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General Overview of the ODC Elimination Effort of the RSRM Program

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ABSTRACT

The purpose of the ODC Elimination Program of the Space Shuttle RSRM Program is to eliminate the usage of 1,1,1 trichloroethane (TCA) in all RSRM (Reusable Solid Rocket Motor) manufacturing processes. This program consists of the following phases and objectives:

- Phase 0 – Convert to greaseless shipping of metal components.
- Phase I – Eliminate TCA vapor degreasing and usage in propellant cleaning operations.
- Phase II – Eliminate TCA usage for hand cleaning operations.

Each phase reduces peak TCA consumption (about 1.4 million pounds in 1989) by about 29, 61, and 10 percent, respectively. Phase 0 was completed in 1992, Phase I in 1997, and Phase II is in progress (about 75% complete). TCA replacement objectives are accomplished by are a series of subscale, full-scale, and static testing outlined by the NASA-funded, ODC Elimination Program.

INTRODUCTION

The RSRM (Reusable Solid Rocket Motor) components are built with great attention to detail because of its man-rated for flight distinction. Therefore, process and material changes are carefully scrutinized prior to implementation. In 1989, the RSRM Program commenced an effort to replace the ozone depleting solvent, 1,1,1 trichloroethane (TCA), which was used pervasively in the manufacturing processes. This effort was meticulously and methodically defined and structured to provide subscale, full-scale and static test data to ensure that adequate replacement materials and methods were incorporated into numerous processes critical to RSRM manufacturing. To date, this effort, the NASA-funded, ODC Elimination Program, has successfully reduced peak usages by approximately 90 per cent. Presently, the final phase is in progress to eliminate the last 10 percent of TCA utilized for RSRM manufacturing. This paper provides general details of the RSRM ODC Elimination effort.

DISCUSSION

In 1989, approximately 1.4 million pounds (125,000 gallons) of TCA was used in the fabrication of RSRM components. Since the commencement of a systematic TCA conservation and elimination effort in 1989, the RSRM production TCA usage rate substantially dropped to about 7, 630 pounds (680 gallons) in 2000. The three-phase ODC Elimination Program accomplished this dramatic reduction in usage of this environmentally harmful solvent. Table 1 summarizes the general details of each phase of this program.

Table 1
Summary of Phases of ODC Elimination Program

Phase	Objective	TCA Savings (lbs/year)
Phase 0	Reduce TCA consumption by eliminating the corrosion prevention practice of coating metal components with HD-2 grease.	400,000
Phase I	Eliminate TCA vapor degreasing and implement alternative solvents for cleaning of propellant process equipment.	860,000
Phase II	Implement alternative solvents/methods to replace TCA in hand cleaning operations.	140,000

The objectives and approaches to Phases 0 and I were straightforward and the efforts resulted in a 90 per cent reduction in TCA consumption for RSRM manufacturing. These phases consisted of the extensive facility changes itemized in Table 2.

Table 2 Key Phase 0 and I Facility Modifications	
Manufacturing Center	**Description of Facility Modification**
Refurbishment	Environmental chambers for the shipping of metal hardware.
Refurbishment	Three-axis water blast facility to refurbish case hardware.
Refurbishment	Five-axis water blast facility to refurbish nozzle hardware.
Refurbishment	Aqueous cleaning system to clean metal hardware.
Insulation	Large aqueous cleaning system to clean case and nozzle metal hardware.
Insulation	Small aqueous cleaning system to clean igniter metal hardware.
Note: Manufacturing Centers are also referred to as Work Centers. See Table 3 for a list of RSRM Manufacturing Centers.	

Table 3 RSRM Manufacturing Centers	
Manufacturing Center	**Principle Production Objective**
Refurbishment	Refurbish post flight hardware
Insulation	Prepare case hardware for propellant casting
Nozzle	Prepare and assemble nozzle hardware
Mix/Cast	Mix and cast propellant
Final Assembly	Install systems tunnel
Test Area	Conduct full-scale static testing

The principal accomplishment of Phase I was the elimination of two large vapor degreasers at the Refurbishment and Insulation Manufacturing Centers. These degreasers consumed copious amounts of TCA. Phase I also down-selected solvents to replace TCA for the majority of the hand and tooling cleaning operations for the Mix/Cast Manufacturing Center.

