THE EFFECTS OF AMBIENT TEMPERATURE ON LIQUID TEMPERATURE AND VAPOR PRESSURE IN UNINSULATED TANK CARS IN ANHYDROUS AMMONIA SERVICE

by

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Bachelor of Science
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Stillwater, Oklahoma
1953

Submitted to the faculty of the Graduate School
of the Oklahoma State University of
Agriculture and Applied Science
in partial fulfillment of the
requirements for the degree
of
MASTER OF SCIENCE
August, 1958

THE EFFECTS OF AMBIENT TEMPERATURE ON LIQUID TEMPERATURE
AND VAPOR PRESSURE IN UNINSULATED TANK CARS
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PREFACE

A great need exists for basic improvement in both the design and operation of the nations' tank car fleet, but very little scientific investigation has been directed toward these goals. By defining internal conditions in terms of external conditions, this paper sets forth a basis on which to make design and operational improvements. As a result of this study, the traditional requirement of insulation on anhydrous ammonia and LP-Gas tank cars has been removed. Also as a result of this study, a scientific basis for the setting of filling densities has been established.

The author thanks Phillips Petroleum Company for permission to use the data from the 1956 series of tank car tests and to reproduce the Company reports contained in the appendices. The author also thanks Professor J. R. Norton and Dr. Clark Dunn for their most valuable guidance and encouragement.

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CHAPTER I

INTRODUCTION AND HISTORICAL BACKGROUND

In the infancy of the petroleum industry, large wooden tanks set on flat cars furnished the means of transporting liquid products. As more volatile products were manufactured, the wooden tanks were replaced with single unit riveted tanks. When production and sale of anhydrous ammonia, liquefied petroleum gas (LP-Gas), and other liquid compressed gases first began, the products were transported in small pressure cylinders loaded on flat cars. Later, pressure tight versions of the single unit, riveted tanks were used. These were essentially the same as the tank cars in this service today. It was the custom to insulate the tank cars used for liquefied compressed gases with 4 inches of cork insulation. Then, under the auspices of the Interstate Commerce Commission, this custom was written into Federal Regulations and became law. Later, the original requirement of 4 inches of cork was supplemented with an alternate, 4 inches of fiber glass. Until the present, no data have been presented either to prove or to disprove the need for insulation, but the early concept of a pressure vessel completely covered with insulation remains until the present day.

However, with ever rising transportation costs, and ever increasing capital investments necessary to keep abreast of an expanding industry, the need has arisen to examine the basic design of tank cars in an effort to halt, or at least slow, the increasing costs of the transportation package. The question, "Is tank car insulation necessary?" becomes pertinent when it is realized that thousands of trucks and millions of storage vessels for anhydrous ammonia and other liquefied compressed gases do not have insulation on them -- and never did.

CHAPTER II

PREVIOUS REPORTS AND PAPERS

Several small scale tests have been conducted with vessels from 33 gallons to 1000 gallons in size. A brief description of the tests and summary of the results reported in those tests are in order.

1. "Temperature and Pressure Variation in Anhydrous Ammonia Containers," by N. E. Ziege, Phillips Petroleum Company, 1951. In this test, 8 containers, two each of 499, 325, 44, and 33 gallon water capacity, were used. These vessels were placed on the ground in a north-south orientation, and the entire area was faced with oyster shell.

The 499 and 325 gallon containers were cleaned to the bare metal by sand blasting; the 198 gallon cylinders had a very dark galvanized surface; and the 33 gallon cylinders had badly peeled and checked painted surfaces. Some of the containers were filled to 100 per cent of allowable capacity with anhydrous ammonia and some were filled to 10 per cent of allowable capacity with anhydrous ammonia. Temperature and pressure were recorded continuously for about 18 hours a day. A summary of conclusions is as follows:

a. In all cases, the containers of the same size and surface conditions which were filled to 100 per cent of allowable capacity, experienced higher maximum pressures than those filled to 10 per cent of allowable capacity.

b. Maximum liquid temperature varied inversely with cylinder size.

c. The highest maximum pressures occurred when there was apparently maximum exposure time to direct sun. Conversely, lower maximum pressures prevailed on days of rain or general cloud cover.

d. The smaller containers always reached higher internal pressures and temperatures on specific days than did the correspondingly filled larger containers.

e. Maximum pressures usually led the maximum liquid temperatures by 2 or 3 hours.

f. General liquid temperatures for cylinders filled to 10 per cent of allowable capacity usually came in close agreement with the ammonia vapor pressure curve between midnight and sunrise.

2. "The Effect of Painting on the Pressure Rise in Liquid Anhydrous Ammonia Containers," Phillips Petroleum Company, 1953.

In this test, 8 containers were filled to allowable capacity with liquid ammonia and placed in the open sunshine for the period from August 7, 1952 through September 24, 1952. Two 1000 gallon, three 499 gallon, and three 325 gallon pressure vessels were used in this test. Some were painted glossy white; some were painted aluminum; and some had previously been allowed to rust. Temperature and pressure from each tank were recorded continuously. A summary of conclusions is as follows:

a. Anhydrous ammonia pressure in containers painted white or aluminum were always substantially lower than in similar, rusted containers under the same exposure conditions.

b. The magnitude of pressure tended to vary inversely with the container size.

c. Aluminum paint produced approximately one-half the benefits attributable to white paint.

d. Benefits from white versus aluminum paint were most apparent under conditions of greatest solar radiation.

Although these reports pointed out no explicit relationships, it was quite apparent that tank temperatures and pressures were, in every instance investigated, influenced by tank size, per cent capacity to which they were filled, reflectivity of the exterior, ambient temperature, and sun radiation intensity. It is certain that several sources of error, such as wind velocity, were present and were neglected.

CHAPTER III

BASIC CONSIDERATIONS

A. Liquid Temperature

The temperature[1] of a liquid confined in a vessel, such as a tank car, under conditions of static equilibrium is dependent on the specific heat of the liquid, net heat input into the vessel from radiation and convection (this is heat input less heat losses) and time. The basic unit of time in an uninsulated tank car will be assumed, for the time being, to be one day, approximately 12 hours of which, in the summer time, the tank car is absorbing heat, and 12 hours of which it is radiating heat to the atmosphere.

Since this study is concerned only with daily maxima and not with instantaneous rates of change, and since it is assumed that a daily maximum will occur only once each day, this discussion can be limited to one cycle, or day, and time need not enter into the consideration as a variable.

Since the specific heat of the liquid can be assumed to remain constant over the short range of temperatures under consideration,

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[1]It must be pointed out that the temperature of liquid in a tank car varies from the shell to the center, and from the bottom to the top. When the term "liquid temperature" is used in this paper, it implies the uniform temperature that would be obtained if the thermal energy in the liquid were uniformly distributed. The liquid temperature was measured experimentally by averaging 6 temperatures read at 1 foot intervals up from the bottom of the tank. See page 2 of Appendix A.

this quantity also need not appear as a variable. This leaves daily maximum liquid temperature as a function of only the net heat input.

Obviously the absorption of radiant energy from the sun is the major source of heat. Therefore, anything that will limit this absorption of thermal energy will be capable of limiting the daily maximum liquid temperature in a tank car. Insulation is capable of retarding this flow of thermal energy (both into the tank and out of the tank). The theory on which these tests were based was that a coat of light colored paint on the outside of the tank could possibly also do an acceptable job of limiting heat absorption.

B. Gas Pressure

Due to the greater specific heat of the liquid, the liquid mass in a tank car acts as a heat sink inside the tank and tends to retard the pressure build up.

Previous studies have shown that, in the absence of internal agitation, the pressures in anhydrous ammonia containers are higher than would be expected from the given average liquid temperature. To explain this, it must be assumed that some stratification takes place in the gas phase and the liquid phase and, that under certain conditions, the layer of gas next to the liquid acts as a layer of insulation between the vapor phase and the liquid phase.

In the case under consideration, the worst condition was assumed, that is, no internal agitation. In this case, the vapor pressure is nearly proportional to the average absolute temperature of the vapor over the temperature range under consideration. For reasons set forth in Section 1 of Chap. III, the gas temperature (and therefore the gas pressure) will be considered to be a function of net absorbed radiant energy. Since the worst conditions are being considered by assuming no agitation, any error from this assumption will be on the safe side.

C. Assumptions

By making several simplifying assumptions, it has been shown that both maximum liquid temperature and maximum vapor pressure are functions of net heat absorption. It has been pointed out that the primary source of the heat is the sun. A correlation of observed maximum liquid temperatures and maximum vapor pressures with measured sun radiation would undoubtedly be very high. However, the purpose of this study is to develop a method to predict temperature and pressure maxima readily. Since sun radiation values are not readily available, and ambient temperature data are available, it is going to be assumed that the ambient temperature is proportional to sun radiation intensity. This is admittedly a radical assumption; however, the resulting empirical equations proved to have very high correlation coefficients (see Figs. 8 and 9). In view of this fact, the author believes that the assumptions stated herein are justified.

CHAPTER IV

DEVELOPEMENT OF THE FORMS OF THE EQUATIONS

Following is the developement of the forms of the equations showing daily maximum liquid temperature and vapor pressure in uninsulated tank cars as a function of ambient conditions.

A. Liquid Temperature

Assuming a uniform liquid temperature at any given time, and neglecting end and film effects

$$\Delta Q = \left[CL(T_s - T_a)\right] \quad K\Delta t$$

Where Q = heat flow
C = wetted periphery
L = length of tank
T_s = skin temperature on the outside of the shell, below the liquid level at a particular time, deg. F.
T_a = temperature of the liquid ammonia at that same time, deg. F.
K = coefficient of conductivity for the shell
t = time

Assuming a constant tank length and a constant liquid level, and therefore a constant wetted periphery

$$\frac{\Delta Q}{\Delta t} = k_1(T_s - T_a)$$

Where k_1 = a constant.

Assuming $T_s = k_2T_b + k_3T_c + k_4S + k_5$ on a particular day

Where $k_{2,3}$, ...are constants

T_b = average ambient temperature for that particular day, deg. F.
T_c = maximum ambient temperature for that particular day, deg. F.
S = reflectivity[1] of the outer surface of the tank, per cent.

$$\frac{\Delta Q}{\Delta t} = k_1(k_2T_b + k_3T_c + k_4S + k_5 - T_a)$$

$$\lim_{\Delta t \to 0} \frac{\Delta Q}{\Delta t} = \frac{dQ}{dt} = (k_6T_b + k_7T_c + k_8S + k_9 - k_1T_a)$$

Setting $\frac{dQ}{dt} = 0$, and solving for T_a

$$T_a = k_{10}T_b + k_{11}T_c + k_{12}S + k_{13} \qquad (1)$$

Where T_a is now maximum liquid temperature on a particular day.

Equation (1) shows the relationship between maximum liquid temperature, surface reflectivity and ambient conditions.

2. Vapor Pressure

$$\Delta Q = \left[C_1L(T_{s_1} - T_v)\right] K\Delta t$$

Where $C_1 = 2\pi R - C$ = dry periphery where R = tank radius
T_v = temperature of the gaseous ammonia at a particular time
T_{s_1} = skin temperature of the shell above the liquid level at that particular time.

$$\frac{\Delta Q}{\Delta t} = k_{14}(T_{s_1} - T_v)$$

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[1] Reflectivity is a measure of the energy that is reflected from the surface. In this study all reflectivity measurements were taken with a Photovolt reflection meter and were based on freshly scraped magnesium carbonate as 97.5%.

Assuming $T_{s_1} = k_{15}t_b + k_{16}T_c + k_{17}S + k_{18}$ on a particular day

$$\lim_{\Delta t \to 0} \frac{\Delta Q}{\Delta t} = \frac{dQ}{dt} = k_{14}(k_{15}T_b + k_{16}T_c + k_{17}S + k_{18} - T_v)$$

Setting $\frac{dQ}{dt} = 0$ and solving for T_v

$$T_v = k_{19}T_b + k_{20}T_c + k_{21}S + k_{22}$$

Where T_v is now maximum temperature of the ammonia vapor.

$$P_v = k_{23}T_v$$

Where P_v is maximum pressure of the ammonia vapor.

$$P_v = k_{24}T_b + k_{25}T_c + k_{26}S + k_{27} \qquad (2)$$

Equation (2) gives the relationship between maximum vapor pressure and ambient conditions. Since size of vessel has not entered into the final equations, the applications of the empirical formulae developed will be limited to vessels of a size close to those from which the data were taken.

CHAPTER V

TEST PROCEDURE

A. Test Cars

A standard I C C 105 A-400 W tank car (Number GATX 67534) was obtained and, by special permission, the outside insulation was removed. A second, conventional tank car (Number PSPX 17643) of about the same size was obtained for use as a comparison (see Figs. 5 and 6 in Appendix A). The insulated tank car was shipped to the test site full of anhydrous ammonia. However, Interstate Commerce Commission regulations forbade shipping of anhydrous ammonia in an uninsulated tank car, so the uninsulated tank car was shipped to the test site empty. Then anhydrous ammonia was trucked to the test site and pumped into the uninsulated tank car. (The ammonia was also shipped from the test site by tank truck at the end of the test.

The uninsulated tank car had a water capacity of 87597 pounds. The allowable filling density[1] by I C C regulation was 55%. So the amount to be loaded into the tank car was 87597 x .55 = 48128 pounds.

When the tank trucks actually weighed in, it was found that 48490 pounds had been loaded into the tank. This represented an excess of 362 pounds, and a filling density of

$$\frac{48490}{87597} = 55.3\%$$

[1]Filling density is the per cent of water capacity of a vessel by weight, to which it may be legally filled. This figure is set for various products in various types of vessels by the Interstate Commerce Commission.

It was believed that a closer estimate of weight was impossible under the field conditions, so no attempt was made to correct the error. (Since this vessel was not going to be transported over railroads while filled, no federal regulations were involved).

B. Location of the Test

A study of available test locations indicated the most desirable location was Borger, Texas. Borger has a record of a high percentage of clear days, which maximized sun radiation, and a north-south spur track was available, which maximized exposure. Complete facilities were available at Borger for tank car repair, instrument repair and maintenance, and the building of special fixtures. A source of anhydrous ammonia is also close by, which minimized shipping and handling.

