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Assessment of Bart Fire-Hardening Programs

W.T. Hathaway
I. Litant

November 1982
Final Report

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Urban Mass Transportation Administration

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This report presents the results of an assessment of the Bay Area Rapid Transit District (BART) vehicle fire hardening. The assessment was conducted for the Urban Mass Transportation Administration Office of Safety and Security in response to a request to the Associate Administrator for Technical Assistance from the UMTA Region IX Administrator.

The report assesses the overall effort to improve the fire safety of the current BART vehicles through the removal of prospective ignition sources, the substitution of more fire-resistant materials, the addition of a special fire-resistant coating on the under surface of the vehicle floor, and the placement of fire stops at strategic places in the walls and ceilings. Specifically, it responds to ten concerns on these improvements that were expressed by the California Public Utilities Commission.

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Conclusions and recommendations pertaining to the fire-hardening program are presented in this report. The authors point out that the fire-hardening program will not eliminate fire and smoke incidents, but it will minimize the effect of such incidents. It is recommended that BART implement the proposed program as soon as it is practical to do so.

17. Key Words
BART; Fire-Hardening Program; Fire Safety; Safety and Security; Smoke

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PREFACE

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The report assesses the overall effort to improve the fire safety of the current BART vehicles through the removal of prospective ignition sources, the substitution of more fire-resistant materials, the addition of a special fire-resistant coating on the under surface of the vehicle floor, and the placement of fire stops at strategic places in the walls and ceilings. Specifically, it responds to ten concerns on these improvements that were expressed by the California Public Utilities Commission.

The authors wish to thank Lloyd G. Murphy and George R. Grainger of UMTA for their guidance of this project and Victor R. Weisser, Alex E. Lutkus and Haji M. Jameel of the California PUC for their guidance and helpful comments on the review draft and the BART safety staff for their cooperation in providing the information. The authors also wish to express their appreciation to Dr. Alfred E. Barrington and Earl C. Klaubert of the TSC staff for their contributions in the preparation of this assessment.

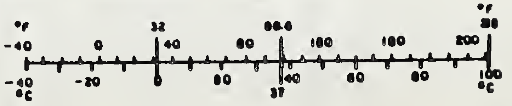
METRIC CONVERSION FACTORS

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. INTRODUCTION

On February 4, 1982, the Urban Mass Transportation Administration (UMTA) Region-IX Administrator requested that the UMTA Associate Administrator for Technical Assistance provide, through the Transportation Systems Center (TSC), technical support to assess the Bay Area Rapid Transit District's (BART) fire-hardening program and address the concerns expressed by the staff of the California Public Utilities Commission (PUC). This document presents the results of TSC's assessment of BART's fire-hardening program. The fire-hardening program was initiated in response to PUC Decision No. 90144,[1] April 4, 1979. This required that BART implement the following two measures.

> "(1) Within 90 days, BART should submit to this Commission a schedule for speedy elimination of polyurethane materials from the passenger seats in BART cars. That schedule should provide for full implementation within 270 days;
>
> (2) Within 180 days, BART should submit to this Commission recommended actions and a proposed timetable for reducing the fire risks associated with the fiberglass reinforced plastic materials used in the floors, ceilings, and side-wall linings of BART cars. The timetable should provide for the reduction of fire hazard from these sources in at least 20% of the BART cars operating in the transbay tube and Berkeley Hills Tunnel by not later than one year from the date of this order so that each such train offers a relatively safer section for possible removal of passengers in the event of emergency."

In response, BART prepared a "Fire Hardening Program Plan."

TSC's assessment was initiated at a meeting on April 15, 1982, between representatives of UMTA, PUC, and TSC, held at the PUC. At this meeting the scope of the assessment was defined as being limited to the vehicle fire-hardening modifications and to their interface with the vehicle evacuation scheme. To assist in this assessment, TSC assembled a review team consisting of in-house experts in specific areas, and also contracted with the Factory Mutual Research Corporation (FMRC) and the Federal Aviation Administration's Civil Aeromedical Institute (CAMI).

The support from FMRC, as outlined in the Statement of Work in Appendix A, is directed at evaluating the test data and subsequent conclusions concerning BART, based on the test data. The CAMI support, outlined in the Statement of Work, also in Appendix A, is directed at evaluating how the BART program has addressed the toxicity threat posed by the vehicle materials. The results of each of these support efforts are summarized in the section addressing the specific PUC staff concerns. The reports from FMRC and CAMI are contained in Appendix B.

2. OVERVIEW OF BART FIRE-HARDENING PROGRAM

Since its initiation, the BART fire-hardening program has been presented and discussed in several reports. References 2, 3 and 4 present the most recent and comprehensive views of the program. As such, these reports, along with other pertinent reports (e.g., the National Bureau of Standards report NBSIR 78-1421) test data, film of the full scale fire test, and vehicle operating experience were reviewed in TSC's assessment. Reference 2 identified the following ten vehicle modifications which are in progress:

1. Modification of the current collector shoe
2. Installation of current collector cable support bracket
3. Modification of the evaporator-box heater bracket
4. Grounding of torpedo air tanks
5. Modification of the dynamic brake grid logic
6. Modification of the evaporator box cover
7. Installation of a shield and cover for the R-5 resistor
8. Installation of a heat shield over the dynamic brake grid
9. Identification of the proper fuse type and rating
10. Replacement of the polyurethane seat cushions.

Also identified and discussed in Reference 2 are five other actions which BART recommends be implemented:

1. Coating of the undercar floor area with a thermal barrier.
2. Replacement of the polyurethane foam at the vehicle floor-to-wall junctions.
3. Replacement of the vehicle wall and ceiling liners.
4. Insertion of fire stops in the vehicle wall and roof.

5. Spraying of the inside of the vehicle roof section with intumescent paint.

Finally in Reference 2, BART identifies six additional materials-related items but does not recommend their replacement.

1. Replacement of vehicle roof sections
2. Replacement of elastomeric foam insulation
3. Replacement of arm rests
4. Replacement of the seat backs
5. Replacement of windscreens
6. Replacement of the vinyl side trim of the seats.

Five of these six items have been identified by the PUC staff as a concern and will be addressed in the next section.

All twenty-one of these elements of the fire-hardening program, are discussed in Reference 2 and as such will not be discussed further in this section, but addressed later in the report. The methodology which BART has utilized to identify and evaluate the fire-hardening elements is also presented in Reference 2. Included in this methodology is a discussion of BART's decision tree, fire chain and those scenarios which BART has employed in their program.

Reference 3 presents the results of the full scale fire-test program conducted for the BART by the McDonnell Douglas Corporation. This program consisted of a series of eight tests intended to evaluate the recommended vehicle fire-hardening improvements. Reference 4 is an analysis of the fire-hardening program, and was performed for BART by the Fire Test Laboratory of the University of California, Berkeley. It is primarily directed at the vehicle floor system and the vehicle liner materials. An additional earlier report,[5] also prepared by the Fire Test Laboratory, presents a series of room fire tests, used to screen the prospective materials for use in the full-scale fire test.

Bearing in mind the purpose of TSC's effort, which is to assess the fire-hardening program and to address the concerns expressed by PUC's staff, we have refrained from critiqueing specific report areas, items, or methods. Our prime concern has been to determine whether the conclusions that BART has drawn from the efforts of their in-house staff and of their contractors have been reasonable and will enhance vehicle safety.

3. CONCERNS OF PUBLIC UTILITIES COMMISSION STAFF

The PUC staff has, since the initiation of the fire-hardening program, worked with BART to address and investigate the fire threat in the BART vehicles. At present BART is preparing to implement the recommended fire-hardening modifications developed from this program. Prior to PUC approval of implementation of these recommendations the staff identified ten areas and items of concern which should be addressed. This section addresses these ten concerns.

3.1 CONCERN NO. 1 - COMPLIANCE WITH THE PUBLIC UTILITIES COMMISSION DECISION 90144

Does BART's proposed program indeed reduce the fire hazards of BART vehicles as intended by Commission order in Decision 90144?

3.1.1 Assessment of Compliance with Commission Decision 90144

The Commission Decision ordered BART to reduce "the fire risks associated with fiberglass reinforced plastic materials used in the floors, ceilings, and sidewall lining of BART cars".

The BART fire-hardening program addresses the fire risk through the removal of identified ignition sources, the replacement of vehicle materials, and the installation of fire stops (wall and floor-to-sidewall junction) to contain the fire. It is our opinion that BART's proposed program does indeed reduce the fire hazards of the BART vehicles.

We are not able to make a precise,quantitative determination, but believe that BART has made a significant improvement by replacing various materials. The original materials which were present in large quantities, have been shown to be highly flammable and/or to produce large quantities of smoke. Standard ASTM tests indicate that the replacement materials have significantly lower levels of flammability and smoke emissions.

3.2 CONCERN NO. 2 - MATERIALS SELECTION

Do the test data and analysis presented support the following:

- a. replacement of wall liners with a combination of phenolic and improved polyester;
- b. replacement of ceiling liner;
- c. spray of intumescent paint in the ceiling areas;
- d. use of Thermolag coating for the undercar floor areas;
- e. installation and location of fire stops in the interior wall liner cavities;
- f. not to replace miscellaneous flammable interior furnishings, such as vinyl trim, arm rests, Kydex ducting, Kydex seat backing and insulation material.

3.2.1 Assessment of Materials Selection

The following assessment of the materials selection is based on the TSC and FMRC analysis of the test data. In several instances where the decision to implement or not implement a fire-hardening action could not be based on the test data, it became a matter of judgement. Where the need for judgement was required, scenarios were constructed to assist in the decision making process.

a. Replacement of wall liners.

The test data does support the replacement of the present wall liners with the phenolic and improved polyester wall liners. It is apparent from the full scale tests that the phenolic liners did not propagate the fire but served to contain it at the site of origin. The laboratory test data obtained using standard ASTM tests, shows that phenolics[6] typically have a flame spread index (I_s) of 1-2 and an optical smoke density (D_s) at 4 minutes of 1.0 while the original wall liners have an I_s of 73 and a D_s at 4 minutes of 604. The Envirez polyester[6] liners have a flame spread index (I_s) of 15.3 and an optical smoke density (D_s) at 4 minutes of 90.5. This replacement will result in a significant improvement in the fire characteristics of the vehicle interior.

b. Replacement of ceiling liners.

As with the wall liners the test data also support the replacement of the ceiling liners. As noted later in Section 3.8, the ceiling liner will serve to provide protection for the polyurethane foam in the roof. An important consideration is that the reduction in the flammability and smoke emission characteristics of the wall and ceiling liner will serve to negate the efforts of an arsonist and assist the fire service should an arsonist start a large trash fire in the vehicle. Although in this scenario the passengers and train crew would not be at risk since the arsonist would probably be alone in the vehicle (or the limited number of passengers could exit with him). The use of these improved materials could prevent extensive damage to the vehicle itself.

c. Intumescent paint on the interior of the roof.

The benefit of having the intumescent paint on the roof interior is questionable. This paint was not present in the tests conducted and hence the test results cannot assist in determining whether to implement this fire-hardening action. We do know the ceiling liner will provide much more protection and feel that the paint will add little to the protection of vehicle.

d. Thermolag coating on the undercar floor.

The test data definitely support the use of the Thermolag coating on the undercar floor. As discussed in Section 3.4 this material provided protection such that the floor was capable of withstanding for fifteen minutes, a test 5.5 percent more severe than the standard ASTM E-119 flooring test.

e. Installation of fire stops.

Unfortunately the fire stops were not installed for the full scale tests at McDonnell Douglas and could therefore not be evaluated for their effectiveness. We believe that the installation of the fire stops is an important element of the fire-hardening program and will serve to contain a fire. To be effective, the fire stops must be properly located and installed so that they will provide an adequate seal. Fire stops should be located in the sidewalls at the window sill height and in the roof cavity at intervals along the car.

f. Miscellaneous materials replacement.

The available test data is not sufficiently comprehensive to serve as the basis for a decision as to whether to replace these materials.

Vinyl Trim and Arm rest.