It is important to mention a TCA replacement effort independent of and parallel to the Phase I. This effort consisted of alternative solvent down-selection and implementation for hand cleaning processes at the Kennedy Space Center (KSC) in Florida. In terms of the diversity of TCA usage applications, this effort was a microcosmic representation of Phase II. Therefore, it helped establish the test protocol for Phase II. Ultimately, this test effort identified two solvents, Reveille and PF Degreaser, as effective TCA replacements.

It should be noted that the Phase 0 and I TCA usage alternatives were mostly implemented prior to the production ban of TCA on January 1, 1996. Clearly, the RSRM program required TCA for production continuation beyond this date. To sustain the program through subsequent years TCA was stockpiled. Also, the United Nations Environmental Programme/Montreal Protocol was petitioned for extended usage through an Essential Use Exemption (EUE) Request. Ultimately, the RSRM Program was granted usage of 375,000 lbs over a 12 to 15 year period to about 2010. This TCA is produced on an as needed basis by the vendor and approximately one-third has been consumed since exemption in 1996. Essentially, these supply extensions support RSRM manufacturing TCA requirements until completion of the Phase II effort.

Phase II, which is still in progress, accounts for the least percentage of production TCA usage. However, it is the most intricate because it involves an array of TCA hand cleaning applications. These applications encompass a range of processing soils, substrate types, and critical bond systems. The TCA Usage Matrix best illustrates the complexity and magnitude of this effort, which is a spreadsheet compilation of all RSRM manufacturing operations that specify TCA usage. This spreadsheet was generated to estimate the magnitude and define the scope of the Phase II effort. It lists about 870 operations that require TCA usage on approximately 30 substrate types and 36 different contaminants. To compound the complexity, each operation was prioritized and categorized by its criticality to the performance of the RSRM system.

The Phase II effort was designed to simplify the convoluted task of TCA replacement in all RSRM hand cleaning applications. In general, the effort is outlined in Table 4.

Table 4 General Description of the Phase II Effort	
Task Name	**Description of Objective**
Stage 1 - Literature Survey	Develop a preliminary list of TCA replacement candidates through a study of the cleaner market. Conduct study of MSDS and technical data to reduce the list to a practicable number of candidates for Stage 2 testing. This effort resulted

Table 4 General Description of the Phase II Effort	
Task Name	**Description of Objective**
	in down-selection from approximately eighty to thirty TCA replacement candidates.
Stage 2 – First Down-Selection	Conduct safety, solubility, and compatibility testing to provide down-selection data for Stage 3 testing. This effort resulted in down-selection from to approximately seven candidates per substrate family.
Stage 3 – Second Down-Selection	Determine cleaning effectiveness of each candidate through surface analysis testing and subscale testing of specimens representative of sensitive RSRM bond systems. This effort resulted in down-selection to approximately three candidates per substrate family.
Stage 4 – Third Down-Selection	Determine cleaning effectiveness of each candidate through subscale testing of specimens representative of critical RSRM bond systems. This effort resulted in down-selection to one candidate per manufacturing center
Stage 5 – Verification Testing	Confirm the cleaning effectiveness of the down-selected candidates on all RSRM bond systems.

The following paragraphs contain a discussion of each stage of the Phase II effort.

Stage 1 - Literature Survey

A survey of the cleaning industry was conducted. The product of this survey was a spreadsheet compilation of about 80 solvent and aqueous cleaning candidates. This spreadsheet contained general information about each candidate amassed from MSDS and technical data documents. This information provided input for a down-selection method called quality functional deployment (QFD). QFD is a technique which scores each candidate based on its potential against performance criteria that are ranked by a representative population of technical experts. Effectively, the QFD analysis reduced the list to 30 candidates of greater TCA replacement potential. The performance criteria ranked and utilized for the QFD analysis included the following items:

- Flammability – flash point
- Evaporation rate – vapor pressure
- Toxicity – carcinogenicity, TLV, and PEL
- Nonvolatile residue
- Cost
- Shelf-life
- Vendor stability
- Regulatory issues
- Cleaning performance
- Compatibility/corrosion
- Industry popularity
- Worker compatibility
- Versatility

Table 5 lists the candidates selected by the QFD analysis.