C. Instrumentation

By means of an adapter, 8 thermocouples, spaced at 1 foot intervals from the bottom of the tank, were mounted in the uninsulated tank car (see Fig. 4 in Appendix A). Three thermocouples, spaced at 2 feet, 5 feet, and 8 feet from the bottom, were placed in the insulated tank car. A pressure recorder was connected to each tank car, and a thermocouple was placed outside in the shade to measure ambient temperature. A 12 point Leeds and Northrup temperature recorder continuously recorded all temperatures and a 2 pen Taylor pressure recorder continuously recorded all pressures.

In addition an Epply Pyrheliometer, a sun radiation measuring device, was used to record sun radiation intensity.

D. Color of Tank

In consecutive test runs, the uninsulated tank car was painted (1) white (reflectivity 84%) (2) gray (reflectivity 27%) and (3) black (reflectivity 5%).

E. Other Data

Precipitation was measured at the test site and, in addition, copies of the standard weather observation sheets containing such standard weather data as wind direction and velocity, relative humidity and temperature were obtained from the Borger airport (see Appendix D). Figure 1 shows a comparison of the temperatures taken at the test site with the temperatures recorded at the Borger Airport.

F. Duration of the Test

The uninsulated tank car was filled with anhydrous ammonia on July 4, 1956. By July 19, all the instruments were recording properly. Approximately 2 weeks of data were taken with the uninsulated tank car painted each of the 3 colors. The test was terminated August 31, 1956.

CHAPTER VI

TREATMENT OF DATA

The purpose of the field tests was to supply data from which to calculate the constants for the equations developed in Chapter IV of this paper. After the determination of the form of the equations

$$T_a = k_{10}T_b + k_{11}T_c + k_{12}S + k_{13} \qquad (1)$$

and

$$P_v = k_{24}T_b + k_{25}T_c + k_{26}S + k_{27} \qquad (2)$$

a least squares linear regression was utilized to calculate the k_i.

A. Determination of Constants in Equation (1)

The left hand side of Eq. (1) is the observed maximum liquid temperature for a particular day, and the right hand side of the same equation is the calculated value of the quantity. It is intended to choose constants that will cause the calculated values to approach the observed values.

The least squares linear regression routine accomplishes this purpose by minimizing the squares of the differences between the observed and the calculated values. Thus, we write the equation

$$\sum(T_a - k_{10}T_b - k_{11}T_c - k_{12}S - k_{13})^2 = 0 \qquad (3)$$

Since T_a, T_b, T_c, and S are observed values (see Appendix B for the observed values of T_a, T_b, T_c, and S) we may consider the

k_i to be the unknowns. Considering the k_i to be unknowns, we may write

$$\frac{\partial \sum (T_a - k_{10}T_b - k_{11}T_c - k_{12}S - k_{13})^2}{\partial k_{10}} = 0 \qquad (4)$$

$$\frac{\partial \sum (T_a - k_{10}T_b - k_{11}T_c - k_{12}S - k_{13})^2}{\partial k_{11}} = 0 \qquad (5)$$

$$\frac{\partial \sum (T_a - k_{10}T_b - k_{11}T_c - k_{12}S - k_{13})^2}{\partial k_{12}} = 0 \qquad (6)$$

$$\frac{\partial \sum (T_a - k_{10}T_b - k_{11}T_c - k_{12}S - k_{13})^2}{\partial k_{13}} = 0 \qquad (7)$$

Thus we have 4 equations and 4 unknowns, the solutions of which are lengthy but routine. This type of problem is excellently suited for electronic computer handling.

B. Determination of Constants in Equation (2)

By the same reasoning as set forth above we may write

$$\sum (P_v - k_{24}T_b - k_{25}T_c - k_{26}S - k_{27})^2 = 0 \qquad (8)$$

and

$$\frac{\partial \sum (P_v - k_{24}T_b - k_{25}T_c - k_{26}S - k_{27})^2}{\partial k_{24}} = 0 \qquad (9)$$

$$\frac{\partial \sum (P_v - k_{24}T_b - k_{25}T_c - k_{26}S - k_{27})^2}{\partial k_{25}} = 0 \qquad (10)$$

$$\frac{\partial \sum (P_v - k_{24}T_b - k_{25}T_c - k_{26}S - k_{27})^2}{\partial k_{26}} = 0 \qquad (11)$$

$$\frac{\partial \sum (P_v - k_{24}T_b - k_{25}T_c - k_{26}S - k_{27})^2}{\partial k_{27}} = 0 \qquad (12)$$

Again using the observed values of T_a, T_b, T_c, and S as recorded in Appendix B, and solving Eqs. (9), (10), (11), and (12) simultaneously, the constants for Eq. (2) were obtained.

C. Handling of Calculations

An electronic computer was utilized for the solution of these two sets of simultaneous equations. When the values of the k_i were substituted in Eqs. (1) and (2), the resulting first order equations expressed maximum liquid temperature and maximum vapor pressure as functions of the maximum ambient temperature, average ambient temperature and color reflectivity. Being of the first order these equations are considered accurate for moderate extrapolation.

CHAPTER VII

TEST RESULTS ON THE UNINSULATED TANK CAR

A. Maximum Liquid Anhydrous Ammonia Temperature

Upon solving Eqs. (4), (5), (6) and (7) simultaneously for k_{10}, k_{11}, k_{12}, and k_{13} the following values were obtained:

$$k_{10} = 0.35$$

$$k_{11} = 0.43$$

$$k_{12} = -0.1$$

$$k_{13} = 18.0$$

Substituting these values into Eq. (1)

$$T_a = .35\ T_b + .43\ T_c - .1S + 18 \qquad (13)$$

Where T_a = maximum liquid anhydrous ammonia temperature on any given day, degrees F.
T_b = average ambient temperature for that day, degrees F.
T_c = maximum ambient temperature for that day, degrees F.
S = reflectivity of the paint on the tank or as measured by a Photovolt Reflection Meter, per cent.

This empirical equation was, of course, checked for reliability. Utilizing the observed T_b, T_c and S values, T_s values were calculated for each day of the test. Figure 4 shows the excellent agreement obtained between the observed maximum liquid temperatures and the calculated maximum liquid temperatures. Since Eq. (13) is a first order equation, it is considered sufficiently accurate for moderate extrapolation.

If a set of extreme values for ambient conditions[1] and reflectivity[2] are assumed a "maximum" temperature condition can be calculated. Assume

$$T_b = 115 \text{ F}$$

$$T_c = 130 \text{ F}$$

$$S = 40$$

$$T_a = .35(115) + .43(130) - .1(40) + 18$$

$$= 100 \text{ F}$$

This value represents a "design" value. In all probability it would never be reached in the normal operation of a white, uninsulated tank car in this service in the United States.

B. Maximum Ammonia Vapor Pressure in an Uninsulated Tank Car

Upon solving Eqs. (9), (10), (11) and (12) simultaneously for k_{24}, k_{25}, k_{26}, and k_{27}, the following values were obtained

$$k_{24} = 0.81$$

$$k_{25} = 1.66$$

$$k_{26} = 0.72$$

$$k_{27} = 2.0$$

---

[1] A search of United States Weather Bureau records covering the past 30 years has shown that the assumed ambient conditions are more severe than anything on record in the United States. As a rule, places experiencing very high maximum temperatures have low minimum temperatures and consequently, moderate average temperatures.

[2] Actual reflectivity readings taken on light colored tank cars in service indicate that a reflectivity of 40% represents an extremely dirty white tank car (see Appendix C for actual observed values).

Substituting these values into Eq. (2)

$$P_a = .81\ T_b + 1.66\ T_c - .72\ S + 2 \qquad (14)$$

Where P_a = maximum vapor pressure on any given day, psig. This empirical equation was also checked for reliability. Utilizing the same values of T_b, T_c, and S, P_a values were calculated daily values of P_a. Substituting the same set of extreme values as used in the calculation of a "maximum" liquid temperature condition

$$P_a = .81(115) + 1.66(130) - .72(40) + 2$$
$$= 282 \text{ psig}$$

This figure also represents a "design" value. In all probability, it would never be reached in the normal operation of a white, uninsulated tank car in this service in the United States.

C. Data Correlation

When the empirical equations were constructed, the observed ambient temperature data were fed back and, for each day, a maximum liquid temperature was calculated. These calculated values were compared with the observed values, and the correlation coefficient calculated as follows:

$$R = \sqrt{1 - \frac{\sum(\text{observed values} - \text{calculated values})^2}{n\ (\text{standard deviation})^2}}$$

Where R = correlation coefficient
n = number of days

This coefficient is a measure of the combined importance of the independent variables. It varies between 0 and 1. Zero means the independent variables make no explanation of the observed results; one means the independent variables completely explain the observed results.

For these tests, the correlation coefficients were as follows:

For Eq. (13), $R = .92$

For Eq. (14), $R = .86$

The coefficient of correlation is very difficult to picture graphically, but the concept is conveyed in Figs. 4 and 5 which show plots of calculated and observed maxima for liquid temperature and vapor pressure and Figs. 8 and 9 which show plots of observed versus calculated values for the same quantities.

CHAPTER VIII

DISCUSSION OF RESULTS

A. Maximum Liquid Temperature

A method of predicting maximum liquid anhydrous ammonia temperature in an uninsulated tank car is now available. Maximum liquid temperature has now been defined as a function of average ambient temperature, maximum ambient temperature and reflectivity. This function can now be utilized with suitable ambient temperature data to calculate design temperatures on which to base filling densities.

Figure 6 as well as Eq. (13) shows that the color of the tank is of considerable importance, and that the lighter the tank color, the lower the maximum liquid temperature to be expected. However, it will be noted that Fig. 6 was plotted for a single average ambient temperature. In practice, the average ambient temperature varies greatly from place to place and from time to time. Therefore, graphs such as Fig. 6 cannot be relied on to predict accurately maximum liquid temperature. These predictions will have to be based either on equations such as Eq. (13) or on nomographs constructed from such equations.

B. Maximum Vapor Pressure

Design and material selection problems are solved most economically when conditions to be encountered are known within close limits. Maximum anhydrous ammonia vapor pressure in an uninsulated tank car has now been defined as a function of average ambient temperature, maximum ambient temperature, and reflectivity. This function can now be utilized with suitable ambient temperature data, to calculate design pressures.

Figure 7 and Eq. (14) show that the color of the tank is quite important in the determination of maximum vapor pressure. Figure 7 is a plot of Eq. (14) with average ambient temperature held constant. Figure 7 shows that the lighter the color, the smaller the pressure rise. When the extreme assumed values for ambient temperature were substituted into Eq. (14) the resulting calculated extreme pressure for a white tank was below the safety valve setting of 300 psig. Thus, the original purpose of this series of tests was accomplished. It was shown that light colored paint could sufficiently reduce the absorption of radiant energy to permit the safe operation of uninsulated tank cars in anhydrous ammonia service.

C. General Discussion of Results on the Uninsulated Tank Car

Figure 3 shows a comparison of observed maximum pressures in the uninsulated and the insulated tank cars. It will be noted that fluctuations in the uninsulated car were more violent, indicating that a great deal of "cooling off" took place at night. Also, the insulated tank car, during most of the test, increased at a steady rate. The implication is that the insulated tank car, if exposed to the right conditions, might gain in pressure until it reached the same maximum pressure as that in the uninsulated tank car.

Toward the end of the test period, an unseasonably cold front moved into the test area (see Fig. 1). This accounts for the slight down turn noted in Figs. 3, 4, and 5. In one way, this turn of the weather was unfortunate. It interrupted a pressure build up, and prevented the obtaining of maximum readings that would probably have otherwise been obtained. On the other hand, the week of unusually cold weather permitted us to obtain a much wider range of data.

Figure 1 of Appendix A shows a relationship between maximum ambient temperature and pressure rise. Although this relationship is not constant, and therefore not well suited to the type of correlation undertaken in this study, it is present. Note that the curves on Fig. 1 in Appendix A converge at the lower ambient temperatures. This reflects the expected lowering of average ambient temperature with the lowering of maximum ambient temperature. On the other hand, Fig. 6, calculated from Eq. (13) with a constant average ambient temperature, shows the three color curves as parallel. This discussion may be summarized by saying that it is not possible to correlate accurately the relationships between ambient temperature, reflectivity and pressure rise (or temperature rise) with a simple curve having 2 dimensions.

D. Sources of Error

During the process of taking data, several sources of error were noted. Showers, cloudy days, wind, etc. all affected the results.

Showers caused an abrupt cooling and a drastic lowering of pressure in the uninsulated tank. Cloudy days produced a somewhat smaller pressure build up than clear days, even though average and maximum ambient temperatures were comparable.

Although no attempts were made to confirm the effects of wind, it is known that wind aids the dissipation of heat from tanks, and thus reduces maximum liquid temperature and retards the pressure build up. This means that a stationary tank represents a more severe condition that a moving tank.

Even with these errors, however, the resulting equations have very high correlation coefficients.

E. Limitations

It has been pointed out earlier that vessel size has a direct bearing on the temperature and pressure behavior. Since this variable does not appear in the developed equations, these equations can be applied only to vessels of the approximate size of the test vessel, about 10,000 gallons.

While the empirical equations herein developed have very high correlation coefficients, they must be considered accurate only in the range of the data taken. Any extrapolation of more than a few degrees above or below the range of data taken would have to be regarded as very unreliable.

This in no way casts doubt on the quality of the data taken, but is merely a fair appraisal of the limitations present, and means that while the equations herein presented are satisfactory for the calculation of summer maxima, they are in all probability, unreliable for calculating conditions to be expected in the winter months or in a location having general ambient conditions quite different from those found in the southwestern United States.

CHAPTER IX

COMPARATIVE RESULTS ON THE INSULATED TANK CAR

When an attempt was made to evaluate the data from the insulated tank car in the same manner as that used with the uninsulated, a very low correlation coefficient, .25, was obtained. Further experimentation with curve fitting procedures showed that a linear equation expressing maximum liquid temperature, or vapor pressure, conditions for a given day as a function of ambient conditions would have to be of the form

$$T_a = K_i \, T_{b1} - K' \, T_c - K'' \qquad (i = 0 \text{ to } n) \qquad (15)$$

Where K_i, K' and K'' are constants, and

T_{b_0} = the average ambient temperature for the day under consideration, degrees F.

T_{b_1} = the average ambient temperature for the day previous to the day under consideration, degrees F.