Materials such as the vinyl trim and arm rests were involved in the fire tests but did not result in any large scale propagation of the fire from the area of origin. An important consideration in determining the need to replace these materials is when and how they would be involved in a fire. There are two basic scenarios in which the arm rest and vinyl trim become involved in a fire: 1) a fire which has propagated into the vehicle from under the car or the side wall plenum and has come through the sidewall liner (the equipment modifications under the car should minimize the occurrence of a fire of this magnitude) and 2) a fire (most probably of arson) in the occupant compartment.

In the first scenario, by the time the fire has grown sufficiently to propagate through the sidewall and ignite the arm rest next to the wall, the fire will be of sufficient magnitude that one or two arm rests involved will not be a major problem.

In the second scenario a localized fire such as the arson fires already discussed, will only involve one arm rest. As past BART experience has shown, this arm rest will not be the first material ignited but will ignite from some other material or accelerant. The arsonist not wanting to be apprehended will work in an empty vehicle and will exit the vehicle before the fire progresses too far. If there are other passengers in the vehicle, they can either leave the vehicle by the same route as the arsonist or they may notify the train operator via the intercom and possibly even extinguish the fire, as has occurred. It does not therefore appear that replacement of the arm rest will significantly affect the vehicle fire safety.

Kydex ducting.

The test data shows that the Kydex ducting burned or melted and fell away from the vehicle underside in the first undercar fire test. This test as discussed in Section 3.4, was more severe than the ASTM E-119 test applied for a fifteen-minute time period. Under this heat flux it is not realistic to expect this or any plastic ducting to be able to withstand such a fire environment. As discussed in Section 3.6.1, the options available for addressing the smoke emission associated with the Kydex ducting are limited. The removal of prospective ignition sources, as identified in the fire hardening program, appears the most efficient option for addressing this concern on the Kydex ducting.

Kydex Seat backing.

The Kydex seat backing material was involved in two tests: Arson Test Number 1, in which a trash bag was placed on the floor under a seat, and ignited and Test Number 8 the floor burn-through test. In both tests the Kydex material was involved in the fire but was not completely consumed. The fact that it was not consumed can be attributed to, among other things, its low flame spread index (I_s) of 14.6.

The scenarios under which the Kydex seat backing material will become involved in a fire are the same as those of the arm rest and vinyl trim. In like manner, we do not feel that the replacement of this material will result in a significant effect on the vehicle fire safety.

Insulation Material.

The Armaflex insulation material contained in the cavity between the vehicle's aluminum shell and the sidewall liner was involved only in the two arson tests. Even here, its involvement was limited as it did not appear to propagate the fire. Armaflex has a low flame spread index (I_s=13) with a specific optical density of 402 at 3 minutes. The two main scenarios by which the Armaflex can become involved are the same as those of the arm rest, except that the exterior fire need not burn through the sidewall. As with the seat backing, replacement of this insulation material will not significantly affect the fire safety.

3.3 CONCERN NO. 3 - FIRE CHAIN CONCEPT

In BART's proposed program, the fire chain concept was used to arrive at various fire-hardening modifications.

a. Determine whether or not this philosophy is valid.

b. Determine if the fire-hardening modifications arrived at, using this concept, are appropriate and would indeed reduce flame spread and fire hazards of BART's vehicles.

3.3.1 Assessment of Fire Chain Concept

The application of the fire chain concept employed by BART in the fire-hardening program is, as stated by Dr. Tewarson of Factory Mutual Research "a proper approach to use in determining the various fire-hardening modifications".

BART utilized this fire chain concept to identify and evaluate several of their fire-hardening actions. Their presentation of the chain showed four basic links or elements; 1) ignition, 2) penetration, 3) propagation and 4) flashover. With this approach, the BART fire-hardening program has identified equipment modifications to reduce the ignition sources, materials to enhance the resistance to penetration into the vehicle and improved materials to minimize propagation of the fire.

The elimination or even the reduction in flammability of the major links must necessarily reduce the rate of spread of a fire, thus performing in the manner of a fire block. As an example the two major contributors to rapid fire spread in the interior of the vehicle were the polyurethane seat cushions and the polyester wall and ceiling panels. The replacement of both with materials of significantly lower fire characteristics (ignitibility, flame spread, and smoke emission), will therefore act as impedances in the fire chain.

3.4 CONCERN NO. 4 - DESIGN BASIS CURVE

UMTA guidelines for flammability and smoke emission specifications for vehicle materials recommend the ASTM-E119 time vs. temperature curve. In BART's proposed program, an alternate time vs. temperature curve (Design Basis Time vs. Temperature Curve) was developed and used for undercar floor testing.

a. Is BART's alternative time vs. temperature curve a valid approach or should BART have followed the ASTM-E119 test, as recommended by UMTA?

b. What parameters and environmental conditions should be looked at in the development of the Design Basis Time vs. Temperature Curve?

c. Evaluate whether or not BART considered these factors in the development of its Design Basis Time vs. Temperature Curve.

d. Determine if the Design Basis Time vs. Temperature Curve was appropriately used in BART's tests (both full-scale test at McDonnell Douglas and furnace tests at U.C. Berkeley).

3.4.1 Assessment of Design Basis Curve

In assessing the design basis curve (DBC) and its application to the BART vehicle, its construction was first examined. The Design Basis Curve (DBC) was developed at the University of California (Berkeley) by Professor R.B. Williamson and it represents a Time vs. Temperature Curve based on an experiment performed at Berkeley.

In the experiment to establish the DBC, the test specimen simulated a 6-foot wide transverse flooring section of a BART car. Nine "fast response" thermocouples were distributed about the underside and upper surfaces of the test specimen. The fuel load consisted of parts of various undercar components such as battery box cover, ducting, Armaflex insulation, urethane board stock and miscellaneous cables and brackets. A total material weight of 168.48 lbs was used, of which 61.48 lbs. were consumed. The ignition source was a burner, producing about 4,000 BTU/min. and operated for a period of 2 minutes and 8 seconds.

The development of this Design Basis Curve was based on Williamson's best judgment, and was used for the evaluation of the specific BART undercar retrofit design.

In comparison to the DBC the ASTM E-119 standard test procedure is the preferred method of evaluating flooring and is so specified in the UMTA proposed "Recommended Fire Safety Practices for Transit Materials Selection". The ASTM E-119 Standard Test Method was selected by UMTA because of its long-time use as a means of determining fire penetration of flooring. This standard test procedure is intended to evaluate the duration for which the types of assemblies indicated will contain a fire, or retain their structural integrity, or exhibit both properties dependent upon the type of assembly involved, during a predetermined test exposure. Meeting its criteria for a nominal 15-minute period is intended to cover the various unknown factors that are inherent in the design of any new product.

The ASTM E-119 Time vs. Temperature Curve is such that the points on the curve are:

Time (min)	Temp. (°F)
5	1000
10	1300
15	1399

The temperature fixed by the curve is the average temperature obtained from the readings of not less than 9 thermocouples. There are two basic conditions of acceptance which are as follows:

1. The partition shall have withstood the fire endurance test without passage of flame or gases hot enough to ignite cotton waste for a period equal to that for which classification is desired.

2. Transmission of heat through the partition during the fire endurance test shall not have been such as to raise the temperature of its unexposed surface more than 250°F (130°C) above its initial temperature.

The best means of determining the usefulness of the DBC in the particular case of the BART vehicle is to evaluate the results of the various tests conducted by both Williamson[4] and McDonnell Douglas[3] in which the DBC time vs. temperature protocol was employed.

The most significant test was probably the one performed by McDonnell Douglas on December 17, 1980 (Test No. 7) In this large-scale test on a vehicle, a coating of Thermolag was applied to the under floor area, and the polyurethane filler at the junction of the floor and side wall was replaced with silicone foam. The DBC was simulated using a propane burner. The locations of the thermocouples are shown in Figure 3-1.

As shown in Figure 3-2, the average readings of thermocouples 20, 24, and 28 (the latter was stationed directly above the burner), are given and compared to the previously established DBC. The individual thermocouple readings are shown in Figure 3-3 (channels 20 and 24 were incorrectly transposed in this figure). It is apparent that the DBC was unintentionally exceeded throughout the test. Thermocouple 24 reached a maximum temperature of about 1750°F which is considerably higher than the maximum for the ASTM E-119 standard test. Figure 3-2 shows the higher and continuous total heat flux that was received by the under surface of the car over the 32 minutes of the test.

Figure 3-4 has had superimposed on it, the actual average ASTM E-119 furnace temperature "fast response" thermocouple curve taken from the February 5, 1981 test run at Berkeley and shown in Figure 3-5. This test was also made on a Thermolag and silicone-protected undersurface of a floor.

Integration of the area under the curve in Figure 3.2, for the first 22.5 minutes (common to both tests), shows that the total heat flux of the actual DBC run at McDonnell Douglas was about 50% greater

