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Non-Polluting Composites Repair and Remanufacturing for Military Applications: An Environmental and Cost-Savings Analysis

by Bruce K. Fink, Steven H. McKnight,
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Abstract

Polymer-matrix composite material and structural adhesive repair and manufacturing have significant environmental costs for Department of Defense (DOD) use. The principal issues for reducing environmental costs are (1) reducing hazardous waste by eliminating shelf-life limitations; (2) reducing nitrogen oxides (NO_x) by replacing global heating of the part with localized heating; (3) reducing volatile organic compound (VOC) emissions by accelerated curing and containment; and (4) reducing production debris hazardous waste through processing step management. Due to the wide range of applications and material systems, as well as scenarios spanning manufacturing and depot and field repair, a family of solutions is described that is expected to meet these needs. An environmental baseline is established by identifying hazardous materials from composite repair and manufacturing operations and estimating usage and waste. The predicted reduction in hazardous waste is 78% for composite materials and 95% for adhesives. NO_x and VOC emissions can be reduced by 100% and 50% by using the proposed techniques. Conservative environmental cost-savings estimates are developed for several potential DOD applications. These estimates indicate that the use of the proposed technologies for DOD systems would provide an annual savings of $15 billion (1997) for the year 2028.

Acknowledgments

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Table of Contents

		Page
	Acknowledgments	iii
	List of Figures	vii
	List of Tables	ix
1.	**Introduction and Overview**	1
2.	**Environmental Baseline**	4
2.1	Volatile Organic Compounds (VOCs)	4
2.2	Nitrogen Oxide (NO_x)	5
2.3	Hazardous Waste Caused by Shelf-Life Expiration	6
2.4	Hazardous Waste—Production Debris	6
3.	**Potential Environmental Savings**	9
3.1	Introduction	9
3.2	Environmental Savings	10
3.2.1	*Reduction in VOC Emissions*	10
3.2.2	*Reduction in NO_x*	11
3.2.3	*Reduction in Waste Due to Shelf-Life Expiration*	12
3.2.4	*Reduction in Production Debris Hazardous Waste*	12
3.3	Cost Savings	13
3.4	Future Usage	13
3.4.1	*Joint Strike Fighter*	14
3.4.2	*Advanced Enclosed Mast/Sensor System*	14
3.4.3	*Future Scout and Cavalry System*	15
3.4.4	*Predicted Future Use*	15
3.5	Summary	17
4.	**Potential Technological Approaches**	17
4.1	Background and Approach	18
4.2	Specific Methods	19
4.2.1	*Radiation Curing*	20
4.2.2	*Electromagnetic Curing*	24
4.2.3	*VARTM/CIRTM Processing*	27
4.2.4	*Comparison of Techniques*	30

Page

5. Analysis of Potential Applications 31

5.1 Aircraft Skin Repair 35
5.2 Airframe Remanufacture 36
5.3 Rotorcraft Repair 37
5.4 AEM/S System Repair/Remanufacture 37
5.5 Integral Armor 40
5.6 Sabot Remanufacture 41

6. Plans for Future Environmental and Cost Analyses 42

7. Summary/Conclusions 43

8. References 45

Appendix: Example Detailed Cost Analyses for Proposed Techniques 49

Distribution List 79

Report Documentation Page 89

List of Figures

Figure		Page
1.	Predicted Growth of Adhesive Demand	1
2.	Hazardous Waste and Emissions as By-Products of Repair and Remanufacturing	3
3.	Emissions Reduction and Recycling via Containment of VOCs	5
4.	Shelf-Life Expiration	6
5.	Waste in Manufacturing Composite Materials for Military Vehicles	9
6.	Waste in Manufacturing Military Vehicles	9
7.	E-Beam Cure for Reduction of Hazardous Emissions	11
8.	E-Beam Cure for Reduction of Hazardous Wastes	12
9.	Use of Composites in Aircraft Manufacture	16
10.	Radiation Repair Techniques	21
11.	Electromagnetic Repair Techniques	25
12.	Induction Heating	26
13.	Optimization of Coil and Mesh Geometries	26
14.	Reduction in Processing Debris Through Reducing Production Steps	28
15.	Integral Armor on the Composite Armored Vehicle	29
16.	Resin System Formulations	30
17.	One-Sided Skin and Honeycomb Core Repair	36
18.	Rotorcraft Repair	38
19.	AEM/S System	39
20.	Crusader Self-Propelled Howitzer and Resupply Vehicle	41
21.	Sabot	42

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List of Tables

Table		Page
1.	Shelf-Life Limitations of Commonly Used Composite Materials	7
2.	Shelf-Life Limitations of Commonly Used Adhesives	7
3.	Hazardous Materials in Uncured and Partially Cured Composites and Adhesives	8
4.	Repair Cure Method Comparison	32
5.	Range of Techniques and Material Forms for Example Applications	33
6.	Range of Scale and Repair/Remanufacture Location for Example Applications	34

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1. Introduction and Overview

Recent (1996) figures for annual defense usage of polymer-matrix composite (PMC) materials are 23.7 M-lb [1]. Total composite shipments by the U.S. in 1997 were 3.42 billion pounds [2], with transportation use of composites exceeding 1 billion pounds for the first time [3]. PMC materials are currently used in Department of Defense (DOD)-fielded applications, including the Army's Apache and Blackhawk helicopter rotorblades, Navy surface ship superstructure components, and Air Force and Navy high-performance aircraft. Common materials used in aircraft applications are carbon-fiber-reinforced epoxies and polyimides. The most prevalent fabrication method is prepreg layup with autoclave cure. For expanding marine and ground vehicle applications, increased use of glass-fiber-reinforced epoxies, vinyl esters, and phenolics is anticipated.

The use of adhesives for aircraft and aerospace has been reported as 21 M-lb in 1996, with a predicted increase of 7.4% a year to 30.0 M-lb in 2001 [4]. Overall usage of structural adhesives by DOD is estimated as 45 M-lb, 5% of total industrial usage of 900 M-lb. Total amounts of common adhesives sold by type are shown in Figure 1. While a breakdown in DOD usage was not available for this report, use of epoxy adhesives is common for DOD repair applications.

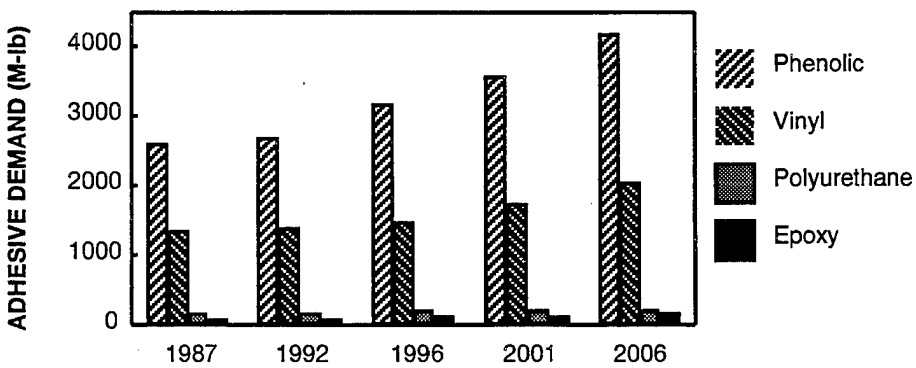


Figure 1. Predicted Growth of Adhesive Demand [4].

In addition, the use of PMC materials and structural adhesives is on the verge of an unprecedented increase as a result of such developmental and future programs as the Army's Comanche helicopter, Composite Armored Vehicle (CAV), and Crusader howitzer as well as the Navy's Advanced Enclosed Mast/Sensor (AEM/S) System and other surface ship superstructures. These applications could all be in production within the next 5–15 years, consuming millions of pounds per year of raw materials. An important part of these current and future programs is the development and implementation of applicable field and depot repair procedures. It is recognized that repair techniques and materials used for the current applications have deleterious environmental effects and that technological improvements can be made to significantly reduce hazardous waste and emissions and reduce costs. In addition, remanufacturing of previously developed PMC components must be considered from two perspectives. First, the same technological improvements may be useful in reducing environmental impact and cost for the manufacture of these PMC components. Second, some of the PMC components in these programs were designed, or are currently being designed, with no provision for practical, environmentally friendly, and affordable repair. The redesign of components to incorporate these processing changes and enable repair is called *remanufacturing*.

There are unique requirements for DOD environmental issues and use of composites. The DOD must be prepared to repair fielded composite applications in the theater of operations where required raw materials are not generally available. Consequently, raw materials are stockpiled in anticipation of use.

Often, raw materials with limited shelf life are shipped to the repair location, the shelf life expires, and the resulting hazardous waste must be shipped back to the continental U.S. for disposal. These resins often expire before delivery to the remote repair facility and must immediately be disposed of as hazardous waste [5]. Composite repair processing sites must meet emissions and hazardous waste standards that vary from nation to nation as well as from state to state within the U.S. While the amount of PMCs and adhesives used for DOD applications is small relative to the overall use of these materials, specific materials and processes are used predominantly for DOD applications. Structural adhesives are an example of a material class

that has relatively high DOD usage. Consequently, the organization with the predominant interest in addressing environmental issues specific to these materials, processes, and repair scenarios must be DOD.

PMC manufacturing and repair processes result not only in a repaired or manufactured part but also in hazardous waste, hazardous emissions, and solid waste (Figure 2). The increased use of composite materials will lead to

(1) increased waste stream (trim, consumables, volatile organic compound [VOC] emissions) for repair,

(2) increased hazardous waste stream due to shelf-life expiration, and

(3) increased dependence on autoclave (nitrogen oxides [NO_x,], refrigeration).

Eliminating or at least minimizing the contribution of composite repair and remanufacture to the waste stream will grow in importance as the use of composite materials expands.

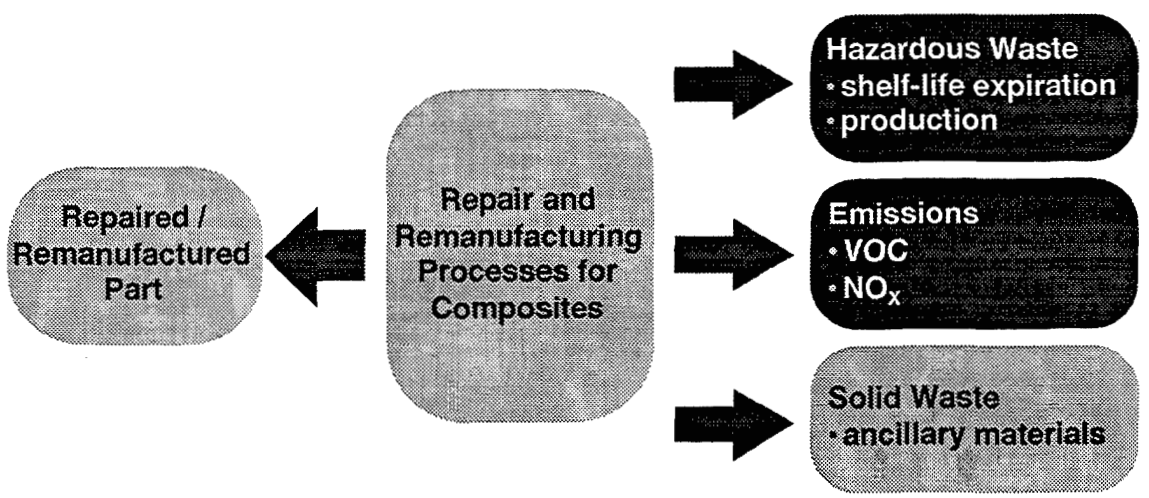


Figure 2. Hazardous Waste and Emissions as By-Products of Repair and Remanufacturing.

Consequently, DOD requires (1) a reassessment of current repair procedures; (2) the maturation of new technologies that reduce hazardous emissions and waste due to repair; and (3) the redesign and remanufacture of components incorporating new technologies that maximize the opportunity for practical, affordable, and reliable repairs. Any new technologies are expected to reduce environmental impact and its associated costs. An analysis of environmental impact and cost is appropriate to evaluate the anticipated benefits of new technologies at the beginning of new technology maturation programs to ascertain whether such improvements are cost beneficial. This environmental and cost analysis is presented in terms of current and future material usage and resulting environmental impact and costs.

2. Environmental Baseline

An environmental analysis of current and potential replacement technologies has been performed to demonstrate how potential replacement technologies would significantly reduce hazardous emissions and hazardous waste. This analysis establishes methods and preliminary numbers.

During repair and manufacturing with structural adhesives and composite materials, hazardous emissions, hazardous waste, and solid waste are generated (Figure 2). Hazardous emissions, primarily VOCs and NO_x, are given off during repair and manufacturing processes. Hazardous and solid wastes result from the raw materials and from subsequent processing. Hazardous wastes include hazardous raw materials whose effective usage has expired and process-dependent materials that are scrapped or contaminated as part of the production process. Nonhazardous solid wastes are not considered in this report.

2.1 Volatile Organic Compounds (VOCs). VOCs are released from adhesives and from the resin component of composite materials during processing. Typical VOC content ranges from 2% by weight for epoxy to 15% for polyimides. The more conservative 2% value has been used in estimates for this analysis. Advantages and disadvantages of closed and open processes are shown in Figure 3. At least equally important are accelerated curing processes in which the raw materials polymerize before they can escape as emissions.

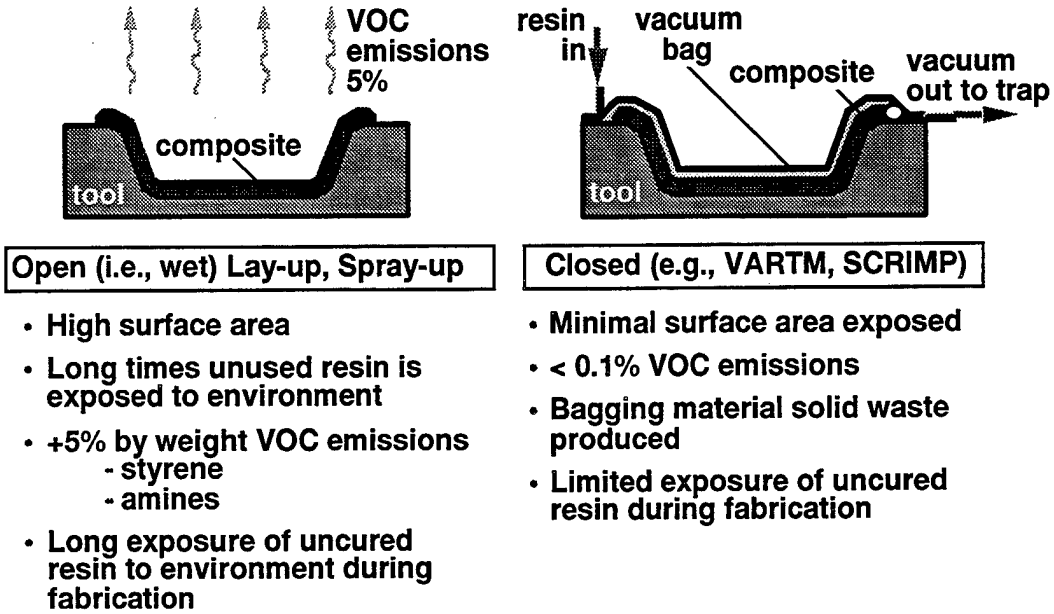


Figure 3. Emissions Reduction and Recycling Via Containment of VOCs.

2.2 Nitrogen Oxide (NO_x). NO_x is considered the sum of nitric oxide (NO), nitrogen dioxides (NO_2), and nitrogen tetroxide (N_2O_4) emitted from combustion sources. The gases affect ozone and are regulated as hazardous emissions. Amounts of NO_x generated are related to the volume pressurized with nitrogen gas during processing. The greatest source for NO_x in composite manufacturing and repair is autoclaves. NO_x generated in two different autoclaves was monitored by Northrop-Grumman for a 1-month period. Data was obtained for an 8,500-Btu autoclave for March 1998. During this period, aircraft control surfaces and composite patches and skins for space vehicles were processed in the autoclave. A total of 85.1 lb of NO_x was generated in 48 runs (averaging 1.77 lb of NO_x per run) and 270 hr (averaging 0.31 lb of NO_x per hr). For the second data set, information was gathered for a 12,000-Btu autoclave for the month of April 1998. Parts processed were aircraft control surfaces and skins for space vehicles. A total of 21.3 lb of NO_x was generated for 110 parts (averaging 0.2 lb of NO_x per part), 39 runs (averaging 0.55 lb of NO_x per run), and 340 hr (averaging 0.5 lb of NO_x per hr). Based on these numbers and typical part sizes, an estimate of 0.02 lb of NO_x per lb of composite was used to evaluate environmental savings. For adhesives, this number was increased to 0.2 lb of NO_x per lb of adhesive because the pressure is applied to the entire part that is processed. This estimate

provides some allowance for the influence of part size but is probably extremely conservative, since the ratio of part size to adhesive is generally higher than 9:1.

2.3 Hazardous Waste Caused by Shelf-Life Expiration. Most adhesive and composite material resin systems cure slowly during storage prior to use. For these systems, processing and performance requirements can be met only within the designated storage period or shelf life (Figure 4). Shelf-life limitations for commonly used composite material systems and adhesives are shown in Tables 1 and 2, respectively. No commercially available structural adhesives approved for use in DOD applications having a shelf life longer than 12 months have been identified. Shelf life is generally documented under a required level of reduced-temperature storage. Once the partially cured material is removed from cold storage, the limit on useful life is called "out-time." Materials that have exceeded shelf life or out-time are partially cured beyond acceptable limits, can no longer be used, and are considered hazardous waste. Epoxy and other commonly used resins have finite shelf lives and must be disposed of after expiration, creating unnecessary and expensive ($25–50 per lb) waste. Each year, millions of pounds of expired material and associated packaging are processed for disposal by DOD.

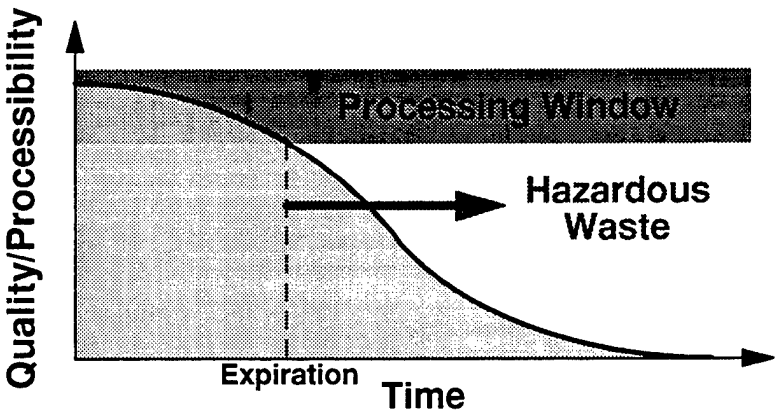


Figure 4. Shelf-Life Expiration.

2.4 Hazardous Waste—Production Debris. Production debris comprises scrap raw materials as well as vacuum bag material, sealants, and liquid shim. While the bagging, sealants, and shim may not be hazardous, they can become contaminated with partially cured resins and

Table 1. Shelf-Life Limitations of Commonly Used Composite Materials [6]

Resin/Fiber System	Processing Temperature (°F)	Service Temperature (°F, Dry)	Shelf-Life at 0°F (Months)	Out-Time at RT[a] (Days)
Epoxy/Carbon Fiber	250–350	180–450	6–12	10–30
Epoxy/Aramid Fiber	250–285	250	6	10–30
Epoxy/S-2 Glass Fiber	250–350	250–350	6	12
Bismaleimide/Carbon Fiber	350–475	450–600	6	28
Cyanate Ester/Carbon Fiber	250–450	450–480	12	30
Cyanate Ester/Quartz Fiber	250–350	200–350	6	21
Polyimide/Quartz Fiber	550–650	600	6	10

[a] Room temperature.