T_{b_2} = the average ambient temperature for the day two days previous to the day under consideration, degrees F.

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T_{b_n} = the average ambient temperature for the day n days previous to the day under consideration, degrees F.

While the uninsulated tank car operated on a cycle of approximately 1 day, the insulated car operated on a cycle of 1 year, with average liquid temperature increasing all summer and, presumably, decreasing all winter.

The layer of insulation, retarding the transfer of heat caused the delay in temperature change, and required that a larger segment of data than 1 day be considered in the correlation of liquid temperature and vapor pressure with ambient conditions. Since a large mass of liquid, or a liquid with a relatively high specific heat, could also be expected to retard temperature change, it would logically be expected that a large mass of liquid, or a mass of liquid having a relatively high specific heat value would require the same mathematical treatment as the data from the insulated tank. Therefore, if uninsulated vessels of large size or vessels containing liquids of relatively high specific heat values are to be examined in the manner herein described, it is expected that the equations satisfactorily relating the maximum tenperature and pressure in the vessel under study to ambient conditions would have to be of the form of Eq. (15).

CHAPTER X

CONCLUSIONS AND APPLICATIONS

This study was originally undertaken by Phillips Petroleum Company, Bartlesville, Oklahoma, to show the feasibility of operating light colored tank cars in anhydrous ammonia[1] and LP-Gas service without the customary insulation jacket. In Appendix A is the report that was written recommending the changes in the I C C regulations.

By showing that, even under ambient conditions more severe than any on record, the maximum pressure to be expected in a light colored, uninsulated tank car was below the danger level, it was proved that light colored tank cars would be safely operated in anhydrous ammonia and LP-Gas service without the insulation. On the basis of this report, the Interstate Commerce Commission altered the applying regulations.

After the original purpose was accomplished, a second goal was set, the establishing of maximum safe filling densities.

Based on Phillips Petroleum Company's Engineering Department Report 390, Supplement I (see Appendix A), the Interstate Commerce Commission adopted a new filling density for tank cars in anhydrous ammonia service. The basis of the new filling density was the maximum liquid temperature calculated by Eq. (14) of this study.

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[1]Anhydrous ammonia has the higher vapor pressure in the temperature range anticipated. Therefore, if tank cars could be proved to be safe in anhydrous ammonia service, the same tank cars would certainly be safe in propane service. For this reason the tests were conducted using only anhydrous ammonia.

CHAPTER XI

FIELDS FOR FURTHER STUDY

In any growing industry, each small step opens the door to a multitude of larger steps. Once a technique is perfected, hundreds of applications for this technique can be seen. This report has shown that light colored tank cars in anhydrous ammonia or LP-Gas service could be operated without insulation.

There are many compressed gases which, at present, are required to be shipped in insulated tank cars. Vast amounts of capital could be released for use elsewhere if these products could be shown to be safe in uninsulated tank cars. Using the method of study outlined in Phillips Petroleum Company's Engineering Department Report 390, Columbia-Southern Chemical Corporation is currently conducting tests to evaluate the effects of ambient conditions on uninsulated tank cars in chlorine service.

A related field of study is the accurate determination of maximum safe filling densities for insulated tank cars in liquid compressed gas service. Experimental work is being done by the author at present in the field of insulated tank cars for LP-Gas and anhydrous ammonia service. This work involves the gathering of sufficient data to supply constants for an equation of the form of Eq. (15), and the determination of a "maximum" liquid temperature to be expected in insulated tank cars. The study is being based on longer range test information and "high temperature location" weather information. A difficulty lies in the determination of suitable ambient temperature values to use for winter calculations.

With equations of the form of Eq. (15) it is important to obtain very accurate weather data for use in design condition calculations. Assuming ultra-conservative ambient temperature values for 1 day is quite different from assuming the same values to be true for a 10 or 15 day period. The assumption for the longer period would be so conservative as to constitute severe penalization. Considerable weather research will be necessary to supply suitable "maximum" ambient temperature values for equations of this form.

It is quite possible that, as larger tank cars are built, the equations for uninsulated tank cars will be considered too conservative. With larger masses of liquid, the empirical equations contained in this paper do become more conservative. Correlations having volume, and perhaps specific heat, as variables will be necessary. Although, as stated before, the correlations resulting from this test were very good, the large constant at the end of Eq. (13) indicates that correlation could be better. It is quite probable that the 10,000 gallon size tank is about the largest that can be considered on a 1 day basis. Tanks over that size will probably require equations of the form of Eq. (15) to satisfactorily relate internal and external temperatures.

Separate summer and winter filling densities are specified by law for some products, but others do not have this advantage. (The advantage consists of carrying more pounds of product in the cooler months, when liquid expansion is less, than in the warmer months of the year).

Studies similar to this one should be undertaken to investigate the feasibility of separate summer and winter filling densities for many other liquefied compressed gases, to guarantee that the present national tank car fleet is being used to the fullest advantage.

With additional data on tank cars, and better correlations involving formulas of the form of Eq. (15) better tabulations of weather history will be necessary.

Correlations of this type will require many and varied types of weather history reports. Some of the typical questions that will have to be answered soon are as follows:

1. What are the average ambient and maximum ambient temperatures for the warmest 11 consecutive days on the North American Continent for the past 25 years? What was the location? In continental United States? What was the location?

2. Same information as above for the winter months.

3. What is the maximum number of consecutive days for which average ambient temperature has exceeded 100 F at a single location on the North American Continent? What location? In continental United States? What location?

4. What is the maximum number of consecutive days for which maximum ambient temperature has exceeded 130 F at a single location on the North American Continent in the past 25 years? What location? In continental United States? What location?

When these questions are answered, there will be others of similar magnitude and difficulty. However, progress is not to be feared or shunned; if the problems are difficult, the more is the satisfaction received with their successful solution. The problem of utilizing to the fullest the country's petroleum product transportation system, and at the same time, forging ahead with improvements in that system is indeed a challenge worth accepting.

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APPENDIX A

Engineering Department Report 390

Phillips Petroleum Company

Bartlesville, Oklahoma

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APPENDIX A

EFFECTIVENESS OF PAINT VERSUS INSULATION FOR LIMITING PRESSURE INCREASE IN TANK CARS

1.00 SUMMARY

.01 Current and long standing ICC regulations require that tank cars used in LP-Gas and anhydrous ammonia service be insulated. However, considering the results of tests run in 1950 and 1953 by Phillips Petroleum Company, and also the information gained in 35 years of operating experience, the decision was made to experimentally determine the effect on tank car pressure of replacing the insulation and jacket with reflective paint on the bare tanks.

.02 An uninsulated ICC 105A-400W tank car (10,518 gallon water capacity) was filled with anhydrous ammonia, and internal temperature and pressure data were taken with the car painted white, gray and black successively. Results were compared with data taken from a conventional insulated ICC 105A-300W tank car filled with anhydrous ammonia from the same source.

.03 Maximum pressures in the uninsulated car were as follows:

Paint		Max. Tank Car	Max. Ambient Temp.
Color	Reflectivity	Pressure	Measured in Shade
White	84%	216 psig	105 F
Gray	27%	265 psig	109 F
Black	5%	295 psig	108 F

Note: These pressures are about 10% high due to air in the vapor space.

Maximum pressure during this time in the insulated tank car used for comparison was 185 psig.

.04 Extrapolated data shows that with 300 psig considered the maximum allowable pressure, paint reflectivity could drop as low as 13% and still be adequate to prevent overpressuring at an ambient temperature of 115 F. (13% represents an extremely dirty white paint.)

.05 Based on these facts, it was concluded that uninsulated tank cars with a relief valve setting of 300 psig could be painted any light color and be safely operated in LP-Gas and anhydrous ammonia service.

2.00 INTRODUCTION

.01 The problems of tank car operation and maintenance are numerous and complex, and since Phillips Petroleum Company operates the largest, pressure tank car fleet in the world, it is fitting that the Company should be always seeking newer and better methods for building and maintaining tank cars.

.02 With this in mind, it was decided to conduct an extensive test program to determine the feasibility of operating tank cars in LP-Gas and anhydrous ammonia service without insulation.

.03 From the results of previous tests[1] and information gathered in 35 years of experience, it was believed that the absorption of heat from the sun could be reduced sufficiently by the application of a reflective paint to allow pressure tank cars with a 300 psig relief valve setting

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[1] Temperature and Pressure Variation in Anhydrous Ammonia Containers, by N. E. Ziege. 1951.
EDR-350. The Effect of Painting on the Pressure Rise in Liquid Anhydrous Ammonia Containers, by N. E. Ziege. 1953.

to be operated safely without insulation. Both tank trucks and stationary storage vessels have been operating on this principle for many years. Consequently, this series of tests was conducted to determine experimentally the effect of paint reflectivity on uninsulated tank car pressures and to compare these pressures with those developed in conventional insulated tank cars under identical conditions of exposure.

.04 An uninsulated ICC 105A-400W (10,518 gallon water capacity) test car was obtained, and, after a study of weather data, a north-south spur track in the Borger, Texas, area was chosen for the test site. The north-south orientation was chosen to maximize exposure. The area was chosen because of sun radiation intensity and the high percentage of clear days. A conventional, insulated ICC 105A-300W tank car (11,070 gallon water capacity) filled with anhydrous ammonia was used as a comparison.

.05 Although the results of these tests, in general, were intended to apply to both LP-Gas and anhydrous ammonia tank cars, ammonia was chosen for the test because it had the higher vapor pressure in the anticipated temperature range.

3.00 CONCLUSIONS

.01 A tank car with a relief valve setting of 300 psig can be operated safely without insulation when painted a light color.

.02 An extension of the data curves indicates the following:

Paint		Max. Pressure at	Max. Pressure at
Color	Reflectivity	115 F Amb. Temp.	130 F Amb. Temp.
White	84%	235 psig	270 psig
Gray	27%	280 psig	340 psig
Black	5%	320 psig	380 psig

Note: These pressures are about 10% high due to air in the vapor space of the test car.

.03 With a filling density of 55.3% the slip tube gauge would indicate 0" outage of 130 F liquid temperature. (This would still leave the space in the manway; so even here, the tank would not be liquid full.)

4.00 RECOMMENDATIONS

.01 It is recommended that uninsulated tank cars with a relief valve setting of 300 psig be approved for LP-Gas and anhydrous ammonia service, and that these cars be painted with a light color, self cleaning, paint.

5.00 TEST SETUP AND PROCEDURE

.01 The test car used was a standard ICC 105A-400W tank car with the insulation and jacket removed.

.02 An instrument adapter was placed in the usual location of the safety valve, and the safety valve was moved to a location on the adapter. See Figure 4. A Fisher Governor Company Level-Trol was mounted in the top of the adapter and adjusted to measure level change. In addition to level data taken with the Level-Trol, periodic level measurements were made with the slip tube on the test car.

.03 Eight thermocouples were mounted in the adapter and spaced down through the tank at 1' intervals from the bottom to measure temperature.

.04 After the test car was outfitted, it was moved to the test site and filled with anhydrous ammonia to a density of 55.3%. The ammonia was trucked in from the Ammonia Plant in Cactus, Texas. A conventional tank car full of ammonia from the same source was shipped to the test for use as a comparison.

.05 Additional thermocouples were installed to measure temperature in the insulated vessel and also to measure ambient temperature. Ambient temperature was measured on the north (shaded) side of the instrument house. See Figure 6. Sun radiation intensity was measured by an Epply Pyrheliometer. This instrument generates a voltage proportional to the intensity of sun radiation striking a horizontal plane. All instruments were connected to indicator-recorders in the instrument house (see Figure 7) and data recorded 24 hours a day.

.06 Precipitation was measured daily at the test site, and wind direction and velocity and other weather information was obtained from the Central Air Lines office at the Borger Airport.

.07 Data were obtained with the test car painted white (duPont Northern Tank White), then gray (duPont Horizon Gray), then black (duPont Utility Black).

6.00 RESULTS

.01 Figure 1 shows the relationship that existed between ambient temperature and tank car pressure throughout the test.

(1) A maximum ambient temperature of 105 F and a maximum tank pressure of 216 psig was obtained with the tank painted white.

(2) A maximum ambient temperature of 109 F and a maximum tank pressure of 265 psig was obtained with the tank painted gray.

(3) A maximum ambient temperature of 108 F and a maximum tank pressure of 295 psig was obtained with the tank painted black.

.02 The temperature-pressure data were conservatively extrapolated to obtain pressures to be expected up to 130 F ambient temperature.

.03 Figure 2 is a plot showing the relationship of the paint reflectivity to the maximum tank car pressure for three maximum ambient temperatures. These curves were produced by taking the tank pressures from Fig. 1 at the desired ambient temperatures and plotting them against the known reflectivities of the paint. This curve permits one to assume a desired maximum tank pressure and, knowing the maximum ambient temperature to be encountered, predict the paint reflectivity required to keep the tank pressure below the desired maximum.

Example: If it were required to keep a tank pressure below 300 psig in an ambient temperature of 115 F, the minimum reflectivity would be 13%.

.04 Also shown in Fig. 2 are the corrected tank pressures vs. reflectivity. These are the values that would be obtained if there were no air in the vapor space.

.05 Figure 3 shows the relationship between liquid temperature and liquid level. The curve is based on slip tube readings and merely serves to confirm the calculated filling density.

.06 Maximum variation of liquid level recorded was 3 1/4". The maximum level occurred at a liquid temperature of 91 F and was recorded at 9 1/4" of outage. The minimum level occurred at 64 F and was recorded as 12 1/2" of outage.

7.00 DISCUSSION

.01 Ideally, the pressure of a confined gas depends primarily on temperature. In the case of a closed vessel such as a tank car, the temperature is largely dependent on the absorption of radiant energy from the sun. Therefore, anything that would limit this absorption would be capable of limiting the pressure. Some doubt might arise over the ability of any light colored paint to retain enough reflectivity to accomplish this purpose. However, white storage tanks have been in operation in the Borger, Texas, area for many years and this area has two carbon black plants. Excellent opportunity has been available for these tanks to darken, but they have not. Furthermore, Fig. 2 shows that for a maximum pressure of 300 psig to be reached even in 115 F weather, the reflectivity would have to drop to 13%. This combination represents an almost impossible set of conditions. Therefore, it is believed that a high reflectivity paint such as that used in these tests would be quite capable of permanently reducing the amount of sun radiation absorbed by pressure tank cars.

