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ENVIRONMENTALLY SOUND MANUFACTURING

BY

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ABSTRACT

During the last three years, the NASA/Thiokol/industry team has developed and started implementation of an environmentally sound manufacturing plan for the continued production of solid rocket motors. NASA Marshall Space Flight Center (MSFC) and Thiokol Corporation have worked with other industry representatives and the U.S. Environmental Protection Agency (EPA) to prepare a comprehensive plan to eliminate all ozone-depleting chemicals from manufacturing processes and reduce the use of other hazardous materials used to produce the space shuttle reusable solid rocket motors. The team used a classical approach for problem-solving combined with a creative synthesis of new approaches to attack this challenge.

INTRODUCTION

The manufacturing processes that were acceptable in the early 1980s are not acceptable in the '90s. Forty-seven percent of the organizations that were Fortune 500 companies 10 years ago are no longer there. They were not adaptive enough to survive in the changing business environment. As budgets become smaller and competition requires us to work smarter, faster, and more efficiently, we need to make sure the processes and products we develop in the '90s serve us well into the 21st century. As our ability to gather data on the state of the Earth's environmental health increases, *Environmentally Sound Manufacturing* must become an integral part of the business decision making process.

BRIEF HISTORY OF ENVIRONMENTAL REGULATORY ACTIVITY

The '70s are remembered as the beginning of the legislative environmental movement with the passage of the National Environmental Policy Act (NEPA, 1969), the Clean Air and Clean Water Acts, the Toxic Substances Control Act (TSCA), and the Occupational Safety and Health Act (OSHA). The '80s concentrated on treatment, storage, disposal, and cleanup of solid and hazardous wastes, and public involvement with the passage of the Emergency Planning and Community Right-to-Know Act (EPCRA). The '90s have given us the Pollution Prevention Act, the Oil Pollution Act, additional regulations on hazardous air pollutants (HAPs), water toxins, acid rain, and the production ban of ozone depleting compounds (ODCs) scheduled to take effect January 1, 1996. The Venn diagram, shown in Fig. 1 illustrates the interrelationships of the various lists of hazardous materials that are a part of the regulatory picture.

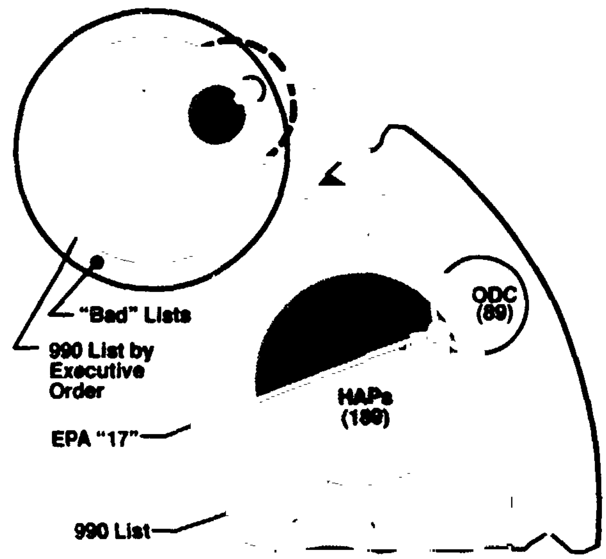

Fig. 1. Sets of Bad Chemical Lists

Successful leaders must anticipate future regulations and design their products and processes to give them an advantage when new regulations are implemented. The dynamic changes in business and technology resulting from the administration's seemingly paradoxical goals of deficit reduction and infrastructure investment demand a stronger focus on the financial challenges facing the industry in the '90s.

This paper summarizes some of the plans and accomplishments made by the NASA/Thiokol/industry team. New partnerships, new technologies, and new approaches and strategies have been some of the new resources employed as part of Thiokol's plan to achieve environmentally sound manufacturing.

TRADITIONAL APPROACH TO PROBLEM-SOLVING

Engineering problem-solving usually consists of the following steps. 1) recognize a problem exists, 2) organize to deal with the problem, 3) more clearly state the problem and establish a plan of action, 4) execute the plan, 5) analyze the data and evaluate solutions, 6) qualify solutions into the manufacturing process, and 7) report solution of the problem.

