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ASSESSMENT OF THE RISKS ASSOCIATED WITH THE USE OF CARBON FIBERS IN SURFACE TRANSPORTATION

W.T. Hathaway
K.M. Hergenrother
C.E. Bogner

U.S. DEPARTMENT OF TRANSPORTATION
Research and Special Programs Administration
Transportation Systems Center
Cambridge MA 02142

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16. Abstract

(20) This report presents the results of an assessment of the potential risks associated with the use of carbon-fiber composites in the surface transportation system and the development of a data base on the vulnerability of the surface transportation system to airborne carbon fibers. In conducting the risk assessment, (TSC) estimated the potential usage rate of carbon-fiber composites in surface transportation, the frequency and severity of vehicle fires and the expected carbon-fiber release from the composite in a fire. In developing the data base on the vulnerability, TSC reviewed and analyzed the electrical and electronic systems present in the various surface-transportation modes.

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PREFACE

The release of carbon fibers into the atmosphere was identified by the Office of Science and Technology Policy (OSTP) Interagency Carbon Fiber Committee as a potential hazard. The coordinated Federal Government action plan, developed by that Committee, assigned the Department of Transportation (DOT) the responsibility to assess the potential risks associated with the use of carbon fiber composites in the surface-transportation system and to develop a data base on the vulnerability of the surface-transportation system to airborne carbon fibers. This report presents the results of the DOT project which was sponsored by the Transportation Programs Bureau (TPB) of the Research and Special Programs Administration.

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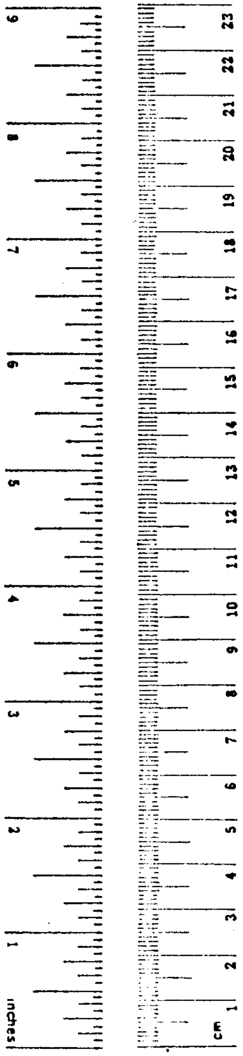
METRIC CONVERSION FACTORS

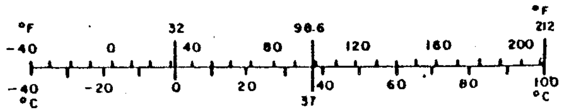
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.

TABLE OF CONTENTS

TABLE OF CONTENTS (CONT.)

LIST OF ILLUSTRATIONS

LIST OF TABLES

1. INTRODUCTION

1.1 PURPOSE AND SCOPE

Carbon graphite composites are a family of important, new, lightweight and high-strength materials finding very rapidly growing use in military and civil aircraft, in space systems, and in a variety of consumer products ranging from sporting goods to automobiles.[1] Carbon graphite composites may become as important to the United States and the international economy as the aluminum and steel they replace.

In a letter to the President, the Deputy Secretary of Defense and the Administrator, National Aeronautics and Space Administration (NASA), recognized the benefits and increasing use of composite materials. They also expressed concern that the carbon fibers if accidentally released into the atmosphere, posed a potential hazard to electrical equipment and possibly to the health of individuals.

In July 1977, the Director of the Office of Science and Technology Policy (OSTP) was directed by the President to investigate the potential problems of graphite composite materials and to prepare a plan for possible Federal action. To accomplish this task, an interdepartment/interagency committee was formed by OSTP. The Department of Transportation (DOT) responsibility as identified in the action plan is as follows:

> Surface transportation equipment. Virtually no data have been generated on the vulnerability of typical civilian surface transportation equipment. DOT will take the lead with assistance from NASA. This DOT program will include studies of surface transportation crash plus fire scenarios. The program will take two years, and will be reviewed at that time for possible continuation.[1]
>
> Commercial aircraft equipment. Studies of vulnerability of commercial grade avionics and control equipment, and other systems essential to the safety of flight, including ground-based equipment, have been started, but data

> are inadequate to permit assurance of protection or accurate assessment of vulnerability. Assisted by consultation with and advice from DOT (FAA), NASA has responsibility for establishing a suitable test program and design of protective measures in concert with the aircraft industry. This program will include studies of crash plus fire scenarios and will be reviewed after one year to establish a completion date.[1]

To address the first task in this responsibility, the Transportation Systems Center was tasked by the Research and Special Programs Administration, Transportation Programs Bureau, to assess the effects of carbon/graphite fiber (CF) composites as related to surface transportation system safety. This report discusses the quantity and applications of carbon fiber reinforced plastic (CRP) in surface transportation, the frequency of release incidents and the quantity of CF released from surface transportation, the risk to society associated with these incidents, and the vulnerability of surface transportation to CF.

1.2 BACKGROUND

Composites have been used for many years in the structure of transportation vehicles. Early applications of glass fiber reinforced plastic (GRP) were in the bodies of the Corvette and Kaiser-Darin sport cars and in the hulls of many recreational boats. More recently, truck fenders and many automobile fenders have also been made of fiber glass composite. In all these applications, GRP has been chosen because of its low tooling cost and its corrosion resistance. The aerospace industry has developed composites from very high strength fibers to produce structures with exceptional strength combined with low weight. The most widely used of this new generation of composites is carbon fiber reinforced plastic (CRP), where the resin is usually epoxy. Because of its unusual combinations of strength, stiffness, light weight, and fatigue life as well as a potential for reduced cost, CRP is expected to find many applications in surface transportation vehicles, particularly in trucks and automobiles. The weight saving potential of CRP is of particular importance in its application to more energy efficient surface transportation.

The history of carbon fibers and filaments extends for many years. In his classic work on the incandescent lamp, Edison made carbon filaments before 1880 by carbonizing natural cellulose fibers, such as cotton and linen. A further development occurred in 1909 when Whitney patterned a process for coating carbon fibers from cellulose with pyrolytic graphite by flashing at temperatures of up to 4,000°C. However, after the introduction of tungsten filaments, interest in carbon for lamp applications declined.

In the 1950's, the search for new materials for structural composites generated an upsurge of interest in carbon fibers. Early work at this time on pyrolyzed viscose rayon, sponsored by the Air Force Materials Laboratory (AFML) at Wright-Patterson Air Force Base, produced relatively strong flexible fibers by stretching the fiber during carbonization at 2,000°C. Although the process for producing high strength fibers was not very reproducible, reliable low-strength carbon and graphite yarns and fabrics could be manufactured. These low-strength fibers found application in tape configurations for strategic missile re-entry vehicle heat shields and rocket nozzles in the early 1960's.

A significant breakthrough in carbon fiber technology occurred in the period 1963-1965 when it was discovered that very high strength carbon filaments could be obtained by subjecting the precursor fiber to a rigidly controlled continuous tensile stress during the high-temperature treatment. It is the high values of the specific modulus and specific strength that make these new carbon fibers attractive materials as structural reinforcing agents.

Despite the advantages associated with the use of CF composites, there are problems which must be addressed before the nation embarks on a course of widespread use of CF. There are circumstances where the individual carbon fibers can be released from the composite. Since these fibers are .008 milimeters in diameter and are very light, they can drift great distances on normal wind and air currents. A carbon fiber is a conducting element with the ability to short out exposed electrical contacts if it comes to rest across a pair of contacts. The effect of such a short depends on the voltage and current characteristics of the circuit being shorted. Problems of this nature may negate the benefits or advantages which accrue from the use of CF.

1.3 DEPARTMENTAL/AGENCY RESPONSIBILITIES

Reference 1 presented a coordinated Federal Government action plan for dealing with the potential problems arising from the use of CF composites in both military and civilian applications. The action plan, which took advantage of the many years of experience possessed by DOD and NASA, addressed the required coordination, dissemination, and declassification of information as well as the research and development work required to support the program. Included in the action plan are both the near-term and continuing actions necessary to minimize the adverse effects resulting from widespread use of CF composites. The responsibility and authority assigned to each department or agency is shown in Table 1-1, the Authority Matrix.

TABLE 1-1. AUTHORITY MATRIX CARBON FIBER RESEARCH AND DEVELOPMENT

AUTHORITY	GOVERNMENT ORGANIZATION									
	DOT	NASA	DOE	EPA	DOC	HEW	DOS	DOD	DOL	DCPA
SURFACE TRANSPORTATION EQUIPMENT	L	A								
AIRCRAFT INCIDENT REPORTING SYSTEM	L	A						A		A
COMMERCIAL AIRCRAFT EQUIPMENT	A	L								
ALTERNATIVE MATERIALS		L						A		
POWER GENERATION AND DISTRIBUTION EQUIPMENT			L					A		
ENVIRONMENT-CLEAN UP AND DISPOSAL				L				A		
ENVIRONMENTAL MONITORING EQUIPMENT				L				A		
COMMERCIAL AND HOUSEHOLD EQUIPMENT					L					
INFORMATION DISSEMINATION, MAINTAIN DATA BASE AND COORDINATE WITH INDUSTRY					L					
HEALTH RELATED EFFECTS						L			A	
INTERNATIONAL CONSIDERATIONS							L			

L - LEAD ORGANIZATION; A - ASSISTING ORGANIZATION. 6/6/78

2. ASSESSMENT OF POTENTIAL CARBON FIBER (CF) USE IN SURFACE TRANSPORTATION

2.1 INTRODUCTION

In an initial effort to examine the potential risks associated with the application of CF composite materials in surface transportation vehicles, an assessment was made to estimate the passenger car and truck market consumption of CF through 1990.

The information presented herein has been obtained from the existing literature and discussions with the CF manufacturers, fabricators, consultants, and the automotive industry. A more comprehensive market survey is being conducted by the Department of Commerce.[2] The following sections examine the economic incentives, composite constructions, proposed vehicle applications, limiting use factors, and market projections for "automotive grade" CF composites. This information will be an input into the CF risk analysis and vulnerability studies discussed in Section 4 and 5.

2.2 INCENTIVES

The major driving force for evolutionary design change in the automobile industry is the legislated goal of 27.5 miles per gallon fleet average required of each car manufacturer by 1985. While down-sizing trends and improvements in drivetrain and engine technologies are expected to continue, it appears that the near-term goal will largely be achieved through component re-design and direct substitution of plastics and aluminum for steel parts. The possibility of more stringent fuel economy standards proposed beyond 1985 may require vehicle manufacturers to incorporate significant quantities of advanced composite fiber materials (ACM) such as carbon, aramid, and glass for a variety of load bearing and non-structural applications. Reference 3 presents an in-depth study that examines, in part, the potential use of ACM in automotive structures based upon a "weight reduction/cost incentive" concept and should be reviewed for additional information.

The economic incentive for use of carbon fiber composites in truck and rail freight applications are potential increases in cargo capacity and payload. These direct advantages could be realized by selective use of ACM in body components to reduce primary and secondary weights of empty vehicles. Since carbon fibers possess superior fatigue-resistant and self-lubricating qualities, it is anticipated that vehicle repairs would be reduced, thus enhancing full-time fleet operations.

In examining rail transit and bus vehicles, only slight improvements in fuel economy are expected from the selective use of CF composites and are not considered significant inducements by vehicle manufacturers to advance high performance fiber composite technology for those applications.

In all cases, both economic and performance incentives are sensitive to manufacturers' raw material costs, retail price of vehicles and life cycle ownership costs. These factors were considered in projecting CF use beyond 1985.

2.3 CONSTRUCTION

Epoxy resins have been the predominant matrix material used to make advanced composites for aerospace applications. These resins have slow cure times and are relatively expensive. Accordingly, they do not lend themselves to high speed automotive processing techniques. Other resin systems are being evaluated as matrix materials to lower the costs of ACM. Thermosetting polyesters and vinyl esters are being extensively examined as candidate materials for high volume production applications. These resins are relatively inexpensive and formulations exist that cure rapidly, and, therefore, are amenable to high speed mass production fabrication methods. There is also interest in thermoplastics that exhibit reasonably high temperature resistance (such as nylon) as matrix materials. These thermoplastic resins lend themselves to rapid processing and to post-forming which can result in significant cost reductions.[3]

In general, the mechanical properties of fibrous composites depend on the type(s) of fiber incorporated in the matrix, its volumetric concentration, and fiber orientation.[3]

High strength fiber materials currently under investigation for use in surface transportation vehicles are available in a variety of forms; the selection of which form to use is dependent upon the desired strength characteristics of the composite part. The principal physical properties of these fibers are presented in Table 2-1.

Selective blending (hybridization) of these fibers when combined in a polyester, vinyl ester, or other resin matrix could result in high performance, automotive composite materials that possess the desired mechanical, chemical, and thermal properties as well as long-term serviceability features.

Discussions with fiber manufacturers, fabricators, and end-users (References 4, 5, and 6) indicated that, depending upon specific component design and structural requirements, advanced composite constructions for passenger car and truck applications could consist of 25-35 percent resin by weight with the remaining fraction containing 10-30 percent unidirectional or cross-ply carbon fiber by weight and 45-65 percent continuous or chopped glass fiber by weight.

The utilization of hybrids in the form of modified sheet molding compounds and sandwich constructions is expected to dominate the "automotive grade" ACM market.

Ultimately, the end-use item and prevailing economic constraints will dictate type, form, orientation, geometry, and loading of CF within the composite structure.

TABLE 2-1. PHYSICAL PROPERTIES OF COMMERCIALLY AVAILABLE HIGH STRENGTH FILAMENTS

Material	E-Glass Fiber	S-Glass Fiber	Aramid Fiber	Boron/Tungsten Fiber	Graphite Filaments		
					High Strength Fiber	High Modulus Fiber	Very High Modulus Fiber
Product	(Roving)	(Roving)	Kevlar^{49}	5.6 mil Diam.	Thermal 300 (WYP 15-1/0)	Magnamite 101S	Celion CY-70
Supplier			Dupont	Avco/CTI	Union Carbide	Hercules	Celanese
Density lbs/in^3	0.092	0.090	0.052	0.090	0.062	0.067	0.071
g/cm^3	2.54	2.48	1.44	2.48	1.72	1.86	1.96
Tensile Strength 10^3 psi	372	550	400	500	360	340	270
MPa	2500	3700	2800	3400	2600	2300	1900
Tensile Modulus 10^6 psi	10.5	12.4	18.0	58.0	32.5	50	75
CPa	73	86	124	406	225	350	520
Ultimate Elongation, %	4.8	5.4	2.5	0.8	1.1	0.58	0.38
Specific Strength, in	4.0×10^6	6.0×10^6	7.9×10^6	5.6×10^6	6.1×10^6	5.0×10^6	3.8×10^6
cm	9.8×10^6	1.5×10^7	1.9×10^7	1.4×10^7	1.5×10^7	1.2×10^9	9.7×10^6
Specific Modulus, in	1.1×10^8	1.4×10^8	3.5×10^8	6.4×10^8	5.2×10^8	7.5×10^8	1.1×10^9
cm	2.9×10^8	3.5×10^8	8.6×10^8	1.6×10^9	1.3×10^8	1.9×10^9	2.7×10^9
Filament Diameter, mile	0.20-0.55	0.35-0.40	0.47	5.6	0.3	0.3	0.33
cm	0.0005-0.014	0.0009	0.0012	0.014	0.0007	0.00075	0.00084
Thermal Conductivity BTU-ft/hr (ft^2)(°F)	0.56				12	70	
W/m °K	0.97				20.8	121	
Electrical Resistivity Ω mil ft					9000	4500	3900
μΩcm					1500	750	650
Curent Price, $/lb	0.49	2.00	8-10 & up to 27 for fine denier fiber	200	32	70	110-250

Source: Automotive Applications of Composite Materials, NHTSA, July 1979

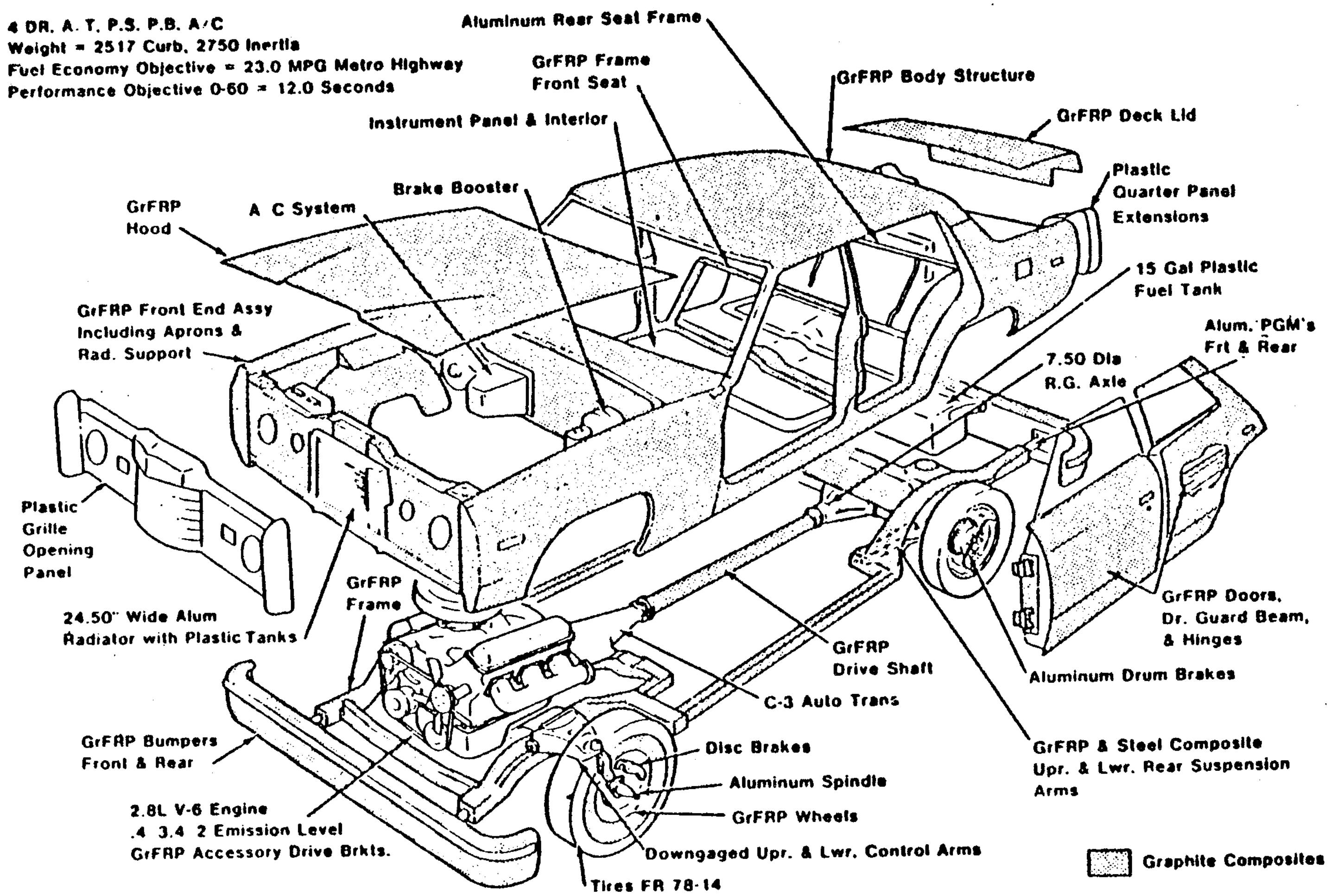
2.4 APPLICATIONS[7]

At the present time, there are no ACM automotive components in production. However, many on-going programs have been initiated to explore the potential uses of CF composites for surface transportation vehicles.

In an experimental program, Ford has demonstrated the feasibility of fabricating CF composite parts to achieve dramatic weight savings and corresponding fuel economy improvements. A cut-out of this vehicle is shown in Figure 2-1 and a list of ACM components is shown in Table 2-2. In addition to the Ford program, a number of smaller individual efforts are being undertaken by the automotive industry to advance the state-of-the-art in ACM technology on a part-by-part basis. A listing of these applications appears in Table 2-3. Some of these will be described to illustrate pertinent composite advantages.

The automotive driveshaft is a particularly interesting component for the use of CF composites. The high dampening characteristics of the composite can be applied to reduce vibrations induced in the engine, transmission, differential, or wheels. The low transmissability factor tends to separate wheel and differential noise from transmission and engine noise. The low noise of the carbon fiber composite, coupled with the high lateral stiffness, permits high rotational speeds to be achieved successfully. In addition to vibrational criteria, driveshafts must withstand static and fatigue torques. The freedom to design with composites allows driveshafts to be constructed from hybrid composites. Graftek, a Division of Exxon Enterprises, has designed, analyzed, fabricated, and tested driveshafts that are hybrids of aluminum and CF composite. The aluminum tube primarily reacts the torque, while the graphite composite increases critical speed.