.02 One source of error that entered into the tests was a small amount of air that was present in the tank car and not eliminated in the process of loading from the tank trailers. However, this was on the safe side; that is, it tended to make the test conditions more severe than actual conditions. A study of data showed that the pressure was running slightly higher than the measured temperatures would have indicated. This indicated the presence of another gas. A spectro-analysis of the vapor in the test car confirmed this. It tested 13% air. This would cause an approximate 10% increase in pressure in the range encountered in the test.

.03 The Level-Trol was somewhat affected by the sun. As the pilot got warm, the Bourdon tube tended to react in the same manner as when the liquid level dropped. Therefore, in studying the data, only Level-Trol data taken after sundown or slip tube readings were considered.

.04 Showers, cloudy days, wind, etc.all affected the data.

(1) Showers caused an abrupt cooling and a drastic lowering of pressure in the uninsulated vessel.

(2) Cloudy days produced a somewhat smaller pressure build up than clear days, even though ambient temperatures were comparable.

(3) Although no attempts were made to confirm the effect of wind, it is known that wind aids the dissipation of heat from tanks and thus retards the pressure build ups, (this would mean that a stationary tank would represent a more severe condition than a moving tank car).

All these factors were reflected as a scattering of points on the pressure vs. ambient temperature curves (Fig. 1), and when the curves were extrapolated it was assumed that atmospheric conditions encountered in the tests were typical. It is believed that the hot, dry climate of the Borger area made this a safe assumption.

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ENGINEERING DEPARTMENT

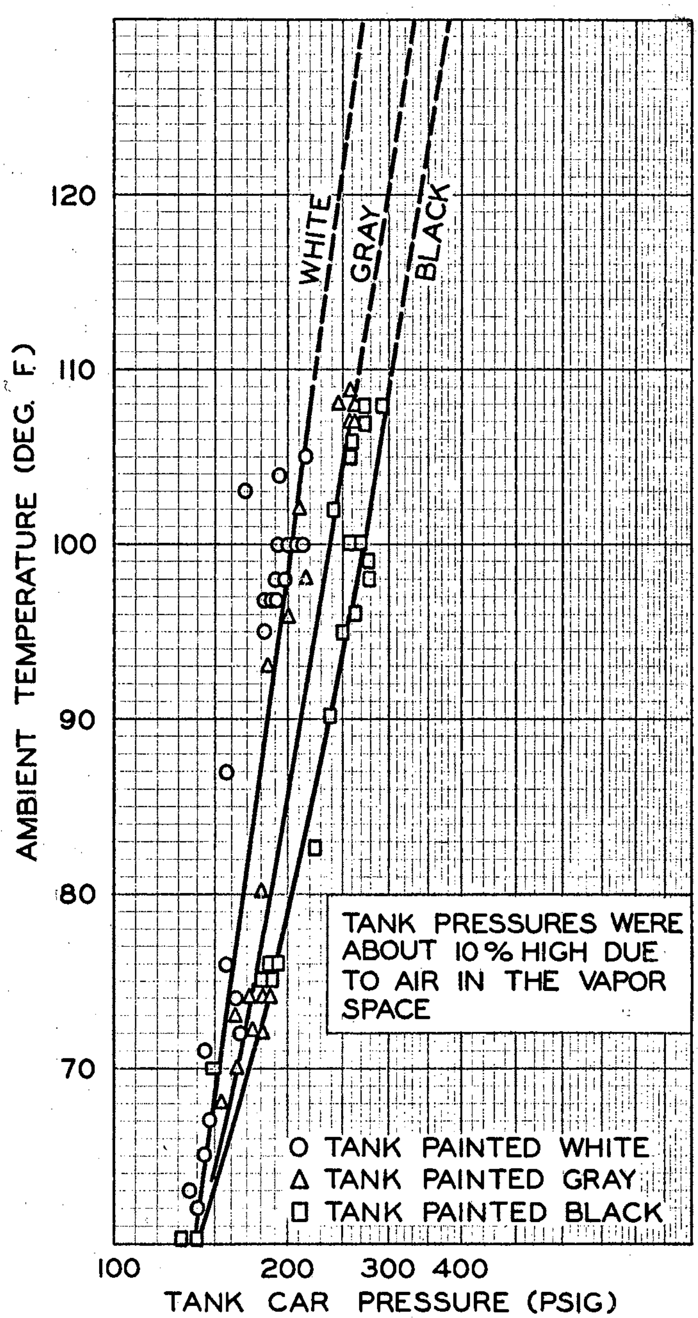

FIGURE I
PRESSURE VS AMBIENT TEMP.
WHEN TEST CAR PAINTED VARIOUS COLORS

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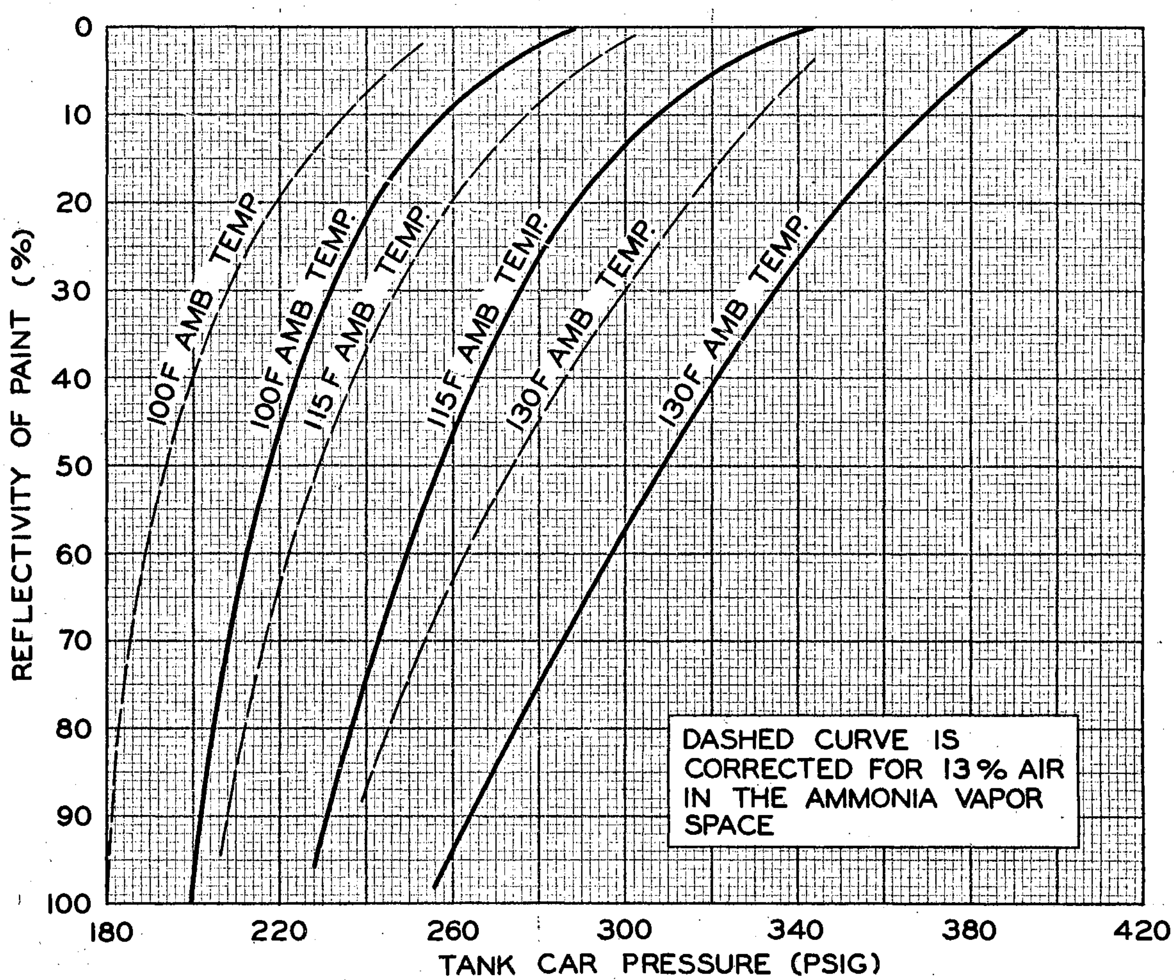


FIGURE 2
TANK CAR PRESSURE VS REFLECTIVITY OF THE PAINT

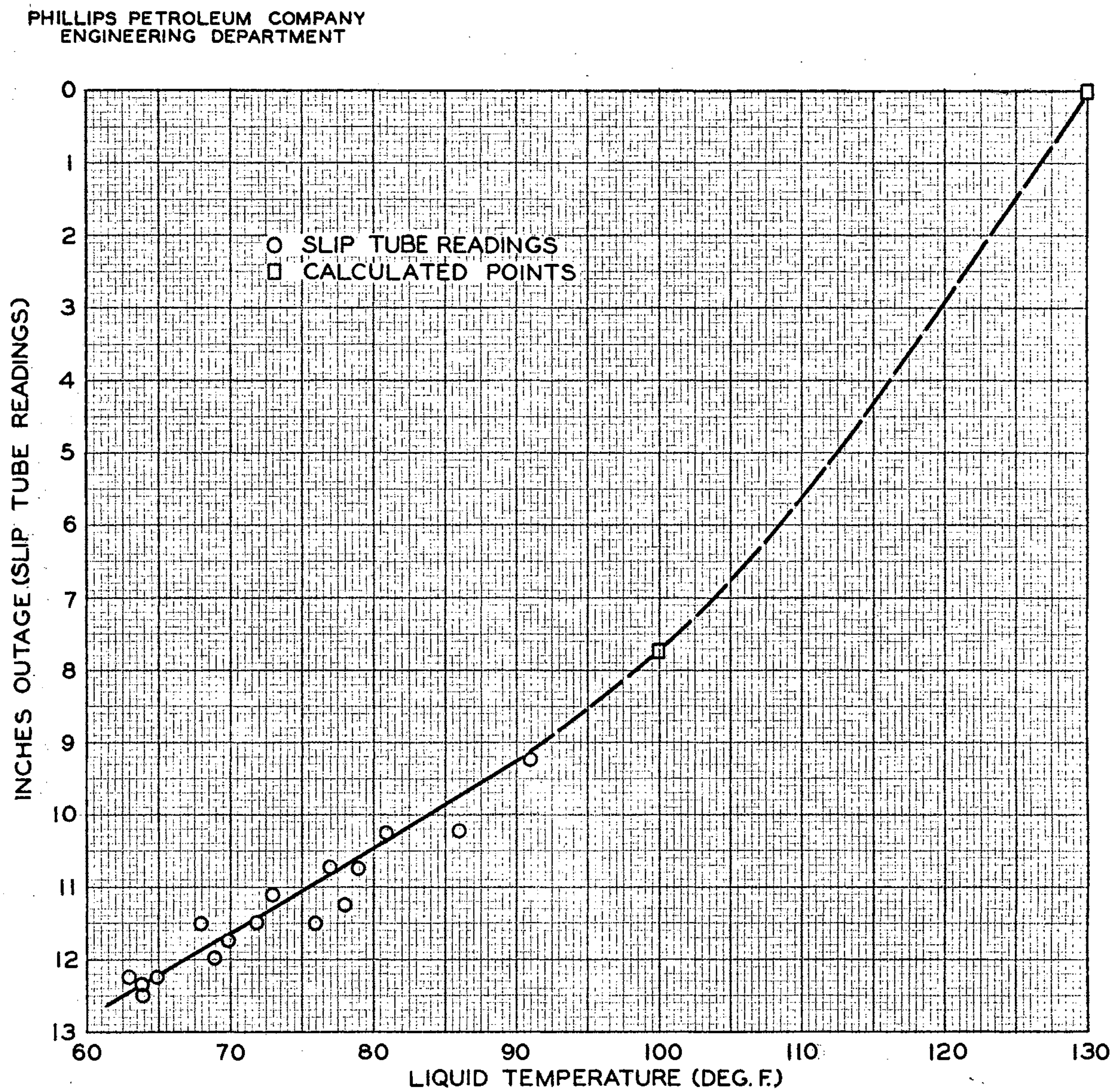


FIGURE 3

LIQUID TEMPERATURE VS. LIQUID LEVEL

FIGURE 4 G-3963

THE UNINSULATED TEST CAR
SHOWING THE INSTRUMENT ADAPTER AND
THE RELOCATED SAFETY VALVE

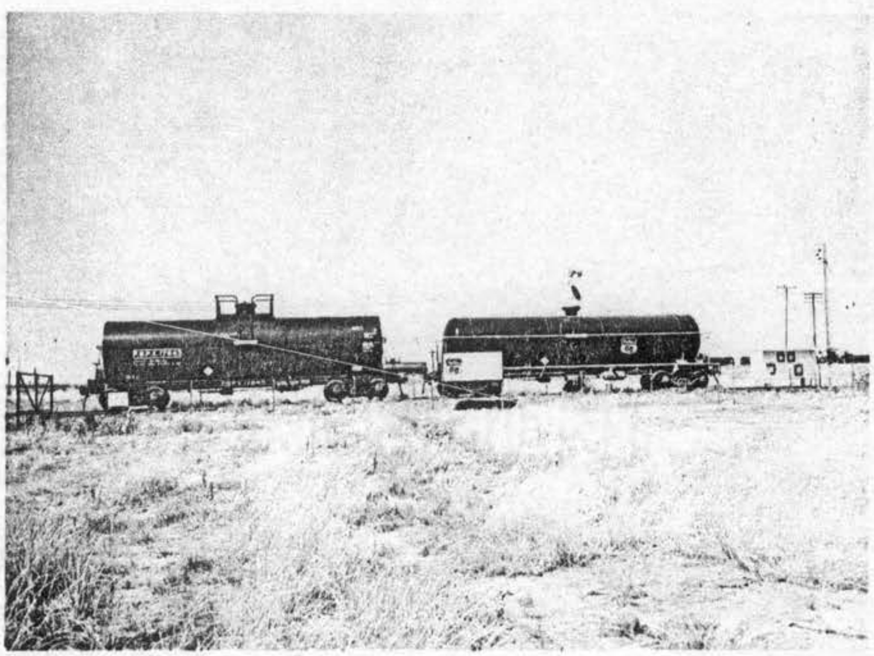


FIGURE 5 G-3964

THE TEST SITE LOOKING WEST

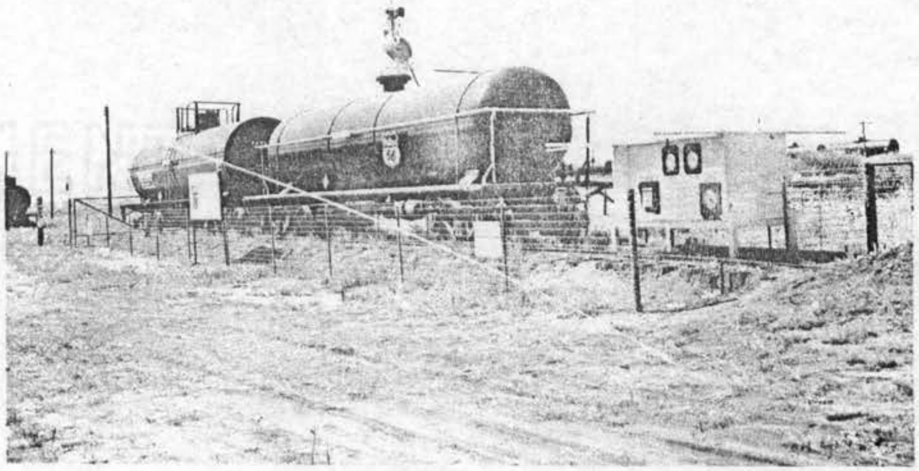


FIGURE 6 G-3960

THE TEST SITE LOOKING SOUTH

NOTE THE PYRHELIOMETER BULB ON TOP AND THE AMBIENT TEMPERATURE THERMOCOUPLE ON THE NORTH SIDE OF THE INSTRUMENT HOUSE.

