Paper 17

An On-Line Analytical System for Corrosion Pittings Analysis for Solid Rocket Booster with the SAS® System

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ABSTRACT

The Solid Rocket Boosters of the Space Shuttle have very unique and critical requirements as airframe structures. They support the entire shuttle stack, absorb stresses of main engine start, experience water impact at greater than 60 miles per hour, and remain immersed in salt water for approximately 48 hours. In addition, the maintenance and deployment of the hardware takes place in a seacoast environment. In order to maintain the integrity of the hardware, inspections are performed on the entire structure after each flight to locate corrosion for remediation and analysis. The data for these inspections has been kept graphically on paper and descriptively on standard spreadsheet software. This paper describes the development of an on-line analytical system that will be used to facilitate inspections through a graphical interface, store all the data in flexible format and allow the mining of the data for new information on the structure. Specifically, the software will be used to identify areas where the corrosion protection design is deficient, monitor the effect of changes to the corrosion protection system, and trend the damage accumulation for life prediction. This is the first phase of implementation of a data warehouse on the structures. Work is also in progress to allow the inclusion of maintenance history, problem reports, materials process and traceability data, and to support the structural analysis of the hardware. The ultimate driver of this effort is increased system reliability by the transformation of currently available data, using data mining techniques, into information, which can be used to make better resource management decisions.

Keyword: *Aerospace, Data Warehouse, Data Mining, and Corrosion Control*

INTRODUCTION

Solid Rocket Boosters for the United States Space Shuttle are divided into two distinct classes of hardware (see Figure 1). The Solid Rocket Motor (SRM) hardware consists of the fueled segments and the nozzle. The remaining hardware is designated Solid Rocket Booster (SRB) hardware and is divided into two functional groups. The Forward Assembly consists of the Nose Cap, Frustum, Forward Skirt, Parachute and Recovery system components. The Aft Hardware Kit includes the Aft Skirt, two Thrust Vector Control (TVC) systems, External Tank Attach (ETA) Ring, ring/tank attach hardware, Systems Tunnel, and associated Recovery System hardware. From a program and corrosion control standpoint, the aft skirt and TVC systems have provided the largest challenge in assuring attainment of mission life requirements. They are the subjects of the initial development of a data warehouse model to monitor the accumulation of structural defects due to corrosion and use. Data mining techniques are also under development to provide continuous evaluation of the design of the damage and corrosion control systems. In order to understand the need for this development we will begin with a description of the hardware and its service requirements. There will also be a description of the current data handling capabilities and targeted areas for improvement.

HARDWARE DESCRIPTION

The Aft Skirt is the basic structure for the entire Space Shuttle Assembly. Integration is begun by placing the two aft skirts into position on the mobile launch platform. Four studs, 28 inches long and 3.5 inches in diameter, fasten each of the skirts in place, and these eight attach points support the entire Space Shuttle vehicle from assembly until launch. Inside there are two hydraulic actuators, which are attached to the exhaust nozzle of the SRM. These provide the principle Shuttle guidance during the SRB boost phase. The outside is fitted with four small Booster Separation Motors (BSM) which are small rockets designed to guide the boosters away from the Orbiter and external tank after separation.

The principal alloy of the aft skirt is AL 2219-T87. The material was chosen for its mechanical properties and resistance to stress corrosion cracking. The relatively high copper content of the alloy gives a natural tendency for pitting corrosion if left uncoated in a seacoast environment. Chromate conversion coating alone can not inhibit the corrosive pitting attack. The minimum coating requirements of SRB hardware, for storage periods greater than 90 days, is a chromate primer. For flight, all areas except for electrical bond points are coated with conversion coating for adhesion followed with a chromate epoxy primer and a urethane topcoat. Joints and faying surfaces are all sealed with a polysulfide sealant.

