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COMPARISON OF THERMALLY COATED AND UNINSULATED RAIL TANK CARS FILLED WITH LPG SUBJECTED TO A FIRE ENVIRONMENT

William Townsend
Charles Anderson
John Zook
Gregory Cowgill

DECEMBER 1974
FINAL REPORT

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December 1974

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ABSTRACT

Two fire tests were conducted on 128 kiloliter, high pressure rail tank cars filled with liquified petroleum gas. Both tank cars were exposed to an intense hydrocarbon fire after being outfitted with appropriate instrumentation. The instrumentation was monitored and its output recorded throughout the fire tests. To test the feasibility of insulating railroad tank cars to protect them from fire exposure, one of the cars was coated with a 0.318 cm thermal shield. A comparison of data conclusively shows that a thermal shield significantly alters the thermal response of a rail tank car in a fire environment.

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INTRODUCTION

The Ballistic Research Laboratories (BRL) are conducting a series of field tests with scaled and standard size railroad tank cars at the request of the Federal Railroad Administration/Department of Transportation (FRA/DOT). This effort is part of an extensive research program jointly sponsored by FRA/DOT and Railway Progress Institute - Association of American Railroads (RPI-AAR). The program is designed to develop methods to minimize personal injury and property damage due to the rupture of railroad tank cars filled with flammable materials.

The basic situation under investigation is unperforated railroad tank cars filled with liquified propane and engulfed in large external fires. The intensive heat of the external fire is conducted through a tank car's shell and into the propane lading. Thus, the lading temperature increases resulting in an increase in the internal pressure. This higher pressure, in combination with a reduced burst strength of the tank car shell caused by the elevated skin temperatures, can lead to a rupture of the shell and the resulting severe conditions that often result in injuries and extensive property damage.

The Federal Railroad Administration desires to develop procedures for ensuring that the railroad tank car will not rupture when subjected to a fire environment, thereby containing the fire and the tank car to the local area. (Often, when rupture does occur, large pieces of the tank car are rocketed a considerable distance.) A less stringent but not as desirable goal is to delay rupture. Delaying rupture allows time for additional lading to escape, allows time to take appropriate measures for minimizing damage to surrounding property, and allows time for evacuating the immediate area. This intermediate goal becomes more desirable as the delay time to rupture becomes long enough to allow the tank to empty its hazardous contents in a controlled manner; i.e., the material escape is controlled by the relief valve as opposed to its being released all at once in a rupture with the consequential explosion.

Two 128 kiloliter (33,700 gallon) high pressure tank cars, loaded with liquified petroleum gas (LPG), were exposed to a large hydrocarbon fire. One car was coated with a thermal protective shield. This report addresses itself to a comparison of the responses of these two tank cars to a fire environment.

II. THE PROBLEM AND A SOLUTION

The basic problem is a consequence of the material properties of steel. Figure 1 graphs the pressure required to burst (or rupture) a cylinder of TC-128 steel. The thickness of the steel in the AAR test

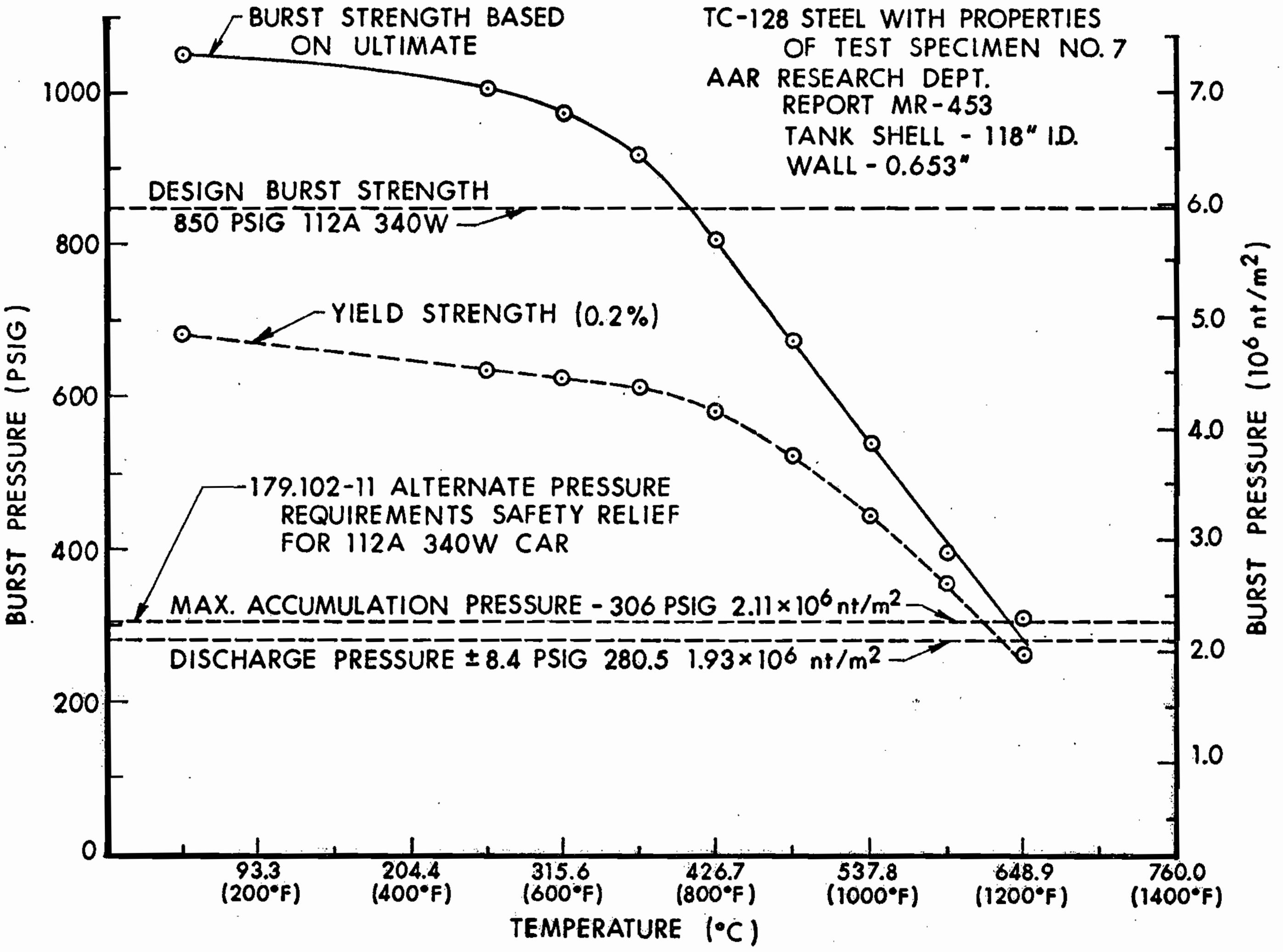

Figure 1. Tank Car Shell Burst Strength Variation with Temperature.

sample closely approximates the 1.59 cm (0.625 in) thickness of the walls of the tank cars under study. Also, the assumed diameter of the cylindrical shell and the tank car's diameter are comparable.

At normal operating temperatures, a rail tank car can survive pressures of the order of at least 5.96 x 10^6 nt/m^2 (850 PSIG). However, above 316°C (600°F), the material strength of the tank car steel begins to degrade. In particular, when shell temperatures are of the order of 650°C (1200°F), the steel shell could possibly fail even though the relief system of the tank car is functioning satisfactorily. Fire temperatures encountered by rail tank cars, involved in some sort of accident, can easily be several hundred degrees higher than the "survival point" of the steels currently used in tank car construction. These elevated skin temperatures can result in the tank car rupturing with the hazardous consequences of property damage and loss of life.

High skin temperatures are expected in the ullage region of the shell. Those portions of the shell which are in contact with the liquid lading remain relatively cool due to the good heat transfer characteristics of the liquid. However, the vapor has very poor heat transfer characteristics. The heat, unable to dissipate away from the shell, raises the temperature of the shell until the external heat source is removed or quenched; or the shell temperature comes to equilibrium with the fire environment; or if the fire temperatues are sufficiently high, the tank car fails.

One of the possible solutions in delaying, and in some cases perhaps preventing the stress-rupture failures of tank cars exposed to fire is to insulate the rail tank cars with a thermal protective coating. The insulation retards the heat flux to the tank wall and thus serves a two fold purpose. First, the steel wall does not heat as quickly and thus, from a material standpoint, makes the tank car less vulnerable to the fire for a longer period of time. Second, with the heat flux to the car less, the "effective capacity" of the relief valve is greater. That is, the flow requirements of the valve are less for the insulated tank in maintaining or precluding some maximum pressure.

III. THE EXPERIMENTAL SETUP

The test procedure consisted of simulating a possible accident environment. Fire engulfment, whether the result of a derailment and puncture, coupler puncture, or a previous rupture, is one of the more severe conditions that a rail tank car can be subjected. For each of the two tests, a full size railroad tank car was positioned in a large excavation and filled with liquified petroleum gas (LPG).

The energy for the external fire was provided by a pool of JP-4 jet fuel situated beneath the tank car. Data were recorded that described important aspects of the test.

The uninsulated tank car, RAX 201, and the insulated car, RAX 202, were especially built for the test. The main differences between the two test cars and a normal rail tank car of the 33,000 gallon DOT 112A340W non-insulated pressure tank car series were the inclusion of a second entrance manway to the interior of the tank and two ports through which instrumentation lines could be run. Otherwise, RAX 201 and RAX 202 met all applicable requirements of the U. S. Department of Transportation and the Association of American Railroads. RAX 201 and RAX 202, except for a few changes to facilitate instrumentation, were standard tank cars for the transportation of liquified petroleum gas, anhydrous ammonia, or vinyl chloride.

The two fire tests were performed in the Hazardous Test Area at White Sands Missile Range, New Mexico. The tests were planned and conducted by BRL personnel.

There existed a few minor differences in the instrumentation of the two tank cars, but essentially, the instrumentation is depicted in the schematic of the tank car, Figure 2. The tank cars were 18.3m (60 ft) long and 3.05m (10 ft) in diameter. The steel shell, constructed of TC-128 steel, was 1.59 cm (5/8 in) thick. Centered on top of the tank car, enclosed in a protective steel dome, were two liquid filler valves, one vapor valve, one gauging device, a thermometer well, a test tube, and a Midland A-3180-N relief valve. The tank cars were provided by the Railway Progress Institute-Association of American Railroads (RPI-AAR).

Instrumentation primarily consisted of thermocouples, pressure gauges, liquid level monitors and devices to measure the lift of the relief valve. Chromel-alumel thermocouples were placed on the interior wall of the tank shell (inner wall thermocouples), on the inner wall of the steel dome (dome thermocouples), and in the lading (grid thermocouples). The inner wall thermocouples and the dome thermocouples were installed by enclosing them in a copper bead and potting them with Saureisen cement. To aid in defining the fire environment, thermocouples were positioned in the fire (fire thermocouples). The relative locations of most of the instrumentation can be identified in Figure 2. For additional information on instrumentation, recording procedures, etc., the reader is referred to other BRL reports given in the Bibliography.

The tank cars were positioned in a large excavation, 45.7m long, 30.5m wide, and 7.92m deep (150 ft by 100 ft by 26 ft). A fuel dike was constructed at the center of the excavation and it measured 24.4m by 9.1m (80 ft by 30 ft). Note that with these dimensions, the flame

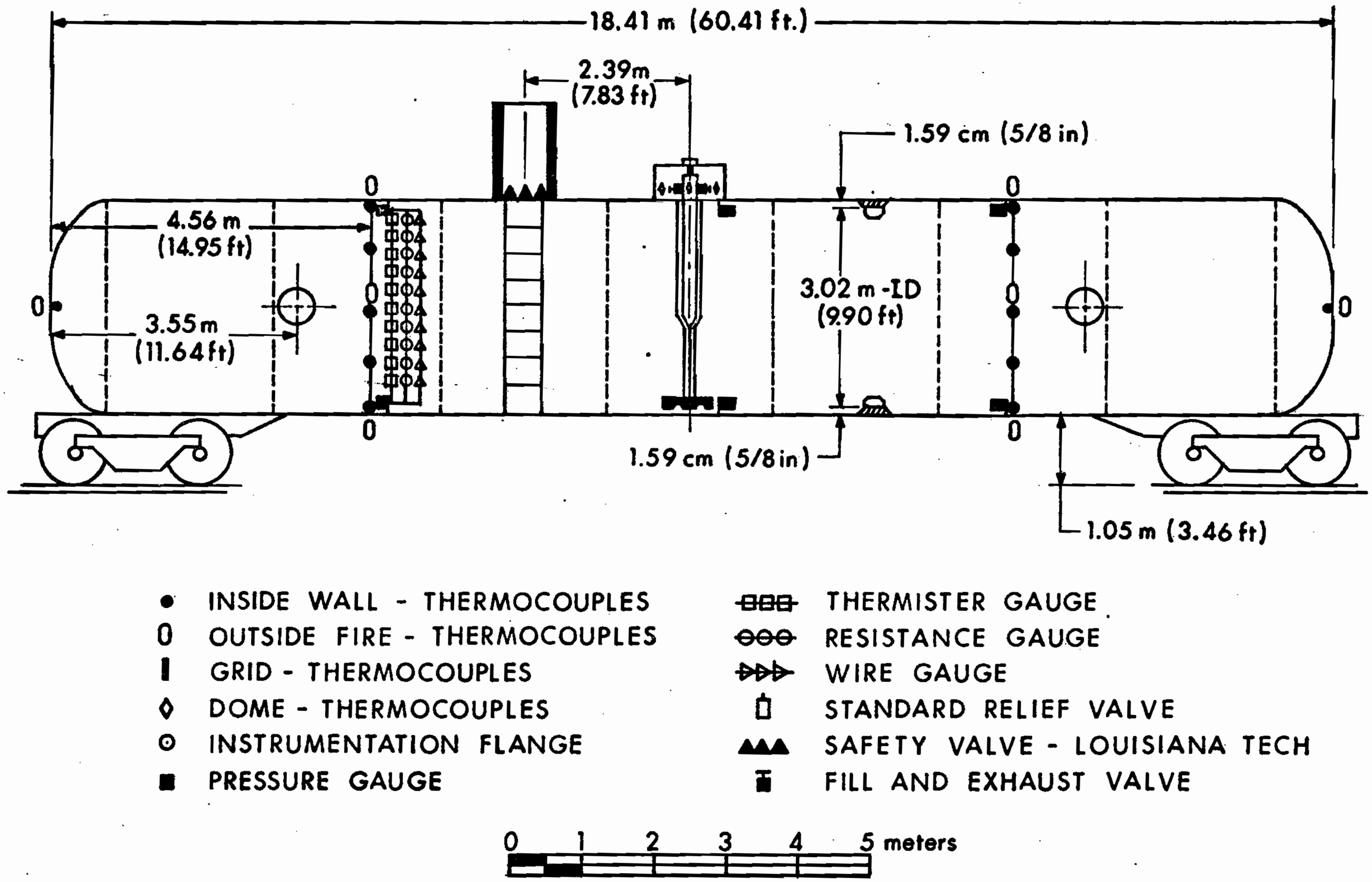

Figure 2. Instrumentation Layout for RAX 201 and RAX 202

engulfed tank cars were situated 3.05m (10 ft) from any edge of the fire. The fuel pit was supplied with JP-4 jet fuel via a 10.2 cm (4.0 in) gravity-fed pipeline from a 113.6 kiloliter (30,000 gallons) storage tank located approximately 183m (600 ft) from the excavation.*

The LPG was donated by El Paso Natural Gas and was delivered to White Sands Missile Range by Desert Air Company of El Paso, Texas. A chemical analysis of the LPG was performed on the LPG supplied for the first fire test (the test on the uninsulated tand car). The constituents of the LPG were:

ethane	1.96%	normal butane	.01%
propane	97.96%	pentanes	.00%
isobutane	.07%		

IV. THE THERMAL COATING

A series of tests on one-fifth scaled model tank cars screened several possible candidates for a thermal coating to be applied to a full scale tank car fire test. The experience gained from these one-fifth scaled model tests enabled the FRA to make a technological decision on the choice of a thermal shield. In choosing an insulating coating, certain properties such as thermal insulation properties, environmental aging properties, and adhesion properties must be considered.