Table 5 Stage 1 Down-Selection Candidates	
Solvent/Aqueous Cleaner	**Vendor**
AmberClean™ Q3 (aqueous)	Innovative Organics
Ax-It (aqueous)	Morrell's Plating
BIOACT® 113	Petroferm
BIOACT® 145	Petroferm
Brulin® SD 1291	Brulin®
Borothene E	Advanced Chemical Designs
Degreeze 500 LO™	Solvent Kleene Inc.
DS-108	Dynamold, Inc.
Ecosolve 5	Spraylat Corp.
Ensolv XT	Enviro Tech
HFE-7100	3M™
Hurrisafe™ 9575 (aqueous)	PCI of America
HTF-60	Solvent Solutions
K-9200	Kyzen Corp.
InproClean 4000 (aqueous)	Chemetall Oakite
Vertrel® MCA Plus	DuPont®
Oxsol® 100	Oxy Chem®
BIOACT® PCG	Petroferm
PFC-265-81	Petroferm
PF™ Ionsol	PTT Technologies
PF™ 145 HP	PTT Technologies
PF™ d'Ink	PTT Technolgies
PLUS-4™	Petroferm
Purasolv® ML	PURAC America
Teksol EP™	Inland Technology
Acetone (90%)/DI Water (10%)	N/A
Reveille	Dubois
Prime (aqueous)	Dubois
Isopropyl Alcohol	N/A
Ionox® BC	Kyzen Corp.
PF™ Degreaser	PTT Technologies

This list encompasses the market range of cleaner chemistries available at that time (circa 1996). The diversity of solvent chemistry was the product of another guideline, avoid selection of candidates with similar basic chemistries; e.g., d-Limonene, glycol ether, n-propyl bromide, etc.

It should also be mentioned that the final five candidates in Table 4 were extensively tested for Propellant and KSC Manufacturing Centers during the Phase I effort. These candidates were logical Phase II insertions for two reasons: 1) practical work experienced gained with the usage of these solvents during testing; and 2) to achieve the ambition of selecting a solvent common to all manufacturing centers.

Stage 2 - First Down-Selection

The list of candidates in Table 5 was recommended to Stage 2 for further down-selection testing. This phase consisted of consisted of the following general tests:

- Solubility testing of various production common soils
- Compatibility testing of various RSRM critical substrates
- Safety testing; e.g., reactivity, flammability, toxicity, etc.
- Evaporation rate testing.
- Clean-ability testing.

The clean-ability tests were subscale production replications of hand cleaning of various RSRM substrates. In the final analysis, this measure of cleaning effectiveness weighed heavily. This test also became a standard of solvent cleaning effectiveness throughout the Phase II effort. The clean-ability data are listed in Table 6.

Table 6
Stage I Clean-Ability Scores

Solvent	Score
AmberClean Q3	0
Ax-It	0
BIOACT 113	15
BIOACT 145	18
Brulin SD 1291	1
Borothene E	8
Degreeze 500 LO	10
DS-108	9
Ecosolve 5	17
Ensolv XT	9
HFE-7100	0
Hurrisafe 9575	3
HTF-60	4
K-9200	9
InproClean 4000	2
Vertrel MCA Plus	7
Oxsol 100	14
BIOACT PCG	17
PFC-265-81	0
PF Ionsol	16
PF 145 HP	15
PF d'Ink	18
PLUS-4	15
Purasolv ML	3
Teksol EP	6
Acetone (90%)/DI Water (10%)	0
Reveille	8
Prime	0
PF Degreaser	6
Isopropyl Alcohol	3
Ionox BC	5
TCA	10

The clean-ability data clearly showed the ineffectiveness of aqueous based cleaners in cleaning RSRM common soils and substrates. Thus, aqueous candidates were eliminated from consideration. The data also isolate a population of superior candidates (score of ≥ 15). These candidates were recommended for Stage 3 testing.

Note that the clean-ability value for TCA is listed in Table 6. This detail indicates that the ultimate measure of cleaning effectiveness for the TCA replacement candidates was performance comparison of equal to or better than the control, TCA hand cleaning. This criterion for success was quantitatively and qualitatively used to judge solvent cleaning effectiveness throughout the Phase II effort for a variety of parameters.

Stage 3 - Second Down-Selection

Stage 3 down-selection testing was segregated by substrate families common to the RSRM system. This approach was logical because there are criteria and issues unique to each type of substrate. For example, corrosion is an issue more crucial to metal substrates. The substrates targeted by and solvents tested during Stage 3 are itemized in Table 7.