In addition to the corrosion protection coatings, the exterior of the aft skirt is covered by a thermal protection coating. This coating prevents heat, due to radiant energy from the Shuttle main engine exhaust and aeroshear, from changing the temper and mechanical properties of the structure. On the interior, the projections (ribs, rings, etc.) receive a coating of polyurethane foam to protect against debris and mechanical damage from water impact. Both the mechanical and thermal coatings become fully saturated with seawater after water splash down and hold the water against the skin of the vehicle until they are removed.

Another significant element in the design of the SRB is the need to maintain an electrical ground path between every element of the entire assembly. This means that bare titanium, stainless steels, inconel and a large carbon-carbon composite nozzle all have electrical paths back to the aluminum structure. An anode system has been designed for the hardware to mitigate some of the corrosion attack. Design and weight constraints prevent the addition of enough anode area to compensate for the recognized cathodes. Additional anodes may be attached to the structure during recovery but this operation can present significant risk to the divers performing the task and is therefore limited in scope and may not be accomplished at all in rough seas.

SERVICE PROCESS

The life cycle of an aft skirt begins when it is fastened to the Mobile Launch Platform to start the full integration of the Space Shuttle vehicle. An integrated shuttle assembly, weighing 3 million pounds, is then stacked on top. The completed assembly is transported to the launch pad and set in place by the Crawler. Fueling operations before launch adding another 1.5 million pounds to the load.

At T-7 seconds, the computers will give a go for Orbiter main engine start. Ignition of the three engines will develop an offset thrust of approximately 1,000,000 pounds. This action sets up a "twang" as the boosters absorb the stress with a slight bending moment (movement of approximately 25.5 inches measured at the tip of the external tank, with movement toward the external tank) and then a slight return toward the upright position. All of this is translated through the eight hold down posts in the aft skirts. At T-0, the SRBs receive simultaneous commands for ignition and come up to full thrust. Simultaneously, commands are sent to the eight nuts on the studs holding down the vehicle setting off pyrotechnic charges and the Shuttle is set free.

SRMs will have developed a nominal thrust of 3,300,000 pounds each. Commands from the Orbiter will be driving the hydraulic actuators, braced against the aft skirt structure, to guide the vehicle along its predetermined flight path. The boosters supply power for approximately 2 minutes, taking the Shuttle to a speed of greater than Mach 4. At separation, explosives are used to sever the structural connections between the SRBs and the Shuttle. BSMs fire and take the boosters on a graceful arc away from the Shuttle.

Apogee occurs at approximately 41 miles down range at which point the boosters will begin to tumble. At 15,700 feet the nosecap of the boosters is jettisoned and a drogue chute is deployed to bring the boosters into a vertical position. With the booster stable, a cutting charge separates the frustum from the booster and the three main parachutes are deployed. With all three of the main chutes fully deployed the booster slows and is doing just over 60 miles an hour when it impacts the ocean. The booster will almost submerge its entire length and then pop back up and slap over on its side. As the motor fills with water through its exhaust cone, the SRB will come up vertical again in what is called the spar mode to wait for the recovery ship.

Recovery ships normally have visual contact with the boosters as they splash down. The Frustums, which came down separately, will be loaded onto the ships along with the parachutes. A plug will be inserted into the booster nozzle by divers and air pumped in to once again lay the assembly over into the log mode for towing. Returning the hardware to Cape Canaveral is generally accomplished in 48 hours or less.

Back at the Cape the boosters are lifted from the water and given an initial inspection. The boosters are rinsed and disassembly begins by removal of undetonated pyrotechnics. High-pressure water is used to remove the majority of the internal foam on the aft skirts and the TPS material on the trailing edge. Once the aft skirts are separated, they are moved to a special facility to remove the unused fuel and hardware of the TVC system. In a normal processing flow it will be approximately six weeks before the remainder of the seawater saturated TPS materials are removed from the structure.

The old corrosion preventative coatings are removed after each flight and a visual inspection for corrosion is performed. There are also x-ray, ultrasonic and eddy current inspections of welds and other critical portions of the aft skirt. The skirt will typically sit bare, in covered facilities but without environmental control, for six to twelve weeks during this inspection period.