The decision was made by the FRA to use a proprietary coating produced by Manufacturer X. The coating we will call Sample Y. Though this coating had not been tested on an one-fifth scaled model tank, it had been tested for some of its properties by RPI-AAR and the National Aeronautical and Space Administration (NASA). However, it was emphasized by the FRA that the fire test was not a proof test for Sample Y, but instead, was a test on the technical feasibility of coating a rail tank car in order to provide it thermal protection from fire.

Therefore, RAX 202 was coated with 0.318 cm (1/8 in) of the insulating thermal shield Sample Y. The coating is basically a three part system consisting of a primer, the Sample Y coating, and a decorative topcoat.

The primer provides the basic adhesion to the substrate and serves as a base coat for the thermal coating. The primer is a two component epoxy which is sprayed over sand-blasted metal to a thickness of approximately 0.0254mm (0.001 in). The primer, which cures at room

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*****_Two 113.6 kiloliter storage tanks were required for the test on the insulated car._

temperatures, is resistant to high heat, provides corrosion protection to the metal, and serves as the "tie coat" for the Sample Y material.

The Sample Y coating provides the basic heat shielding properties of the coating system. This thermal shield is a two component urethane material which is sprayed over the prime coat in multi-coates to a thickness not to exceed approximately 6.35mm (0.25 in). The Sample Y layer also cures at room temperatures.

The decorative topcoat, a two component urethane sprayed over the Sample Y coating to approximately 0.0508mm (0.002 in), protects Sample Y against film degradation during exposure to environmental conditions and the loss of its properties due to such exposure. The topcoat cures at room temperature, and has gloss and color retention.

V. COMPARISON OF TEST RESULTS

A. Initial Conditions

RAX 201, the uninsulated tank car, had a capacity of 127.47 kiloliters (33,674 gallons). The car was loaded with approximately 122 kiloliters (32,200 gallons) of LPG. The temperature of the LPG inside the tank car, at test time, was nominally 21° C (70° F), and the pressure was $9.63 \times 10^5 nt/m^2$ (125 PSIG). Knowing the volume of LPG loaded, and its temperature, the total mass of the LPG loaded is estimated to be 60,800 kg (134,000 lb_m). A photograph of RAX 201, positioned in the fuel pit inside the large excavation just prior to the start of the fire test is shown in Figure 3. The fire test was conducted on 27 July 1973.

RAX 202, the insulated car, had a capacity of 127.54 kiloliters (33,692 gallons). The car was filled with approximately 110 kiloliters (29,000 gallons). The pressure of the LPG inside the tank car was $7.63 \times 10^5 nt/m^2$ (96 PSIG). Hence, approximately 56,700 kg (125,000 lb_m) of LPG were loaded into the tank car. A photograph of the insulated car, RAX 202, positioned in the pit, just prior to test time,is shown in Figure 4. The fire test on tank car RAX 202 was conduted on 6 December 1973.

A summary of the initial conditions of the two fire tests is given in Table I.

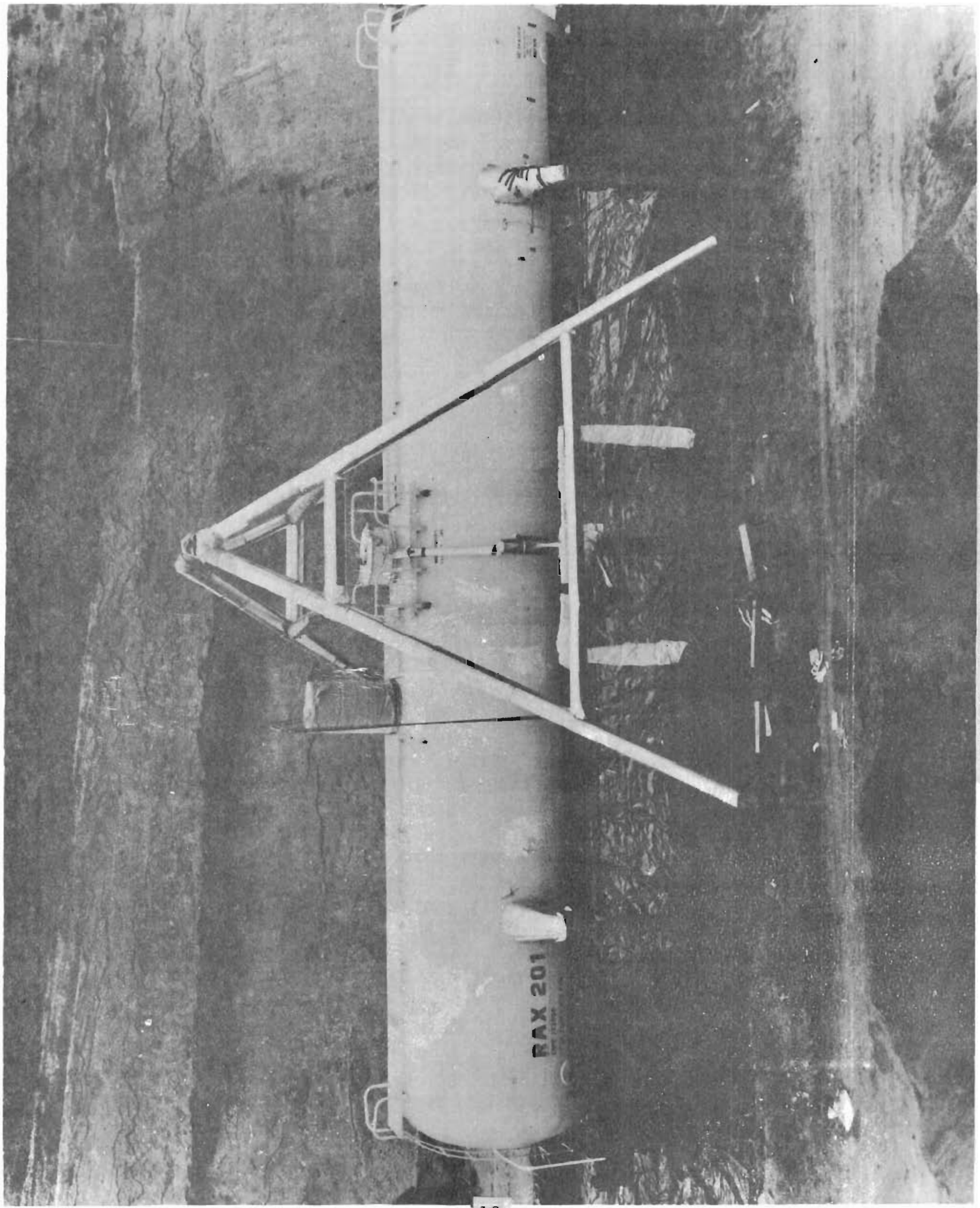

FIGURE 3. RAX 201 - The Uninsulated Tank Car

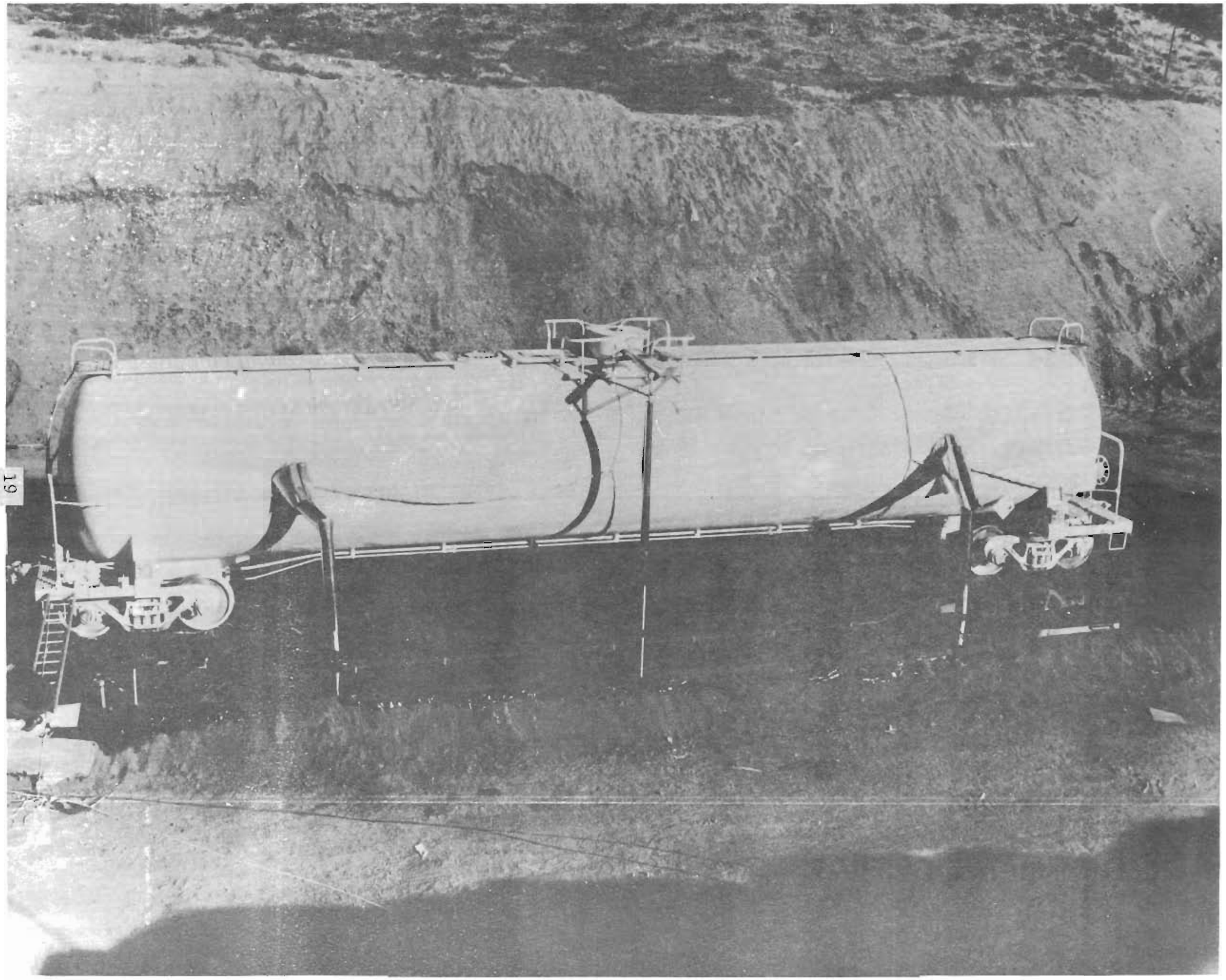

Figure 4. RAX 202 - The Thermally Coated Tank Car

TABLE I

SUMMARY OF INITIAL CONDITIONS

	Uninsulated Car (RAX 201)	Insulated Car (RAX 202)
Insulation	None	0.318 cm of Sample Y
Capacity of Tank Car	127.47 kiloliters	127.54 kiloliters
Volume of Propane Loaded	122 kiloliters	110 kiloliters
% of Tank Initially Filled with Propane	96%	84%
Initial Angle to Liquid Level	35^o	56^o
Mass of Propane Loaded	60,800 kg	56,700 kg
Initial Temperature	21^oC	6^oC
Initial Pressure	9.63×10^5 nt/m^2	7.63×10^5 nt/m^2

B. The Fire Environment

Fire temperatures fluctuated between 650°C and 990°C (1200°F to 1800°F) though flame temperatures were recorded as high as 1100°C (2000°F), for the test on the uninsulated car. Heat flux data registered an average heat flux of 3.30 cal/sec-cm^2 (43,900 BTU/hr-ft^2).

For the test on the insulated car, the auto-ranging mechanism did not function on the thermocouple output recording unit. Hence, whenever temperatures went above 732°C (1350°F), the recorded temperature read offscale. However, examination of the data from the fire thermocouples indicate that generally, the fire temperatues were above 990°C (1200°F), and quite often the flame temperatures were above 732°C (1350°F). Therefore, it can be assumed that the fire environment for both tests were similar.

Summarizing, the fire engulfed the tank car with flames whose temperatures were of the order of 650°C to 990°C (1200°F to 1800°F). Data from the test on RAX 201, and data from tests run on one-fifth scaled model tank cars, indicate that the heat flux from a JP-4 fuel pool fire is of the order of 2.93 cal/sec-cm^2 to 3.30 cal/sec-cm^2 (38,900 BTU/hr-ft^2 to 43,900 BTU/hr-ft^2).