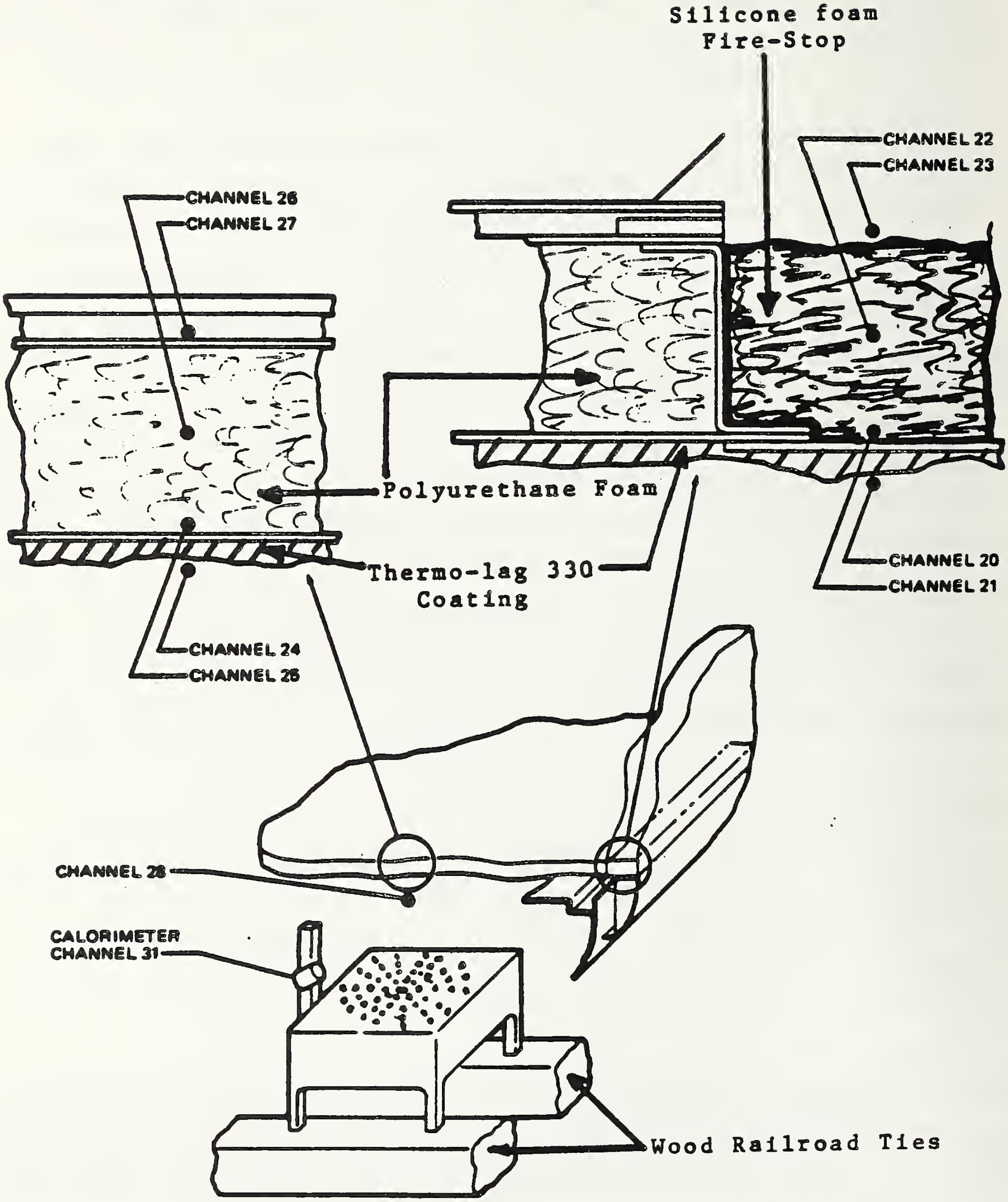


Figure 3.1 Discrete Instrumentation for Undercar Burner Tests

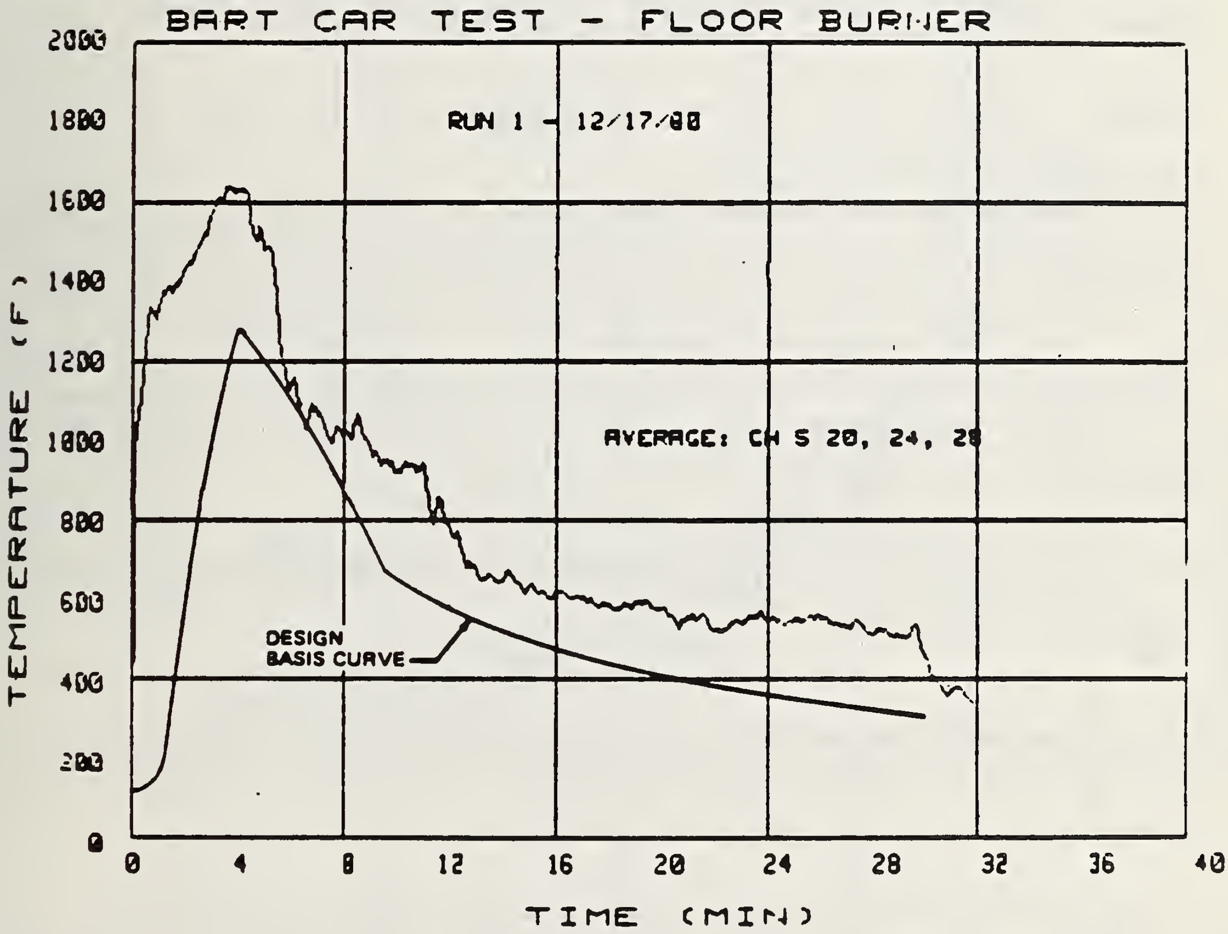


Figure 3.2 Comparison of Air Temperatures Above Burner with Design Basis Curve. See Figure 3.1 for location of thermocouples.

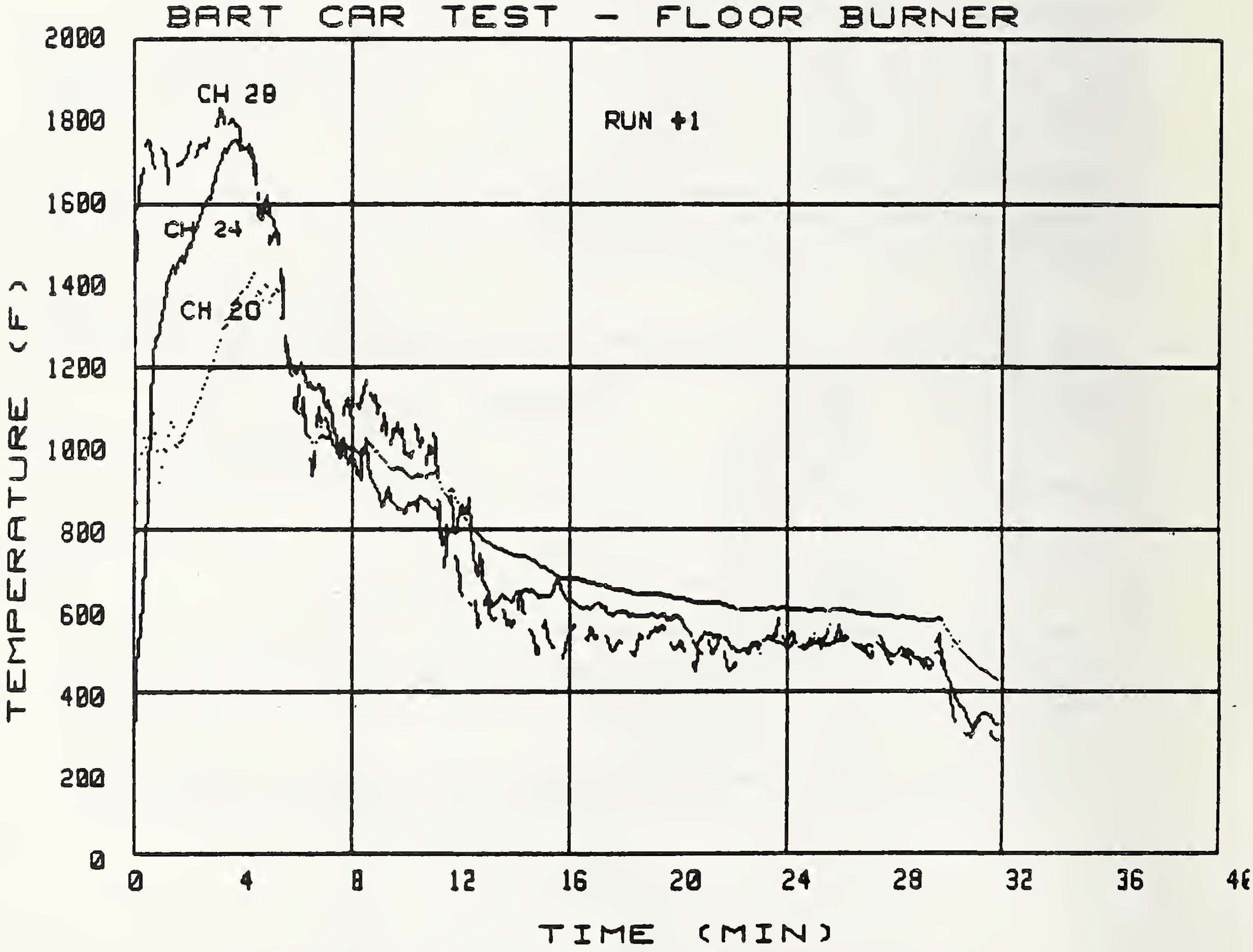

BART CAR TEST - FLOOR BURNER
RUN #1
CH 28
CH 24
CH 20
TEMPERATURE (F)
2000
1800
1600
1400
1200
1000
800
600
400
200
0
TIME (MIN)
0
4
8
12
16
20
24
28
32
36
4

Figure 3.3

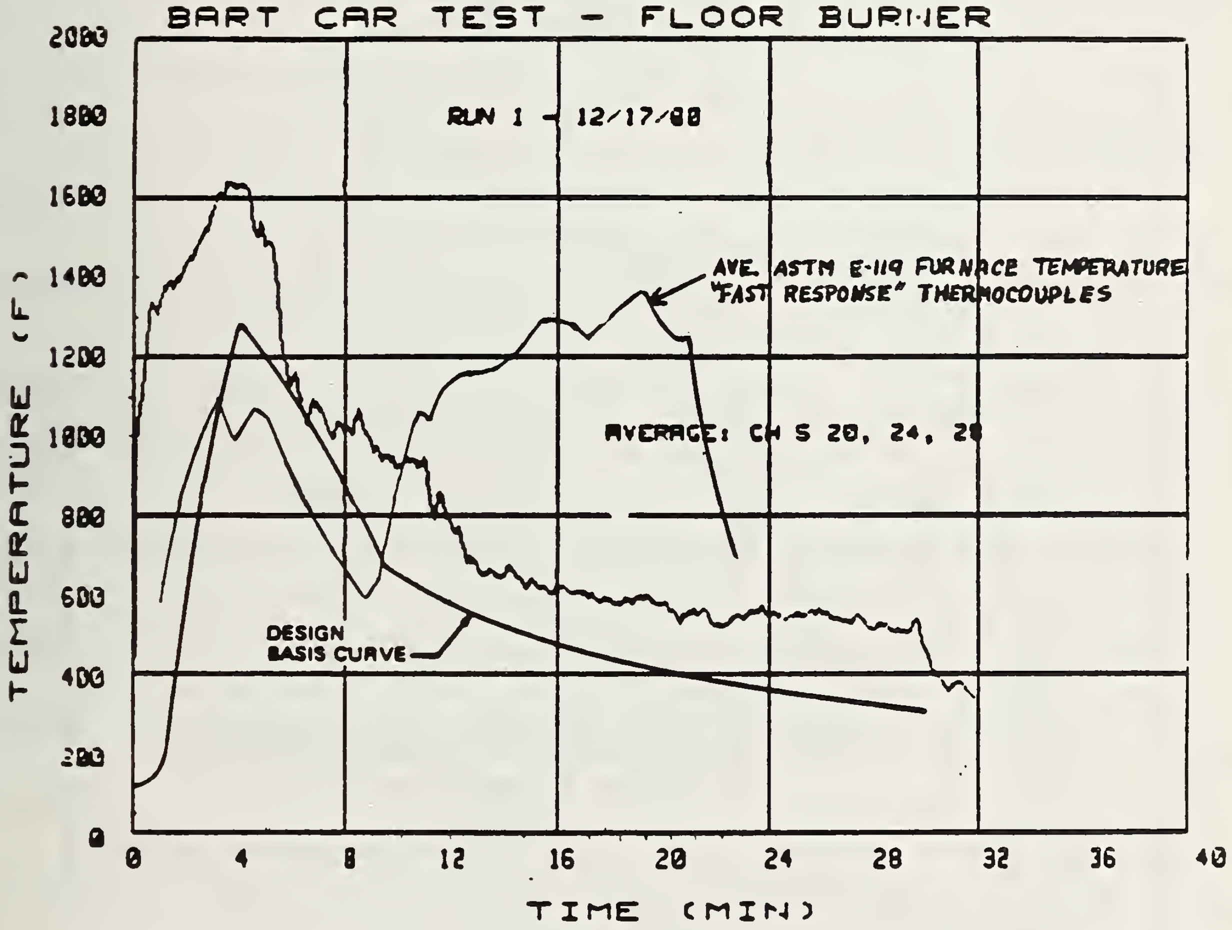


Figure 3.4 Comparison of Air Temperatures Above Burner with Design Basis Curve. See Figure 3.1 for location of thermocouples.