Table 2. Shelf-Life Limitations of Commonly Used Adhesives

Adhesive System	Processing Temperature (°F)	Service Temperature (°F, Dry)	Shelf Life at <40°F (Months)	Shelf Life at <77°F (Months)	Out-Time at RT[a]
Hysol EA 9390 two-part epoxy paste [7]	200	350	12	6	2 hr
Hysol EA 9394 two-part epoxy paste [8]	RT	350	12	12	1.5 hr
Hysol EA 9396/C-2 two-part epoxy paste [9]	200	400	12	12	8 hr
Hysol EA 9695 epoxy film [10]	250-350	300	6 at 0°F	3	90 days

[a] Room temperature.

adhesives during the production process. In this case, they must be treated as hazardous waste. Figures for production debris were identified for one site producing B-2 and F-18 composite parts. For 112 tons of raw material, 38 tons (34%) of production debris were generated [11].

Information on solid waste for composite materials for military vehicles was reported in 1995 [12]. The most common composite material system was carbon/epoxy (Figure 5). The largest

Table 3. Hazardous Materials in Uncured and Partially Cured Composites and Adhesives

	Chemical Name	Carcinogen	Mutagen
Epoxy	Boron Trifluoride, BF3	International Agency for Research on Cancer (IARC) Group 3 unclassified carcinogen to humans	No data available
	Bisphenol A	No data available	Potential mutagen
	Diglycidyl Ether of Bisphenol A, $C_{21}H_{24}O_4$	IARC Group 3 unclassified carcinogen to humans	Ames test both positive and negative results
	Epichlorohydrin, C_3H_5ClO	IARC Group 2A probable carcinogen to humans	Mutagenic activity in bacteria, animal tests positive
	Tetraglycidylbis (P-aminophynyl) methane	IARC Group 3 unclassified carcinogen to humans	Ames test positive
Epoxy Curing Agents	4,4' Methylene bis (2-Choloraniline) (MOCA), $C_{13}H_{10}Cl_2O_2$	IARC Group 2A probable carcinogen to humans	Ames test positive
	4,4' Methylenedianiline (MDA), $C_{13}H_{14}N_2$	IARC Group 2B possible carcinogen to humans	No data available
	Diethylenetriamine (DETA) $C_4H_{13}N_3$	No data available	Positive results in cultured mammalian cells
	Triethylenetetramine (TETA), $C_6H_{18}N_4$	Not classified	Ames test positive, found to be a direct acting mutagen
	Dicydiamide (DICY), $C_2H_4N_4$	Has not been investigated	Has not been investigated
	4,4' Sulfodianiline (DDS), $C_{12}H_{12}N_2O_2S$	Similar to MDA	Similar to MDA
Vinyl Ester	Styrene, C_8H_8	IARC Group 2B possible carcinogen to humans	Positive in vivo tests of animals
	Divinylbenzene, $C_{10}H_{10}$	No data available	No data available
Vinyl Ester Curing Agents	Benzoyl peroxide, $C_{14}H_{10}O_4$	IARC Group 3 unclassified carcinogen to humans	No data available
	Methyl ethyl ketone peroxide, $C_8H_{16}O_4$	No data available	No data available
	2,5-Dimethyl-2,5-di(2-ethylhexanoyl peroxy) Hexane, $C_{24}H_{46}O_6$	No data available	No data available
	Cumene hydroperoxide, $C_9H_{12}O_2$	No data available	Ames test positive
Phenolic	Phenol, C_6H_6O	IARC Group 3 unclassified carcinogen to humans	No data available
	Formaldehyde, CH_2O	IARC Group 2A probable carcinogen to humans	Positive in bacterial tests and in isolated human and animal tests
Phenolic Curing Agents	p-Phenolsulfonic acid, sodium salt, $C_6H_5SO_4Na$	By-product sulfuric acid mist is a Group 1 carcinogen	No data available
	p-Toluenesulfonic acid, $C_7H_8O_3S{\cdot}H_2O$	By-product sulfuric acid mist is a Group 1 carcinogen	No data available
Urethane	Methylenedi-p-Phenyl Diisocyanate (MDI), $C_{15}H_{10}N_2O_2$	IARC Group 3 unclassified carcinogen to humans	No data available
	Toluene-2,6-diisocyanate, (TDI) $C_9H_6N_2O_2$	IARC Group 2B possible carcinogen to humans	Positive in a number of vitro tests
Urethane Curing Agents	4,4' Methylene bis (2-Choloraniline) (MOCA), $C_{13}H_{10}Cl_2O_2$	IARC Group 2A probable carcinogen to humans	Ames test positive

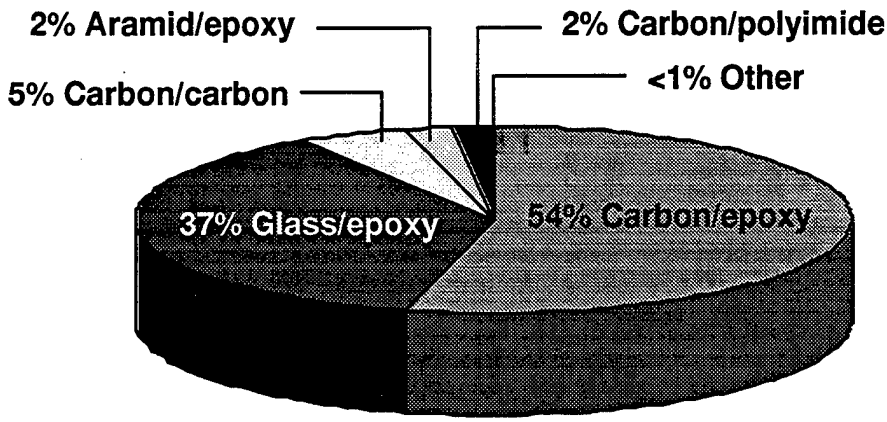


Figure 5. Waste in Manufacturing Composite Materials for Military Vehicles [12].

component of solid waste was prepreg (Figure 6). For this study, at least two-thirds of the waste material requires treatment as hazardous waste. Conservative estimates of production debris for this evaluation are 30% for composites and 10% for adhesives.

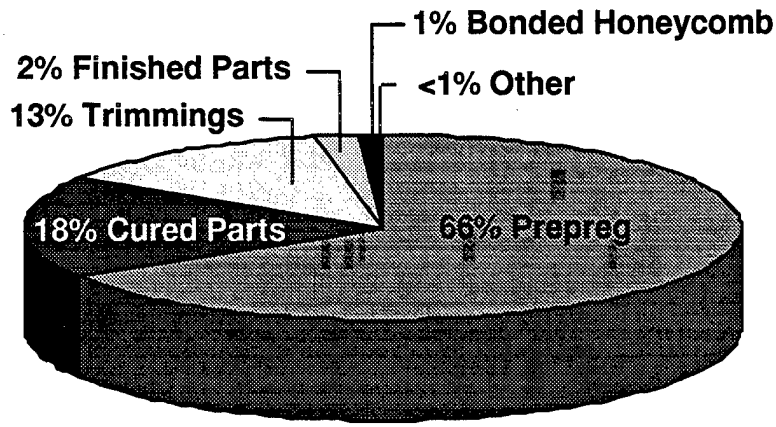


Figure 6. Waste in Manufacturing Military Vehicles [12].

3. Potential Environmental Savings

3.1 Introduction. No single solution can reduce the environmental impact of the entire range of materials, applications, and processing scenarios for composite repair and

remanufacture throughout DOD. However, there are a number of approaches to mitigating environmental impact. Reducing the production of hazardous emissions and wastes can be achieved by localized heating, reduction in shelf-life limitations, reduction in processing steps, and containment and recycling of VOCs.

Global heating in an autoclave requires the application of pressure on the entire part. Nitrogen is used to provide the pressure and leads to the large amount of NO_x generated in an autoclave. Curing processes with localized heating do not require the application of pressure on the entire part and are expected to reduce NO_x emissions. A secondary effect of localized heating is greater control of the cure process. A reduction in the number of parts that need to be reprocessed helps reduce production debris hazardous waste. The change to localized heating is the primary enabler for "moving-out-of-the-autoclave."

Hazardous waste generated as a result of shelf-life expiration can be eliminated by using alternative processing where appropriate. Furthermore, the number of processing steps can be reduced by combining processing steps with co-injection and, to a lesser extent, with localized heating. VOC emissions are reduced primarily by rapid curing, which ensures that low-molecular-weight materials polymerize before evaporating, thus providing large reductions in the production of volatile species. Shelf-life expiration can also be eliminated by remanufacturing thermoset-based composite components with thermoplastic-based designs and processes. The use of thermoset-based composites also eliminates VOC emissions.

3.2 Environmental Savings. Each replacement technology may produce different environmental savings. Depending on the selection and identification of criteria for the most appropriate replacement method for any given scenario, the savings will be different. For each type of savings, the amount expected for each procedure is provided below. Global savings are estimated, but the immediate target savings must be considered on a per-pound or per-part basis.

3.2.1 Reduction in VOC Emissions. A 50% reduction in VOC emissions is anticipated for thermoset-based composite processes that do not require an autoclave. For every pound of

adhesive or resin in a composite, VOC emission is conservatively estimated at 0.02 lb. The greatest reduction in VOC emissions among the replacement thermoset curing techniques is expected from E-beam curing. VOC emission for E-beam curing is expected to be 0.01 lb per pound of adhesive or resin. Reduction in VOC emissions for induction curing is not as substantial. It can be generalized that half of all current composites processing is in the autoclave, producing an average resin content of 50% by weight. With an overall DOD composites usage of 23.7 M-lb, the estimate of VOC emission from autoclave processing is 118,000 lb. If E-beam curing replaces autoclave cure, VOCs emitted will be reduced to 58,000 lb (Figure 7).

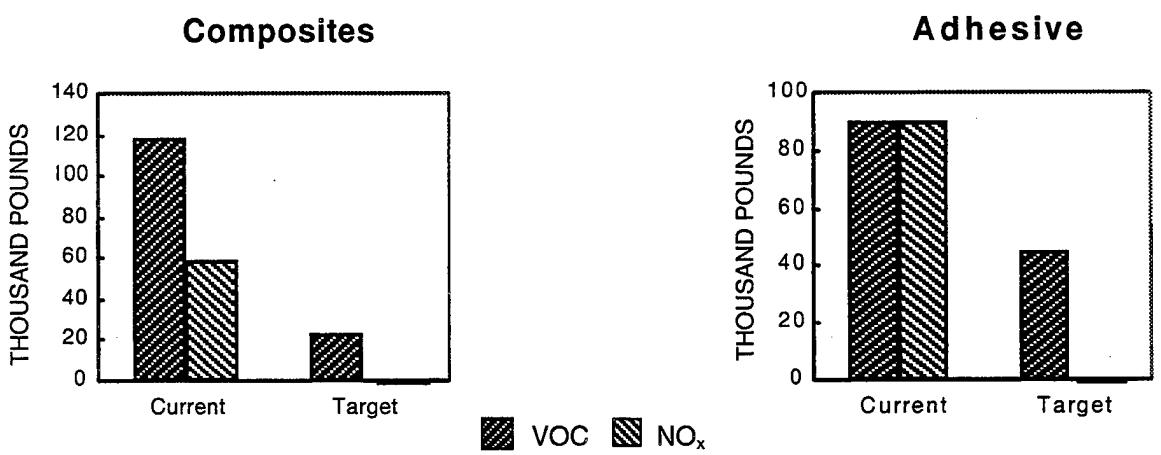


Figure 7. E-Beam Cure for Reduction of Hazardous Emissions.

For adhesives, much less material is processed in the autoclave. For this report, that amount has been estimated as 10% of all adhesives processed for DOD applications. Consequently, current VOC emissions generated in the autoclave are estimated as 90,000 lb/year. Assuming that processing improvements permit elimination of autoclave processing, the VOCs generated will be reduced to 45,000 lb/year.

3.2.2 Reduction in NO_x. Based on the previous numbers, current NO_x generated in autoclave processing is estimated as 0.02 lb per lb of composite. Thus, an estimate for current NO_x production is 23,700 lb. Eliminating the autoclave reduces this number to zero. Both

E-beam and induction curing meet these requirements. Estimates for adhesive processing in the autoclave are based on a factor-of-ten increase in the amount of NO_x per pound of adhesive, since the adhesive is processed with the adherends it joins. The factor-of-ten increase is based on the assumption that the part is nine times larger than the amount of adhesive.

3.2.3 Reduction in Waste Due to Shelf-Life Expiration. Extending or eliminating shelf-life restrictions is expected to reduce hazardous waste of expired material. Costs of rotating expired materials and replacing them with fresh materials would also be eliminated. Based on the proposed technologies, resins and adhesives that have limited shelf life can be replaced by materials with infinite shelf life. This replacement eliminates all hazardous waste from shelf-life and out-time expiration. Such hazardous waste generated currently is estimated as 20% of composites, or 4.7 M-lb, and 40% of adhesives, or 22 M-lb (Figure 8).

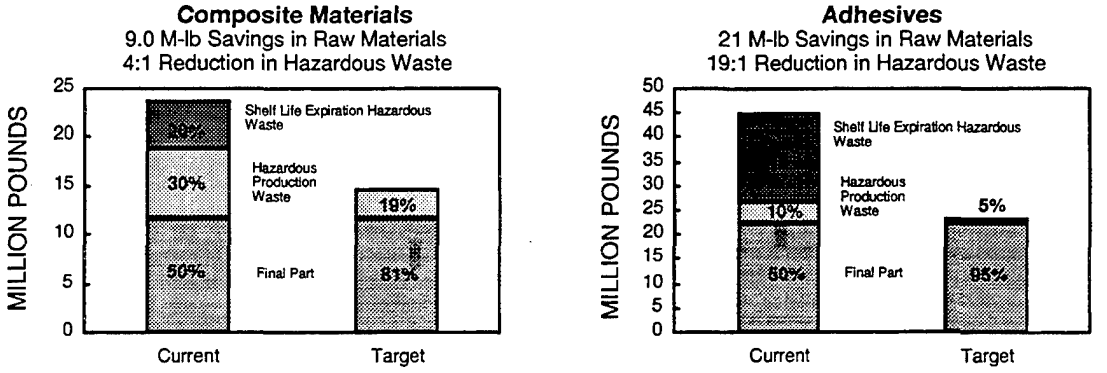


Figure 8. E-Beam Cure for Reduction of Hazardous Wastes.

3.2.4 Reduction in Production Debris Hazardous Waste. Production debris can be reduced by reducing the number of processing steps. Incorporating co-injection resin transfer molding technology, predictions for reduction in production debris hazardous waste are 33% for composite materials and 50% for adhesives. In addition, greater control associated with localized heating reduces requirements for reprocessing and thus reduces production debris. Estimates indicate that current production debris of 30% or 7.1 M-lb for composites can be reduced to 4.7 M-lb (Figure 8). Combined savings in hazardous waste (and, consequently, raw

materials) is 7.1 M-lb/year, or 78%, for composite materials and 20.3 M-lb/year, or 95%, for adhesives. This represents a total potential reduction in hazardous waste produced by DOD of nearly 24 M-lb/year.

3.3 Cost Savings. Assuming that all composites used at current annual DOD rates could be processed with the proposed methods, estimates of cost savings in raw materials exceed $270 M for composites ($30/lb) and $210 M for adhesives ($10/lb). A conservative estimate for handling hazardous waste for both composites and adhesives is $5/lb, with anticipated savings of $152 M. Thus, a conservative order-of-magnitude estimate for potential cost savings is $630 M. Furthermore, 10% is a reasonable estimate for repair usage and 25% for appropriate remanufacturing applications. Thus, 35%, or approximately $220 M, is an ultraconservative estimate for combined raw material and hazardous waste savings.

3.4 Future Usage. Predictions for future DOD usage of composite materials begin with consideration of a number of recent and current advanced development programs, including the following:

- Unmanned aerial vehicles Predator and Dark Star (Air Force) [13, 14].
- Comanche helicopter (Army).
- CAV (Army).
- Crusader Self-Propelled Howitzer (SPH) and Resupply Vehicle (RSV) (Army).
- Composite Army Bridge (Army/Defense Advanced Research Projects Agency [DARPA]).
- Future Scout and Cavalry System (Army/UK).
- Objective Individual Combat Weapons (Marines) [15].
- AEM/S System (Navy).
- Low Observable Multifunction Stack (Navy) [16].
- Multifunction Electromagnetic Radiating System (Navy) [16].
- Composite bumpers (Navy).

- Composite helicopter hangars and hangar doors (Navy) [16].
- Joint Strike Fighter (multiservice).

Other applications for composite materials under development include Navy corvette, mine hunter, and small combatant hulls, topside armor, internal decks, diesel power system components, and waterfront upgrades of reinforced concrete structures. Three of the advanced technology programs are considered as examples for the expanded use of composites.

3.4.1 Joint Strike Fighter. The JSF program is currently at the stage of competing concept demonstrations by two design teams [17, 18]. Over 3,000 aircraft are scheduled to go into production in 2008 for the combined needs of the U.S. Air Force, Navy, and Marines and the U.K. Royal Navy. Expected composites usage on the JSF is 45% by weight. The Air Force plan is for 2,036 JSFs to replace F-16s and A-10s. The use of composites on an F-16 is less than 5%, so replacement with a JSF increases use greater than eight-fold. The U.S. Navy (300) and U.S. Marine Corps (642) will replace F-18s (9%) and AV-8Bs (~22%), for smaller relative increases. Repair of the JSFs is estimated as approximately 3,000 planes × 45% composite × 5,800 lb/plane × 1% repair = 78,000 lb/year. Manufacture of the JSF is conservatively estimated at 200 planes per year, or 522,000 lb/year.

3.4.2 Advanced Enclosed Mast/Sensor System. With a prototype currently in use on the USS Radford, the AEM/S System is planned for the next 12 amphibious transport dock ships, LPD 17 onward, as well as the replacement carrier, CV(X), the Mid-term Sealift, LH(X), and the 21st Century Surface Combatant family, including 32 destroyers and additional cruisers [16, 19, 20]. Thus, equivalents of the mast/sensor system and more extensive use of composite structures are expected on more than 50 ships. If the same amount of composite material as on the initial AEM/S System is used on 45 ships, the manufacture of composites would average 6 ships/year × 30 tons/ship = 360,000 lb/year. Repair for 50 ships is estimated at 50 ships × 30 tons/ship × 1% repair/year = 30,000 lb/year. The amount of composites used per ship is expected to increase. The 21st Century Surface Combatant family includes advanced technology programs for composite helicopter hangar and hangar doors [19]. The hangar is viewed as a test case for

meeting more stringent fire and structural requirements than the AEM/S System. In addition, the possibility of using composites for the entire topside of the replacement carrier has been suggested.

