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COST/BENEFIT ANALYSIS OF THERMAL SHIELD COATINGS APPLIED TO 112A/114A SERIES TANK CARS

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FINAL REPORT

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FOREWORD

The work described in this technical report was performed under Contract No. DOT-FR-20069 by the Systems Research Department of Calspan Corporation for the U.S. Department of Transportation, Federal Railroad Administration. The basic contract deals with the general design of tank cars for transporting hazardous materials.

This special report deals only with the results of a limited scope ad hoc task concerned with the cost/benefit analysis of thermal shield coatings. This work was monitored by Mr. Donald Levine of the Rail Systems Division of the Federal Railroad Administration and Mr. William Hathaway of the Transportation Systems Center.

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I. SUMMARY

A cost/benefit analysis of thermal shield coatings on 112A/114A tank cars was performed. Thermal shield coatings are coatings which are applied to the outside of a tank to act as an insulator in the event of a fire. The intent is that the coating prevent or delay overheating and overpressurization of the tank which could lead to tank rupture and large loss of life and property. The data for the analysis presented in this report were taken from Railway Progress Institute (RPI) - Association of American Railroads (AAR) cooperative research program reports. The RPI/AAR determined accident data for the years 1965-1970 and based their cost/benefit analysis on this data. In this report, the data of RPI/AAR is updated to present dollars and a re-evaluation of the accident losses is made.

An adjustment is also considered in the interest rate used in the RPI/AAR analysis. The interest rate used in their analysis was 10 percent. A valid question is, however, whether the capital recovery implied by this interest rate should be allowed at all for correction of a design defect affecting safety. Considering thermal shields to be a design correction, a portion of the earnings of current cars without such protection must be considered as coming from the misfortune of others (losses of accident victims). Results of Calspan's analysis are presented in terms of both 10 percent interest rate and zero interest rate.

The "efficiency" of a thermal shield is a dimensionless factor determined by dividing expected overall savings with modified cars by anticipated losses with unmodified cars. Efficiency as defined here is an index of the expected effectiveness of the shields in the aggregate. It is not a measure of the expected effectiveness of an individual shield in a given accident. Higher percentage efficiencies imply higher levels of overall protection. The historical data for insulated 105A tank cars in comparison with uninsulated 112A/114A tank cars show that at the most 3 out of 20 of the 105A cars ruptured after exposure to fire and one of these three may have had an unrelated equipment failure and the other two were exposed to fire for over 8 hours each. Of 55 of the 112A/114A cars exposed to fires of sufficient severity to cause venting from the safety relief valve, 50 ruptured. The efficiency of the thermal shield on the 105A cars, therefore, appears to be nearly 100 percent at least in the early critical hours. Computer calculations of the temperatures and pressures produced in tank cars have indicated that significant reductions in the probability of tank rupture are expected for even thin insulations if the insulation remains attached to the tank during the fire. For example, 0.3 in. of a typical insulation would protect an inverted tank against failure in a fire with a cold wall heat flux of 27,000 Btu/hr ft^2, whereas an uninsulated tank would fail in 14 minutes.

The best estimates of the justifiable cost of thermal shield coatings are given in Table I. This justifiable cost is the amount that could be spent today on a thermal shield coating and the savings due to lowered accident costs and elimination of a separate corrosion protection coating would be paid back plus interest over the life of the coating. As data on expected life of thermal shield coatings are developed, Table I can be consulted to determine whether the coatings can be justified on a cost/benefit basis.

Table I

BEST ESTIMATES OF JUSTIFIABLE COST OF 100% EFFECTIVE THERMAL SHIELD COATINGS ON 112A/114A TANK CARS

LIFE OF THERMAL SHIELD, YRS.	JUSTIFIABLE COST, $	
	10% INTEREST RATE	0% INTEREST RATE
1	429	451
5	1772	2255
10	2850	4510
15	3504	6765
30	4284	13,530

II. INTRODUCTION

About 20,000 railroad tank cars of the 112A and 114A series are presently in service. The 112A/114A cars are used in pressurized service mainly for transporting compressed liquefied gas. A number of the tanks have ruptured after being heated by fires resulting from accidents. The tank ruptures have caused substantial dollar losses and casualties.