1. RECOGNIZE A PROBLEM EXISTS

When the Montreal Protocol members promulgated their document outlining the end of production of ODCs, the NASA/Thiokol team realized a need to start looking at changes to Thiokol materials and processes in order to be prepared for eventual elimination of ODCs. In 1992, when President Bush moved those elimination dates to 1996, the awareness of future challenges became much more acute. A likely extension to the end of RSRM production added to the immediacy of the problem of ODC replacement. When a survey was completed determining the processes that used ODCs and the quantities being used by the various divisions, we recognized the magnitude of our problem.

2. ORGANIZE TO DEAL WITH THE PROBLEM

Thiokol's Corporate Safety and Environmental Affairs director appointed an interdivisional solvent elimination coordinator in early 1991. Each Thiokol division then selected a coordinator and was assigned a solvent replacement task based upon highest usage. Space Operations was assigned methyl chloroform—1.1.1–trichloroethane (TCA). Each division was eventually tasked with replacement of the solvents peculiar to their programs.

3. MORE CLEARLY STATE THE PROBLEM AND ESTABLISH A PLAN OF ACTION

An overall corporate hazardous solvent elimination plan was produced. Each division submitted a preliminary elimination plan. An overall schedule was prepared in early 1991 predicting that production phaseout would come at the end of 1995. Bonds were recognized as being critical to the reliability of the motors, therefore, no bonds would be changed without data to qualify equal or better margins of safety.

4. EXECUTIVE PLAN— ODC ELIMINATION STRATEGY

The Thiokol/NASA strategy used to eliminate all ODC from solid rocket motor production followed sound engineering principles. The issue was well defined. There would be a production ban of ODCs on January 1, 1996. Thiokol Space Operations ODC use in 1989 had been almost one million pounds in direct manufacturing operations and another 400,000 pounds in indirect use (Fig. 2). A detailed study of each ODC used identified 852 manufacturing llouts in official planning documents. Over 100 different bonds in the motor were affected. The reliability of the motor depends on these bonds to prevent hot gases from reaching metal structural components. A Pareto analysis (Fig. 3) was conducted to prioritize the 32 major categories of use. The two biggest users were vapor degreasers like the one shown in Fig. 4. This analysis indicated that approximately 90 percent of the TCA use was in the top four categories, i.e., two large TCA vapor degreasers, diluent for preservative grease, and as a cleaner for propellant mix and cast tooling. Possible replacement processes for the vapor degreaser were evaluated. Requalification testing required for all of the 852 planning changes and 100 plus affected bonds were identified. An ODC team sorted through all of the possible alternate solutions to the required changes and developed a plan to eliminate all ODCs from the process.