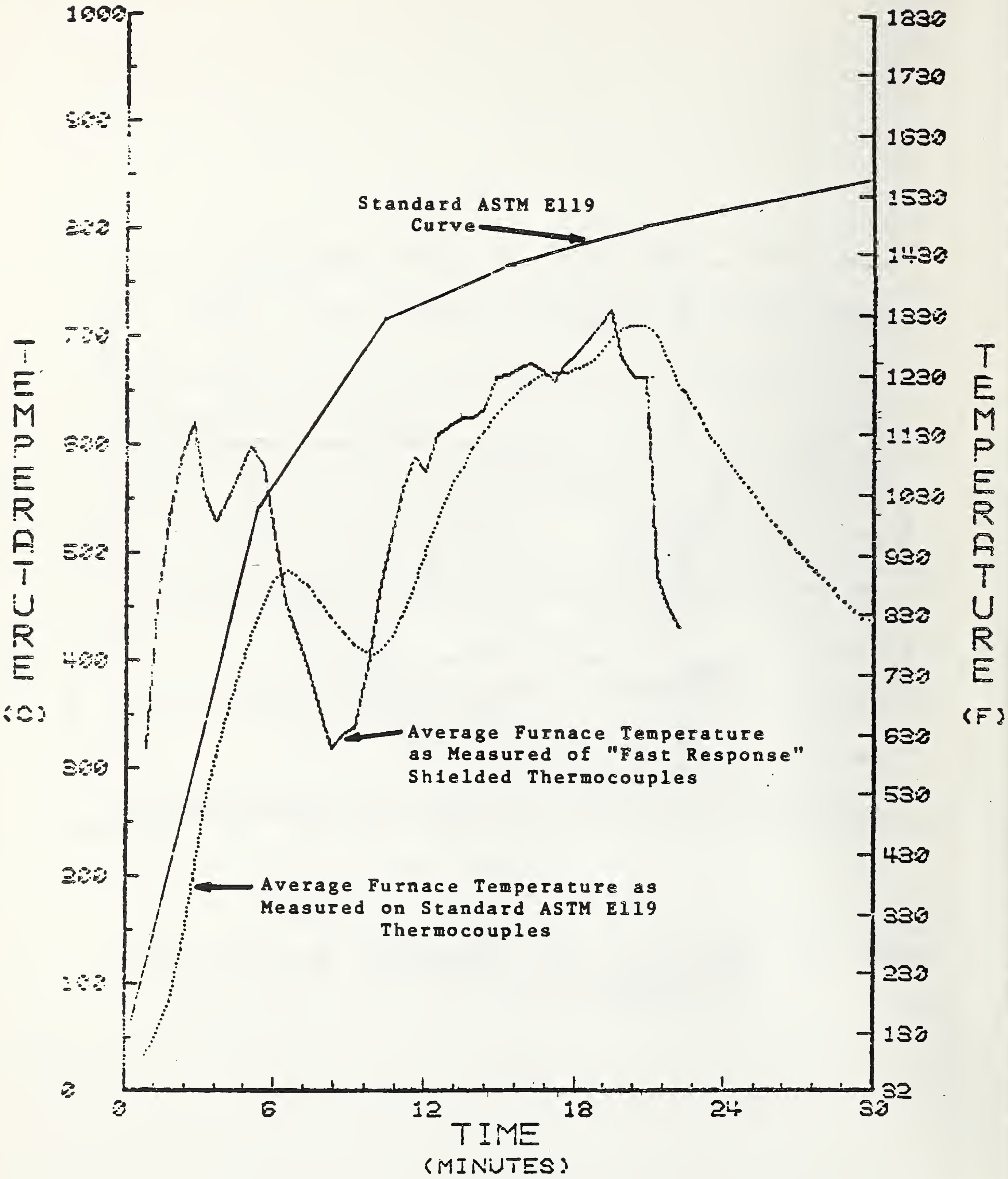


Figure 3.5 The furnace temperatures measured by Standard ASTM E119 thermocouples (which have a slow response) as compared to the temperature measured with fast response thermocouples.

than the intended DBC. Similarly, analysis of the initial 15-minute period shows that the area under the actual ASTM E-119 curve was about 13.7% less than for a superimposed similar time period for the standard ASTM E-119 curve. Furthermore, comparing the actual DBC test with the standard ASTM E-119 curve for the initial 15-minutes of the test shows that the heat flux received during the DBC test was 5.5% greater than for a like time period for the standard ASTM E-119 curve.

Observation of the physical results of both the McDonnell Douglas and Berkeley tests referred to above showed that the vehicle floor had survived both fire assaults without penetration or excessive heating of the upper surface.

The concern expressed by the Public Utilities commission relating to the appropriateness of the DBC in relation to the ASTM E-119 in the light of the actual tests, have become academic. In Test No. 7 at McDonnell Douglas the DBC was overrun by a heat flux of about 50%. The ASTM E-119 test run in a similar manner at Berkeley was underrun by about 9.5% for a 22.4 minute period. Comparing the actual DBC run with the standard ASTM E-119 curve for their respective first 15-minute periods shows the DBC to have exceeded the total heat flux of the standard ASTM E-119 by 5.5%.

It would then appear, that for the 15-minute period, that is the minimum time called for by the proposed UMTA Recommended Practices, the floor afforded the required protection, and the protection afforded by the proposed modifications to the vehicle is adequate.

3.5 CONCERN NO. 5 - TOXICITY THREAT

Does BART's proposed program adequately address the smoke emission and toxicity issue? Review the list of materials to be utilized in the fire-hardening program along with the available test data and, where possible, ascertain whether the materials used in the refurbishment program will significantly reduce the toxicity threat. What are your recommendations for further reducing the toxicity threat?

3.5.1 Assessment of the Toxicity Threat

Dr. Charles Crane of the Federal Aviation Administration's Civil Aeromedical Institute addressed this concern for the toxicity threat. The following paragraphs contain his evaluation of the materials; his entire response to this concern is contained in Appendix B.

Evaluation of Materials for Toxic Threat

It is an unfortunate consequence of the relatively undeveloped state-of-the-art of combustion toxicology that the prudent person simply dares not make very precise predictions about the absolute (or even relative) toxicities of thermal decomposition products from a real fire. This caveat is especially appropriate when the materials under consideration have not ever been tested, by any technique, for toxic effects on animals.

In the case at hand, only the replacement materials have been subjected to toxicity tests (DAC) of any kind; so in the best of circumstances there would be no data from the original materials with which to make even a relative comparison. The Douglas full-scale studies utilizing animals were accomplished, unfortunately for the purpose of determining toxicity, at an exposure level that neither incapacitated nor killed; therefore, the results are not particularly useful for establishing either absolute or relative toxic threats.

It has been the contention of this reviewer for some time, however, that the lack of a dependable and relevant procedure for quantifying the toxicity of smoke does not dictate a total inability to reduce environmental toxic hazards. This is especially true for the fire environment associated with transportation vehicles and other occupied spaces that are small enough so that escape from the hazardous environment can be effected in a relatively short time, e.g., in less than 15 minutes.

When the above conditions apply, the primary factors controlling whether one escapes or succumbs (which equates with toxic hazard) are the toxicity of the smoke and how long one is forced to breath it, i.e., the product of toxic potency and exposure time. A reduction in toxic hazard obviously can be achieved by reducing either or both of these factors.

For any specific locale and any given fire scenario, there will be a minimum time required for each potential smoke victim to become aware of, and escape from, the potentially hazardous area. The greater the fractional part of this escape time that can be kept smoke-free, or at a lower toxic gas concentration, the smaller will be the toxic insult acquired by the individual during his escape to a smoke-free environment--or the longer will be the time available for that escape.

Consequently, any change in material or material property that delays the initiation of thermal degradation or decreases the rate at which decomposition proceeds, the rate of toxic gas generation, or its overall production will usually accomplish a reduction in toxic threat indirectly. Without having actually measured smoke toxicity, we can, therefore, certainly improve the overall <u>fire</u> threat and probably the <u>toxic</u> threat by judicious manipulation of those material properties such as: ignition temperature, flame-spread rate, rate of heat release, smoke production, and even the weight of material required for the installation.

The evaluations and comments that follow are primarily based on a consideration of these "other-than-toxic" properties of the original and replacement materials--provided such data were available.

Evaluation of Proposed Wall and Ceiling Liners

In the U.C. screening tests, both types of new materials (phenolics and polyester) exhibited marked improvement over the liners previously used. Comparative results for the attempted arson scenario (1-kg trash bag) are especially indicative of the reduced fire hazard associated with the replacement liners.

The McDonnell Douglas tests (retrofitted vehicle) also suggest satisfactory fire performance characteristics; although, unfortunately, there are no similar test results with original materials for actual comparison. The animal results are of little value in this case because there are no data (from original materials) with which to compare them. In addition, animal data cannot at this time be related by anyone to human response times--or survival times--under the same exposure conditions.

Protection of Polyurethane Foam in the Roof

Of the original polymeric materials that were not replaced, it is obvious that the polyurethane foam (PUF) in the roof structure probably represents the greatest single fire hazard and potential toxic threat. It would seem, however, that the likelihood of ceiling involvement has been decreased considerably as a consequence of the other fire-hardening measures. The decision to spray-coat the interior surface of the roof liner with intumescent paint should further delay involvement of the PUF in any given fire scenario.

Therefore, to the extent that the laboratory screening and full-scale test data are pertinent and that one can make meaningful risk-benefit and cost-benefit analyses in this area, the BART approach seems justifiable. However, the use of this type of polymer, in large quantities, should be seriously questioned on the occasion of future renovations or vehicle redesign.

Comments on Seat Pan Decision

The seat pans (polyvinyl chloride-acrylic) actually weighed 67 percent of what each foam (PUF) seat did, and represented more of a potential heat load per car than the PUF itself (640,000 BTU vs 624,000 BTU). The justifications for not replacing this material were its relatively slow flame-spread rate, its thermoplastic nature (which causes it to soften and sag away from the flames), and the observation that it was not usually consumed in previous vehicle fires. While this decision seems adequately supported, it should be noted that, should the right set of circumstances occur in a particular incident, both the acrylics and PVC decompose rapidly at relatively low temperatures and PVC can yield over half its weight as gaseous hydrogen chloride (HCl) a potentially potent agent of human incapacitation.

It would seem advisable to continue monitoring the degree to which these items are involved in future fires, to see if the previous observations are borne out. If it is found that they are significantly involved, then they should be seriously considered for replacement at some future date.

Summary Comments on Potential for Reduced Toxic Threat

There can be little doubt that the single, most effective, element of the fire-hardening program was the elimination of the original urethane foam seat cushions. Based on test results, this action greatly reduces the ease of ignition and the likelihood of a fire spreading beyond the initial site before it can be detected and controlled. (There has to be some question, however, of the accuracy of the statement[2] on page 39, Section 4.3.1, to the effect that the LS-200 Neoprene cushions do "not produce toxic smoke.")

The cushion replacement, in concert with the use of ceiling and wall liners having significantly improved fire characteristics, surely represents a reduction in the ignition and rate-of-fire-spread hazards.

The decision to protect the car interior by using Thermolag coatings under the floor, replacing PUF with fire-retarded silicone foam at floor-sidewall junctions, and installing silicone foam fire-stops in walls should significantly reduce the threat of fire penetration. Coupling the improved materials with the penetration barriers should produce a car with an undeniably improved fire-hazard rating.

And the important point for toxicity considerations is that this reduced level of <u>fire</u> hazard carries with it a reasonable expectation (if not guarantee) of a concomitantly reduced <u>toxic</u> hazard. This is true if only for the reasons that a material that does not become involved does not produce toxic smoke, and a slower rate of fire propagation means a slower build-up of toxic concentrations. Both of these conditons result in an increased time interval available for successful escape and we therefore have an environment with a reduced toxic threat.

3.6 CONCERN NO. 6 - VENTILATION SYSTEM

During the full-scale fire testing, smoke entered the vehicle occupant compartment through the vehicle ventilation system ducting. The passage of smoke through this ducting started then stopped, and then started again. Examine the ventilation system for the following:

a. Determine normal migration paths for smoke and hot gases into the car.

b. What would be the role or response of the ducting to a vehicle undercar fire?

   1) Would the Kydex ducting close and stop the smoke and heat penetration into the car?

   2) What is the melting point for the Kydex ducting?