Leaf springs are another potential application for hybrid composites. The high specific strength of CF composites leads to weight savings of from 40 to 85 percent compared to steel.



Source: Automotive Applications of Composite Materials, NHTSA, July 1978.

FIGURE 2-1. FORD LIGHTWEIGHT VEHICLE PROGRAM

TABLE 2-2. FORD LIGHTWEIGHT VEHICLE PROGRAM GRAPHITE COMPONENT WEIGHT SUMMARY

COMPONENT	COMPONENT WEIGHT, lbs.		REDUCTION lbs.
	STEEL	GRAPHITE COMPOSITE	
Hood	40.0	15.0	25.0
Door, R.H. Rear	30.25	12.65	17.60
Hinge, Upper L.H. Front	2.25	0.47	1.78
Hinge, Lower L.H. Front	2.67	0.77	1.90
Door Guard Beam	3.85	2.40	1.45
Suspension Arm, Front Upper	3.85	1.68	2.17
Suspension Arm, Front Lower	2.90	1.27	1.63
Transmission Support	2.35	0.55	1.80
Driveshaft	17.40	12.00	5.40
Air Conditioning, Lateral Brace	9.50	3.25	6.25
Air Conditioning, Compressor Bracket	5.63	1.35	4.28

Source: Ford Motor Company, Automotive Industries 157 (no. 8), Dec. 1, 1977, p. 39.

TABLE 2-3. REPRESENTATIVE LOW WEIGHT COMPONENTS MADE WITH ACM

AREA OF APPLICATION	COMPONENT	COMPOSITE STRUCTURE	COMPONENT STEEL Ws	WEIGHT, lbs. COMPOSITE Wc	WEIGHT REDUCTION lbs.	SOURCE OF DATA
Body Structure	Hood, Fiesta	4-ply graphite; 2 unidirectional (HM) + 2 0/90 fabirc layers with Nomex honeycomb core buildup	23.6	6.0	17.6	Hercules, 1978 SAE Exhibition
	Hood	Graphite - not otherwise specified	40	16	24	Hercules Brochure (4/78)
	Door Intrusion Beam	Graphite/aluminum honeycomb	17	7	10	D. Hiler Union Carbide 1977 SAE Exposition
	Bumper Beam, Fiesta	Pultruded graphite/glass hybrid composites	12 lbs. alum. ≈30 lbs. steel	7	23 (over steel)	Hercules 1978 SAE Exposition
Chassis and Suspension	Leaf Spring, Auxilliary Light Duty Truck	High strength graphite/epoxy - constant cross-section	16.2	4.8	11.4	Dharan - ICCM-2
	Leaf Spring, auto	Graphite/glass composite	28	5	23	D. Hiler Union Carbide - 1977 SAE Exposition
	Leaf Spring, auto	1 leaf - not specified	--	--	---	Graftek
	Leaf Spring, auto	Not specified	28	5.5	22.5	Hercules - 1978 SAE Exposition
	Transmission Support Bracket	Graphite/polyester, Compression Molded	20.5	4.7	15.3	Hercules - 1978 SAE Exposition
	Engine Support Bracket (Fiesta)	Unidirectional HM Graphite and Type A Graphite cloth	5.2	1.3	3.9	Hercules - 1978 SAE Exposition
	Air conditioner Support Bracket for 1980 Mustang	Continuous graphite/chopped glass polyester composite	7.0	1.9	5.1	R. Schmidt Great Lakes Carbon, Pers. Communication
	Air Conditioner Bracket	Graphite composite	12.0	2.5	9.5	Hercules 1978 SAE Exhibition

Source: Automotive Applications of Composite Materials, NHTSA, July 1978.

TABLE 2-3. REPRESENTATIVE LOW WEIGHT COMPONENTS MADE WITH ACM (CONTINUED)

AREA OF APPLICATION	COMPONENT	COMPOSITE STRUCTURE	COMPONENT STEEL Ws	WEIGHT, lbs. COMPOSITE Wc	WEIGHT REDUCTION lbs.	SOURCE OF DATA
Power Train	Drive Shaft (no yokes)	Graphite-epoxy	7.4	2.4	5.0	Dharan - ICCM-2
	Drive Shaft, auto	Graphite composite	12.6	6.5	6.1	Hercules - 1978 SAE Exhibition
	Drive Shaft, truck	Graphite composite	165	50	115	Hercules - 1978 SAE Exhibition
	Drive Shaft, light truck with fittings)	Graphite/glass composite	32.9	17.9	15	Shakespeare - 1978 SAE Exhibition
	Drive Shaft, 64 in. long (no fittings)	All graphite composite	15.7	5.3	10.4	Graftek - 1978 SAE Exhibition
		Aluminum and graphite composite	17.5	5.5 Ae +0.5 graphite	9.7	Graftek - 1978 SAE Exhibition
	Drive Shaft (with metal end fittings)	Graphite composite	22.6	9.5	13.1	
Engine Componnents	Push Rods	Graphite composite				Hercules Brochure

Source: Automotive Applications of Composite Materials, NHTSA, July 1978.

The principal advantages of using ACM in a leaf spring are its light weight and the ability to design for either softer or stiffer ride characteristics. In addition, such a spring does not corrode, provides better vehicle handling, and reduces the noise level in the vehicle. A four-leaf steel truck spring weighing 28 lb was duplicated by Lockheed Missile and Space Company from a CF glass hybrid at a weight of 5 lb.

Prototype springs for cars and trucks are also among Ford's development efforts. A truck spring of CF/epoxy weighs 30 lbs -- exactly 100 lb less than its steel equivalent. A single-leaf spring under development for automotive use weighs 4.5 lb, down from 28 lb for its four-leaf steel counterpart. Composite springs have been designed with the same rates and load capabilities as the steel springs they would replace and vehicle testing has confirmed their interchangeability. Both CF and CF/glass hybrids have been evaluated, with the latter employing distinct layers of each fiber. Composite springs would appear to be especially cost-effective in truck applications. Reduced weight and increased payload could mitigate a fleet owner's higher initial cost. A composite spring design also has the potential for modifying spring rates and loads within a given geometric envelope.

NASA has studied the feasibility of reinforcing truck frame rails with CF/epoxy strips. Currently, many of these frame rails have steel reinforcing sections welded in place. An alternate composite concept would be to bond prepreg strips adhesively to the rail and hold them in place by expandable, rubber-backed steel guides. Differential thermal expansion of the rubber would generate the required pressure for a heated cure cycle. NASA estimates that this concept could reduce reinforcement weight by a factor of 10 and yield a 35 percent weight reduction in the finished frame rail.

There has been considerable work during the past several years in composite transmission supports. In some cases, all-glass fiber composites meet the requirement. However, in those cases in which fatigue, high heat distortion temperature, or increased stiffness are needed, a hybrid of carbon fibers and glass fibers should be beneficial.

Another area of interest is radiator supports, in which a hybrid composite of carbon fibers and glass fibers should provide an excellent marriage of materials for strength, stiffness, high heat distortion capability, and corrosion resistance.

Suspension arms, a fatigue-critical, safety-related component, is an excellent candidate for a carbon fiber composite because it becomes part of the unsprung weight of a vehicle, thus maximizing the effect of weight reduction through secondary weight savings.

An air conditioner mounting bracket was fabricated by Hercules Incorporated. The composite weight was 2-1/2 lb versus 12 lb for the steel component. The composite component matched the natural frequency of the steel part and provided more vibration damping.

A transmission crossmember support bracket for a Ford LTD was fabricated by Budd at 4-1/2 lb versus 20 lb for the steel bracket. Manufactured of CF/polyester, fabrication time was 3 min. at 300°F.

Another component in the unsprung weight area is the wheel. Composite wheels primarily made of glass fiber reinforced polymers have been under test both here and in Europe. Carbon fibers have been suggested as an additive to the glass fibers to assist in controlling creep, extending fatigue life, and, if required, increasing stiffness. It appears that carbon fibers can be applied selectively in areas of need in a wheel application depending upon the particular molding practice employed.

Widespread use of composite materials by the automotive industry is contingent upon the development of cost-effective materials and manufacturing processes. The aerospace industry has used composites for years, but has a low production volume and is very labor-intensive. Aerospace manufacturing processes consist mainly of hand layups and have long cure cycles. The automotive industry has a very high volume of production and requires fast rates of production. Auto manufacturers have been studying the use of injection molding, reaction injection molding, and stamped thermoplastics, but it is not yet clear whether any of these processes can be used for the high volume, low cost production required.

2.5 LIMITING USE FACTORS

A number of factors will tend to limit the application of ACM for surface transportation vehicles.[2] They include:

1. Cost of raw materials - At current prices, advanced composites are prohibitively expensive for nearly all automotive uses. Applications would become more attractive at CF prices of less than $10/lb.
2. Manufacturing - Most of the experimental advanced composite automotive components have been made with all CF composites formed by aerospace fabrication techniques that are too expensive and too slow to be considered for high volume automotive applications. The electrical conductivity of CF will require that provisions be made for containing these fibers during shipping, storage, and manufacture of composite structures.
3. Durability - There has been no demonstration that ACM components can survive miles of actual automotive use over an extended period of years.
4. Damageability and Crashworthiness - The failure mode of fibrous composites is very different from the failure of metals. Composites are less likely to deform under light loads than metals, but could shatter and form jagged edges upon severe impact in some cases, or simply delaminate in other instances.
5. Repair Upon Damage - The ability to be able to repair major structural components made of any reinforced plastic is an open issue. It would be desirable to be able to repair rather than replace large components.

6. Noise Vibrations and Handling - The road handling characteristics of a large, low weight automobile are not known at the moment and it may be necessary to include load leveling provisions into the design of an automobile if the maximum payload becomes a significant fraction of the gross vehicle weight.

7. Recycling and Disposal - Reinforced thermosetting resins can not be economically recycled at the moment, so that land fill of scrap advanced composite parts is the only current available option.

8. Carbon Fiber Release - See Section 3.

In view of the potential benefits to be gained by the use of CF composites beyond 1985, it will be necessary for the surface transportation industry to address these major issues.

2.6 MARKET PROJECTIONS

As indicated in Table 2-4, the expected projections for carbon fiber in surface transportation vehicles vary according to information source and economic assumptions. Despite the variety of "automotive grade" CF composite parts currently under investigation (see Section 2.4), vehicle manufacturers have become less vocal and more conservative in their efforts to introduce ACM in the marketplace.

The first production use of CF composites will most probably be the air conditioner support bracket identified in Table 2-3. If this effort is successful, pilot production of other CF parts for cars and light/heavy trucks can be expected and could result in a demand of several hundred thousand pounds of CF by 1985.

Beyond 1985, increased CF use in passenger cars and trucks will largely depend upon the prevailing fuel economy standards and the other pertinent factors discussed in Section 2.2

On the basis of discussions with vehicle manufacturers and independent consultants, the application of ACM, if used in 20 percent of all automobiles and 100 percent of all heavy trucks

TABLE 2-4. EXPECTED CF USE IN PASSENGER CARS AND TRUCKS

VEHICLES PRODUCED	AVG. WEIGHT COMPOSITE/CAR	AVG. WEIGHT CF/CAR	CONSUMPTION POUNDS/YEAR	REFERENCE
1985: 10×10^6 (All Cars)	3 LBS	0.6 LBS	6×10^6	ARGOS, 4-78
1990: 10×10^6 (All Cars)	10-20 LBS	2-4 LBS	$20\text{-}40 \times 10^6$	
1990: 1×10^6 (Luxury Cars)	600 LBS	120 LBS	120×10^6	
1985: 10×10^6	5 LBS	2 1/2 LBS		NASA, 5-78
1995: 10×10^6	90 LBS	45 LBS	450×10^6	
1985:	5 LBS			ECON, 7-77
1990: 19×10^6	90 LBS	45 LBS	860×10^6	
1985: $12 - 15 \times 10^6$	5-8 LBS	3 LBS	$3 - 5 \times 10^6$	BATTELLE, 12-77
1985:				ARGOS, 7-78
1990: $10 - 20 \times 10^6$	40 LBS	4 LBS	$40 - 80 \times 10^6$	
1990:		1 - 2 LBS	10×10^6 (CARS)	DEPT. OF COMMERCE DRAFT REPORT, 1979
			15×10^6 (TRUCKS)	
1995		4 - 30 LBS	20×10^6 (CARS)	
			20×10^6 (TRUCKS)	

produced through 1990, should fall within the following range:

	AVG. WT. CF (UP TO 20% IN ACM)
Passenger Cars and Light Trucks	
Forward of the Firewall	2 LBS
Total Vehicle	5 LBS
Heavy Trucks	
Forward of the Firewall	5 LBS
Total Vehicle	30 LBS

These estimates assume a total production of 14 x 10^6 vehicle/year (13.5 x 10^6 cars and light trucks; 0.5 x 10^6 heavy trucks) and a raw material CF cost of \$6 - \$8/pound. The total projected consumption of CF in surface transportation vehicles will be 28.5 x 10^6 pounds per year. This would be achieved through composite hybridization using glass or aramid fibers (up to 65 percent by weight) making the overall cost to performance trade-off more attractive. By similar analysis concomitant with lower fiber costs, it is estimated that the demand for CF in surface transportation vehicles beyond 1990 could reach 50 x 10^6 pounds per year.

3. ASSESSMENT OF POTENTIAL RELEASE MECHANISM

3.1 INTRODUCTION

Previous efforts by NASA have identified two major mechanisms by which carbon fibers are accidentally released into the atmosphere: 1) exposure to fire and, 2) disposal of the CF composites. Secondary release mechanisms may be possible through weathering and manufacturing. The weathering mechanism is a slow degradation of the matrix at the surface and its subsequent erosion which will release only very short fibers under 0.1 mm. Since it is difficult for these fibers to bridge electrical contacts, they present little hazard to electrical equipment. Also, since manufacturing operations such as machining of CF composites do not separate the fiber from the matrix, the hazardous free fiber does not exist. Experience has shown that when a manufacturer handles raw carbon fibers, he uses precautions such as hoods and filtering to control the fibers which escape as the manufacturer must protect his own equipment. For these reasons manufacturing is considered to present little hazard. There is cause for concern that a possibility exists for a massive release of CF while it is being transported from the fiber manufacturer to the composite fabricator. This problem was beyond the scope of the work reported here.

TSC has evaluated the fire problem as it relates to the surface transportation system and the results are presented in the following sections. The question of fiber release by disposal is briefly addressed, but a more thorough analysis is being undertaken by the Environmental Protection Agency (EPA).

3.2 RELEASE BY FIRE

The primary release mechanism for CF from surface transportation vehicles is expected to be from severe thermal degradation of the CF composite under fire conditions. The study of potential release incidents was therefore a study of vehicle fires. A risk assessment of the impact of CF released by automobile and truck fires requires that the location, frequency, and severity of these fires be known or estimated. Fire data from many sources were reviewed. Details of this review can be found in Reference 8. No single data source provided the necessary information, but it was possible to estimate the location, frequency, and severity parameters by combining the data from several sources.

3.2.1 Available Automobile Fire Data Bases

As indicated in Section 2, the major use of the CF composites in surface transportation is expected to be the automobile and the truck. The data bases discussed here are limited to those containing fire data which would provide an estimate of automobile and truck fire incidence and location.

3.2.1.1 U.S. Fire Administration (USFA) - The National Fire Incident Reporting System (NFIRS) has been developed by the USFA in partial fulfillment of the mandate of the Federal Fire Prevention and Control Act of 1974. NFIRS is intended to serve as a collection of national fire loss statistics of fires that have required action by fire departments. Data are collected concerning the factors involved in fire ignition, spread, extinguishment, and fire loss and casualties.

NFIRS also includes procedures for achieving uniform fire data reporting at local, state, and federal levels. USFA is working with the NFPA and the National Bureau of Standards (NBS) to develop the reporting procedures and the data base. The NFPA No. 901 Code has been used as the basis of USFA fire reporting code.

Data collection for NFIRS began in 1976 in five states: Ohio, California, Oregon, Missouri, and Maryland. Recently, sixteen additional states have been added: Tennessee, North Carolina, New York, Delaware, Maine, West Virginia, Illinois, Wisconsin, Minnesota, Michigan, Montana, South Dakota, Utah, Alaska, Iowa, and Rhode Island. Data are collected on transportation fires as follows:

transportation mode,

year, make, model, and serial number of vehicle, license number,

origin of fire,

fire-fighting actions,

fixed properties at site of fire; e.g., airport, RR yard,

vehicle part involved in fire,

ignition source,

type of material; e.g., fuel, tire,

method of extinguishment,

estimated total dollar loss,

property damage classification,

time from alarm to agent application,

casualties - type, severity, location, cause of injury, nature of injury, part of body injured, condition preventing escape, activity at time of injury.

USFA's projection of the total number of transportation fires in 1977 is shown in Table 3-1. As noted there, the USFA projection of 460,000 transportation fires is within seven percent of the National Fire Protection Association estimate of 490,000 transportation fires. Table 3-2 is an USFA breakdown of the origin of vehicle fires, not just the passenger vehicles. The USFA data are presently the most detailed and best data available on transportation fires, their cause, and their location on the vehicle.

3.2.1.2 California State Fire Marshal's Office - The California State Fire Marshal publishes an annual statistical summary of fire related data. This summary contains estimates of the dollar losses of passenger vehicles which were involved in a fire. The cost data were aggregated as shown in Figure 3-1. If it is assumed that all fires which cause less than $100 damage are not severe enough to release CF, it is seen that 33 percent of the automobile fires

TABLE 3-1. TRANSPORTATION FIRES* 1977

PASSENGER VEHICLES	325,000
FREIGHT ROAD VEHICLES	58,000
RAIL TRANS. VEHICLES	2,800
WATER TRANS. VESSEL	1,850
AIR TRANS. VEHICLE	550
HEAVY EQUIPMENT	7,000
SPECIAL VEHICLES	2,700
OTHER MOBILE PROPERTY	100
UNDETERMINED	62,000
	460,000
NFPA EST.**	490,000

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*EST. BASED ON 26% SAMPLE OF U.S. POP. (8 STATES)

**BASED ON DATA FROM 4% OF FIRE DEPTS (IN 50 STATES)

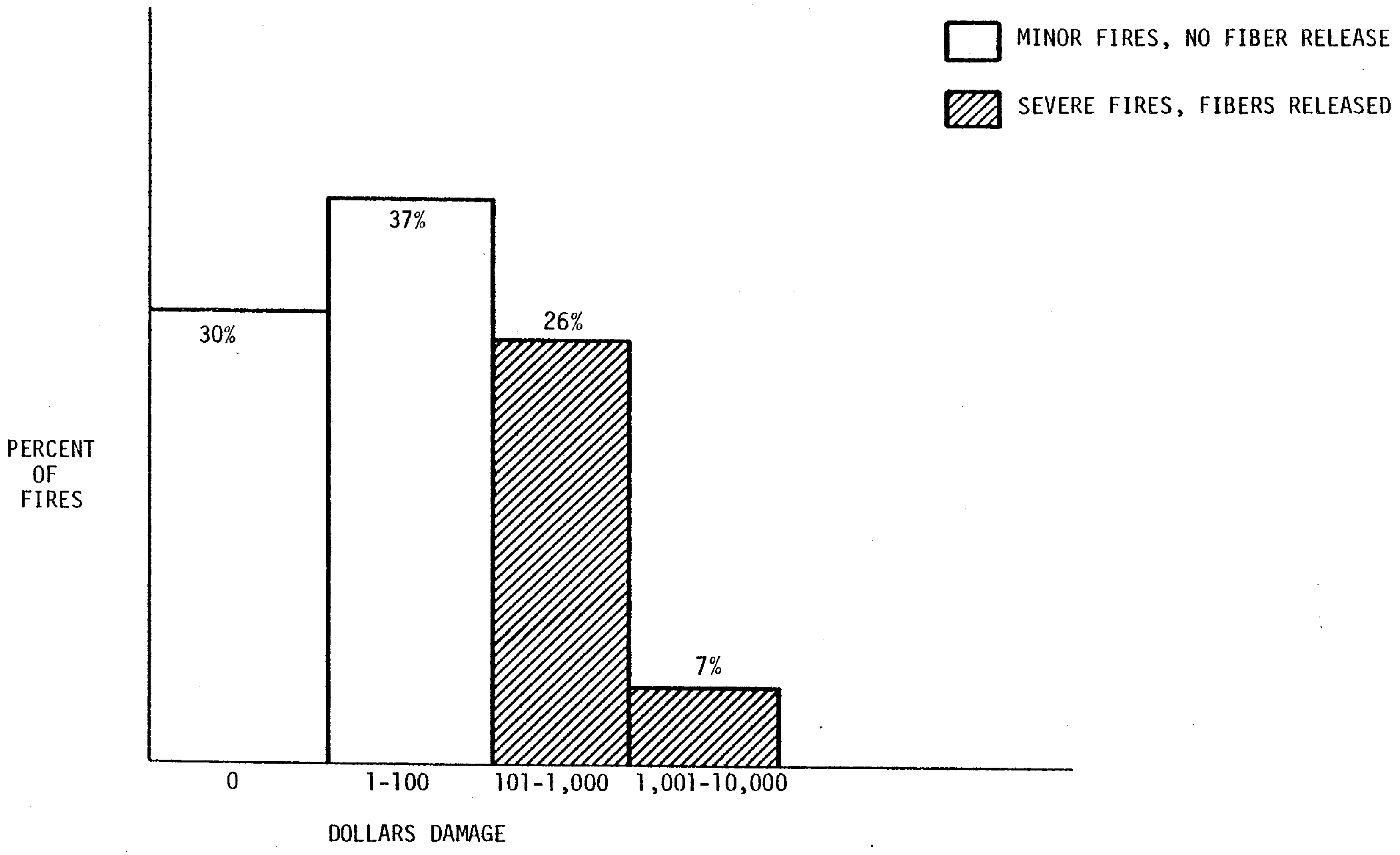
Source: USFA

TABLE 3-2. AREA OF MOST FREQUENT FIRE ORIGIN

ALL VEHICLES

ENGINE AREA	58	PERCENT
PASSENGER AREA	14	
TRUNK AREA	3	
OTHER	4	
UNKNOWN	21	
	100	

Source: USFA



Source: California Annual Fires, Summary

FIGURE 3-1. ESTIMATED LOSSES PER FIRE IN PASSENGER VEHICLES will release CF and the rest will not. The fire severity was established in this way. This method is crude, but it was the only way found in the existing data to estimate the distribution of fire severity.