C. Response of the Tank Cars

1. Heat Flux to the Wetted Surface

The heat from the fire is conducted through the steel shell of the tank car into the interior of the car. Almost exclusively, the heat transfer from the shell to the contents of the car occurs along the portion of the shell covered by the liquid (i.e., the wetted surface) due to the large difference in the thermal conductivities of gaseous propane versus liquid propane.

The liquid level as a function of time is required in order to calculate the heat flux to the wetted surface. A fundamental characteristic of the temperature profiles for the thermocouples attached to inner wall of the tank car provides a procedure for inferring the liquid level. For some specific internal pressure the temperature of the liquid will reach a maximum and begin boiling. This maximum liquid temperature is only a function of the pressure (neglecting impurities in the propane). As long as liquid propane is in contact with the inner tank shell wall, the temperature of the wall will remain near this boiling point, even though a high heat flux may exist. Convection is the mechanism of heat transfer from the steel wall to the lading.

Hence, for a constant or nearly constant pressure, a thermocouple attached to the inner wall of the tank car records a constant wall temperature, and a plateau appears in the temperature versus time plot for that thermocouple. For a specified thermocouple, this constant temperature condition will persist until the liquid level recedes below the thermocouple. At this time due to the inefficient heat transfer characteristics of the vapor, the wall temperature rapidly rises; thus, the plateau on the temperature-time plot is terminated.

By recording the time a temperature plateau was terminated for each wall thermocouple, and plotting this datum against the corresponding thermocouple position, a curve of the liquid level as a function of time is generated.

More information can be gleaned from the temperature-time plots of the thermocouple data. Due to the thermal expansion, the liquid level rose and covered previously exposed thermocouples, evidenced by the sharp decrease in the temperatures recorded by these particular thermocouples.

These procedures were followed for both tests, and the liquid level curves are shown in Figure 5.* The dotted portions of the graphs for small and large θ in Figure 5 indicate that some uncertainty exists in interpolating the liquid level as a function of time. The fire destroyed all of the instrumentation lines running from RAX 202 after approximately 60 minutes of fire exposure. Hence, results must be extrapolated after 60 minutes. However the general trend of the liquid level-time curves for both tests have been obtained.

The heat flux to the wetted surface can be calculated using:

$$q = + \frac{2Vh_{\ell g}\rho_{\ell}\sin^2\theta}{S(\pi-\theta)}\,\frac{d\theta}{dt} + \frac{c_{\ell}\rho_{\ell}\pi V_{\ell}}{S(\pi-\theta)}\,\frac{dT_{\ell}}{dt} - \frac{\pi V_{\ell}}{S(\pi-\theta)}\left(h_{\ell g} + \frac{P}{\rho_{\ell}}\right)\frac{d\rho_{\ell}}{dt} \qquad (1)$$

where

q = heat flux to the wetted surface (cal/sec-cm^2),

$h_{\ell g}$ = latent heat of vaporization (cal/gm),

ρ_{ℓ} = liquid density (gm/cm^3),

V = volume of the tank car (cm^3),

V_{ℓ} = volume of the liquid in the tank car (cm^3),

T_{ℓ} = temperature of liquid (°C),

P = pressure (nt/m^2),

Figure 5 was solely determined from an interpretation of the thermocouple data.

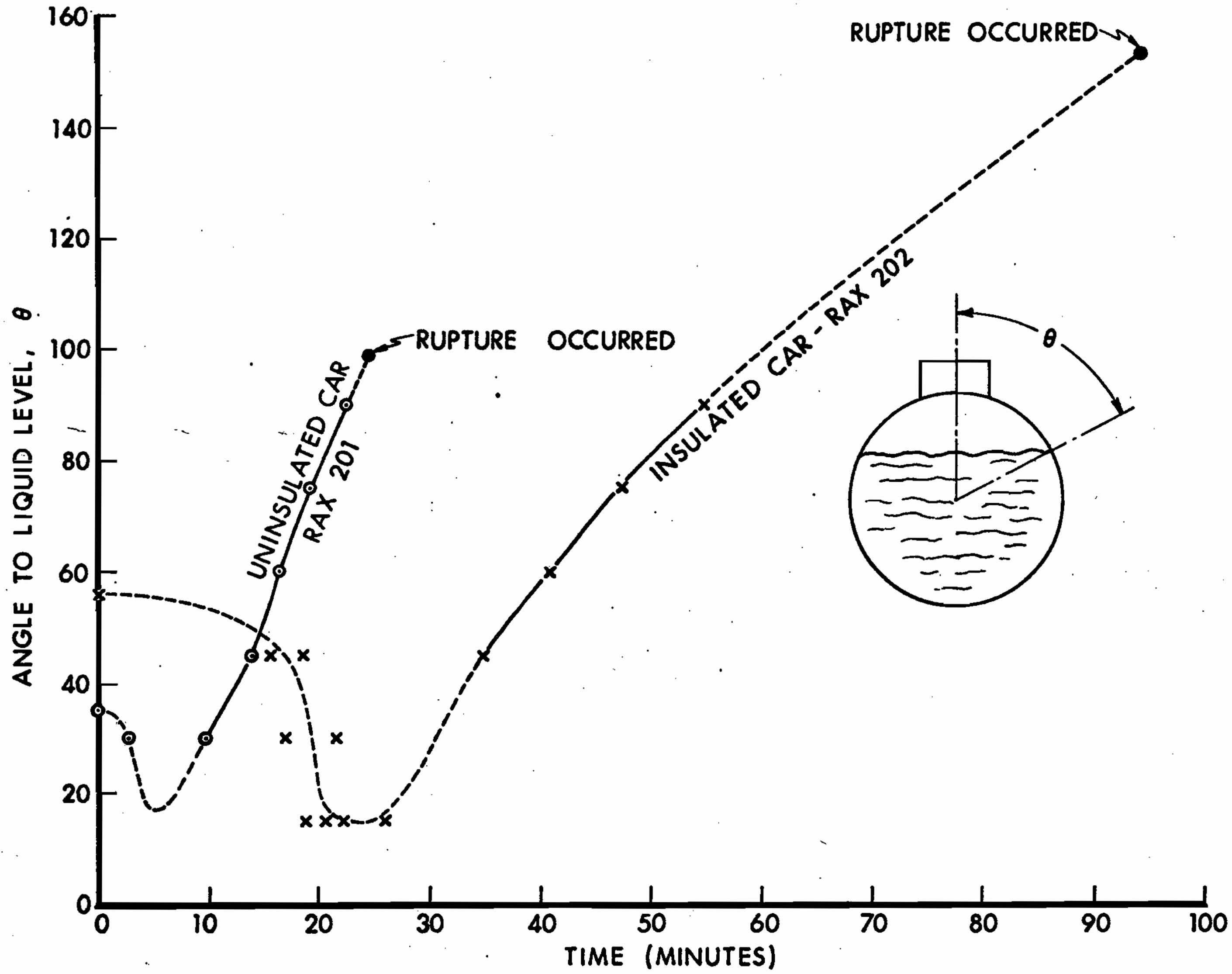

Figure 5. Liquid Level Versus Time

S = surface area of the tank car (cm^2),

c_ℓ = specific heat of the liquid (cal/gm-^oC),

θ = angle to the liquid level - θ is the number of degrees between 12:00 and a line drawn from the center of a cross-section of the tank to the point where the liquid surface intersects the circumference,

t = time (seconds).*

Assuming that q is constant over a time interval Δt, the above equation can be integrated to give:

$$q = < q >_1 + < q >_2 + < q >_3 + < q >_4 \qquad (2)$$

where

$$< q >_1 = \frac{2V\bar{h}_{\ell g}\bar{\rho}_\ell}{S(t_2 - t_1)} \int_{\theta_1}^{\theta_2} \frac{\sin^2 \theta d\theta}{\pi - \theta} , \qquad (2a)$$

$$< q >_2 = \frac{\bar{c}_\ell \bar{\rho}_\ell \pi V_\ell(\bar{\theta}) (T_2 - T_1)}{S(\pi - \bar{\theta}) \quad (t_2 - t_1)} , \qquad (2b)$$

$$< q >_3 = \frac{\bar{h}_{\ell g} \pi V_\ell(\bar{\theta})}{S(\pi - \bar{\theta})} \quad \frac{(\rho_\ell)_2 - (\rho_\ell)_1}{(t_2 - t_1)} , \qquad (2c)$$

and

$$< q >_4 = \frac{-\bar{P}\pi V_\ell(\bar{\theta})}{S(\pi - \bar{\theta})} \quad \frac{\ell n \left[(\rho_\ell)_2 / (\rho_\ell)_1 \right]}{(t_2 - t_1)} . \qquad (2d)$$

---

*The basic formulation of Equation (1) is due to Mr. Leo Manda, Consultant, Association of American Railroads.

The bar over a quantity indicates that a time averaged value is used to compute that quantity for the time interval $\Delta t = (t_2 - t_1)$. The subscripts 1 and 2 denote the value of the quantity at times t_1 and t_2 respectively. The numerical method for evaluating the integral over θ was Simpson's Rule with a relative error tolerance of 1.0×10^{-10}.

Each of the terms in Equation 2 has a physical interpretation. The first term, $< q >_1$, is the amount of heat used to vaporize a quantity of liquid. Vaporization of liquid causes the liquid level, here measured by θ, to change. The second term, $< q >_2$, is the amount of heat absorbed in increasing the temperature of the lading. The third term, $< q >_3$ is a correction to the first term. The liquid level can change due to thermal expansion of the lading (as the temperature of the lading increases); thus, more of the lading would have been vaporized than accounted for in the change of the liquid level. The last term, $< q >_4$, is a measure of the rate at which work is being done by the system on its surroundings as the liquid volume increases due to thermal expansion.

Using Equation 2 and Figure 5, the heat flux to the wetted surface can be calculated for the two fire tests. In calculating the heat flux for a specific time interval, it is essential to take time intervals over increments in which the pressure is relatively constant, as all numerical values for specific heat, heat of vaporization, density, etc., are temperature dependent - and under saturation or near saturation conditions, temperature dependence implies pressure dependence. Therefore, time intervals were chosen such that the pressure never varied by more than 3.45×10^4 nt/m^2 (5 PSI) from the beginning to the end of a time increment. Tables II and III present the time intervals, the contributions to the heat flux from each term in Equation 2, and the total heat flux over the respective time intervals.

2. Cycling of the Relief Valve and the Interior Pressures

The relief valve opened for the first time after 2.20 minutes for the uncoated tank. In comparison, the first valve opening did not occur until 15.80 minutes for the insulated tank car. Most of this time lag is due to the effects of the insulation, but some of this time difference is the result of the initial temperature difference of the two ladings. An estimate can be made of how long it would take to uniformly heat the propane in the insulated tank car to the initial temperature of the uncoated car. Considering an average heat flux of 1.23 cal/sec-cm^2 to the insulated car, a specific heat of liquid propane of 0.68 cal/gm-$^\circ$C in the temperature range of interest, and the average wetted surface area was 92 percent of the total surface area of the car, it would take approximately 5.1 minutes to heat the contents of the car from 6°C to 21°C. Hence, using the adjusted time, the relief valve on the insulated car opened for the first time 10.7 minutes after the first cycling of the relief valve on the uncoated tank car.

TABLE II

HEAT FLUX TO THE WETTED SURFACE - UNINSULATED CAR

Time Interval (Minutes)	$< q >_1$	$< q >_2$	$< q >_3$	$< q >_4$	q_{Total}*
10.3 - 10.9	0.42 (5590)	1.50 (19,920)	0.59 (7820)	0.011 (150)	2.52 (33,490)
10.9 - 11.4	0.41 (5500)	0.60 (8030)	.23 (3110)	.005 (60)	1.26 (16,700)
11.4 - 11.9	0.60 (8000)	1.22 (16,160)	.47 (6200)	.010 (130)	2.29 (30,490)
11.9 - 12.4	0.49 (6470)	1.22 (16,240)	.58 (7680)	.013 (170)	2.30 (30,560)
12.4 - 12.8	0.65 (8600)	0.77 (10,190)	.36 (4770)	.008 (110)	1.78 (23,670)
12.8 - 13.3	0.94 (12,540)	0.62 (8200)	.26 (3430)	.006 (80)	1.82 (24,250)
13.3 - 14.2	1.09 (14,530)	0.34 (4580)	.16 (2120)	.004 (50)	1.60 (21,280)
14.2 - 15.1	1.46 (19,350)	0.35 (4600)	.16 (2110)	.004 (50)	1.96 (26,110)
15.1 - 16.1	2.06 (27,400)	0.31 (4140)	.13 (1690)	.003 (40)	2.50 (33,270)
16.1 - 20.7	2.42 (32,180)	-0.06 (-860)	-.03 (-350)	-.001 (-10)	2.33 (30,950)
20.7 - 23.0	3.23 (42,980)	-0.11 (-1520)	-.05 (-700)	-.002(-20)	3.07 (40,740)
23.0 - 24.5	2.85 (37,900)	0.0 (0.0)	0.00 (0.0)	0.00 (0.0)	2.85 (37,900)

Time Weighted Average: 2.38 (31,650)

*Units are: cal/sec-cm^2 (BTU/hr-ft^2)

TABLE III

HEAT FLUX TO THE WETTED SURFACE - INSULATED CAR

Time Interval (Minutes)	$< q >_1$	$< q >_2$	$< q >_3$	$< q >_4$	q_{Total}*
20.0 - 27.5	0.00 (0.0)	0.80 (10,640)	0.28 (3750)	0.004 (50)	1.09 (14,430)
27.5 - 29.2	0.21 (2790)	.84 (11,120)	.29 (3870)	.005 (60)	1.34 (17,840)
29.2 - 30.5	.40 (5340)	.45 (5960)	.16 (2070)	.002 (30)	1.01 (13,400)
30.5 - 32.0	.48 (6360)	.60 (7910)	.22 (2920)	.004 (50)	1.30 (17,240)
32.0 - 33.5	.63 (8320)	.20 (2680)	.06 (840)	.001 (10)	0.89 (11,850)
33.5 - 35.0	.79 (10,500)	.41 (5430)	.15 (1960)	.003 (40)	1.35 (17,920)
35.0 - 37.0	.71 (9500)	.62 (8220)	.23 (3120)	.005 (60)	1.57 (20,900)
37.0 - 38.9	.89 (11,830)	.00 (0.0)	.00 (0.0)	.000 (0.0)	0.89 (11,830)
38.9 - 41.0	.94 (12,490)	.29 (3910)	.12 (1560)	.002 (30)	1.35 (17,980)
41.0 - 43.1	1.07 (14,280)	.00 (0.0)	.00 (0.0)	.000 (0.0)	1.07 (14,280)
43.1 - 47.5	1.25 (16,560)	.19 (2560)	.08 (1002)	.002 (20)	1.52 (20,140)
47.5 - 49.8	1.34 (17,780)	-.25 (-3300)	-.10 (-1290)	-.002 (-30)	0.99 (13,170)
49.8 - 52.3	1.35 (17,890)	.00 (0.0)	.00 (0.0)	.000 (0.0)	1.35 (17,890)
52.3 - 55.0	1.33 (17,720)	.00 (0.)	.00 (0.0)	.000 (0.0)	1.33 (17,720)

Time Weighted Average: 1.23 (16,300)

*Unites are: cal/sec-cm^2(BTU/hr-ft^2)

The ability of the relief valve to handle the buildup of pressure in the interior of the two tank cars can be measured by the number of times the relief valves cycled opened and then closed, and the maximum pressure to which the tank car was subjected. The uninsulated car's relief valve cycled three times. When the valve opened the third time, it remained opened; the valve was still open at the time of failure of the car. The relief valve on RAX 202 (the insulated car) cycled eleven times, with the valve remaining open after the eleventh "popping" of the valve. Not only did the relief valve on RAX 201 cycle fewer times, but the time between successive valve openings was generally greater. For the insulated car, the valve openings were spaced on the order of one minute apart for the first several openings, then gradually the time between successive openings decayed to around one-fifth of a minute before the valve remained open. In both cases, the valve was cycling on the order of every 20 to 27 seconds just before it remained open. A history of the valve openings, the duration of the openings, and the time between successive valve openings is given in Table IV for both tests. A graphic display of the cycling of the valves is given in Figure 6.

