance information for space applications.

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Spacecraft operate under severe conditions and the consequences of hardware and/or system failures, in terms of cost, loss of information, and time required to replace the loss, are extreme. Performance information for long-term space applications is relatively scarce and specific information is often rather narrowly distributed within a single project. These risk factors place a premium on appropriate choice of materials and components for space applications. An expert system is a very cost-effective method for sharing valuable and scarce information about spacecraft performance. Several organizations have developed artificial intelligence systems that support design of spacecraft and assess performance and the effects of environmental exposures[1-4].

Materials performance data from operational satellites and flight experiments has been collected from published results and recent laboratory measurements. This materials data has been used to assemble a knowledge base that combines available data, stores the data and then makes materials and environmental exposure data rapidly available. The data may be used to make an assessment of performance of specific materials or to predict the contribution of up to 27 different factors to the environmental exposure conditions around a spacecraft. The knowledge base in combination with an inference engine, the Boeing Expert System Tool (BEST) forms an expert system used to electronically distribute information. The knowledge base is a backward-chaining rule-based system that is used for storage and rapid retrieval of information from a specific body of information. This system is different than forward-chaining systems that gradually improve predictions as new inputs are provided.

The expert system, BEST plus a specific knowledge base, is a quick screening tool that allows designers to be alerted to significant environmental factors that may influence their design and/or selection of materials. This expert system is also suitable for use by materials engineers checking their spacecraft materials selections.

The Spacecraft Materials Selector (SMS) knowledge base is being developed and coupled to a previously constructed knowledge base, called the Spacecraft Environments Advisor (SEA), under a contract (NAS8-98213) with the NASA Space Environments & Effects program. Specific enhancements have also been made to the initial version of the SEA (developed initially through a Boeing IR&D program) under the current contract and through previously funded efforts.

The SMS knowledge base consists of several individual knowledge bases. The main knowledge base stores all the parameters used in the knowledge base and identifies the task of interest to the user. A materials identifier knowledge base determines the material of interest. A set of materials knowledge bases includes a separate knowledge base for each type of material. An environments knowledge base determines all the environmental contributions significant to the mission that has been defined. The system is still under development. Knowledge bases for certain materials are currently being written.

The overall expert system essentially determines a "mission profile", the launch date, orbital characteristics, and length of the mission and predicts the environments that will be significant to the specified mission. Once the environmental conditions have been established, the knowledge base for the material of interest may be called and the expected performance of the material is discussed. For situations where sufficient environmental exposure data is available, quantitative changes in selected material properties are determined. Mass loss, changes in solar absorptance and thermal emittance, variations in reflectance, appearance (darkening), and mechanical properties may all be evaluated, depending on the mission and the material.

Occasionally, there may be similarities between environmental conditions on previous operational spacecraft or flight experiments and the conditions of current interest. Whenever possible results from previous flight experiments and experiences from previous spacecraft [5-17] are referred to as examples. Data from LDEF, Solar Maximum Recovery Mission, SCATHA, ML-101, experiments on certain GPS, SKYLAB, IMP-I and IMP-H, OSO III, POSA I & II, the Optical Properties Monitor (OPM) experiment on MIR, experiments from several GEO and one LEO spacecraft, and multiple Space Shuttle flights, are used in this expert system.

The BEST inference engine contains several functions that may be called from the knowledge base. These functions calculate the atomic oxygen fluence, trapped and solar protons total dose and fluence, and trapped and solar electrons total dose and fluence. A library of standard mathematical functions is also contained within the inference engine.

An Application Using the SMS Knowledge Base

Assessment of an experiment planned for flight on the ISS will be used to describe how the SMS is used and the type of outputs that may be expected. The planned experiment is called MISSE (Materials-International Space Station-Experiment). MISSE will make use of four containers previously used for the Passive Optical Sample Assembly (POSA I and POSA II) experiments and two meteoroid & debris detection experiments that made up the MEEP (the MIR

Environmental Effects Payload) experiments. The deployment of MISSE is planned for about November of 2000. One of the four containers is planned to be deployed for about a year under "sweeping ram" conditions. The ISS will be in a solar inertial orbit. The container will be mounted in a fixed location and will experience atomic oxygen impingement from all possible directions.

An estimate has been made of the exposure conditions for the specific MISSE container described in the previous paragraph. An estimate has also been made of the expected performance of silverized Teflon thermal control blanket for these conditions expected for this MISSE container.

