THE EFFECTS OF AMBIENT TEMPERATURE

ON LIQUID TEMPERATURE IN PROPANE

STORAGE AND CARGO TANKS

By

RYAN D. MOATS, JR.

Bachelor of Science

University of Kansas

Lawrence, Kansas

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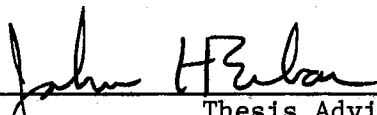
THE EFFECTS OF AMBIENT TEMPERATURE

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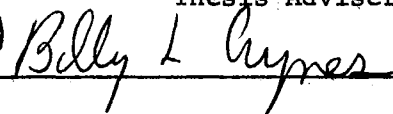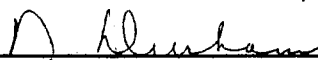# STORAGE AND CARGO TANKS

Thesis Approved:

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Thesis Adviser

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Dean of the Graduate College

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PREFACE

This thesis developes a mathematical model relating liquid temperatures in propane storage tanks to maximum and minimum daily ambient temperatures. A temporary propane storage site was built near the campus of Oklahoma State University approximately one mile south of the Stillwater airport. Data obtained at this location were the liquid temperatures in the propane storage tanks, tank pressures and daily maximum and minimum ambient temperatures. Weather data were also monitored at the Stillwater airport and the Agronomy research site located about two and one half miles southwest of the propane storage site. These data were compared with the temperatures measured at the research facility.

I am deeply grateful to my thesis advisor, Professor John H. Erbar, for giving me technical and moral support during my M.S. program. I also wish to thank the following people: Mr. E. E. McCroskey for valuable help with the construction and operation of the research site, Mr. B. Baker of Central Propane whose assistance with storage problems aided in completion of the experimental phase, and Mr. M. Cooper, Oklahoma Liquefied Petroleum Gas Administrator, for help in interpreting the State of Oklahoma LPG regulations.

Further, I wish to thank the National Liquefied Petroleum-Gas Association for their support of this research project; in particular, the donations of Bastian-Blessing Company, Continental Oil Company, Skelly Oil Company, Trinity Industries, Incorporated, American Meter

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Company, A. M. F. Beaird, Incorporated and Central Propane.

Personal thanks must go to my wife Judith for her moral support and valuable proof reading and to my three sons for their understanding.

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CHAPTER I

INTRODUCTION AND HISTORICAL BACKGROUND

Liquefied Petroleum Gases (LPG) have become important in the con-
sumer market. One particular LPG, propane, is used for heating and en-
gine fuel. Thus, it is necessary to store propane both at plants and
local distributers, and at homes to allow for fluctuations in its use.
Each state has adopted rules, based primarily on "filling density," for
governing the storage and transportation of LPG (1). ("Filling density"
is defined as percent ratio of the weight of the gas in a container to
the weight of water the container will hold at 60°F.) The "filling
density" criteria limits the amount of LPG in a vessel, thereby pre-
venting an internal pressure in excess of 250 psig. In practice, the
temperature in the storage vessel is read and used with published charts
to determine the maximum amount of propane that can be stored in a
given vessel (1).

However, the amount of propane stored in a tank may be increased
and still remain below the desired safe limit. If so, the storage
capacity of the present propane facilities would be increased. Since
filling density is a function of the tank liquid temperature, a method
of predicting these temperatures is necessary. This study concerns the
development and discussion of a mathematical model which relates the
propane storage vessel liquid temperature to atmospheric temperature.

CHAPTER II

PREVIOUS REPORTS AND PAPERS

In a literature survey, no non-proprietary studies concerning

pressurized vessel storage of LPG were to be found. This type of stor-

age is unique in that no air (respectively vapor) is allowed into (re-

spectively out of) the storage vessel as is the case with storage in

floating head tanks or non-pressurized vessels. However, one study in-

volving storage of liquefied ammonia in railroad tank cars was avail-

able (3). In this study, a standard ICC 105 A-400W tank car was ob-

tained and filled to a 55% filling density. After the car was set on a

siding at Borger, Texas, its outside insulation was removed. The color

of the tank car was varied from white to gray to black. Each color was

tested for two weeks. Temperatures, pressures and sun radiation were

continuously monitored and recorded at the test site. Weather observa-

tions made at the Borger airport were correlated with the data measured

at the test site.

Maximum liquid temperature (T_a) and vapor pressure (P_v) were re-

lated to average ambient temperature (T_b), maximum ambient temperature

(T_c), and reflectivity (S) using linear functions:

$$T_a = k_1 T_b + k_2 T_c + k_3 S \qquad\qquad 1.$$

$$P_v = k_4 T_b + k_5 T_c + k_6 S \qquad\qquad 2.$$

A least squares, linear regression technique, which minimizes the sum

of the squares of the differences between the observed and calculated

values, was used to determine the six coefficients. Correlation coef-

ficients were calculated as 0.92 and 0.86 for equations 1 and 2,

respectively. (A correlation coefficient of 1.0 means that the indepen-

dent variables completely explain the observed results.)

The conclusions of this study were:

1. An empirical mathematical relationship for maximum liquid

   temperature exists for use in calculating filling densities.

2. Tank color is an important variable in restricting tank tem-

   peratures to a certain range, the color white being the best

   color for maintaining tank liquid temperatures relatively

   close to the ambient temperatures.

The mathematical relationships, equations 1 and 2, are limited to

the narrow range of temperature data resulting from the relatively short

two week test. Effects outside this range are speculative.

A method of calculating the liquid tank temperature from the maxi-

mum and average temperatures was proposed. The basic equation was

$$T_L = k_0 T_{B0} + k_1 T_C + k_2 T_{B1} + \ldots + k_{11} T_{B10} + k_{12} \qquad 3.$$

where T_L is maximum liquid temperature in an insulated tank car for any

given day, $^{\circ}F$.

T_{B0} is average ambient temperature for that day, $^{\circ}F$.

T_C is maximum ambient temperature for that day, $^{\circ}F$.

$T_{B1} \ldots T_{B10}$ are average ambient temperatures for the preceding

10 days, respectively, $^{\circ}F$.

$k_0 \ldots k_{12}$ are constants.

The twelve constants were determined by linear regression analysis

of equation 3 using the test data.

An estimate of the eleven hottest consecutive days over a 25 year period was obtained from the United States Weather Bureau. These data were used with equation 3 to estimate maximum liquid temperature in a storage tank. The estimated maximum tank liquid temperature was 97°F. This new tank temperature allowed the maximum allowable filling density to be raised from 57% to 59%.

Baird pointed out that several important variables were not covered in his equation. He suggested that further investigation might reveal that the maximum predicted liquid temperature, 97°F, was still higher than the actual liquid temperature under equivalent ambient conditions. If this supposition were true, filling density could be increased even more.

CHAPTER III

DESCRIPTION OF EQUIPMENT

A schematic diagram, Figure 1, shows the overall propane research site. Photographs (Figures 2, 3, 4, 5 and 6) exhibit each of the five propane tanks.

The following pieces of equipment were used in this project:

1. 100-pound cylinder storage tank.