Table 7 Stage 3 Down-Selection Candidates		
Substrate Family	**Substrates**	**Solvent Candidates**
Metal	Aluminum Steel	BIOACT PCG PF 145 HP Ecosolve 5 Oxsol 100 PF d'Ink BIOACT 145 BIOACT 113
Rubber	EPDM NBR	PF Degreaser BIOACT PCG PF 145 HP BIO ACT 145 PF d'Ink Ecosolve 5 PF Ionsol BIOACT 113 Reveille
Phenolic	Glass cloth Carbon cloth Silica cloth	BIOACT PCG PF 145 HP Ecosolve 5 Oxsol 100 PF d'Ink BIOACT 145 BIOACT 113
Painted	Aluminum paint system Steel paint system	PF Degreaser BIOACT PCG PF 145 HP BIOACT 145 Oxsol 100 Ecosolve 5 Reveille

The basic objective of this phase was to down-select and recommend three candidates for Stage 4 testing of each substrate family.

This phase involved a series of tests, which assessed the cleaning effectiveness of each solvent on substrates of specimens representative of **sensitive** RSRM bond systems. Also, tests were conducted to characterize the properties (surface morphology, diffusion, chemistry, surface energy, etc.) of the residues of each candidate. These data were processed through another QFD analysis and a list of candidates was recommended into the next phase of testing.

Another important Stage 3 activity was a survey of personnel in the Industrial Hygiene and Environmental organizations. This survey considered the following health and regulatory issues:

- NESHAP impact
- Vapor pressure
- Similarity with other HAPS
- Air permit impact
- Flash point
- Toxicity
- History
- OSHA regulatory concerns

The feedback of this survey contributed heavily to the elimination of Oxsol 100 and Ecosolve 5. The solvents are ranked in order of preference in Table 8.

Table 8 Environmental and Industrial Hygiene Survey Results	
Environmental Ranking	**Industrial Hygiene Ranking**
PF Degreaser	PF Degreaser
PF-145 HP	PF-145 HP
PF d'Ink	PF d'Ink
PF Ionsol	PF Ionsol
PLUS-4	Reveille
Reveille	PLUS-4
BIOACT PCG	BIOACT PCG
BIO CT 113	BIOACT 113
BIOACT 145	BIOACT 145
Ecosolve 5	Ecosolve 5
Oxsol 100	Oxsol 100
Note: PLUS-4 was added as a candidate during performance of this survey.	

Stage 4 Down-Selection

The objective of this phase was to down-select to one candidate for each substrate family. The list of candidates tested is compiled in Table 9.

Table 9 Stage 4 Down-Selection Candidates		
Substrate Family	**Substrates**	**Solvent Candidates**
Metal	Aluminum Steel	BIOACT PCG PF 145 HP BIOACT 145 PF Degreaser PLUS-4 PREPSOLV
Rubber	EPDM NBR	PF Degreaser BIOACT PCG PLUS-4 PREPSOLV BIOACT 145 BIOACT 113

Table 9 Stage 4 Down-Selection Candidates		
Substrate Family	**Substrates**	**Solvent Candidates**
Phenolic	Glass cloth Carbon cloth Silica cloth	BIOACT PCG PF 145 HP BIOACT 145 PF Degreaser PLUS-4 PREPSOLV
Painted	Aluminum paint system Steel paint system	PF Degreaser BIOACT PCG PF 145 HP BIOACT 145 PLUS-4 BIOACT 113
Miscellaneous	Cork Propellant Castable inhibitor Polysulfide Silicone rubber RTV Other	PLUS-4 PF Degreaser PREPSOLV BIOACT 145 Ionox BC BIOACT PCG
Hybrid	Bond systems, which involve a variety of the above substrates.	PF Degreaser BIOACT PCG PLUS-4 PREPSOLV BIOACT 145 BIOACT 113

PREPSOLV and PLUS-4, previously untested and unselected candidates, were added because of successful implementation at other Thiokol Propulsion manufacturing centers. Also, the candidate lists were adjusted in pursuit of the goal to implement a manufacturing center common solvent. For example, PF Degreaser was inserted as a candidate for metal substrates because of its effective performance on other substrates and successful implementation in the Propellant and KSC Manufacturing Centers.