The rate at which the pressure increased inside the car was significantly lower for the insulated car. The pressure versus time plot for both tests is presented in Figure 7. The pressure trace was terminated after one hour in the test on RAX 202 when the JP-4 fuel fire destroyed the instrumentation lines running from the tank car. The pressure achieved a maximum of 2.51 x 10^6 nt/m^2 (350 PSIG) at 17.9 minutes into the test on RAX 201. The relief capacity of the valve was not capable of precluding a pressure rise to 2.51 x 10^6 nt/m^2 with a heat flux of the order of 2.38 cal/sec-cm^2 (31,650 BTU/hr-ft^2). The pressure had begun to decrease slightly when the car ruptured. The pressure was 2.41 x 10^6 nt/m^2 (335 PSIG) when RAX 201 ruptured.

The pressure rise for the test on the insulated car levelled off at approximately 2.20 x 10^6 nt/m^2 (305 PSIG), with a maximum pressure of the order of 2.24 x 10^6 nt/m^2 (310 PSIG) at approximately 48.5 minutes. Though none of the instrumentation registered reliable data after 60 minutes, film coverage showed that the relief valve on RAX 202 was still open at the time of rupture. While the relief valve was open, the torch plume was small compared to the observed torch plumes from the valve openings earlier in the test. Therefore, since the relief valve closes at approximately 1.76 x 10^6 nt/m^2 (240 PSIG), it is estimated that the pressure was approximately 1.76 x 10^6 nt/m^2 when RAX 202 ruptured.

TABLE IV

HISTORY OF VALVE OPENINGS

Time Opened (Min)	Duration (Sec)	Time Between Successive Openings (Sec)
	Uninsulated Car - RAX 201	
2.20	6	
2.60	10	24
2.93	Stayed Open	20
	Insulated Car - RAX 202	
15.80	9	
16.85	8	63
17.82	9	58
18.75	8	56
19.43	8	41
20.02	7	35
20.62	9	36
21.17	9	33
21.62	10	27
22.07	9	27
22.42	Stayed Open	21

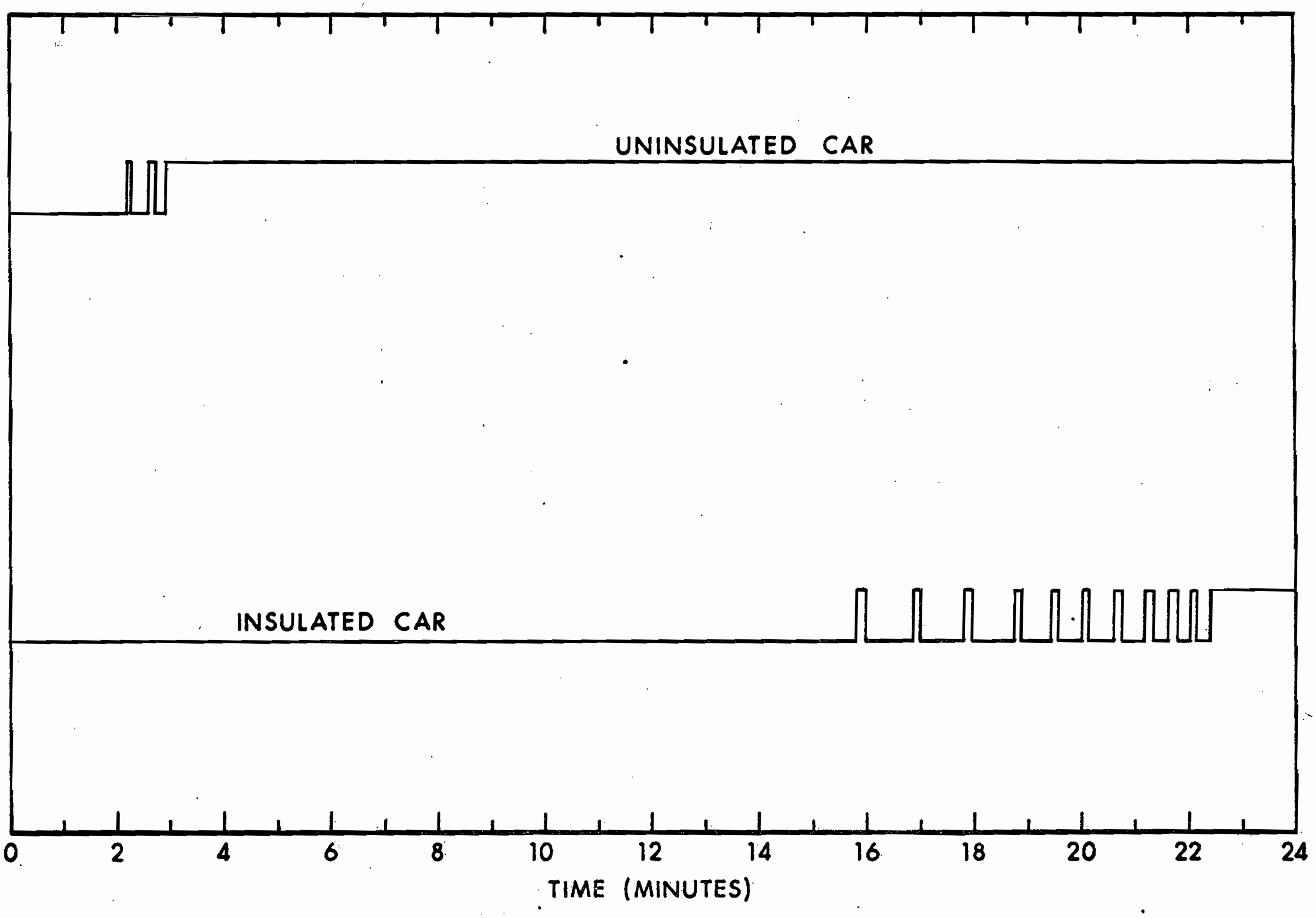

Figure 6. Comparison of Valve Openings

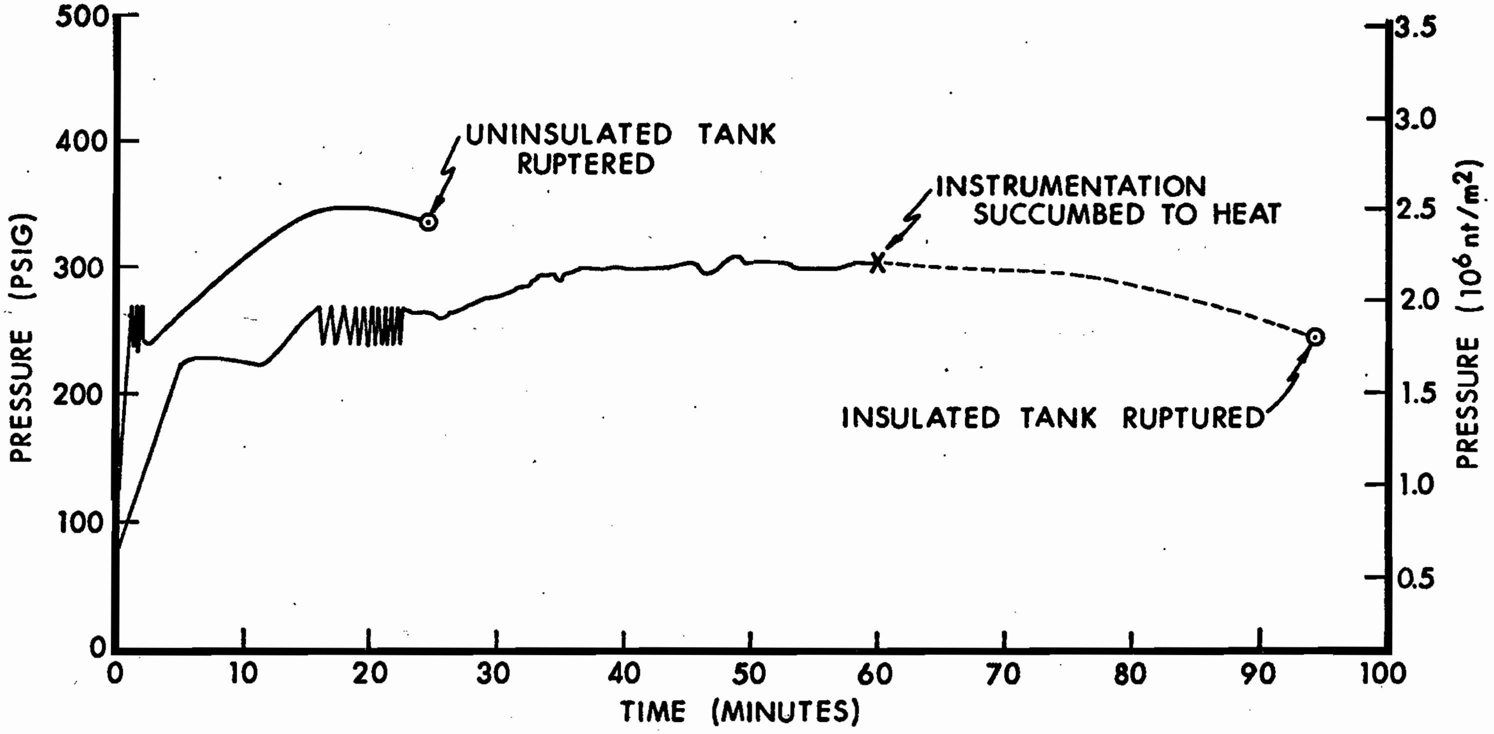

Figure 7. Pressure vs. Time

D. Fragmentation of the Tank Cars

The combination of exposure to high temperatures and the internal pressures encountered resulted in catastrophic failures of the two tank cars. All evidence supports the conclusion that both tank cars failed via stress-rupture. However, the "violence" of the rupture, and the resultant fireball were markedly different for the uninsulated and insulated cars.

Figure 8 is a photograph of the resultant fireball of the rupturing of RAX 202, the insulated car. A photograph taken from the same location does not exist of the fireball from the rupturing of RAX 201. However, in contrast, the fireball from the uninsulated car was at least one order of magnitude greater than the one shown in Figure 8.

The rupturing of RAX 201 resulted in ten major fragments from the tank car shell. Figures 9 and 10 are photographs of the two largest fragments which formerly were portions of the two ellipsoidal heads. The fragments of RAX 201 were reassembled on paper as they existed before rupture. Figures 11 and 12 show the end views of the tank car, and the origins of the two fragments of Figures 9 and 10. Some of the smaller fragments which were originally part of the ellipsoidal heads are also shown in Figures 11 and 12.

The cylindrical portion of the tank shell fragmented into two very large pieces, and several small sections. One of these major pieces, more or less flattened out from its cylindrical shape, is shown in the photograph of Figure 13. The other large piece of the cylindrical shell was hurled 133.4m (437.7 ft) from the center of the test pit. Figure 14 shows this, the largest fragment. Its relative size can be compared with the height of the two men investigating the fragments. Figure 15 is the main body of the tank car reassembled on paper from the fragments. The fracture paths and the initial fracture site are also depicted on this drawing. Several of the major fragments, Figure 16, can be seen and identified in the aerial photograph of the test area as it appeared one day after the fire test on RAX 201. Figures 17 and 18 are scaled maps of the general test area, and the area in the vicinity of the test pit. These two figures show the general distribution of the fragments. The fragment numbers of Figures 17 and 18 are identified in Table V. The ten major fragments and their respective distances from the center of the test pit are summarized in Table VI. Counting all the pieces of the tank car that were found and identified, including pieces of catwalk, trucks and wheels, etc., RAX 201 ruptured into approximately 65 fragments. Fragment number 47, a large piece of the catwalk was hurled the farthest, 407m (0.25 miles).