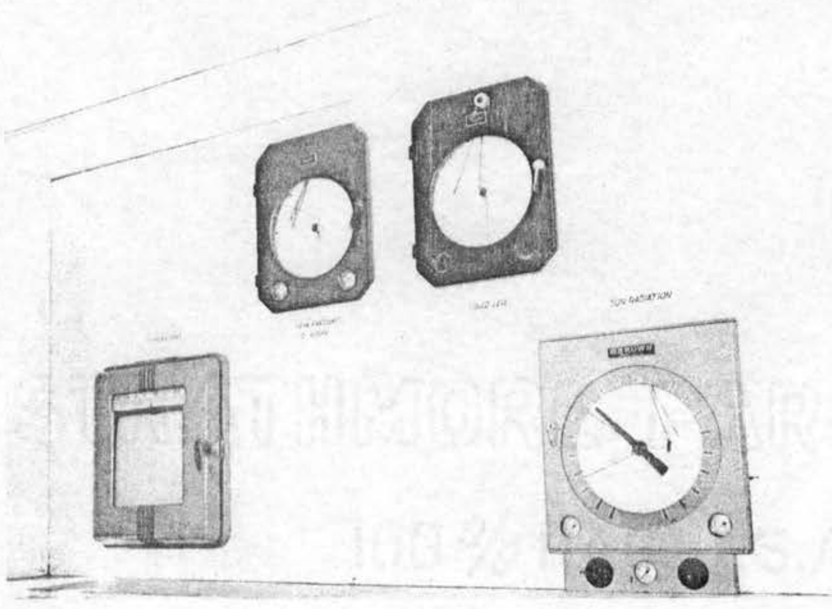


FIGURE 7 G-3962

A CLOSE UP VIEW OF THE INDICATOR - RECORDERS

1. Maximum Temperatures of Liquid Anhydrous Ammonia and Propane in Uninsulated Tank Cars

INTRODUCTION:

APPENDIX A, "Effectiveness of Paint vs. Insulation for Limiting Pressure Increase in Tank Cars", was presented to establish the feasibility of operating uninsulated tank cars in anhydrous ammonia and propane service. After the completion of APPENDIX A, the second phase of data evaluation, the development of information concerning liquid temperatures in uninsulated tank cars began. This was required if full advantage were to be taken of information presented in APPENDIX A.

Maximum summer and winter liquid temperatures of ammonia and propane were required. Summer maximums were required for filling density calculations. Winter maximums were required to pave the way for the establishing of separate summer and winter filling densities. It was believed that considerable saving could be realized if separate summer and winter filling densities could be established.

Therefore, this supplement was written to present a design liquid temperature for uninsulated dual service tank cars, and temperatures on which to base filling densities for both summer and winter.

CONCLUSIONS:

Maximum liquid ammonia temperature in an uninsulated dirty tank car would not exceed 108 F in 125 F maximum ambient temperature.

Maximum liquid propane temperature under the same conditions would not exceed 112 F.

Maximum liquid temperatures during winter months would not exceed 88 F and 93 F for ammonia and propane respectively.

RECOMMENDATIONS:

It is recommended that 115 F be adopted as the design liquid temperature for uninsulated dual service tank cars, and that summer filling densities be based on this temperature.

It is further recommended that winter filling densities be established for uninsulated dual service tank cars, and that 95 F be adopted as the basis for their calculation.

MAXIMUM LIQUID AMMONIA TEMPERATURE:

Adequate data were gathered during the summer of 1956 to determine the temperature behavior of liquid ammonia. By means of an electronic computer and a linear regression curve fitting routine, an equation to fit the experimental data was determined. It is,

$$T_a = .35\ T_b + .43\ T_c - .1\ S + 18 \qquad (1)$$

where T_a = Maximum liquid ammonia temperature in an uninsulated tank any given day, degrees F.
T_b = Average ambient temperature for that day, degrees F.
T_c = Maximum ambient temperature for that day, degrees F.
S = Reflectivity of the paint on the tank car as measured by a Photovolt Reflection Meter, per cent.

Using the above equation, and the extreme summertime conditions,

T_b = 110 F
T_c = 125 F
S = 30%

T_a = 108 F

The value of S was an actual reading taken from an extremely dirty, gray tank car. A light colored paint would probably never get this low.

MAXIMUM LIQUID PROPANE TEMPERATURE:

The value obtained for maximum liquid ammonia temperature could not be applied directly to propane since propane has a lower specific heat and would, therefore, get hotter with the same heat input.

To arrive at a liquid propane temperature, a mathematical approach utilizing the very complete data taken on ammonia was used.

It was assumed that liquid propane temperature would bear a constant relationship to liquid ammonia temperature such that,

$$T_p = T_a + K(T_c - T_a) \qquad (2)$$

Where T_p = Maximum liquid propane temperature in an uninsulated tank car on any given day, degrees F.
K = A constant.

To evaluate the constant, data from a series of tests[1] run in 1932 were used. In these tests, temperature and pressure measurements were made on an 85" I.D. x 40' white uninsulated propane storage tank. A maximum liquid temperature of 90 F was obtained with a maximum ambient temperature of 105 F and an average ambient temperature of 86 F.

Knowing these conditions, a T_a could be calculated from equation (1), and then K could be determined from equation (2).

$$K = \frac{T_p - T_a}{T_c - T_a} = \frac{90 - 85}{105 - 85} = .25$$

Combining equations (1) and (2)

$$T_p = .26\ T_b + .57\ T_c - .08\ S + 14 \qquad (3)$$

Using the above equation, the extreme case was examined.

---

[1] "Summary of Recorded Temperatures and Pressures on Propane Storage Tank at Rockville, Maryland", by W. Z. Friend, 1935. Reference file WZF-25-35D, Research and Development Department Library, Phillips Petroleum Company.

$T_b = 110$ F
$T_c = 125$ F
$S = 30\%$

$T_p = 112$ F

DESIGN LIQUID TEMPERATURE AND SUMMER FILLING DENSITIES:

The maximum liquid ammonia and propane temperatures obtained indicate that 115 F could be safely used as a design liquid temperature on uninsulated dual service tank cars.

Furthermore, past experience has proved 115 F to be a safe design figure for tank trucks, and the larger the vessel the slower the contents heat and the more conservative this figure becomes.

Therefore, it is recommended that 115 F be adopted as the design liquid temperature for uninsulated dual service tank cars, and that summer filling density calculations be based on this temperature.

MAXIMUM LIQUID TEMPERATURES FOR WINTER FILLING DENSITIES:

A search of the past 20 years' weather records[1] revealed that the highest average ambient temperature recorded in the United States during the months of November through March was 76.4 F. This was in Florida in March, 1952. The highest maximum ambient temperature in the same period was 104 F. This was in Texas in March, 1952.

Using the extreme values,

$T_b = 80$ F
$T_c = 105$ F
$S = 30\%$

$T_a = 88$ F From Equation (1)
$T_p = 93$ F From Equation (3)

---

[1]United States Department of Commerce, Weather Bureau Climatological Data. Published monthly.

Inasmuch as there is at least a 20 degree differential between summer and winter maximum product temperatures, it is recommended that winter filling densities be established for uninsulated dual service tank cars, and that 95 F be adopted as the basis for their calculation.

2. A Basis for the Determination of Filling Densities in Insulated Tank Cars

INTRODUCTION:

Appendix A, "Effectiveness of Paint vs. Insulation for Limiting Pressure Increase in Tank Cars," and Appendix A-1, "Maximum Temperature of Liquid Anhydrous Ammonia and Propane in Uninsulated Tank Cars," presented information on the operation of uninsulated dual service tank cars.

Subsequent to these reports, a study of insulated tank cars in the same service has been made. From this study it appears that an increase in filling densities of insulated tank cars is feasible.

It is the purpose of this supplement to present a method for the determination of summer and winter filling densities for insulated tank cars.

RECOMMENDATIONS:

As an interim measure, it is recommended that summer filling density for anhydrous ammonia in insulated tank cars be based on 100 F and be established at 58.33%[1].

It is also recommended: (1) that additional tests be conducted to establish fully and confirm the relationships between the temperatures of LP-Gas and liquid anhydrous ammonia in insulated tank cars and ambient temperature; and (2) that the results of these tests be used as bases for the determination of summer and winter filling densities for LP-Gas and anhydrous ammonia in insulated tank cars.

---

[1]It is interesting to note that ICC Regulations, Paragraph 73.314 specifies a filling density of 57%, and further states that a lagged tank must not be completely full at 105 F. Based on a liquid temperature of 105 F, the filling density would be 57.92%.

PROPOSED PROCEDURE:

Following the general pattern of the 1956 tests, liquid temperatures of anhydrous ammonia and of propane in insulated tank cars would be recorded along with ambient temperature for about a 6-month exposure period. With the aid of an electronic computer and by a linear regression curve fitting routine, liquid temperature in the tank car would be expressed as a function of ambient conditions. Study of the 1956 test data has shown that the resulting equations will be of the form

$$T_L = K_0 T_{b_0} + K_1 T_{b_1} + K_2 T_{b_2} + \ldots\ldots + K_{10} T_{b_{10}} + K_{11} T_c + K_{12} \qquad (1)$$

where

T_L = maximum liquid temperature in an insulated tank car for any given day, degrees F.

T_{b_0} = Average ambient temperature for that day, degrees F.

T_c = maximum ambient temperature for that day, degrees F.

$T_{b_1} \ldots T_{b_{10}}$ = average ambient temperatures for the preceding 10 days, respectively, degrees F.

$K_0 \ldots K_{12}$ = constants

Having the basic equations for maximum liquid temperatures in terms of ambient temperature, it will be necessary only to determine "maximum" average ambient temperature conditions for summer and winter in order to establish the temperature bases for summer and winter filling densities.

ESTIMATED RESULTS:

Summer Filling Densities

As an indication of results to be expected, the data from the insulated ammonia car in the 1956 tests were correlated in the manner just described. The resulting equation was

$$T_{ia} = .14T_{b_0} + .11T_c + .12T_{b_1} + .11T_{b_2} + .10T_{b_3} + .09T_{b_4} + .08T_{b_5} + .07T_{b_6} + .06T_{b_7} + .04T_{b_8} + 03T_{b_9} + .02T_{b_{10}} + 1 \qquad (2)$$

An estimate of the 11 hottest consecutive days over the past 25 years was obtained from the United States Weather Bureau. When these values were substituted into Eq. (2)

$$T = .14(96) + .11(110) + .12(97) + .11\ (98) + .10(98) + .09(98) + .07(97) + .06(97) + .04(97) + .03(96) + .02(97) + 1 = 97 \text{ F}$$

The present filling density for ammonia in insulated tank cars is 57%. The filling density based on a maximum liquid temperature of 97 F would be 59%.

A similar increase could be expected for propane.

Winter Filling Densities

By substituting the highest ambient temperatures to be expected during winter months into the temperature correlation equation, maximum winter liquid temperature would be obtained. An investigation would be required to determine suitable ambient temperatures. This would involve considerably more record searching than the investigation of summer conditions, as the trends are much less definite. It is believed that such an investigation would show increases in winter filling densities to be possible.

DISCUSSION:

During the 1956 tests, data were taken only on ammonia. Furthermore, the test period was not long enough to fully establish and verify the relationship between liquid temperature and ambient temperature in the insulated tank car. The data were sufficient, however, to obtain an estimate of results to be expected from more complete tests.

Based on knowledge of known hot years and known hot locations, the United States Weather Bureau supplied maximum and average ambient temperatures for the period of August 29 through September 8, 1952, for Yuma, Arizona. More complete test data will justify a more complete study of weather records. It must be kept in mind that the constants in Eq. (2) were determined by incomplete data. It is quite possible that more complete data will show that 97 F is too high.