3.4.3 Future Scout and Cavalry System. The Future Scout and Cavalry System (FSCS) is a ground-vehicle application of composite materials, with the first production vehicle scheduled for 2007 as part of Army XXI transitioning into the Army After Next (AAN) [21]. Each vehicle is estimated at 30% composite by weight. Anticipated manufacturing can be estimated at 80 per year for composites usage of 61 vehicles/year × 20 tons × 30% composite = 730,000 lb/year. Repair for 1,042 vehicles is predicted at 125,000 lb/year. This represents an immense increase in composite usage by the Army, as very little composite material is used at the present time. A number of similar vehicle structures are in the development and scale-up stages for AAN.

3.4.4 Predicted Future Use. Based on these example programs, a gross estimate of future (2028 timeframe) use of composite materials by DOD can be made. Current use of composites is primarily for fixed- (Air Force and Navy) and rotary-wing aircraft (Army and Navy) with some shipboard applications (Navy). A gross estimate of the increase of composites usage by the Air Force is one order of magnitude. Increased use by the Navy is significantly higher, with composites just beginning to be used for shipboard superstructure. The increase in the Army's use of composites is more difficult to address in terms of a percentage increase, since current usage is limited to rotorcraft applications, while composites are being considered for use in ground vehicles, bridging, and other applications that require relatively large amounts of material. The use of composite materials in military aircraft has expanded at an increasing rate over the past 30 years (Figure 9). If the use of composites in ground vehicles, marine structures, infrastructure, etc., increases at the same rate, a tremendous overall increase in the use of composites by DOD can be expected. In addition, these new applications can build on the experience garnered from aircraft, and the use of composite materials may increase at even higher rates. Consequently, an overall estimate of an increase of composite materials in DOD use by 2028 might reasonably be two orders of magnitude.

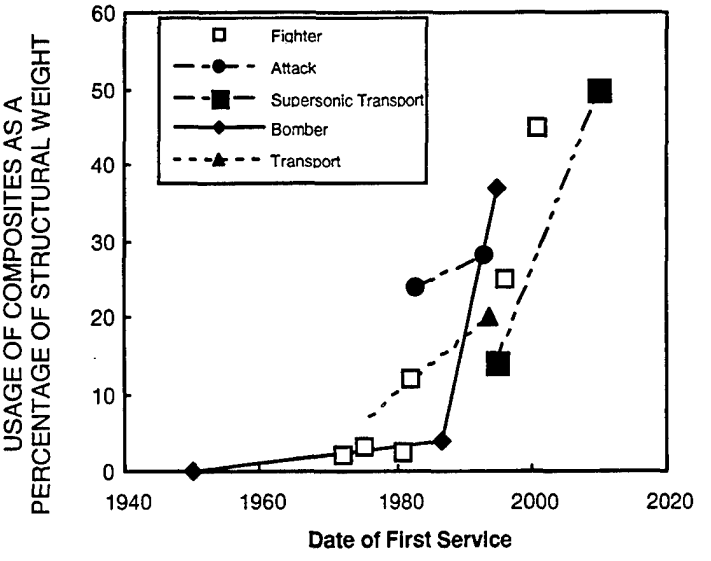


Figure 9. Use of Composites in Aircraft Manufacture.

Environmental savings can be scaled by a corresponding two orders of magnitude. Cost savings are not expected to expand at exactly the same rate, as current composites usage has not yet reached the point of greatest economies of scale. However, cost savings on overall implementation of the proposed techniques are estimated to increase by a factor of 70. Using the same 10% repair and 25% remanufacturing estimates noted previously, annual savings of $15 billion (1998) are predicted for 2028.

The use of adhesives is somewhat more difficult to predict. Based on 1996 figures and usage, aircraft and aerospace use of adhesives was predicted to expand at a rate of 7.4% per year [4]. As composites usage increases, the use of adhesives is likely to increase, but relative rates depend on particular processing methods. Also note that repair of metallic military aircraft structures is reported to be transitioning from bolted repair to bonded repair [7] and, in some cases, composite patches are being adhesively bonded to metal substrates. A significant increase in the use of adhesives is expected to result from this transition. An overall estimate of the increase in DOD adhesives is a factor of 20 by the year 2028.

3.5 Summary. Reductions in the environmental impact of repair and remanufacture of composite materials implemented now provide improvements in the short-term DOD usage of composite materials. Based on the expected increase in composites usage, reductions in environmental impact will have a much greater effect in the future. For adhesives, reductions in environmental impact implemented now provide improvements in the short term. Anticipated increases in DOD usage of structural adhesives support a prediction of significant increases in environmental improvement based on future usage.

4. Potential Technological Approaches

PMC applications in currently fielded applications and in development programs represent a wide range of component scales, manufacturing and repair techniques, and repair facilities. A few examples will highlight the breadth of issues to be addressed. The Navy superstructure components and Army ground-vehicle applications represent thick and sandwich structures manufactured using resin transfer molding with field repair requirements. Aircraft metallic and composite skins are repaired in the field and depot using composite prepregs and adhesives. Helicopter rotorblades include thin and sandwich composite structures, which are manufactured using composite prepregs and paste and film adhesives. Each application has different performance requirements, which lead to different designs, processing technologies, and materials systems. Consequently, one solution is not expected to provide reasonable improvements to all of these applications; rather, a family of solutions to improve these repair and remanufacturing scenarios is anticipated.

Based on assessment of existing repair procedures and direct involvement in many of the previously mentioned advanced development programs, a variety of recently developed composite processing and cure methods are considered as potential solutions for many of the wide range of DOD applications. These processing and cure methods include vacuum-assisted resin transfer molding (VARTM) and multi-resin co-injection resin transfer molding (CIRTM) processing techniques and electromagnetic (induction) and radiation (E-beam and ultraviolet [UV]) cure techniques to solve pollution problems in composites remanufacturing and repair for

military applications. These approaches will enable out-of-autoclave processing as well as reduce emissions from adhesive bonding operations. Used in tandem, these techniques can substantially reduce pollutants and waste in composite repair and remanufacturing. An additional benefit is the significant decrease in the need for recycling of scrap and waste materials through efficient use of materials. The number of processing steps required for the manufacture of multifunctional PMC components (e.g., Crusader and AEM/S System) will also be reduced, by up to 80%.

Different material forms, including film and paste adhesives and resins and prepregs for composite materials, are considered for each technique, as appropriate. Four different material systems—epoxy, vinyl ester, phenolic, and urethane—are considered, since they are common systems for these applications and represent reasonable examples to span the breadth of potential DOD applications. Common themes for the family of repair-friendly manufacturing techniques and repair procedures are processing without the use of an autoclave, elimination of limitations on the useful life of raw materials, and processing of more complex PMC components.

4.1. Background and Approach. A number of difficult issues are associated with the use of conventional heating and fabrication methods such as autoclaves and platen presses, e.g., high-temperature tooling requirements, tooling/part thermal expansion differences, and high-temperature bagging and sealant materials for autoclave processing. In particular, autoclave curing is used extensively for advanced composite material applications. As noted previously, relatively high VOC and NO_x emission are associated with autoclave curing, and hazardous waste generation can also be high due to expiration of resin shelf life and the use of sealants and bagging that are contaminated with hazardous waste during processing. Other disadvantages of high-temperature curing may also be alleviated by improvements in technology. For adhesive bonding, repair designs and design of the original component to allow for repair are constrained by processing limits of the adherends as well as the adhesive. These complexities increase the processing costs and thus reduce and in some cases negate the advantages of using these materials. The use of focused or directed-energy heating techniques can resolve these high-temperature processing problems. The ability to focus the heat for processing in thermoset

materials allows the use of low-cost/low-temperature tooling, reduces or eliminates part-to-tooling thermal expansion mismatches, eliminates the need for high-temperature sealants and bagging, allows bonding of low-temperature substrates, and, when combined with novel pressure application concepts, eliminates the need for expensive capital equipment such as autoclaves and presses.

For more than 20 years, various alternative curing techniques have been studied for composites and adhesive bonding processing, including radio frequency, UV, ultrasonic, microwave, electron beam (E-beam), induction, infrared, hot gas, and localized resistive heating. In general, these techniques use a focused/directed beam or energy field to generate heat only in the material to be processed and, in many cases, in only a very localized region of that material. Each of these techniques has merits and limitations, and, in general, understanding of these techniques and their applicability to processing has been limited to a relatively small number of researchers. Technical developments over the past 5 years, in areas such as susceptors for induction bonding and microwave applicators for carbon-fiber composites processing, offer significant opportunities to overcome the processing limitations of thermoplastic composites and adhesive bonding and can lead to very low-cost application of these materials in a wide variety of military and commercial end uses. The specific intent of this program is to research, select, and optimize the most promising alternate heating technologies; combine them with novel low-cost tooling concepts and repair methods; and demonstrate low-cost application to DOD demonstration components.

The following provides some background on the specific electromagnetic and radiation methods that offer the most value in repair and the most promise of successful transition in the near future.

4.2 Specific Methods. Out-of-autoclave processing using alternative cure technologies is an attractive method for reducing the environmental impact of repair processes. Controlled localized heating or site-specific curing of adhesives could reduce the number of repairs that require reprocessing due to improper heating blanket/autoclave cure. This would have great

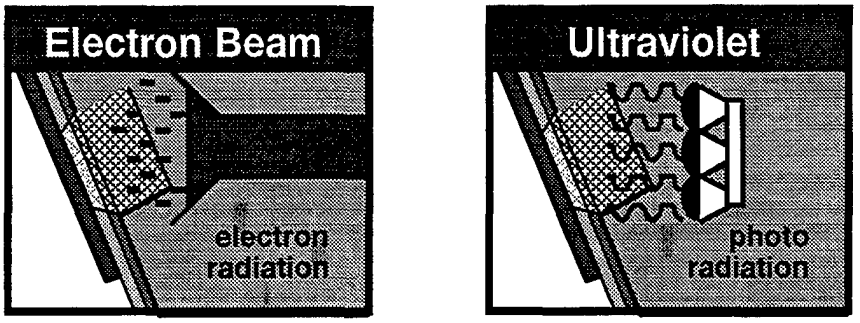
impact on the amount of waste generated during repair, including abrasive paper; paint, adhesive, and composite debris; wiping cloths; silicone sealants; bagging materials; and other consumables needed for current repair methods. Techniques such as E-beam, UV, resistance, and induction heating are all viable alternatives to standard autoclave processing. For purposes of discussion, this report focuses on E-beam (radiation) and induction (electromagnetic) as representative nonautoclave cure technologies.

4.2.1 Radiation Curing. The use of radiation-curable resins and thermoplastics for composite repair applications has significant advantages in terms of shelf life [22–26]. Since cure is controlled by exposure to radiation, the occurrence of slow reactions during storage is minimized. In the case of thermoplastic bonding, induction heating of a susceptor (or in the case of metals, the substrate) can be used to bond the adherends. Curing via radiation methods occurs at ambient temperature, avoiding severe thermal gradients and possibly reducing residual stresses and heat-induced distortion. Rapid curing also ensures that low-molecular-weight materials polymerize before evaporating, thus eliminating the production of volatile species. The advantages of radiation processing techniques—principally E-beam but also UV and visible light—to cure PMCs include the following:

- **Less atmospheric pollution**—VOC and NO_x emissions are reduced as a result of rapid, lower temperature processing, processing out of the autoclave, and reduced energy consumption.

- **Less hazardous waste**—Resins with extended to infinite shelf life can be formulated for radiation curing. Curing agents can be eliminated, and the number of processing steps can be reduced.

Other advantages include reduced curing times, continuous operation, and increased design flexibility through process control. The advantages and required approach for radiation repair techniques are summarized in Figure 10.



Advantages

- **reduction of hazardous materials**
  - **unlimited shelf life**
  - **elimination of curing agents**
  - **elimination of processing steps**
- **reduction of VOC and NO_x emissions**
  - **low-temperature processing**
  - **out-of-autoclave processing**
  - **low energy consumption**

Approach

- **toughened e-beam and UV-curable resin formulation**
- **repair sequencing**
- **optimize for testbed applications**

Figure 10. Radiation Repair Techniques.

E-beam curing is a nonthermal curing process that uses high-energy electrons and/or x-rays to initiate polymerization and cross-linking reactions at controlled rates. E-beam advantages counter many of the disadvantages of thermal curing. One particularly important advantage of E-beam-curable resins in terms of environmental concerns is long shelf life. Since the cure mechanisms are not triggered until the resin is exposed to the E-beam energy, the slowly occurring side reactions typical of epoxy adhesives formulated for thermal cure are not observed in E-beam systems. Thus, the disposal of over-aged and expired adhesives currently used in composite repair applications would be significantly reduced or even eliminated. The savings associated with reducing disposal and energy costs are also attractive from an economic standpoint.

While E-beam cure offers high potential as a low-cost, nonautoclave process for cure of large composite structures, few fundamental studies have been conducted on the radiation chemistry of composites. The primary challenges facing the current state-of-the-art E-beam resins are lack of

toughness, hot/wet operating temperature limits, consolidation rheology, the cost of E-beam equipment, and the perception of radiation safety concerns.

There are two common cure chemistries for inducing cure by irradiation: (1) vinyl-based systems, which cure via a free-radical chain addition mechanism, and (2) epoxy-based systems, which cure via chain polymerization. Examples of free-radical curing resins are unsaturated polyester, urethane acrylates, epoxy acrylates, and methacrylates. They all have double bonds in their molecular structures capable of sustaining free-radical chain polymerization initiated by radiation. Disadvantages of traditional free-radical curing resin systems include high shrinkage, brittleness, and low service temperature. Many of these shortcomings have been addressed by interpenetrating networks. These systems, developed by Science Research Laboratory and the University of Delaware Center for Composite Materials (UD–CCM) under Army Research Laboratory (ARL) Small Business Technology Transfer (STTR) funding (Contract No. DAAL01-96-C-0083), are based on the combination of step growth systems with free-radical polymerizable systems. They provide low shrinkage while possessing wet T_g values approaching 300°F; however, these materials must still be formulated to improve toughness. Most epoxies, including cycloaliphatic and bisphenol A systems, can be cured via cationic reactions by adding a photoinitiator such as diaryliodonium or triarylsulfonium salts. Cationic systems tested at Northrop-Grumman have shown encouraging thermal and mechanical property data, comparable with state-of-the-art thermally cured epoxy systems. The CAT-B system, developed for the "Affordable Polymer Composite Structures" program (Contract No. F33615-94-C-5014), has a 180°F/wet-service temperature and mechanical properties about 90% of the baseline 3501-6. The toughness is about 20% better than 3501-6. Another system, CAT-M, has a 250°F/wet-service temperature but requires substantially improved toughening to meet DOD requirements.

The proposed technologies promote out-of-autoclave processing methods and validate these techniques for specific manufacturing and repair applications. Nonautoclave processing using E-beams is very attractive for a number of reasons. Since the process occurs at room temperature, the need for external heating for adhesive cure can be eliminated, and very efficient

repairs can be performed at ambient conditions. An added benefit of the low-temperature processing associated with E-beams is the reduction of volatiles produced during cure. If this reduction is sufficient to prevent void formation, the need for vacuum bagging and autoclave applied pressure could be eliminated. The amount of consumables associated with vacuum bagging can be significant, and elimination of these materials from the repair process would represent a major step toward achieving the overall goal of providing nonpolluting composite repair technologies.

Recent research has also pointed to the possibility of integrating adherend surface preparation with the adhesive bonding process. Electron beams have been shown to produce bondable adherend surfaces and in certain instances create specific functional groups at the adherend-adhesive interface, which can bond covalently to the adhesive through grafting reactions. Improved joint properties can result, while the surface preparation steps become integrated into the bonding operation. Thus, the number of steps for the entire repair is decreased, which has a direct impact on reducing the waste associated with multistep processing.

The steps necessary to develop these techniques to the point where they can reasonably be adopted in the field are as follows:

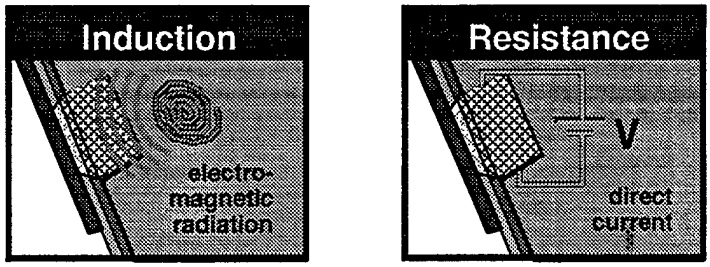
(1) **Formulate toughened E-beam adhesive and composite resin systems.** This effort is intended to toughen existing structural resins and adhesive formulations for assessment of their potential use in manufacturing and repair.

(2) **Demonstrate acceptable performance.** For each material, the properties of the resin need to be assessed through mechanical testing, related to cure conditions, and compared to baseline adhesive materials. Materials with the desired mechanical properties could then be selected for adhesive bonding assessment using the aluminum, composite, and mixed joint configurations and composite material studies. Thermochemical characterization techniques can be used to assess post-process degree of cure and glass

transition temperature. Chemical resistance to common solvents and fluids (fuels, oils, detergents, and decontaminants) should also be examined.

(3) **Develop and document repair sequencing and procedures.** E-beam curing methods should be investigated and optimized for repair and remanufacturing schemes. The techniques should be investigated and optimized for uniformity of bond, degree of cure, application to large-scale bonding and curing, and ease of operation. On-line feedback such as ultrasonic scanning, flow and cure sensors, and thermography should be employed for process and quality control. Nondestructive evaluation techniques such as sectioning/micrography and ultrasonic scanning should be used to assess post-process bond coverage. The schemes should include the appropriate sequence of repair steps, the applicable consolidation pressure technique, and the most suited cure technique.

4.2.2 Electromagnetic Curing. Electromagnetic cure methods involve using induction or electrical resistance heating focused directly at the material to be cured [27–32]. Induction heating occurs when a current-carrying body, or coil, is placed near another conductor, the susceptor material. The magnetic field caused by the current in the coil induces a current in the susceptor. This induced current causes the susceptor to heat due to Joule heating, and in the case of a ferromagnetic material, due to hysteresis losses. Carbon-fiber reinforcement in composite materials can function as the susceptor. For other material systems, the susceptor is a metallic mesh or magnetic particles. Energy can be introduced into the precise region to be cured both in the plane of the structure and at the specific depth required. Advantages of induction include reduction of VOC and NO_x emissions by processing out of the autoclave and processing a much smaller volume. Eliminating processing steps reduces hazardous waste, and energy consumption is also reduced. Other advantages of induction include internal, noncontact heating, the possibility of a moving heat source (the coil) to heat large areas, high power transmission, control of the heat generation by coil design or by susceptor design, and powerful, portable, and easy-to-operate units. The advantages and required approach for radiation repair techniques are summarized in Figure 11.



Advantages

- reduction of VOC and NO_x emissions
  - out-of-autoclave processing
  - smaller size
- reduction of hazardous waste generation by eliminating processing steps
- reduced energy consumption

Approach

- optimize thermal production/ distribution (particle size/ distribution, mesh density/ thickness, process cycle)
- performance evaluation (coupon testing, baseline with autoclave)
- develop repair schema
- optimize for testbed applications

Figure 11. Electromagnetic Repair Techniques.

Optimization of the induction bonding process (Figure 12) requires knowledge of the electromagnetic and thermal response of the adherends. Fink and colleagues at ARL and UD–CCM have modeled the response of the composite adherend to the alternating magnetic field and the field strength as a function of the coil dimensions and properties. Additionally, models have been developed to optimize the bond strength as a function of pressure, time, and temperature. Current collaborative work between ARL and UD–CCM in the area of induction welding involves modeling the response of the metal mesh/epoxy (Joule losses) or a magnetic particle-filled polymer layer (hysteresis losses) to the alternating magnetic field as a function of possible screen geometries, particle size, particle loss properties, etc. This two-part approach will help identify the advantages and disadvantages of the respective susceptor configurations and define applicability to cases of practical interest.