Typically, when a tank containing compressed liquefied gas is exposed to fire conditions, the contents first begin to heat and expand to fill the ullage space with liquid. After the ullage space is filled, the liquid continues to expand and forces open the safety relief valve with which each tank must be equipped. On further heating, the saturation pressure of the lading reaches the start-to-discharge pressure of the relief valve and the liquid level recedes as lading is released. While the lading is being heated, the tank shell is also increasing in temperature. Because of the low heat transfer coefficient from the tank shell to gaseous portions of the lading, the portions of the shell in contact with gaseous lading increase in temperature at a faster rate than portions of the shell in contact with liquid lading. If at any time during the heating, the stress in the shell due to internal pressure, and to a small degree thermal stress, exceeds the strength capability of the shell material at temperature, the tank will fail. (Analysis of failures of tanks in fires indicates that the predominant failure mode is thinning of the shell over the vapor space followed by the initiation of a crack along a longitudinal line. This indicates a pressure induced failure rather than a thermal stress failure.) Tank failures have often taken the form of large, rapidly propagating cracks with large, nearly instantaneous, release of burning lading. As the pressure is released, large amounts of lading are converted to the gaseous state. The result has been that portions of tank weighing tons have rocketed hundreds of feet with resulting physical destruction and fire spread. Even without rocketing the area of damage increases greatly when a tank ruptures.

Safety relief valves on 112A/114A tank cars are required to limit pressures to less than 306 psig (49 CFR 179.102-11). In Reference 1, calculations were made which show that present safety valves do not have sufficient flow capacity to limit pressures to 306 psig when a tank is exposed to severe fires especially when the tank is overturned and the valve is communicating with liquid. It was also determined the the combination of pressures and tank shell temperatures resulting from fires could result in tank failures.

The 112A/114A series cars have bare, uninsulated tanks. The possibility exists for thermally insulating cars to reduce the effects of fires on the ability of the tank to contain the lading. Thermal insulation can reduce the effects of fires on tanks in two ways. The insulation reduces heat input to the car which, therefore, reduces safety valve flow requirements. Thus a smaller valve can maintain safe tank pressure in an insulated car compared to that for an uninsulated car. In addition, the insulation may reduce the heating to an extent such that the temperature of even the portions of the tank shell in contact with gaseous lading is less. This reduced shell temperature arises from the fact that the heat transfer away from the portion of the shell in contact with gaseous lading, even though low compared with heat transfer away from the portion of the shell in contact with liquid, is sufficient to maintain a low shell temperature because of the lowered heat transfer through the insulation. (Thermal insulation also reduces thermal gradients in the tank shell and therefore the thermal stresses although small compared with pressure stresses).

This report deals with a cost/benefit analysis of thermal shield coatings for 112A/114A series tank cars. A thermal shield coating is a coating which is applied to the outside of a tank and acts as an insulator in the event of a fire. A thermal shield of the jacketed insulation type used previously on tank cars is not in the category of a coating and is given only brief consideration later in this report. A cost/benefit analysis is composed of three key factors, namely:

1. The magnitude of expected dollar losses.
2. The cost per car of implementing a proposed modification.
3. The "efficiency" of the modification in reducing the dollar losses.

The amount of expected losses can be estimated from statistical review of historical data on losses. The cost of implementing a proposed modification will not be determined in this report. Instead, we will determine at what cost a modification would be cost beneficial. Some information will also be given on possible costs of coatings. The efficiency of the modification can be estimated from analysis combined with available historical data on losses from insulated and uninsulated tank cars in compressed gas service. The term "efficiency" as expressed here is a dimensionless factor determined by dividing expected overall savings with modified cars by losses anticipated with unmodified cars. The savings obtained by adoption of the modification results from a reduced frequency of occurrence of tank rupture. Reduction in the magnitude of loss for a given accident for which rupture occurs is not implied.

The amount of expected losses with unmodified cars multiplied by the efficiency determines the reduction in losses, i.e. savings, that can be expected. These savings can be utilized to pay for the modification plus interest over a number of years. The amount at 100 percent efficiency that could be paid back, including interest, from the expected savings is termed present value. Any reduction in efficiency of the modification reduces the present value proportionately. The economic benefit is the cost of the modification subtracted from the present value at the efficiency of the modification. If the economic benefit is positive, it is then economically justifiable to make the modification.

The Railway Progress Institute (RPI) and the Association of American Railroads (AAR) in a cooperative research program have investigated thermal shields and the losses occurring in tank car accidents due to fires.[2,3,4] The RPI/AAR reports list all loaded tank cars known to have been exposed to fire during the years 1965-1970. Some data were also published for fires outside of this time period but primary emphasis was on these years. Incidents of loss are sorted by class of tank car. Loss figures are composed of two parts: (1) cost of lost lading and (2) other losses caused by the loss of this lading, including fire damage to equipment, real property, and loss of life. A review of the RPI/AAR loss data for 112A/114A tank cars exposed to fires is given in Table II.