APPENDIX B

OBSERVED VALUES OF T_a, T_b, T_c AND S

Date	Observed Values			
	T_a	T_b	T_c	S
June				
20	73	70	89	84
21	78	82	97	84
22	82	84	104	84
23	80	78	96	84
24	81	83	102	84
25	83	86	100	84
26	85	87	102	84
27	86	87	102	84
28	88	88	102	84
29	85	80	100	84
30	85	82	102	84
31	81	79	99	84
July				
1	80	80	94	27
2	84	84	100	27
3	84	83	98	27
4	87	86	102	27
5	92	90	110	27

APPENDIX B (CON'T)

Date	Observed Values			
	T_a	T_b	T_c	S
6	94	91	109	27
7	94	92	108	27
8	95	91	110	27
9	93	87	108	27
10	92	87	108	27
11	94	92	108	27
12	94	89	106	27
13	94	90	109	27
14	97	90	109	5
15	95	90	110	5
16	94	90	108	5
17	97	91	110	5
18	95	77	99	5
19	91	57	62	5
20	72	66	77	5
21	72	70	84	5
22	78	75	90	5
23	88	80	96	5
24	91	86	106	5
25	92	83	102	5
26	90	81	97	5

APPENDIX B (CON'T)

Date	Observed Values			
	T_a	T_b	T_c	S
27	92	85	102	5
28	92	85	102	5
29	94	81	103	5
30	96	88	108	5
31	72	75	83	5

APPENDIX C

OBSERVED REFLECTIVITY READINGS ON LIGHT COLORED TANK CARS*

Date of Reading	Car No.	Original Color	Date Painted	Original Reflectivity	Top	Side	End	Weighted Average**
10-29-56	WRNX471	Gray	8-8-53	58	26	29	25	27
10-29-56	WRNX642	Gray	8-8-53	58	20	22	19	21
9-30-57	PSPX21560	White	8-57	84	57	56	56	56
9-30-57	PSPX16713	White	7-57	84	58	55	55	56
10-29-57	PSPX25154	White	9-57	84	56	69	65	62
2-5-58	PSPX13289	Gray	9-57	42	29	36	34	32
- - - - - - - - - -								
3-27-58	PSPX16708	White	7-57	84	67	65	67	66
3-27-58	PSPX16630 (Very dirty car)	White	7-57	84	44	51	56	48
4-22-58	PSPX16630 (Somewhat cleaner than 16630	White	7-57	84	52	63	56	56
4-22-58	PSPX16708	White	7-57	84	70	67	66	68
5-7-58	PSPX16708	White	7-57	84	73	71	70	72
5-7-58	PSPX16630	White	7-57	84	57	71	61	62

*The first six readings were taken at random on light colored tank cars in Bartlesville, Oklahoma, and Phillips, Texas. The second six readings were made on two tank cars at Bartlesville which are part of a test setup. Progressive chalking (cleaning) is reflected in the readings on the two cars in the last six readings.

**The weighted average was calculated as follows: wt. avg. $= \frac{(3)(\text{top}) + 2(\text{side}) + \text{end}}{6}$

APPENDIX D

A SUMMARY OF SUPPLEMENTAL WEATHER DATA OBTAINED FROM BORGER, TEXAS, AIRPORT*

Date	Wind Direction	Wind Velocity mph	Remarks
July 11	SW	17	Clear
12	S	20	Clear
13	S	16	Partly Cloudy
14	SSW	15	Partly Cloudy
15	SSW	8	Cloudy
16	NNE	9	Overcast
17	ENE	14	Overcase
18	NNE	6	Partly Cloudy
19	NE	6	Cloudy
20	S	13	Overcast
21	WSW	8	Clear
22	SSW	9	Cloudy
23	N	2	Partly Cloudy
24	S	1	Partly Cloudy
25	SSW	9	Clear
26	S	14	Partly Cloudy
27	S	17	Partly Cloudy
28	SSW	16	Partly Cloudy

APPENDIX D (CON'T)

Date	Wind Direction	Wind Velocity mph	Remarks
July			
29	S	23	Overcast
30	NW	8	Overcast
31	NW	8	Overcast
August			
1	SSW	12	Overcast
2	S	14	Overcast
3	S	15	Overcast
4	SW	21	Partly Cloudy
5	SW	7	Clear
6	SSW	11	Partly Cloudy
7	SSW	12	Partly Cloudy
8	SSW	17	Partly Cloudy
9	SSW	10	Overcast
10	S	14	Clear
11	S	12	Clear
12	S	9	Clear
13	S	12	Clear
14	S	2	Clear
15	S	11	Cloudy
16	SSW	17	Cloudy

APPENDIX D (CON'T)

Date	Wind Direction	Wind Velocity mph	Remarks
August			
17	SW	14	Cloudy
18	N	17	Overcast
19	NNE	14	Overcast
20	NE	9	Cloudy
21	SW	9	Clear
22	E	2	Clear, Gusts of wind
23	N	9	Clear
24	S	12	Cloudy
25	SSW	14	Cloudy
26	Sw	17	Cloudy
27	SSW	12	Clear
28	SSW	9	Overcast
29	SW	11	Clear
30	WSW	17	Clear
31	S	16	Partly Cloudy

* No measurable precipitation was recorded during the above period of time.

APPENDIX E

The following list of figures refer to the data in the thesis and not the Phillips Petroleum Company Report.

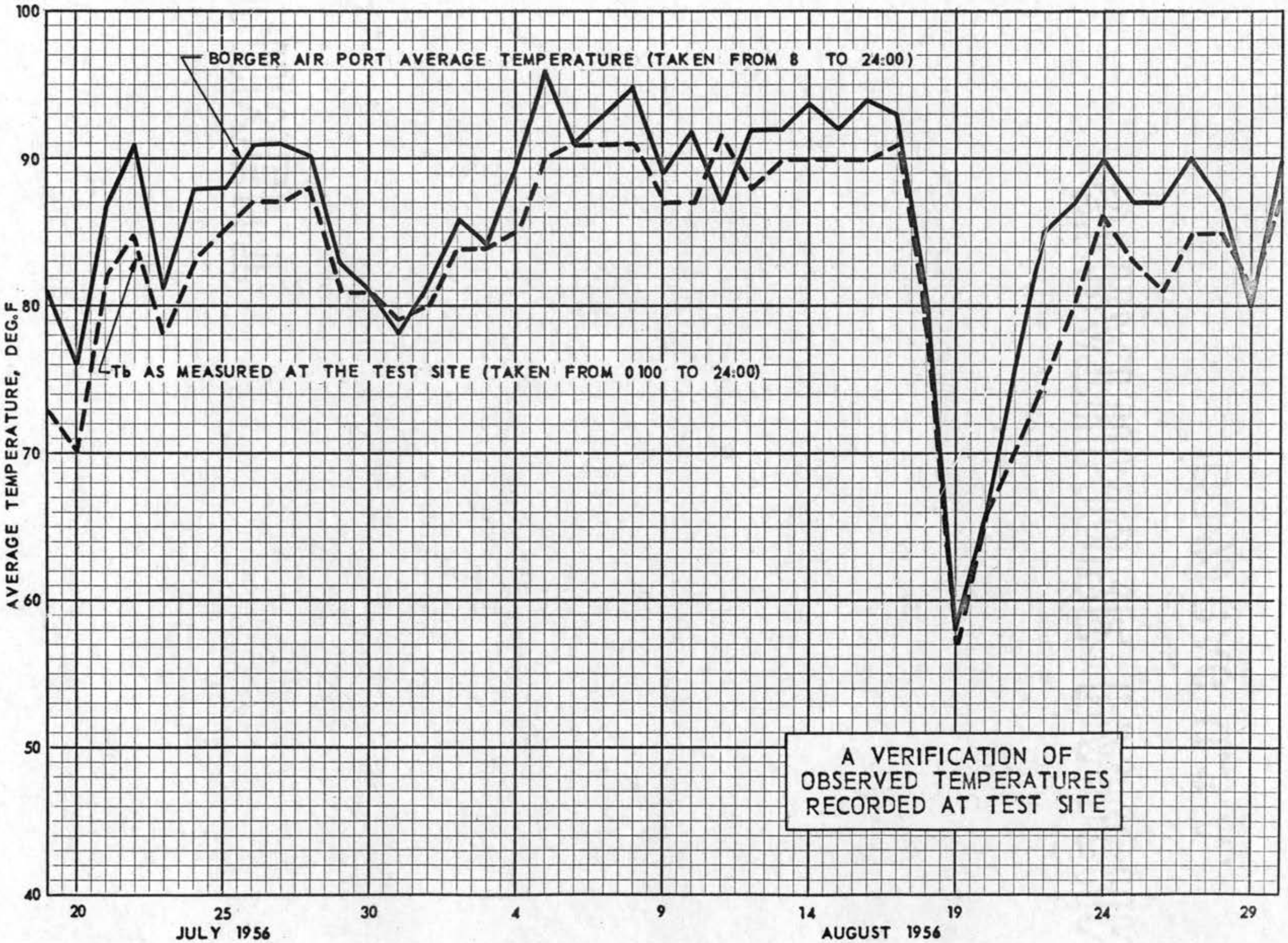

BORGER AIR PORT AVERAGE TEMPERATURE (TAKEN FROM 8 TO 24:00)
Tb AS MEASURED AT THE TEST SITE (TAKEN FROM 0100 TO 24:00)
A VERIFICATION OF
OBSERVED TEMPERATURES
RECORDED AT TEST SITE
AVERAGE TEMPERATURE, DEG. F
100
90
80
70
60
50
40
20
25
30
4
9
14
19
24
29
JULY 1956
AUGUST 1956

FIGURE 1

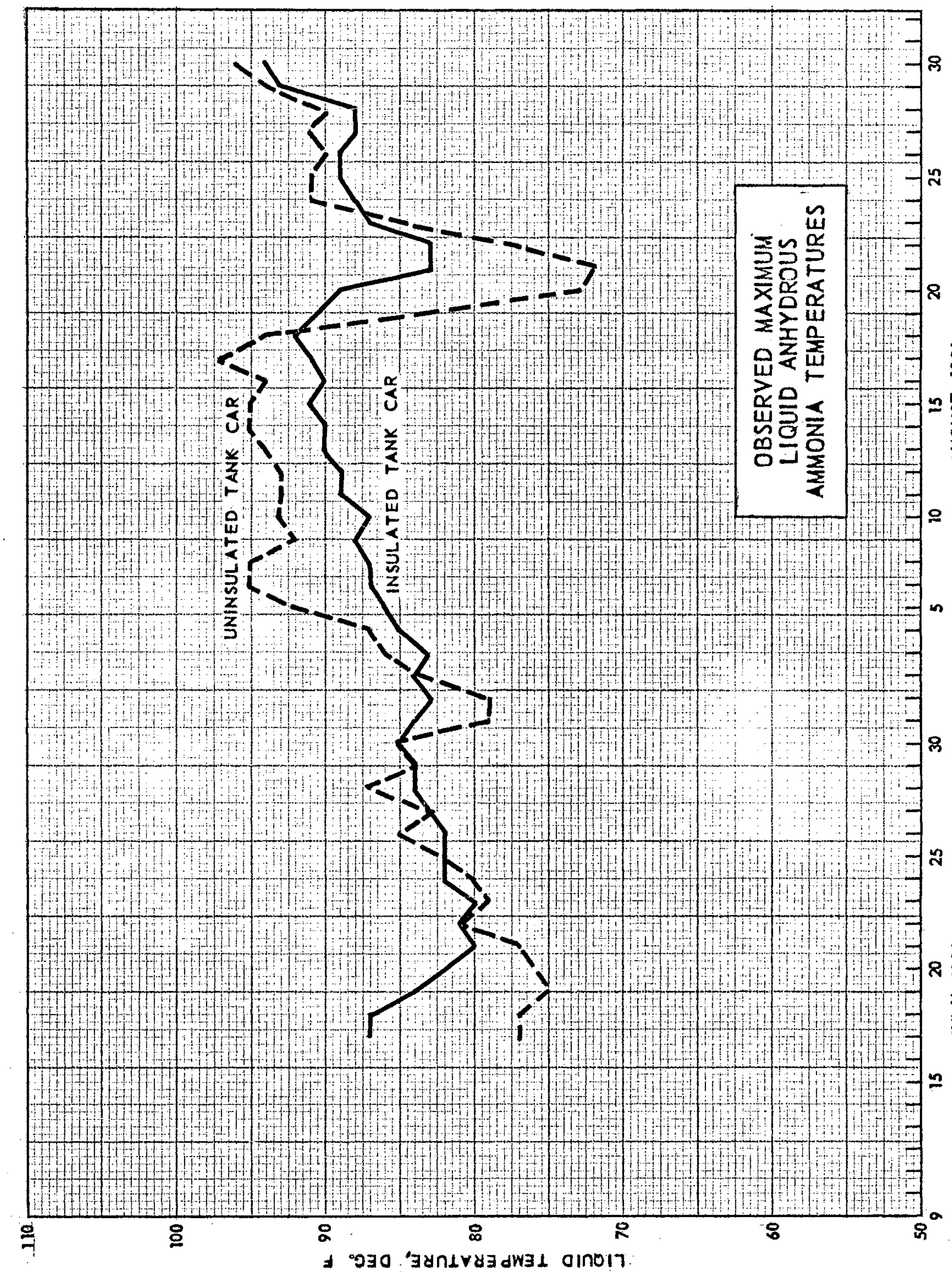

OBSERVED MAXIMUM
LIQUID ANHYDROUS
AMMONIA TEMPERATURES
UNINSULATED TANK CAR
INSULATED TANK CAR
LIQUID TEMPERATURE, DEG. F
110
100
90
80
70
60
50
9
15
20
25
30
5
10
15
20
25
30
JULY 1956
AUGUST 1956