Once the hardware has been analyzed any required remediation actions will be initiated. Full acceptance of the skirt will start the refurbishment process. All of the surfaces are cleaned and receive a new application of chromate conversion coating. Chromated primer and polyurethane topcoat will be reapplied along with the TPS coatings, and the structure will be recycled through integration of its subsystems for another flight.

PROBLEM DESCRIPTION

Readers familiar with seawater corrosion potentials will have already realized that the possible corrosion cells in the aft skirt will be quite active. Tracking corrosion damage in a meaningful way, however, has proven to be quite difficult. Some progress has been made, but generating the information necessary to assure the design mission life is achieved for each piece of hardware has been the subject of a seven-year search.

DATA GATHERING

For the first ten years of the Shuttle program all corrosion was documented using the NASA standard Problem Reporting and Corrective Action (PRACA) system. This was entirely a paper system at that time. The inspector was sent out to the structure with a blank piece of paper in their hand and told to find any defect larger than 10 mils and “write it up”. No standard points of reference were established from which to describe the defects. In 1991, a complete corrosion control review was held for the SRB hardware. In one of the findings from the review, it was pointed out that the data gathered to that point could not provide any information outside that individual report. No means of correlating data between reports was available.

Quality Assurance acted on the findings of the review and began developing methods to standardize the way the structures were inspected and the findings were reported. This has evolved into a standard set of graphical images, which represent all of the aft skirt surfaces. Defect locations are provided from the edges or prominent features of the graphic. Location and depth information, along with standardized descriptions of the defects, are entered into a computer spreadsheet. Some problems remain due to starting each inspection with a blank graphic and spreadsheet. Defects can still shift locations, have oscillating dimensions, or disappear entirely.

During the same period that the inspection method was being improved, the inspection requirements were also revised. General analysis of the structural loads has led to identification of new defect tolerances for some areas. Defects in some areas are not required to be reported until they exceed 25 mils. This truncates the corrosion data but actually clarifies the reports by eliminating points which are not of interest and tend to clutter the graphics.

Scans of the graphic sheets and copies of the spreadsheets are now being entered into a computerized version of the PRACA system. This enhances the ability to retrieve information on a specific structure and provides a basic definition of areas for comparison. Inspectors will eventually not have to go out to the structures with blank pages to begin inspecting. A reprint of the previous inspection can verify the data and increase the reliability of the process. Still, there will not be a link between the graphical and spreadsheet information necessary for our desired analysis.

DATA PROCESSING

Current processing of the inspection data is limited to the closing of the PRACA actions. Each recorded defect will be addressed as required by NASA refurbishment requirements with input from an engineering analysis of the structural integrity. Once the PRACA document has been closed out it is archived and is available by computer network to anyone who would need to retrieve the information. We have described such a system as a data landfill. Just like archaeologists reconstructing an ancient civilization, We can dig down to a date “strata” and dig around until we have the clues to reconstruct an event. This, by nature, is completely limited to a reactive approach to problems. It will not support proactive decision-making.

At this point no standard process exists for the comparison of the information within one PRACA report with another. Since the average length of these documents is 300 pages, it is apparent that manual reconciliation of the individual points between even two documents would be a difficult task. To complicate the situation, multiple PRACA reports may be generated against a single structure during a refurbishment cycle. No mechanism exists to connect the data through a single report or file that builds a complete picture of the hardware for any given point in time.

ANALYSIS

Early in the Shuttle program, engineers would review the list of defects in a PRACA report and request additional data until they were certain they had the information necessary to perform strength analysis. Individual engineers would maintain private defect lists for structures in order to try to reduce the analysis requirements as the same defects were reported flight after flight. Standardization of inspection reports and warranted increases in the minimum reportable defect have provided considerable relief on this problem.