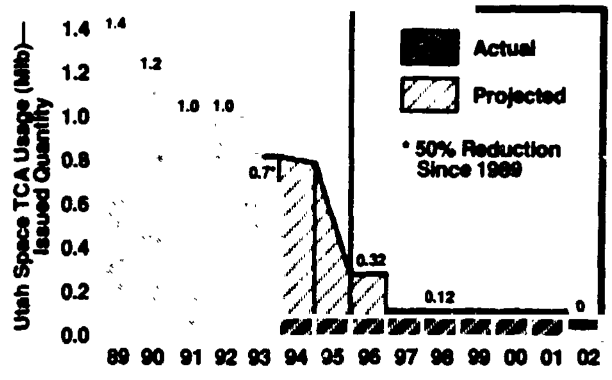

Fig. 2. Actual and Projected Reduction in TCA Usage

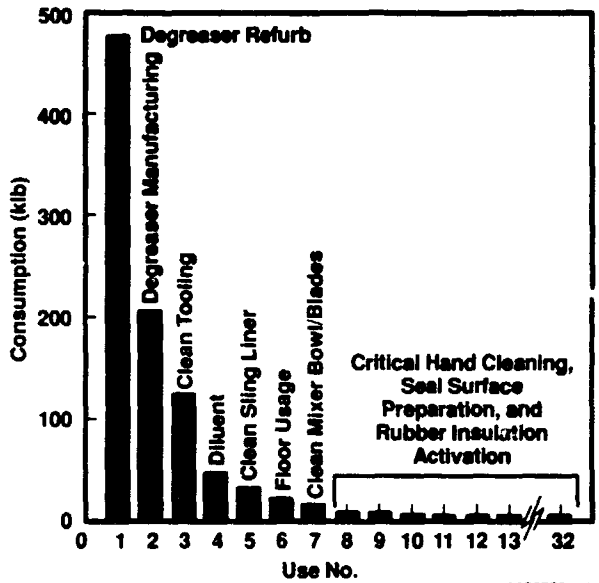

Fig. 3. RSRM Uses of TCA

Fig. 4. Case Vapor Degreasing

Industry Survey

As the scope of the bonding process changes became clear, NASA and Thiokol engineers began an industry survey to identify options and alternative processes. Over a two–year period, 31 different companies were surveyed to determine how they were responding to the production phaseout of TCA. Forty–nine technical papers presented at seminars, workshops, and NASA–sponsored working groups were evaluated. Data were summarized, and a report was published in March of 1993. A matrix was prepared listing the substrates, preferred cleaners, and the person leading the project at each company. A distribution analysis was made of usage for cleaners selected by two or more organizations. From this survey, a list of factors to consider in the selection of replacement solvents and cleaners was created:

- Industrial safety considerations
  - Flammability, toxicity, allowable exposure
- Environmental release requirements
  - Ozone–depleting and global–warming potential, volatile organic compound level
- Product safety
  - Cleaning effectivity as measured by bond test results, residue on substrate, effect on metallurgical properties, material compatibility, corrosion potential, shelf–life (aging) capability
- Cleaning efficiency
  - Material and labor cost, availability, evaporation rate, soil loading capacity, stability, recyclability, disposal cost, energy cost, versatility
- Capital investment
  - Floor space required, capital expenditures, estimated life–cycle cost for equipment

THE MAIN CONCLUSION OF THE INDUSTRY SURVEY WAS THAT WHILE MUCH CAN BE LEARNED FROM OTHER COMPANIES' EXPERIENCES AND DATA, EACH COMPANY MUST TAILOR CLEANING PROCESSES TO THE PARTICULAR SOILS, SUBSTRATES AND PERFORMANCE REQUIREMENTS OF THE PRODUCT BEING MANUFACTURED.

Hierarchy of Suitable Cleaning Alternatives

Time and money are saved when permanent solutions are selected rather than short–term fixes. Dr. Katy Wolf, the executive director of the Institute for Research and Technical Assistance (IRTA), was very helpful in suggesting that companies follow her low–risk hierarchy of alternate cleaners, i.e., no clean, water, aqueous, semiaqueous, combustible solvents, and flammable solvents in decreasing order of desirability

5. ANALYZE DATA—PRELIMINARY TEST PROGRAM

In the early stages of selecting a replacement cleaner for TCA at Thiokol, all potential cleaners were considered. Initial screening tests favored organic cleaners because the hardware's preservative grease is soluble in organic cleaners. If all aqueous cleaners had been eliminated because the grease preservative was not soluble in them, the best cleaners would have been missed as measured by fracture energy, tensile adhesion, and residue after final rinse. Fortunately, the test program was structured to continue testing with five of the best cleaners from each group: five aqueous, five semiaqueous, and five organic—or 15 total—before a final down–selection of the two best cleaners was made. Both an aqueous and a semiaqueous cleaner produced bonds that demonstrated superior fracture toughness and tensile adhesion test data, with acceptable results in all other areas tested. A typical set of data for steel tensile adhesion strength is shown in Fig. 5.