3.2.1.3 Highway Safety Research Institute (HSRI) - The Highway Safety Research Institute at the University of Michigan has collected information from fire department records on automobile fires in the state of Michigan for the two-year period, 1976-1977. These data are made up of 27,708 fires of which about 400 are crash fires, and roughly one third are either arson or suspected arson. The number of fires which occurred over the two-year period in each county is reported.

It is expected that the number of automobile fires which occur in a particular location is related to some other property of that location. Because of the way in which the Michigan data is reported, a location is defined here as a county and some logical correlation parameters might be 1) county population, 2) county density, 3) number of automobiles, or 4) automobile density. Prior to analysis it is not certain how fire incidence might vary with any of these paraemters, but it is conceivable, for instance, that a higher automobile density might result in a larger number of crashes and thus a higher automobile fire rate. The automobile fire rate was calculated as a function of each of the four proposed correlation parameters for each county in Michigan and is tabulated in Table 3-3, with the definitions of the column headings as follows:

County - County in Michigan

Accidents (1976 - 1977) - Total number of automobile fires in that county over the two-year period,

Population - County population as of 1975 census data,

APY/TP - Automobile fires per year per thousand pouplation (Accidents/2. * 1000./population),

TABLE 3-3. AUTOMOBILE FIRE INCIDENCE AS A FUNCTION OF FOUR PROPOSED CORRELATION PARAMETERS

COUNTY	ACCIDENTS 1976-1977	POPULATION	APY/TP	PASSENGER CARS	APY/TPC	POPULATION DENSITY	APY/PD	AUTOMOBILE DENSITY	APY/AD
ALCONA	8.000E+00	8.640E+03	4.630E-01	4.937E+03	8.102E-01	1.300E+01	3.077E-01	7.428E+00	5.385E-0
ALGER	1.300E+01	8.977E+03	7.241E-01	4.183E+03	1.554E+00	1.000E+01	6.500E-01	4.660E+00	1.395E+0
ALLEGAN	1.220E+02	7.150E+04	8.531E-01	3.609E+04	1.690E+00	8.700E+01	7.011E-01	4.391E+01	1.389E+0
ALPENA	7.500E+01	3.329E+04	1.126E+00	1.654E+04	2.267E+00	5.900E+01	6.356E-01	2.931E+01	1.279E+0
ANTRIM	2.200E+01	1.531E+04	7.185E-01	8.109E+03	1.357E+00	3.200E+01	3.438E-01	1.694E+01	6.492E-0
ARENAC	1.900E+01	1.318E+04	7.208E-01	6.531E+03	1.455E+00	3.600E+01	2.639E-01	1.784E+01	5.325E-0
BARAGA	2.400E+01	8.060E+03	1.489E+00	3.826E+03	3.136E+00	9.000E+00	1.333E+00	4.272E+00	2.809E+0
BARRY	8.600E+01	4.143E+04	1.038E+00	1.961E+04	2.193E+00	7.500E+01	5.733E-01	3.549E+01	1.212E+0
BAY	2.930E+02	1.201E+05	1.220E+00	6.273E+04	2.335E+00	2.690E+02	5.446E-01	1.405E+02	1.043E+0
BENZIE	2.500E+01	9.870E+03	1.266E+00	5.570E+03	2.244E+00	3.100E+01	4.032E-01	1.749E+01	7.145E-0
BERRIEN	5.150E+02	1.705E+05	1.510E+00	9.191E+04	2.802E+00	2.940E+02	8.759E-01	1.584E+02	1.625E+0
BRANCH	1.210E+02	3.787E+04	1.598E+00	2.012E+04	3.007E+00	7.500E+01	8.067E-01	3.985E+01	1.518E+0
CALHOUN	5.550E+02	1.417E+05	1.959E+00	7.653E+04	3.626E+00	2.000E+02	1.387E+00	1.080E+02	2.569E+0
CASS	1.450E+02	4.553E+04	1.592E+00	2.349E+04	3.086E+00	9.300E+01	7.796E-01	4.799E+01	1.511E+0
CHARLEVOIX	4.700E+01	1.847E+04	1.273E+00	1.008E+04	2.332E+00	4.500E+01	5.222E-01	2.455E+01	9.571E-0
CHEBOYGAN	1.000E+01	1.942E+04	2.575E-01	1.018E+04	4.910E-01	2.700E+01	1.852E-01	1.416E+01	3.531E-0
CHIPPEWA	4.100E+01	3.599E+04	5.696E-01	1.556E+04	1.317E+00	2.300E+01	8.913E-01	9.944E+00	2.061E+0
CLARE	4.800E+01	2.124E+04	1.130E+00	1.074E+04	2.234E+00	3.700E+01	6.486E-01	1.872E+01	1.282E+0
CLINTON	8.500E+01	5.250E+04	8.096E-01	2.586E+04	1.643E+00	9.200E+01	4.620E-01	4.533E+01	9.376E-0
CRAWFORD	1.900E+01	8.248E+03	1.152E+00	4.693E+03	2.024E+00	1.500E+01	6.333E-01	8.535E+00	1.113E+0
DELTA	5.800E+01	3.936E+04	7.368E-01	1.885E+04	1.538E+00	3.300E+01	8.788E-01	1.580E+01	1.835E+0
DICKENSON	4.700E+01	2.498E+04	9.409E-01	1.348E+04	1.744E+00	3.300E+01	7.121E-01	1.780E+01	1.320E+0
EATON	1.650E+02	7.780E+04	1.060E+00	3.782E+04	2.182E+00	1.360E+02	6.066E-01	6.610E+01	1.248E+0
EMMET	1.000E+01	2.121E+04	2.357E-01	1.181E+04	4.233E-01	4.600E+01	1.087E-01	2.561E+01	1.952E-0
GENESEE	1.483E+03	4.496E+05	1.649E+00	2.401E+05	3.088E+00	7.000E+02	1.059E+00	3.739E+02	1.983E+0
GLADWIN	3.000E+01	1.677E+04	8.945E-01	8.165E+03	1.837E+00	3.300E+01	4.545E-01	1.607E+01	9.336E-0
GOGEBIC	3.500E+01	2.081E+04	8.409E-01	9.237E+03	1.895E+00	1.900E+01	9.211E-01	8.434E+00	2.075E+0
GRAND TRAVERSE	1.340E+02	4.486E+04	1.493E+00	3.000E+04	2.233E+00	9.700E+01	6.907E-01	6.486E+01	1.033E+0
GRATIOT	1.030E+02	3.995E+04	1.289E+00	1.948E+04	2.644E+00	7.100E+01	7.254E-01	3.462E+01	1.488E+0
HILLSDALE	8.800E+01	4.014E+04	1.096E+00	1.971E+04	2.232E+00	6.700E+01	6.567E-01	3.290E+01	1.337E+0
HOUGHTON	2.800E+01	3.696E+04	3.788E-01	1.533E+04	9.132E-01	3.600E+01	3.889E-01	1.493E+01	9.376E-0
HURON	5.500E+01	3.588E+04	7.665E-01	1.850E+04	1.487E+00	4.400E+01	6.250E-01	2.268E+01	1.212E+0
INGHAM	7.270E+02	2.676E+05	1.358E+00	1.411E+05	2.576E+00	4.790E+02	7.589E-01	2.526E+02	1.439E+0
IONIA	6.600E+01	4.735E+04	6.969E-01	2.214E+04	1.491E+00	8.200E+01	4.024E-01	3.833E+01	8.609E-0
IOSCO	3.400E+01	2.822E+04	6.025E-01	1.422E+04	1.195E+00	5.200E+01	3.269E-01	2.621E+01	6.487E-0
IRON	2.100E+01	1.435E+04	7.320E-01	7.172E+03	1.464E+00	1.200E+01	8.750E-01	6.000E+00	1.750E+0
ISABELLA	1.250E+02	4.930E+04	1.268E+00	1.980E+04	3.156E+00	8.600E+01	7.267E-01	3.455E+01	1.809E+0
JACKSON	3.510E+02	1.465E+05	1.198E+00	7.625E+04	2.302E+00	2.100E+02	8.357E-01	1.093E+02	1.606E+0
KALAMAZOO	5.610E+02	2.014E+05	1.393E+00	1.118E+05	2.509E+00	3.580E+02	7.835E-01	1.988E+02	1.411E+0

TABLE 3-3. AUTOMOBILE FIRE INCIDENCE AS A FUNCTION OF FOUR PROPOSED CORRELATION PARAMETERS (CONTINUED)

COUNTY	ACCIDENTS 1976-1977	POPULATION	APY/TP	PASSENGER CARS	APY/TPC	POPULATION DENSITY	APY/PD	AUTOMOBILE DENSITY	APY/AD
KALKASKA	2.400E+01	1.034E+04	1.161E+00	8.000E+03	2.400E+00	1.800E+01	6.667E-01	8.707E+00	1.378E+00
KENT	1.353E+03	4.236E+05	1.597E+00	2.427E+05	2.787E+00	4.940E+02	1.369E+00	2.831E+02	2.390E+00
KEWEENAW	2.000E+00	2.173E+03	4.602E-01	1.047E+03	9.551E-01	4.000E+00	2.500E-01	1.927E+00	5.189E-01
LAKE	1.900E+01	6.834E+03	1.390E+00	3.350E+03	2.836E+00	1.200E+01	7.917E-01	5.882E+00	1.615E+00
LAPEER	1.200E+02	6.161E+04	9.739E-01	2.941E+04	2.040E+00	9.400E+01	6.383E-01	4.487E+01	1.337E+00
LEELANAU	1.200E+01	1.253E+04	4.790E-01	6.636E+03	9.042E-01	3.600E+01	1.667E-01	1.907E+01	3.146E-01
LENAWEE	1.740E+02	8.667E+04	1.004E+00	4.479E+04	1.943E+00	1.150E+02	7.565E-01	5.943E+01	1.464E+00
LIVINGSTON	1.980E+02	7.786E+04	1.272E+00	4.191E+04	2.362E+00	1.360E+02	7.279E-01	7.320E+01	1.353E+00
LUCE	4.000E+00	7.115E+03	2.811E-01	3.041E+03	6.577E-01	8.000E+00	2.500E-01	3.419E+00	5.849E-01
MACKINAC	1.300E+01	1.071E+04	6.067E-01	4.510E+03	1.441E+00	1.100E+01	5.909E-01	4.630E+00	1.404E+00
MACOMB	1.966E+03	6.698E+05	1.468E+00	4.033E+05	2.438E+00	1.395E+03	7.047E-01	8.398E+02	1.170E+00
MANISTEE	3.200E+01	2.177E+04	7.351E-01	1.155E+04	1.385E+00	3.900E+01	4.103E-01	2.070E+01	7.730E-01
MARQUETTE	8.900E+01	6.947E+04	6.406E-01	3.337E+04	1.334E+00	3.800E+01	1.171E+00	1.825E+01	2.438E+00
MASON	5.000E+01	2.452E+04	1.020E+00	1.324E+04	1.888E+00	5.000E+01	5.000E-01	2.700E+01	9.259E-01
MECOSTA	4.400E+01	3.402E+04	6.467E-01	1.297E+04	1.696E+00	6.100E+01	3.607E-01	2.326E+01	9.459E-01
MENOMINEE	3.900E+01	2.556E+04	7.628E-01	1.280E+04	1.523E+00	2.500E+01	7.800E-01	1.252E+01	1.558E+00
MIDLAND	1.190E+02	6.755E+04	8.809E-01	3.822E+04	1.557E+00	1.300E+02	4.577E-01	7.356E+01	8.089E-01
MISSAUKEE	6.000E+00	8.767E+03	3.422E-01	4.214E+03	7.119E-01	1.600E+01	1.875E-01	7.691E+00	3.901E-01
MONROE	3.110E+02	1.271E+05	1.224E+00	6.544E+04	2.376E+00	2.280E+02	6.820E-01	1.174E+02	1.324E+00
MONTCALM	9.100E+01	4.414E+04	1.031E+00	2.190E+04	2.078E+00	6.200E+01	7.339E-01	3.076E+01	1.479E+00
MONTMORENCY	7.000E+00	6.990E+03	5.007E-01	3.692E+03	9.480E-01	1.300E+01	2.692E-01	6.866E+00	5.097E-01
MUSKEGON	4.860E+02	1.570E+05	1.548E+00	8.239E+04	2.949E+00	3.130E+02	7.764E-01	1.643E+02	1.479E+00
NEWAYGO	5.400E+01	3.124E+04	8.642E-01	1.522E+04	1.774E+00	3.700E+01	7.297E-01	1.803E+01	1.498E+00
OAKLAND	3.104E+03	9.666E+05	1.606E+00	5.923E+05	2.620E+00	1.115E+03	1.392E+00	6.832E+02	2.272E+00
OCEANA	4.400E+01	2.066E+04	1.065E+00	9.515E+03	2.312E+00	3.900E+01	5.641E-01	1.796E+01	1.225E+00
OGEMAW	3.000E+01	1.480E+04	1.014E+00	7.668E+03	1.956E+00	2.600E+01	5.769E-01	1.348E+01	1.113E+00
ONTONAGON	1.300E+01	1.136E+04	5.723E-01	5.145E+03	1.263E+00	9.000E+00	7.222E-01	4.077E+00	1.594E+00
OSCEOLA	4.300E+01	1.734E+04	1.240E+00	8.210E+03	2.619E+00	3.000E+01	7.167E-01	1.421E+01	1.513E+00
OSCODA	5.000E+00	6.152E+03	4.064E-01	3.256E+03	7.678E-01	1.100E+01	2.273E-01	5.822E+00	4.294E-01
OTSEGO	2.700E+01	1.346E+04	1.003E+00	7.279E+03	1.855E+00	2.600E+01	5.192E-01	1.406E+01	9.599E-01
OTTAWA	2.370E+02	1.406E+05	8.431E-01	7.698E+04	1.539E+00	2.500E+02	4.740E-01	1.369E+02	8.655E-01
PRESQUE ISLE	1.400E+01	1.400E+04	5.000E-01	6.868E+03	1.019E+00	2.200E+01	3.182E-01	1.079E+01	6.486E-01
ROSCOMMON	2.300E+01	1.449E+04	7.937E-01	8.579E+03	1.340E+00	2.800E+01	4.107E-01	1.658E+01	6.937E-01
SAGINAW	6.620E+02	2.267E+05	1.460E+00	1.196E+05	2.767E+00	2.780E+02	1.191E+00	1.467E+02	2.256E+00
ST. CLAIR	3.050E+02	1.307E+05	1.166E+00	6.749E+04	2.260E+00	1.780E+02	8.567E-01	9.187E+01	1.660E+00
ST. JOSEPH	1.720E+02	5.087E+04	1.691E+00	2.753E+04	3.124E+00	1.010E+02	8.515E-01	5.465E+01	1.574E+00
SANILAC	4.800E+01	3.898E+04	6.157E-01	1.892E+04	1.268E+00	4.100E+01	5.854E-01	1.990E+01	1.206E+00
SCHOOLCRAFT	1.000E+01	8.659E+03	5.774E-01	4.446E+03	1.125E+00	7.000E+00	7.143E-01	3.594E+00	1.391E+00
SHIAWASSEE	1.450E+02	6.922E+04	1.047E+00	3.388E+04	2.140E+00	1.280E+02	5.664E-01	6.265E+01	1.157E+00
TUSCOLA	6.900E+01	5.378E+04	6.415E-01	2.551E+04	1.353E+00	6.600E+01	5.227E-01	3.130E+01	1.102E+00
VAN BUREN	1.380E+02	6.173E+04	1.118E+00	3.102E+04	2.225E+00	1.020E+02	6.765E-01	5.125E+01	1.346E+00
WASHTENAW	8.380E+02	2.447E+05	1.712E+00	1.327E+05	3.157E+00	3.440E+02	1.218E+00	1.866E+02	2.246E+00
WAYNE	1.012E+04	2.518E+06	2.009E+00	1.283E+06	3.943E+00	4.162E+03	1.216E+00	2.121E+03	2.385E+00
WEXFORD	5.600E+01	2.195E+04	1.275E+00	1.218E+04	2.300E+00	3.900E+01	7.179E-01	2.163E+01	1.295E+00

Passenger Cars - Total number of registered passenger cars in that county as of 1977,

APY/TPC - Automobile fires per year per thousand passenger cars (Accidents/2. * 1000./passenger cars),

Population Density - County population density (number of people/square mile),

APY/PD - Automobile fires per year per population density (Accidents/(2. * population density).

The parameter which gave the best correlation was the number of cars registered in the county. The equation $y = 2.7 \times 10^{-4} x^{1.191}$ where y is the number of car fires each year and x is the number of cars registered in the county, has a correlation coefficient of 0.97, which is an excellent fit. The data and this equation are plotted in Figure 3-2. This equation predicts about 280,000 automobile fires a year for the nation. This estimate is low compared to other data sources, but is satisfactory for calculating the CF risk.

3.2.2 Truck Fires

The requirement for reporting a truck fire to the Bureau of Motor Carrier Safety is death, injury, or $2,000 property damage. By our fire scenario classification, the majority of these fires would rate as severe fires. Carriers required to report are regulated carriers which are engaged in interstate transportation of goods, with the exclusion of raw farm products. Since these carriers are in the long-haul trucking business, nearly all of their trucks are trailer or semi-trailer trucks. There are 2.8×10^6 trailer and semi-trailer trucks registered. Roughly half of this fleet is under the regulation of the Bureau of Motor Carrier Safety. In 1977, approximately 700 severe fires were reported by the regulated carriers. At this rate, about 1 in 2000 heavy trucks has a severe fire a year or an annual severe fire probability of 5×10^{-4} /year. This is comparable to the 10^{-3} severe fire probability experienced by private automobiles and estimated for light trucks.