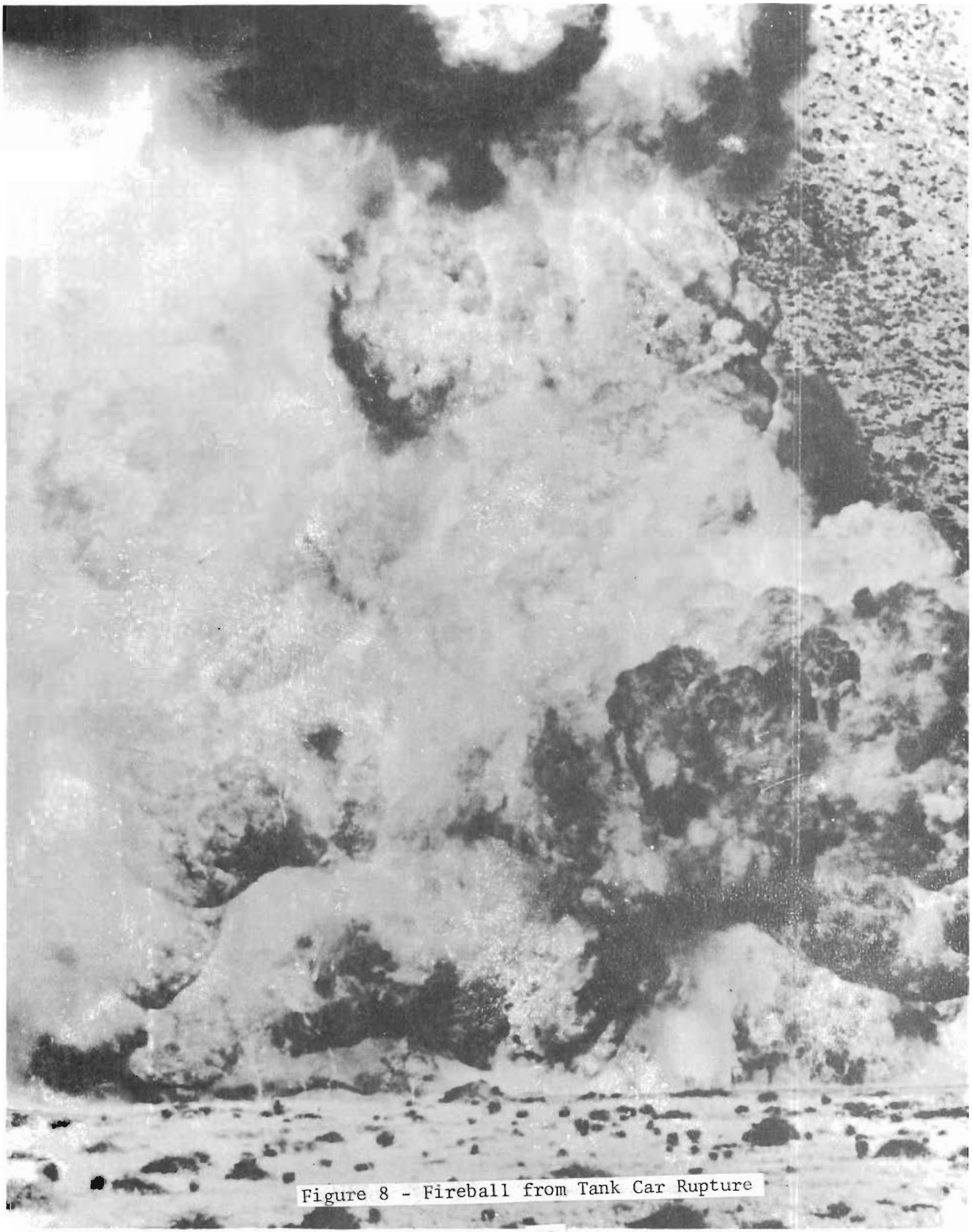

Figure 8 - Fireball from Tank Car Rupture

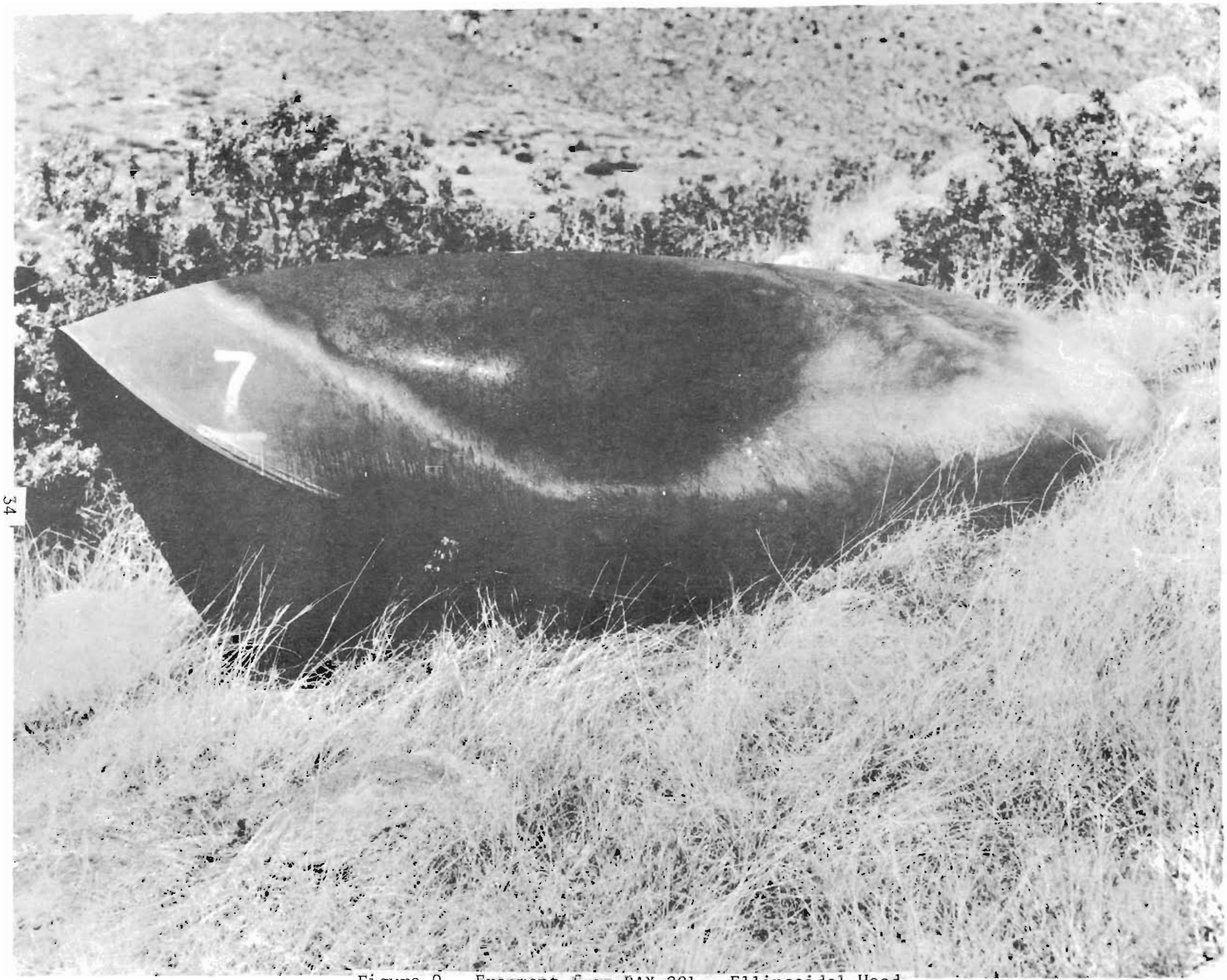

Figure 9. Fragment from RAX 201 - Ellipsoidal Head

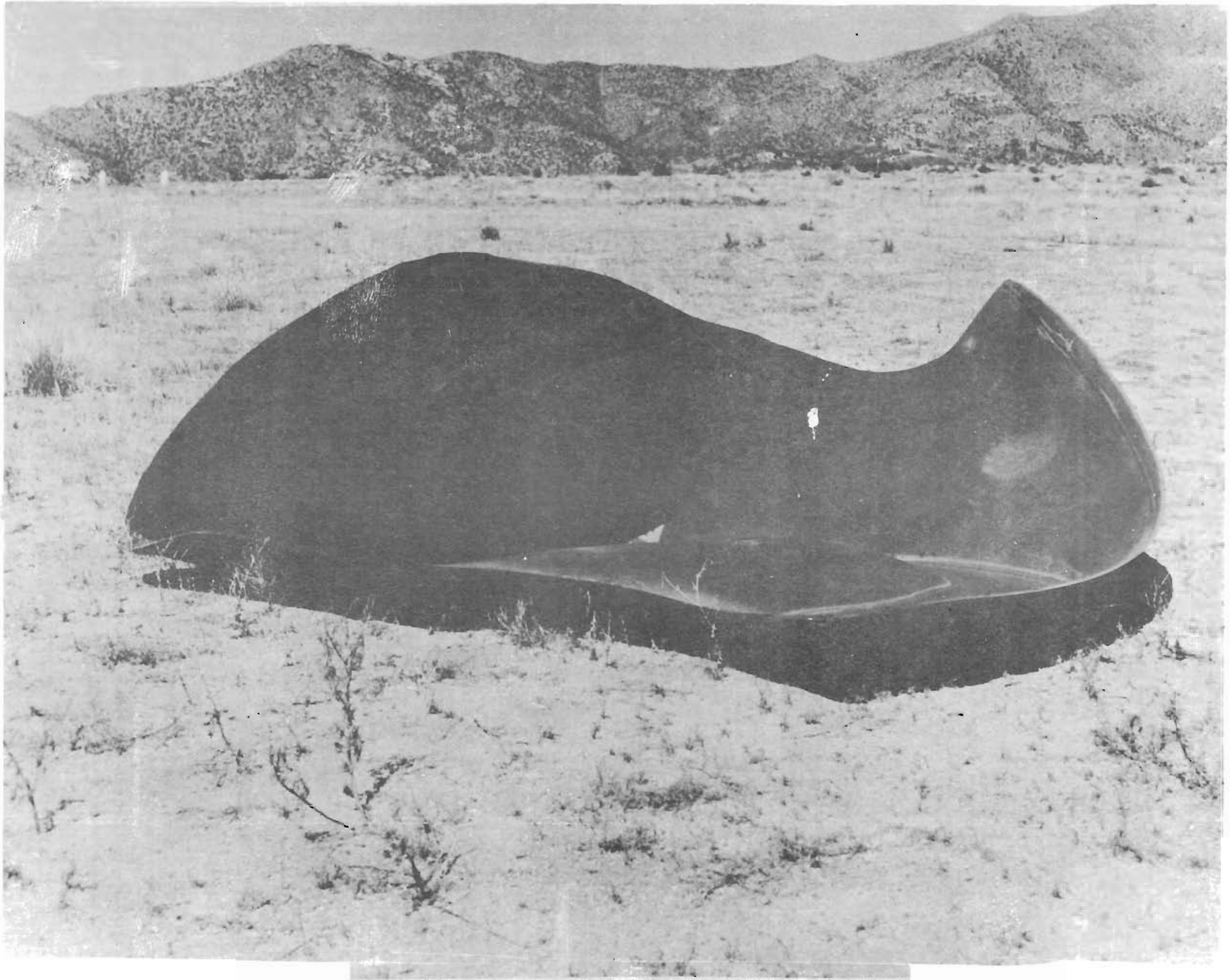

Figure 10. Fragment from RAX 201 - Ellipsoidal Head

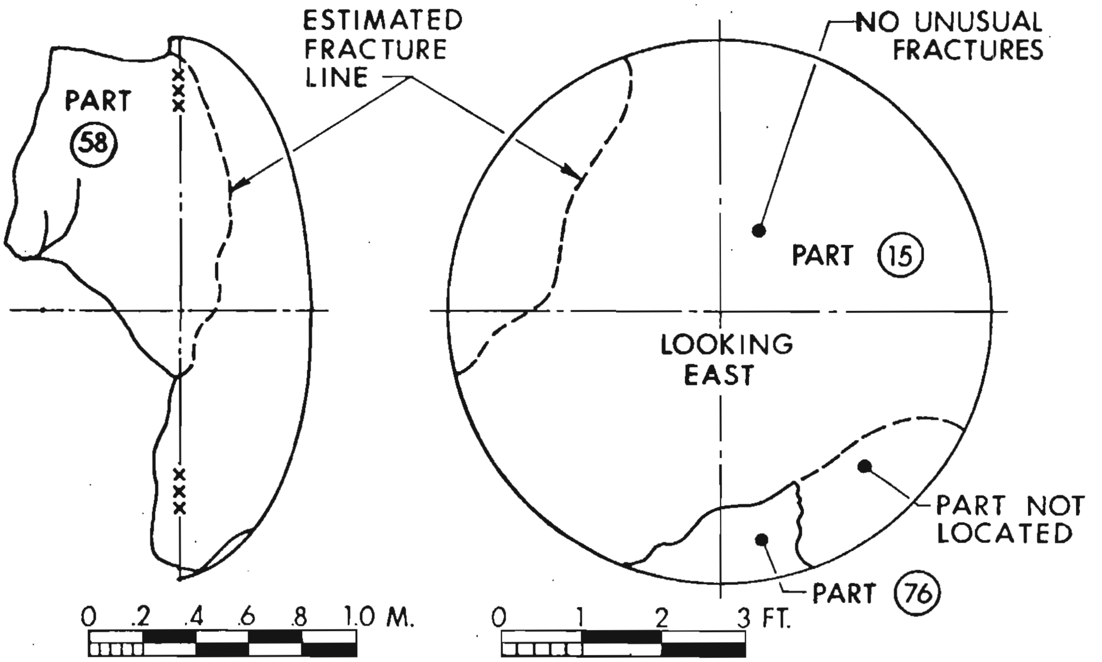

Figure 11. West End View of Fragments as They Were Positioned Before Rupture, RAX 201