The two key requirements of the susceptors are uniform temperature distribution in the susceptor layer and temperature control. Two novel techniques are being developed to meet these requirements. For the metal mesh/epoxy susceptor, uniform temperature distribution and control can be achieved by the presence of cutouts in the susceptor to redirect current flow paths

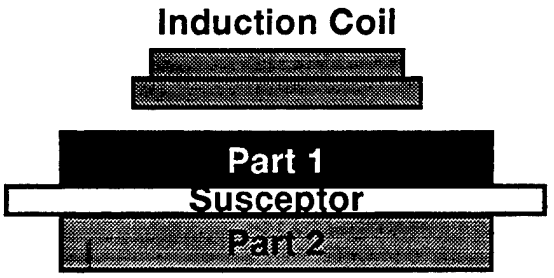


Figure 12. Induction Heating.

(Figure 13). In the magnetic particle susceptor case, ferromagnetic particles undergo a transition to paramagnetic at the Curie temperature. Since the heat generation mechanism in ferromagnetic particles is hysteresis heating, which is not exhibited after the transition to paramagnetic behavior, this transition effect can be used for temperature control. This phenomenon can be exploited for adhesive and composite bonding and curing by selecting particles with a Curie temperature within the desired processing window. Experimental tests have demonstrated the feasibility of both metal mesh and ferromagnetic particle techniques.

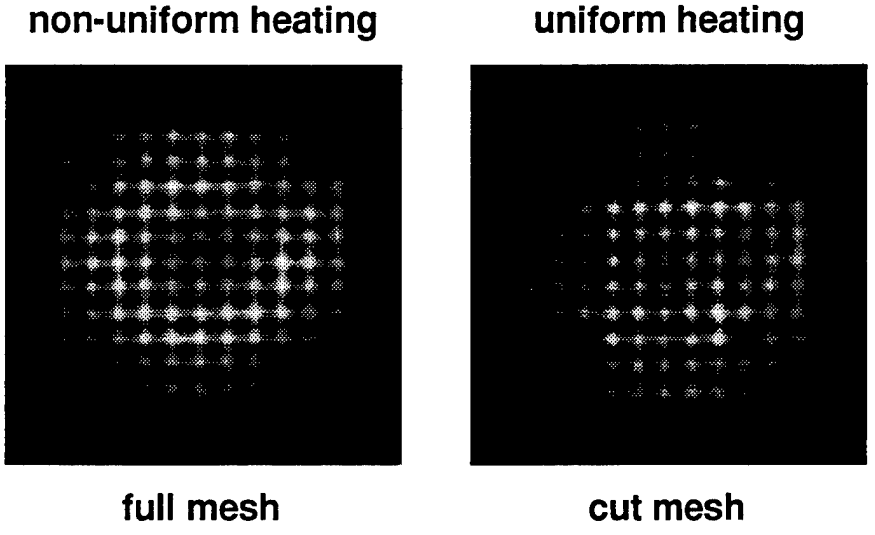


Figure 13. Optimization of Coil and Mesh Geometries.

The steps necessary to develop these techniques to the point where they can reasonably be adopted in the field include the following:

- **Formulate loaded resins for induction.** Magnetic particles are added to adhesives and resins to function as susceptors.

- **Optimize process parameters.** Issues to be addressed include thermal production, thermal distribution, and mesh density as a function of thickness and process cycle.

- **Demonstrate acceptable performance.** Materials bonded and cured using induction techniques are compared to baseline materials using the same criteria as for E-beam techniques.

- **Develop repair schemes.** As discussed for E-beam curing, the schemes include the appropriate sequence of repair steps, the applicable consolidation pressure technique, and the most suited cure technique.

4.2.3 VARTM/CIRTM Processing. VARTM and CIRTM are manufacturing techniques and repair procedures that allow for the repair of more complex PMC components and provide the required localized temperature and pressure needed for repair without the use of an autoclave [33–37]. VARTM starts with placement of a continuous-fiber reinforcement in a closed mold. Resin injected while the mold is under vacuum flows through the reinforcement and fills the mold. VARTM has proven to be very cost effective in the manufacture of large composite parts, but it has been used primarily with single-resin systems. CIRTM expands VARTM capabilities by enabling the injection of multiple resin systems into a single fiber layup, in a single mold/vacuum bag procedure. Several techniques have been developed that define procedures for maintaining and controlling the separation of flow between multiple resins through the thickness of the part. By using a single-step co-cure process that injects multiple resin systems, CIRTM offers the potential to satisfy multifunctional requirements, reduce costs, and increase quality, performance, and durability (Figure 14). CIRTM eliminates the need for secondary bonding operations. Both RTM methods are completely closed systems that trap VOCs, reduce the need for solvents, and result in less scrap than other processes. VARTM and CIRTM provide the means for getting the composite material into the mold/vacuum bag, where they may be cured via E-beam or induction methods.

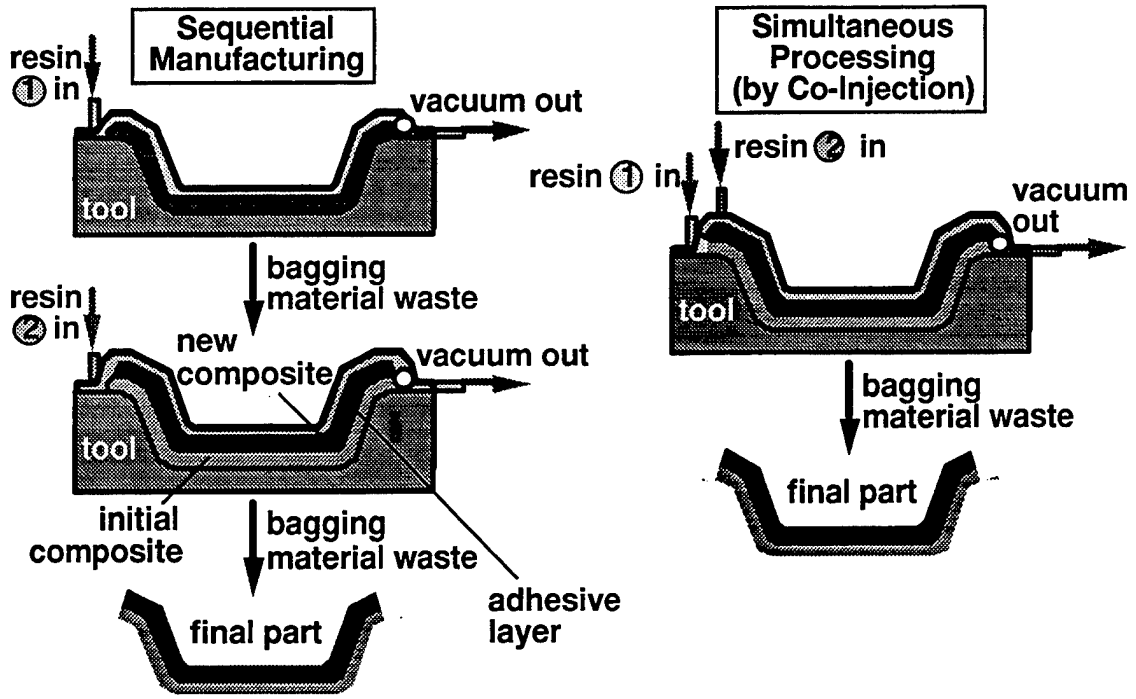


Figure 14. Reduction in Processing Debris Through Reducing Production Steps.

The need certainly exists for processing technologies that simplify the integration of complex designs and thereby simplify repair and reduce reliance on bonding agents for multilayered, multifunctional structures. Existing manufacturing technologies cannot fabricate these integrated structures in a clean and simple process. For example, the CAV requires an extensively layered and bonded structure (Figure 15). The current multistep process involves multiple vacuum bagging, tooling, and adhesive bonding operations, leading to multiplicity in environmentally hazardous emissions, scrap production, and consumable use and waste (e.g., vacuum bag material waste). When put into production, the CAV platform vehicle will use more than 1 M-lb of glass/thermoset resin composites manufactured in more than 3 M separate composite structure processing operations per year. For complex structures like this, repair operations would require (1) removing material by media blasting, (2) applying cutting media, applying cleaning agents, and solvent wiping, (3) building multiple layers, (4) rebonding multiple interfaces with adhesives, and (5) autoclaving the repair in multiple steps.

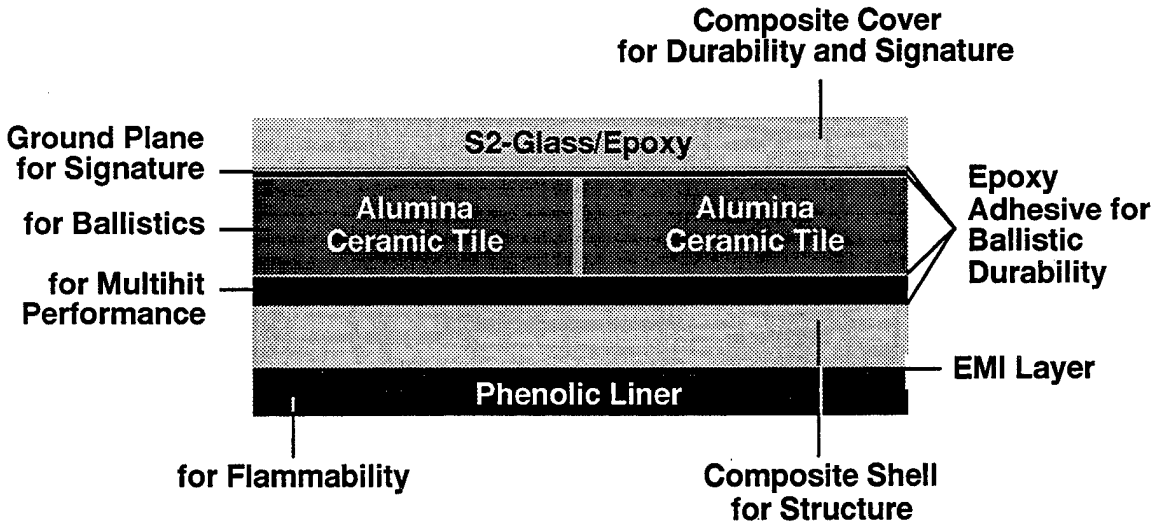


Figure 15. Integral Armor on the Composite Armored Vehicle [38].

VARTM/CIRTM could be used in conjunction with one of the other techniques described previously. Steps necessary to develop these techniques to the point where they can reasonably be adopted for repairs in the theater of operations include the following:

(1) **Optimize process parameters.** Issues to be addressed include selection of consolidation pressure, integration of VARTM/CIRTM with E-beam curing (resin temperature, injection pressure, mold temperature, etc.), vacuum bag cures with hot-vs.-cold debulk, and optimum E-beam dosage vs. degree of cure. Concurrent with the development of the cure technologies, CIRTM should be further developed and enhanced specifically for repair and remanufacture of potential applications. This includes the incorporation of appropriate resin systems and their compatibility with each other in the process.

(2) **Demonstrate acceptable performance.** A limited composite property characterization matrix should be repeated for each resin/fiber system for comparison to baseline properties. Selected tests should be performed under elevated-temperature and/or wet conditions. Adhesive properties should be measured to enable comparison of new adhesives to baseline materials. A testing program designed to characterize the

mechanical performance of new resin systems on as-manufactured fabrics should be conducted.

(3) **Demonstrate and document repair sequencing and procedures.** The schemes should include the appropriate sequence of repair steps, the applicable consolidation pressure technique, and the most suited cure technique. Subcomponent repairs should be tested for appropriate performance standards per MIL-HDBK-17 guidance [36] and Federal Aviation Agency (FAA) repair criteria [37].

4.2.4 Comparison of Techniques. A comparison of repair technologies shows that the proposed techniques offer a variety of means of reducing hazardous emissions and waste while meeting a range of repair and performance criteria, as shown in Table 4. VARTM/CIRTM is used in conjunction with either E-beam or induction curing. Evaluation of the techniques is based on the use of appropriate material forms and reformulation of resins, as shown in Figure 16.

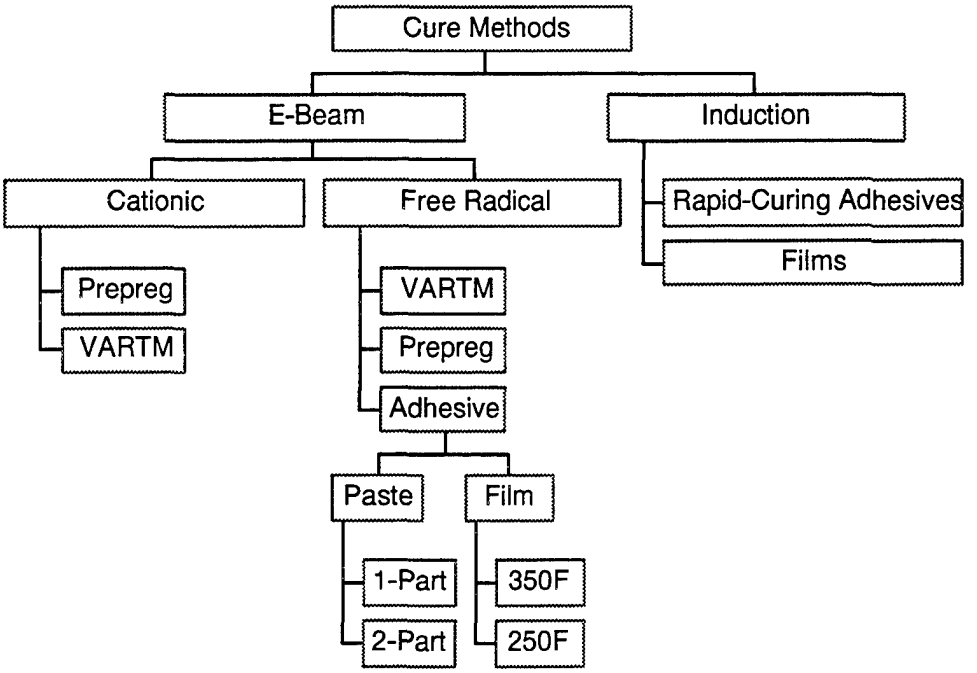


Figure 16. Resin System Formulations.

Table 4 provides a qualitative comparison of the techniques described using plus (+) and minus (–) symbols. The predominant existing techniques for repair and manufacture are autoclave cure and low-temperature cure. Autoclave cure develops the best properties and performance characteristics but is limited for field and remote depot repair and has substantial environmental impact in hazardous emissions and hazardous waste (as noted previously). The low-temperature cure has less severe environmental impact in hazardous emissions and shelf-life hazardous waste, with a significant improvement in production debris, but does not provide materials that perform adequately. Of the proposed techniques, E-beam radiation provides the best material performance characteristics but is the most limited in terms of field repair. It should be noted, however, that E-beam is an improvement over autoclave cure for field repairability. While both E-beam and autoclave require an enclosure, the E-beam equipment that must be transported is much smaller, and the remainder of the equipment can be assembled from local materials (e.g., sandbags). For autoclave cure, the entire autoclave must be shipped. Electromagnetic techniques are not quite as successful as E-beam in reduction of shelf-life hazardous waste. However, they provide a significant improvement over low-temperature cure where field repair requirements do not permit the use of E-beam.

Additionally, in terms of safety issues, electromagnetic methods carry little risk for insertion into a broad variety of repair and remanufacturing conditions, from field to depot and from stand-alone units to large robotic manufacturing systems. The key technological challenges for the proposed techniques include toughened processible resins for the radiation techniques and optimized energy distribution for the electromagnetic techniques. Of the electromagnetic techniques possible, induction heating offers the most promise for control of energy distribution.

5. Analysis of Potential Applications

Five DOD applications highlight issues that must be addressed and constraints that must be satisfied by the proposed techniques based on the criteria established in this report. The applications selected for this report represent different services as well as a range of process and

Table 4. Repair Cure Method Comparison

	Current		Replacement			
			Radiation		Electromagnetic	
	Autoclave	Low-Temp. Cure	E-beam	UV	Induction	Resistance
Reduction of NO_x Emissions	--	++	++	++	++	++
Reduction of VOC Emissions	--	-	+++	++	-	+
Reduction of Shelf-Life Hazardous Waste	--	-	++	++	-	-
Reduction of Production Debris Hazardous Waste	---	+	+	+	+	+
Field Repairability	---	+	-	++	++	++
Performance	+++	--	++	-	++	+
Key Technical Challenge			Toughened Processible Resins		Energy Distribution	

cure methods and material forms. The applications provide reasonable coverage of the range of materials used for repair and remanufacture. Material forms under consideration include paste and film adhesives and prepregs and resins for composites. Requirements such as service temperature, fatigue life, etc., are expected to differ with each application. The use of composites is roughly divided into thin, thick, sandwich, and more complex structures. The application examples cover thin, thick, and sandwich structures; more complex structures are addressed for composite integral armor. Processing scenarios include field or depot repair and remanufacturing at an original manufacturing location. Table 5 summarizes the range of techniques and composite and adhesive material forms relevant to the examples. The various composite forms—thin, sandwich, and thick—are listed in Table 6. The anticipated scenario or location for each repair or remanufacture operation is also provided in Table 6. The examples are described in greater detail in the following sections.

Table 5. Range of Techniques and Material Forms for Example Applications

			Aircraft Skin Repair	Airframe Remanufacture	Rotorcraft Repair	Mast Repair/ Remanufacture	Integral Armor Repair	Sabot Remanufacture
E-beam	Cationic	Prepreg						
		VARTM		X		X		
	Free Radical	Prepreg	X		X			
		VARTM		X		X		
		One-Part Paste Adhesive			X			
		Two-Part Paste Adhesive			X			
		350F Film Adhesive	X		X			
		250F Film Adhesive	X		X			
Induction		Rapid-Curing Adhesive				X	X	
		Film Adhesive				X	X	
		Prepreg	X					X
		VARTM	X			X	X	X
RT. Cure		VARTM				X	X	

Table 6. Range of Scale and Repair/Remanufacture Location for Example Applications

		Aircraft Skin Repair	Airframe Remanufacture	Rotorcraft Repair	Mast Repair/ Remanufacture	Integral Armor Repair	Sabot Remanufacture
Scale	Thin	X	X	X			
	Sandwich	X	X	X	X		
	Thick				X	X	X
	More Complex					X	
Location	Field	X			X	X	
	Depot	X		X		X	
	Manufacturer		X		X		X

5.1 Aircraft Skin Repair. Damage mechanisms for aircraft composite components include impact from bird strike, foreign object damage (FOD), ballistic impact, moisture intrusion and expansion, maintenance-induced damage, and corrosion [5, 39]. Damage levels are categorized as follows:

(1) **Light**—aesthetic repairs and coating repairs.

(2) **Moderate**—delaminations, small patches, and edge repairs.

(3) **Heavy**—full depth, core, and substructure repairs.