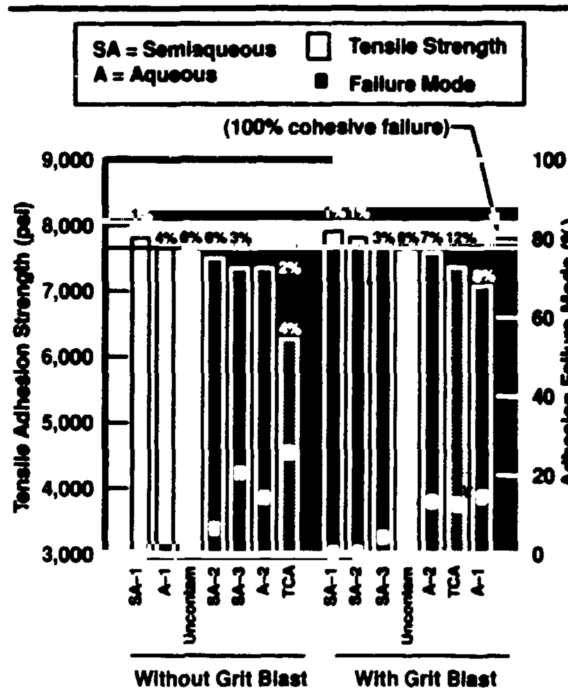

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Fig. 5. Nozzle Bondline—Tensile Adhesion Test Data

6. QUALIFY SOLUTIONS INTO PROCESS—DESCRIPTION OF PHASE I—ELIMINATE 90 PERCENT OF TCA

The Phase I plan to eliminate 90 percent of the TCA was focused first on eliminating the four biggest users, i.e., the solvent in two large vapor degreasers, a cleaner for propellant tooling once it is out of the propellant mix and cast buildings, and diluent used to thin the preservative grease. This effort is time–phased: Step 1—replace the Refurbishment Center's vapor degreaser with a high–pressure water wash system and implement greaseless storage and shipment of hardware; Step 2—replace the Manufacturing Center's vapor degreaser with a spray–in–air precision cleaner and qualify tool cleaning process for propellant mix and cast tooling. The master schedule for this effort is shown in Fig. 6.

The Step 1 effort is 30 percent complete. Components for the high–pressure water wash system are in the procurement cycle.

The Step 2 development and qualification effort is continuing with the selection of a final cleaner to be made by mid–1994. The designing of the spray–in–air system will begin in October of 1994 and will be operational by early 1996. At that time, TCA usage will have been reduced by 90 percent from 1989 levels and TCA emissions by 95 percent.

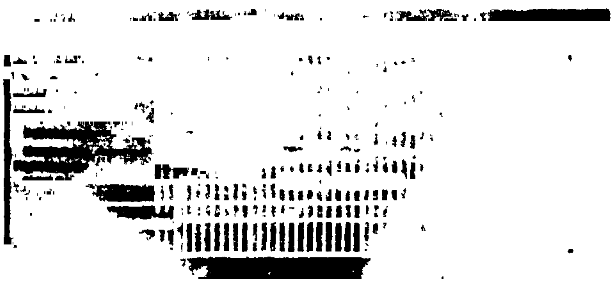

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Fig. 6. Master Schedule for Replacement of ODC

Phase II—Eliminate Remaining 10 Percent of TCA, Stockpile, and Obtain Essential Use Waiver

The Phase II plan eliminates the remaining 10 percent of TCA usage by the end of 1999. Critical uses of TCA associated with hand cleaning, rubber activation, and equipment cleaning that could affect critical bonds and processes essential in propellant mix and cast areas where a flash fire could be catastrophic are included in Phase II. The remaining 10 percent TCA use affects approximately 80 percent of the bonds (78 of the 101) critical to the reliability of the Space Shuttle system. An approach was established to request an Essential Use Exemption from the Solvents, Coatings, and Adhesives Technical Options Committee of the United Nations Environmental Program. This approach would allow time to address schedule and cost to ensure changes could be qualified prior to use on flight motors. Discussions were held with the Environmental Protection Agency (EPA), NASA, and Thiokol regarding the approach, and positive indications were received. The Montreal Protocol criteria for an exemption were obtained, and a final request to purchase 125,000 pounds of TCA per year was submitted to the EPA on June 24, 1993. The United Nations committee met in October of 1993 and reviewed the exemption request with final decision on the exemption to be made in the fall of 1994. If the exemption request is approved and schedules are met, we will not require stockpiling of TCA (Fig. 7).

Creative Synthesis of New Resources

The execution of our plans involved a bringing-together of a number of new resources: 1) new partnerships, 2) new technologies, and 3) new approaches and strategies.