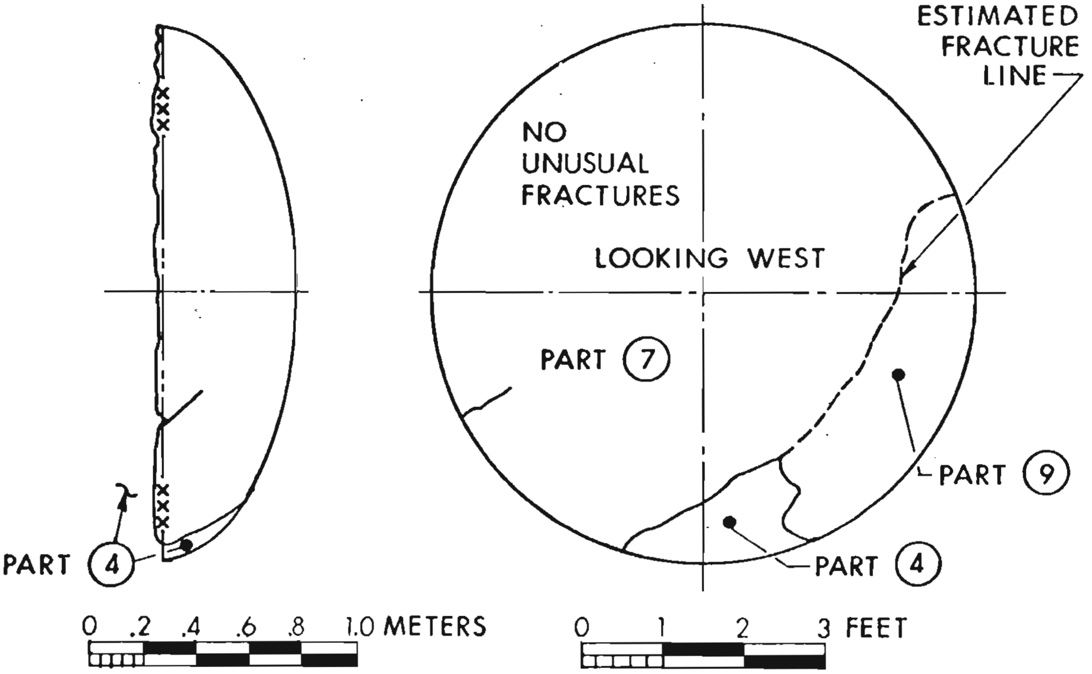

Figure 12. East End View of Fragments as They Were Positioned Before Rupture, RAX 201

Figure 13. Fragment of RAX 201 in Test Pit

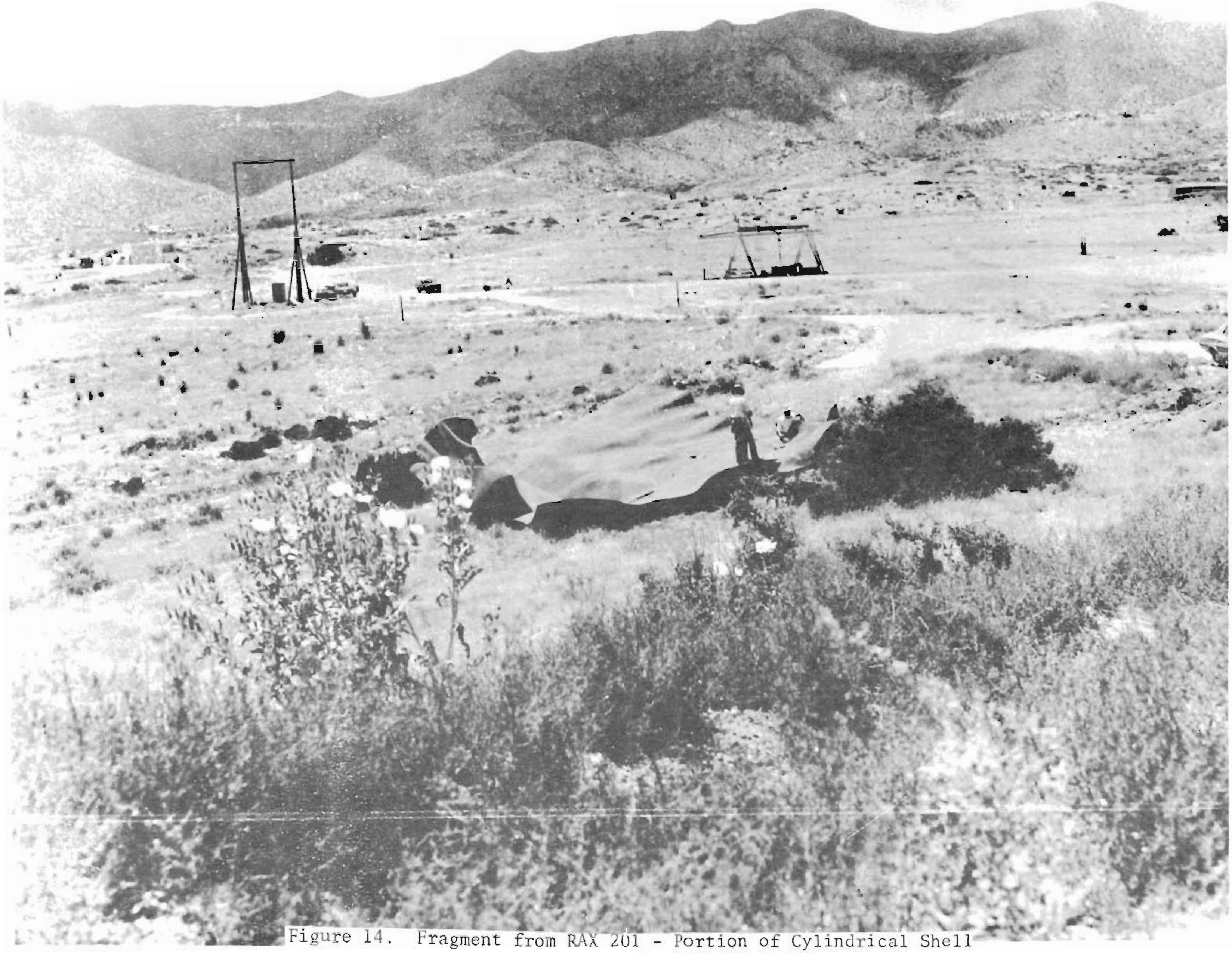

Figure 14. Fragment from RAX 201 - Portion of Cylindrical Shell

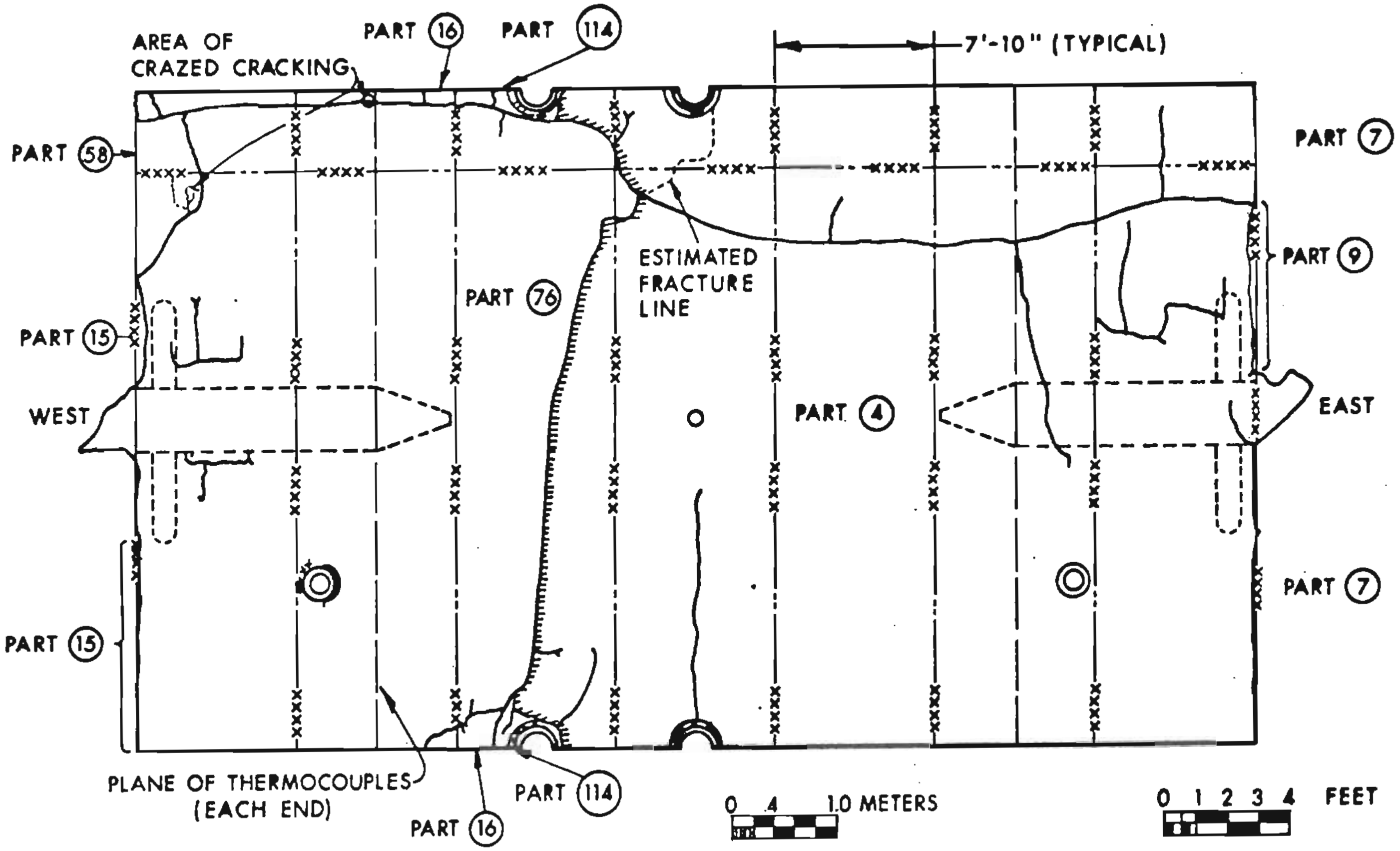

Figure 15. - Fragments of Ruptured Tank Car, RAX 201 Assembled as They Existed Before Rupture