Other criteria for selecting the appropriate repair procedure include whether the component can be removed and whether the back side is accessible. A typical moderate repair is one-sided damage to the skin and underlying honeycomb core (Figure 17). Any remaining coating in the repair area is removed by hand sanding or portable tools. Damage is machined out in an appropriate configuration, often circular or racetrack. Scarfing, removal of skin material at a shallow angle, is commonly accomplished by hand, as automatic scarf routers are still under development. The surface is prepared with grit blasting and solvent wiping. A plug of honeycomb core replaces the damaged material. A skin patch is often partially cured off the aircraft using a double vacuum bag cure. The patch is then bonded to the aircraft using film adhesive and a heat blanket for thermal cure.

The anticipated technique for aircraft skin repair is E-beam cure for thin and sandwich structures. Material forms being considered are prepregs and film adhesives with free-radical reformulations for toughness. The effect of this technique on estimates of JSF repair involves hazardous waste reduction as shown in Figure 8 and reductions in VOC emissions (Figure 7). Based on annual composite repair of 78,000 lb, the reduction in hazardous waste by using E-beam rather than a heat-blanket thermal cure is 62,500 lb/year. The reduction in VOC emissions is 281 lb/year. Although these amounts are relatively small, the percentages are large, and this repair technique can be applied to all composite and metallic aircraft. Aircraft skin repair is a high-priority application for evaluating replacement techniques.

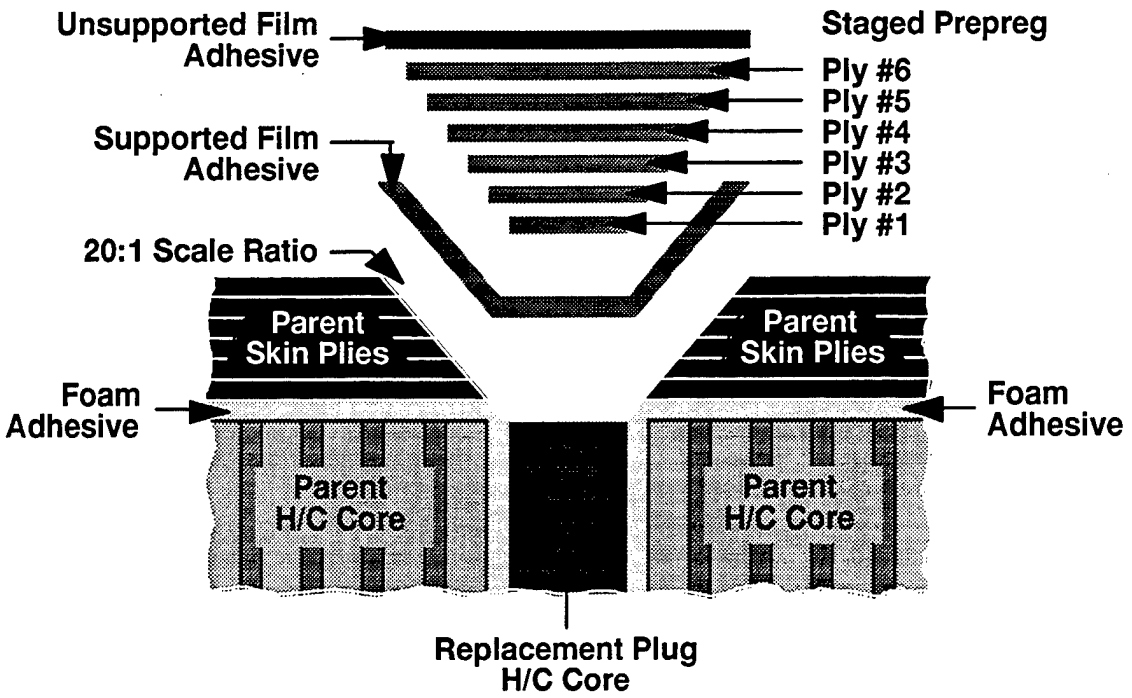


Figure 17. One-Sided Skin and Honeycomb Core Repair [39].

5.2 Airframe Remanufacture. Baseline processing for airframe component manufacture is prepreg layup with autoclave cure. Due to the size of these components, large autoclaves with correspondingly high levels of NO_x generation are required. An example component is a sandwich panel with stiffeners. The anticipated technique for this component is E-beam cure combined with VARTM on thin and sandwich composites. Material forms being considered are VARTM resins with either cationic or free-radical reformulation.

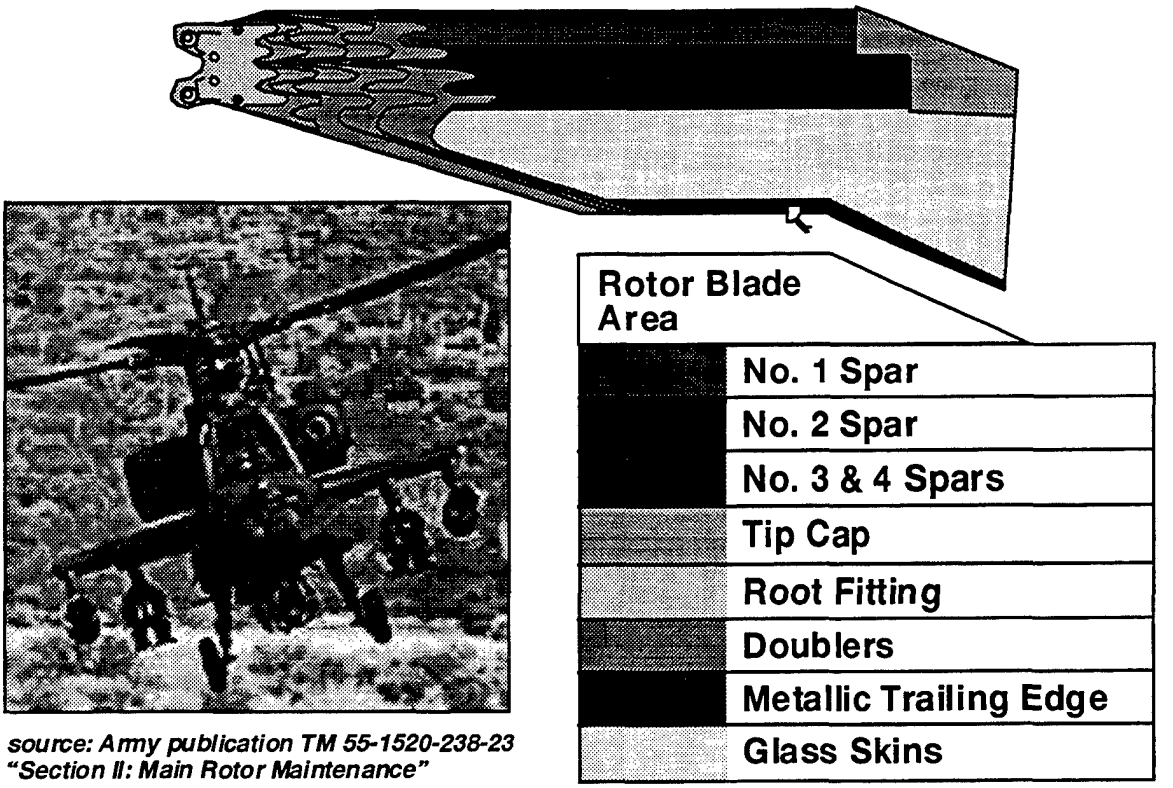
With E-beam cure and VARTM applied to JSF manufacturing, assuming 75% replacement of the current baseline autoclave cure, reduction in hazardous waste exceeds 1,000 lb per aircraft. Based on 200 aircraft per year, the annual reduction in hazardous waste exceeds 206,000 lb; cost savings in raw materials and hazardous waste disposal exceeds $11 M. NO_x is reduced 72 lb/aircraft or 14,400 lb/year. The corresponding reduction of VOCs is 14 lb/aircraft and 2,800 lb/year. Clearly, aircraft remanufacture is a high-priority application for evaluating the replacement techniques.

5.3 Rotorcraft Repair. Specific composite rotorcraft components that are repaired include the main and tail rotorblades, panels, and doors on the newer Army rotorcraft (CH-47D Chinook, AH-64 Apache, UH-60 Black Hawk, and OH-58D Kiowa Warrior Scout). While in service, rotorcraft (Figure 18) are subject to various types of damage including impact damage of skin and sandwich structures, delamination of bonded surfaces (dissimilar material joints), delamination, and various dents and gouges. During x-ray radiography inspection, pockets of standing water are often found in honeycomb core; perforation of the composite skins to remove the accumulated water causes defects that must be repaired in addition to in-service damage.

Well-developed repair procedures are specified for each damage type. Much like the aircraft skin repair described previously, damaged honeycomb material is replaced with a repair plug bonded into place with adhesives. Small areas of delamination damage are repaired by injecting additional adhesive into the debond, while large delaminated areas are replaced with a repair plug. At the depot, repaired areas of rotorblades are vacuum bagged, heating blankets are applied to the exterior of the bag, and the entire assembly is placed in a large autoclave to provide consolidation pressure. Autoclave size constrains the processing to two blades per run. Consequently, out-of-autoclave processing using alternative cure technologies is attractive for reducing processing time and environmental impact.

The anticipated solution for rotorcraft repair is E-beam cure for thin and sandwich structures. Material forms involved are prepregs and a range of adhesives with free-radical reformulations for toughness. The extreme technical requirements for processing and dynamic testing repaired rotorblades limit replacement techniques and overwhelm cost savings for major repairs of rotorblades. Minor repairs of rotorblades and repairs for airframe skin and structure are similar to the previous examples. Rotorcraft repair was determined by the U.S. Army Aviation and Missile Command to be a low-priority application for evaluating these techniques.

5.4 AEM/S System Repair/Remanufacture. The AEM/S System (Figure 19) is a marine composite structure currently under advanced development designed to serve as a protective enclosure for Navy ship mast/sensor systems providing improved survivability, combat



source: Army publication TM 55-1520-238-23 "Section II: Main Rotor Maintenance"

Figure 18. Rotorcraft Repair [40].

effectiveness, and offensive capability by reducing signature and improving sensor performance [19]. Polymer-matrix composites are attractive for such a structure due to their excellent combination of strength, stiffness, weight, and signature management performance. PMCs are amenable to use as part of multifunctional composite systems. A current drawback is that many multifunctional material designs require multiple processing steps and adhesive bonding operations on extremely large structures such as the AEM/S System (93 ft high, 29 tons). The current design of the AEM/S System does not include the use of a phenolic liner for fire safety due to the increased expense of manufacturing the separate components and bonding them to the interior of the enclosure. With future designs calling for manufacture of the phenolic substructure separately, it is estimated that the processing of a single enclosure would create an additional 1.5 tons of hazardous waste material using VARTM.

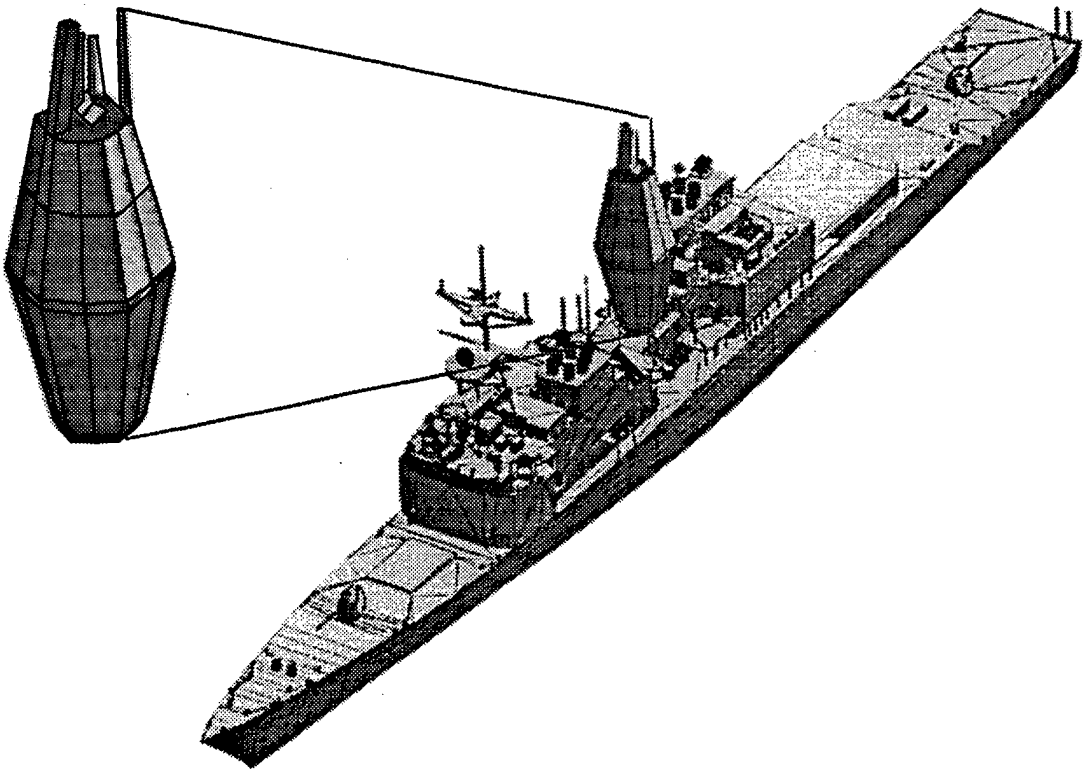


Figure 19. AEM/S System.

The anticipated solution for field repair of the mast system is VARTM/CIRTM processing with room-temperature cure or accelerated induction cure of thick and sandwich composites. CIRTM provides a means for incorporating the phenolic liner without additional processing steps and the concomitant additional hazardous waste. A significant payoff for this and countless other composite systems in DOD is the ease of repairability of such multifunctional structures and elimination of the need for adhesives in the repair process. The anticipated material form is VARTM resins. CIRTM is also worth investigating for remanufacturing. The effect of CIRTM processing on mast repair involves reduction in processing debris by reducing the number of processing steps, elimination of VOC emissions, and reduction in shelf-life hazardous waste. Based on 30,000 lb/year composite repair, hazardous waste is reduced by 12,000 lb/year and VOC emissions are reduced by 600 lb/year. For remanufacturing of six ships per year, the

reduction in hazardous waste is 18,000 lb/year. These numbers are relatively small, and mast repair and remanufacturing is considered a medium-priority application for evaluating these techniques. The volume of material in use when composites are applied to entire topside structures for Navy applications may increase the priority of these applications.

5.5 Integral Armor. Integral armor is key to the development of the next generation of ground vehicles such as the CAV, the Crusader self-propelled howitzer and resupply vehicle (Figure 20), and the Future Scout and Cavalry System [21]. These vehicles have greater mobility, transportability, and durability combined with affordable manufacturing. Integral armor represents a highly complex material structure of significant thickness. Not only are a variety of materials laid up in one component, but the ceramic tiles are often surrounded by a different material within one layer. Both ballistic protection and structural functions are addressed by this combination of materials. While a CIRTM approach was investigated toward the end of the Advanced Technology Demonstrator (ATD) program for the CAV, the current Crusader program has taken a more conservative design approach, with each layer processed separately. For the example layup in Figure 15, this entails 16 bonding steps for assembly. Repair procedures were prepared and demonstrated for the CAV as part of the ATD program [38].

The anticipated solution for field repair of integral armor is induction bonding of replacement ceramic tiles and prepreg or VARTM patches. More extensive repairs can be handled at the depot using induction curing and VARTM/CIRTM processing for these thick and sandwich composites. For remanufacturing, VARTM/CIRTM processing has high potential based on its ability to reduce the number of processing steps.

With induction repair applied to integral armor, significant improvements in readiness should be obtained due to the reduction in processing steps. Based on the estimate of 125,000 lb/year composite repair for the FSCS, reduction in hazardous waste due to production debris is 37,500 lb/year. Considering these repairs may well take place in the theater of operations,

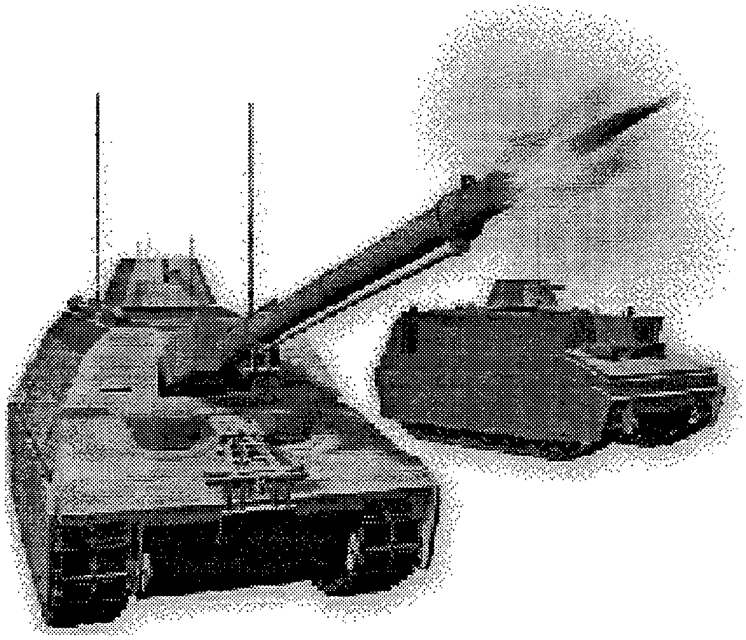


Figure 20. Crusader Self-Propelled Howitzer and Resupply Vehicle [41].

associated cost reductions are relatively large since shipping of extra material for repair and the return shipping of hazardous waste is included. Integral armor repair is a medium-priority application for evaluating replacement techniques.

Replacing the multiple bonding steps of integral armor manufacturing with a single-step induction process produces significant savings in hazardous waste. For the FSCS, the reduction in hazardous waste exceeds 600,000 lb/year. VOC emissions are reduced by 2,920 lb/year. Remanufacturing of integral armor is a high-priority application for evaluating replacement techniques.

5.6 Sabot Remanufacture. A sabot is a component of an armor-piercing kinetic energy tank round. The manufacture of sabots (Figure 21) represents DOD's largest use of composite materials. Due to concerns about limitations on publishing specific information about sabots, the environmental and cost analysis is focused on total numbers of hazardous waste and emissions for one particular round. Raw materials for this application exceed 1 M-lb/year. Baseline

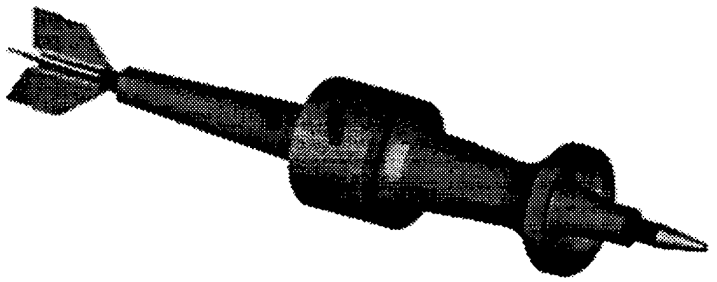


Figure 21. Sabot.

processing for a typical sabot is hot-press curing of thermoset prepreg. Several stages of assembly and curing are required to achieve a thick near-net shape piece. Extensive effort has been expended into bringing the size and shape of this hot-pressed piece as close to final net shape as possible. While this effort has reduced post-cured scrap, the greatest amount of waste is hazardous uncured thermoset prepreg material.

The anticipated remanufacture of this component is reduced-step induction curing of thermoplastic prepregs. Significant advances in induction-assisted processing technology at ARL and UD–CCM provide the enabling technologies that render thermoplastic sabots cost-effective for mass production. With induction cure and reduced steps applied to thermoplastic prepreg, hazardous emissions are reduced by 60% and 30,000 lb of hazardous waste per year is eliminated for the particular sabot round used in the example cost analysis. Clearly, remanufacture of sabots is a high-priority application for evaluating the replacement techniques. It should also be noted that this example has the greatest difference between the baseline and the proposed replacement techniques. While this represents a high technological risk, the associated reduction in environmental costs is also large.