2. 250-gallon home storage tank.

3. 1000-gallon home storage tank.

4. 1800-gallon truck tank.

5. 2800-gallon truck tank.

6. Two American Meter 12 inch, two pen measurer-recorders.

7. One Honeywell 6-point and one 16-point recorder.

8. Fourteen Conax thermocouples.

Research Site

The research area, 150 feet square, lies just north of the Civil Defense area, west of married student housing, and about one mile south of the Stillwater airport, Figure 7. The tanks were located on the site according to safety regulations outlined in the "Rules and Regulations for Liquefied Petroleum Gas in the State of Oklahoma," page 14. The two truck tanks are mounted on three foot high saddles anchored in 18 inches of concrete and are painted white. The other tanks are set on

①	100 Pound Tank	⑦ ⑨	Pressure Lines – Thermocouple Lines
②	250 Gallon Tank		
③	1000 Gallon Tank	⑧	Pressure Line
④	1800 Gallon Tank	⑩	Electric Line
⑤	2800 Gallon Tank	⑪	12' Gate
⑥	Instrument Shed	⑫	4' Fence Posted with Safety Signs

Figure 1. Schematic Diagram of Overall Propane Research Site
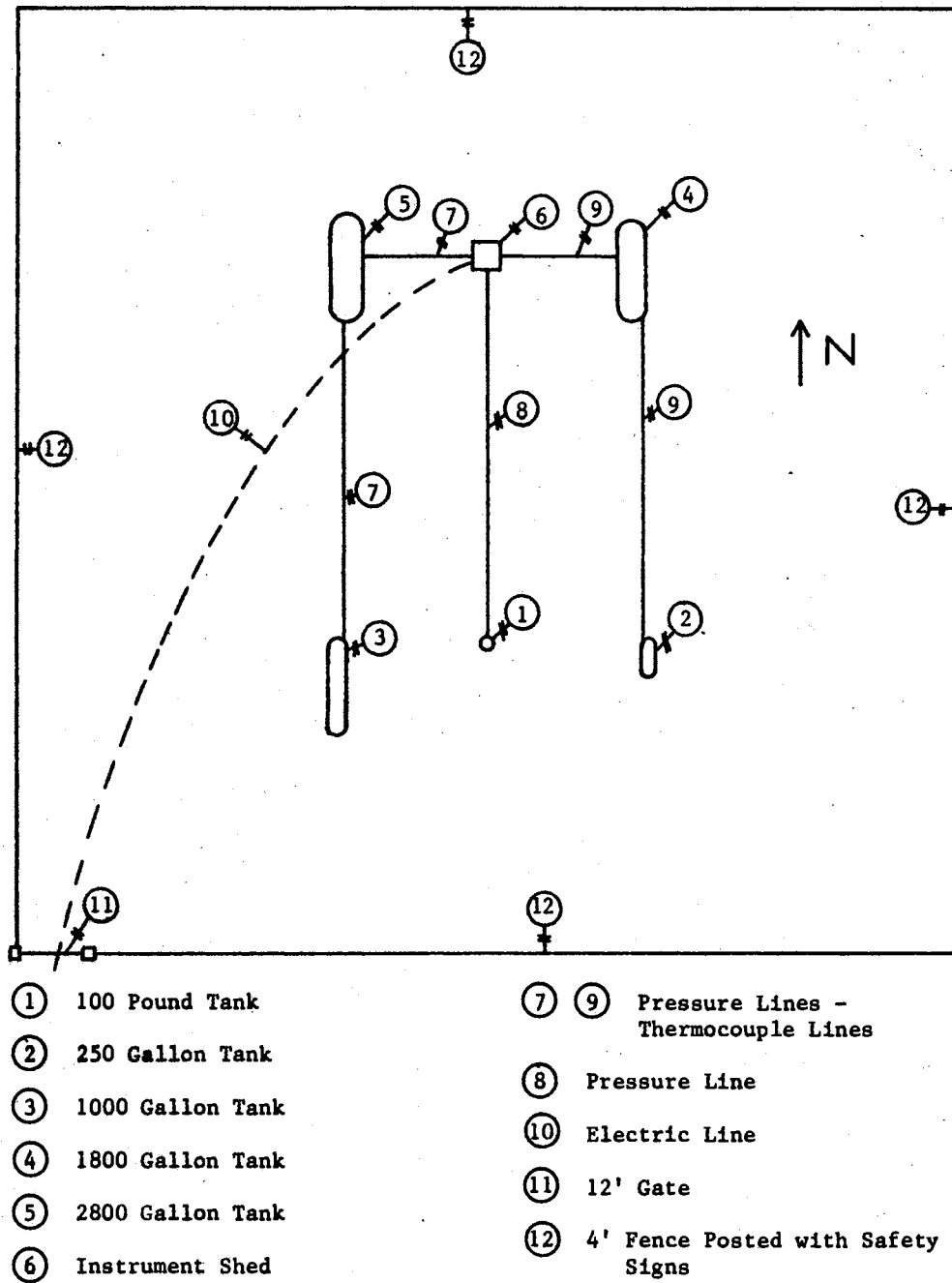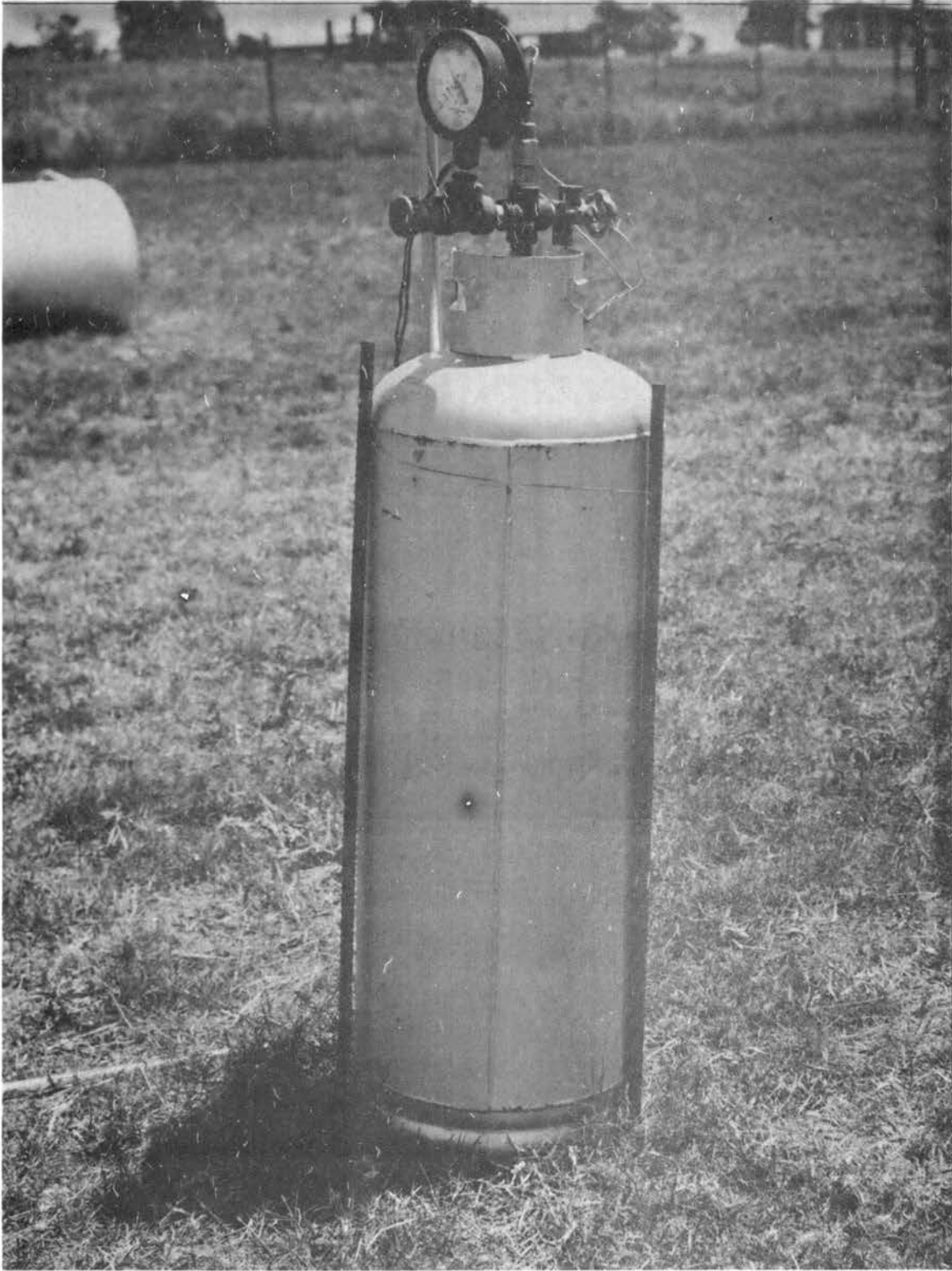
Figure 2. 100 Pound Cylinder Storage Tank
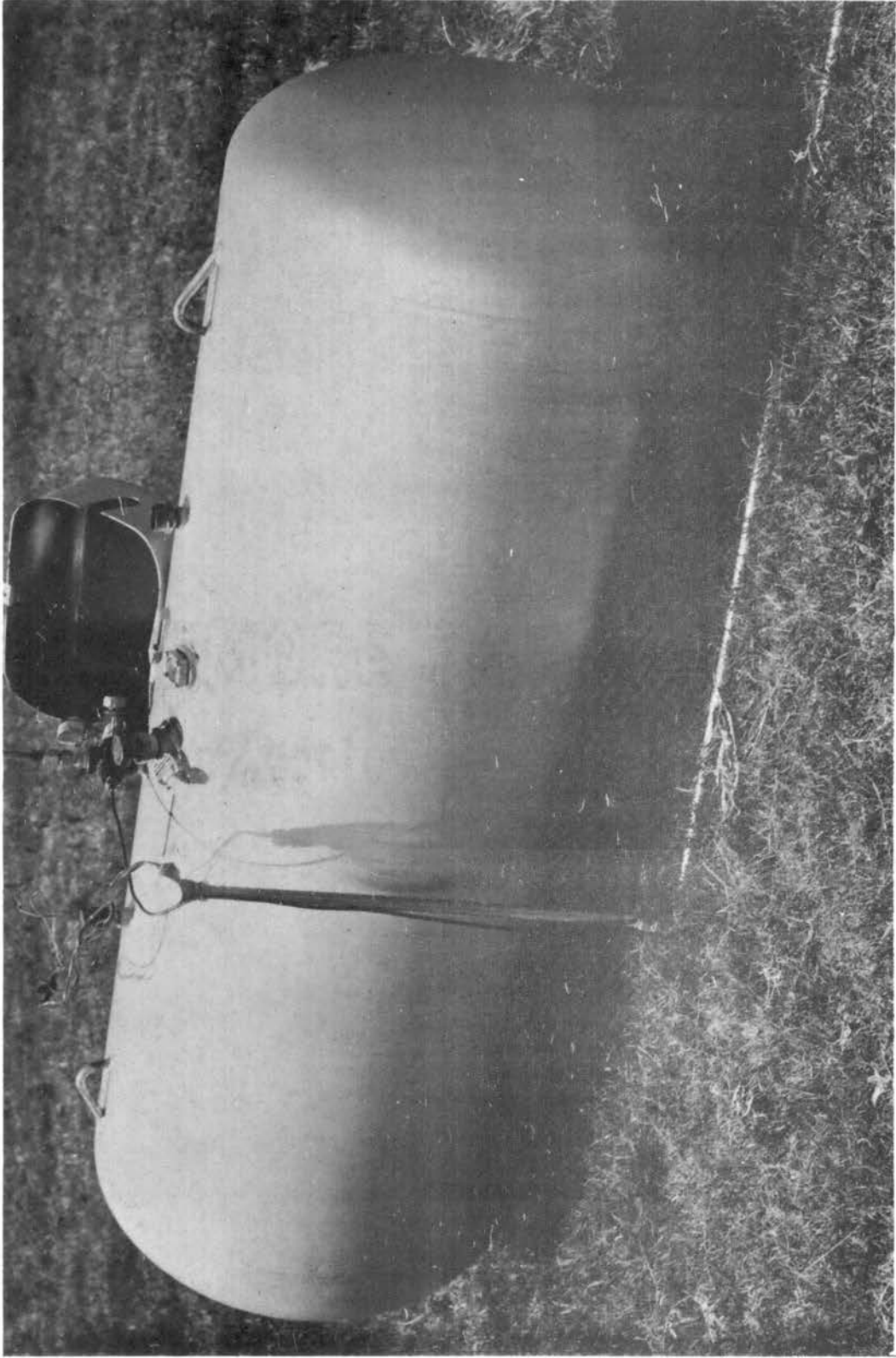
Figure 3.   250 Gallon Storage Tank
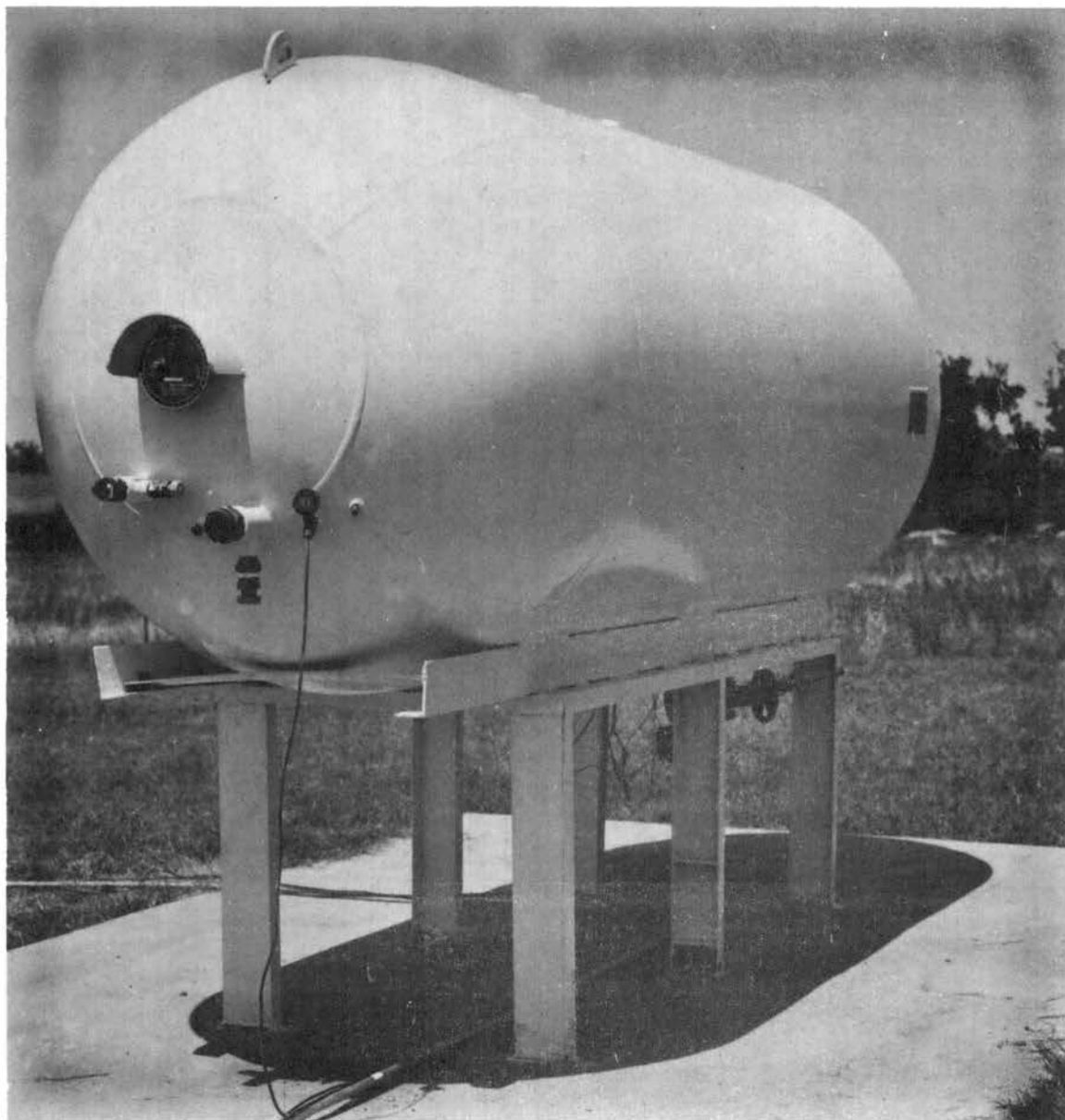
Figure 4. 1000 Gallon Storage Tank
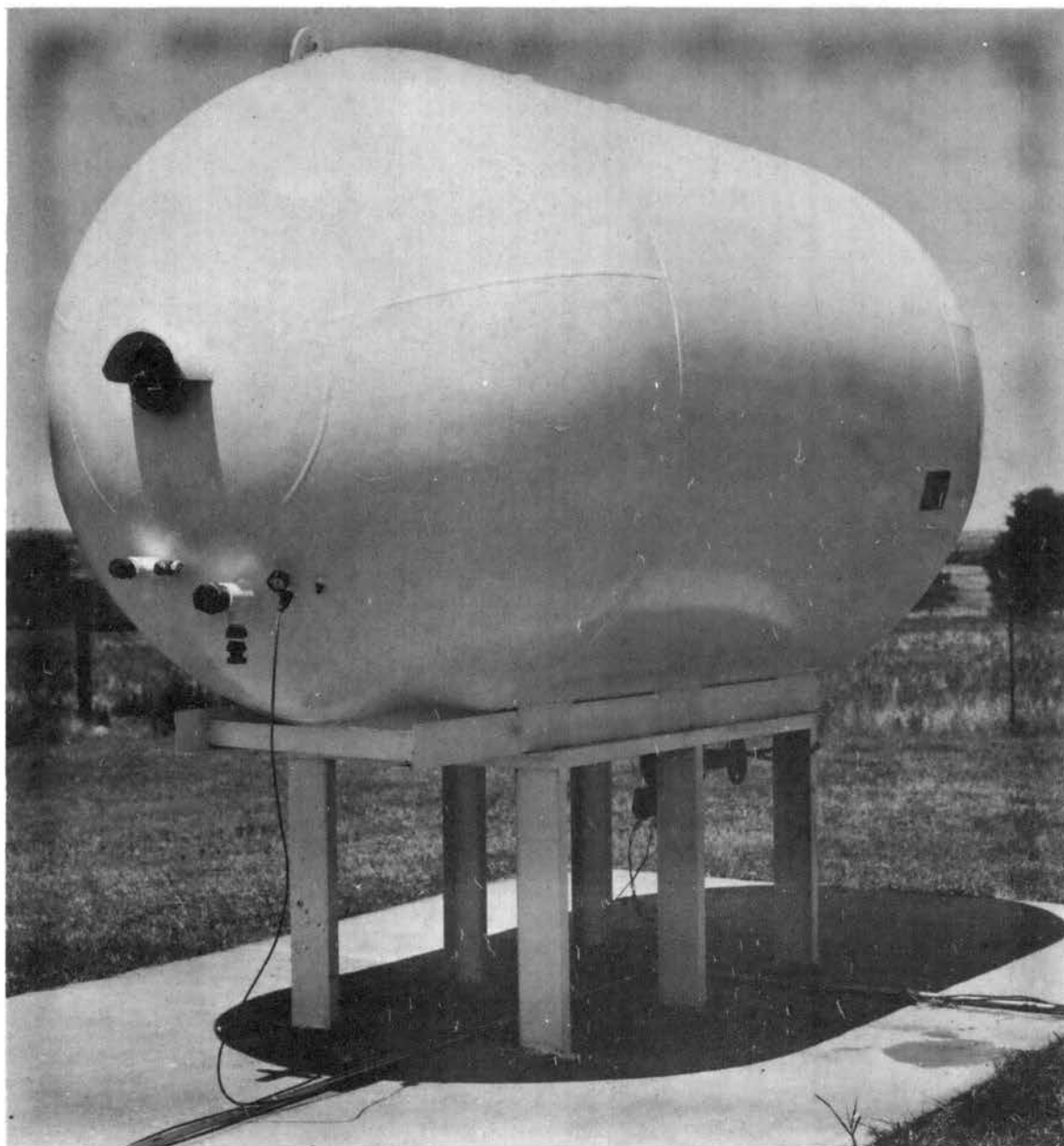
Figure 5.   1800 Gallon Storage Tank
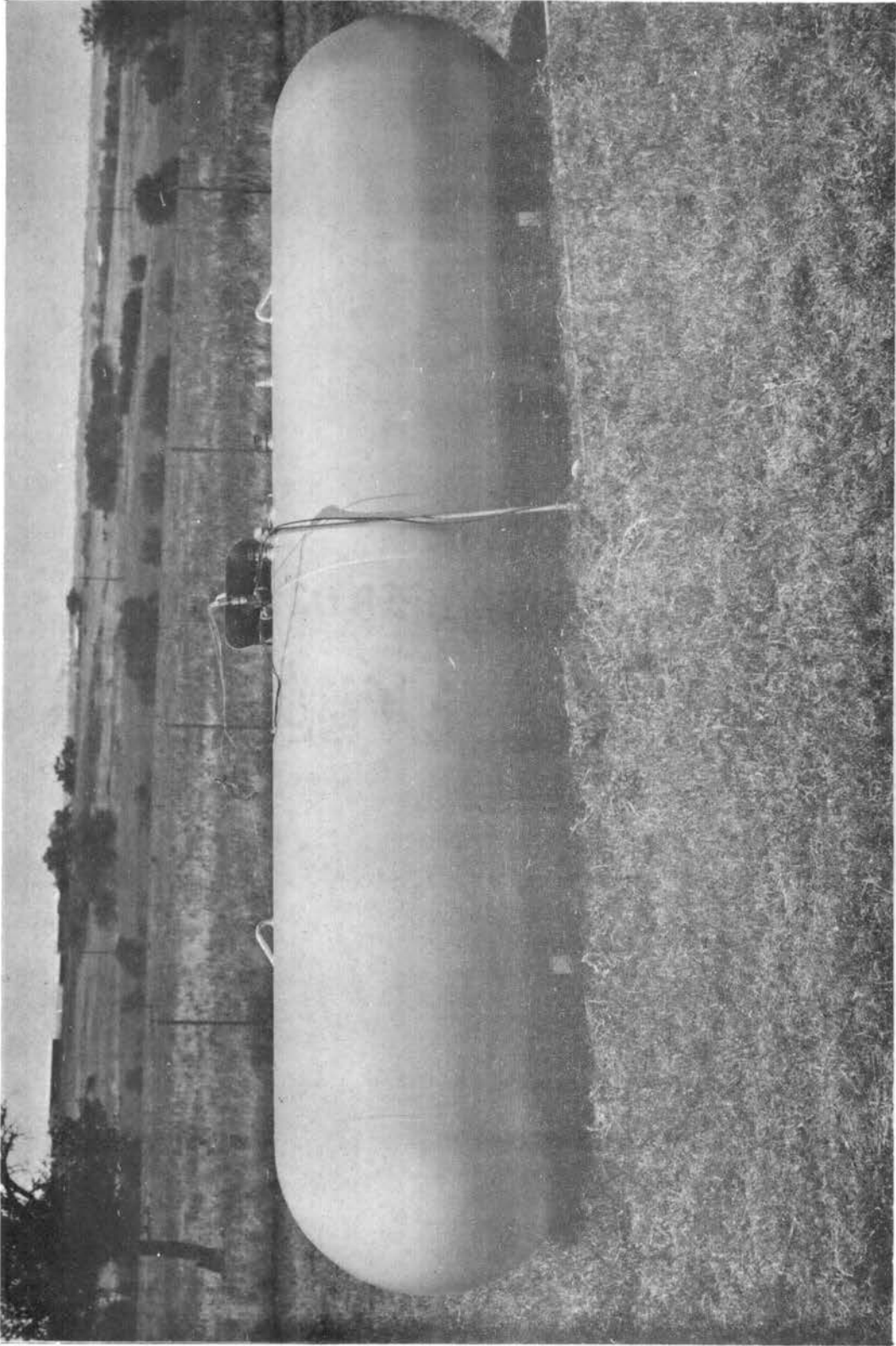
Figure 6.   2800 Gallon Storage Tank