The Department of Commerce estimates that 30 lb of CF will

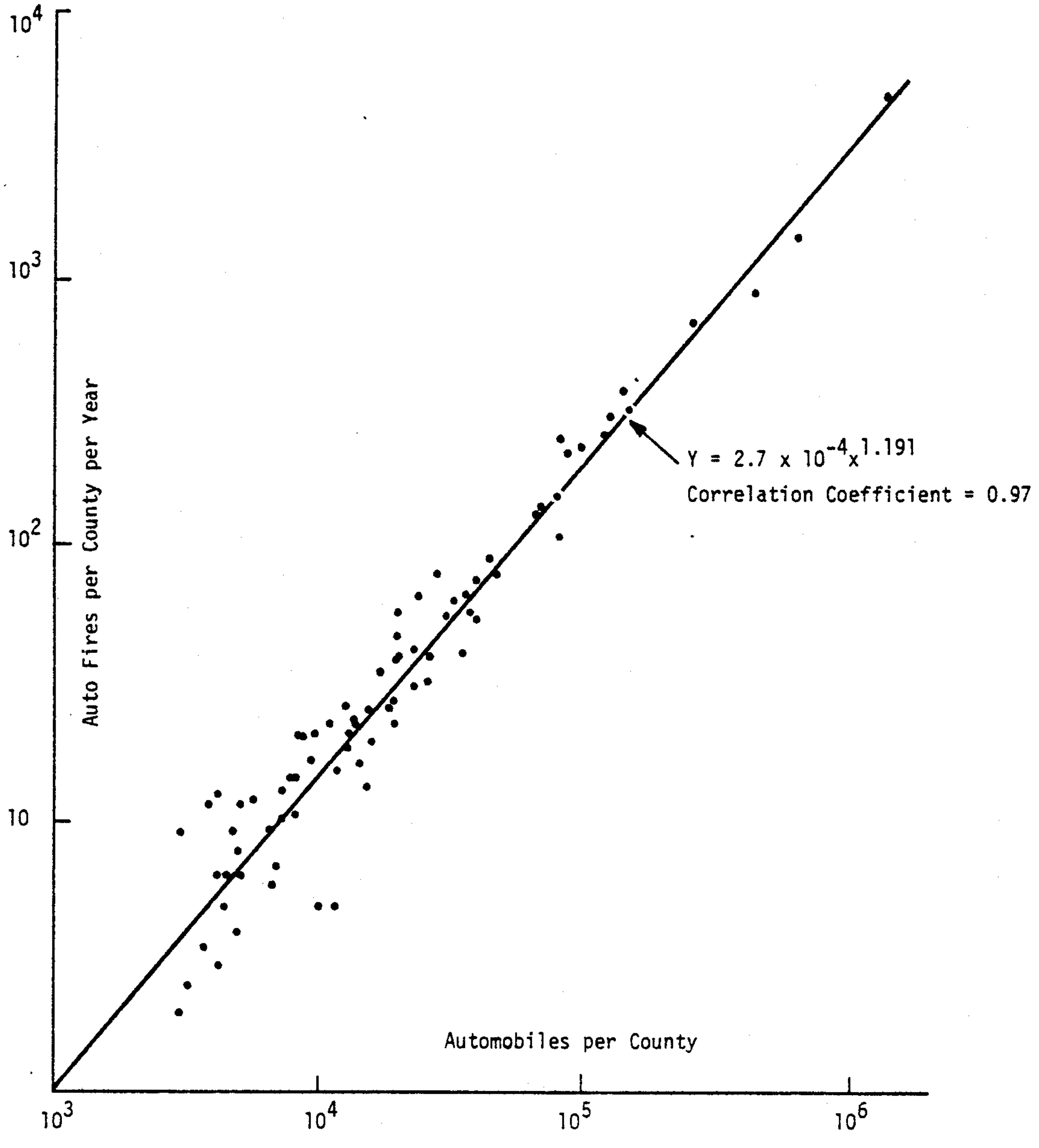


FIGURE 3-2. AUTOMOBILE FIRES PER COUNTY PER YEAR VS. AUTOMOBILES PER COUNTY

be found on each heavy truck manufactured in the year 1990.[2] All this fiber will be under the truck in the driveshaft, frame members, and springs. The distribution of the fire damage to heavy trucks is unknown. The conservative assumption is that every large truck fire burns all the composite and that 1 percent of the fibers i.e. 0.3 lbs, is released.

The Department of Commerce estimates that 5 lb of CF will be found on light trucks. We will assume that this fiber is distributed as it is on a passenger car. The annual probability of a severe light truck fire is 10^{-3} as it is with the passenger car.

The following information summarizes the parameters which were used to generate the portion of the risk profile which can be attributed to trucks.

Estimated Registration	Class of Truck	Pounds of CF 1990	Annual Severe Fire Probability
2.8×10^6	Heavy truck	30	5×10^{-4}
25×10^6	Light truck	5	10^{-3}

The assumption was made that the spatial distribution of truck fires is the same as with passenger cars. This assumption is probably in error on the conservative side. The heavy trucks are primarily engaged in long-haul freight; they drive most of their miles on interstate highways far from the cities and vulnerable electrical equipment. Light trucks appear to be used much like private automobiles and should cause little error in fire estimation.

3.2.3 Vehicle Fire Scenarios

A variety of scenarios may be created and structured, depending upon the data available and the end use of the scenario. In this study, the scenario was intended to describe the type of fire and use this information to assess the potential for CF release. For this reason, the scenarios were constructed by severity of the vehicle fire and the part of the vehicle burned. Fire locations and percentage of incidence are shown in Table 3-4, while fire severity has been categorized as minor fires, severe fires, and total conflagration.

TABLE 3-4. DISTRIBUTION OF FIRE AREAS

AREA	PERCENT
ENGINE COMPARTMENT	55
PASSENGER COMPARTMENT	14
ENTIRE VEHICLE	8
OTHER	23
	100

Source: TSC Distribution of Table 3-2

Minor fires are defined as those fires which do not release fibers. These fires are extinguished in some manner or simply do not produce sufficient heat to result in the release of fibers. Severe fires produce sufficient heat to thermally degrade some composite structures and to release fibers. Total conflagration implies total vehicle involvement with subsequent release of fibers from all CF components.

The establishment of the fire severities, described above, poses some problems. For example, the hood of a car may be constructed entirely from a general purpose plastic material in lieu of steel; thus, a minor engine compartment fire may become a severe fire as the plastic is a more flammable material than the non-combustible steel hood it replaced.

From well defined scenarios and fire severities, Table 3-5 provides a qualitative view of fiber release. It should be noted that even severe passenger compartment fires do not release fibers. At present, it is not expected that CF composite will be employed within the passenger compartment, except possibly as a door crash bar.

3.3 RELEASE DURING VEHICLE DISPOSAL

TSC briefly examined the concern of fiber release in the vehicle disposal process.[8] The analysis presented herein is only a broadbrush review and a more comprehensive study is required by EPA. Based on the TSC examination, it appeared that the release of CF in the vehicle-disposal process could far exceed release from accidental fires involving in-service vehicles. Figure 3-3 summarizes the results of the examination and presents the process through which this CF release may occur.

Construction of Figure 3-3 was based on the following seven assumptions:

1. Ten million new vehicles will enter the market each year.
2. For general applications, approximately 100 pounds of CF composites per vehicle will be used (50 pounds of CF per vehicle).

TABLE 3-5. VEHICLE FIRE INCIDENTS - FIBER RELEASE SCENARIOS

FIRE LOCATION	MINOR FIRE	SEVERE FIRE	CONFLAGRATION
ENGINE COMPARTMENT	NO RELEASE	RELEASE	--
PASSENGER COMPARTMENT	NO RELEASE	NO RELEASE	--
ENTIRE VEHICLE	--	--	RELEASE

BASIC ASSUMPTIONS:

MINOR FIRES RELEASE NO FIBERS.

OTHER FIRES RELEASE 1 PERCENT OF FIBERS, EXCEPT PASSENGER COMPARTMENT FIRE WHICH RELEASES NONE.

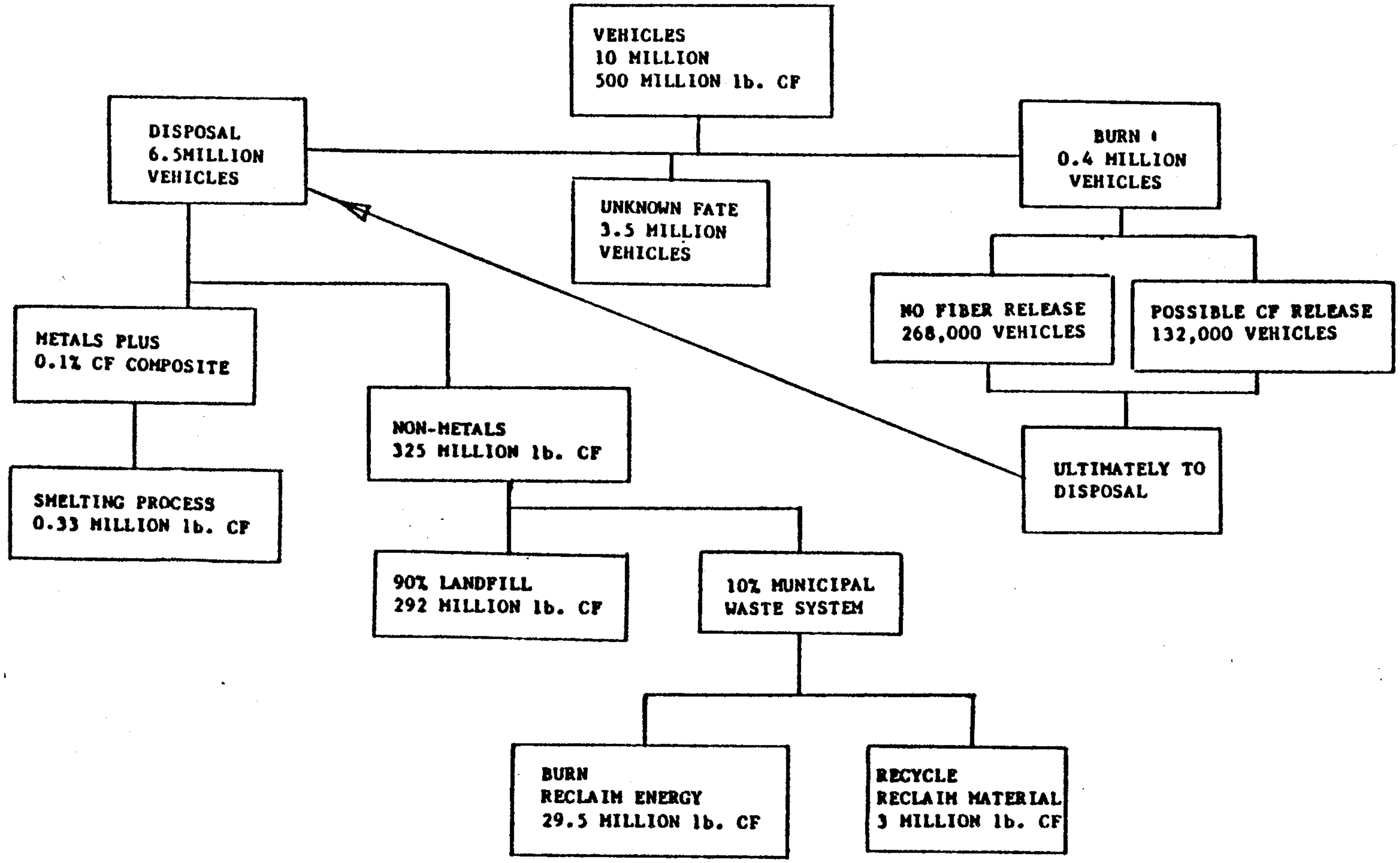


FIGURE 3-3. AUTOMOBILE DISPOSAL FLOW

3. The total vehicle population will contain CF composites.

4. In the vehicle recycling process, the metals will be separated from the non-metals. Some scraps of burnables will inevitably be processed with the separated metals and will include 0.1 percent CF composites.

5. Of the remaining non-metals, 90 percent will be dumped in sanitary landfill areas. The remaining 10 percent will be introduced into muncipal solid waste disposal systems for recycling of materials and reclamation of energy.

6. Ten percent CF composites will not be completely separated in the municipal waste system and will undergo material recycling.

7. Only 65 percent of the annual vehicle production reaches the recycling system. This is according to data from the Motor Vehicle Manufacturers Association.

It can be seen from Figure 3-3 that all the composite from 6.5 million highway passenger vehicles eventually finds its way to the disposal or recycle system. Under the stated assumptions, this is 325 million pounds of CF. If this vehicle scrapping system is under such good control that 99 percent of the CF is safely and permanently disposed of, the remaining 1 percent of the CF released is greater than the fiber released in the fire incidents described in Section 3.2. There is a great deal which is not known about the fate of CF in the disposal system or its effects on it. For example, will the fibers interfere with incinerator filters or be removed by electrostatic precipitators? What assurance is there that the CF used as landfill will not be uncovered and released at some future time? The potential for release of CF during disposal could be many times greater than the release due to fire incidents.

3.4 LABORATORY TESTS TO CHARACTERIZE CF RELEASE

This section reports the results of a study to investigate the CF released from automotive grade CF composites exposed to a fire environment. The objectives of the study, conducted by the NASA Ames Research Center under a reimbursable agreement from TSC, were as follows:

1. Determine the quantity of CF released from selected composites during and after fire exposures.
2. Characterize the shape, length, and distribution of CF released.

The scope of this effort was limited to collecting and counting fibers released from burning "automative grade" CF composites (see Table 3-6) and did not include analyses of any other related fiber contributions resulting from vehicle assembly line processes.

3.4.1 Approach to CF Characterization

A review of all applicable CF test data revealed that the only CF release data available were limited to "aerospace grade" composite materials that were exposed to severe thermal stress (2,000°F) and high post-burn shock loads. While these conditions may well apply to an aircraft fire followed by a crash, they were not considered appropriate in simulating the automobile fire scenario, where collision, if any, usually preceeds the fire. Furthermore, the available fuel, thermal intensity profile, and burn duration factors in automobile fires are significantly different (i.e., reduced in magnitude) from those experienced in aircraft fire situations.

In view of the above, a plan to generate the necessary information was proposed and consisted of the following three tasks:

(A) The development of a new data base through laboratory testing of "automotive grade" composite samples which would allow estimates of CF released in automobile fires.

(B) The burning of full-sized, instrumented passenger cars to determine the progress of fires in automobiles including time-temperature histories at those vehicle locations where CF composites are likely to be used.

(C) The burning of full-sized, instrumented passenger cars which contain CF composite parts and measuring the quantities of CF released for validation of the data developed in tasks (A) and (B), above. Considering the comprehensive nature of the problem, discussions were held with fiber manufacturers, composite fabricators, vehicle manufacturers, and leading fire experts to assist DOT in formulating the test plan. However, only Task I was adopted. Specifically, the five major elements of Task I were:

1. Sample Construction,
2. Sample Fabrication,
3. Fire Test Conditions,
4. Fire Test Apparatus,
5. Fiber Collection and Counting Techniques.

Consideration was given to a number of government and private testing centers having advanced materials' flammability expertise, state-of-the-arts knowledge of CF release mechanisms, proven fiber collection and counting capability, and prior risk analysis experience. On this basis, a reimbursible agreement[9] was negotiated with NASA/Ames to provide the personnel, materials, and facilities to execute Task I.

3.4.2 Definition of Test

A preliminary statement of work addressing the five elements of Task I was forwarded to fiber manufacturers, composite end-users, and consultants for review. Essential comments were incorporated in the test plan and a coordinated final work statement was issued. The selection of resins and reinforcements, including hybrids, represented several composite combinations being considered by the major automobile manufacturers for new light weight vehicle applications. (See Section 2.4.) The majority of the 6 in.^2, 1/8 in. thick flat plate CF test samples were fabricated by HITCO Inc. of Gardena CA and are identified in Appendix A.

The test facility was originally designed for NASA's aircraft CF Fire Research Program and was operated by Scientific Services, Inc., Redwood City CA. However, in view of the obvious differences in material constructions and potential fire environments between CF composite structures used for aircraft/military applications and automotive applications, it became appparent that meaningful burn tests could not be conducted in the same manner as NASA had done previously.[10] Among those items of importance and associated issues that required further resolution prior to testing automotive composites, were:

(A) The selection and monitoring of fire test exposure conditions -

1. Time of exposure
2. Temperature limits
3. Type and control of fuel
4. Gas flow velocity
5. Variations in fire environment

(B) The exposed sample characteristics -

1. Type of holding fixture
2. Position of sample to the flame
3. Stressed sample conditions
4. Post-fire clean-up procedures

(C) The collection scheme for released fibers during and after burn -

1. Anticipated fiber settling rate
2. Type, size, and configuration of the collection chamber
3. Type and size of filtering system, if needed
4. Type of medium to gather and hold released fibers

(D) The counting technique employed -

1. Smoke particulate and hot gas encumbrances
2. Examination method of chamber grid
3. Fiber length counting limits
4. Computerized or manual counting scans.

On the basis of discussions between DOT and NASA personnel on the key issues identified above, a series of unique modifications in construction detail (Figures 3-4, 3-5, 3-6, 3-7, and 3-8) were affected which: 1) permitted the natural settling of CF released both during and after thermal exposure, 2) allowed for visual observation and automatic recording of sample performance characteristics throughout the test, 3) accommodated CF samples of the required size, configuration, and orientation, 4) provided fire environments that were judged to be representative of actual automobile burn scenarios, 5) facilitated the time consuming task of counting and characterizing single fibers released, and 6) incorporated the flexibility needed to examine "worst-case" release situations.

Furthermore, the following test conditions were established:

1. Sample Position - edge exposure
2. Fuel Mixture - propane/air
3. Flame Exposure Time - 10 minutes

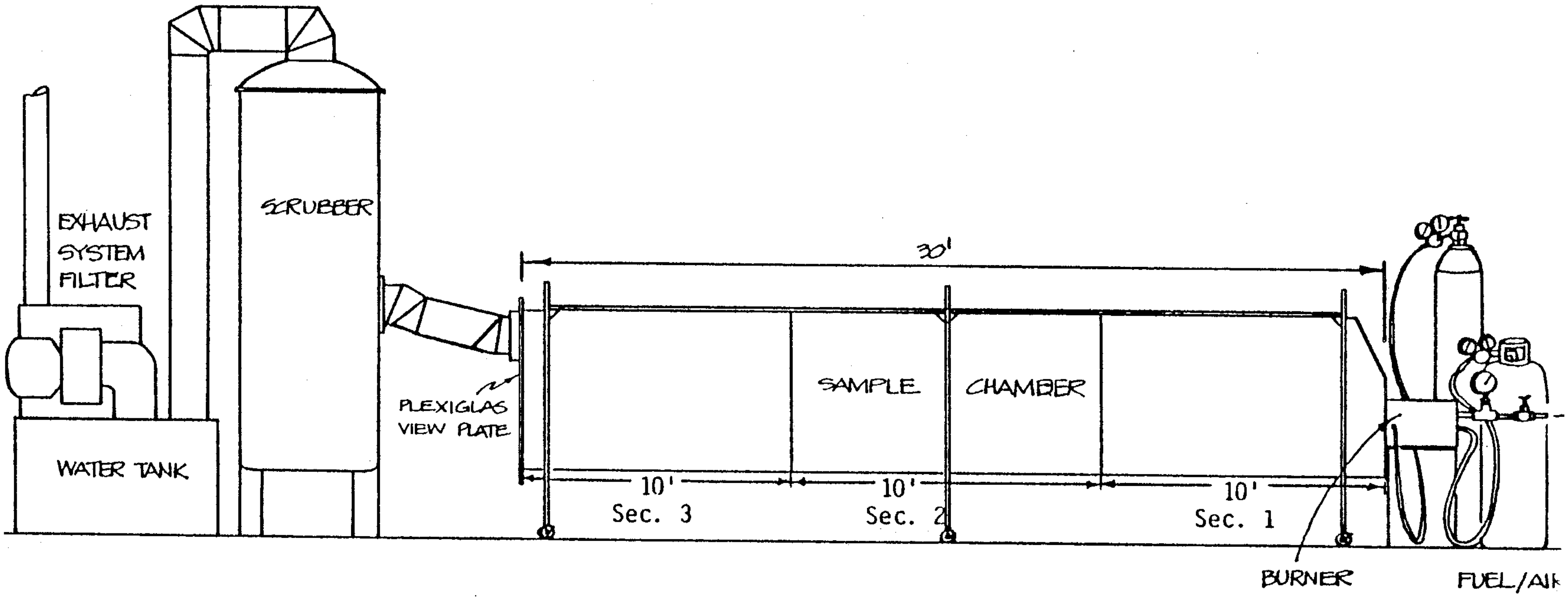


FIGURE 3-4. SKETCH OF MODIFIED TEST FACILITY

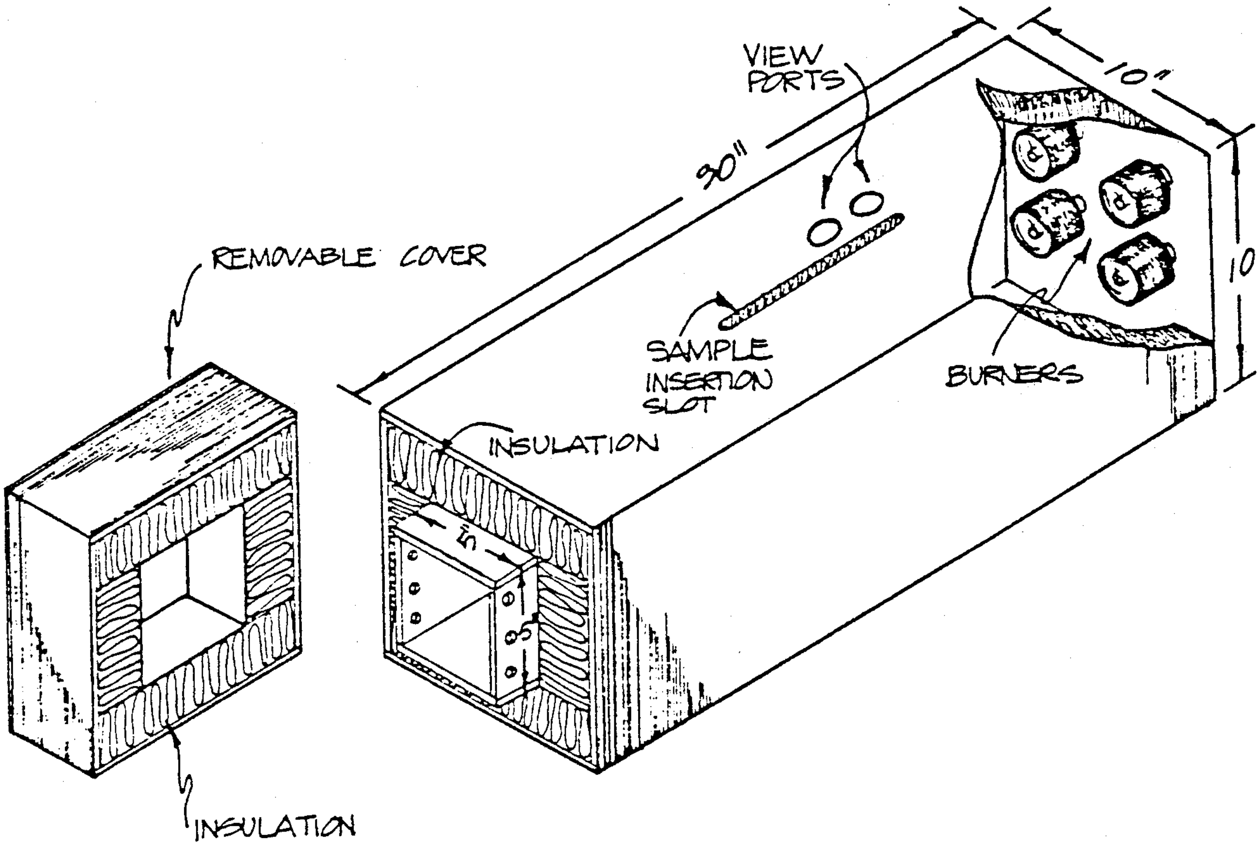
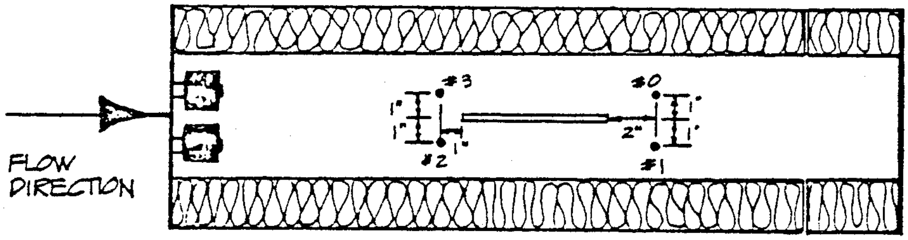
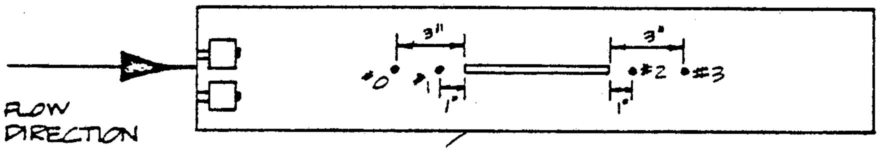


FIGURE 3-5. SKETCH OF HIGH RADIANT BURN CHAMBER



HIGH RADIANT FURNACE



LOW RADIANT FURNACE

FIGURE 3-6. LOCATION OF THERMOCOUPLES IN BURN CHAMBERS

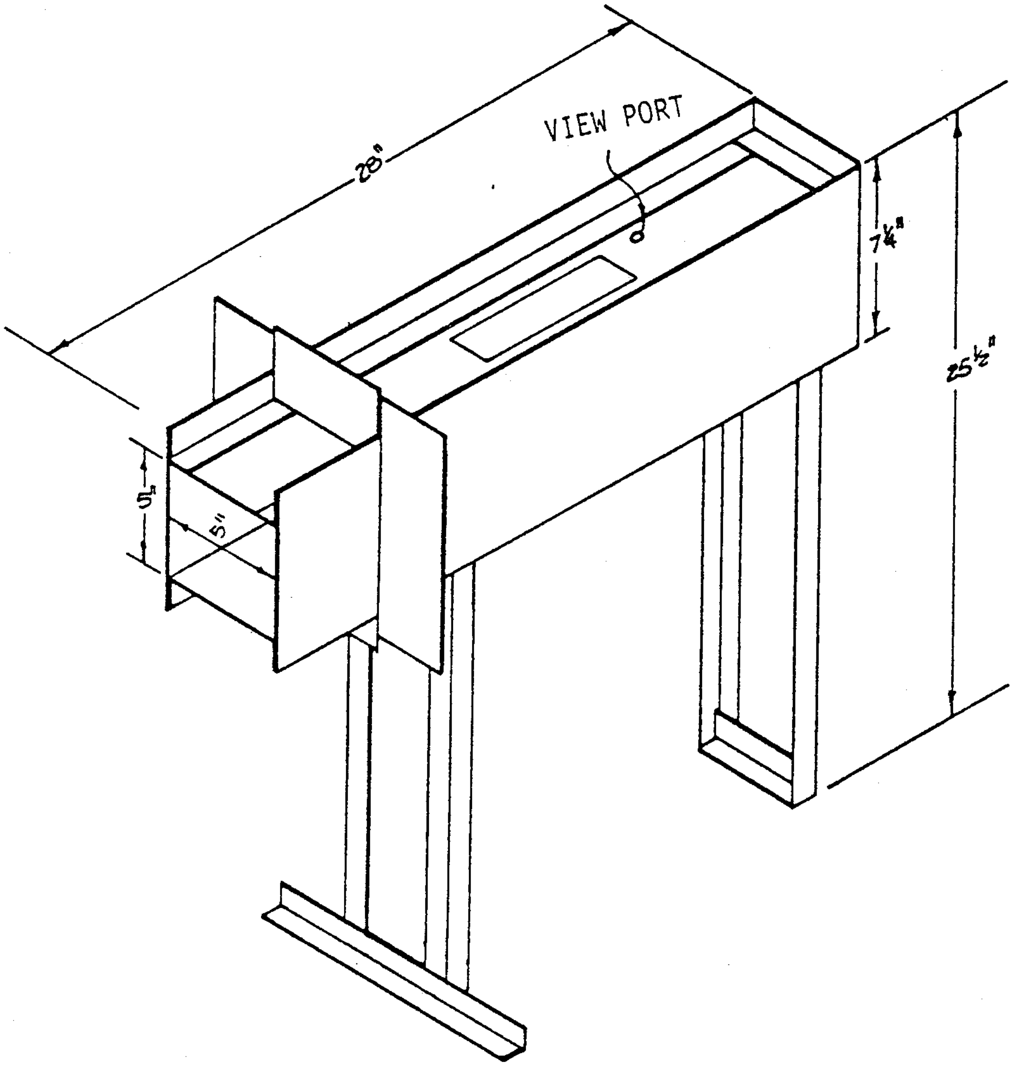


FIGURE 3-7. SKETCH OF LOW RADIANT BURN CHAMBER

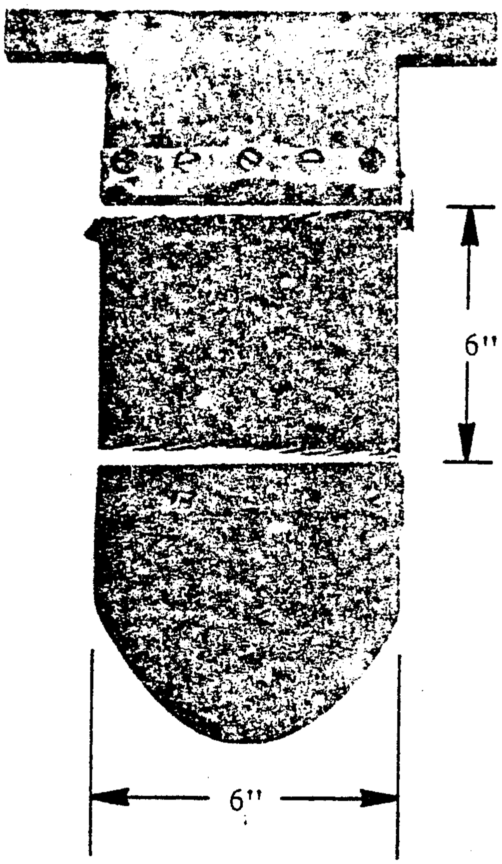


FIGURE 3-8. PHOTOGRAPH OF SAMPLE HOLDER

4. Flow Velocity Across Sample - 10 ft/sec
5. Gas Temperature at Sample - ∿1200°F; ∿1800°F
6. Burn Chamber Pre-Heat - ∿1600°F (electric)(only for 1800°F)
7. Flame Types - Fuel rich and oxygen rich
8. Radiant Exposures - high and low.

The exposure requirements necessitated two different types of burn chambers. The high radiant chamber (shown in Figure 3-5) was constructed of ceramic slabs containing embedded Nichrome heating elements. The purpose of the heating elements was to pre-heat the chamber prior to initiation of the flame. The ceramic liner was insulated by about two inches of Fiberfrax insulation and enclosed in a stainless steel protective cover.

The low-radiant burn chamber, which required cooler walls, was constructed of stainless steel with no ceramic insulation (Figure 3-7). The flame source consisted of four "Durradiant" burners mounted in the end of the furnace as shown in Figure 3-5. Propane fuel and air from an air compressor were supplied to these burners through the fuel system. Nitrogen gas was inserted ahead of the sample location to cool the flame temperature to the desired ∿1800°F.

Characterization of the air flow and thermal parameters were determined by mass balance equations using the measured input gas volumes and temperatures at the inlet and outlet. Data measuring devices, including time/temperature recorders, thermocouples, and gas flow meters, were used to monitor test parameters.

3.4.3 Test Procedure

The burn chamber was electrically pre-heated to ensure uniform thermal distribution and reduce warm-up time. The furnace burner was ignited just prior to sample insertion with the latter remaining in place for the duration of the test. After flame exposure, the chambers were allowed to cool. The burner section was then rolled away from the collection chamber and the opening sealed. The collection chamber was then dismantled into its three, ten-foot long sections and thin membranes were carefully inserted between the sections to minimize fiber disturbance. Gummed paper rollers were then used to gather the fibers from selected areas in the collection chamber. These gummed paper samples were then removed from the roller and placed on a piece of clear acetate film to trap the collected sample in a sandwich. This sandwich was photographed at approximately 3x magnification and then printed at another 3x magnification, so that each area selected was magnified nine times. A transparent grid placed over the photograph was used to aid in counting the fibers. Typical CF samples after exposure are shown in Figures 3-9, 3-10, 3-11, and 3-12. The test scheme proceeded, as planned, with initial data indicating low orders of fiber release. In an attempt to identify and quantify the "worst case" release scenario, the following procedural variations were made:

1. Air Blow-By - The original test method described above included a 6 MPH gas flow velocity past the sample during the burn; it was thought that the same or more severe wind condition would prevail after the fire was extinguished. Accordingly, selected samples were allowed to cool in place and were then exposed to 6 and 12 MPH air blow-by velocities, respectively. The release of any additional fibers was noted.

2. Damage Plus Air Blow-By - Post fire mechanical disturbances of CF composites could occur during rescue and clean-up operations. Therefore, after thermal exposures, selected CF samples were partially damaged, (flexural buckling) followed by air blow-by as in 1, above, and then checked for any additional fiber release.

3.4.4 Test Results[11]

A summary of the test performed is presented in Table 3-6. Table 3-7 is a matrix that summarizes the data on total release of single fibers during each of the tests. Table 3-8 is similar to Table 3-7 except the data is summarized in terms of percent of fibers released. The release ranges from 947 to 319,260 free fibers.

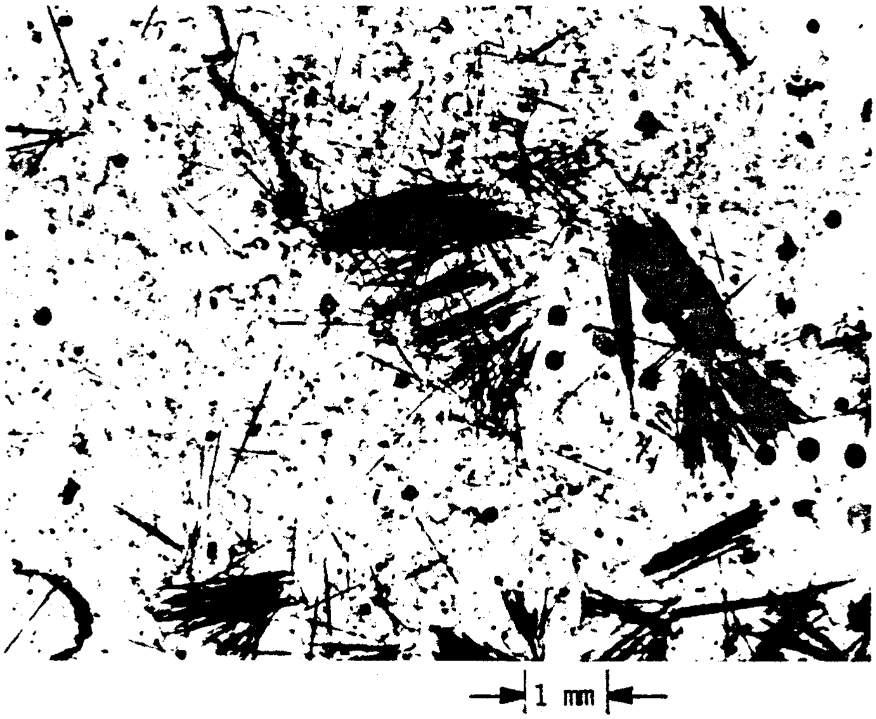


FIGURE 3-9. PHOTOGRAPH OF SAMPLE FROM FLOOR OF FURNACE END OF SECTION 1; TOTAL SAMPLE 929 cm^2 (1 ft^2), AREA OF PHOTOGRAPH ≃ 0.8 cm^2 (0.15 in.^{2})

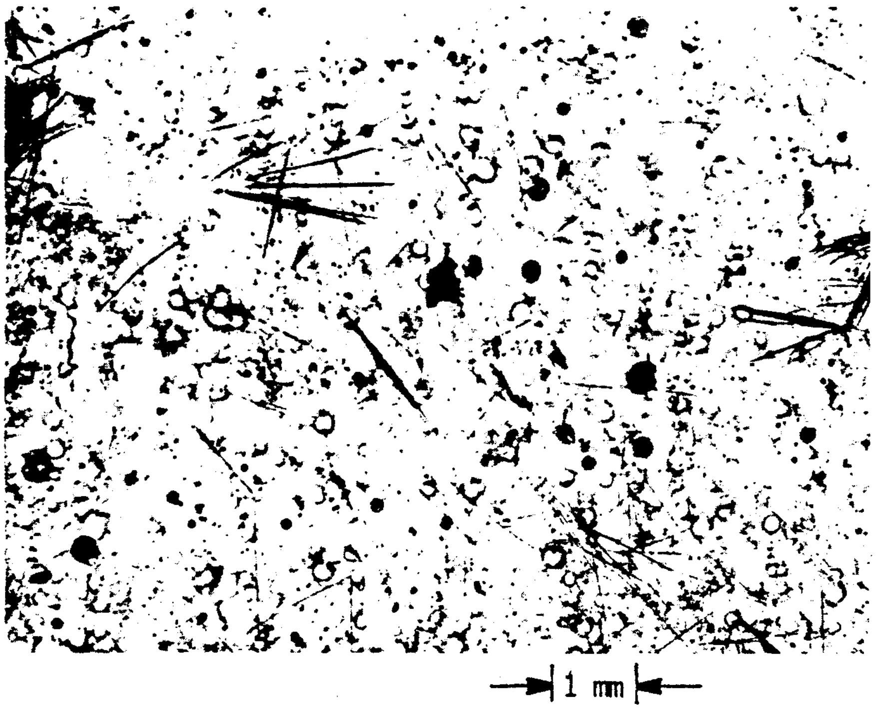


FIGURE 3-10. PHOTOGRAPH OF SAMPLE FROM FLOOR OF FURNACE END OF SECTION 1; TOTAL SAMPLE AREA 929 cm^2 (1 ft^2), AREA OF PHOTOGRAPH ≃ 0.8 cm^2 (0.15 in.^{2})

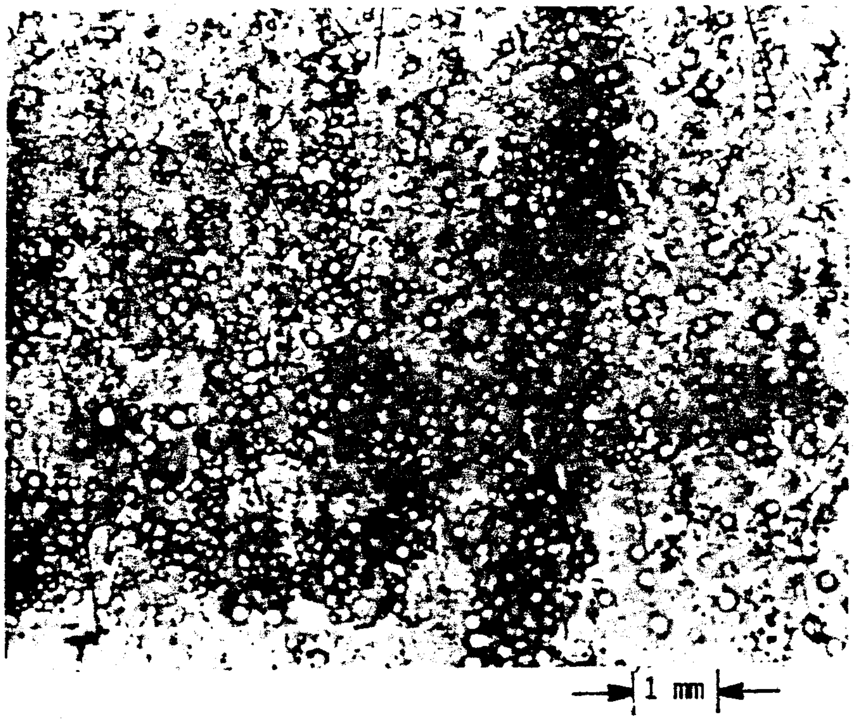


FIGURE 3-11. PHOTOGRAPH OF SAMPLE FROM FLOOR OF CENTER OF SECTION 2; AREA OF SAMPLE 464 cm^2 (1/2 ft^2), AREA OF PHOTOGRAPH ≃ 0.8 cm^2 (0.15 $in.^2$)

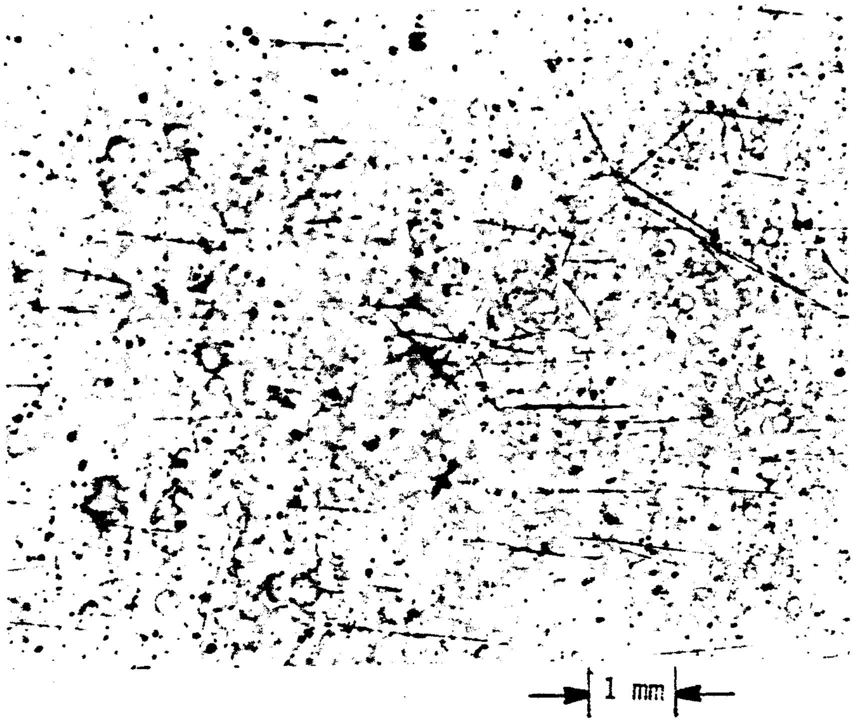


FIGURE 3-12. PHOTOGRAPH OF SAMPLE FROM FLOOR OF FURNACE END OF SECTION 3; AREA OF SAMPLE 464 cm^2 (1/2 ft^2), AREA OF PHOTOGRAPH ≃ 0.8 cm^2 (0.15 $in.^2$)