6. Plans for Future Environmental and Cost Analyses

Cost analyses for the replacement technologies require detailed information for each scenario. One method for approaching the cost analyses has been laid out for the example

applications in the Appendix. In these calculations, the cost of compliance has been included solely as the cost of treating hazardous emissions and disposing of hazardous waste. No effect of penalties or other costs has been included. The general trend of reduction in cost is evident in these examples, but the magnitude of cost savings across the range of DOD applications is difficult to predict in detail at this time. As one or more of these technologies is selected for a specific application, more detailed usage and environmental data should be collected. When sufficient data are available, complete environmental cost analyses should be performed.

7. Summary/Conclusions

Using an analysis of baseline and predicted environmental improvements, significant savings have been demonstrated for proposed technologies for repair and remanufacturing of DOD polymer-matrix composite applications. The baseline and current practice is described in terms of commonly used hazardous materials and current and future usage of composite materials. Anticipated environmental cost savings are estimated for the improved technologies as a result of reducing or eliminating shelf-life limitations, moving curing out of the autoclave, and reducing the number of processing steps. The proposed technologies include radiation and electromagnetic curing and improved resin transfer molding processing. Evaluation of environmental cost savings and descriptions of the improved technologies have focused on electron beam curing, induction curing, and co-injection resin transfer molding.

Technical barriers that need to be addressed for the proposed cure and processing methods are as follows:

(1) Formulate toughened resins and adhesives,

(2) Optimize process parameters,

(3) Demonstrate acceptable performance,

(4) Develop and document repair sequencing and procedures, and

(5) Optimize repair schemes for specific applications.

The particular steps needed for process optimization and repair procedure development depend on the method, as discussed previously. Optimizing repair schemes for various applications depends both on the application and on the selected method. The proposed technologies constitute a family of solutions. Each technology is not universally applicable, but environmental improvements over the existing practice are possible by proper selection from among these technologies.

Conservative estimates of environmental cost savings associated with the implementation of the proposed technologies should be further developed and brought to maturation for broad application within DOD. During the development process for specific applications, environmental data should be accumulated. When sufficient data are available, complete cost analyses can be performed using details for each application under different scenarios. It is anticipated that these more in-depth analyses will highlight the benefits of implementing the proposed technologies.

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Appendix:

Example Detailed Cost Analyses for Proposed Techniques

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Example Application: Repair of Aircraft Skin

BASELINE PRACTICE
Heat blanket – film adhesive and prepreg repair of aircraft skin

REPLACEMENT TECHNOLOGY ALTERNATIVE
E-beam – film adhesive and prepreg repair of aircraft skin

LOCATION
Depot

ADVANTAGES

- Reduction by half of volatile organic compound (VOC) emissions
- Reduction in shelf-life expiration and production debris hazardous waste
- Faster cure

DISADVANTAGES

- Training in new technology

Note that costs presented in this example may vary greatly depending on labor costs, number of repairs, volume, material disposed, unit costs, and uncertainties in available data.

CAPITAL COSTS	
BEFORE alternative	**AFTER alternative**
Not applicable.	$C_C = C_{C(E)}$ Where: C_C = Total capital costs $C_{C(E)}$ = Capital costs of equipment

CAPITAL COSTS include the cost of a portable E-beam unit.

DATA RANGES FOR CAPITAL COSTS (based on available information): portable E-beam unit ($400,000).

ANNUAL OPERATING COSTS	
Supply Costs	
BEFORE alternative	**AFTER alternative**
$C_{S(tot)} = N_{repairs}[(C_{RM} + C_L) + Q_{W(HW)} (C_{RM})]$ Where: $C_{S(tot)}$ = Total supply cost per year $N_{repairs}$ = Number of repairs C_{RM} = Raw materials cost per repair C_L = Labor cost per repair $Q_{W(HW)}$ = Waste disposal quantity of hazardous waste	$C_{S(tot)} = N_{repairs}[(C_{RM} + C_L) + Q_{W(HW)} (C_{RM})]$ Where: $C_{S(tot)}$ = Total supply cost per year $N_{repairs}$ = Number of repairs C_{RM} = Raw materials cost per repair C_L = Labor cost per repair $Q_{W(HW)}$ = Waste disposal quantity of hazardous waste

SUPPLY COSTS are equal to the cost per repair times the number of repairs plus stockpiling costs.

DATA RANGES FOR SUPPLY COSTS (based on available information): cost of raw materials (1 lb composite @ $30/lb; 1/4 lb adhesive @ $10/lb per repair); labor cost per repair (heat blanket) is $1,600, labor cost per repair (E-beam – reduced cure monitoring time) is $1,400*; percentages of shelf-life expiration and production debris hazardous waste from Figure 8 in the main body of this report.

For cost estimate only, assume 400 repairs per year. Production materials assumed equivalent.

Waste Disposal Costs	
BEFORE alternative	**AFTER alternative**
$C_{W(tot)} = N_{repairs}[(C_{W(HE)})(Q_{W(HE)}) + Q_{W(HW)} (C_{HW})]$ Where: $C_{W(tot)}$ = Total waste disposal cost per year $N_{repairs}$ = Number of repairs $C_{W(HE)}$ = Waste disposal cost of VOC $Q_{W(HE)}$ = Waste disposal quantity of VOC $Q_{W(HW)}$ = Waste disposal quantity of hazardous waste C_{HW} = Cost of disposing expired shelf-life and Production debris material as hazardous waste	$C_{W(tot)} = N_{repairs}[(C_{W(HE)})(Q_{W(HE)}) + Q_{W(HW)} (C_{HW})]$ Where: $C_{W(tot)}$ = Total waste disposal cost per year $N_{repairs}$ = Number of repairs $C_{W(HE)}$ = Waste disposal cost of VOC $Q_{W(HE)}$ = Waste disposal quantity of VOC $Q_{W(HW)}$ = Waste disposal quantity of hazardous waste C_{HW} = Cost of disposing expired shelf-life and production debris material as hazardous waste

* Note greatest cost savings will result from automated scarfing equipment.

WASTE DISPOSAL COSTS. Before the alternative, waste disposal costs are equal to the amount of VOC times the cost of hazardous emission treatment plus the cost of the disposal of materials treated as hazardous waste for materials with expired shelf-life or out time. After the alternative, waste disposal costs are equal to the amount of VOC times the cost of hazardous emission treatment.

DATA RANGES FOR WASTE DISPOSAL COSTS: Data above; percentages from Figures 7 and 8 in the main body of this report; hazardous emission disposal cost is $100/lb*; hazardous waste disposal cost is $40/lb.

Total Operating Costs	
BEFORE alternative	**AFTER alternative**
$C_{OB(tot)} = C_{S(tot)} + C_{W(tot)}$ Where $C_{OB(tot)}$ = Total operating costs before alternative	$C_{OA(tot)} = C_{S(tot)} + C_{W(tot)}$ Where $C_{OA(tot)}$ = Total operating costs after alternative

* While VOC emissions are currently released, restrictions on this practice are anticipated.

INCREASE OR DECREASE IN ANNUAL OPERATING COSTS	
BEFORE alternative	**AFTER alternative**
$C_O = C_{OB(tot)} - C_{OA(tot)}$ Where: C_O = Increase or decrease in annual operating costs	

PAYBACK PERIOD
$T_{PAY} = (C_C)/(-C_O)$ (in years) Where: T_{PAY} = Time required for implementation of alternative to pay back any capital costs

COST EXAMPLE

CAPITAL COSTS	
BEFORE alternative	**AFTER alternative**
Not applicable.	$C_C = C_{C(E)}$ $C_C = \$400,000$

ANNUAL OPERATING COSTS	
Supply Costs	
BEFORE alternative	**AFTER alternative**
$C_{S(tot)} = N_{repairs}[(C_{RM} + C_L) + Q_{W(HW)} (C_{RM})]$ $C_{S(tot)}$ = 800 repairs [(1 lb composite)($30/lb) + (0.25 lb adhesive)($10/lb) + $1,600 + (30%+20%)/50%_ (1 lb composite)($30/lb) + (40% + 10%)/50%_(0.25 lb adhesive)($10/lb)] $C_{S(tot)}$ = 800($32.50 + $1,600 + $32.50) $C_{S(tot)} = \$1,332,000$	$C_{S(tot)} = N_{repairs}[(C_{RM} + C_L) + Q_{W(HW)} (C_{RM})]$ $C_{S(tot)}$ = 800 repairs [(1 lb composite)($30/lb) + (0.25 lb adhesive)($10/lb) + $1,400 + (19%/81%)_ ($30/lb) + (5%/95%)_(0.25 lb adhesive)($10/lb)] $C_{S(tot)}$ = 800($32.50 + $1,400 + $8.15) $C_{S(tot)} = \$1,152,500$
Waste Disposal Costs	
BEFORE alternative	**AFTER alternative**
$C_{W(tot)} = N_{repairs}[(C_{W(HE)})(Q_{W(HE)}) + Q_{W(HW)} (C_{HW})]$ $C_{W(tot)}$ = 800 repairs {[(2.5%)(1 lb) + (5%)(0.25lb)]_$100/lb + [(30% + 20%)/50%_(1 lb composite) + (40%+10%)/50%_ (0.25 lb adhesive)]($40/lb)]} $C_{W(tot)}$ = 800 ($3.75 + $50) $C_{W(tot)} = \$43,000$	$C_{W(tot)} = N_{repairs}[(C_{W(HE)})(Q_{W(HE)}) + Q_{W(HW)} (C_{HW})]$ $C_{W(tot)}$ = 800 repairs {[0.5(2.5%)(1 lb) + 0.5(5%)(0.25 lb)]$100/lb + [(19%)/81%_(1 lb composite) + (5%)/95%_(0.25 lb adhesive)]($40/lb)]} $C_{W(tot)}$ = 800 ($1.88 + $9.70) $C_{W(tot)} = \$9,300$
Total Operating Costs	
BEFORE alternative	**AFTER alternative**
$C_{OB(tot)} = C_{S(tot)} + C_{W(tot)}$ $C_{OB(tot)}$ = $1,332,000 + $43,000 $C_{OB(tot)} = \$1,375,000$	$C_{OA(tot)} = C_{S(tot)} + C_{W(tot)}$ $C_{OA(tot)}$ = $1,152,500 + $9,300 $C_{OA(tot)} = \$1,161,800$

INCREASE OR DECREASE IN ANNUAL OPERATING COSTS	
BEFORE alternative	**AFTER alternative**
$C_O = C_{OB(tot)} - C_{OA(tot)}$ C_O = $1,375,000 – $1,161,800 $C_O = \$213,200$	

PAYBACK PERIOD
$T_{PAY} = (C_C)/(C_O)$ (in years) T_{PAY} = $400,000/$213,200 T_{PAY} = 1.88 years

Example Application: Remanufacture of Airframe Component

BASELINE PRACTICE
Autoclave cure – manufacture of panel with stiffeners

REPLACEMENT TECHNOLOGY ALTERNATIVE
E-beam/vacuum-assisted resin transfer molding (VARTM) – remanufacture of panel with stiffeners

LOCATION
Manufacturer

ADVANTAGES
- Elimination of NO_x
- Reduction by half of VOC emissions
- Reduction in shelf-life expiration and production debris hazardous waste
- Faster cure

DISADVANTAGES
- Training in new technology

Note that costs presented in this example may vary greatly depending on labor costs, number of parts, volume, material disposed, unit costs, and uncertainties in available data.

CAPITAL COSTS	
BEFORE alternative	**AFTER alternative**
Not applicable.	$C_C = C_{C(E)}$ Where: C_C = Total capital costs $C_{C(E)}$ = Capital costs of equipment

CAPITAL COSTS include the cost of an E-beam unit.

DATA RANGES FOR CAPITAL COSTS (based on available information): E-beam unit ($400,000).

ANNUAL OPERATING COSTS	
Supply Costs	
BEFORE alternative	**AFTER alternative**
$C_{S(tot)} = N_{parts}[(C_{RM} + C_L) + Q_{W(HW)} (C_{RM})]$ Where: $C_{S(tot)}$ = Total supply cost per year N_{parts} = Number of parts C_{RM} = Raw materials cost per part C_L = Labor cost per part $Q_{W(HW)}$ = Waste disposal quantity of hazardous waste	$C_{S(tot)} = N_{parts}[(C_{RM} + C_L) + Q_{W(HW)} (C_{RM})]$ Where: $C_{S(tot)}$ = Total supply cost per year N_{parts} = Number of parts C_{RM} = Raw materials cost per repair C_L = Labor cost per repair $Q_{W(HW)}$ = Waste disposal quantity of hazardous waste

SUPPLY COSTS are equal to the cost per repair times the number of parts plus stockpiling costs.

DATA RANGES FOR SUPPLY COSTS (based on available information): cost of raw materials (26.1 lb composite @ $30/lb; 1 lb adhesive @ $10/lb per repair); labor cost per part (before) is $1,600, labor cost per repair (E-beam - reduced cure monitoring time) is $1,400; percentages of shelf-life expiration and production debris hazardous waste from manufacturer's data and Figure 8 in the main body of this report.

For cost estimate only, assume 2,000 parts per year. Production materials assumed equivalent.

Waste Disposal Costs	
BEFORE alternative	**AFTER alternative**
$C_{W(tot)} = N_{parts}[(C_{W(HE)})(Q_{W(HE)}) + Q_{W(HW)} (C_{HW})]$ Where: $C_{W(tot)}$ = Total waste disposal cost per year N_{parts} = Number of parts $C_{W(HE)}$ = Waste disposal cost of NO_x and VOC $Q_{W(HE)}$ = Waste disposal quantity of NO_x and VOC $Q_{W(HW)}$ = Waste disposal quantity of hazardous waste C_{HW} = Cost of disposing expired shelf-life and production debris material as hazardous waste	$C_{W(tot)} = N_{parts}[(C_{W(HE)})(Q_{W(HE)}) + Q_{W(HW)} (C_{HW})]$ Where: $C_{W(tot)}$ = Total waste disposal cost per year N_{parts} = Number of parts $C_{W(HE)}$ = Waste disposal cost of NO_x and VOC $Q_{W(HE)}$ = Waste disposal quantity of NO_x and VOC $Q_{W(HW)}$ = Waste disposal quantity of hazardous waste C_{HW} = Cost of disposing expired shelf-life and production debris material as hazardous waste

WASTE DISPOSAL COSTS. Before the alternative, waste disposal costs are equal to the amount of NOx and VOC times the cost of hazardous emission treatment plus the cost of the disposal of materials treated as hazardous waste for materials with expired shelf-life or out time. After the alternative, waste disposal costs are equal to the amount of VOC times the cost of hazardous emission treatment.

DATA RANGES FOR WASTE DISPOSAL COSTS: Data above; percentages from Figures 7 and 8 in the main body of this report; hazardous emission disposal cost is $100/lb*; hazardous waste disposal cost is $40/lb.

Total Operating Costs	
BEFORE alternative	**AFTER alternative**
$C_{OB(tot)} = C_{S(tot)} + C_{W(tot)}$ Where $C_{OB(tot)}$ = Total operating costs before alternative	$C_{OA(tot)} = C_{S(tot)} + C_{W(tot)}$ Where $C_{OA(tot)}$ = Total operating costs after alternative

* While VOC emissions are currently released, restrictions on this practice are anticipated.

INCREASE OR DECREASE IN ANNUAL OPERATING COSTS	
BEFORE alternative	**AFTER alternative**
$C_O = C_{OB(tot)} - C_{OA(tot)}$ Where: C_O = Increase or decrease in annual operating costs	

PAYBACK PERIOD
$T_{PAY} = (C_C)/(-C_O)$ (in years) Where: T_{PAY} = Time required for implementation of alternative to pay back any capital costs

COST EXAMPLE

CAPITAL COSTS	
BEFORE alternative	**AFTER alternative**
Not applicable.	$C_C = C_{C(E)}$ $C_C = \$400,000$

ANNUAL OPERATING COSTS	
Supply Costs	
BEFORE alternative	**AFTER alternative**
$C_{S(tot)} = N_{parts}[(C_{RM} + C_L) + Q_{W(HW)}(C_{RM})]$ $C_{S(tot)} = 2,000$ parts {(26.1 lb composite)($30/lb) + (1.0 lb adhesive)($10/lb) + $1,600 + [(34%)(66%)+15%] (26.1 lb composite)($30/lb) +_[(34%)(66%) + 40%](1.0 lb adhesive)($10/lb)]} $C_{S(tot)} = 2,000(\$793 + \$1,600 + \$299)$ $C_{S(tot)} = \$5,384,000$	$C_{S(tot)} = N_{parts}[(C_{RM} + C_L) + Q_{W(HW)}(C_{RM})]$ $C_{S(tot)} = 2,000$ parts {(26.1 lb composite)($30/lb) + (1.0 lb adhesive)($10/lb) + $1,400 + [(34%)(66%)/4] (26.1 lb composite)($30/lb) +_[(34%)(66%)/4](1.0 lb adhesive)($10/lb)]} $C_{S(tot)} = 2,000(\$793 + \$1,400 + \$44)$ $C_{S(tot)} = \$4,474,000$
Waste Disposal Costs	
BEFORE alternative	**AFTER alternative**
$C_{W(tot)} = N_{parts}[(C_{W(HE)})(Q_{W(HE)}) + Q_{W(HW)}(C_{HW})]$ $C_{W(tot)} = 2,000$ parts {[(2.5%)(26.1 lb) + (5%)(1.0 lb) + 1.0 lb] _$100/lb + [(34%)(66%)+15%] (26.1 lb composite)($40/lb) +_[(34%)(66%) + 40%](1.0 lb adhesive)($40/lb)]} $C_{W(tot)} = 2,000\ (\$170 + \$416)$ $C_{W(tot)} = \$1,172,000$	$C_{W(tot)} = N_{parts}[(C_{W(HE)})(Q_{W(HE)}) + Q_{W(HW)}(C_{HW})]$ $C_{W(tot)} = 2,000$ parts {[0.5(2.5%)(26.1 lb) + 0.5(5%)(1.0 lb)] $100/lb + [(34%)(66%)/4] (26.1 lb composite)($40/lb) +_[(34%)(66%)/4](1.0 lb adhesive)($40/lb)]} $C_{W(tot)} = 2,000\ (\$35 + \$61)$ $C_{W(tot)} = \$192,000$
Total Operating Costs	
BEFORE alternative	**AFTER alternative**
$C_{OB(tot)} = C_{S(tot)} + C_{W(tot)}$ $C_{OB(tot)} = \$5,384,000 + \$1,172,000$ $C_{OB(tot)} = \$6,556,000$	$C_{OA(tot)} = C_{S(tot)} + C_{W(tot)}$ $C_{OA(tot)} = \$4,474,000 + \$192,000$ $C_{OA(tot)} = \$4,666,000$

INCREASE OR DECREASE IN ANNUAL OPERATING COSTS	
BEFORE alternative	**AFTER alternative**
$C_O = C_{OB(tot)} - C_{OA(tot)}$ $C_O = \$6,556,000 - \$4,666,000$ $C_O = \$1,890,000$	

PAYBACK PERIOD
$T_{PAY} = (C_C)/(C_O)$ (in years) $T_{PAY} = \$400,000/\$1,189,000$ $T_{PAY} = 0.34$ years

Example Application: Repair of Rotorblade

BASELINE PRACTICE
Heat blanket (pressure application by autoclave) – film adhesive and prepreg repair of rotorblade

REPLACEMENT TECHNOLOGY ALTERNATIVE
Induction – film adhesive and prepreg repair of rotorblade

LOCATION
Depot

ADVANTAGES

- Faster cure

DISADVANTAGES

- Training in new technology
- Stringent recertification requirements

Note that costs presented in this example may vary greatly depending on labor costs, number of repairs, volume, material disposed, unit costs, and uncertainties in available data.