It is not necessary to analyze each defect as assumptions may be used based on analysis with the worst defect in a region. This being the case, there has been no driver to identify how many new defects occurred from flight to flight. It does not change the workload involved in determining the factor of safety to approve the structure for reuse. Identification of common areas where structures are consistently damaged is also left to chance observation as no requirement currently drives this activity.

PREDICTIVE CAPABILITY

One current requirement is looming out ahead of us and still needs to be addressed. Each piece of hardware in the shuttle program has a minimum mission life assigned to it. Beyond this, as everyone associated with a government program knows, funding for replacement hardware is elusive, even when planned. Every effort is being made to extend the life of each structure as long as possible. For our program, as well as most similar programs, we would like to be able to look at two trends to reach this goal.

The first trend we have dubbed vertical trending. This provides the historical information for a specific piece of hardware. It is incremented by use cycles and/or chronological measurements. All programs with extended lives will inevitably face changes in design. This has been particularly true in the corrosion control arena as materials and processes become obsolete or even outlawed. Pressures for cost savings and new design requirements as the mission capability of hardware is broadened also push corrosion protection systems toward their "cost effective" minimums. Since the effects of such changes may not be seen for some time, it can be difficult to properly assign the correct level of resources to corrosion prevention. It is an unexplained phenomena of human nature to prefer to manage things as crises rather than progressively. Unfortunately corrosion has the bad habit of not generating a crisis until it is too late to do anything except discard the pieces and start over.

Vertical trending is necessary to provide information to make technical resource management decisions. For instance, if a new coating system is qualified for use and deployed, how do we rate its performance if there are no catastrophic failures? If the defects generated per use cycle are statistically identical then we can state that we have a good alternate system. Decreasing new defects after material introduction may justify a more rapid deployment than originally planned. Increases in reported defects could initiate a decision to recall the system for further study or elimination. Ideally this would also aid our testing by identifying ways to close the gap between laboratory results and the field. We should also be provided with the data to attach remediation cost to specific material systems to produce the best overall program decisions. The same sorts of information would also be used to support or rescind reductions in levels of a corrosion control system.

Horizontal trending is our second identified need. This would be described as a comparison of defects across a fleet of hardware. In a practical sense horizontal analysis gives an evaluation of the corrosion control system design. Ideally, the only time we should see corrosive attack is when there is random damage to the corrosion control system. When a location is identified where an attack has been consistent for a statistically significant portion of the fleet, it should enable us to identify a possible inadequacy in the corrosion prevention system before failure occurs in any single unit. Some of us would miss the adrenaline rush and the excitement of the crisis handling of such items, but it is believed that most of us would not.

DATA WAREHOUSE SOLUTION

For the last seven years the SRB Corrosion Control Team has searched for a system that would provide the tools to accomplish the trending tasks identified above. It was believed that such tools would be useful, not only to our program, but also to any organization tasked with maintaining airframes or any similar critical hardware. This system should ideally include the following seven capabilities. First, this system must be user-friendly, i.e., a menu-driven system in a point-and-click environment is in order. Second, this system must have data gathering capability that can help field personnel to perform their inspection and to increase inspection efficiency and accuracy. Third, this system must be able to dynamically create a wide range of graphical reports such as 3D-bar charts (stacked and grouped) and 3D pie charts in a hierarchical manner for a quick review of the data. Fourth, this system must have the capability to produce drill down reports with system details such as multi-dimensional reports, top ten reports, ranking reports, and expanding reports. Fifth, this system must have statistical analysis capability to perform vertical and horizontal trending analysis. Sixth, this system must have forecasting capability to identify potential problems. Seventh, this system must be flexible, i.e., it should be able to run on different platforms, access data in other databases, and expand to address other program problems. The SAS/Warehouse Administrator™ (SAS[3], 1997), a recognized leading data warehouse software development environment, was used to develop this system.