New Partnerships. Our efforts benefitted greatly from the new partnerships formed with governmental organizations, professional groups, industry associations, and academia.

a. NASA Operational Environmental Team

The NASA Operational Environmental Team (NOET) was established in April 1992 to provide the entire NASA team a central resource to pursue replacement technology. The focus of this team is environmentally questionable materials and related processes involved in the design, development, test, and manufacture of NASA hardware. The two elements of the NOET, the Replacement Technology Team (RT^2) and the Propulsion Technology Team (PT^2), work through the existing program structure to emphasize resource prioritization and trade studies, to address technical issues, and to avoid redun-

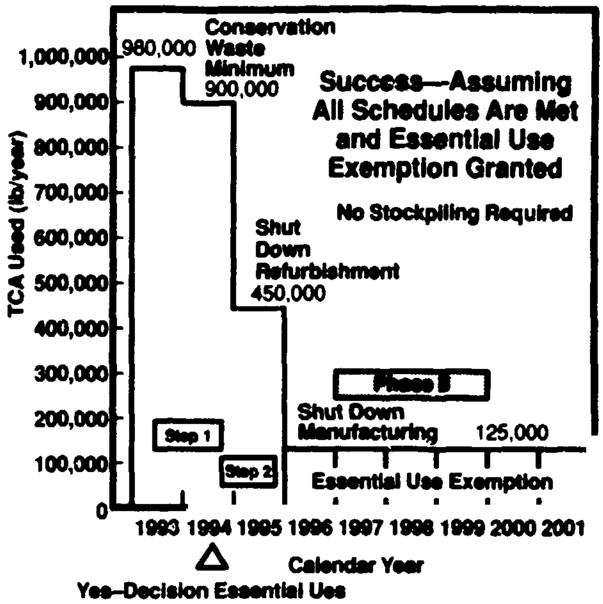

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Fig. 7. ODC Program—TCA Usage

dancy. The NOET provides excellent opportunities for cooperative efforts among NASA centers, other federal agencies, subcontractors, educational institutions, and private industry. The NOET team leader is NASA's Robert (Bob) J. Schwinghamer, deputy director of Science and Engineering at MSFC.

b. NASA: Assured Shuttle Availability

In 1992, Johnson Space Center (JSC) and MSFC provided funding to allow Thiokol to conduct testing of alternate hardware preservation and shipping techniques at the refurbishment facility. The Assured Shuttle Availability (ASA) program demonstrated a process flow that eliminated the need for the three vapor degrease cycles and proved preservative grease is not required if the hardware is protected from the weather and high humidity conditions (less than 45 percent relative humidity). This program generated data to support the concept of "clean once and keep it clean," and will result in substantial cost savings and environmental benefits when qualified for production. An environmentally controlled trailer has been procured to ship segments 60 miles between plants without preservative grease diluted with TCA (Fig. 8).

c. Environmental Protection Agency

The EPA Stratospheric Ozone Protection Division and the United Nations Solvents, Coatings, and Adhesives Technical Options Committee are providing on-going support to the aerospace industries' efforts to find acceptable alternatives for ozone-depleting chemicals. This partnership has provided access to foreign and domestic experts and has helped avoid duplication of effort while increasing confidence in the performance of selected alternate materials and processes. Dr. Stephen O. Andersen is the deputy director of the U.S. EPA Stratospheric Protection Division and chairman of the United Nations Solvents, Coatings, and Adhesives Technical Options Committee.

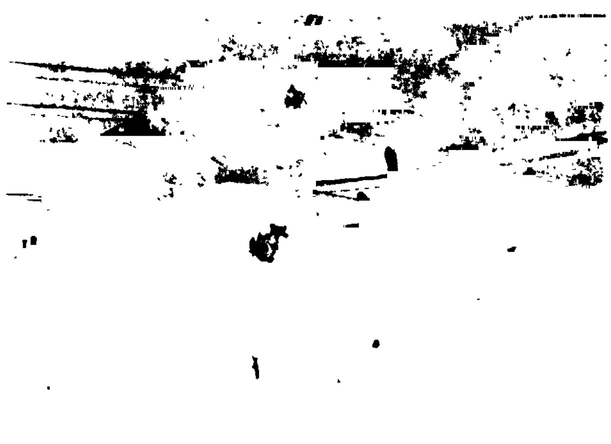

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Fig. 8. RSRM Case Shipping System ODC Phase Zero

d. NASA Headquarters (Environmental Engineering)