Airport

Boomer
Lake

Highway 177

N

X Site Location

McElroy Avenue

Oklahoma State
University

Western
Avenue

Highway 51
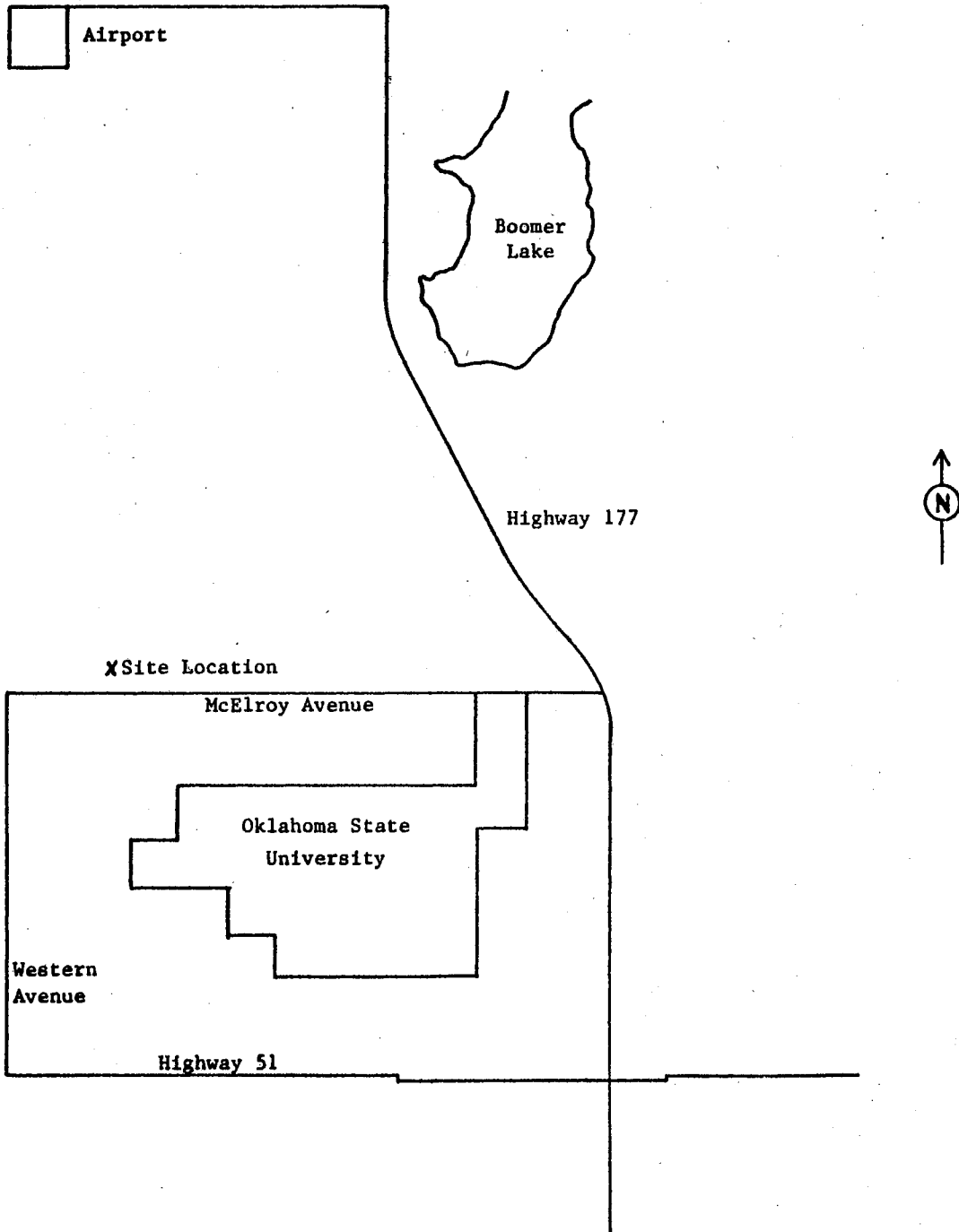
Figure 7. Location of Propane Storage Site

the ground and painted aluminum. The entire area is surrounded by a four foot high fence with one entrance, a twelve foot gate, in the southwest corner. Warning signs, "KEEP OUT" and "NO SMOKING," are posted around the perimeter of the site. Signs with emergency instructions are also posted on the east, west and south fences.