TABLE 3-6. CF COMPOSITE TEST SUMMARY

TEST	SAMPLE DESCRIPTION	BURN CONDITIONS						NOTES
		Low Rad	High Rad	Fuel Rich	O_2 Rich	Burn Time	Vel ft/s	
1	Epoxy - Graphite, woven		X		X	10	10	(1)
2	Polyester - Graphite/glass hybrid unidirectional		↓		↓	↓	↓	(2)
3	Vinyl Ester - Graphite (AS-5)/glass hybrid cross ply		↓		↓	↓	↓	(3)
4	Polyester - Graphite (GLC)/glass hybrid unidirectional		↓		↓	↓	↓	
5	Polyester - Graphite (AS-5) unidirectional		↓		↓	↓	↓	
6	Epoxy - Graphite (T-300) unidirectional		↓		↓	↓	↓	
7	Polyester - Graphite (GLC) unidirectional		↓		↓	↓	↓	
8	Epoxy - Graphite (AS-5) unidirectional		↓		↓	↓	↓	
9	Polyester - Graphite (AS-5)/glass hybrid cross ply		↓		↓	↓	↓	
10	Polyester - Graphite (AS-5)/glass hybrid cross ply		↓		↓	↓	↓	
11	Vinyl Ester - Graphite (AS-5)/glass hybrid cross ply		↓		↓	↓	↓	
12	Vinyl Ester - Graphite (AS-5)/glass hybrid cross ply		↓		↓	↓	↓	
13	Polyester - Graphite (AS-5)/glass hybrid unidirectional		↓		↓	↓	↓	

TABLE 3-6. CF COMPOSITE TEST SUMMARY (CONTINUED)

TEST	SAMPLE DESCRIPTION	BURN CONDITIONS						NOTES
		Low Rad	High Rad	Fuel Rich	O_2 Rich	Burn Time	Vel ft/s	
14	Vinyl Ester - Graphite (AS-5)/glass hybrid cross ply		X		X	10	10	
15	Vinyl Ester - Graphite (AS-5)/glass hybrid unidirectional		X		X	↓	↓	
16	Polyester - Graphite (AS-5)/glass hybrid unidirectional	X		X		↓	↓	
17	Polyester - Graphite (AS-5)/glass hybrid unidirectional	X		X		↓	↓	
18	Polyester - Graphite (AS-5)/glass hybrid unidirectional	X		X		↓	↓	
19	Polyester - Graphite (AS-5)/glass hybrid unidirectional		X	X		↓	↓	
20	Repeat of Sample 18	na	na	na	na	na		(4)
21	Repeat of Sample 19	na	na	na	na	na		(5)
22	Repeat of Sample 19	na	na	na	na	na		(6)
23	Repeat of Sample 19	na	na	na	na	na		(7)

Notes:
(1) Aircraft grade Sample — used for system checkout only.
(2) Experimental grade sample — used for system checkout only
(3) Burned with outside fiber layer horizontal instead of vertical
(4) Sample 18 at 6 mph
(5) Sample 19 at 6 mph
(6) Sample 10 at 12 mph
(7) Sample 19 — borken — at 12 mph

TABLE 3-7. MATRIX OF TEST DATA

Fiber Orientation				Unidirectional				Cross Ply	
Glass Content				YES		NO		YES	
Fiber Type				AS 5	GLC	AS 5	GLC	AS 5	GLC
Oxygen Rich	High Radiant Input	Binder	Vinyl Ester	15 - 4,125				11 - 11,535 12 - 19,602 14 - 43,182 3 - 947 *	
			Epoxy			6 - 41,486 8 - 22,806			
			Poly-Ester	13 - 3,390	4 - 1,883	5 - 56,983	7 - 9,296	9 - 13,046 10 - 11,415	
Fuel Rich	Low Radiant Input	Binder	Polyester	16 - 319,260 17 - 126,339 18 - 44,239					
	High Radiant Input	Binder		19 - 1,351					

* Sample was oriented with the outside layer of fibers horizontal; in all other cases this layer was vertical.

TABLE 3-8. PERCENTAGE OF FIBERS RELEASED

Fiber Orientation				Unidirectional				Cross Ply	
Glass Content				YES		NO		YES	
Fiber Type				AS 5	GLC	AS 5	GLC	AS 5	GLC
Oxygen Rich	High Radiant Input	Binder	Vinyl Ester	* ⑮ 0.32×10^{-3}				⑪ 0.52×10^{-3} ⑫ 0.89×10^{-3} ⑭ 1.97×10^{-3} [illegible] 0.11×10^{-3}	
			Epoxy			⑥ 1.49×10^{-3} ③ 0.57×10^{-3}			
			Poly-Ester	⑬ 0.18×10^{-3}	④ 0.21×10^{-3}	⑤ 3.03×10^{-3}	⑦ 1.77×10^{-3}	⑨ 1.06×10^{-3} ⑩ 0.92×10^{-3}	
Fuel Rich	Low Radiant Input	Binder	Polyester	⑯ 0.070 ⑰ 0.022 ⑱ 0.011					
	High Radiant Input	Binder		⑲ 0.22×10^{-3}					

* Test number in ○

† Sample was oriented with the outside layer of fibers horizontal; in all other cases this layer was vertical.

It should be noted tha duplicate tests were conducted when possible (under the prevailing time and funding constraints) to permit statistical and qualitative correlation of data.

Size-frequency distributions of single-fiber lengths for the fibers gathered on each test have also been analyzed to help identify differences. Plots of the data appear in Reference 11. Where tests were repeated, data from all tests that are presumably identical are plotted on a single figure. Those are Tests 11, 12, and 14; 6 and 8; 9 and 10; and 16, 17, and 18. (Note Test No. 3 was not included with the first group for the reason given in Table 3-6).

Item 2 shows the size-frequency distribution data to be virtually identical for each of the three tests presented. (Note how different Test 3 data of Item 3 are from those in Item 2.) The largest spread in size-frequency distribution data from a set of "identical tests" is shown in Item 4. The data from Test 8 is suspect because it is not well behaved when plotted, yet all of the other data are. Further analysis showed that the counts from section 1 (nearest the furnace) were the cause; the sections 2 and 3 data taken alone are reasonably well behaved. It is believed that a tuft of fibers may have been formed in this test and released to bias the data near the furnace towards large fiber sizes.

Differences in size-frequency distribution that appear to be significant can be observed to set apart Tests 3; 4 and 7; 16, 17, and 18; and 19 from the rest. Within this group, Tests 4 and 7 were the only ones that involved Great Lakes carbon fibers; Test 3 was the only one that involved a different orientation of the outside fibers to the flow of gases; and Tests 16, 17, 18, and 19 were the only ones that involved fuel-rich input conditions. Based on the limited data, it is probably unjustified to attempt to make more of these data at this time.

The results from the burn test data seem to indicate that the release of significant quantities of single fibers by burning alone is unlikely. Additional observations and analyses of the samples point up another important consideration: the burning process could produce a state in graphite composites that is particularly vulnerable to mechanical degradation and could subsequently lead to the release of large numbers of single fibers.

Additional tests were conducted on one of the composite specimens (Test 19) in which the burning removed the binder to expose the graphite fibers. A gas flow rate which simulated a 6 mph wind was introduced after the collecting chamber had been cleaned following the burning process and continued for 10 minutes. The fibers were released in fuzz balls in quantities too great to count, so they were weighed. The weight of fibers released at 6 mph corresponded to 3.1 percent of the fiber content. After these fibers were collected and the duct cleaned, the flow was started again, but increased to about 12 mph and continued for 10 minutes. Additional fuzz balls of fiber were collected and weighed and corresponded to an additional 1.3 percent. It may be assumed that at an initial wind loading of 12 mph, the combined total would have been released.

If it is typical for winds to exist that could disrupt fibers, it is certain that the process of fighting the fire and collecting the debris will introduce even greater stresses that could cause fibers to be released. If the composite were a support bracket, the weight alone could crack the damaged material in two. To simulate this condition, the above sample was subjected to an impulse that severed the fibers, and then the gas flow rate of 12 mph was applied for 10 minutes to simulate a wind stream blowing on the damaged fibers. The result was an additional release of 9.5 percent. Thus, the aggregate release for this credible condition corresponded to 3.1 percent + 1.3 percent + 9.5 percent or 13.9 percent.

3.4.5 Conclusions

The overall conclusions from these tests are that automotive fires, per se, are unlikely to be the cause of serious risk from single carbon fiber release. However, the possibility of automobile fires occurring in combination with other forces, such as wind and fire fighting, rescue, and disposal operations could result in significant CF release.

4. VULNERABILITY OF SURFACE TRANSPORTATION

One of the primary tasks assigned to the Department of Transportation by the Carbon Fiber Study[1] is the assessment of the vulnerability of surface transportation to airborne carbon fibers. Most of the estimated carbon fiber composite materials production in the 1990's will be used in surface transportation. Since surface transportation modes are often found to use the same right-of way (trucks, buses, cars) or adjacent rights-of-way (light rail, highway), the opportunity for self-contamination and cross-contamination is high. These facts make the vulnerability of surface transportation a critical parameter in the assessment of the national risk with the use of carbon fiber composites.

4.1 METHODOLOGY

All the carbon fiber vulnerability data available on electrical equipment are on a component or simple subsystem level. The evaluation of surface transportation systems must be based on an analysis of the systems in terms of these known components. The system being studied is broken down into subsystems and eventually into components of known or estimated vulnerability. The system may consist of an individual vehicle such as a truck or a complete system such as a transit system.

Once the components have been identified, it is necessary to estimate the impact of component failure in general terms. If a component failure allows the vehicle to operate while significantly decreasing its operating safety or causes the vehicle to fail in a way which is unsafe, then the failure is classified as safety related. If the component failure significantly degrades or halts the vehicle operation in a safe manner, then the failure is classified as a system failure. If the component failure does not significantly degrade either vehicle operation or safety, then the failure only reduces the comfort or convenience of the passenger and is classified as a convenience failure.

The next step is to estimate the vulnerability of the component to airborne carbon fibers. Components which are protected with dust-tight housings or are potted in plastic and have insulating covering over their connections are not vulnerable because of this protection. Components which operate at voltages less than 600 volts and draw over an ampere of current are invulnerable because the shorting carbon fiber burns out at less than 100 milliamperes.[12] Components which do not fit either of these descriptions are considered potentially vulnerable. Potentially vulnerable components which are classified under either safety or system failure should be further analyzed or tested to establish the carbon fiber exposure level necessary to cause failure. Components with failure levels determined to be greater than 10^8 fiber seconds/meter^3 are not considered vulnerable.

4.2 VULNERABILITY OF TRANSPORTATION MODES

For the purpose of the vulnerability assessment, the various forms of surface transportation were divided into modes including highway, electrified rail, diesel powered rail, and water. These divisions were selected because commonalities in the system designs reduce the number of analyses required to cover all of surface transportation.

4.2.1 Highway Vehicles

The bulk of the surface transportation of people and freight travels over the highway system in automobiles, trucks, and buses. These vehicles are almost exclusively powered with either the spark ignition gasoline fueled engine or the diesel engine. Only these vehicles and engines are considered here. Special purpose highway vehicles such as motor homes or electric cars have not been evaluated.

The electrical system in the vehicle is divided into functional subsystems for the purpose of the vulnerability assessment. Within a vehicle type, e.g., the private automobile, these functional subsystems vary little over the entire range of the fleet. The largest vehicles have the same electrical equipment as the smallest. The functional subsystems are further divided into specific parts or components. Table 4-1 shows the division of functional subsystems and components for the private automobile; there are five subsystems and twenty components. Some of the components such as emission controls could be detailed further but for the purposes of this study it is not necessary.

It is possible in certain cases that alternative procedures can compensate for a failed component. When available, alternative procedures compensate for a failed component on a temporary basis, usually resulting in a loss of convenience. For example, a flashlight can be used as an alternative to a failed interior light.

Table 4-1 shows that only two of the twenty components listed have any possibility of being vulnerable. This result is partly fortuitous because most of the electrical components are low-voltage, high-current devices which will burn out a carbon fiber before it can do any damage. The remainder of the invulnerability can be attributed to the hostile environment found around the automobile. Any components exterior to the passenger compartment must be able to survive high levels of dust, oil vapor, water, and salt spray, as well as temperature extremes. Interior components must survive temperature extremes, high humidity, and moderate dust levels. All exterior electrical components which would be sensitive to electrical leakage are potted or sealed to prevent the entrance of dust or salt spray. The exterior connections are normally covered with insulation and separated by several millimeters. The electrical components in the automobile's interior appear to be the only ones with any chance of vulnerability. This equipment is of the convenience class, and its possible vulnerability is due to convective cooling holes punched in the equipment cases.

TABLE 4-1. PRIVATE AUTOMOBILE ELECTRICAL SYSTEMS

Subsystem/Component	Vulnerability	Effect	Alternative
Engine - ignition	N-P	System	N
alternator	N-C	Convenience	N
voltage regulator	N-P	Convenience	N
battery	N-C	System	N
starter	N-C	System	Y
Chassis - heater	N-C	Convenience	N
window defogger	N-C	Convenience	Y
wiper/washer	N-P	Safety	N
Fuel - pump	N-P	System	N
emission controls	N-P	Convenience/ System	N
injection	N-P	System	N
Lighting - headlight	N-C	System	N
tail light	N-C	Safety	N
brake	N-C	Safety	N
turn	N-C	Safety	Y
interior	N-P	Convenience	Y
Accessories - clock	N-P	Convenience	N
entertainment	V-E	Convenience	N
CB	V-E	Convenience	N
digital inst.	N-P	Convenience	N

Vulnerability:

N = not vulnerable; V = vulnerable; following the hyphen is a letter indicating the reason for the system vulnerability; C = high current, at least 100 times greater than that carried by a single fiber (10 ma); P = the system is well protected by housing, potting or insulation against the hazard; E = circuit/components exposed to possible interference by the hazard.

Effect:

system = vehicle inoperable under certain or all conditions; safety = vehicle safety is impaired; convenience = vehicle operable and safe but its utility, comfort and convenience may be degraded.

Alternative:

N = no alternatives to the system function; Y = there are alternatives to replace the system function.

However, limited testing on an automobile radio has shown its sensitivity to carbon fibers to be greater than 10^8 fiber sec. per $meter^3$.

Table 4-2 shows the analysis of the vulnerability of a transit bus. It can be seen that the transit bus subsystem vulnerablity is similar to that of the private automobile with a few exceptions. Since transit buses are diesel powered and use no electrical or emission controls in the fuel system, the fuel system is missing. Interior lighting is necessary for the operation of a bus at night and is labeled as a system effect. Transit buses sometimes carry a communications radio for certain dispatching operations. Failure of this radio may cause a convenience or a system effect depending upon the type of service the bus is providing. The transit bus does not appear to be vulnerable to airborne carbon fibers.

Intercity buses would have a vulnerability table similar to Table 4-2. School buses, by virture of their spark ignition engine, will have a vulnerability somewhere between the transit bus and the private automobile.

The vulnerability of the intercity truck is detailed in Table 4-3. This truck is broken down into four subsystems consisting of a total of 16 components. The only equipment which may be vulnerable appears to be in the convenience category. The reasons are much the same as noted above for the private automobile and the transit bus. This conclusion of low vulnerability has been supported by the experience of trucks operating at Dugway Proving Grounds, Utah. Several years ago, a large quantity of carbon fibers was deliberately released at a Dugway site. Because of the low rainfall and sparse vegetation at this site, much of this fiber still remains exposed on the soil surface. When a truck is driven through this site, some of these fibers re-enter the air, but there has never been a subsystem failure in these trucks which appeared to be due to the carbon fiber.

Intracity trucks are predominantly powered by spark ignition engines and therefore will have an ignition system vulnerability similar to the private automobile.

TABLE 4-2. TRANSIT BUS ELECTRICAL SYSTEMS

Subsystem/Component	Vulnerability	Effect	Alternative
Engine - alternator	N-P	System	N
voltage regulator	N-P	System	N
battery	N-C	System	N
starter	N-C	System	N
Chassis - heater	N-C	System	N
wiper/washer	N-P	Safety	N
Lighting - head	N-C	Safety	N
tail	N-C	Safety	N
brake	N-C	Safety	N
turn	N-C	Safety	N
interior	N-P	System	N
Accessories			
communications radio	N-P	Convenience/ System	N
digital inst.	N-P	Convenience	N

TABLE 4-3. INTERCITY TRUCK ELECTRICAL SYSTEMS

System/Component	Vulnerability	Effect	Alternative
Engine - alternator	N-P	System	N
voltage regulator	N-P	System	N
battery	N-C	System	N
starter	N-C	System	N
Chassis - heater	N-C	Convenience	N
wiper/washer	N-P	Safety	N
Lighting - head	N-C	Safety	N
tail	N-C	Safety	N
brake	N-C	Safety	N
turn	N-C	Safety	N
interior	N-P	Convenience	Y
running	N-P	Safety	N
Accessories - CB	V-E	Convenience	N
entertainment	V-E	Convenience	N
digital inst.	N-P	Convenience	N
hydraulic/pneumatic	N-P	Safety	N

4.2.2 Electrified Rail

A preliminary assessment of electrified rail systems indicated that these systems were potentially vulnerable by virtue of their electric propulsion motors, power distribution systems, and signal systems. A detailed analysis of electrified rail systems was completed under contract with Applications Research Corporation of Warminster, PA. This section contains a brief summary of the results of this analysis. A detailed description of this analysis can be found in Reference 13.

The electrified rail systems were divided into two subsystems: power and propulsion, and signal and control. The power and propulsion subsystem was further divided into airborne and wayside subsystems.

4.2.2.1 Power and Propulsion - A detailed evaluation of the components currently used in electrical power and propulsion subsystems indicated that the following components show the greatest vulnerability to carbon fibers:

1. Bushings and insulators found on transformers,
2. Circuit breakers and other substation equipment,
3. Insulators isolating the catenary or third rail,
4. Dry-type transformers and inductors,
5. Semiconductor assemblies for vehicle power supplies.

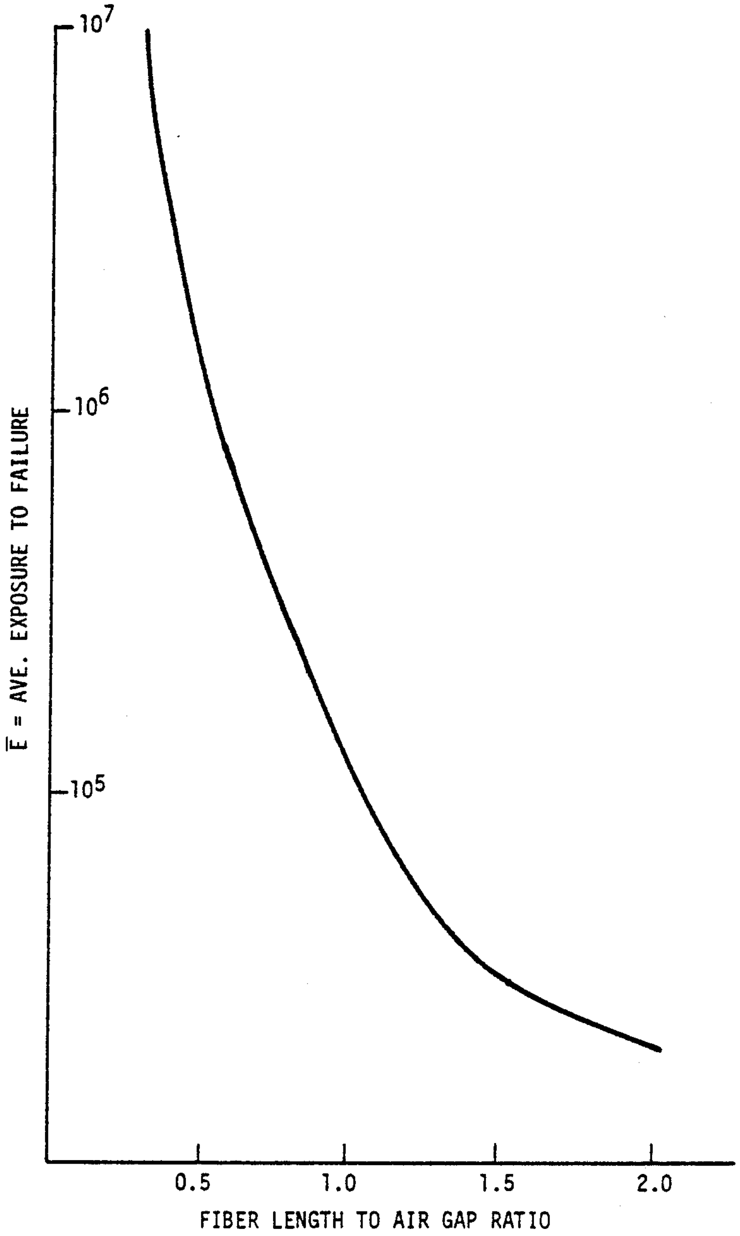
Much of this equipment will still be in use in the 1990's. There is expected to be a wider use of semiconductors, plastic insulators, regenerative braking, automatic train controls, longer third rail insulators, and improved power cables. On the average, these changes are not expected to appreciably change the vulnerability of the power and propulsion subsystems.