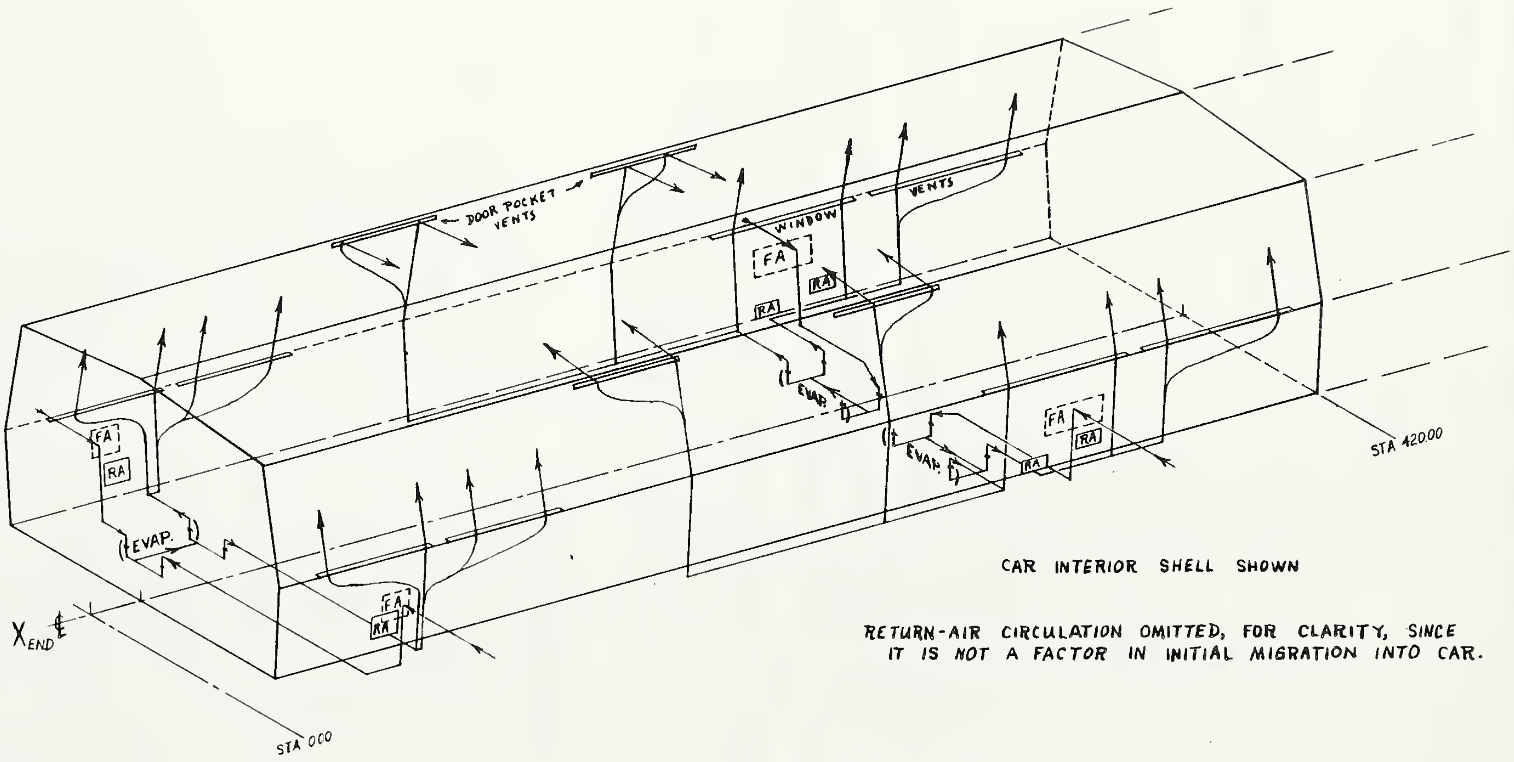
   3) Can the hot combustible gases or flame penetrate into the car along the interior of the Kydex ducting?

c. Determine the feasibility of installing fire dampers or other alternatives inside the existing Kydex ducting to prevent smoke and heat penetration into the car.

3.6.1 Assessment of Ventilation System

a. The normal migration paths by which smoke and hot gases enter the car are shown in Figure 3-6. This figure, constructed from the engineering drawings of the vehicle manufacturer, ROHR Industrial Systems group, show the fresh air intake on the side of the vehicle, as well as the vehicle evaporators, and air entrance into and exit from the occupant compartment of the vehicle.

b. The response of the Kydex ducting, to an undercar fire, will vary with the location and the magnitude of the fire. As shown in the full scale undercar fire tests at McDonnell Douglas, in an intensive fire the ducting will burn or melt and fall away from the vehicle underside. In this instance if the fire then continues at that intensity the closing off of the duct is not



CAR INTERIOR SHELL SHOWN

RETURN-AIR CIRCULATION OMITTED, FOR CLARITY, SINCE IT IS NOT A FACTOR IN INITIAL MIGRATION INTO CAR.

FA	FRESH AIR INTAKE ON EXTERIOR OF CAR
RA	RETURN AIR GRILLE ON CAR INTERIOR WITHDRAWING AIR FOR RECIRCULATION

SYMBOL	SPECIFICATION	CODE IDENT	PART OR IDENT NO.	FIND NO	QTY REQD	MATERIAL	NOMENCLATURE

LIST OF MATERIALS

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES

DO NOT SCALE THIS DRAWING

MATERIAL

FINISH

NEXT ASSY | USED ON

APPLICATION

DRAWN E. C. KLAUBERT V/19/82
CHECKED
APPROVED
APPROVED

DEPARTMENT OF TRANSPORTATION
TRANSPORTATION SYSTEMS CENTER
55 BROADWAY CAMBRIDGE, MASSACHUSETTS 02142

BART CAR VENTILATION SYSTEM:
MIGRATION PATHS OF SMOKE & HOT GASES INTO CAR FROM AMBIENT.
ONE-HALF OF "B" CAR SHOWN (OTHER END SIMILAR).

SIZE C | CODE IDENT NO. | DRAWING NO.

SCALE 1/32 | SHEET

FIGURE 3.6

pertinent for although the duct may close, the fire could burn through the ducting at the floor-sidewall junction and enter the vehicle sidewall behind the liner.

For a small fire where the ducting remains in place, an analysis has shown that the ducting could close and seal off the smoke.

The Kydex ducts are comprised of 0.06-in.-thick outer and 0.03-in.-thick inner shells of Kydex with 1.0 to 1.5 inches of fiberglass insulation sealed between the inner and outer shells. Each section of duct appears to be fabricated, initially, in two halves which are similar except for the thickness of fiberglass insulation; the two halves are fused together along longitudinal seams. The data available on the physical properties of Kydex are as follows:

Estimated ignition temperature - 900°F*

Thermo forming temperature - 360°F to 390°F*

Deflection temperature - 177°F at 66 psi**

Modulus in temperature range 350°F - 450°F is approximately 30 psi**

Data on the engineering properties of Kydex duct materials as functions of temperature are not available in sufficient detail to permit rigorous calculations of duct deflection and collapse temperatures. However, limited analyses were possible which indicated probable duct failure (inner shell sagging), and failure to resist circulation-blower stagnation pressure (i.e., failure of duct to remain open) when certain temperatures are reached in the Kydex (polyvinyl chloride/acrylic) duct material. The precise temperature-versus-time histories to develop such shell temperatures cannot be calculated, presently; but, again, it is probable that conditions sufficient to cause duct collapse can develop in the case of an undercar fire.

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*Data provided by BART.
**Data provided by manufacturer.

A simpler view of this is as follows: In a fire the ducting will initially be heated and may begin to degrade when sufficient heat is transferred to the inner duct. Smoke is simultaneously produced and is seen entering the vehicle. As the fire continues and the Kydex material melts or burns the flame can then penetrate the outer and the inner ducting. When the inner duct collapses from the heat the smoke from the fire and the burning ducting may then be sealed. If the fire then enlarges or continues further it may be prevented from entering the vehicle for a brief period of time. However, if the fire does persist (as in the case of a large fire) then it is possible for the fire and smoke to enter the sidewall. This particular scenario may or may not occur. Although BART may consider this duct collapsing and sealing a benefit of the Kydex ducting, it certainly is not a significant benefit and should not be considered as such.

c. To prevent the fire and smoke from penetrating into the vehicle occupant compartment there are two alternatives:

1. A damper could be placed in the ventilation system to close off the ducting or,
2. The ducting could be replaced with a different material.

To evaluate the first alternative, an analysis was performed to determine the technical feasibility of installing, in the ventilation ducts of BART cars, dampers which would close automatically to prevent smoke and heat from entering the cars in the event of a fire under the car. No proven, commercially available damper systems were found which could be installed. Technology does exist from which at least three systems employing active sensing of smoke, fumes and/or heat apparently could be developed. These systems can potentially protect passengers against low-temperature smoke in addition to protecting against heat. Two other, possibly less-expensive, passive systems which may be technically feasible could protect passengers against intense heat but probably not against low-temperature smoke. In conducting this analysis the active systems and technologies considered were:

- Airbag damper.
- Airbag inflated damper.
- Firefighting foam as a damper.

The major problem with any active system is the need to detect the heat or smoke with some type of sensor. Only after the heat or smoke has been detected can the damper then be deployed or activated. UMTA, through TSC, is presently funding a study by the IIT Research Institute[7] to identify and evaluate undercar fire detection devices. This study, which is the first step in the development process, has identified the use of microprocessors as a potential means of accomplishing undercar fire detection and minimizing the false alarm rate which has been a major problem in past detection devices. With an adequate sensing device, the need for dampers may be negated if the fire is detected early, and action taken before the heat and smoke threaten the passengers.

For passive systems, which require no sensor, two conceptual designs using 1) an intumescent material or 2) a fusible link were examined as prospective methods. The major problem with these passive systems is their failure to protect against low temperature smoke. Consider the scenario where fire may be localized under one side of the vehicle. Each evaporator has, as shown in Figure 3-7 four separate ducts, two supply and two return. Because of the various locations where a fire could start under the vehicle, and the desire to mitigate the fire penetration into the vehicle, the only logical place to install the damper is at the vehicle floor level. Hence each evaporator should have four dampers installed in the duct for a total of twenty-four dampers per vehicle. If a fire occurs and affects only one side of the vehicle or one damper, the smoke from the decomposing ducting will flow into the vehicle until the ducting has been burned through sufficiently to activate the damper at that location. For the other three ducts associated with that evaporator the dampers will not be affected and hence the smoke may enter the vehicle after

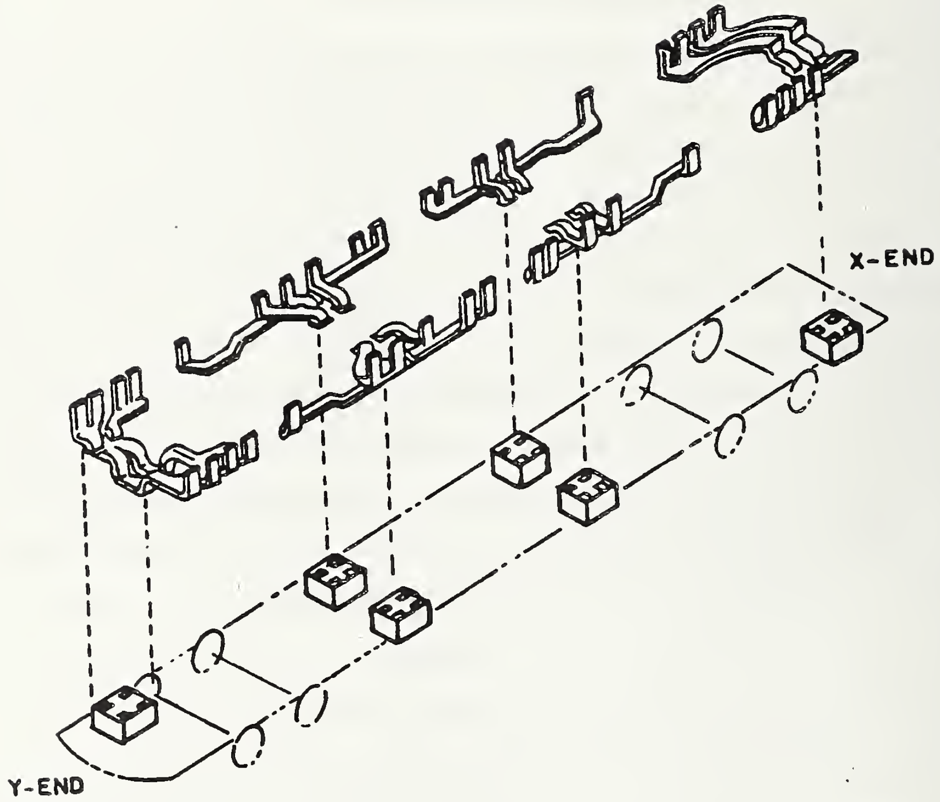

FIGURE 3.7 A/C (KYDEX) DUCTS

moving through the evaporator and ducting. As such these passive systems do not offer the needed protection and should not be considered further.