Tank Specifications

Specifications for the five storage tanks are given in Table I. Other pertinent tank information is that all tanks were rated for an allowable working pressure of 250 psig at a maximum temperature of 100°F and had been tested to at least 375 psig.

Piping

The cylinder and home storage propane tanks were fitted to allow measurement of liquid temperatures and internal pressure. New fittings were either ones rated for at least 300 psig, W-O-G (water-oil-gas), or were solid plugs and/or steel bushings. The 100-pound tank was repiped according to Figure 8. A 6 inch and a schedule 80 close nipple, a 3000 psig rated cross and tee, a 3/4" x 1/4" steel bushing, a pressure gauge (0 to 500 pounds), a Conax mounting gland (for holding thermocouples in the tank without any leakage) and a #7547B filler valve were added.

The 250- and 1000-gallon tanks were refitted according to Figure 9. The vapor relief valve on each tank was removed and a 3000 psig rated cross connected to the tank with a schedule 80 close nipple. The vapor relief valve was reinstalled on one side of the cross. On the other side, a 1/4" copper tube adapter and a 3/4" x 1/4" bushing were installed. (Copper tubing connected the adapter to the pressure

TABLE I

TANK SPECIFICATIONS

Tank Size	100 Pound	250 Gallon	1000 Gallon	1800 Gallon	2800 Gallon
Serial Number	A1755015	212629-270	212640-52	10099	10098
Water Capacity (gallons)	100[a]	250	1000	1800	2800
Weight (pounds)	239	–	–	–	–
Diameter (inches)	15.0	30.0	41.0	61.0	79.0
Overall Length (inches)	34.0	89.875	194.5	227.0	240.0
Surface Area (square feet)	16.2	65.0	174.0	221.0	279.0
Shell Thickness (inches)	–	0.25	0.32	0.357	0.463
Head Thickness (inches)	–	0.1993	0.2306	0.260	0.308
A/V[b]	–	1.508	1.585	1.200	1.168
Manufacturer & Location	Sprague Cedartown, Ga.	A.M.F. Beaird, Inc. Shrevesport, La.		Trinity Industries, Inc., Tulsa, Oklahoma	

[a] Water capacity is pounds, not gallons.
[b] A/V is based on the A/V of tank car, 0.8354 ft^{-1}.
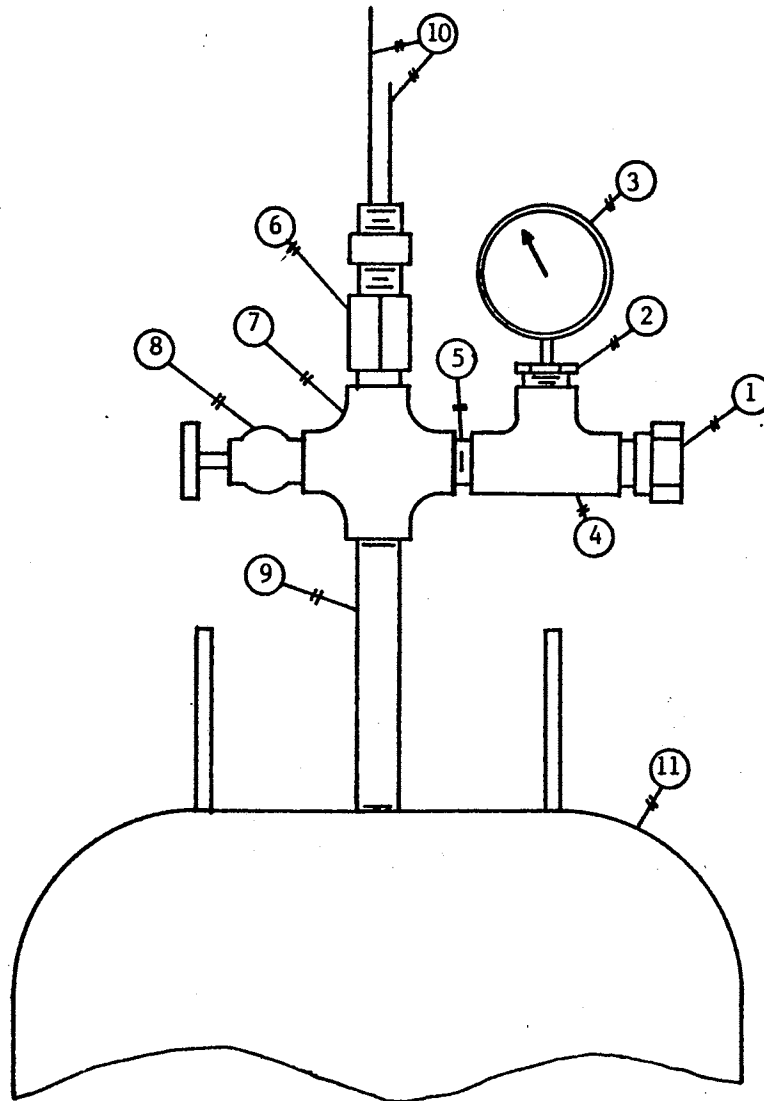
1	#7547B Filler Valve
2	3/4" x 1/4" Steel Bushing
3	0 to 500 Pounds Pressure Gauge
4	Tee (3000 Psig Rated)
5	Close Nipple (Schedule 80)
6	Conax Mounting Gland
7	Cross (3000 Psig Rated)
8	Vapor Relief Valve
9	6" Nipple (Schedule 80)
10	Thermocouples
11	100 Pound Storage Tank