The Chief Environmental Engineering Office at the Office of Space Flight (OSF), NASA Headquarters, has taken an aggressive approach to protecting the environment. This small staff has opened channels of communication between the EPA, NASA, and contractors to provide the free exchange of information. Mr. Steven Newman is OSF's chief environmental engineer.

e. Aerospace Industries Association

Thiokol Corporation, as a member of the Aerospace Industries Association (AIA), has participated on the Environmental Activities Committee. Members include the major air frame manufacturers and their suppliers, the solid rocket motor manufacturers, and other aerospace organizations. Meetings have provided valuable contacts with knowledgeable senior experts where information is exchanged in many areas of environmental concern. Mr. Glynn Rountree is the AIA chairman of this committee.

f. Academia

Brigham Young University was given a study contract to evaluate improved shipping and preservation methods. Their study supported the ASA Project conclusions which were to get the hardware clean at the refurbishment facility and provide shipping containers to keep it clean during the 60–mile transportation trip to the main plant.

The University of Alabama was contracted to develop and demonstrate a single strand fiber optic system capable of providing quantitative information on the nature of contaminants on steel, aluminum, and phenolic systems. The principal investigators on this study are Mr. Roy Marrs of Thiokol and Dr. Gary Workman of University of Alabama at Huntsville.

New Technologies. The team implemented plans for solving environmental problems. We benefitted from the application of new technologies and provided additional processing benefits. Some of those are described below.

a. High–Pressure Water Wash

Thiokol has used high–pressure water systems in the 10,000– to 15,000–psi range to remove insulation from metal parts since the mid–1960s. A new application of ultrahigh–pressure water up to 36,000 psi is planned as a replacement process for TCA vapor degreasing and grit blast with zirconium silicate. This environmentally superior process will eleminate TCA use, reduce process cycle times, and increase hardware life because metal removal rates with water are an order of magnitude less than with grit blast media. This equipment is being demonstrated in the NASA Technology and Productivity Enhancement Laboratory at MSFC. Production equipment is on order and is scheduled for installation and checkout during the first quarter of 1995. A sketch of the new equipment is shown in Fig. 9.

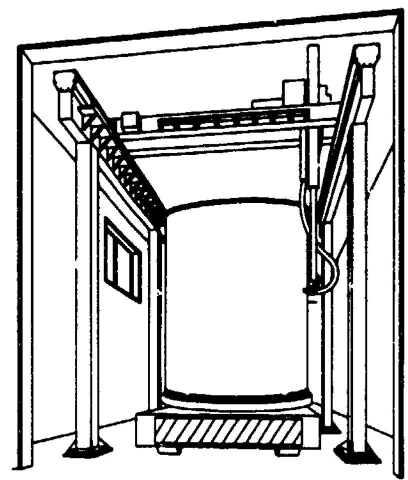

Fig. 9. Ultrahigh–Pressure Water Wash System

b. Spray–in–Air With Aqueous and Semiaqueous Cleaners

Aqueous and semiaqueous cleaners had been used in dip tanks followed by a rinse and drying of the soiled part. Thiokol proposed using a spray–in–air method that would be cheaper and give a cleaner part. Data gathered are shown in Fig. 5.

c. Low–Emission Vapor Degreasing

The first consideration in finding a replacement for TCA used in the vapor degreasers was to evaluate a switch to perchloroethylene. It does pose health risks, and, therefore, has a low (50 ppm) permissible exposure limit. An alternative to open–top vapor degreasers is an airtight system known as low–emission vapor degreasers (LEVDs). Two manufacturers were contacted and several meetings held to understand how the LEVD system works. The process was determined to be a viable alternative, but was not selected because of relatively little demonstrated use in U.S. industry on parts the size of RSRM cases. Also, the potential for future legislation on exposure and use of perchloroethylene was a concern. The two leading suppliers of this equipment are Dürr Industries, Inc., and Baron Blakeslee.