CAPITAL COSTS	
BEFORE alternative	**AFTER alternative**
Not applicable.	$C_C = C_{C(E)} + C_{C(C)}$ Where: C_C = Total capital costs $C_{C(E)}$ = Capital costs of equipment $C_{C(E)}$ = Costs of certification

CAPITAL COSTS include the cost of an induction unit and the cost of certifying processing change.

DATA RANGES FOR CAPITAL COSTS (based on available information): induction unit ($50,000); certification of processing change ($500,000).

ANNUAL OPERATING COSTS	
Supply Costs	
BEFORE alternative	**AFTER alternative**
$C_{S(tot)} = N_{repairs}[(C_{RM} + C_L) + Q_{W(HW)} (C_{RM})]$ Where: $C_{S(tot)}$ = Total supply cost per year $N_{repairs}$ = Number of repairs C_{RM} = Raw materials cost per repair C_L = Labor cost per repair $Q_{W(HW)}$ = Waste disposal quantity of hazardous waste	$C_{S(tot)} = N_{repairs}[(C_{RM} + C_L) + Q_{W(HW)} (C_{RM})]$ Where: $C_{S(tot)}$ = Total supply cost per year $N_{repairs}$ = Number of repairs C_{RM} = Raw materials cost per repair C_L = Labor cost per repair $Q_{W(HW)}$ = Waste disposal quantity of hazardous waste

SUPPLY COSTS are equal to the cost per repair times the number of repairs plus stockpiling costs.

DATA RANGES FOR SUPPLY COSTS (based on available information): cost of raw materials ($100 per repair); labor cost per repair (heat blanket) is $2,400, labor cost per repair (induction-reduced cure monitoring time) is $2,370; percentages of shelf-life expiration and production debris hazardous waste from Corpus Christi Army Depot (CCAD).

For cost estimate only, assume 1,000 repairs per year. Production materials assumed equivalent.

Waste Disposal Costs	
BEFORE alternative	**AFTER alternative**
$C_{W(tot)} = N_{repairs}[(C_{W(HE)})(Q_{W(HE)}) + Q_{W(HW)} (C_{HW})]$ Where: $C_{W(tot)}$ = Total waste disposal cost per year $N_{repairs}$ = Number of repairs $C_{W(HE)}$ = Waste disposal cost of VOC $Q_{W(HE)}$ = Waste disposal quantity of VOC $Q_{W(HW)}$ = Waste disposal quantity of hazardous waste C_{HW} = Cost of disposing expired shelf-life and production debris material as hazardous waste	$C_{W(tot)} = N_{repairs}[(C_{W(HE)})(Q_{W(HE)}) + Q_{W(HW)} (C_{HW})]$ Where: $C_{W(tot)}$ = Total waste disposal cost per year $N_{repairs}$ = Number of repairs $C_{W(HE)}$ = Waste disposal cost of VOC $Q_{W(HE)}$ = Waste disposal quantity of VOC $Q_{W(HW)}$ = Waste disposal quantity of hazardous waste C_{HW} = Cost of disposing expired shelf-life and production debris material as hazardous waste

WASTE DISPOSAL COSTS. Before the alternative, waste disposal costs are equal to the amount of VOC times the cost of hazardous emission treatment plus the cost of the disposal of materials treated as hazardous waste for materials with expired shelf-life or out time. After the alternative, waste disposal costs are equal to the amount of VOC times the cost of hazardous emission treatment.

DATA RANGES FOR WASTE DISPOSAL COSTS: Data above; percentages from CCAD; hazardous emission disposal cost is $100/lb*; hazardous waste disposal cost is $30/lb.

Total Operating Costs	
BEFORE alternative	AFTER alternative
COB(tot) = CS(tot) + CW(tot) Where COB(tot) = Total operating costs before alternative	COA(tot) = CS(tot) + CW(tot) Where COA(tot) = Total operating costs after alternative

* While VOC emissions are currently released, restrictions on this practice are anticipated.

INCREASE OR DECREASE IN ANNUAL OPERATING COSTS	
BEFORE alternative	AFTER alternative
CO = COB(tot) – COA(tot) Where: CO = Increase or decrease in annual operating costs	

PAYBACK PERIOD
TPAY = (CC)/(-CO) (in years) Where: TPAY = Time required for implementation of alternative to pay back any capital costs

COST EXAMPLE

CAPITAL COSTS	
BEFORE alternative	**AFTER alternative**
Not applicable.	CC = CC(E) + CC(C) CC = $550,000

ANNUAL OPERATING COSTS	
Supply Costs	
BEFORE alternative	**AFTER alternative**
	CS(tot) = Nrepairs[(CRM + CL) + QW(HW) (CRM)] CS(tot) = 1,000 repairs [($100/repair) + $2400 + 5%_($100/repair)] CS(tot) = 1,000($100 + $2400 + $5) CS(tot) = $2,505,000 CS(tot) = Nrepairs[(CRM + CL) + QW(HW) (CRM)] CS(tot) = 1,000 repairs [($100/repair) + $1400 + (4.5%)_($100/repair)] $C_{S(tot)}$ = 1,000($100 + $2370 + $4.50) $C_{S(tot)}$ = $2,474,500
Waste Disposal Costs	
BEFORE alternative	**AFTER alternative**
$C_{W(tot)} = N_{repairs}[(C_{W(HE)})(Q_{W(HE)}) + Q_{W(HW)} (C_{HW})]$ $C_{W(tot)}$ = 1,000 repairs {[(0.02 lb)• $100/repair] + [5%• ($30/repair)]} $C_{W(tot)}$ = 1,000 ($2.00 + $1.50) $C_{W(tot)}$ = $3,500	$C_{W(tot)} = N_{repairs}[(C_{W(HE)})(Q_{W(HE)}) + Q_{W(HW)} (C_{HW})]$ $C_{W(tot)}$ = 1,000 repairs {[50%(0.02 lb)_$100/repair] + [4.5%_($30/repair)]} $C_{W(tot)}$ = 1,000 ($1.00 + $1.35) $C_{W(tot)}$ = $2,350
Total Operating Costs	
BEFORE alternative	**AFTER alternative**
$C_{OB(tot)} = C_{S(tot)} + C_{W(tot)}$ $C_{OB(tot)}$ = $2,505,000 + $3,500 $C_{OB(tot)}$ = $2,508,500	$C_{OA(tot)} = C_{S(tot)} + C_{W(tot)}$ $C_{OA(tot)}$ = $2,474,500 + $2,350 $C_{OA(tot)}$ = $2,476,900

INCREASE OR DECREASE IN ANNUAL OPERATING COSTS	
BEFORE alternative	**AFTER alternative**
$C_O = C_{OB(tot)} - C_{OA(tot)}$ C_O = $2,508,500 – $2,476,900 C_O = $31,600	

PAYBACK PERIOD
$T_{PAY} = (C_C)/(C_O)$ (in years) T_{PAY} = $550,000/$31,600 T_{PAY} = 17.4 years

Example Application: Repair of AEM/S System

BASELINE PRACTICE
Heat blanket – film adhesive and prepreg repair of mast

REPLACEMENT TECHNOLOGY ALTERNATIVE
Room-temperature cure CIRTM – integrally cured resin/reinforcement repair of mast

LOCATION
Shipboard

ADVANTAGES

- Elimination of VOC emissions
- Reduction in shelf-life expiration and production debris hazardous waste
- Faster cure/improved readiness

DISADVANTAGES

- Training in new technology
- Challenge to use CIRTM with two-sided, not through, access

Note that costs presented in this example may vary greatly depending on labor costs, number of repairs, volume, material disposed, unit costs, and uncertainties in available data.

CAPITAL COSTS	
BEFORE alternative	**AFTER alternative**
$C_C = C_{C(E)}$ Where: C_C = Total capital costs $C_{C(E)}$ = Capital costs of equipment	$C_C = C_{C(E)}$ Where: C_C = Total capital costs $C_{C(E)}$ = Capital costs of equipment

CAPITAL COSTS include the cost of heat blanket thermal-cure equipment (BEFORE) and cost of CIRTM equipment (AFTER). BEFORE costs are included as neither alternative is currently implemented. Analysis is on a per ship basis.

DATA RANGES FOR CAPITAL COSTS (based on available information): Heat blanket thermal-cure equipment ($10,000); CIRTM equipment ($15,000).

ANNUAL OPERATING COSTS	
Supply Costs	
BEFORE alternative	**AFTER alternative**
$C_{S(tot)} = Q_{repairs}[(C_{RM} + C_L) + Q_{W(HW)}(C_{RM})]$ Where: $C_{S(tot)}$ = Total supply cost per year $Q_{repairs}$ = Quantity of repaired material C_{RM} = Raw materials cost C_L = Labor cost $Q_{W(HW)}$ = Waste disposal quantity of hazardous waste	$C_{S(tot)} = Q_{repairs}[(C_{RM} + C_L) + Q_{W(HW)}(C_{RM})]$ Where: $C_{S(tot)}$ = Total supply cost per year $Q_{repairs}$ = Quantity of repaired material C_{RM} = Raw materials cost C_L = Labor cost $Q_{W(HW)}$ = Waste disposal quantity of hazardous waste

SUPPLY COSTS are equal to the cost per repair times the number of repairs plus stockpiling costs.

DATA RANGES FOR SUPPLY COSTS (based on available information): cost of raw materials ($15/lb); quantity of repaired material (1% of 30 tons); labor cost per pound (heat blanket) ($200), labor cost per pound (CIRTM) ($200); production debris hazardous waste same ratio as manufacturing (1.5 tons/30 tons per step); steps (BEFORE) (3), steps (AFTER) (1), shelf-life expiration (BEFORE) (Figure 8 in the main body of this report), (AFTER) (reduced by half).

Waste Disposal Costs	
BEFORE alternative	**AFTER alternative**
$C_{W(tot)} = Q_{repairs}(Q_{W(HW)})(C_{HW})$ Where: $C_{W(tot)}$ = Total waste disposal cost per year $Q_{repairs}$ = Quantity of repaired material $Q_{W(HW)}$ = Waste disposal quantity of hazardous waste C_{HW} = Cost of disposing expired shelf-life and production debris material as hazardous waste	$C_{W(tot)} = Q_{repairs}(Q_{W(HW)})(C_{HW})$ Where: $C_{W(tot)}$ = Total waste disposal cost per year $Q_{repairs}$ = Quantity of repaired material $Q_{W(HW)}$ = Waste disposal quantity of hazardous waste C_{HW} = Cost of disposing expired shelf-life and Production debris material as hazardous waste

WASTE DISPOSAL COSTS. Waste disposal costs are equal to the cost of the disposal of materials treated as hazardous waste for production debris and materials with expired shelf-life or out time.

DATA RANGES FOR WASTE DISPOSAL COSTS: Data above; hazardous waste disposal cost is $50/lb.

Total Operating Costs	
BEFORE alternative	**AFTER alternative**
$C_{OB(tot)} = C_{S(tot)} + C_{W(tot)}$ Where $C_{OB(tot)}$ = Total operating costs before alternative	$C_{OA(tot)} = C_{S(tot)} + C_{W(tot)}$ Where $C_{OA(tot)}$ = Total operating costs after alternative

INCREASE OR DECREASE IN ANNUAL OPERATING COSTS	
BEFORE alternative	**AFTER alternative**
$C_O = C_{OB(tot)} - C_{OA(tot)}$ Where: C_O = Increase or decrease in annual operating costs	

PAYBACK PERIOD
$T_{PAY} = (C_C)/(-C_O)$ (in years) Where: T_{PAY} = Time required for implementation of alternative to pay back any capital costs

COST EXAMPLE

CAPITAL COSTS	
BEFORE alternative	**AFTER alternative**
$C_C = C_{C(E)}$ $C_C = \$15{,}000$	$C_C = C_{C(E)}$ $C_C = \$15{,}000$

ANNUAL OPERATING COSTS	
Supply Costs	
BEFORE alternative	**AFTER alternative**
$C_{S(tot)} = Q_{repairs}[(C_{RM} + C_L) + Q_{W(HW)}(C_{RM})]$ $C_{S(tot)} = 1\%\ (30\ \text{tons})\ \{\$15/\text{lb} + \$200/\text{lb} + [(3)(1.5/30) + 15\%/50\%](\$15/\text{lb})\}$ $C_{S(tot)} = 600\ \text{lb}\ \{\$15/\text{lb} + \$200/\text{lb} + 0.45(\$15/\text{lb})\}$ $C_{S(tot)} = \$133{,}050$	$C_{S(tot)} = Q_{repairs}[(C_{RM} + C_L) + Q_{W(HW)}(C_{RM})]$ $C_{S(tot)} = 1\%\ (30\ \text{tons})\ \{\$15/\text{lb} + \$200/\text{lb} + [(1)(1.5/30) + (15\%/50\%)/2](\$15/\text{lb})\}$ $C_{S(tot)} = 600\ \text{lb}\ \{\$15/\text{lb} + \$200/\text{lb} + 0.20(\$15/\text{lb})\}$ $C_{S(tot)} = \$130{,}800$
Waste Disposal Costs	
BEFORE alternative	**AFTER alternative**
$C_{W(tot)} = Q_{repairs}(Q_{W(HW)})(C_{HW})$ $C_{W(tot)} = 1\%\ (30\ \text{tons})\ [(3)(1.5/30) + 15\%/50\%](\$50/\text{lb})$ $C_{W(tot)} = 600\ \text{lb}\ (0.45)(\$50/\text{lb})$ $C_{W(tot)} = \$13{,}500$	$C_{W(tot)} = Q_{repairs}(Q_{W(HW)})(C_{HW})$ $C_{W(tot)} = 1\%\ (30\ \text{tons})\ [(1)(1.5/30) + (15\%/50\%)/2](\$50/\text{lb})$ $C_{W(tot)} = 600\ \text{lb}\ (0.20)(\$50/\text{lb})$ $C_{W(tot)} = \$6{,}000$
Total Operating Costs	
BEFORE alternative	**AFTER alternative**
$C_{OB(tot)} = C_{S(tot)} + C_{W(tot)}$ $C_{OB(tot)} = \$133{,}050 + \$13{,}500$ $C_{OB(tot)} = \$146{,}550$	$C_{OA(tot)} = C_{S(tot)} + C_{W(tot)}$ $C_{OA(tot)} = \$130{,}800 + \$6{,}000$ $C_{OA(tot)} = \$136{,}800$

INCREASE OR DECREASE IN ANNUAL OPERATING COSTS	
BEFORE alternative	**AFTER alternative**
$C_O = C_{OB(tot)} - C_{OA(tot)}$ $C_O = \$146{,}550 - \$136{,}800$ $C_O = \$9{,}750$	

PAYBACK PERIOD
$T_{PAY} = (C_{CA} - C_{CB})/(C_O)$ (in years) $T_{PAY} = \$15{,}000 - \$10{,}000/\$9{,}750$ $T_{PAY} = 0.51$ years

Example Application: Remanufacture of AEM/S System

BASELINE PRACTICE
Room-temperature cure VARTM – resin/reinforcement manufacture of mast

REPLACEMENT TECHNOLOGY ALTERNATIVE
Room-temperature cure CIRTM – resin/reinforcement manufacture of mast

LOCATION
Manufacturer

ADVANTAGES
- Reduction in production debris hazardous waste
- Faster processing

DISADVANTAGES
- Training in new technology

ASSUMPTION
- Assumes inclusion of phenolic liner

Note that costs presented in this example may vary greatly depending on labor costs, number of repairs, volume, material disposed, unit costs, and uncertainties in available data.

CAPITAL COSTS	
BEFORE alternative	**AFTER alternative**
Not applicable	$C_C = C_{C(E)}$ Where: C_C = Total capital costs $C_{C(E)}$ = Capital costs of equipment

CAPITAL COSTS include the cost of CIRTM equipment.

DATA RANGES FOR CAPITAL COSTS (based on available information): CIRTM equipment ($150,000).

ANNUAL OPERATING COSTS	
Supply Costs	
BEFORE alternative	**AFTER alternative**
$C_{S(tot)} = N_{ships}\ Q_{material}\ [(C_{RM} + C_L) + Q_{W(HW)}\ (C_{RM})]$ Where: $C_{S(tot)}$ = Total supply cost per year N_{ships} = Number of ships $Q_{material}$ = Quantity of material per ship C_{RM} = Raw materials cost C_L = Labor cost $Q_{W(HW)}$ = Waste disposal quantity of hazardous waste	$C_{S(tot)} = N_{ships}\ Q_{material}\ [(C_{RM} + C_L) + Q_{W(HW)}\ (C_{RM})]$ Where: $C_{S(tot)}$ = Total supply cost per year N_{ships} = Number of ships $Q_{material}$ = Quantity of material per ship C_{RM} = Raw materials cost C_L = Labor cost $Q_{W(HW)}$ = Waste disposal quantity of hazardous waste

SUPPLY COSTS are equal to the cost per repair times the number of repairs plus stockpiling costs.

DATA RANGES FOR SUPPLY COSTS (based on available information): cost of raw materials ($8/lb); number of ships per year (6); quantity of material per ship (30 tons); labor cost per pound (VARTM) ($40), labor cost per pound (CIRTM) ($30); production debris hazardous waste same ratio as manufacturing (1.5 tons/30 tons per step); steps (BEFORE) (3), steps (AFTER) (1).

Waste Disposal Costs	
BEFORE alternative	**AFTER alternative**
$C_{W(tot)} = N_{ships}\ Q_{material}\ (Q_{W(HW)})(C_{HW})$ Where: $C_{W(tot)}$ = Total waste disposal cost per year N_{ships} = Number of ships $Q_{material}$ = Quantity of material per ship $Q_{W(HW)}$ = Waste disposal quantity of hazardous waste C_{HW} = Cost of disposing expired shelf-life and production debris material as hazardous waste	$C_{W(tot)} = N_{ships}\ Q_{material}\ (Q_{W(HW)})(C_{HW})$ Where: $C_{W(tot)}$ = Total waste disposal cost per year N_{ships} = Number of ships $Q_{material}$ = Quantity of material per ship $Q_{W(HW)}$ = Waste disposal quantity of hazardous waste C_{HW} = Cost of disposing expired shelf-life and production debris material as hazardous waste

WASTE DISPOSAL COSTS. Waste disposal costs are equal to the cost of the disposal of materials treated as hazardous waste for production debris and materials with expired shelf-life or out time.

DATA RANGES FOR WASTE DISPOSAL COSTS: Data above; hazardous waste disposal cost is $30/lb.