Figure 8. Piping for 100 Pound Tank
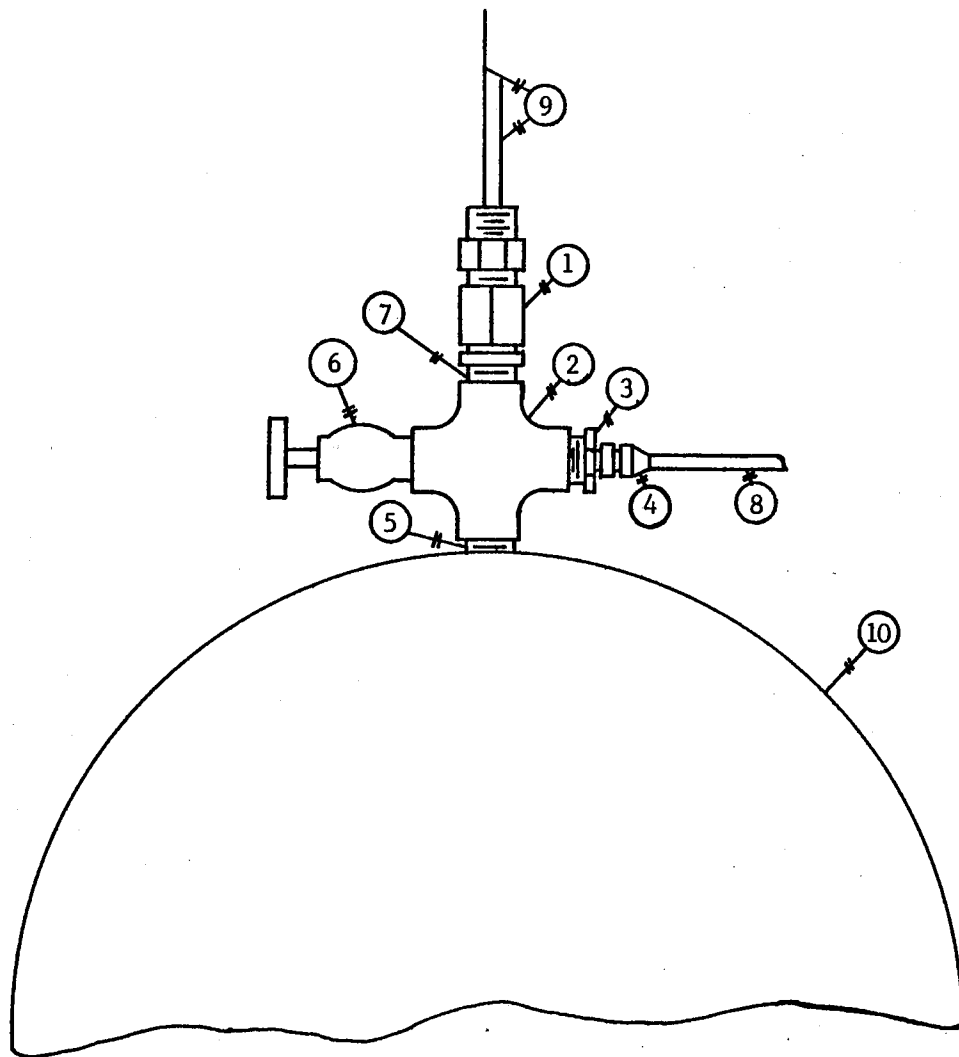
①	Conax Mounting Gland
②	Cross (3000 Psig Rated)
③	3/4" x 1/4" Steel Bushing
④	1/4" Copper Tube Adapter
⑤	Close Nipple
⑥	Vapor Relief Valve
⑦	1/4" x 1/2" Steel Bushing
⑧	1/4" Copper Tubing
⑨	Thermocouples
⑩	250- or 1000-Gallon Storage Tank

Figure 9. Piping for 250- and 1000-Gallon Storage Tank

recorder in the instrument shed.) The top of the cross was fitted with a 3/4" x 1/2" bushing and another Conax mounting gland.

Only the barrels of the 1800- and 2800-gallon truck tanks were received, so each tank was completely fitted according to Figure 10. Two pressure relief valves, Roney #3112G, rated at 250 psig were installed in the top of each tank. A Rego #A7517FP, 3 inch flanged globe valve was installed on the bottom of the tank and blanked with a blind flange. The 1-1/4" drain in the bottom of the tanks was fitted with a 1-1/4" x 1/2" bushing and a Conax mounting gland. The other drain, 3/4", was plugged.

On the head of each tank, an Acme filler valve, #7579, was placed in the 1-1/4" outlet containing the Rego #3282C excess flow valve, and a vapor equalizing valve, #7573A, was placed in one of the 3/4" outlets containing the Rego #3272G vapor flow valve. (This change was made to allow the domestic supplier to charge liquid and remove vapor using his normal filling procedure.) The other Rego #3272G and #3186 valves were plugged. A rotary gauge, Rego #A-9093TX, was installed in the center opening to measure the liquid level inside the tank. For safety, the thermowell was plugged. A Rego #3165, 90% liquid level valve and a 3000 psig rated tee containing a pressure gauge and a copper tube adapter were installed to connect the tank to the pressure recorder.

Pressure Recorder

Two American, 12 inch, two pen measurer-recorders were loaned by American Meter Company for use in this study. These meters are mounted on the wall inside the instrument shed. One meter records the pressure of the 250-gallon tank in blue and that of the 1800-gallon in red.
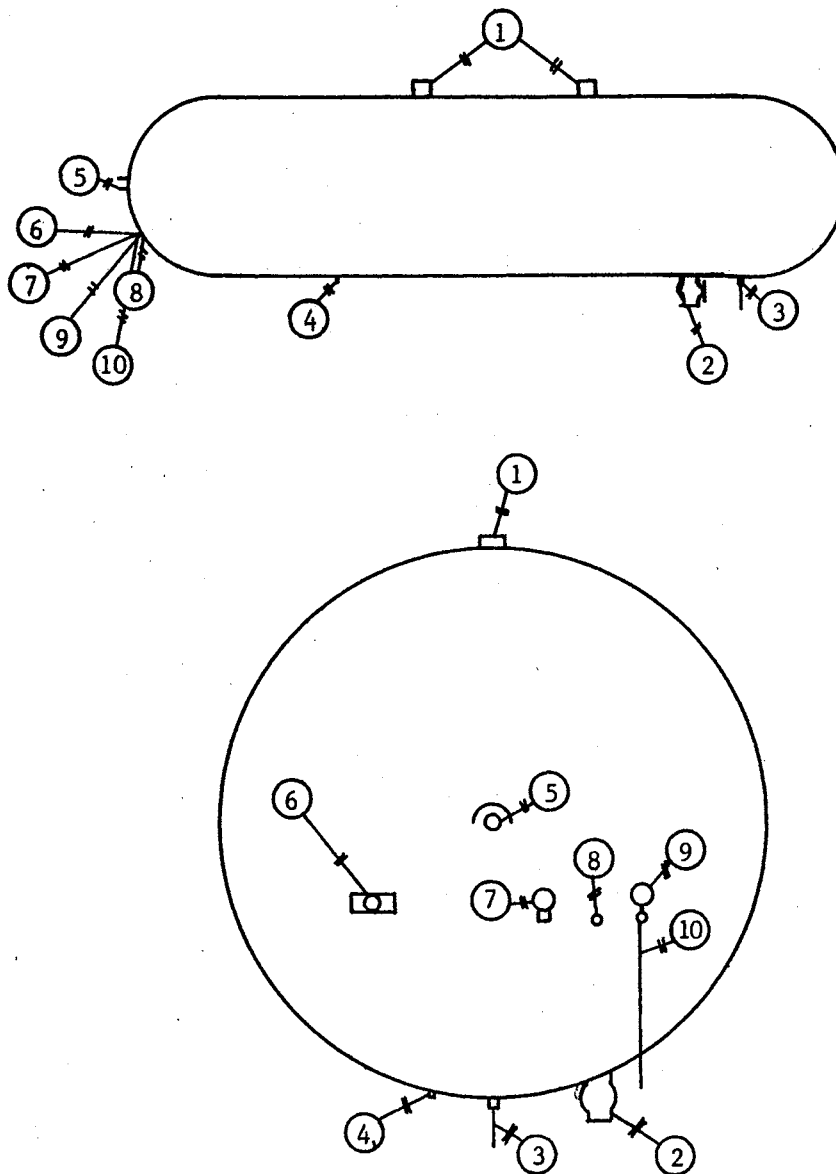
① Roney 3112G Relief Valves