COMPONENTS OF THIS SYSTEM

To satisfy all the identified capabilities, this system includes a data gathering component, data register and cleaning component, dynamic graphical report component, drill-down tabulate report component, statistical analysis component, and a forecasting and prediction component. An executive information system (SAS[4], 1997 and SAS[5], 1997) software development component was used in the first stage implementation.

DATA GATHERING COMPONENT

The data-gathering component consists of ninety-five frames. The first frame includes two menu buttons, one button for the outside flat map of the SRB aft skirt and another for the map of the inside of the structure. The second frame is the flat map of the outside of the SRB that has been divided into 46 different parts. Each part has been linked to an inspection frame that can be used by field personnel to perform inspection. The third frame is a flat map of the inside of the aft skirt, divided into 46 parts as well. The rest of the frames are expanded views of the 46 areas which are designed to be used for inspection. Each of these frames contains two parts - the left part of the frame is a data entry table and the right part of the frame is the detailed map of the part to be inspected. The inspector can simultaneously access the previous inspection results and key in data from the new inspection thus reducing location shifts, oscillating dimensions and drop out of points.

DATA REGISTER AND CLEANING COMPONENT

Before an inspector and/or the engineer can perform an analysis, they must register the raw data in a meta-base. A meta-base is a master data set that stores information about the data from the data-gathering component. This is not the raw data but rather a statistical description of it. When you register the inspection data, you assign the data a file name and its variables. In addition, you can define as many hierarchies (or data dimensions) as you like. This hierarchy register will be used in generating dynamic graphical reports and drill-down tabular reports. The same variable can be used in as many hierarchies as desired, increasing the flexibility the user will have in looking at summaries of the data. After registering the inspection data, the user can browse through the data and correct the inputs if any errors are detected. Standard software utilities were were available in our development environment to aid in setting up this component.

DYNAMIC GRAPHICAL REPORT COMPONENT

The dynamic graphical component allows the user to view the graphical summary information of the data in four different graphical forms - 3D Vertical Bar Chart, 3D Horizontal Bar Chart, 3D Pie Chart, and 3D Bar Chart with Line. Four hierarchies have been predefined. The first hierarchy allows the user to view the information for a given SRB inspection report of a specific mission. This hierarchy contains four variables: Surface

Designation, Part Designation, Location Designation and Discrepancy Designation. The user can use this hierarchy to look at the total number of pits, the maximum depth of pits, and the average depth of pits at each level of these hierarchy variables. The second grouping includes one more hierarchy variable, "mission", which creates the vertical trend view of the data. Our third hierarchy adds the variable "structure" to the first hierarchy and allows the user to view the horizontal trend. The last hierarchy combines all of the hierarchy variables and allows the user to compare the overall trend of each structure.

DRILL-DOWN TABULATE REPORT COMPONENT

The drill-down tabular component allows the user to look at summary statistics of the inspection data in four different tabular report forms - multi-dimensional reports, ranking reports, top ten reports, and an expanding reports. For the multi-dimension tabular report, the user can use the same hierarchies defined in the dynamic graphical component. In addition, a wide range of statistics can be chosen to summarize the data. The ranking report is used to rank the ninety-two separate sections of a structure based on the number of pits in each of these areas. The top ten report is used to locate those areas that contain the deepest pits on a given structure. The expanding report is a tool that allows the user to identify those pitting patterns that are growing and might cause serious problems.

STATISTICAL ANALYSIS COMPONENT

The statistical analysis component uses the Lartin-Hypercube design to assign a "serious pitting score" to each part of the aft skirt structure using a built in standard software component.

FORECASTING AND PREDICTION COMPONENT

Four different prediction models are implemented in the forecasting and prediction component. These models include a multiple regression model, a linear time series model, a non-linear time series model, and a local spline model. Users can choose the appropriate model to make a forecast or prediction. These diagnostic statistics are included for personnel with an adequate statistical background to correctly interpret the results of the analyses and will not be made available to all users.