FIGURE 2

FIGURE 3

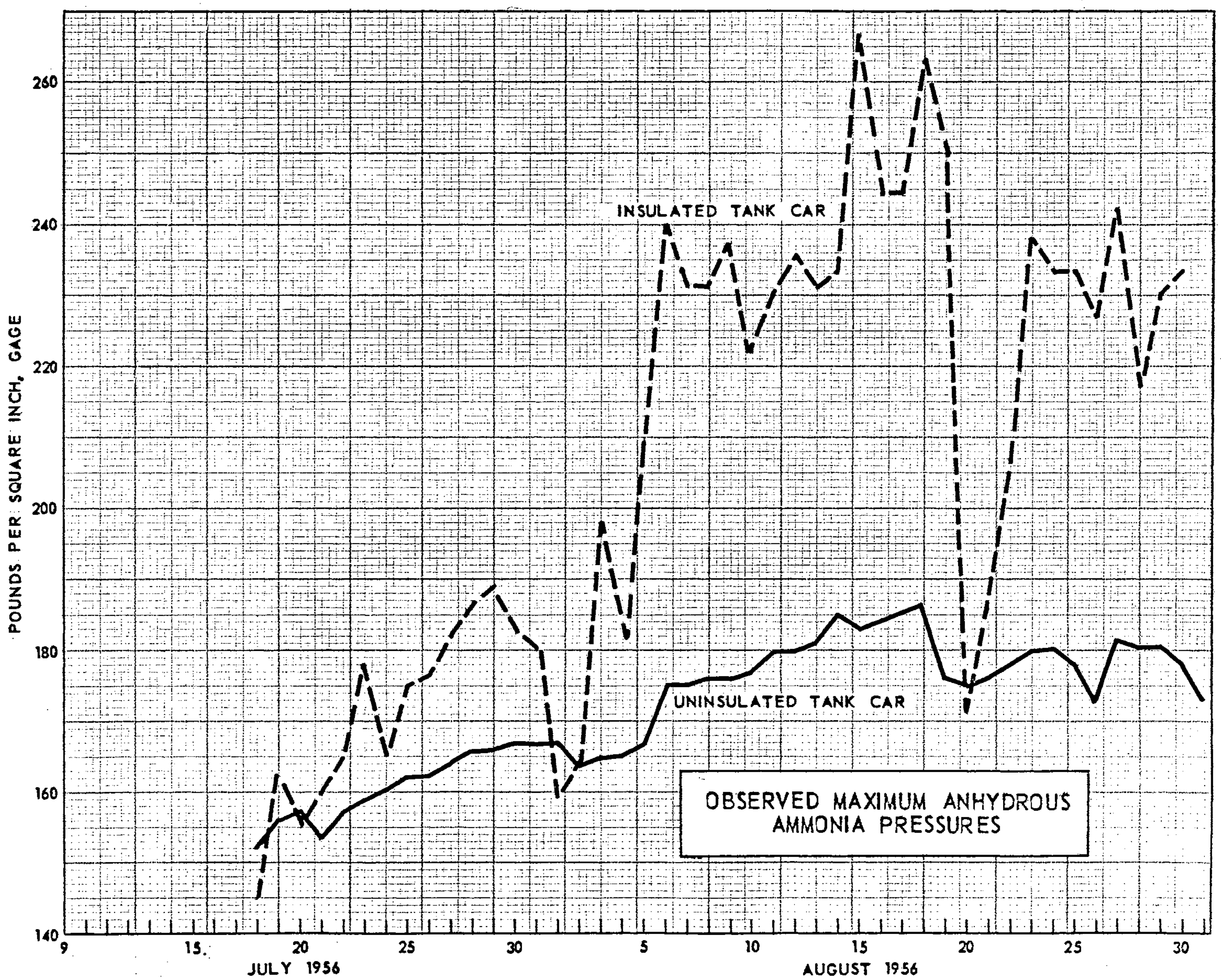
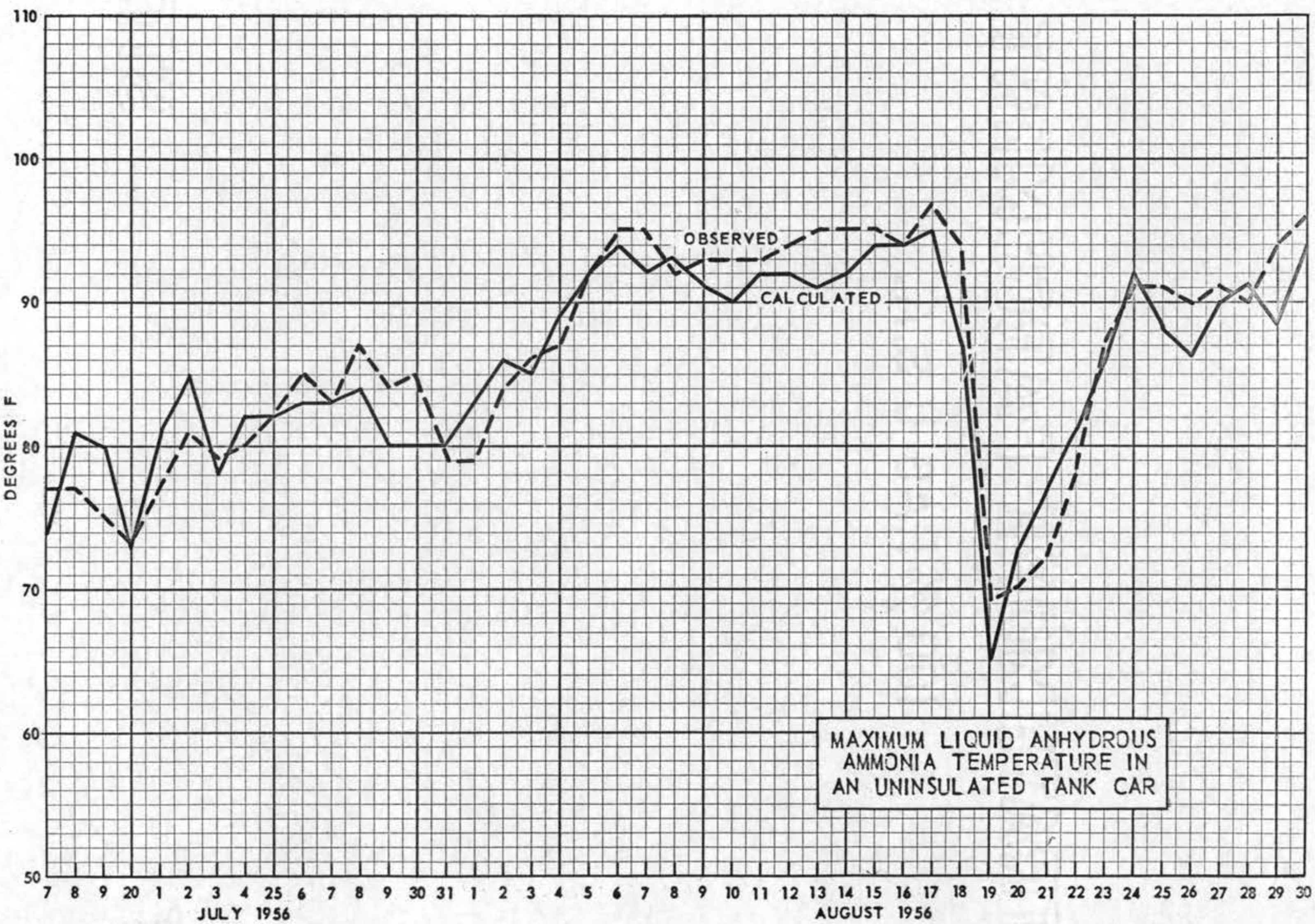

INSULATED TANK CAR
UNINSULATED TANK CAR
OBSERVED MAXIMUM ANHYDROUS
AMMONIA PRESSURES
POUNDS PER SQUARE INCH, GAGE
260
240
220
200
180
160
140
9
15.
20
25
30
5
10
15
20
25
30
JULY 1956
AUGUST 1956

FIGURE 4


DEGREES F
110
100
90
80
70
60
50
OBSERVED
CALCULATED
MAXIMUM LIQUID ANHYDROUS AMMONIA TEMPERATURE IN AN UNINSULATED TANK CAR
7 8 9 20 1 2 3 4 25 6 7 8 9 30 31 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30
JULY 1956
AUGUST 1956

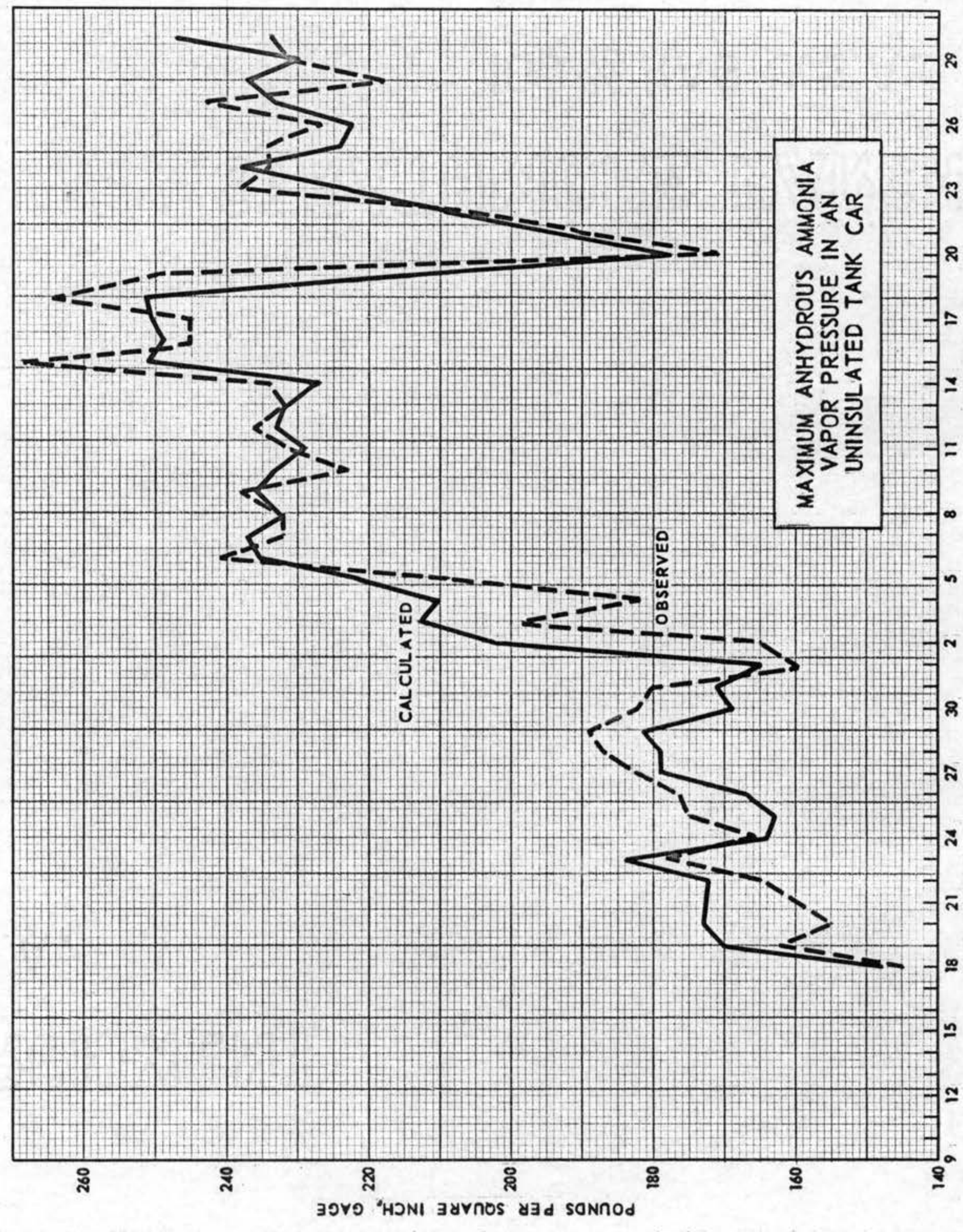

MAXIMUM ANHYDROUS AMMONIA
VAPOR PRESSURE IN AN
UNINSULATED TANK CAR
CALCULATED
OBSERVED
POUNDS PER SQUARE INCH, GAGE
140
160
180
200
220
240
260
9
12
15
18
21
24
27
30
2
5
8
11
14
17
20
23
26
29
JULY 1956
AUGUST 1956

FIGURE 5

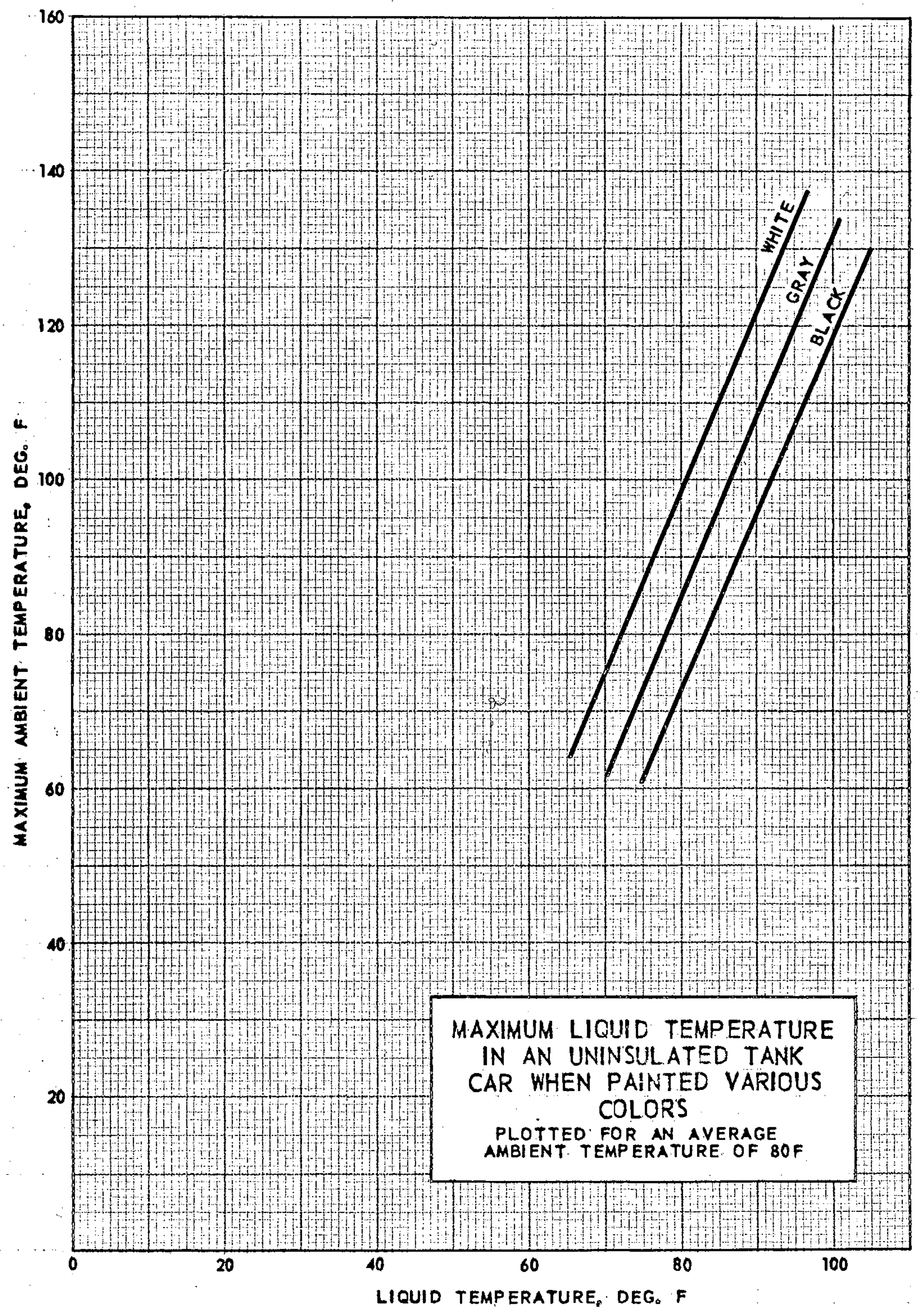

160
140
120
100
80
60
40
20
0
MAXIMUM AMBIENT TEMPERATURE, DEG. F
WHITE
GRAY
BLACK
MAXIMUM LIQUID TEMPERATURE
IN AN UNINSULATED TANK
CAR WHEN PAINTED VARIOUS
COLORS
PLOTTED FOR AN AVERAGE
AMBIENT TEMPERATURE OF 80F
0
20
40
60
80
100
LIQUID TEMPERATURE, DEG. F