A specific use of the knowledge base is called a consultation. A consultation is started when the SMS knowledge base is "loaded." The results of a consultation are shown below. The computer prompts, user inputs, and knowledge base outputs are shown below in bold print.

To start, the knowledge base is "loaded" into the BEST software.

>load sms

The BEST software returns the prompt **material**, and then the command **run** is entered.

material> run

The knowledge base begins to ask a series of questions. The first several questions establish certain pieces of information that are "initial data" to be determined prior to starting to exercise the rules within the knowledge base. The initial questions determine the intent of the consultation and define those mission parameters that are known, such as launch date, length of mission, orbital parameters such as altitude and inclination, satellite orientation and motion about its center-of-mass. When a mission is still in its preliminary planning stages, all the mission details may not be known. In such a case the answers provided by the knowledge base will be less quantitative than for cases where mission details are known precisely. For the current example each parameter has been assigned a definite known value.

1 :Is this consultation for a materials performance assessment or to make an environmental exposure estimate? Materials-performance-estimate

2 :Is the mission launch date known (even approximately)? (For short missions, year, month, and day are needed. For longer missions, year and month are enough.) yes

3 :What calendar year will the spacecraft be launched? 2000

4 :What month of the year will the spacecraft be launched? november

5 :What day of the month will the spacecraft be launched? 15

6 :Would you characterize the mission as lasting days, weeks, months, or years? years

7 :Is the orbit shape approximately circular? yes

8 :What is the orbital inclination (0 east, 90 at poles, and 180 west)? 51.6

As the knowledge base questions the user it also begins to reach certain conclusions, first about the environmental parameters, and later about the material performance. For example, once the knowledge base learns that the inclination of a particular Space Shuttle flight was to be about 51° (as in making a trip up to ISS), the following responses would be provided.

"Particles ejected from the sun during solar flare activity will reach spacecraft flying in orbits between ~45 and 135

degrees inclination, at any altitude, and could lead to significant radiation dose, depending on the intensity of solar particle event, level of shielding and altitude. Taking into account the self-shielding of the spacecraft structure, the effective dose is reduced by a factor of 2 from the numerical value of the surface dose predicted here."

9 :How would you describe the general motion of the spacecraft? spinning

Following the questions that gather the initial data, the knowledge base asks questions to obtain more detail about the exposure conditions.

10 :Material performance data is available from a number of operational satellite and flight experiments. Selected flights have been grouped into several general exposure categories. Do you wish to review previous mission profiles for one or more mission exposure categories? No

It is assumed that the planned flight will have an exposure profile different from the flight profiles "known" to the SMS.

11 :How many years will(did) the spacecraft fly? 1

12 :What is the approximate initial altitude of the spacecraft in km? 400

13 :What is the orientation of the axis of rotation? earth-space-axis

Similarly, when sufficient information is provided to the knowledge base, numerical estimates of the value of certain parameters are made. Numerical values of certain parameters are computed within specific rules in the knowledge base. Determinations of other parameters are carried out by external functions called from the knowledge base. This is the case for detailed calculations for both atomic oxygen and particulate radiation fluences. Examples of this type of response are listed below:

The approximate fluence of solar ultraviolet radiation is about 965. Equivalent Sun Hours.
The approximate fluence of atomic oxygen is 3.30e+021 atoms/cm2
The dose level of electrons from all sources is 4.21e+005
The fluence of protons from all sources is 1.51e+009

When each environmental factor has been determined as well as possible from the known information about the mission profile, the knowledge base provides outputs defining the exposure conditions for the specific mission-of-interest. The current version of the knowledge base does not have capability to provide quantitative information about fluences of meteoroids, debris, cosmic-rays, soft-x-rays, hard-x-rays, or high-energy-protons. The outputs below are examples of output provided when the knowledge base has made a qualitative assessment about the presence of a particular environmental factor:

Solar exposure environment factors present include soft-x-rays, hard-x-rays, high-energy-protons, solar-protons.
Solar UV radiation levels present are moderate-solar-UV and Earth-albedo.
Additional environments present are micro-meteoroids, thermal-cycling, trapped cosmic rays, debris, and cosmic-rays.