The second alternative, to replace the Kydex with a different material, was examined and the following substitute materials identified

- all metal ducting
- a different plastic material.

The all-metal ducting would be similar to that used in the ventilation systems of buildings. Although there is no flammability problem with this type of ducting the condensation and acoustical problems associated with its installation are enormous. To minimize the noise would require special insulation which would, by its nature, be flammable but could be accomplished with a less flammable material than Kydex. The condensation problem associated with this ducting could be very difficult to address and may result in a coating being applied to the ducting. This coating could then present another flammability problem.

Replacing the Kydex with another polymer, although a perhaps attractive approach, may not really accomplish that much. The Kydex has a flame spread index of $I_S = 14.6$ and a specific optical smoke density (D_S) of 306 at four minutes. The replacement of the Kydex by another plastic would not result in a significant improvement in flammability. However, the possible reduction in smoke could be significant but would require further study to evaluate the properties of a replacement material. In summary, it does not appear that the installation of dampers or the replacement of Kydex with another material is a feasible approach at this time.

3.7 CONCERN NO. 7 THERMOLAG COATING ON UNDERCAR FLOOR

What precautions should be taken to insure that Thermolag would properly adhere to the undercar floor areas? How often should Thermolag be inspected to insure full fire protection at all times. Assessment of partial vs. full undercar floor spray protection.

3.7.1 Assessment of Thermolag Coating on Under Car Floor

There are two basic concerns associated with the application of the Thermolag material on the undercar floor: 1) What portions of the undercar should be coated and 2) what precautions should be taken to insure the maximum fire protection from the Thermolag.

Addressing the first concern, namely, which undercar areas should be coated, was accomplished by examining the past fire experience of the BART vehicles and discussions with several individuals familiar with transit vehicle equipment operation.

A review of PUC data on BART fire and smoke incidents revealed that for the period from 1975 through 1981 the predominant sources of undercar fire and smoke incidents were as follows:

evaporator	-	9 incidents
dynamic brake grid	-	9 incidents
traction motor	-	4 incidents
disc brakes and pads	-	3 incidents

These four components are then prime candidates against which the vehicle floor should be protected. Additional fire and smoke incident data, presented in Reference 8 confirms the BART data on traction motor, resistor grids, and brakes.

Discussions with several individuals in the transit industry confirmed that the traction motor and resistor grids are major heat sources. In a meeting with L. Engleman, J. Flynn, and WMATA maintenance personnel at WMATA, they stated that their only problems were with these components, but noted that their vehicles, although built by Rohr, are of a different design. However, they contain several similar components. The WMATA and BART vehicles are the only transit vehicles built by Rohr. This fact has also made it difficult to obtain any consensus from other members of the transit community, as their vehicle designs and equipment also differ.

The question of the full undercar coating versus the partial undercar coating specified in the fire-hardening program plan has been resolved in the following manner. To cover the entire undercar with the Thermolag will require dropping all of the vehicle equipment and then coating the entire floor. This coating would then cover the entire undercar and would thereby hinder the vehicle's future maintenance and inspection operations. The full coating could possibly conceal prospective problems, e.g., structural cracking, broken insulation, etc. The undercar would be coated to protect against a concern which is perhaps not nearly as severe as the problems that would be concealed.

The second basic concern with the Thermolag is what precautions should be taken to insure the maximum fire protection?

The use of the TSI Thermolag 330 for protection of critical surfaces against fire has had a relatively long history. It was employed as an ablative thermal protection for the gantries in the launching of rockets beginning in the early 1960's. Subsequently, the FRA conducted successful tests of Thermolag coatings on tank cars containing combustible liquids.

An analysis of the thermally protective properties of Thermolag in Section 3.4 of this report demonstrates its adequacy in preventing an undercar thermal assault from penetrating the floor of a vehicle or causing excessive heat to develop on the interior floor surface. It remained to be determined whether a coating of Thermolag has the necessary endurance in terms of adhesion and weatherability.

A review of reports on other uses of Thermolag indicate that if Thermolag is applied according to the manufacturers instructions, adhesion should be good. One of the basic rules in forming a good adhesive bond for any material is proper preparation of the surface to which it is to be bonded. An absolutely clean surface is necessary, particularly where a mechanical bond is not available. In the case of Thermolag, a primer is first used on the clean surface, and the Thermolag is then sprayed on in the required thickness, followed by a curing period. Strict quality control must be assured during the surface cleaning operation and the application of the primer and the Thermolag.

The manufacturer conducted accelerated weathering tests according to Federal Standard 141a, Method 6152. The results showed a 10 percent drop in adhesion at the end of a simulated 40 years of exposure.

It is recommended, however, that a sealer be applied to the coating after curing (following the manufacturer's instructions). It is also recommended that a periodic inspection program be conducted to determine continued adhesion. This can be augmented by a more detailed inspection of the surface during the regular scheduled overhaul.

3.8 CONCERN NO. 8 - REPLACEMENT OF CEILING LINERS

BART's Fire-Hardening Program recommends the replacement of ceiling liners. Based on temperature data for ceiling and wall areas, would it be appropriate not to replace the ceiling liner, but instead spray it with Thermolag or intumescent paint and fire-harden the wall cavities (insulation, ducting, etc.) so that ceiling temperatures would never rise high enough to get liner materials involved?. What would be the cost savings for such an alternative?

3.8.1 Assessment of Ceiling Liner Replacement

As noted in the McDonnell Douglas tests the highest ceiling temperature occurred in arson attempt Number 1 (trashbag under the seat) with the thermocouples registering temperatures of 775°F at approximately 30 minutes into the tests. Although this temperature did not affect the phenolic ceiling liner it cannot be assumed that it would not affect the existing polyester ceiling liner. Applications of an intumescent paint or the Thermolag may not provide the needed protection. Furthermore the adhesion or aging characteristics of these materials is suspect. As noted in Section 3.2, we do not feel the intumescent paint is the sole solution to the problem in this area.

As regards fire-hardening of the insulation and ducting it is questionable as to how much improvement can be achieved by replacing the Armaflex and fiberglass insulation materials and the Kydex ducting. From the standpoint of the flame spread index (I_s) the I_s of Armaflex is 13 while the fiberglass also has a low I_s and the Kydex ducting I_s is 14.6. These flame spread indices are already very low and as such further fire-hardening will not significantly affect the flame spread to the ceiling.

There would be no basic improvement with this approach.

Our lack of confidence in the employment of intumescent paint and Thermolag is offset by confidence in the protection afforded by the phenolic liner. Even a small flame impinging on the ceiling could require replacement of an entire polyester panel, whereas the same fire source might only require modest repair of the phenolic liner. For these reasons, we have not felt that a cost-benefit analysis would be necessary.

3.9 CONCERN NO. 9 - ARC TESTS AT McDONNELL DOUGLAS

In the arc test performed at McDonnell Douglas, the target was aimed at a single point. In the event of the breakage of the collector shoe assembly, the cable could cause arcing at several places. Can the results of the McDonnell Douglas test be applied to the multiple arc case? Would BART's proposed program prevent undercar penetration and fire hazard due to multiple arcing in undercar floor areas?

3.9.1 Assessment of Arc Test

In addressing the concerns on the arc tests conducted at McDonnell Douglas and the concern on multiple arcing, two questions are in order, namely, 1) how did multiple arcing occur and 2) what was the magnitude of the arc current following the destruction of the current collector assembly? Multiple arcing, resulting from the motion of the cable when separated from the current collector assembly, could occur only while the train's motion exerted a mechanical force on the cable. Once the train was stopped the cable would be at rest and there would be no multiple arcing. In regard to the magnitude of the arc current, since the current collector fuses were blown, we must conclude from their inverse time characteristics that the current from the third rail, causing the fuses to blow,was 450 amps for not more than 4 seconds, or 950 amps for not more than 0.02 seconds, or a still larger current of approximately 2000 amps for less than 0.01 second. In this case, the arc energy of the McDonnell Douglas test (2000 amps for 10 seconds) is far in excess of the actual current available through the fuse. The two-inch diameter hole in the steel bolster is evidence of the intensity of this test. If, however, the train was in motion,then the fault current causing the arc could have been due to the dynamic braking of the trains. This arc current would have been independent of the fuse protection and,with the cable detached from the current collector assembly could have resulted in multiple arcing to the vehicle underside. If this was the case , then, to determine the validity of the McDonnell Douglas simulation would require a knowledge of the dynamic braking characteristics (current vs. time profile).

In summary, the McDonnell Douglas simulation does appear to be reasonable; however, it is not possible, with the presently available information, to fully ascertain the validity of the simulation as it relates, to the concerns expressed by the PUC.

3.10 CONCERN NO. 10 - INSTALLATION OF FIRE STOPS

BART is proposing to install fire stops in the wall and ceiling areas. Determine if this could cause accumulation of combustible gases due to the pyrolysis and/or combustion of flammable materials behind the liners, such as insulation, intumescent paint in the ceiling areas, etc.

3.10.1 Assessment of Installation of Fire Stops

The installation of the fire stops, if properly placed and installed, will be a most beneficial means of preventing fire spread in the area between the liners and the vehicle's aluminum shell. The accumulation of combustible gases behind the liner will not occur as the manufacturing drawings show that any gases generated below the window will exit to the vehicle through the window vent.

Discussions with PUC and BART staff revealed that the liners are not airtight and as such the gases will vent through the seams and penetrations (light fixtures, etc.) in the wall and ceiling liners.

4. CONCLUSIONS AND RECOMMENDATIONS

In summary, the BART fire-hardening program has been assessed and the concerns of the PUC staff addressed. The following conclusions and recommendations are provided for consideration.

4.1 CONCLUSIONS

a. The available BART operating data show that the fire and smoke incidents are basically of two types, 1) arson-initiated in the occupant compartment and 2) undercar fires resulting from a mechanical or electrical failure. The full scale fire tests have shown that with the new interior materials, the arson fire is no longer expected to result in the spread of the fire beyond the area of origin. Similarly, the removal of several undercar equipment ignition sources and the fire-hardening of the floor will minimize the probability of penetration or lengthen the time to penetrate the floor. This will thereby allow time for passenger egress.

It must be understood, the fire-hardening program will not eliminate fire and smoke incidents, but it will minimize the effect of such incidents.

b. Although the basic BART concept of the fire chain and decision tree is a proper approach, and the ultimate conclusions derived by BART are appropriate, the reports of BART and their contractors contain several questionable or unsubstantiated statements. Among these, for example, are: that seat replacement will result in "a hundred-fold improvement in smoke and toxicity generations has been achieved"[2]; the conclusion regarding the flashover of the Melaminium; the importance of the assumption that the Kydex ducting will collapse and several other statements.

c. Fire-hardening actions such as the fire stops and intumescent paint were not included in the full-scale fire test. The lack of these fire-hardening actions prevented their full evaluation in the full-scale fire test.

d. In several instances the decision on replacement of several of the materials could not be based on test data and necessitated the construction of scenarios to evaluate the need to replace the materials.

4.2 RECOMMENDATIONS

4.2.1 The proposed fire-hardening program should be implemented as soon as practical. In addition, BART should accomplish the following:

a. The Thermolag coating should be applied at the selected areas in accordance with the instructions or recommendations of the Thermolag manufacturer. A quality control program should be established to insure proper application of the Thermolag. Furthermore, a topcoat should be applied to the Thermolag.

b. BART should develop and initiate a program to inspect the Thermolag coating to insure that it will provide the intended protection. This inspection program should include all of the areas coated as well as those areas where the thermal protection is accomplished through the use of a heat shield which is mechanically attached to the floor (i.e., floor above the dynamic brake grids and other floor areas covered by pre-coated sheets of Thermolag).

c. The design reviews conducted during the design phase of the fire-hardening program should be used to fully define the number and location of the fire stops. The contractor should be encouraged to be creative in developing approaches to implementing the fire-hardening actions.