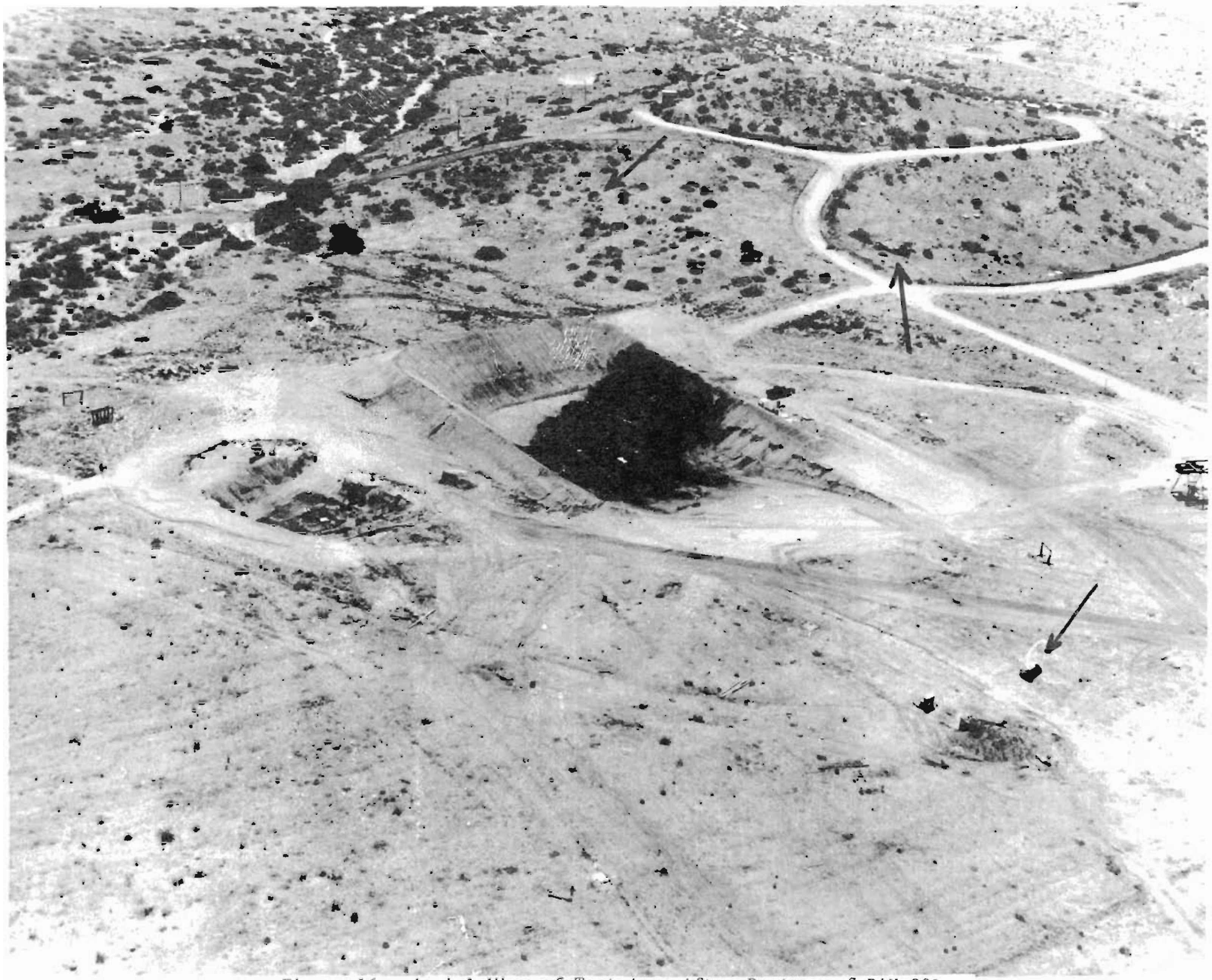

Figure 16. Aerial View of Test Area After Rupture of RAX 201

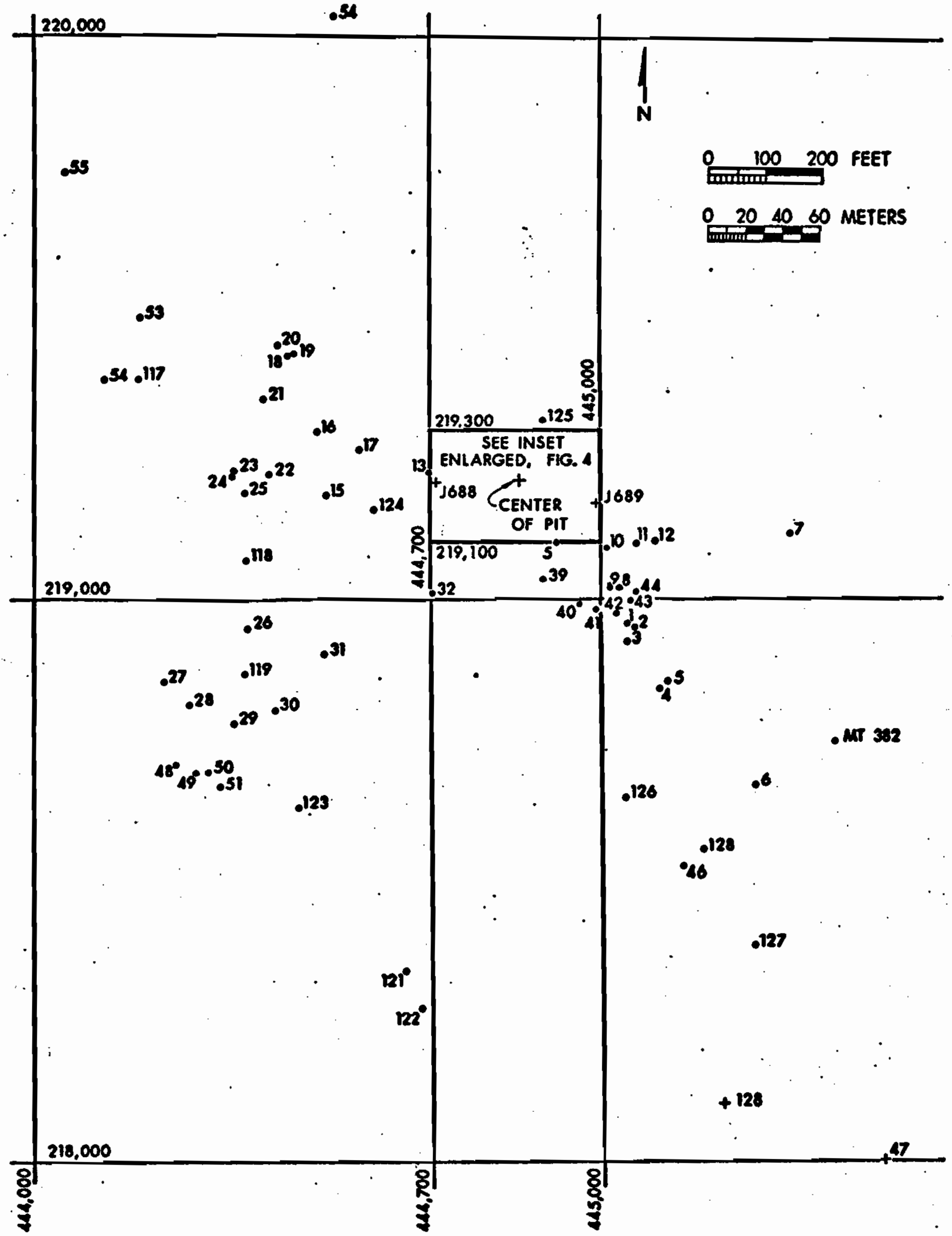

Figure 17- Fragment Locations for Rupture of RAX 201

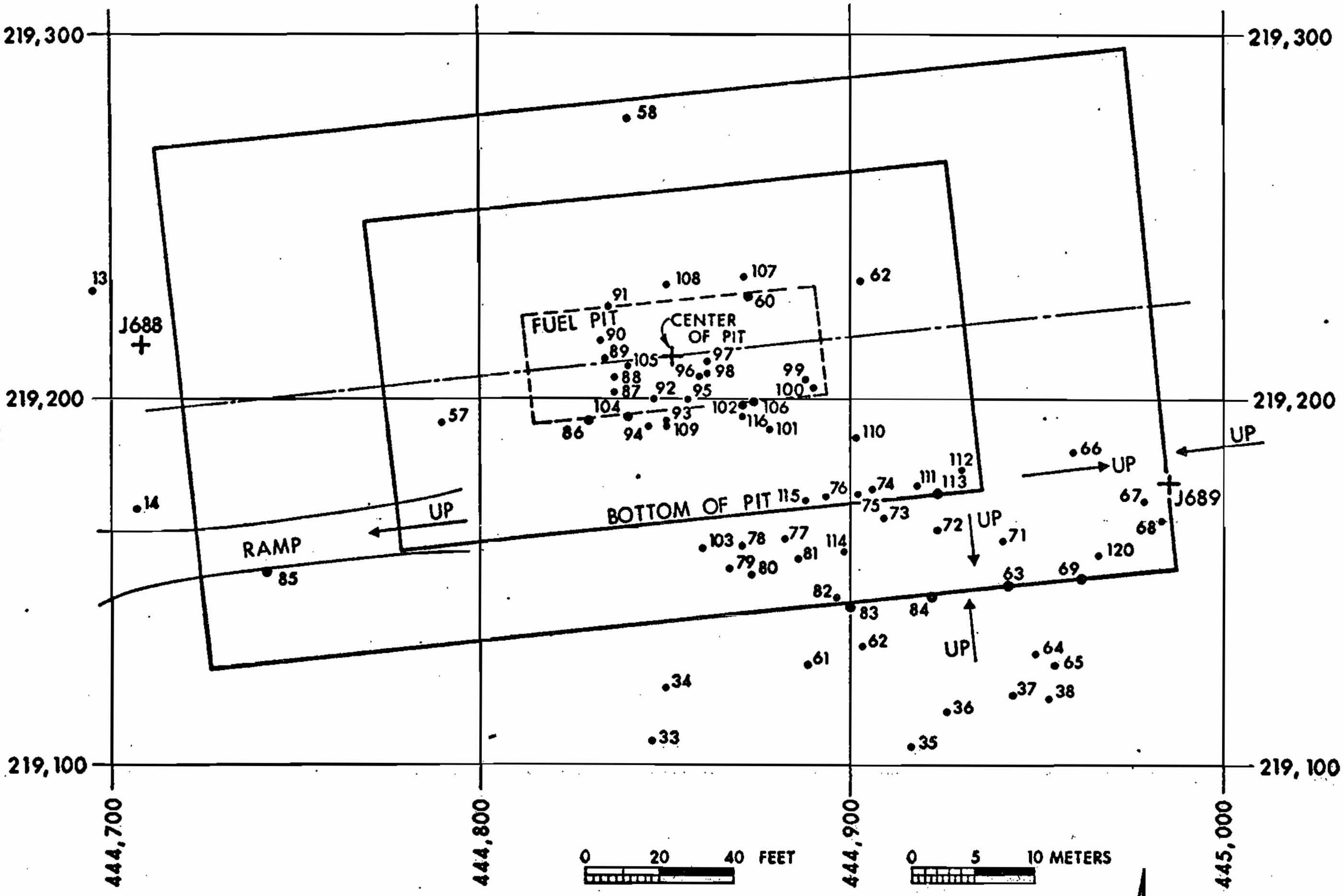

Figure 18 - Fragment Locations for Rupture of RAX 201 within Test Pit Area

TABLE V

Identification of Fragments - RAX 201

Item No.	Identification
1	Main valve flange
2	Piece of handrail (center of car)
3	End bumper with foot step
4	East half of car shell (lettering: 173,000 201 Lt.Wt. 89900 New 9-72
5	Piece (large) of undercarriage
6	Piece of catwalk
7	Section of east end of tank
8	Air hose coupler
9	Small piece of tank shell
10	Air line valve
11	Piece of coupler
12	Section of under channel
13	West end ladder
14	Piece of handrail
15	West end of tank shell
16	Small fragment of shell 3' x 5'
17	Fill pipes (liquid) from center of tank
18	Upper most member of NASA stand
19	#1 heat flux gauge (NASA)
20	#2 heat flux gauge (NASA)
21	Jeter's slotted angle thermistor gauge
22	18" piece of catwalk
23	Jeter's wire gauge support
24	Piece of catwalk
25	LVDT support
26	Thermocouple grid from inside west end of tank
27	8' piece of catwalk grid
28	15' piece of catwalk
29	Section of railing
30	Piece of thermocouple grid from the west end of the tank
31	Piece of end of tank 3' x 5'
32	Jeter's wire gauge support
33	Leg of pot stand
34	12' piece of NASA stand
35	Upright wire conduit to Louisiana Tech relief valve

TABLE V (Continued)

Item No.	Identification
36	25' section of NASA stand
37	5' section of NASA stand
38	10" piece of under casting
39	lid of dome cover
40	Vapor vent valve pipe
41	Strap 4" x 12"
42	Other piece of strap
43	Strap
44	8' section of fill pipe-center
45	Piece of solid steel rail
46	Piece of strap (catwalk)
47	Large piece of catwalk
48	Piece of catwalk
49	Hydraulic ram for Louisiana Tech.valve
50	Hydraulic ram for Louisiana Tech. valve
51	Water jacket for Louisiana Tech valve
52	Piece of catwalk
53	Thermocouple grid
54	Piece of NASA stand
55	Piece of top railing
56	****
57	6' piece of handrail
58	Portion of tank shell
59	Gauge mount; angle iron
60	Pressure gauge mount
61	Metal strap, approximately 2' long
62	Angle iron, approximately 12" long
63	Piece of catwalk
64	Piece of tank car truck
65	Hand brake wheel, bracket and chain
66	Coupler
67	Metal plate, approximately 6" x 18"
68	Small piece of truck
69	3" stainless steel tubing from shock absorbers on Louisiana Tech valve
70	Air line (brake) pipe
71	Truck and one set of wheels
72	One set of wheels
73	Gauging device (from main manway flange)

TABLE V (Continued)

Item No.	Identification
74	3" Angle valve (fill valve) from main manway flange
75	Pipe fitting
76	Tank shell
77	One set of wheels
78	Instrumentation cylinder
79	I-beam from instrumentation stand (NASA)
80	I-beam from instrumentation stand (NASA)
81	Piece of instrumentation stand (NASA)
82	Instrumentation cylinder
83	Dome housing
84	Piece of Midland valve, top housing
85	Approximately 10' section of handrail
86	9" square piece of metal, unknown
87	Settlement bowl (?)
88	****
89	Piece of Midland valve bracket
90	****
91	Air tank for brakes
92	Truck piece
93	****
94	Brake Shoe
95	Metal block, part of truck
96	Platform piece of catwalk
97	Metal casting - unknown
98	Metal block, part of truck
99	JP-4 liquid level indicator and mount
100	Rail, 2' long
101	Truck spring mount
102	Air line, 18" long
103	Pressure gauge mount
104	Piece of Midland valve- plunger or stem
105	One set of wheels
106	Concrete block for NASA stand
107	Concrete block for NASA stand
108	Concrete block for NASA stand
109	Concrete block for NASA stand
110	JP-4 liquid level float
111	Truck part
112	Rail, approximately 2' long
113	Piece of instrumentation (NASA) stand
114	Portion of Louisiana Tech relief valve
115	Truck casting

TABLE V (Continued)

Item	Identification
116	Portion of instrumentation (NASA)stand
117	South end of 30,000 gallon JP-4 fuel tank
118	Cable manhole
119	****
120	****
121	Platform piece of catwalk
122	Piece of catwalk
123	Piece of instrumentation (NASA)stand
124	Pressure gauge mount
125	Pressure gauge mount
126	Tubing (from NASA stand?)
127	****
128	Piece of instrumentation (NASA) stand

TABLE VI

SUMMARY OF MAJOR FRAGMENTS OF RAX 201

Item No.	Description of Item	Location	Distance from Center of Pit	
			(M)	(Ft)
76	Portion of Tank Car Shell	In Pit	15.4	50.7
58	Portion of Ellipsoidal Head	In Pit	21.2	69.4
114	Added Manway	In Pit	19.9	65.4
15	Portion of Ellipsoidal Head	West of Pit	104.2	342.0
16	Portion of Tank Car Shell	West of Pit	112.9	370.3
1	Standard Manway	Southeast of Pit	94.5	310.0
4	Portion of Tank Shell	Southeast of Pit	133.4	437.7
7	Portion of Ellipsoidal Head	South of Pit	145.7	477.9
9	Portion of Ellipsoidal Head	South of Pit	73.6	241.5

As previously mentioned, the failure of the insulated car, RAX 202, resulted in fewer fragments than the failure of RAX 201. The tank shell ruptured into four major fragments. It is thought that the initial fracture site occurred in the section of the tank car containing the "extra" manway.* The main fracture paths ran from the initial fracture site until they hit weld seams, and then, unable to cross the welds, they propagated around the car. Thus, the car was divided into two tubs; these tubs are shown in the photograph of Figure 19. The fragments were not surveyed for their exact locations, but the piece of the tank shell containing the initial fracture site and formerly connected the two tubs, Figure 20, was hurled approximately 150m (500 ft) from the center of the pit. A small piece, originally attached to the "connecting" fragment, is shown in Figure 21. Counting the four pieces of the tank shell, the catwalk torn from the top of the car at rupture, the dome cover, and the two wheel trucks, RAX 202 ruptured into approximately ten fragments. Only the two pieces shown in Figures 20 and 21 were ejected from the test pit.

An estimate of the masses of the major fragments which were thrown the furthest at rupture has been made. Assuming that the fragment from RAX 201 pictured in Figure 14 comprised approximately 0.62 of the tank shell (refer to Figure 15), the mass is 12,300 (13.6 tons). The fragment from RAX 202 in Figure 20 has a mass of the order of 2800 kg (3.1 tons) assuming that the fragment consisted of an entire section between girth-weld seams. This estimated mass is slightly large because the mass of the fragment shown in Figure 21 is included. It is difficult to determine the size of the fragment in Figure 21, but crude estimates yield that the mass is approximately 230 kg with an upper limit of 680 kg (1/4 tons to 3/4 tons). Table VII summarizes the information on the rupturing and fragmentation of RAX 201 and RAX 202.

VI. SUMMARY AND CONCLUSIONS

The 0.318 cm (1/8 in) thickness of Korotherm thermal insulation extended the time a rail tank car loaded with LPG could survive a fire environment from 24.5 minutes to 94.5 minutes. This particular thermal coating lowered the heat flux to the wetted surface of the car from 2.38 cal/sec-cm^2 to 1.23 cal/sec-cm^2 (31,650 BTU/hr-ft^2 to 16,300 BTU/hr-ft^2).

The National Bureau of Standards is currently investigating the failure of the insulated tank car, RAX 202.