FUTURE EXPANSION

One key to a successful data warehouse system is flexibility, as stated previously. Operating system mobility and network access options are basic advantages of our chosen development environment. To date, the system has only been run on an IBM compatible personal computer with Windows 95, Windows 98, or Windows NT. However, this system can also be ported to UNIX systems so working across almost any network can be easily accommodated. Access using browser software through a network environment can also be programmed in through additional modules to allow service to any desktop within a corporation, or beyond, if desired. Beyond this, the authors also plan to expand the system to cover the following three program needs:

STRUCTURAL ANALYSIS

The most challenging extension of this system will include developing a system that is based on a probabilistic model developed by Nicholson, Ni, Ahn, and Wang at the University of Central Florida(Nicholson and Ni, 1997[1] & Ahn, Nicholson, and Wang, in press[2]). In their model, not only pitting but also cracks will be considered. This will significantly increase the prediction and forecasting capability of the system. It will be theoretically possible to produce a structural analysis within hours of completion of an inspection, instead of weeks later.

MATERIAL TRACKING

Another of the challenges for the Solid Rocket Booster program is the large number of materials (sealants, coatings, adhesives, fluids) that are used for each flight. Each of these are logged in, identified, and have various amounts of testing performed on them. All of this is dutifully recorded on paper, or with independent computer systems, and stored per contract requirements. If at any point we experience a failure related to one of these items, the records may be collected and the cause of the failure reconstructed. Unfortunately, the current methods of retaining the records do not allow for any proactive use of the information beyond the acceptance requirements for a single operation.

Additional modules to the Data Warehouse will place the data that is gathered into a format which can be analyzed for improved process control. Acceptance criteria can be scrutinized against real world population results to raise reliability levels. Equally important, the data itself could be analyzed for value. Some tests are run and inspections performed because it seemed like a good idea at some point in time in a program. The need for the tests have past or the test does not prove what it was intended to prove. Unfortunately, it is often too late when someone realizes that the confidence in a system, because of an irrelevant test, was misplaced. By proactively attempting to transform all data gathered into information, we can identify these situations and make appropriate program decisions.

MAINTENANCE RECORDS

Fields with critical requirements, such as aerospace, can not afford to lose track of maintenance process records and material deployment locations. For instance, if an alert is issued regarding a specific batch of material or an unexpected degradation of a material is revealed due to certain process conditions, the identification and location of any affected material on our hardware is critical. Exercises of this sort have historically taken from six weeks to six months to resolve fully. The cost of performing the search, impacts to schedule, and remediation easily reach into the hundreds of thousands of dollars. Through the use of data warehouse technology, we can reduce the time for the first two steps from weeks to hours and protect the program from serious impact from these types of problems.

CONCLUSIONS

In 1991, a study of the corrosion control system and the status of the SRB hardware led us to an inescapable conclusion: Data is not information. Even though we had thousands of data points available from our system, no method was available to transform it into the information that program managers needed for long term decisions. Tools are now available to address these needs.

Data warehouse architecture consisting of modules for data collection, data verification (scrubbing), data storage, analysis, and reporting have addressed our program needs. Enhanced feedback to inspectors on the front end, using graphical elements, can reduce mistakes and omissions. Warehouse storage of data points allow us to search beyond immediate questions to define relationships among the variables in our processing and hardware use. Trending information can provide the rate of degradation of the structures and identify where changes to the corrosion control design are called for before hardware is lost. We can get relatively rapid feedback from the field on the performance of a new material or changes to the corrosion control system. Perhaps most important, we can better relate decisions made on corrosion control to hardware reliability and program costs.

While the system presented has been confined to SRB hardware during development, the authors feel that similar systems would be applicable to airframes in general or any critical structures that are maintained in a similar manner. Moving forward to data warehouse architecture is the next step in our industry's evolution from data systems, to information systems, to knowledge systems leading to intelligence systems. Shared information that is made available in data warehouse format can be the next step in translating more of the art of corrosion control into technology.

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FIGURE 1. SPACE SHUTTLE SOLID ROCKET BOOSTER