FIGURE 6

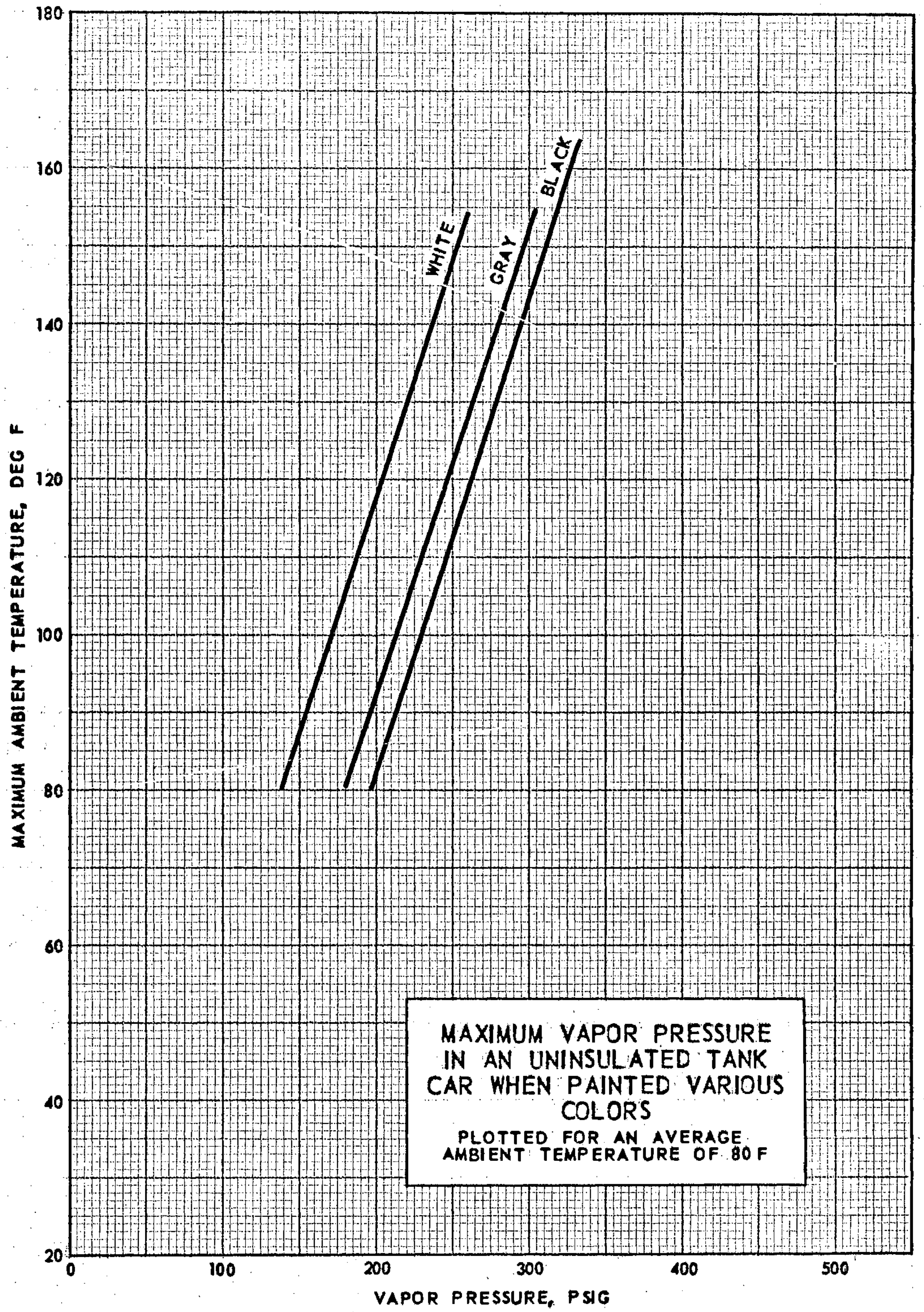

MAXIMUM VAPOR PRESSURE IN AN UNINSULATED TANK CAR WHEN PAINTED VARIOUS COLORS
PLOTTED FOR AN AVERAGE AMBIENT TEMPERATURE OF 80 F
WHITE
GRAY
BLACK
MAXIMUM AMBIENT TEMPERATURE, DEG F
180
160
140
120
100
80
60
40
20
0
100
200
300
400
500
VAPOR PRESSURE, PSIG

FIGURE 7

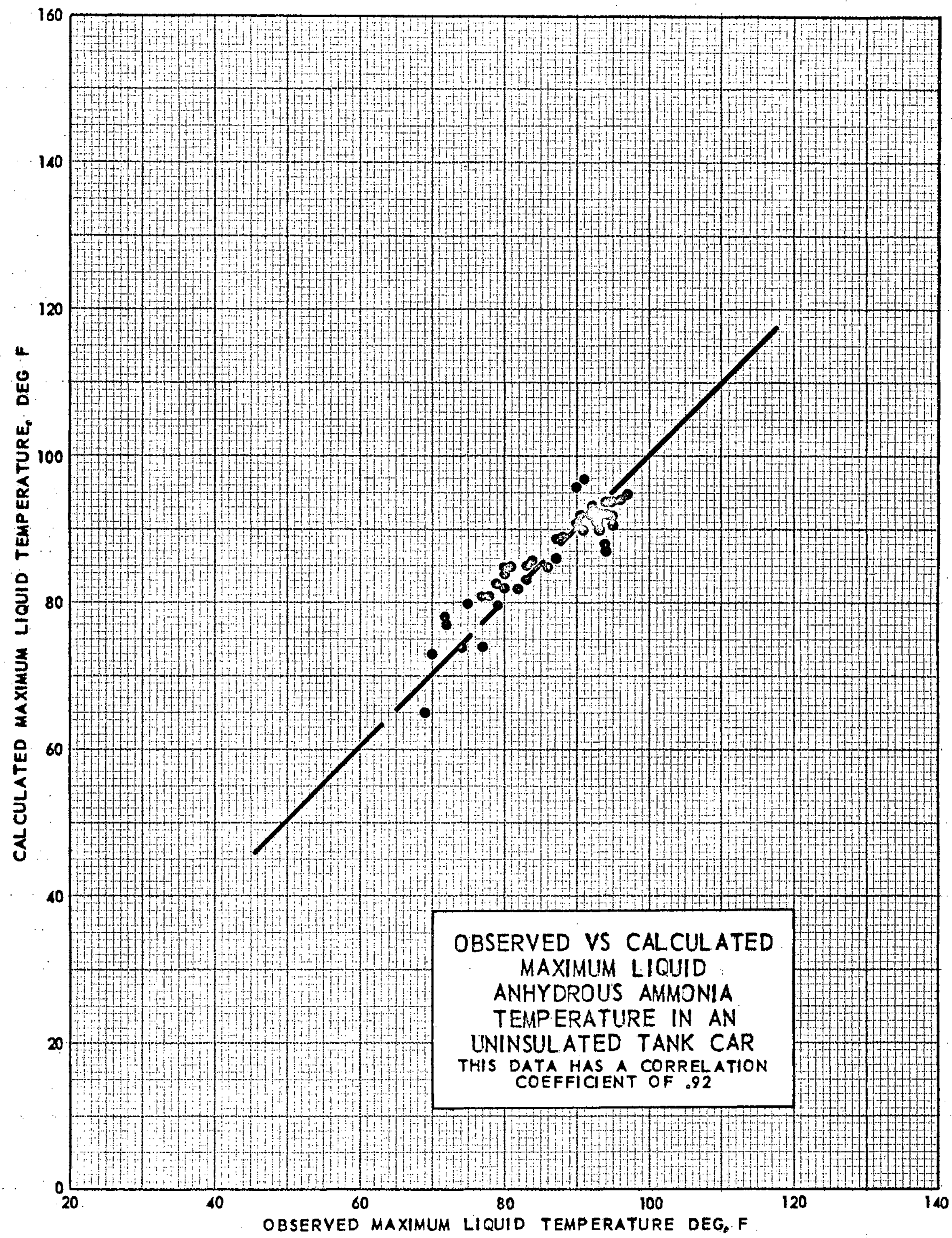

160
140
120
100
80
60
40
20
0
CALCULATED MAXIMUM LIQUID TEMPERATURE, DEG F
20
40
60
80
100
120
140
OBSERVED MAXIMUM LIQUID TEMPERATURE DEG, F
OBSERVED VS CALCULATED MAXIMUM LIQUID ANHYDROUS AMMONIA TEMPERATURE IN AN UNINSULATED TANK CAR
THIS DATA HAS A CORRELATION COEFFICIENT OF .92

FIGURE 8

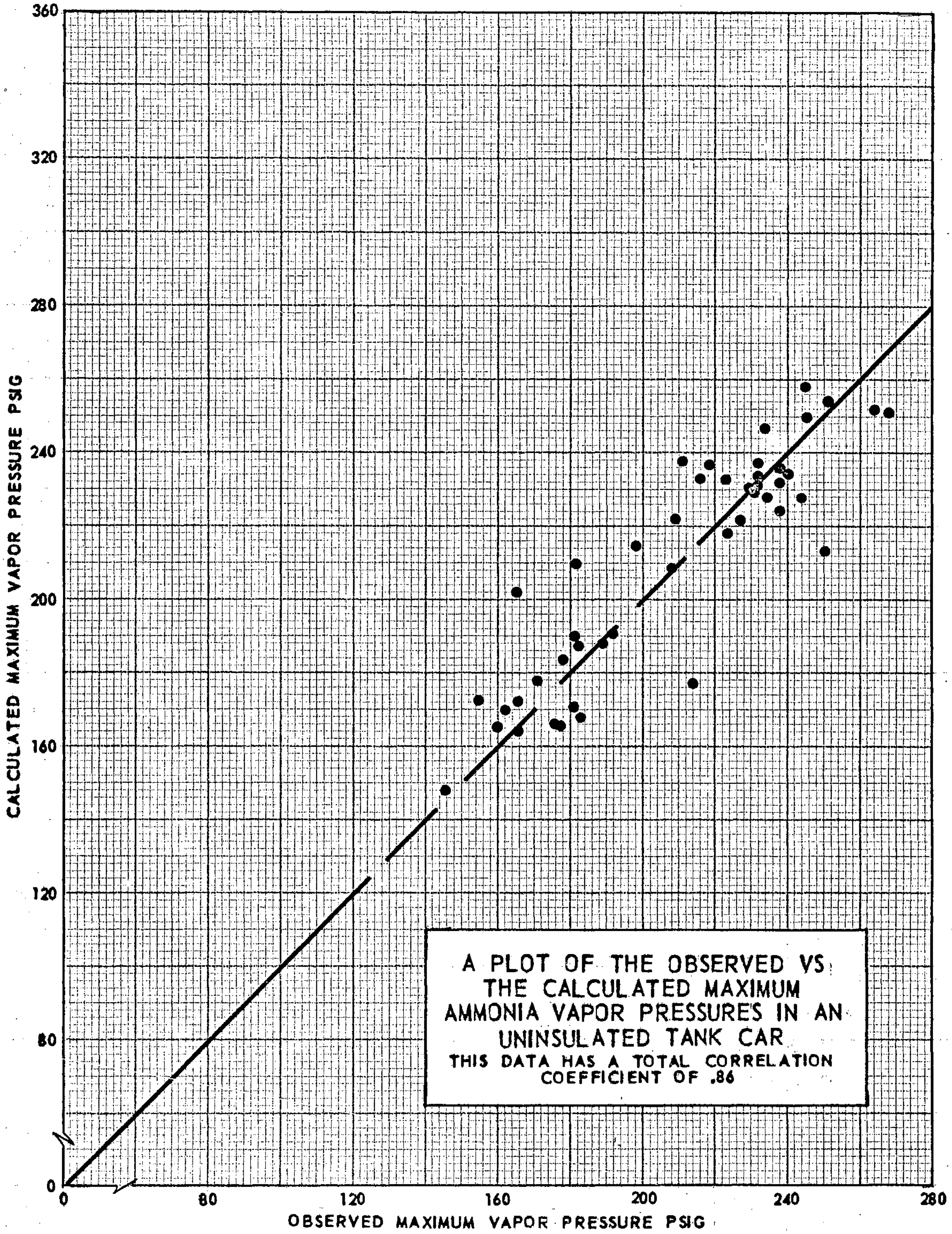

360
320
280
240
200
160
120
80
0
CALCULATED MAXIMUM VAPOR PRESSURE PSIG
0
80
120
160
200
240
280
OBSERVED MAXIMUM VAPOR PRESSURE PSIG
A PLOT OF THE OBSERVED VS THE CALCULATED MAXIMUM AMMONIA VAPOR PRESSURES IN AN UNINSULATED TANK CAR
THIS DATA HAS A TOTAL CORRELATION COEFFICIENT OF .86

FIGURE 9

VITA

Dale S. Baird

Candidate for the Degree of

Master of Science

Thesis: THE EFFECTS OF AMBIENT TEMPERATURE ON LIQUID TEMPERATURE AND VAPOR PRESSURE IN UNINSULATED TANK CARS IN ANHYDROUS AMMONIA SERVICE

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