The estimates of the component vulnerability were based on exposure to fibers 5 mm long. The subsystems proved to have very little vulnerability because of the redundancy built into it by design. An exposure of a substation or a rail car to 10^4 fiber

sec/m^3 has a probability of 10^{-2} of an operational failure and 10^{-4} of a safety failure. These probabilities are further reduced by redundancies in the operating systems. For example, a six-car train must have more than three failed cars before its operation is significantly affected. In this case, the probability of an operational failure is 10^{-7}. As an example of the system impact of a substation failure, two adjacent substations must fail on the same day to cause even a small loss in operational capability. Since the spacing between substations is greater than three miles on the average, the same release will not affect two adjacent substations. It is estimated that there would be one substation interference incident due to carbon fiber each month. With the total substations estimated at 100, the probability that two adjacent substations will fail within a 24-hour period from carbon fibers is 5×10^{-4}. This leads to the result that, on the average, adjacent substations will fail once every 170 years.

It is emphasized that these vulnerabilities are based on 5-mm length fibers and, as such, provide an extremely conservative failure estimate. Nearly all the released fibers are less than 2 mm. It can be seen from Figure 4-1 that the vulnerability is reduced dramatically as the fiber lengths fall below the electrode spacing. Most of the electrode spacing in the power and propulsion systems is in excess of the 5-mm fiber length used for the vulnerabilities calculated above. The figure shows that a reduction of fiber lengths from 5 mm to 1 mm will reduce the vulnerability of the equipment to the shorter fiber by a factor of 100 or more.

4.2.2.2 <u>Signal and Communication</u> - The signal systems used for electrified or non-electified rail are similar to the extent that the vulnerability of a signaling subsystem can be considered as the same, independent of train power. The following section, therefore, will assess the vulnerability of all railroad block signal systems.



Source: Vulnerability of Quick Disconnect Connectors, Jerome Meyers, NASA Contractor Report No. 158999

FIGURE 4-1. VULNERABILITY AS RELATED TO FIBER LENGTH

There are many types of signal systems used for the control of trains. Their identification is along the lines of their function. For example, the automatic block signal system is used to control trains from block-to-block between terminals; the interlocking system provides protection for trains where one railroad crosses another or where the train moves from one track to another; and the traffic control system permits supervisory control of all train movements on a segment of railroad from a single centralized location, to name a few. In addition to the variety of functions signal systems are designed to perform, there are many variations and modifications within those systems, as well as considerable variance among the individual railroads on their application.

The function of the signal system is to detect the presence of a train within a specific section of track known as a block. The signal system consists of a set of relays with associated power supplies and operates between 0.6 and 10 volts with a current of 10 to 150 mA. The circuit is "failsafe" to power interruptions such as broken wires by using the logic that an open relay indicates the presence of a train. It is possible in this situation that a block occupied by a train will indicate as empty when there is a short between the relay terminals. This false signal condition due to relay shorting by carbon fibers or other foreign matter is extremely unlikely due to the design of the relay itself.

The working parts of the relay are contained in a sealed enclosure making them invulnerable. The only opportunity for shorting is where the electrodes protrude from the relay case. Those relays which are connected to the circuit by plugging into a socket are invulnerable because the socket completely covers and protects the electrodes. The more common relay, the shelf-mounted relay, has its electrodes exposed when it is in use. For the following reasons, a false signal due to shorting is unlikely:

1. Many of the vital circuits use double break circuitry where two simultaneous shorts are required to cause a failure.

2. The electrode insulation is extended 1/4 inch above the relay base making it difficult for fibers settling on the relay base to cause a short.
3. The electrodes that must be shorted to produce a false signal are not adjacent to each other.

The probability of an operational failure of a signal circuit is 2×10^{-3} when exposed to 10^4 fiber sec/m^3 of 5-mm length fibers. These same exposure conditions lead to a safety failure probability of 10^{-5}. Assuming 10^3 such exposures a year, there will be two operational failures a year and one safety failure in a century. It should be noted that a safety signal failure does not inevitably lead to an accident. Train accidents due to signal malfunctions are very rare events even though there are hundreds of such malfunctions each year.

4.2.3 Diesel Powered

The signal system vulnerability for non-electrified rail was assessed in the previous section. The railroad locomotive is powered by electric motors which are in turn powered by an on-board generator turned by a diesel engine. The diesel engine is invulnerable. The generator, which is very powerful, is difficult to short with a foreign object as fragile as carbon fiber. In addition, the generator is housed along with most of the power conditioning equipment in a tight chamber where fiber penetration is impossible. The electric traction motors are sealed and invulnerable. Thus, the diesel-electric locomotive is invulnerable to carbon fibers.

4.2.4 Water Transportation

Most of the carbon fiber released will be from highway vehicles. The carbon fiber from burning highway vehicles does not carry far at a high concentration. Under these conditions, ships and barges which are more than a few hundred meters from a highway will never experience exposures greater than 10^2 fiber sec/m^3 and most ships will never be exposed. Any shipboard electrical equipment is sealed and housed against an environment of high humidity and water spray. The combination of low fiber exposure and the enclosure of electrical equipment has rendered shipboard electrical systems invulnerable.

5. RISK ASSESSMENT

The previous sections have identified and discussed the data elements necessary to assess the potential risks that may result from the use of carbon fiber composites in the ground transportation system. This assessment was accomplished by the NASA Langley Research Center through one of their contractors, Arthur D. Little, Inc. DOT worked closely with NASA as much of NASA's and its contractor's data was necessary for the surface transportation risk assessment. Furthermore, it was initially expected that the risk assessment methodology developed by NASA for commercial aviation could be applied to the surface transportation risk assessment. As discussed in the following sections (much of which has been extracted from Reference 15) the application of the NASA commercial aviation methodology was not considered practical for the surface transportation assessment.

The assessment of the risks resulting from the release of carbon fibers from automobile fires was different from the previous risk assessment work regarding CF releases from commercial aircraft in several ways. For one thing, there are a great many more automobile accidents per year than commercial aircraft accidents. This difference allows some analysis that utilizes the statistics of large numbers. A second difference is that automobile accidents are likely to occur on any public road, which implies that automobile accidents are much more uniformly distributed geographically than commercial aircraft accidents. Perhaps the most significant difference is that automobile fire accidents result in relatively small amounts of carbon fiber releases. As a result, the failure probabilities for equipment located near the accident are very small.

The fact that the individual releases result in very small failure probabilities has several implications. If one assumes that each individual fiber or groups of fibers has a small but finite probability of causing a failure and that equipment failures obey an exponential probability law, then it follows that the release conditions, except for total amount of fibers released, are relatively unimportant. This is especially true in a situation where equipment is uniformly distributed. The reason for this is that the low probability situation can be approximated by a linear function of the amounts released. Independent treatment of the fibers or groups of fibers then results in a Poisson distribution for the number of failures. This distribution is generally applied to events for which there are a large number of probabilistic trials with a low probability of occurrence in each trial.

Another effect of the low probability of failure is that it makes a simulation of the risk difficult to implement, because the dominant contribution in determining the number of failures is the probabilistic nature of the individual failures (i.e., the Poisson variation) rather than variations due to accident locations and release conditions. As a result, any Monte Carlo simulation requires a very large number of trials in order to develop any confidence in the results. In addition, because automobile fires can occur all over the nation, a simulation would require a data collection effort that would be prohibitively costly.

As a result of these considerations, a method was developed that primarily analyzes the Poisson nature of failures and utilizes numerical calculations of probabilities rather than a Monte Carlo simulation. The analysis of equipment and facilities is performed on the county level. The actual probability calculations are based on mixtures of Poisson distributions that apply for each county, amount released, and equipment category combination. The validity of this approach is a crucial consideration for the risk assessment.

The basic elements in a risk assessment are as follows:

- Identification and characterization of the hazard. In this instance, the hazard is free airborne carbon fibers released from surface transportation. This step includes estimates of the quantity of carbon fiber used by surface transportation, the frequency and location of the release incidents, and the quantity and size distribution of the released fibers.

- Identification and characterization of the paths from the hazard source to the impact point. This step is not meaningful in every risk assessment task, but it is important in the carbon fiber problem. It includes the plume dynamics and meteorology which contribute to the transportation of the fiber from the point of release to the point of impact on an electrical or electronic system.
- Identification and characterization of the effects due to equipment exposure to the hazard. In this case, it is the exposure of electrical and electronic equipment to airborne carbon fibers. This step includes estimating the vulnerability of the equipment, the failure mode, the number exposed, and the cost of failure.
- The risk is the product of the hazard times the exposure. This is the final step in a risk assessment and produces the desired quantification of the negative impact.

The following sections provide a detailed discussion of the risk assessment.

5.1 DEMOGRAPHIC ANALYSIS OF VULNERABLE FACILITIES

The first step in the analysis was to represent the facilities considered to be potentially vulnerable by a demographic category such as households or the Standard Industrial Classification (SIC) code for business. For several other facility categories, indices were required where actual data on facilities were not available; e.g., population was used as a surrogate to measure the amount of police and fire protection services.

The transformation of facility categories from the economic analyses to demographic data categories involved some aggregation. The general manufacturing category included equipment classes identified in specific manufacturing environments which were taken as representative of the level of vulnerable equipment in all manufacturing plants.

Given the data categories for facilities, the amount of activity, in terms of pieces of equipment in each county, was determined from scaling factors. These scaling factors included number of employees in a SIC category, population, families, etc. For each facility surveyed for the economic analysis, the number of pieces of equipment and the value of the scaling factor for that facility were determined. From the survey, a factor could be developed such as one piece of equipment class x for every 1,000 employees in SIC category y. In this manner, the number of pieces of equipment in each category of vulnerable equipment in each facility category was determined.

For each category of equipment associated with the number of pieces are the mean dosage for failure, the transfer functions for outside to inside CF exposure, and the dollar cost per failure. The mean dosage for failure and the transfer functions were combined to develop the effective mean outside dosage $\bar{E}$ for failure. When there was a range of transfer functions depending on building characteristics, the arithmetic mean of the high and low transfer factors was used; this procedure results in a number which is in the same order of magnitude as the high end of the transfer function range, which is a consistently conservative assumption. Equipment categories which had equivalent $\bar{E}$ values and equivalent demographic data categories were combined for efficiency in computer processing. The dollar cost per failure of one piece of equipment was derived as the weighted average of the unit costs for each equipment category.

Given the estimate of the number of pieces of equipment of each category in each equipment type, the risk analysis procedure described in Figure 5-1 could be implemented, providing probabilities of equipment failure for each category. The risk profile for dollar losses was derived by combining these probabilities with the dollar loss per failure of equipment. These losses were taken as the sum of the equipment repair and facility disruption costs per failure of equipment. In theory, this procedure could overestimate losses if the expected number of pieces of equipment failing in a single facility were greater than one; in that case the facility disruption cost, which might not increase beyond the first equip-

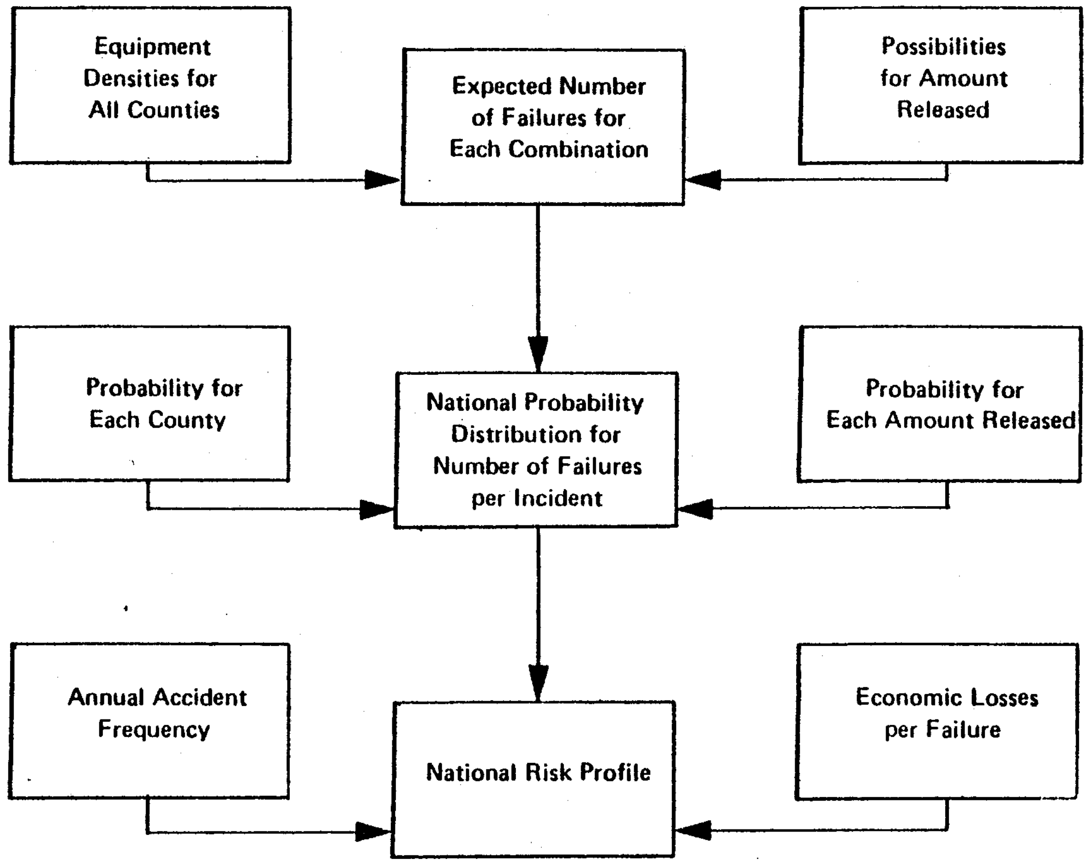


FIGURE 5-1. RISK ANALYSIS PROCEDURE

ment failure, would be overestimated. However, with the CF releases being very low relative to the $\overline{E}$'s, the expected number of equipment failures in one facility would always be lower than one.

5.2 DEVELOPMENT OF NATIONAL RISK

This section presents a summary of the risk assessment methodology and results. A more detailed discussion is contained in Reference 15. The risk analysis procedure is presented in Figure 5-1 and utilizes imputs from the previous sections of this report.

Most of the analytical details inherent in the methodology are presented in the appendices of Reference 15. However, there are some fundamental mathematical relationships that control the results and are presented herein. These relationships are discussed to emphasize their importance in the final analysis. A glossary of symbols used in the relationships discussed in this chapter is presented in Table 5-1.

The first key relationship is between λ, the expected number of equipment failures in an accident, and such parameters as the amount of carbon fibers released, the equipment vulnerability, and the density of facilities. For any given county and equipment class, the expected number of equipment failures per accident is proportional to the amount of carbon fibers released and the density of facilities, and is inversely proportional to the mean exposure to failure for the equipment. The actual computation of λ is done by summing up contributions from each county in the U.S. and from each equipment class.

The second set of relationships links the mean and standard deviation of the dollar loss in a single accident to the parameters of the distribution for the number of equipment failures in an accident. These relationships are based on standard formulae for conditional expectation, and they can be found, for example, in Parzen, E., Stochastic Processes, p. 55. The equations imply that the expected value of L, the total dollar loss in a single accident, is proportional to λ, the expected number of equipment failures in an accident, and that the variance of L has two terms, one which is

TABLE 5-1. GLOSSARY OF SYMBOLS

$\overline{E}$ = Mean outside exposure to failure

N_o = Number of equipment failures in an accident

L = Total dollar loss in a single accident

X_o = Dollar loss resulting from a single equipment failure

$\overline{L}$ = Total dollar loss annually for all accidents

M = Number of accidental failures involving CF nationally

λ = Expected value of N_o

E = Expectation

n = Dummy variable to denote number of events

X = Dummy variable for dollar loss

Var = Variance

$(X|n)$ = Variable X given dummy value n

Y = Dummy variable for dollar loss per accident proportional to λ and one which is proportional to the variance of the number of failures per accident.

The final set of important relationships links the statistics of the total annual dollar loss for all accidents to the statistics of the dollar loss in a single accident. These results are based on the same type of conditional expectation relationships referred to above. The expected value of the annual dollar loss is proportional to the number of accidents per year and the expected value of the dollar loss per accident. The variance of the dollar loss per year is approximately proportional to the variance of the dollar loss per accident and the expected number of accidents per year.

To convert the statistics of annual dollar loss into a distribution, some standard statistical methods are used. The results obtained and the outcome of a sensitivity analysis, are presented below.

5.2.1 Computation of Losses Per Incident

The computation of the dollar losses per automobile accident is performed in two separate steps. In the first step, a probability distribution of the number of failures (Section 5.1) contingent upon a single accident is calculated. In the second step, the statistics of the dollar losses (rather than the number of failures) are computed.

An analytic methodology was developed to compute the distribution of the number of failures contingent on a single fire accident. The methodology is based upon the fact that for a given county and equipment class, the number of failures is approximately Poisson distributed. This is due to the extremely low probability of equipment failure at the levels of exposure typically computed for automobile fires. Because the dominant variation in economic losses is due to the Poisson failure process, this methodology does not require detailed modelling of release conditions or accident locations. It can be shown that the expected number of failures per accident is directly proportional to the geographic density of equipment and the amount of fibers released and inversely proportional to the equipment's mean failure level, $\bar{E}$.

Implementation of the Poisson methodology required tabulation of data for approximately 3,000 counties in the United States, 81 equipment categories, and several possible release amounts. To handle these data, a computer model was developed and used to determine the distribution of failures contingent upon a single fire incident. Figure 5-1 describes the logical flow of the model and its extrapolation to the national level. The model tabulates a mixture of a large number of Poisson random variables. There is a separate random variable for each combination of county, equipment category and amounts released. The model adds up the probabilities of any number of failures given each of these possible combinations and weighs them by the appropriate conditional probability of that scenario. The result is the probability that, given an accident in some county, a given number of failures will occur. This distribution is presented in Table 5-2.

The next step in the analysis was to develop the distribution of dollar loss given an accident. The mean and variance of the dollar losses per accident depend on the statistics of the number of failures and of the dollar loss per failure. For example, if there were five equipment failures, then the expected value of the dollar losses in the accident would be five times the expected value of the dollar loss per accident, and the variance would be five times the variance of the dollar loss per accident.

The following equations are used to find the mean and variance of L, the total loss per accident.

$$\begin{aligned} EL &= (EX_0)\,(EN) \\ \text{Var } L &\simeq EN \text{ Var } X_0 + (EX_0)^2 \text{ Var } N. \end{aligned} \qquad (5\text{-}1)$$

The expectation equation simply states that the expectation of total dollar loss in an accident is equal to the number of failures times the dollar loss per failure. There are two terms in the variance expression. The first term represents the variability due to the dollar loss per failure distribution, while the second term represents the variability in the number of failures

TABLE 5-2. PROBABILITY DISTRIBUTION OF NUMBER OF FAILURES GIVEN AN ACCIDENT

Number of Failures	Probability
0	.99952
1	4.834×10^{-4}
2	1.496×10^{-6}
3	1.6×10^{-8}
>4	~0
Mean	$.4854 \times 10^{-3}$
Standard Deviation	.0222

per accident.