TABLE II

112A/114A TANK CARS EXPOSED TO FIRE - 1965-1970*

Losses, $	11,879,000
No. of Cases	65
Lost All of Lading Due to Fire	56
Ruptured	50
Avg. No. of Cars in Service	~12,000
No. of Years	6
Losses, $/Car/Year	165

*Data taken from Ref. 3, p. 7 and 8.

The RPI/AAR has also developed an estimate of the maximum value of a 100 percent effective thermal shield applied to 112A/114A tank cars. The analysis includes the effect of the reduction in costs normally incurred in applying a corrosion protection coating on uninsulated tanks. The report here presented includes an estimate of expected thermal shield efficiency, an update of the losses in terms of present costs, a re-evaluation of losses, and the effects of cost of capital.

III. COST/BENEFIT ANALYSIS

A. Thermal Shield Efficiency

The efficiency of a thermal shield is a dimensionless factor determined by dividing expected overall savings with modified cars by losses anticipated with unmodified cars. Efficiency as defined here is an index of the expected effectiveness of the shields in the aggregate. It is not a measure of the expected effectiveness of an individual shield in a given accident. Higher percentage efficiencies imply higher levels of overall protection. Because the thermal shield is not fully defined, it is not possible to determine an efficiency. Appendix A presents historical data on 105A insulated tank cars which indicates that they have an insulation efficiency approaching 100 percent. In Appendix B are analyses which show the value of typical coatings in reducing heat input to a tank car. These considerations indicate that thermal shield coatings in conjunction with present relief valves sized for uninsulated 112A/114A tank cars can have an efficiency of nearly 100 percent if the coating remains attached to the tank shell during a fire. An efficiency of 100 percent has been used for all calculations in this report.

B. Update of Losses

The RPI/AAR cooperative research program has evaluated losses due to exposure of loaded tank cars to fire by examining data on accidents for the years 1965 through 1970. This data is the most extensive available at the present time. As more recent data becomes available it should be utilized in the analysis; however, obtaining the necessary data is beyond the scope of this work. RPI/AAR is planning to compile losses for more recent years. As this data becomes available, the analysis should be modified. In this report the losses for the period, 1965-1970 will be updated to present dollars to account for changing values of damaged items. A re-evaluation of the losses also will be made based on a more extensive investigation of losses for a few accidents. Some discussion will also be presented of losses since the time period of the RPI/AAR report.

The dollar losses in the RPI/AAR report are composed of the cost of lading and other losses cuased by the loss of this lading including fire damage to equipment, real property, personal injury, and loss of life. The loss data are given in Table I. Since the time period of the report, the values of many of the damaged items have increased substantially. For example, lost propane lading was priced at 6¢/gal. for the RPI/AAR report but present source prices are 7.9¢/gal. for the 2/3 of the supply produced from natural gas and therefore regulated and this is expected to go to 11-13¢/gal. shortly.[7] The wholesale price index has increased by 67 percent since 1967 (U.S. Department of Labor). To account for these changes in loss values, values of ladings have been adjusted to their present worth and other losees have been evaluated on the basis of the change in the wholesale price index. This results in losses in terms of present costs of $19,800,000 compared with the $11,879,000 for the period 1965-1970.

In References 5 and 8, a review of accident statistic research was reported. These reports looked in detail at the losses in five accidents chosen to be representative of a range of dollar losses per accident. For this reassessment of losses, a number of information sources were utilized. Individual accident files of the RPI/AAR group, the National Fire Protection Association, Railroad Transportation Insurers, eye witnesses, city officials, and an attorney were among the sources utilized. The particular accidents studied do not only include losses due to fire exposure, but the re-evaluation of losses is probably indicative of fire exposure accidents. In some instances the RPI/AAR estimates were found to have omitted some of the actual losses. In other instances more than direct damage were included by Calspan such as the cost of evacuation, manhours expended by public safety personnel, and loss of earnings resulting from temporary evacuation of businesses. Additional information was available at the time of the Calspan re-evaluation as a result of actual litigation settlements rather than projected settlements. The results of the re-evaluation are presented in Table III. In general, the RPI/AAR estimates are lower than the Calspan estimates, primarily because Calspan included more than just direct damage.

TABLE III

RESULTS OF ACCIDENT LOSS RE-EVALUATION

Accident	RPI/AAR	Calspan	% Increase
New Athens, Ill. 4/9/70	$ 84,000	$ 128,000	52
Armitige, Ohio, 4/25/70	4,800	11,100	131
Crescent City, Ill., 6/21/70	1,900,000	2,200,000	15
South Byron, N.Y., 8/27/70	119,000	146,000	22
Crete, Neb., 2/18/69	2,000,000	2,000,000	0

The arithmetic average of the increased costs presented in Table III is 44 percent. However, Calspan is of the opinion that increasing all costs by 44 percent based on such a small sample would be unrealistic. Our own investigator was on the site at both Crescent City, Illinois, and South Byron, New York, and these data are believed to be the most accurate. We believe that a reasonable estimate of the increased costs is 25 percent. Applying this increase to the RPI/AAR estimate of total losses adjusted to present dollars ($19,800,000) results in total losses of $24,750,000.