In the current case, the atomic oxygen fluence was calculated. Were the mission profile not well enough known to allow a calculation, qualitative statements such as the following may be reported:

Atomic oxygen exposure level may be insignificant-ao, minimal-ao, moderate-ao, significant-ao, high-ao, extreme-ao.

This output essentially says that the knowledge base did not have enough information to decide about the particular exposure level.

If the purpose of the consultation was declared to be an estimate of the environmental factors present, the consultation is complete at this point. If the purpose of the consultation was declared to be a materials evaluation, the knowledge base will begin to ask questions related to material performance.

14 :What is the engineering application being considered? thermal-control
15 :On what hardware is the material being used? radiator
16 :Are you examining a specific material? yes

The current version of the knowledge base is set up to only describe performance characteristics of specific materials. Information about Kapton, Ag/FEP, "silicones, A276 and other paints, and selected metals are contained in the knowledge base.

17 :What is the material of interest? agfep

18 : Does the material have a coating applied? No

If the material is a thin film, additional detailed questions are asked to determine the thickness of the film and nature of any coatings applied to the surface(s).

19 :What is the initial film thickness (in mils)? Typical commercially available thicknesses include 0.3, 0.5, 1, 2, 3, 5, 7.5 and 10 mils. 5.0

20 :Does the polymeric film have a metallized mirror surface? Answer y/n. yes

21 :Is the mirror a first surface mirror (FSM) or a second surface mirror (SSM)? i.e., Will light be reflected from the metallized surface and not pass through the thin film or will light be transmitted through the thin film and then be reflected from the metallized surface? SSM

For applications such as thermal control, the effects of contamination must always be considered. SMS specifically considers the influence of molecular film contaminant on optical properties.

22 :Is contamination likely to be a factor? no

Once the knowledge base has exhausted its sources of information, it provides all remaining outputs it can about the goals of the consultation. The outputs below are representative of an evaluation of the performance of silverized Teflon under LEO conditions and significant atomic oxygen exposure.

The material is : specular
The initial material properties are as follows:
The initial thickness of the material is 5 mil(s).
The initial thermal emittance is 0.77.
The initial solar absorptance is 0.07.
For a mission experiencing a total atomic-oxygen-fluence of 3.30e+021 atoms O/cm2,
The following end-of-mission properties are expected:
The thickness loss of the silverized Teflon film will be 0.4 mil(s).
The end-of-mission Silverized Teflon thickness will be 4.6.
The end-of-mission thermal emittance will be 0.75
The end-of-mission solar absorptance will be 0.07

A knowledge base may provide useful results even while it is under development. As new information is learned and added, the capability of the knowledge base increases. This can occur by adding new conclusions to existing rules, adjusting the certainty factors associated with previously developed conclusions and/or writing entirely new rules. The SMS structure is designed so that a knowledge base containing information about additional materials can be added independently of the current materials knowledge bases.

Rules development

The knowledge base essentially consists of a set of goals, parameter list with allowed values of each parameter, and a set of rules that contain the detailed information. The goal list is a subset of the complete parameter list. Goals are those parameters whose specific values the knowledge base tries to determine by asking questions of the person consulting the knowledge base. The SMS is a rule-based, backward-chaining knowledge base. The system tries to determine the value of each goal parameter, one by one, until each and every goal parameter has been determined.
The individual rules are a series of If.(premise)...;Then.(conclusion)...statements . Typical examples are shown below:

rule r20(antecedent);
if material known and material is Kapton and coating-status is no;
then conclude atomic-oxygen-reaction-efficiency 3.0e-24;

This rule essentially states if the material is bare Kapton, then the material reacts with atomic oxygen at a rate of $3x10^{-24}$ cm^3/oxygen atom. The rule is also identified as an "antecedent" rule, which means that the value of the atomic oxygen reaction efficiency will be established just as soon as all parts of the premise are determined to be true.

rule r1280;
if altitude>350 and altitude<600;
then conclude external-factor debris(cf 0.15);

This rule essentially says that if the altitude of a spacecraft is known to be between 350 and 600 km, then there may be man-made debris present that will impinge on the spacecraft. The value of the certainty factor indicates that the "expert" thinks that it is highly likely that debris will be present in these orbits, but the information in this rule is not conclusive by itself.