This phase involved solvent cleaning effectiveness evaluation on substrates of specimens representative of **critical** RSRM bond systems.

In parallel with the subscale testing of Stage 4, the manufacturing centers (Table 3) began testing the cleaning effectiveness of the solvents on full-scale hardware. During full-scale hardware cleaning, operators were surveyed for a reaction to the odor and cleaning effectiveness of each solvent. This feedback provided crucial input for subsequent QFD analyses. In fact, negative operator reactions to solvent odor eventually resulted in the elimination of BIO ACT 145 and PF-145 HP.

The full-scale simulation activities were invaluable in acclimating the operations workers to the intricacies of using a new solvent and hand-wipe process. These experiences provided lessons learned information and circumvented potential catastrophic production problems. Table 10 provides a list of lessons learned during full-scale testing.

Table 10 Lesson Learned from Full-Scale Testing		
Manufacturing Center	**Lesson Learned**	**Mitigation Response**
Insulation	Uncured rubber incompatibility with terpene-based solvents.	Eliminate hand cleaning of uncured rubber.
Insulation	Flex bearing bond system incompatibility with low vapor pressure solvents.	Short term; segregate flex bearing bond system cleaning for TCA critical usage. Long term, down-select a niche solvent.
Final Assembly	Operator incompatibility with BIO ACT 145.	Implement the back-up candidate, PF Degreaser.
Refurbishment	Operator incompatibility with PF-145 HP.	Implement the back-up candidate, PF Degreaser.

<u>Stage 5 – Verification Testing</u>

Stage 5 testing involves verification of the down-selected solvent and hand wipe process on all RSRM critical bond systems. Essentially, Stage 5 consists of execution of matrices that include subscale specimens representative of all bond systems for each manufacturing center. These matrices include zero time and aging testing. This effort is largely complete for the Mix/Cast, Refurbishment, Insulation, and Final Assembly Manufacturing Centers. Table 10 lists the solvents down-selected for verification testing.

Table 10 Down-Selected Solvents	
Manufacturing Center	**Solvent**
Refurbishment	PF Degreaser
Insulation	PLUS-4
Nozzle	Stage 5 is in progress
Mix/Cast	PF Degreaser Ionox BC
Final Assembly	PF Degreaser
Test Area	Stage 5 is in progress

Ultimately, the Stage 5 data provided a basis for full-scale RSRM static motor testing of the replacement solvents and associated hand cleaning processes. Upon successful demonstration through static motor testing each replacement solvent will be implemented for production usage. To date, PF Degreaser was successfully implemented for most Propellant and Refurbishment Manufacturing Center applications through static motor testing.

Activator Down-Selection

A previously unmentioned part of Phase II involves testing to identify a replacement solvent for rubber activation. Considerable TCA quantities are used for rubber activation during lay-up in the Insulation Manufacturing Center. This unique application requires a high vapor pressure solvent, which can make the rubber tacky. Activation tests were conducted on the solvent candidates listed in Table 11.

Table 11 Activator Candidates	
Solvent	**Vendor**
Ensolv XT	Enviro Tech International
Leksol	Advanced Chem Design
Vertrel MCA	DuPont
PF d'Ink	PTT Technologies
PLUS-4	Petroferm

Eventually, Vertrel MCA was down-selected through QFD analysis of the subscale data. However, this solvent performed unacceptably during full-scale tests. (This event was another manifestation of the usefulness of lessons learned through full-scale tests.) Consequently, the candidate, Leksol, was reconsidered. Leksol demonstrated activation properties superior to TCA during full-scale testing. However, the industrial hygiene organization judged it unacceptable because of n-propyl bromide regulatory uncertainties. As a result, the search for an alternative activation solvent continues.

CONCLUSIONS

In theory, the objective to eliminate TCA usage in the manufacturing of the RSRM components is straightforward. However, the mechanism to achieve this objective is technically challenging and requires considerable time and resources. The scope and complexity of this objective is compounded by the conservative approach of the RSRM Program toward process and material changes. Nevertheless, the ODC Elimination effort successfully identified and implemented TCA alternatives to reduce usage by ninety percent. The balance of RSRM TCA usage will be eliminated over the next three years. Ultimately, TCA elimination will be accomplished without compromise to the performance of the RSRM components.