In the time period of the RPI/AAR evaluation of losses (1965-1970), two accidents accounted for over 80 percent of the total losses. Laurel, Miss., 1/25/69, resulted in $7,813,000 in losses and Crescent City, Ill., 6/21/70, resulted in $1,850,000 in losses due to exposure to fire. Are accidents of this size during a six-year time period likely? Since 1970 several large accidents of 112A/114A cars have occurred. On October 19, 1971, in Houston, Texas, two tank cars were punctured and the subsequent fire caused 112A/114A tank cars to rupture.[9] No detailed estimate of the amount of damage was presented in the National Transportation Safety Board (NTSB) report but one fireman was killed, 50 people were injured including 20 hospitalized, 2 cars were destroyed, 14 cars were extensively damaged and six others lightly damaged. Also destroyed were a residence, a fire truck, an automobile, and a railroad motor truck. Several buildings incurred such damage as paint blisters or broken windows.

On July 15, 1973, at Kingman, Arizona, a car ruptured after a fire erupted on a siding. Thirteen people died as a result and 95 were injured, many very severely. Extensive property damage occurred in the surrounding area. Property damage has been estimated to be $1,000,000 (Fire Journal, January 1974). No value of total losses can be made because litigation is still in process but considering the number of deaths and injuries the total is expected to be more than $10 million. This accident is not being investigated by the NTSB as it is not considered to be a transportation accident because the car was parked in a private siding. However, the losses were a result of fire exposure of a 112A/114A tank car and these losses must be assigned to the 112A/114A category. It is not known whether any non-transportation accidents were omitted from the RPI/AAR data.

Other recent large accidents involving 112A/114A cars include Oneonta, N.Y., February 12, 1974, Decatur, Illinois, July 19, 1974, Houston, Texas, September 21, 1974, and La Mirada, California, October 31, 1974. Detailed reports have not been issued on these accidents so that conclusions on the amounts of losses and influence played by fire exposure must be tentative but the accidents indicate that there continues to be large dollar losses and often fire exposure plays an important role in the losses. In the Oneonta, N.Y. accident, 52 people were injured when four cars ruptured after being heated in a fire (Oneonta Star, February 13, 1974). At Decatur, Illinois, damage estimates are $14 million and two people were killed and 6 of 140 injured were in critical condition. Evidently, this accident did not involve fire exposure of a car but it is indicative of the possible losses (Decatur Review, July 21, 1974). In the second Houston accident there was one death, 190 railcars destroyed, 240 cars heavily damaged, and several residences and businesses damaged. Total damage was estimated by the railroad to be $12-$14 million of which $4 million was damage incurred by the railroad (Railway Age, October 14, 1974). At La Mirada, California, an LPG tank car ruptured after fire exposure. There were no injuries but a railroad spokesman estimated damage at $1 million (Los Angeles Times, November 2, 1974).

The accidents mentioned above are a sampling of large accidents since 1970. They indicate a continuing problem of accidents involving losses of millions of dollars. Hence, the years 1965-1970 do not represent an overly severe loss period. There have been accidents since 1970 in which losses due to fire exposure were even greater than the Laurel, Mississippi, accident which was by far the largest in the years 1965-1970. We shall, therefore, use the losses from the RPI/AAR report as representative of the expected losses in future years.

The updated losses developed in this section are given in Table IV along with the 1965-1970 RPI/AAR data. Presently there are about 20,000 cars in service rather than the average 12,000 cars in 1965-1970. The precise number of cars is not important because per car costs are actually required for the cost/benefit analysis.

TABLE IV

LOSSES FOR 112A/114A TANK CARS EXPOSED TO FIRE

	RPI/AAR[3] 1965-1970	Updated To Present Dollars	Losses Increased By 25 Percent	Increased No. of Cars
Losses, $	11,879,000	19,800,000	24,750,000	41,250,000
Avg. No. of Cars	12,000	12,000	12,000	20,000
No. of Yrs.	6	6	6	6
Losses, $/Car/Year	165	275	344	344

C. Cost of Capital

In the calculations by RPI/AAR of economic benefit of potential design changes, such as a thermal shield, a stream of payments was converted to a present sum by means of conventional interest formulas. The interest factor used was 10 percent. The use of 10 percent for capital recovery and earnings can be considered conservative. The question is, however, whether capital recovery should be allowed at all for correction of a design defect affecting safety.