4.2.2 BART should periodically review its operating experience to identify and correct prospective safety problems. Such an effort will serve to further enhance the fire safety of the BART vehicle.

4.2.3 Materials which replace damaged or worn components such as arm rests, vinyl trim, seat backing, insulation, etc., should comply with the UMTA "Recommended Fire Safety Practices for

Transit Materials Selection". As an example, a worn or damaged arm rest should be replaced with a material which meets the UMTA "Recommended Fire Safety Practices for Transit Materials Selection."

4.2.4 During vehicle inspection or operations, BART should, when equipment is removed from the vehicle underside, thoroughly inspect the floor for any signs of excessive heating or the thermal decomposition of the flooring material.

4.2.5 The following two recommendations are presented in an effort to identify and address prospective problems in future BART vehicles.

a. BART should employ the ASTM E-119 test for selecting all future floor materials.

b. A study should be conducted to evaluate the feasibility of installing the ventilation system ducting in the ceiling or roof plenum of future BART vehicles.

4.2.6 BART should keep abreast of the advances in fire safety, with regard to materials selection and fire testing and evaluation methods.

4.2.7 BART should continue its training and evacuation drills to insure emergency preparedness. In the event of a fire, the fire-hardened vehicle and the emergency egress capabilities should be treated as a system. Evacuation of personnel is one of the options available for mitigating the effects of vehicle fires.

REFERENCES

1. Public Utilities Commission of the State of California Decision No. 90144, April 4, 1979, Case No. 9867.
2. BART Vehicle Fire-Hardening Program - C.E. Jenkins and M.K. du Plessis (BART) - March 2, 1981.
3. BART Transit Vehicle Full-Scale Fire Test - Final Report - McDonnell Douglas Corporation - February 27, 1981.
4. Analysis of BART Fire-Hardening Program - R.B. Williamson (University of California, Berkeley) - April 29, 1981.
5. Room Fire Screening Test of Candidate BART Materials - R.B. Williamson - February, 1981.
6. Information from UMTA/TSC Materials Data Bank.
7. Study of Smoke Detection and Fire Extinguishment for Rail Transit Vehicles, K. Mniszewski, et al, IIT Research Institute, August, 1982 (unpublished).
8. Identification of the Fire Threat in Urban Transit Vehicles, W.T. Hathaway and A. Flores, UMTA-MA-06-0051-50-1, June, 1980.

APPENDIX A

FACTORY MUTUAL RESEARCH CORPORATION

Statement of Work

The contractor shall, with assistance from the TSC and the Bay Area Rapid Transit District, review pertinent literature including the following four reports:

1) BART Transit Vehicle Full-Scale Fire Test - Final Report - McDonnell Douglas - February 27, 1981.

2) BART Vehicle Fire-Hardening Program - C. E. Jenkins and M. K. du Plessis (BART) - March 2, 1981.

3) Analysis of BART Fire-Hardening Program - R. B. Williamson (U. Cal.) - April 29, 1981.

4) Room Fire Screening Test of Candidate BART Materials - R. B. Williamson - February, 1981.

Upon completion of this review the contractor shall, in a letter report, address the following questions:

1) Is the fire chain concept employed by BART in the fire-hardening program a valid approach to use in determining the various fire hardening modifications?

2) Do the test data and analysis presented in the above four reports support the following:

   a. replacement of polyurethene seat cushions with low smoke neoprene;

   b. replacement of wall liners with a combination of Phenolic and improved Polyester;

   c. replacement of ceiling liner;

   d. spray of intumescent paint in the ceiling areas;

   e. use of Thermolag coating for the undercar floor areas;

   f. installation and location of fire stops in the interior wall liner cavities;

g. not to replace miscellaneous flammable interior furnishings, such as vinyl trim, arm rests, Kydex seat backing and insulation material.

3) When implemented, will the BART Fire-Hardening Program significantly address the flammability problem?

CIVIL AEROMEDICAL INSTITUTE

Statement of Work

The Civil Aeromedical Institute shall, with assistance from the TSC perform the following tasks.

Task 1. Survey the materials list, and together with information to be supplied to you concerning materials composition, general vehicle construction, and fire testing (both laboratory and full scale), attempt to ascertain what the toxic gas environment might be in the event of a tunnel fire under different scenarios for such a fire. If this is determined to be too difficult, we would at least want to know if the refurbishment has reduced the toxicity threat significantly.

Task 2. Describe the current status in the toxicology community of the efforts to arrive at a toxicity standard that could apply to conditions such as would be encountered in the transit environment.

Task 3. Prepare a final report to TSC on the above tasks.

APPENDIX B

System

Factory Mutual Research

1151 Boston-Providence Turnpike
Norwood, Massachusetts 02062
Telephone (617) 762-4300
Telex 92-4415

August 31, 1982

Mr. William T. Hathaway
DTS-331
Department of Transportation
Transportation Systems Center
Kendall Square
Cambridge, Massachusetts 02142

Subject: Review of Literature on Fire Tests
Involving BARTD Rail Vehicles
Contract No. DTRS57-82-P-80560
FMRC J. I. No. 0H3N4.RC

Dear Mr. Hathaway:

We have reviewed the following four reports:

1) BART Transit Vehicle Full-Scale Fire Test - Final Report - McDonnell Douglas - February 27, 1981,

2) BART Vehicle Fire-Hardening Program - C. E. Jenkins and M. K. du Plessis (BART) - March 2, 1981,

3) Analysis of BART Fire-Hardening Program - R. B. Williamson (U. Cal.) - April 29, 1981,

4) Room Fire Screening Test of Candidate BART Materials - R. B. Williamson - February, 1981,

to answer the following questions specified in the contract:

1) Is the fire chain concept employed by BARTD in the fire hardening program a valid approach to use in determining the various fire hardening modifications?

2) Do the test data and analysis presented in the above four reports support the following:

    a. replacement of polyurethane seat cushions with low smoke neoprene;

    b. replacement of wall liners with a combination of Phenolic and improved Polyester;

    c. replacement of ceiling liner;

    d. spray of intumescent paint in the ceiling areas;

e. use of Thermolag coating for the undercar floor areas;

f. installation and location of fire stops in the interior wall liner cavities;

g. not to replace miscellaneous flammable interior furnishings such as vinyl trim, arm rests, Kydex seat backing and insulation materials.

3) When implemented, will the BARTD Fire Hardening Program significantly address the flammability problem?

In our opinion, a significant effort was made by BARTD to reduce the flammability problem using the state of the art available at the time the study was performed.

The following are our answers:

1. Fire Chain Concept

The fire chain concept employed by BARTD in the fire hardening program is a proper approach to use in determining the various fire hardening modifications.

The concept allows a systems approach to the fire questions and essentially points to the weaker links in terms of ignition which would be eliminated by using proper materials selection. In general, it should be noted that this concept is also capable of directly addressing the hazards due to heat, "smoke," toxic and corrosive products without assuming a direct dependence on the ignition characteristics as was reported by BARTD.

2. Conclusions Derived from the Fire Tests

a. Replacement of polyurethane seat cushions with low smoke neoprene

The test data show that an improvement has been made by replacing the polyurethane seat cushions with neoprene. This improvement is also supported by our data obtained from the Factory Mutual Small-Scale Combustibility Apparatus under simulated large-scale fire conditions.

The reduction in the surface flame spread by a factor of approximately three with using neoprene instead of polyurethane foam appears to be due to enhancement of surface charring.

b. Replacement of wall liners with a combination of phenolic and improved polyester

The test data do show that an improvement has been made by replacing the wall liners with a combination of phenolic and improved polyesters.

Our studies at Factory Mutual also show that phenolic is a better polymer to consider for improving fire safety.

Cambridge, Massachusetts 02142

c. and d. Replacement of ceiling liner/intumescent paint on surfaces

Replacement of ceiling liner with phenolic would be beneficial. The additional benefit of coating the ceiling with intumescent paint is uncertain. Also, the reports did not point out the benefits of other coatings. Thus, if intumescent paint or another coating is to be seriously considered, further examination is needed.

Our studies at Factory Mutual show that, in general, coatings are effective in increasing time to ignition and reducing surface flame spread. The effectiveness, however, depends on the type of material being coated, coating thickness and coating technique. Environmental effects, especially humidity, temperature and erosion, are also important factors to be considered.

e. Thermolag coating of undercar floor areas

The test data do indicate that the time for floor protection from undercar fires is extended by Thermolag coating. This is consistent with the fact that coating acts as a heat insulator. At Factory Mutual we have shown this for Flamemastic coatings (77 and 71A) by quantifying thermal diffusivity of the coatings.

By proper application of the coating for undercar floor areas, a reduction in the fire hazard is expected. However, the effectiveness of the coating will vary with aging as well as with coating thickness, coating adhesion, etc.

f. Fire stops

Installation of fire stops in the interior wall liner cavities, as recommended by BARTD, would improve fire safety. For maximum effectiveness, fire stops must be properly installed in pertinent locations.

g. Not to replace miscellaneous flammable interior furnishings

Based on the BARTD reports, it is difficult to quantitatively support the conclusion of not to replace miscellaneous flammable interior furnishings.

The fire chain concept needs to be extended further to justify the conclusion.

3. Flammability Problem

In our opinion, BARTD study has shown that the flammability problem can be reduced by: 1) replacing polyurethane seat cushions with neoprene; 2) replacing wall liners with a combination of phenolic and improved polyester; 3) replacing ceiling liner with phenolic and intumescent paint/coating; and 4) Thermolag coating of undercar floor areas.

The limited data presented in the reports, however, do not allow us to assess quantitatively the degree of improvement in the flammability problem as a result of the above changes.

Sincerely yours,

A. Tewarson Jeffrey S. Newman

A. Tewarson J. S. Newman

AT/JSN:ema

cc: File

U.S. Department
of Transportation
**Federal Aviation
Administration**

Memorandum

Subject: Final Report: Evaluation of Toxic Threat Associated with Renovated BART Interiors

Date: August 12, 1982

From: C. R. Crane, Ph. D.

Reply to Attn. of: AAC-114

To: I. Litant,
DTS-332

The final report on the evaluation of the fire-hardened BART vehicles is enclosed. It was unfortunate that there were so few data points in common where new material could be directly compared with old material.

It should be emphasized that the philosophy, judgment, and conclusions contained in this report are solely those of the author speaking only in his capacity as a scientist. They do not necessarily represent the philosophy, and assuredly not the official policy of the Federal Aviation Administration or the Department of Transportation.

PART I

EVALUATION OF MATERIALS FOR TOXIC THREAT

It is an unfortunate consequence of the relatively undeveloped state-of-the-art of combustion toxicology that the prudent person simply dares not make very precise predictions about the absolute (or even relative) toxicities of thermal decomposition products from a real fire. This caveat is especially appropriate when the materials under consideration have not ever been tested, by any technique, for toxic effects on animals.

In the case at hand, only the replacement materials have been subjected to toxicity tests (DAC) of any kind; so in the best of circumstances there would be no data from the original materials with which to make even a relative comparison. The Douglas full-scale studies utilizing animals were accomplished, unfortunately for the purpose of determining toxicity, at an exposure level that neither incapacitated nor killed; therefore, the results are not particularly useful for establishing either absolute or relative toxic threats.

It has been the contention of this reviewer for some time, however, that the lack of a dependable and relevant procedure for quantifying the toxicity of smoke does not dictate a total inability to reduce environmental toxic hazards. This is especially true for the fire environment associated with transportation vehicles and other occupied spaces that are small enough so that escape from the hazardous environment can be effected in a relatively short time, e.g., in less than 15 minutes.

When the above conditions apply, the primary factors controlling whether one escapes or succumbs (which equates with toxic hazard) are the toxicity of the smoke and how long one is forced to breathe it, i.e., the product of toxic potency and exposure time. A reduction in toxic hazard obviously can be achieved by reducing either or both of these factors.

For any specific locale and any given fire scenario, there will be a minimum time required for each potential smoke victim to become aware of, and escape from, the potentially hazardous area. The greater the fractional part of this escape time that can be kept smoke-free, or at a lower toxic gas concentration, the smaller will be the toxic insult acquired by that individual during his escape to a smoke-free environment -- or the longer will be the time available for that escape.