Several additional pieces of information (that need to be added to this rule, or contained in other rules) will alter the ultimate determination of the presence or lack of debris in the particular case being evaluated. The duration of the exposure may be short, perhaps just a few days, decreasing the likelihood of significant debris impacts. The orientation of the surface of interest may be away from the direction of motion. The opposite could also be true, the flight may be a long flight (months or years) and the spacecraft may be spinning, allowing most surfaces the chance of encountering man-made debris particles. Parameters in addition to orbital altitude, such as length of mission, surface orientation, and motion of the satellite, are determined by SMS. The specific values of these parameters may lead to further assessments of the likely presence of man-made debris that may either support the conclusion in "rule r1280" or contradict it.

Certainty Factors

Certainty factors are numbers that range from +1 to –1 and are used to express the degree of confidence in a particular piece of information. The advantage of certainty factors is that they are used directly. A person developing a knowledge base assigns a specific value to the certainty factor for each conclusion in each rule Assigning certainty factors is the method used to estimate the significance of experience-based information. Therefore, certainty factors essentially represent the knowledge and/or opinion of the "expert" creating the knowledge base and are essential to development of a knowledge base. Certainty factors also contain the risk factor associated with knowledge bases. People are not infallible, if the assessment of a particular piece of information is not correct, the knowledge base will be in error.

To determine the value of a particular parameter, the certainty factors associated with specific values of the parameter in different rules are combined by the knowledge base in order to reach a conclusion (that is, pick a value, or values, of a parameter that the knowledge base thinks is true). A more detailed discussion of certainty factors may be found in References 18 and 19.

Assignment of Certainty Factor Values to Parameters

A parameter value that has been calculated will be given a certainty factor of 1.0. A conclusion that may be true is assigned certainty factor values of 0.15, 0.1, or 0.05, each of which is used for slightly different circumstances. This range of values is for cases where even if the premise is true, additional information is required to verify the conclusion is true. A certainty factor of 0.15 is for a result that is highly likely to be true. A certainty factor of 0.1 is the "standard" which implies a result is probably true but needs further proof (or will be true in certain conditions, which must be independently identified as being present). A certainty factor of 0.05 is for a conclusion that is possible under circumstances that need considerable further definition. Similarly, for highly unlikely results a certainty factor of -0.15 is assigned, for results probably not true but needing further proof, a certainty factor of-0.1 is used, and a certainty factor of -0.05 is for a negative conclusion possible under circumstances that need considerable further definition.

A conclusion believed to be true is assigned a CF of 0.2. Because the program requires a CF >0.2 to consider a fact known, assigning values of 0.2 to a conclusion means the program must have some form of supporting evidence to "know" the fact is true.

A certainty factor of 0.3, 0.4, or 0.5 on specific conclusions are assertions that such conclusions are believed to be true and would require very strong contrary data to change that belief.

Addition or subtraction of 0.02 to a certainty factor may used to differentiate between two or more possible results when it is believed one result might be slightly more or less likely than the other(s). This slight adjustment is be used when the conditions that would make the particular result true are more likely than other sets of conditions. A few of the rule conclusions in the SMS knowledge base have this adjustment to certain concluded parameter values, but the practical impact of such small adjustments on the conclusions reached are not significant for the initial operating capability of the SMS knowledge base.

Currently the SMS knowledge base uses only the default certainty factor of 1.0 for the premise clauses. Varying the certainty factors for selected premises could be used to fine tune a knowledge base, but this subtlety is not required at the present stage of development of the SMS.

Summary

The SMS knowledge base is intended to provide preliminary assessments of materials performance and estimates of exposure levels to assist in preliminary design, mission planning, and/or materials trade studies. This tool may also be used to provide an independent check of conclusions reached from other sources. Similarly, results predicted by electronic knowledge bases should always be verified be other sources if possible.

Backward chaining rule-based expert systems, such as the SMS combined with BEST, are an effective method for storing and retrieving information. The rule-based nature of the knowledge base makes addition of new information relatively easy. When new information becomes available, new rules may be added to the knowledge base. New conclusions may be added to previously developed rules. Certainty factors assigned to specific parameter values in a rule conclusion may be adjusted. A knowledge base needs to be maintained if it is to grow in capability over time.

This knowledge base is planned to be at its initial operating capability and available for use by the end of 2000. It will be capable of evaluations of selected properties of Kapton, Ag/FEP, selected white paints, metals, and silicone-based coatings under exposure to space. The system will also be able to estimate environmental exposures under a wide variety of orbital conditions.

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