There is a very strong precedent for no capital recovery allowance with respect to safety defects. It should be noted that automobile manufacturers have absorbed the total cost of the vast majority of recall campaigns for the correction of safety-related items. Other examples of instances where strict cost/benefit analyses have not been adhered to can also be cited. Nursing homes are subject to strict fire prevention safety measures. A cost/benefit analysis would reveal that the cost of safety items exceeds the reduction of losses. Because of the age of the victims, considerations of such things as potential future earnings result in no change in the conclusion that improvements are not cost effective. The response to the nursing home fire problem, on the other hand, has been one of increasingly stringent design requirements. A principal driving force behind these requirements has been the desire to prevent injury and death, with consideration beyond simple dollar balancing. Similarly, in the transportation industry, e.g., airline and pipeline, both voluntary and mandatory standards have not been derived from equalized cost of design versus loss data. For one thing, historical loss data are frequently unavailable or, in the case of new design, not applicable.

Cost/benefit studies are a very useful tool. However, with regard to safety considerations, they should extend beyond derivation of a balance point between cost of improvement and loss reduction. As a minimum, assessment of the impact of adoption of an improvement on the viability of the service should be considered. It is to this point that the sensitivity of transportation cost to car initial cost applies. The RPI/AAR study did not address this point at all. In essence, they looked only at a lower bound of a "permissible" expense based on current economics and did not include a look at an upper bound, i.e., the best design consistent with the viability of the service. The National Transportation Safety Board (NTSB) commented on the problems of implementing design changes following the Crete, Nebraska, incident.[10] To paraphrase this NTSB report: Changes to existing cars required because of faulty initial design should be considered as corrections of an overlooked matter rather than being considered as costly and profit reducing and therefore as questionable improvements.

In the next section, justifiable costs of thermal shields are computed on the basis of cost of capital of both 10 percent and zero percent.

D. Justifiable Cost of Thermal Shield Coatings

The RPI/AAR[3,4] determined the maximum justifiable cost of applying 100 percent effective thermal shield coatings to entire tank cars by estimating the cost of corrosion protection which the coating would replace and the accident losses that the coating would prevent. These savings can be utilized to pay for the modification plus interest over a number of years. The amount at 100 percent efficiency that could be paid back, including interest, from expected savings is termed present value. Any reduction in efficiency of the modification reduces the present value proportionately. The present value represents the economically justifiable cost of using a thermal shield.

RPI/AAR determined that the value of the corrosion protection of a thermal shield was $121/car/year. (Note: This saving would not be realized for conventional jacketed insulation construction. Otherwise the savings would be similar.) This was determined in 1972. We shall increase this by 20 percent to $145/car/year to update the savings to present dollars. An upper and a lower bound were put on the accident losses. The lower bound assumes that damage to the car itself (including trucks, brakes, etc.) would not be prevented by a thermal shield. The upper bound assumes that the thermal shield would have prevented all car damage. (Accident loss data have not delineated whether car damage was due to fire or the initial accident which necessitates the upper and lower bounds on losses.) The upper bound was $165/car/year (Tables II and IV) and the lower bound was $147/car/year. We shall use these same values updated to present dollars and including an increment to account for the re-evaluation of losses. RPI/AAR used an interest rate of 10 percent in their calculations. We shall use this value and also a zero percent interest rate as discussed in the preceding section.

The results of the calculation of justifiable cost of applying a 100 percent effective thermal shield are shown in Table V. All of the updated values in this Table are based on current dollars. No projection has been made in terms of future dollars. Also, Table V is based on the assumption that the years 1965-1970 were a normal period for tank car accidents. Based on the previous sections of this report, the columns headed "Losses Increased by 25 Percent" are believed to more closely represent the actual justifiable cost. Also, the lower bound probably is closest to being correct because it is believed that a thermal shield will not prevent much damage to a car, at least the car will often have to be taken out of service and shopped, which involves considerable expense. In any event, the lower bound provides a conservative estimate of the justifiable cost of a thermal shield coating. Based on the above comments, the justifiable cost of a thermal shield coating has been defined dependent only on the expected life of the shield and the chosen interest rate for cost of capital. For example, a coating with a life of 10 years which might be a desired goal, can be justified if its installed cost were $2850 at an interest rate of 10 percent or $4510 at zero interest rate.