Consequently, any change in material or material property that delays the initiation of thermal degradation or decreases the rate at which decomposition proceeds, the rate of toxic gas generation, or its overall production will usually accomplish a reduction in toxic threat indirectly. Without having actually measured smoke toxicity, we can, therefore, certainly improve the overall fire threat and probably the toxic threat by judicious manipulation of those material properties such as: ignition temperature, flamespread rate, rate of heat release, smoke production, and even the weight of material required for the installation.

The evaluations and comments that follow are primarily based on a consideration of these "other-than-toxic" properties of the original and replacement materials -- provided such data were available.

EVALUATION OF PROPOSED WALL AND CEILING LINERS

In the U.C. screening tests, both types of new materials (phenolics and polyester) exhibited marked improvement over the liners previously used. Comparative results for the attempted arson scenario (1-kg trash bag) are especially indicative of the reduced fire hazard associated with the replacement liners.

The McDonnell-Douglas tests (retrofitted vehicle) also suggest satisfactory fire performance characteristics; although, unfortunately, there are no similar test results with original materials for actual comparison. The animal results are of little value in this case because there are no data (from original materials) with which to compare them. In addition, animal data cannot at this time be related by anyone to human response times -- or survival times -- under the same exposure conditions.

PROTECTION OF POLYURETHANE FOAM IN THE ROOF

Of the original polymeric materials that were not replaced, it is obvious that the polyurethane foam (PUF) in the roof structure probably represents the greatest single fire hazard and potential toxic threat. It would seem, however, that the likelihood of ceiling involvement has been decreased considerably as a consequence of the other fire-hardening measures. The decision to spray-coat the interior surface of the roof liner with intumescent paint should further delay involvement of the PUF in any given fire scenario.

Therefore, to the extent that the laboratory, screening, and full-scale test data are pertinent and that one can make meaningful risk-benefit and cost-benefit analyses in this area, the BART approach seems justifiable. However, the use of this type of polymer, in large quantities, should be seriously questioned on the occasion of future renovations or vehicle redesign.

COMMENTS ON SEAT PAN DECISION

The seat pans (polyvinyl chloride-acrylic) actually weighed 67 percent of what each urethane foam (PUF) seat did, and represented more of a potential heat load/car than the PUF itself (640,000 BTU vs 624,000 BTU). The justifications for not replacing this material were its relatively slow flame-spread rate, its thermoplastic nature (which causes it to soften and sag away from the flames), and the observation that it was not usually consumed in previous vehicle fires. While this decision seems adequately supported, it should be noted that, should the right set of circumstances occur in a particular incident, both the acrylics and PVC decompose rapidly at relatively low temperatures and PVC can yield over half its weight as gaseous hydrogen chloride (HCl) -- a potentially potent agent of human incapacitation.

It would seem advisable to continue monitoring the degree to which these items are involved in future fires, to see if the previous observations are borne out. If it is found that they are significantly involved, then they should be seriously considered for replacement at some future date.

SUMMARY COMMENTS ON POTENTIAL FOR REDUCED TOXIC THREAT

There can be little doubt that the single, most effective, element of the fire-hardening program was the elimination of the original urethane foam seat cushions. Based on test results, this action greatly reduces the ease of ignition and the likelihood of a fire spreading beyond the initial site before it can be detected and controlled. (There has to be some question, however, of the accuracy of the statement on page 39, Section 4.3.1, to the effect that the LS200 Neoprene cushions do "not produce toxic smoke."(1))

The cushion replacement, in concert with the use of ceiling-wall liners having significantly-improved fire characteristics, surely represents a reduction in the ignition and rate-of-fire-spread hazards.

The decision to protect the car interior by using Thermolag coatings under the floor, replacing PUF with fire-retarded silicone foam at floor-sidewall junctions, and installing silicone foam fire-stops in walls should significantly reduce the threat of fire penetration. Coupling the improved materials with the penetration barriers should produce a car with an undeniably improved fire hazard rating.

And the important point for toxicity considerations is that this reduced level of <u>fire</u> hazard carries with it a reasonable expectation (if not guarantee) of a concomitantly reduced <u>toxic</u> hazard. This is true if only for the reasons that a material that does not become involved does not produce toxic smoke, and a slower rate of fire propagation means a slower build-up of toxic concentrations. Both of these conditions result in an increased time interval available for successful escape, and we therefore have an environment with a reduced toxic threat.

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(1) BART VEHICLE FIRE-HARDENING PROGRAM, Office of C.E.Jenkins & M.K.DuPlessis, March, 1981

PART II

Combustion toxicology is possibly the youngest and least-advanced of the major sub-disciplines in toxicology. In a recent, in-depth review (2) of the subject, a total of 114 scientific publications was cited by the authors as presumably representing significant contributions to this area -- at least in the judgment of those authors. Of these 114 papers: one was from the 1930s, one from the '50s, one from the '60s, 80 from the '70s, and 31 from the 1980s. Over 100 of them had been published since 1975. So, one can see that, although interest rose in the early 1970s, most of the effort has occurred in just the past 4 or 5 years.

Combustion toxicology (CT) can be considered a branch of inhalation toxicology (IT), for the toxic materials are acquired by the potential victims almost exclusively by inhalation. One might have thought that, since IT is a much older and well-established discipline, the emerging specialty of CT could have borrowed heavily from established experimental techniques as well as a large bank of accumulated, and relevant, data. Unfortunately this has not proved to be the case.

There are several reasons why inhalation toxicology provided so inadequate a base on which combustion toxicology could build. It, IT, had been concerned primarily with two types of experimental data, both addressing the absolute or relative toxicities of single toxic species (chemicals) administered in air.

Of these two concerns, one was evaluating individual gas toxicity for acute exposures with animals, wherein the lengths of exposures were fixed and in the range of one to eight hours. Results of such evaluations were usually expressed in terms such as: 4-hour LC50, which signified the concentration in air that would kill 50 percent of the animals when they were exposed for 4 hours.

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(2) Kaplan, H.L., et al., "A Critical Review of the State-of-the-Art of Combustion Toxicology," Southwest Research Institute Report, 1982 (in press).

The second type of general procedure was a long-term exposure of experimental animals, for 8 to 24 hours per day for weeks, months, or even years. The primary purpose was to establish an exposure level that had no detectable deleterious effect on any animal. From such data, an extrapolation -- often including safety factors of up to 100-fold -- was made to predict the "no effect" concentration to which humans could be exposed for at least 40 hours per week, 50 weeks per year, for a working lifetime. These "safe" concentrations, for the industrial environment, have been identified by several terms over the years: TLV (threshold limit value), MAC (maximum allowable concentration), and MAE (maximum allowable exposure).

These values were not very useful to combustion toxicologists because they applied only to a single toxic gas, while smoke is a complex, time-variant mixture of a large and generally unknown number of individual gases. In addition, almost nothing is known concerning the combined effects of several toxic gases.

The exposure periods for most IT studies are also not very relevant to the short times available for successful escape from a fire environment; and it is very risky to attempt the prediction of a 10-minute lethal concentration using, for example, data from a 4-hour LC_{50} study.

Lastly, and maybe of most importance, is the question of the lethality endpoint. It is a statistical fact that most individuals involved in a fire either effect their own escape or perish. In the early 1970s, this reviewer began emphasizing the importance of two major departures from the typical design of IT experimental protocols. One was that incapacitation -- loss of the ability to successfully remove oneself from the life-threatening environment -- was a more appropriate endpoint than death. The second was that time-to-incapacitation (available escape time) was a more meaningful basis on which to compare toxic atmospheres than was the LC_{50} for some stated exposure time. These concepts are now being accepted by a significant number of combustion toxicologists.

So, combustion toxicology has had to start at the very beginning and build its own foundation. Few scientists would agree that it has progressed beyond the stage of a descriptive science. There are many fundamental areas that have not even been explored, much less described.

Major problem areas that have not been adequately resolved include:

a) *What is the appropriate technique for thermally decomposing a test specimen?* (Since the composition of smoke, and therefore its toxicity, has been observed to change dramatically as a result of small changes in the thermal environment, how does one insure that the smoke generated in a test laboratory can be equated with the smoke from that same material in a "real" fire?)

b) *What kind of incapacitation endpoint, measured in an experimental animal, is dependably related to loss of escape potential?* (Should this be a physical incapacitation, a psychological one; should animals actually be trained to escape from a flaming environment?)

c) *What, if any, experimental animal is an acceptable model for human behavior?* (As long as research was concentrating on effects of carbon monoxide and hydrogen cyanide, it seemed the rat could be used successfully as a human model -- provided one utilized the appropriate scaling and kinetic factors. Now that the effects of irritant gases are being explored, hydrogen chloride and acrolein, for example, there is some concern that the rat may be totally inappropriate.)

This reviewer is not alone in feeling that laboratory measurements of the relative toxicities of thermal decomposition products should not be used for regulatory purposes. The National Materials Advisory Board (NMAB) of the National Academy of Sciences stated in 1978 (3) that data obtained from laboratory tests cannot be extrapo-

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(3) National Materials Advisory Board, *Fire Safety Aspects of Polymeric Materials*," Vol. 3: Smoke and Toxicity," NMAB 318-3(1978).

lated to real fire situations. This committee felt that such tests should be used only for screening purposes during development work and as a research tool.

A U.S. Army Technical Report (4) concerned with personnel hazards associated with helicopter fires stated that combustion toxicity testing was "in its infancy and no one is willing at this time to devise design criteria ... much more work must be done in this area, both in identification of toxic products and in understanding their effect on people."

The report of a special advisory committee to the Administrator of the Federal Aviation Administration (5) stated that it was beyond present capabilities of small-scale laboratory toxicity tests to dependably rank-order materials according to their potential toxic hazard.

The very recent critical review of combustion toxicology (2) contained the following statements by the authors:

> "Materials should not be compared or ranked on the basis of smoke toxicity tests."
>
> "Materials should not be regulated on the basis of data from laboratory smoke toxicity tests."
>
> "Regulations based on a laboratory smoke toxicity test conducted under arbitrary conditions could not, with any degree of confidence, assure a reduced risk to life safety associated with the actual use of a material."

In July of this year, the New York State Assembly passed a bill (S.8988) sponsored by State Senator John R. Dunne that would appropriate $300,000.00 for the development of a system of rating the toxicity of smoke and gases emitted by synthetic materials used in building construction and furnishings. (An obvious statement

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(4) U.S. Army Research and Technology Laboratories, "Investigation of the Structural Degradation and Personnel Hazards Resulting from Helicopter Composite Structures Exposed to Fires and/or Explosions," USAAVRADCOM-TR-81-D-16, August 1981.

(5) Final Report of the SAFER Advisory Committee, Office of Aviation Safety, FAA, DOT, Washington, DC (1980).

by the Assembly that, in effect, no acceptable methodology is yet available.)

Apparently the California legislature recently adopted an Assembly Concurrent Resolution (#146) urging that California either adapt or devise a toxicity ranking procedure that could be used for regulatory purposes. (Again a tacit admission that no existing methodology is acceptable.)

The judgment of this reviewer, and the authors cited above, on this subject is not, however, a universally held one. There are other scientists (of greater prominence), other legislative bodies, and other code/regulatory officials who maintain that we do have in hand acceptable methodologies.

The National Bureau of Standards has published a procedure (6) that is being very actively lobbied for across the country (by one of its co-designers, Merritt Birky, Ph.D.). Although a caveat in the report cautions against using the protocol for ranking and selecting end-use materials, it is being considered by several organizations for just such use. (The reviewer, as one of the scientists who participated in the interlaboratory evaluation of the NBS method, does not happen to share the opinion that it has been properly designed, evaluated, and documented as a reliable method.)

Professor Yves Alarie, University of Pittsburgh, (a highly-respected toxicologist) has a selection of several procedures that he has offered as reliable ranking techniques.

So, it is obvious that there is no consensus on this question. And, unfortunately, there may not be in the near future, for the major problem that has existed since 1970, still exists: there has been no real effort by any group, society, or organization to support the required basic research.

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(6) U.S. National Bureau of Standards, "Further Development of a Test Method for the Assessment of the Acute Inhalation Toxicity of Combustion Products," NBSIR 82-2532 (June 1982).

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