Although this methodology does not permit a determination of the precise distribution of dollar losses per accident, upper bounds were developed for these probabilities based on a standard result from probability theory. This result, which is known as the Chebyshev inequality, was used to determine upper bounds for the probability distribution of dollar losses per accident as well as upper bounds for the distribution of the dollar losses annually. The Chebyshev inequality (see, for example, Feller, Introduction to Probability Theory and Its Applications, Vol. ii, p. 151) states that:

$$\text{Prob } (L \geq EL + t\sigma(L)) \leq 1/t^2 .$$

Thus, the probability that the risk is more than 100 standard deviations above the mean is less than or equal to 10^{-4}. Utilizing the Chebyshev inequality, upper bounds were developed for the risk values and are shown in Table 5-3.

5.2.2 Derivation of National Loss Statistics

The next step in the analysis was to compute the national risk profile, which required only a knowledge of the mean and variance of dollar losses per accident. A two-step procedure was employed to derive the national risk profile. These steps consisted of:

- Computation of the mean and the variance of the national risk profile
- Estimation of a probability distribution based on statistical results.

The following conditional expectation equations were utilized to compute the mean and the variance of the national risk profile.

$$E(\overline{L}) = (EM)\ EL$$
$$Var(\overline{L}) = (EM)\ Var\ L + (Var\ M)\ (EL)^2$$

where

L = Dollar loss per accident

TABLE 5-3. RISK PARAMETERS FOR THE THREE SCENARIOS STUDIED AND SINGLE ACCIDENT CASE

	Mean Loss Per Accident	Expected Annual Loss	10^{-2}	10^{-4}	10^{-6}
Best Estimate	6¢	5,570	$56,250	$512,400	$5.075 million
Fiber Damage reduced 10 times	0.6¢	$557	$16,800	$161,000	$1.603 million
Worst Case Scenario	$16.30	$1.54 million	1.75 million	3.69 million	22 million
Single Accident	6¢	-	160	1,600	16,000

$\bar{L}$ = National dollar loss

M = Number of accidental fires with CF nationally

EM = Expected value of M

EL = Expected value of L.

There are approximately 310,000 fire accidents (automobiles and trucks) annually. Since 67 percent of these result in no release, there are 33.% x 310,000 = 102,000 fire accidents per year resulting in a loss of carbon fibers. Assuming that the number of accidents per year M is a Poisson random variable, then EM = 102,000, Var M = 102,000, and hence, $E\bar{L}$ = \$5,570 and $\sigma_{\bar{L}}$ = \$5,070. These statistics are summaried in Table 5-3.

The number of accidents annually is a very large number, and as a result of the statistics of large numbers, the standard deviation of the national risk is quite small. In addition, because the dollar loss on an annual national basis is the sum of losses for so many accidents, one can apply the central limit theorem and can conclude that the distribution of annual dollar loss is approximately normal. It is therefore concluded, that the annual dollar loss is very close to its expectation.

The only part of the distribution where a normal approximation may not be accurate is in the "tail" of the distribution corresponding to the high dollar losses. Since each of the individual dollar loss distributions are extremely skewed with mass in the far tail, then the annual risk profile may show a tail that diverges moderately from the tail for the corresponding normal distribution. It is uncertain exactly where the tail of the annual risk profile lies. However, we can again derive an upper bound for this tail based on the Chebyshev inequality. These results are presented in Table 5-3. The national risk profile is depicted graphically in Figure 5-2, incorporating the Chebyshev bounds for losses in excess of \$50,000.

5.3 SENSITIVITY ANALYSIS

Next, the sensitivity of the national risk profile to input

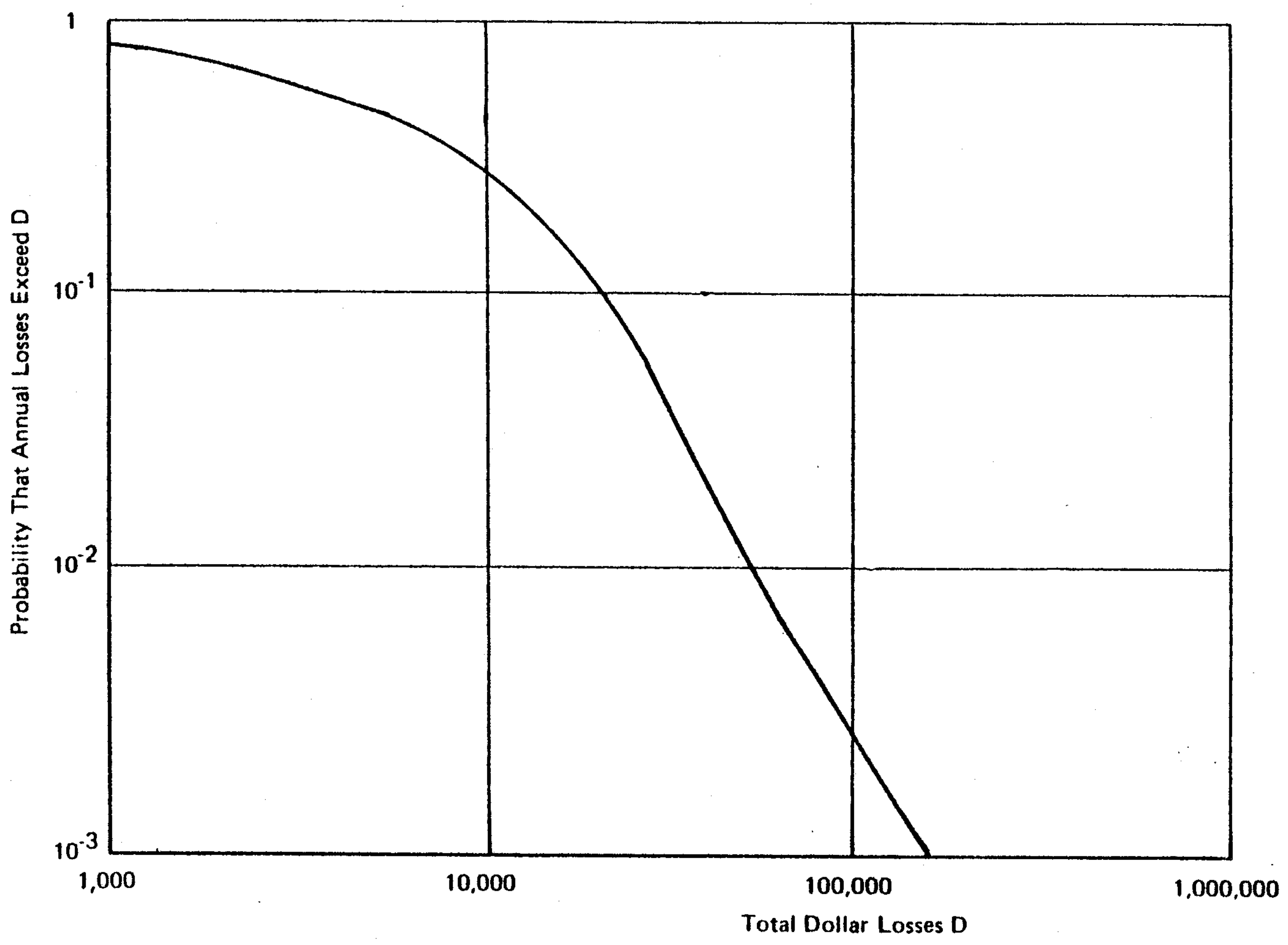


FIGURE 5-2. NATIONAL RISK PROFILE FOR MOTOR VEHICLES (1993)
(Including Upper Bounds for High Loss Probabilities)

assumptions was examined. Some of these sensitivities could be hand calculated without any additional computer runs. The reason for this is that the number of failures per accident is a Poisson random variable. Hence the expected value and variance for the number of failures are approximately λ and from Equations (5-1), the expected loss per accident is:

$$\lambda \, E \, X_o \; .$$

The variance of loss per accident is approximately equal to:

$$\lambda (E \, X_o{}^2 + \mathrm{Var} \, X_o) \; .$$

As an example of a sensitivity analysis using these equations, suppose that the CF amounts released in an accident decrease by a factor of 10. In this case the expected numbers of failures for the various equipment classes would all decrease by a factor of 10, while the conditional probability of dollar loss given a single failure would remain the same. As a result we can make the following calculations for the loss statistics. Note that the expected national loss has decreased by a factor of 10, to $557.

$$\lambda = .4854 \times 10^{-4}$$

$$EL = .0059$$

$$\sigma_L = 5.2$$

$$E\bar{L} = 557$$

$$\sigma_{\bar{L}} = 1602 \; .$$

The Chebyshev inequality results are tabulated in Table 5-3.

The sensitivity was also examined for a scenario which represents an extreme worst case. We analyzed a situation where the amounts released were increased by a factor of 10 and the $\bar{E}$ values for the various categories were, on average, decreased by a factor of 40. In determining the $\bar{E}$ values for this worst-case scenario, it should be noted that there is a great deal of uncertainty in estimating failure levels for electronic equipment. This was the rationale for allowing individual $\bar{E}$ values for the various categories to vary up to two orders of magnitude. The dominant equipment category in this scenario was household goods and the $\overline{E}$ for household goods was decreased by two orders of magnitude. In the resulting computer analysis, household goods resulted in 95% of the failures. The relevant summary statistics and probabilities are presented in Table 5-3; the expected national annual loss increased to $1.54 million. As before, upper bounds were computed for high loss probabilities.

5.4 SUMMARY DISCUSSION OF RESULTS

The first step in the risk analysis number was to project the number of equipment failures (Section 5.1), given that an accident occurred somewhere in the U.S. and released some quantity of carbon fibers. The expected number of failures per release incident was extremely small, resulting in an expected dollar loss per incident of only 6 cents, with a standard deviation of $16.50. The probability of an accident resulting in losses exceeding $1,600 was estimated to be at most one in ten thousand. Then based on an estimated 102,000 fire accidents per year which could potentially release CF, it was found that by 1993 the expected annual loss to the nation as a whole was $5,570, with a standard deviation of $5,070. The probability that the national loss will exceed $512,000 was estimated to be at most one in ten thousand.

The sensitivity of these results to several input parameters was explored. The key parameter affecting the national risk is the amount of carbon fiber which could potentially be released in an accident. For example, decreasing the CF release quantities by a factor of 10 was found to decrease the national risk by about a factor of 10, to $557. Conversely, increasing the CF released by a factor of 10 would increase the expected national risk to about $56,000. To investigate an extremely conservative "worst case" scenario, a sensitivity run was performed with the CF release increased by a factor of 10, and with the mean exposure to failure of household equipment decreased by a factor of 100 (making it more vulnerable). In this case, the national risk was found to have an expected value of $1.54 million per year. The chances of the national losses exceeding $3.7 million were estimated at one in ten thousand for this scenario.

6. CONCLUSIONS

6.1 THE VULNERABILITY OF SURFACE TRANSPORTATION

Electrical and electronic equipment utilized in the surface transportation system is subjected to a hostile environment. Dirt, metal filings, humidity, salt spray, general debris and vandalism are some of the elements that make up the harsh surface transportation environment in which the equipment is designed to operate. Because of these elements and general transit operations, these electrical and electronic systems are designed to continue to operate with subsystem failures and when the total system finally fails, it fails in a safe mode.

All of these circumstances combine to provide surface transportation an enormous capacity to resist the CF hazard. The vulnerability of surface transportation to the CF hazard is very low and should not cause the transportation industry any special problem at the projected level of use during the 1990's.

6.2 THE NATIONAL RISK FROM CF IN SURFACE TRANSPORTATION

The results of the risk analysis indicate that the potential risks of economic losses due to CF releases from accidental fires in motor vehicles are relatively small. The expected national risk was estimated to be only about $5,600 per year for 1993, with the average loss per incident being on the order of a few cents. Furthermore, due to the high number of accidental fires per year, the national risk estimate is not subject to much variation. For example the probability of exceeding $56,000 loss in one year was estimated to be about 1/100 (see Section 5.2.1). Although the possible consequences of a single fire can vary greatly, depending upon whether equipment failures do occur, the likelihood of such a failure is only 5×10^{-4} per incident.

It should be noted, however, that the risk estimates are subject to uncertainty from a number of different sources. The assumptions or uncertainties incorporated into the analysis are discussed below. Even when sensitivity analyses were performed to test the effect of these assumptions, the risks were found to be reasonably low in comparison to other types of risks. For example, the annual losses due to motor vehicle accidents are on the order of twenty billion dollars[4], whereas the likelihood of exceeding $4 million due to CF releases in motor vehicle fires in any one year is only 10^{-4} even in the worst-case fiber release scenario.

6.3 SUMMARY OF UNCERTAINTIES

The uncertainties in the national risk estimate may be analyzed by considering the different data inputs incorporated into the model. The chief areas of uncertainty are the fraction of fibers released and the vulnerability levels of electronic equipment. However, even the most conservative scenarios in our sensitivity analyses indicate that the overall national risk is low. Some of the major areas of uncertainty are discussed below.

- Carbon fiber usage -- The projected usage could conceivably vary by a factor of 2 or 3 in terms of CF weight per auto. However, such variations are taken into account in the sensitivity analysis by varying the fraction of CF released given an accidental fire.
- Number of fibers by weight -- The present report assumes that there are 10^9 single fibers per kilogram of CF available for release, based on previous NASA estimates. Although this number could be as much as five times greater (with smaller fiber lengths), the uncertainty is again accounted for by varying the fraction of CF released.
- Fraction of CF released -- Recent tests results[11] indicate that the 1 percent figure used in our base analysis is extremely conservative, and that it is possible that no more than 0.1 percent of single fibers by weight would be released. Hence, the worst-case scenario, in which fiber releases were increased by an order of magnitude to 10 percent, can be considered an extreme upper bound on the true risk.

- Accident probability -- The extrapolation of Michigan data could result in about a 50 percent error in estimating the national accidental rate of fire in motor vehicles. Also, the number of cars carrying CF was assumed to be 57 percent of the fleet. The net uncertainty due to these sources might increase the total number of fires per year involving CF by a factor of about 3, which would directly multiply the expected annual national risk for 1993 of $56,000 by 3. This effect is small compared to some of the other uncertainties in the analysis.
- Equipment vulnerability -- The estimated mean failure levels could vary by several orders of magnitude, but this possibility was addressed in the high-risk scenario described in Section 5. The expected annual losses in this case, also assuming a ten-fold increase in CF release, were about $1.5 million for 1993.
- Economic losses -- The estimates of losses per equipment failure are subject to variations between facilities and regions, but this will contribute negligibly to the overall uncertainty.
- Reentrainment -- The assessment presumes that the CF stops at its first point of impact and is not reentrained in the atmosphere. If this is not the case and the environment begins to become contaminated with CF, then the risk could be many times greater. At present this increase in risk can not be estimated.
- Disposal -- The only CF source considered was that released from vehicle fires which occurred during the normal service life of the vehicle. If vehicle disposal is not controlled to limit the release of CF during that operation, the risk could increase several orders of magnitude.

In summary, the sensitivity analysis indicates that the national risk could vary from less than a thousand dollars to several million dollars per year with the "best estimate" expected annual loss for 1993 estimated at $5,600. Given this level of risk, even in the upper-bound scenario, it is clear that the risk is quite small compared to the approximately twenty billion dollars lost annually in automobile accidents without CF composites.

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APPENDIX A - TEST SAMPLE COMPOSITION

HITCO
GARDENA, CALIFORNIA
CUSTOMER NASA/Ames
ORDER NO. A67290B EAF
PART NO. Crossplied UMC-8057/790
PART NAME Vinyl Ester/Graphite
HITCO S/O NO. Glass Hybrid

Test Number(s) 3, 11, 12, 14

Vinyl Ester/Graphite/Glass Hybrid - Crossplied

Dow Chemical - Derekane 790	25%/wt
Hercules-AS-5 Graphite - Crossplied	30%/wt
Owens Corning or Pittsburgh Corning E Glass	45%/wt

Cure

(a) 300° F. - 1 hr - 300 psi

(b) No Post Cure

Layup Sequence

Graphite/Glass/Graphite/Glass/Glass/Graphite/Glass/Graphite

HITCO
GARDENA, CALIFORNIA
CUSTOMER NASA/Ames
ORDER NO. W.O. 9353
PART NO. Experimental UMC
PART NAME Polyester/Graphite/
HITCO S/O NO. Glass Hybrid

Test Number(s) 4

Polyester/Graphite/Glass Hybrid - Unidirectional

Great Lakes Carbon Graphite - H-40	30%/wt
U.S.S Chemical Co. #14029	25%/wt
Owens Corning or Pittsburgh Corning E glass	45%/wt

Cure

(a) 375°F - 2 hrs - 200 psi

(b) No Post Cure

Layup Sequence

0 90 90 0

Graphite/Glass/Graphite/Glass/Glass/Graphite/Glass/Graphite

HITCO

GARDENA, CALIFORNIA

CUSTOMER NASA/Ames
ORDER NO. A67290B EAF
PART NO. Unidirect. AS-5/14029
PART NAME Polyester/Graphite
HITCO S/O NO. 144450 Item 010

Test Number(s) 5

Polyester - Graphite - Unidirectional

U.S.S. Chemical Co. #14029	40%
Hercules AS-5 Graphite	60%

Cure

(a) 300° F. - 1 hr - 300 psi

(b) No post cure

HITCO

GARDENA, CALIFORNIA

CUSTOMER NASA/Ames
ORDER NO. A67290B EAF
PART NO. Unidirect. 5208/T300
PART NAME Epoxy/Graphite
HITCO S/O NO. None

Test Number(s) 6, 8

Epoxy - Graphite - Unidirectional

Narmco Company Resin # 5208	40%/wt
Union Carbide - Thornal # 300	60%/wt

Cure (Amine cured)

(a) 355° F. - 2 hrs - 100 psi

(b) Post Cure - 400° F. - 4 hrs

HITCO
GARDENA, CALIFORNIA
CUSTOMER NASA/Ames
ORDER NO. W.O. 9353
PART NO. Experimental Compound
PART NAME Polyester/Graphite
HITCO S/O NO. Unidirectional

Test Number(s) 7

Polyester - Graphite - Unidirectional

Great Lakes Carbon Graphite H-40 & Hercules Thornall # 300	60%/wt
U.S.S. Chemical Company #14029	40%/wt

Cure

(a) 375°F - 2 hr - 200 psi
300°F - 1 hr - 300 psi

(b) No Post Cure

Layup Sequence

3 Thornal/2 H-40/4 Thornal/2 H-40/3 Thornal

HITCO
GARDENA, CALIFORNIA

CUSTOMER NASA/Ames
ORDER NO. A67290B EAF
PART NO. Crossplied UMC 8057
PART NAME Polyester/Graphite/
HITCO S/O NO. Glass Hybrid

Test Number(s) 9, 10

Polyester Graphite/Glass Hybrid - Crossplied

U.S.S. Chemical Company #14029	25%
Hercules AS-5 Graphite - Crossplied	30%
Owens Corning or Pittsburgh Corning E Glass	45%

Cure

(a) 300° F. - 1 hr - 300 psi

(b) No post cure

Layup Sequence

Graphite/Glass/Graphite/Glass/Glass/Graphite/Glass/Graphite

HITCO
GARDENA, CALIFORNIA

CUSTOMER NASA/Ames
ORDER NO. Work Order 9353
PART NO. Unidirectional UMC-8057
PART NAME Polyester/Graphite/
HITCO S/O NO. Glass Hybrid

Test Number(s) 13, 16, 17, 18, 19

Polyester - Graphite/Glass Hybrid - Unidirectional

U.S.S. Chemical Co. #14029	25%
Hercules AS-5 Graphite - Unidirectional	30%
Owens Corning or Pittsburgh Corning E Glass	45%

Cure

(a) 300° F. - 1 hr - 300 psi

(b) No post cure

Layup Sequence

Graphite/Glass/Graphite/Glass/Glass/Graphite/Glass/Graphite

HITCO

GARDENA, CALIFORNIA

CUSTOMER NASA/Ames
ORDER NO. Work Order 9353
PART NO. Unidir.UMC-8057/Dow 790
PART NAME Vinyl Ester/Graphite/
HITCO S/O NO. Glass Hybrid

Test Number(s) 15

Vinyl Ester - Graphite/Glass Hybrid - Unidirectional

Dow Chemical - Derekane 790	25%/wt
Hercules AS-5 Graphite	30%/wt
Owens Corning or Pittsburgh Corning E Glass	45%/wt

Cure

(a) 300° F. - 1 hr - 300 psi

(b) No post cure

Layup Sequence

Graphite/Glass/Graphite/Glass/Glass/Graphite/Glass/Graphite