Total Operating Costs	
BEFORE alternative	**AFTER alternative**
$C_{OB(tot)} = C_{S(tot)} + C_{W(tot)}$ Where $C_{OB(tot)}$ = Total operating costs before alternative	$C_{OA(tot)} = C_{S(tot)} + C_{W(tot)}$ Where $C_{OA(tot)}$ = Total operating costs after alternative

INCREASE OR DECREASE IN ANNUAL OPERATING COSTS	
BEFORE alternative	**AFTER alternative**
$C_O = C_{OB(tot)} - C_{OA(tot)}$ Where: C_O = Increase or decrease in annual operating costs	

PAYBACK PERIOD
$T_{PAY} = (C_C)/(-C_O)$ (in years) Where: T_{PAY} = Time required for implementation of alternative to pay back any capital costs

COST EXAMPLE

CAPITAL COSTS	
BEFORE alternative	**AFTER alternative**
Not applicable	$C_C = C_{C(E)}$ $C_C = \$150{,}000$

ANNUAL OPERATING COSTS	
Supply Costs	
BEFORE alternative	**AFTER alternative**
$C_{S(tot)} = N_{ships}\, Q_{material}\, [(C_{RM} + C_L) + Q_{W(HW)}\, (C_{RM})]$ $C_{S(tot)} = 6(30 \text{ tons})\ \{\$8/\text{lb} + \$40/\text{lb} + (3)(1.5/30)\ (\$8/\text{lb})\}$ $C_{S(tot)} = 360{,}000 \text{ lb}\ \{\$8/\text{lb} + \$40/\text{lb} + 0.15(\$8/\text{lb})\}$ $C_{S(tot)} = \$17{,}712{,}000$	$C_{S(tot)} = N_{ships}\, Q_{material}\, [(C_{RM} + C_L) + Q_{W(HW)}\, (C_{RM})]$ $C_{S(tot)} = 6(30 \text{ tons})\ \{\$8/\text{lb} + \$30/\text{lb} + (1)(1.5/30)\ (\$8/\text{lb})\}$ $C_{S(tot)} = 360{,}000 \text{ lb}\ \{\$8/\text{lb} + \$40/\text{lb} + 0.05(\$8/\text{lb})\}$ $C_{S(tot)} = \$13{,}824{,}000$
Waste Disposal Costs	
BEFORE alternative	**AFTER alternative**
$C_{W(tot)} = N_{ships}\, Q_{material}\, (Q_{W(HW)})(C_{HW})$ $C_{W(tot)} = 6(30 \text{ tons})\ (3)(1.5/30)\ (\$30/\text{lb})$ $C_{W(tot)} = 360{,}000 \text{ lb}\ \ (0.15)(\$30/\text{lb})$ $C_{W(tot)} = \$1{,}620{,}000$	$C_{W(tot)} = N_{ships}\, Q_{material}\, (Q_{W(HW)})(C_{HW})$ $C_{W(tot)} = 6(30 \text{ tons})\ (1)(1.5/30)\ (\$30/\text{lb})$ $C_{W(tot)} = 360{,}000 \text{ lb}\ \ (0.05)(\$30/\text{lb})$ $C_{W(tot)} = \$540{,}000$
Total Operating Costs	
BEFORE alternative	**AFTER alternative**
$C_{OB(tot)} = C_{S(tot)} + C_{W(tot)}$ $C_{OB(tot)} = \$17{,}712{,}000 + \$1{,}620{,}000$ $C_{OB(tot)} = \$19{,}332{,}000$	$C_{OA(tot)} = C_{S(tot)} + C_{W(tot)}$ $C_{OA(tot)} = \$13{,}824{,}000 + \$540{,}000$ $C_{OA(tot)} = \$14{,}364{,}000$

INCREASE OR DECREASE IN ANNUAL OPERATING COSTS	
BEFORE alternative	**AFTER alternative**
$C_O = C_{OB(tot)} - C_{OA(tot)}$ $C_O = \$19{,}332{,}000 - \$14{,}364{,}000$ $C_O = \$4{,}968{,}000$	

PAYBACK PERIOD
$T_{PAY} = (C_C)/(C_O)$ (in years) $T_{PAY} = \$150{,}000/\$4{,}968{,}000$ $T_{PAY} = 0.03$ years

Example Application: Repair of Integral Armor

BASELINE PRACTICE
Heat blanket – film adhesive and prepreg multi-step repair of integral armor

REPLACEMENT TECHNOLOGY ALTERNATIVE
Induction – film adhesive and prepreg single-step repair of integral armor

LOCATION
Theater depot

ADVANTAGES

- One-step process – significant increase in readiness
- Reduction in shelf-life expiration and production debris hazardous waste
- Faster cure
- Relatively large cost reduction by eliminating shipping extra raw material to and hazardous waste from theater of operations

DISADVANTAGES

- Training in new technology

Note that costs presented in this example may vary greatly depending on labor costs, number of repairs, volume, material disposed, unit costs, and uncertainties in available data.

CAPITAL COSTS	
BEFORE alternative	**AFTER alternative**
Not applicable.	$C_C = C_{C(E)}$ Where: C_C = Total capital costs $C_{C(E)}$ = Capital costs of equipment

CAPITAL COSTS include the cost of an induction unit.

DATA RANGES FOR CAPITAL COSTS (based on available information): induction unit ($15,000).

ANNUAL OPERATING COSTS	
Supply Costs	
BEFORE alternative	**AFTER alternative**
$C_{S(tot)} = N_{repairs}[(C_{RM} + C_L) + Q_{W(HW)}(C_{RM})]$ Where: $C_{S(tot)}$ = Total supply cost per year $N_{repairs}$ = Number of repairs C_{RM} = Raw materials cost per repair C_L = Labor cost per repair $Q_{W(HW)}$ = Waste disposal quantity of hazardous waste	$C_{S(tot)} = N_{repairs}[(C_{RM} + C_L) + Q_{W(HW)}(C_{RM})]$ Where: $C_{S(tot)}$ = Total supply cost per year $N_{repairs}$ = Number of repairs C_{RM} = Raw materials cost per repair C_L = Labor cost per repair $Q_{W(HW)}$ = Waste disposal quantity of hazardous waste

SUPPLY COSTS are equal to the cost per repair times the number of repairs plus stockpiling costs.

DATA RANGES FOR SUPPLY COSTS (based on available information): cost of raw materials (5 lb composite @ $30/lb; 1 lb adhesive @ $10/lb per repair) plus shipping ($50/lb); labor cost per repair (heat blanket) is $800, labor cost per repair (induction - reduced steps) is $400; percentages of shelf-life expiration and production debris hazardous waste (BEFORE) (Figure 8 in the main body of this report), (AFTER) shelf-life expiration hazardous waste reduced by 20%, production debris reduced by 75%.

For cost estimate only, assume 200 repairs per year. Cost of other components is constant and neglected.

Waste Disposal Costs	
BEFORE alternative	**AFTER alternative**
$C_{W(tot)} = N_{repairs}(Q_{W(HW)}(C_{HW}))$ Where: $C_{W(tot)}$ = Total waste disposal cost per year $N_{repairs}$ = Number of repairs $Q_{W(HW)}$ = Waste disposal quantity of hazardous waste C_{HW} = Cost of disposing expired shelf-life and production debris material as hazardous waste	$C_{W(tot)} = N_{repairs}(Q_{W(HW)}(C_{HW}))$ Where: $C_{W(tot)}$ = Total waste disposal cost per year $N_{repairs}$ = Number of repairs $Q_{W(HW)}$ = Waste disposal quantity of hazardous waste C_{HW} = Cost of disposing expired shelf-life and production debris material as hazardous waste

WASTE DISPOSAL COSTS. Waste disposal costs are equal to the cost of the disposal of materials treated as hazardous waste for production debris and materials with expired shelf-life or out time.

DATA RANGES FOR WASTE DISPOSAL COSTS: Data above; hazardous waste disposal cost is $40/lb plus shipping ($50/lb).

Total Operating Costs	
BEFORE alternative	**AFTER alternative**
$C_{OB(tot)} = C_{S(tot)} + C_{W(tot)}$ Where $C_{OB(tot)}$ = Total operating costs before alternative	$C_{OA(tot)} = C_{S(tot)} + C_{W(tot)}$ Where $C_{OA(tot)}$ = Total operating costs after alternative

INCREASE OR DECREASE IN ANNUAL OPERATING COSTS	
BEFORE alternative	**AFTER alternative**
$C_O = C_{OB(tot)} - C_{OA(tot)}$ Where: C_O = Increase or decrease in annual operating costs	

PAYBACK PERIOD
$T_{PAY} = (C_C)/(-C_O)$ (in years) Where: T_{PAY} = Time required for implementation of alternative to pay back any capital costs

COST EXAMPLE

CAPITAL COSTS	
BEFORE alternative	**AFTER alternative**
Not applicable.	$C_C = C_{C(E)}$ $C_C = \$15,000$

ANNUAL OPERATING COSTS	
Supply Costs	
BEFORE alternative	**AFTER alternative**
$C_{S(tot)} = N_{repairs}[(C_{RM} + C_L) + Q_{W(HW)} (C_{RM})]$ $C_{S(tot)}$ = 200 repairs [(5 lb composite) ($30/lb+$50/lb) + (1 lb adhesive)($10/lb+$50/lb) + $800 + (30%+20%)/50%_ (5 lb composite) ($30/lb+$50/lb) + (40%+10%)/50%_(1 lb adhesive)($10/lb+$50/lb)] $C_{S(tot)}$ = 200($400 + $60 + $800 + $400 + $60) $C_{S(tot)}$ = $344,000	$C_{S(tot)} = N_{repairs}[(C_{RM} + C_L) + Q_{W(HW)} (C_{RM})]$ $C_{S(tot)}$ = 200 repairs {(5 lb composite) ($30/lb+$50/lb) + (1 lb adhesive)($10/lb+$50/lb) + $400 + [(30%)(80%)+(20%)/4]/50%_ (5 lb composite) ($30/lb+$50/lb) + [(40%)(80%)+(10%)/4]/50%_(1 lb adhesive)($10/lb+$50/lb)} $C_{S(tot)}$ = 200($400 + $60 + $400 + $232 + $41.40) $C_{S(tot)}$ = $226,680
Waste Disposal Costs	
BEFORE alternative	**AFTER alternative**
$C_{W(tot)} = N_{repairs}(Q_{W(HW)} (C_{HW})$ $C_{W(tot)}$ = 200 repairs {(30%+20%)/50%_ (5 lb composite) ($40/lb+$50/lb) + (40%+10%)/50%_(1 lb adhesive)($40/lb+$50/lb)} $C_{W(tot)}$ = 200 ($540) $C_{W(tot)}$ = $108,000	$C_{W(tot)} = N_{repairs}(Q_{W(HW)} (C_{HW})$ $C_{W(tot)}$ = 200 repairs {[(30%)(80%)+(20%)/4]/50%_ (5 lb composite) ($40/lb+$50/lb) + [(40%)(80%)+(10%)/4]/50%_(1 lb adhesive)($40/lb+$50/lb)]} $C_{W(tot)}$ = 200 ($261 + $62.10) $C_{W(tot)}$ = $64,620
Total Operating Costs	
BEFORE alternative	**AFTER alternative**
$C_{OB(tot)} = C_{S(tot)} + C_{W(tot)}$ $C_{OB(tot)}$ = $344,000 + $108,000 $C_{OB(tot)}$ = $452,000	$C_{OA(tot)} = C_{S(tot)} + C_{W(tot)}$ $C_{OA(tot)}$ = $226,680 + $64,620 $C_{OA(tot)}$ = $291,300

INCREASE OR DECREASE IN ANNUAL OPERATING COSTS	
BEFORE alternative	**AFTER alternative**
$C_O = C_{OB(tot)} - C_{OA(tot)}$ C_O = $452,000 – $291,300 C_O = $160,700	
PAYBACK PERIOD	
$T_{PAY} = (C_C)/(C_O)$ (in years) T_{PAY} = $15,000/$160,700 T_{PAY} = 0.10 years	

Example Application: Remanufacturing of Sabots

BASELINE PRACTICE
Hot press - thermoset prepreg multi-step manufacture of sabots

REPLACEMENT TECHNOLOGY ALTERNATIVE
Induction - thermoplastic prepreg single-step manufacture of sabots

LOCATION
Manufacturer

ADVANTAGES

- One-step process
- Elimination of shelf-life expiration and production debris hazardous waste
- Faster cure
- Reduction in VOC emissions

DISADVANTAGES

- Training in new technology

Note that costs presented in this example are for one particular round. Total emission and hazardous waste figures are presented without providing a specific number of parts based on information available for unlimited distribution.

CAPITAL COSTS	
BEFORE alternative	**AFTER alternative**
Not applicable.	$C_C = C_{C(E)}$ Where: C_C = Total capital costs $C_{C(E)}$ = Capital costs of equipment

CAPITAL COSTS include the cost of an induction unit.

DATA RANGES FOR CAPITAL COSTS (based on available information): induction unit ($100,000).

ANNUAL OPERATING COSTS	
Supply Costs	
BEFORE alternative	**AFTER alternative**
$C_{SE(tot)} = Q_{W(HW)} (C_{RM})$ Where: $C_{SE(tot)}$ = Total supply cost per year from environmental factors C_{RM} = Raw materials cost per part $Q_{W(HW)}$ = Waste disposal quantity of hazardous waste	$C_{SE(tot)} = Q_{W(HW)} (C_{RM})$ Where: $C_{SE(tot)}$ = Total supply cost per year from environmental factors C_{RM} = Raw materials cost per part $Q_{W(HW)}$ = Waste disposal quantity of hazardous waste

SUPPLY COSTS are equal to the cost per part times the number of parts plus stockpiling costs.

DATA RANGES FOR SUPPLY COSTS (based on available information): cost of raw materials (composite @ $30/lb); shelf-life expiration and production debris hazardous waste (BEFORE) 30,000 lb, (AFTER) shelf-life expiration hazardous waste and production debris are eliminated.

For cost estimate only, assume 200 parts per year. Cost of other components is constant and neglected.

Waste Disposal Costs	
BEFORE alternative	**AFTER alternative**
$C_{W(tot)} = Q_{W(HE)} (C_{HE}) + Q_{W(HW)} (C_{HW})$ Where: $C_{W(tot)}$ = Total waste disposal cost per year $C_{W(HE)}$ = Waste disposal cost of VOC $Q_{W(HE)}$ = Waste disposal quantity of VOC $Q_{W(HW)}$ = Waste disposal quantity of hazardous waste C_{HW} = Cost of disposing expired shelf-life and production debris material as hazardous waste	$C_{W(tot)} = Q_{W(HE)} (C_{HE}) + Q_{W(HW)} (C_{HW})$ Where: $C_{W(tot)}$ = Total waste disposal cost per year $C_{W(HE)}$ = Waste disposal cost of VOC $Q_{W(HE)}$ = Waste disposal quantity of VOC $Q_{W(HW)}$ = Waste disposal quantity of hazardous waste C_{HW} = Cost of disposing expired shelf-life and production debris material as hazardous waste

WASTE DISPOSAL COSTS. Waste disposal costs are equal to the cost of the disposal of materials treated as hazardous waste for production debris and materials with expired shelf-life or out time plus cost of treating VOCs to meet relevant standards.

DATA RANGES FOR WASTE DISPOSAL COSTS: Data above; hazardous waste disposal cost is $20/lb, amount of hazardous emissions 1,200 lb, reduction in hazardous emissions 60%, cost of treating VOCs $100/lb.

Total Environmental Operating Costs	
BEFORE alternative	**AFTER alternative**
$C_{OB(tot)} = C_{SE(tot)} + C_{W(tot)}$ Where $C_{OB(tot)}$ =Total operating costs before alternative	$C_{OA(tot)} = CE_{S(tot)} + C_{W(tot)}$ Where $C_{OA(tot)}$ =Total operating costs after alternative

INCREASE OR DECREASE IN ANNUAL OPERATING COSTS	
BEFORE alternative	**AFTER alternative**
$C_O = C_{OB(tot)} - C_{OA(tot)}$ Where: C_O = Increase or decrease in annual operating costs	

PAYBACK PERIOD
$T_{PAY} = (C_C)/(-C_O)$ (in years) Where: T_{PAY} = Time required for implementation of alternative to pay back any capital costs

COST EXAMPLE

CAPITAL COSTS	
BEFORE alternative	**AFTER alternative**
Not applicable.	$C_C = C_{C(E)}$ $C_C = \$100{,}000$

ANNUAL OPERATING COSTS	
Supply Costs	
BEFORE alternative	**AFTER alternative**
$C_{SE(tot)} = Q_{W(HW)} (C_{RM})$ $C_{SE(tot)} = 30{,}000$ lb($30/lb) $C_{S(tot)} = \$90{,}000$	$C_{SE(tot)} = Q_{W(HW)} (C_{RM})$ $C_{SE(tot)} = 10\%(30{,}000$ lb)($30/lb) $C_{S(tot)} = \$9{,}000$
Waste Disposal Costs	
BEFORE alternative	**AFTER alternative**
$C_{W(tot)} = Q_{W(HE)} (C_{HE}) + Q_{W(HW)} (C_{HW})$ $C_{W(tot)} = (1{,}200$ lb) ($100/lb) + (30,000 lb) ($20/lb) $C_{W(tot)} = \$120{,}000 + \$600{,}000$ $C_{W(tot)} = \$720{,}000$	$C_{W(tot)} = Q_{W(HE)} (C_{HE}) + Q_{W(HW)} (C_{HW})$ $C_{W(tot)} = 40\%(1{,}200$ lb) ($100/lb) + 0%(30,000 lb) ($20/lb) $C_{W(tot)} = \$48{,}000 + \$0$ $C_{W(tot)} = \$48{,}000$
Total Environmental Operating Costs	
BEFORE alternative	**AFTER alternative**
$C_{OB(tot)} = C_{SE(tot)} + C_{W(tot)}$ $C_{OB(tot)} = \$90{,}000 + \$720{,}000$ $C_{OB(tot)} = \$810{,}000$	$C_{OA(tot)} = C_{SE(tot)} + C_{W(tot)}$ $C_{OA(tot)} = \$9{,}000 + \$48{,}000$ $C_{OA(tot)} = \$57{,}000$

INCREASE OR DECREASE IN ANNUAL OPERATING COSTS	
BEFORE alternative	**AFTER alternative**
$C_O = C_{OB(tot)} - C_{OA(tot)}$ $C_O = \$810{,}000 - \$57{,}000$ $C_O = \$753{,}000$	

PAYBACK PERIOD
$T_{PAY} = (C_C)/(C_O)$ (in years) $T_{PAY} = \$100{,}000/\$753{,}000$ $T_{PAY} = 0.13$ years

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13. ABSTRACT *(Maximum 200 words)*

Polymer-matrix composite material and structural adhesive repair and manufacturing have significant environmental costs for Department of Defense (DOD) use. The principal issues for reducing environmental costs are (1) reducing hazardous waste by eliminating shelf-life limitations; (2) reducing nitrogen oxides (NO_x) by replacing global heating of the part with localized heating; (3) reducing volatile organic compound (VOC) emissions by accelerated curing and containment; and (4) reducing production debris hazardous waste through processing step management. Due to the wide range of applications and material systems, as well as scenarios spanning manufacturing and depot and field repair, a family of solutions is described that is expected to meet these needs. An environmental baseline is established by identifying hazardous materials from composite repair and manufacturing operations and estimating usage and waste. The predicted reduction in hazardous waste is 78% for composite materials and 95% for adhesives. NO_x and VOC emissions can be reduced by 100% and 50% by using the proposed techniques. Conservative environmental cost-savings estimates are developed for several potential DOD applications. These estimates indicate that the use of the proposed technologies for DOD systems would provide an annual savings of $15 billion (1997) for the year 2028.

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