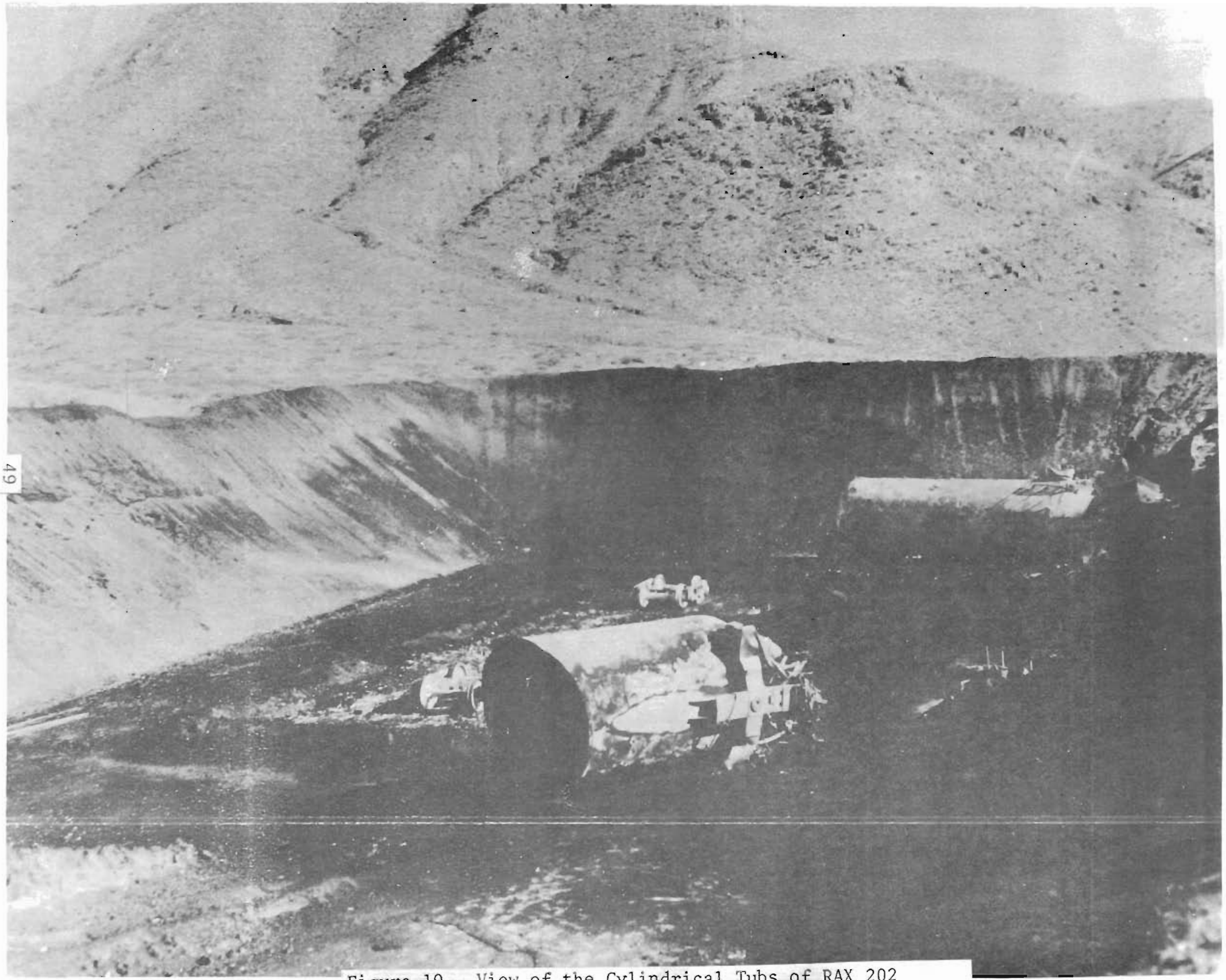

Figure 19. View of the Cylindrical Tubs of RAX 202

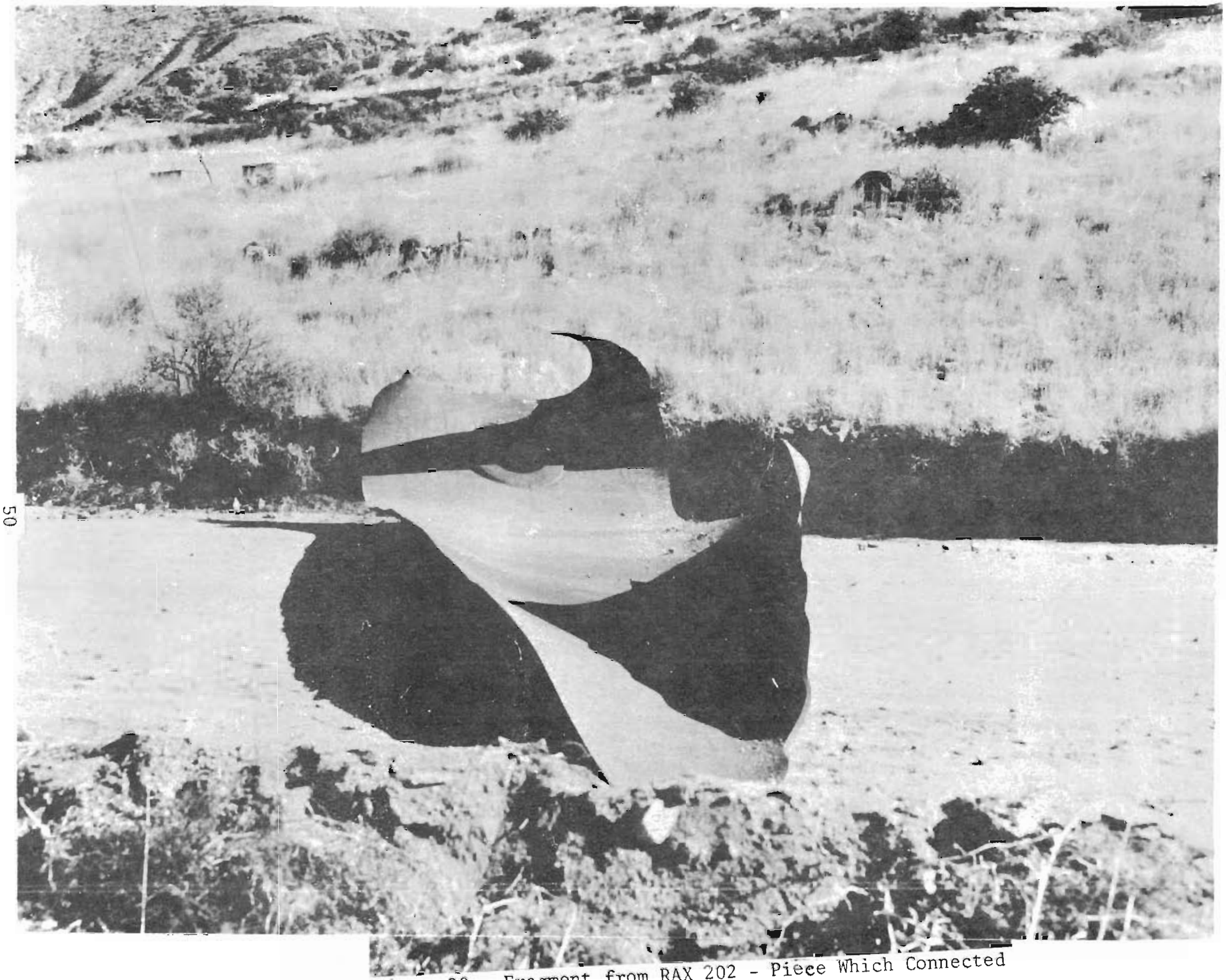

Figure 20. Fragment from RAX 202 - Piece Which Connected the Cylindrical Tubs

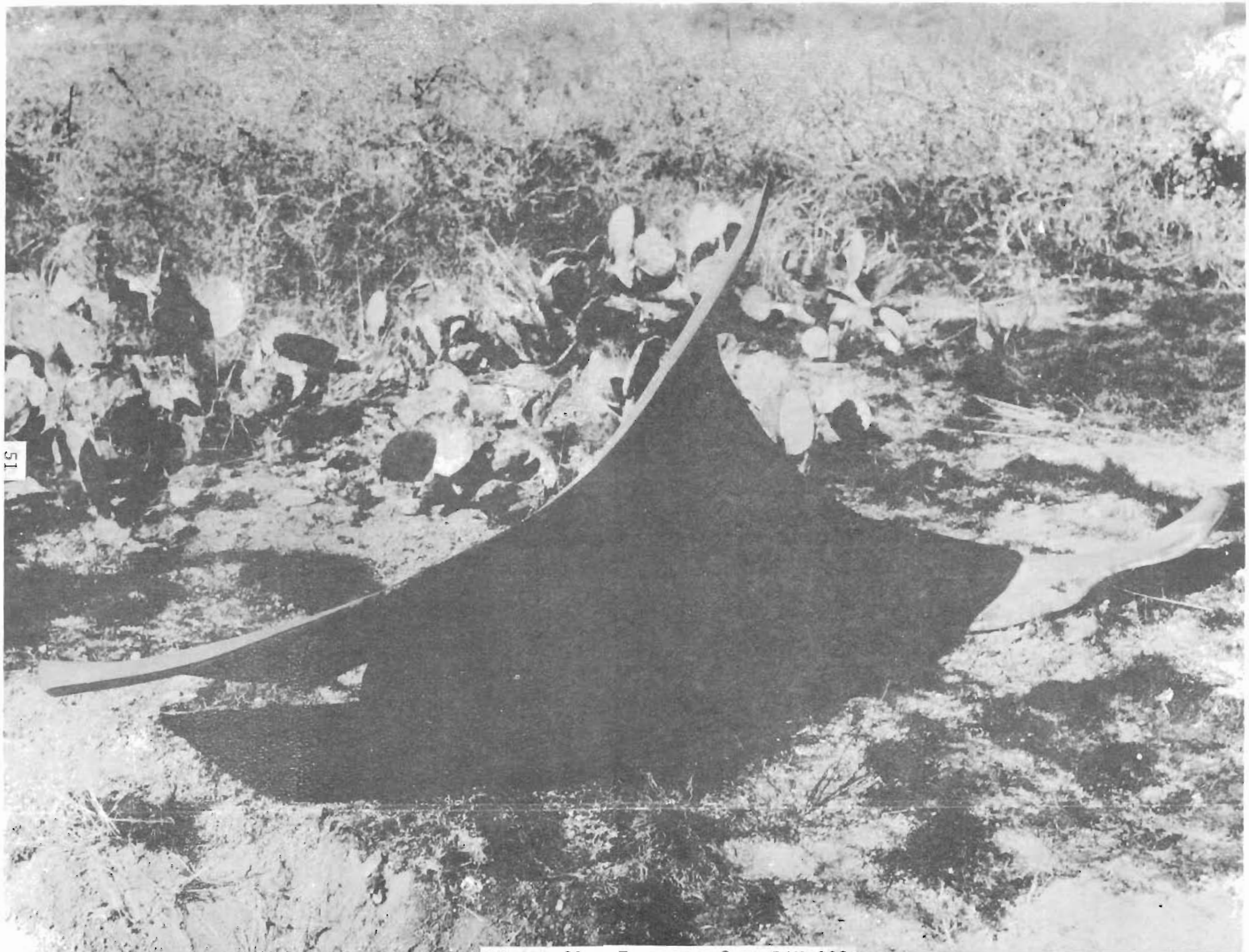

Figure 21. Fragment from RAX 202

TABLE VII

SUMMARY OF FRAGMENTATION

	Uninsulated Car (RAX 201)	Insulated Car (RAX 202)
Violence of Rupture	Extremely violent; loud sonic boom; large fireball	One to two orders of magnitude less
Number of Major Fragments	10	4
Number of Tank Car Fragments	65	10
Greatest Distance of a Major Fragment	133m	150m
Estimated Mass of Above Fragment	12,300 kg	2500 kg
Greatest Distance of Any Fragment	407m	150m

The thickness of the Sample Y coating, Sample Y being an ablative coating, was significantly reduced at the end of the 94.5 minutes. It was reported that only a thin, powdery substance remained on the tank shell. However, the application of a thermal coating, resulting in a lower heat flux, had three major effects on the response of the tank car.

First, the rate at which the temperature of the tank car shell increased was significantly lower for the insulated car. As Figure 1 indicates, the lower the shell temperature, the greater the pressure required to cause rupture.

Secondly, because of the lower heat flux to the wetted surface in the coated tank car, the rate of vaporization of LPG was low enough to preclude the large pressure buildup of the uncoated car (with the existing capacity of the relief valve on tank cars). Again, referencing Figure 1, the smaller pressure buildup extends the life of the tank car by requiring a higher skin temperature to initiate rupture.

Finally, because the pressure was lower, and it took a longer time to reach specific skin temperature, the release of the contents of the insulated car was controlled by the relief valve. Thus, when rupture did occur, the car was almost empty of liquid.

If 0.635 cm (1/4 in) of Sample Y had been sprayed onto RAX 202, it would be reasonable to state that the tank car would have been emptied of its liquid contents at rupture. A significantly longer period of time would have elapsed before rupture because of the additional thermal protection.

The effects of a wind blowing during the tests are difficult to estimate. Results from the test on RAX 201 show that flame temperatures can differ (200° C) over the length of the pool fire (remembering that the pool fire was contained in a large excavation). The temperature gradient can be explained by a slight wind bringing oxygen to the fire. The failure of the auto-ranging mechanism on the temperature recording unit, along with the failure of all instrumentation lines after 60 minutes in the second fire test makes it impossible to directly compare the flame temperature of the two tests. A slight wind did exist in both tests however, easily evident from motion picture coverage.

Whether or not the average flame temperatures of the two tests are radically different due to wind effects (the authors do not believe that they were), a comparison of the two tank car fire tests demonstrate conclusively that a thermal shield is feasible and extends the life of a rail tank car in a fire environment. Table VIII summarizes the response of the uninsulated and insulated rail tank cars to a fire environment.

TABLE VIII

RESPONSE OF THE TANK CARS

	Uninsulated Car (RAX 201)	Insulated Car (RAX 202)
Estimated Minimum Angle to Liquid Level (Due to Thermal Expansion)	20^o	15^o
% Full of Liquid at Minimum Angle	99%	99.6%
Maximum Pressure	2.51×10^6 nt/m^2	2.24×10^6 nt/m^2
Number of Times the Relief Valve Vented	3	11
Heat Flux to the Wetted Surface	2.50 cal/sec-cm^2	1.37 cal/sec-cm^2
Estimated Angle at Rupture	99^o	153^o
% Full of Liquid at Time of Rupture	40%	2%
Pressure at Time of Rupture	2.41×10^6 nt/m^2	1.76×10^6 nt/m^2 (?)
Time Subjected to Fire Before Rupture	24.5 min	94.5 min

ACKNOWLEDGMENT

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