Development of costs of coatings is not within the scope of this work but some discussion of the justifiable costs in terms of per square foot or per gallon of coating is possible. A 33,000 gallon 112A/114A tank car has very nearly 2000 ft^2 of outside surface area. Therefore, the justifiable cost is $1.40/$ft^2$ to $2.30/$ft^2$ for a coating with a 10 year life. Also, for this same coating a total of 370 gallons of coating would be required for a 0.3 in. thick coat. This is gallons actually remaining in the tank after cure. Depending on the type of application procedure and evaporation percentage, the actual amount of coating used could be much more. For 370 gallons the justifiable applied cost is $7.70/gal. to $12.20/gal.

Conventional jacketed insulation such as found on 105A cars might also be considered for thermal shields. The analysis presented in this section would also be applicable to this type of construction except that the savings due to the lack of additional corrosion protection would not be realized. This type of construction would then only be justified if it were less costly or if the

Table V

JUSTIFIABLE COST OF 100% EFFECTIVE THERMAL SHIELD COATING ON 112A/114A TANK CARS

LIFE OF THERMAL SHIELD, YRS.	RPI/AAR VALUES, 10% INTEREST RATE		UPDATED TO PRESENT DOLLARS				LOSSES INCREASED BY 25%			
			10% INTEREST RATE		0% INTEREST RATE		10% INTEREST RATE		0% INTEREST RATE	
	LOWER BOUND[1]	UPPER BOUND[2]	LOWER BOUND[3]	UPPER BOUND[4]	LOWER BOUND[3]	UPPER BOUND[4]	LOWER BOUND[5]	UPPER BOUND[6]	LOWER BOUND[5]	UPPER BOUND[6]
1	$ 255	$ 272	$ 371	$ 400	$ 390	$ 420	$ 429	$ 466	$ 451	$ 489
5	1053	1124	1533	1651	1950	2100	1772	1922	2255	2445
10	1694	1808	2465	2654	3900	4200	2850	3090	4510	4890
15	2082	2222	3030	3263	5850	6300	3504	3800	6765	7335
30	2546	2717	3705	3990	11,700	12,600	4284	4646	13,530	14,670

	ACCIDENT LOSS SAVINGS	+	CORROSION PROTECTION SAVINGS	=	TOTAL SAVINGS ($/CAR/YR)
1	147	+	121	=	268
2	165	+	121	=	286
3	245	+	145	=	390
4	275	+	145	=	420
5	306	+	145	=	451
6	344	+	145	=	489

LOWER BOUND ASSUMES THAT THERMAL SHIELD DOES NOT PREVENT ANY DAMAGE TO THE TANK CAR

UPPER BOUND ASSUMES THAT THERMAL SHIELD PREVENTS ALL DAMAGE TO CAR AND SUFFERS NONE ITSELF.

life of the shield were expected to be longer or if the efficiency were greater. Greater shield life has been found to be true compared with the coatings tested to date but final comparisons await further testing. Because the thickness is greater, the jacketed insulation would probably provide greater thermal protection and therefore efficiency more closely approaching 100 percent. For this configuration, the best estimate of justifiable cost at 100 percent efficiency would be $2907 for 30 years shield life at 10 percent interest rate. At zero interest the corresponding value would be $9180.

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APPENDIX A

HISTORICAL LOSSES OF INSULATED AND UNINSULATED TANK CARS DUE TO FIRE

As an aid to estimating the efficiency of thermal shield coatings for reducing losses due to fire, this Appendix examines the losses that have been experienced historically by 105A (insulated) tank cars in comparison with 112A/114A (uninsulated) tank cars.

Prior to the introduction of the 112A/114A series tank cars, series 105A tank cars were utilized for compressed gas service and 105A cars are still utilized for this service. The 105A cars consist of an inner tank which is covered with insulation. The insulation is covered with a metal jacket. The insulation is required to "be of sufficient thickness so that the thermal conductance at 60^{o}F is not more than 0.075 Btu per hour, per square foot, per degree F temperature differential" (49 CFR 179.100-4) but is otherwise unspecified. Typically, the insulation is rock wool, glass wool, cork, or a foamed in place synethetic material. The major concern of this report is insulators which are coated directly on the tank shell without an outside metal jacket. However, the purpose is thermal insulation similar to that of 105A cars. It is informative to look at the history of losses of 105A insulated cars compared to 112A/114A uninsulated cars that have been exposed to fires.