d. Surface Cleanliness Measurements

The question of "How clean is clean?" has been with us for a long time. Much has been accomplished to quantify the measure of cleanliness. NASA developed an optically stimulated electron emission (OSEE) device called ConScan that measures surface cleanliness levels and oxides and plots them for acceptance analysis. Thiokol has been using the system since 1988 to ensure acceptable surface cleanliness prior to bonding and continued reliability of motor performance. The principle contact at NASA/MSFC is Mr. Billy Nerren. The Thiokol-developed SurfMap™ infrared contamination detection device uses diffuse, back-scattered light in the mid-infrared region to monitor a surface for the presence of hydrocarbons. The contact at Thiokol is Mark Walker.

e. Surface Chemistry Analysis

Thiokol has made extensive use of laboratory surface chemical analysis methods in the evaluation of replacement cleaning processes for methyl chloroform vapor degreasing of steel and aluminum bonding surfaces. Techniques include electron spectroscopy for chemical analysis (ESCA), auger electron spectroscopy (AES), and static secondary ion mass spectrometry (static SIMs). ESCA, AES, and static SIMS are sensitive to changes in the topmost atomic layers of a surface which are directly involved in bonding. The principal investigator at Thiokol is Dr. Mike Lesley.

New Approaches and Strategies

a. Pollution Prevention

The 1990s approach to enhancing the environment is preventing pollution at the source by better, smarter planning of the product design and the manufacturing process. The EPA has published a document (*Facility Pollution Prevention Guide*, EPA/600/R-92 088) May 1992, that provides excellent instructions on how to establish and maintain a successful pollution prevention program. The document may be obtained from: **U.S. EPA, Office Research & Development, Washington, D.C. 02460.**

b. Unit-of-Issue to Match Usage

Most large organizations have a supply system that issues materials to the production line. On controlled programs, the quality of the material is assured by the seal on the container. Once it is broken, and residual material cannot be returned to Stores. If the smallest unit of issue is a gallon and the user only needs a pint, the result is scrap material, which is wasteful and expensive to dispose of. By understanding the needs of the production line, material can be issued in quantities actually used, avoiding waste and expense.

c. Listen to the User

A significant change in direction occurred in December of 1992 when Manufacturing Center directors responsible for the cleaning operations made several suggestions that completely changed the direction of the ODC replacement program. They suggested that high-pressure water be used for refurbishment operations and the final precision cleaning be reserved for use just prior to bonding operations at the Manufacturing work center. High-pressure water could remove paint and adhesive residue faster and better than the existing grit blast process. The life of the flight hardware could be extended with the high-pressure water wash because less metal would be removed than with grit blast. The change to ultra-high-pressure cleaning at the Refurbishment Center was accepted and eventually proved to be the best plan, once again demonstrating that "the user knows more about the real process than anybody else."

7. REPORT SOLUTION OF PROBLEM

An engineering and environmental challenge was presented to the NASA/Thiokol/industry team when the international decision was made to stop the production of ODCs. The team used a classical approach for problem-solving combined with a creative synthesis of new approaches to attack the challenge.

Summary of Lessons Learned

- Establishing clear selection criteria for decisions at the beginning keeps the program on track
- Industrial safety considerations must be evaluated when selecting alternate cleaners
- Examination of current process and minor changes reduced TCA useage by 50 percent
- Bond strengths depend on cleanliness and surface chemistry
- Listening to the people who will have to implement the plan improves results
- Cost considerations are important and can be a positive competition factor
- While much information can be learned from other companies' experience, each company must tailor the cleaning process to the particular soils, substrates and performance requirements of the product being manufactured

CONCLUSION

Since many of the processes that were acceptable in the early 1980s are no longer environmentally acceptable in the 1990s, companies need to make drastic changes to their thinking, materials, processes, and manufacturing in order to stay competitive. Companies are basically concerned with how to get the best environmental program while under tight budget constraints. Meeting environmental requirements necessitates making changes to the way products are manufactured. The requirement to make changes to processes can be an opportunity rather than a burden. Since all companies must make changes at this time, leaders can make changes in a manner that will give them a competitive edge. They have an opportunity to examine their manufacturing paradigms and incorporate better ones. New cleaning methods should make operations more economical where possible. These new environmental requirements give companies an opportunity to modernize while making the workplace safer and reducing emissions of hazardous materials.