Insulated cars are allowed to have smaller safety relief valves because of the reduced heating load through the insulation. For safety valve sizing, the assumed heating load is increased over that through an insulator of 0.075 Btu/hr ft^{2o}F because of the increase in conductivity at elevated temperatures, the possibility of losing insulation in an accident, and the heat transferred through connections and fittings. The sufficiency of the assumed increased heating has been found to be somewhat dubious (Ref. 1, p. 47). That is, the supposed large safety factor in safety valve sizing for insulated cars (105A's) may not exist. However, in actual practice, the valves that have been used for uninsulated 112A/114A cars are only 30 percent larger than the minimum allowable according to the specifications whereas the valves that have been used for insulated 105A cars are 11 times the minimum allowable (Ref. 5, p. 70). If insulating coatings were put on 112A/114A cars without changing the valve from the one used for the uninsulated cars, then the valve would also be substantially oversized compared with the specified minimum allowable. Therefore, looking at the efficiency of the thermal shield on 105A cars would appear to be indicative of the efficiency that could be expected for one particular specification of thermal shield on 112A/114A cars with the present safety relief valves.

Reference 3 gives the RPI/AAR data on loaded tank cars exposed to fires for 1965 through 1970. "Exposed to fire" is defined as suffering visible fire damage, i.e. at least blistered paint. Loaded tank cars includes all cars "which were known to have been loaded when exposed to fire as well as those where it was not known whether the tanks lost lading prior to the fire exposure due to a puncture in the initial accident. Tank cars punctured initially are excluded only if they were known to be essentially empty when later exposed to fire." Thirty series 105A cars were reported to have been exposed to fire. Of these, 26 lost all of their lading due to fire including 9 that ruptured. Further examination of the data in Reference 3 indicates that 5 of the cars exposed to fire were 105A100W's containing ethylene oxide and all five of these cars ruptured (actually stated as exploded in this instance). Ethylene oxide may polymerize when heated. It is not a commodity that is shipped in 112A/114A cars, LPG is the major commodity shipped in 112A/114A cars and it does not polymerize. Commodities that may polymerize and which are commonly shipped in both 105A and 112A/114A cars are vinyl chloride and butadiene. However, explosive polymerization in tank car fires of these commodities is rare, whereas it is not in the case of ethylene oxide. Therefore, 105A100W cars loaded with ethylene oxide should be eliminated from historical data on the efficiencies of thermal shields considered for 112A/114A cars. In addition, one of the cars that ruptured was actually an ARA V series car which is a predecessor of 105A series cars and probably not indicative of modern insulated car technology. Eliminating the five 105A100W cars loaded with ethylene oxide and the ARA V car leaves 24 of the series 105A cars which were exposed to fire. Twenty of these lost all of their lading, including 3 that ruptured. Of the three that ruptured; one was loaded with anti-knock compound and had been heated an unknown time before rupture, one was loaded with butadiene and had been heated for 8 hours and 52 minutes, and one was loaded with vinyl chloride, and had been heated for 10 hours and 15 minutes. Valve operation or lack of operation is not known for two of these ruptures but in the third, the valve was known to have remained closed, an anomaly which may indicate faulty valve operation and which may have influenced car rupture. Also, none of the ruptured cars contained LPG, the major commodity shipped in 112A/114A cars. In any event, the vast majority of 105A cars did not rupture during exposure to fires.*

By comparison with 105A series cars, of the 65 112A/114A series cars exposed to fires, 56 lost their lading including 50 that ruptured. Of the 15 cars without ruptures, 7 did not vent at all, i.e., they must have been very small fires as the contents could not have heated to even 115°F, the maximum summer loading condition. For three cars, it is not known if they vented or not and it was assumed by RPI/AAR that one or more of these were punctured in the initial accident. Eliminating the 7 cars in which there was not venting and the 3 cars for which venting was not known, leaves 50 ruptures of 55 cars exposed to fires which were at least of sufficient severity to cause venting.

In summary, during the time period 1965-1970, 3 of 20 (15%) insulated cars which had been exposed to fire eventually ruptured and some of these ruptures may have had safety equipment failures. Of 55 series 112A/114A cars exposed to substantial fires, 50 ruptured (91%). It is evident that 105A cars are very much less apt to rupture on fire exposure than 112A/114A cars. This information suggests that the insulation combined with safety relief valves larger than called for in the Tank Car Specifications result in cars less prone to rupture during fire involvement.

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* In the decades prior to 1965 some 105A cars loaded with LPG have ruptured when exposed to fire, but it has been a rare event. The Shattuck, Oklahoma, accident of March 4, 1958, being about the only notable major accident.

APPENDIX B

CALCULATIONS OF EFFECTIVENESS OF THERMAL SHIELDS

A simplified analysis gives an indication of the effectiveness of even thin layers of insulation as may be found in coatings. The effective combined radiant-convective coefficient for a noninsulated tank is about

$$h_{non} = \frac{30{,}000 \text{ Btu/ft}^2 \text{ hr}}{1700^{o}\text{F}} = 17.6 \text{ Btu/hr ft}^{2\,o}\text{F}$$

The conductance of a coating is given by:

$$h_{coating} = \frac{k}{\delta}$$

where k is the thermal conductivity of the coating and δ is the coating thickness. The composite or net effective heat transmission coefficient through a coating is

$$h_{eff} = \frac{h_{non}\ k}{k + h_{non}\delta} = \frac{17.6k}{k + 17.6\delta}$$

The ratio of heat input to the lading for an insulated versus a noninsulated tank is given by

$$\frac{q_{ins}}{q_{non}} = \frac{h_{eff}}{h_{non}}$$

$$\frac{q_{ins}}{q_{non}} \approx \frac{k}{k + 17.6\delta}$$

The thermal conductivity of the insulation is not known because various coatings could be used but reasonable insulation would be expected to range from 0.1 to 0.3 Btu/hr ft°F. For an insulation thickness of 0.3 in. and assuming no intumescence of the coating, we get

$$0.19 \leq \frac{q_{ins}}{q_{non}} \leq 0.41$$

Hence, substantial heating reductions should be expected even for relatively thin insulative coatings.

Using a Calspan computer program developed as a part of this work, more rigorous evaluation of the effectiveness of insulations may be made. The thermal model represents a tank car enveloped by fire either upright or rolled over at any angle. The tank car geometry is described by inputs for its length, diameter, shell thickness, number of relief valves, their position along the tank, their flow area, discharge coefficient, and the tilt or roll angle from the vertical. In addition, if external insulation is present, it is specified by its thickness, thermal conductivity (which may be varied with temperature) and the product of density and specific heat.

The heat input from the fire is described by inputs for its temperature, emissivity, and the heat transfer coefficient for convective heating. These quantities may be varied around the tank. Heat input to the lading is described for liquid and vapor separately by a heat transfer coefficient. Liquid heat transfer coefficients are computed by equations that represent curve fits to experimental data, and are valid for propane only.

The model computes heat penetration to the lading, which results in a computed rise in temperature of the external insulation, if any, the tank shell, the vaporized lading, and the liquid lading. In computing the external heating, heat is reradiated to the fire at increasing rate, and convective heating decreases as the outer surface temperature rises, resulting in a reduced heat penetration to the lading. The steel of the shell is described by burst pressure tables that are based upon ultimate strength, and are prepared by calculating burst pressure from simple thin shell relations.

Using the computer program, calculations have been made for 112A/114A cars exposed to fire conditions and have included both insulated and uninsulated configurations. One set of computations has shown that an uninsulated car would fail after 14 min. under a 27,000 Btu/hr ft^2 cold wall heat flux (representing a fairly severe fire) with the valve in the 150^o down position (Ref. 6). Under similar conditions, a car with 0.3 in. thick insulation of 0.25 Btu/hr ft^{o}F would have a maximum tank pressure of 250 psi-less than the tank burst pressure. Other calculations show similar improvement for relatively thinly insulated cars.

APPENDIX C

SIGNIFICANCE OF HEAD SHIELDS ON THERMAL SHIELD COATINGS COST/BENEFIT ANALYSIS

The objective of this work has been to determine the cost/benefit of thermal shield coatings on 112A/114A tank cars. However, since the work began an amendment to the Specifications for Tank Cars (49 CFR 179.100-23) has been made by the Hazardous Materials Regulations Board, Department of Transportation (Docket No. HM-109, Amdt. Nos. 173-83, 179-15). The amendment states that "each end of a specification DOT-112A and 114A tank car must be equipped with a protective head shield." The purpose of the head shield is to reduce accidental punctures of the heads. Numerous incidents of head punctures have occurred with resulting lading loss and fire. These fires are one of the sources of fires to which other tank cars have been exposed and which led to the consideration of thermal shields as a potential means of loss reduction. To the extent that head shields are effective in preventing fire exposure of other tank cars, thermal shields provide superfluous protection and conversely to the extent that thermal shields prevent losses due to fires, head shields are superfluous. Determination of the interaction of the protection afforded by head shields and thermal shields is beyond the scope of this work.

If both thermal shields and head shields are put on the same cars, the cost/benefit analysis will have to consider the redistribution of losses as described in Reference 11. In that report it was found that because of the small amount of historical data, shell punctures which accounted for only 18 percent of the lading spills were responsible for 68 percent of the dollar losses. The historical data were too limited to provide the correct distribution of losses between shell and head punctures. This necessitated a redistribution of losses. A cost/benefit analysis of thermal shields combined with head shields would also require a similar redistribution of losses. Data relative to these losses are given in Ref. 4, p. D-12.