② A7517FP, 3" Flanged Globe Valve

③ 1 1/4" x 1/2" Steel Bushing, Conax Mounting Gland and
Thermocouple

④ 3/4" Plug

⑤ Rego A-9093Tx Rotary Gauge

⑥ Rego #3272G Vapor Flow Valve, 7573A Vapor Equilizing
Valve and Plug

⑦ Rego #3282C Excess Flow Valve, 7579 Acme Filler Valve
and Plug

⑧ Rego #3165 - 90% Liquid Level Valve

⑨ Tee (3000 Psig Rated), Pressure Gauge and Copper Tube
Adapter

⑩ Copper Tubing (1/4")

Figure 10. Piping for 1800- and 2800-Gallon Storage
Tank

Similarly, the 1000-gallon tank pressure is recorded in red and the 2800- in blue. Weekly charts are on file in the School of Chemical Engineering.

Temperature Recorders

A temperature recorder, serial number 15305816-16-01-000-995-10, was bought from Honeywell, Inc., and installed in the instrument shed. The recording temperature range is 0 to 150°F. The basic chart speed is 1/2 inch per hour; however, six times the basic speed of 3 inches per hour was required to distinguish between the sixteen different temperatures recorded from the system. The location of each temperature point is shown in Table II.

TABLE II

THERMOCOUPLE LOCATION

Tank Size (gallons)	Temperature Recorder Printout Number	Location in Tank[a]
100[b]	7 & 8	12" & 24"
250	2, 1 & 3	9", 15" & 24"
1000	11, 10 & 9	11.5", 20.5" & 29.5"
1800	4, 5 & 6	18.5", 30.5" & 42.5"
2800	14, 13 & 12	27.5", 39.5" & 51.5"
Ambient	15 & 16	Instrument Shed

[a]Location is measured from the top down in the home storage tanks and from the bottom up in the truck tanks.

[b]100-pound tank.

A six-point temperature recorder (Honeywell, serial number 534711) was loaned by Skelly Oil Corporation and used as a backup recorder. The meter range is -25 to 125°F and was calibrated for copper-constantan thermocouples.

Thermocouples

Conax thermocouples with an accuracy of ± 0.75°F in the range of -75 to 200°F were used to measure the propane tank temperatures. They are copper-constantan, ungrounded, sheathed in stainless-steel, and protected with standard lead wire terminations. The thermocouples are mounted in each tank using Conax mounting glands (catalog number—MHM-125-B-2 or 3-T).

Thermocouples are located in the 100-pound tank at 12 inch intervals, in the 250-gallon tank at 6 inch intervals, in the 1000-gallon tank at 9 inch intervals, and in the 1800- and 2800-gallon tanks at 12 inch intervals. The exact locations are given in Table II.

Temtex Corporation copper-constantan extension wire (catalog number—TT-1-TX-16), enclosed in conduit, connects the thermocouples to the recorder in the instrument shed.

CHAPTER IV

EXPERIMENTAL METHODS

Thermocouple Calibrations

A low-temperature bath from the School of Chemical Engineering Unit
Operations Laboratory with temperature range of -10 to 100°C was deemed
sufficient to simulate the actual operating range of the Conax thermo-
couples. Using this bath and a potentiometer with ambient temperature
reference, the thermocouples were checked at -10, 20, 50 and 80°C. All
results were within the specified ± 0.75°F accuracy of the thermo-
couples.

Pressure Testing of the Tanks

After the tanks were installed and piped, an air compressor bor-
rowed from the OSU Physical Plant was used to raise the pressure in
each tank to approximately 100 psig. Soap solution was used to locate
the leaks. After the leaks were sealed, the tanks were left for four
days and then rechecked for leaks. Following four days of no pressure
loss due to leakage, the tanks were exhausted to the atmosphere and
readied for filling.

Filling Procedure

A suggested filling procedure is outlined by Bastian-Blessing Com-
pany in their "Rego Topics". (7) The procedure recommends six purgings

of a propane tank using 15 psig propane. Calculations based on complete mixing and partial pressures of air and propane indicate that 1.56% air would be left in the tanks after the sixth purge.

Central Propane, Inc., a local LPG supplier, uses the following filling procedure. Three 50 psig purges followed by a vapor recycle through their truck assures that essentially all air has been removed. Calculations similar to the Rego procedure show that only 1.23% air would be left in the tank after the third purge. This air would then be removed by the vapor being recycled through the truck. So, the filling procedure of Central Propane was used to charge the five tanks.

During the blow-down prior to the third purge, samples of tank discharge were collected over water to assure that no air could contaminate the gas sample. These samples were analyzed using the F&M Scientific Corporation Model 500 High Temperature Gas Chromatograph. Results were compared to the results from analyzing a sample of instrument grade, minimum 99.5%, propane sold by Phillips Petroleum Company. The comparison indicated that there was no air present. Since instrument grade propane has finer specifications than does HD-5 or commercial grade propane (2), and since no air was present in the comparison to instrument grade, the conclusion can be made that no air would be present in a comparison to HD-5 propane.

A double dosage of ethyl mercaptan was added to each tank for safety and to account for the ethyl mercaptan losses due to adsorption and/or reaction with the mill scale inside the tanks. Standard dosage is 1.0 pound of ethyl mercaptan per 10,000 gallons of propane (1). The amounts used are shown in Table III.

The tanks with less than 1200-gallons capacity were charged to a

filling density of 42%. The tanks with a capacity over 1200 gallons
were charged to a filling density of 45%. By using the temperature of
the tank and the chart in the State of Oklahoma Rules and Regulations
et al, the filling percentage of each tank was obtained. The amounts
of propane charged to each tank are also shown in Table III.

TABLE III

AMOUNT OF PROPANE AND ETHYL
MERCAPTAN CHARGED TO EACH TANK

Tank Size (gallons)	Propane (gallons)	Ethyl Mercaptan (milliliters)
100[a]	20	1.0
250	221	1.5
1000	845	5.0
1800	1782	10.0
2800	2410	13.5

[a]Tank size is pounds, not gallons.

Data Gathering

As previously mentioned, liquid temperatures were measured at four-
teen locations in the system. The daily minimum and maximum tempera-
tures of each thermocouple were read from the recorder strip chart and
recorded on punched cards for use in the calculations.

Weather data were accumulated at these sites:

1. Propane storage-research site,

2. Stillwater airport (reports obtained through the United
    States Weather Bureau in Ashville, North Carolina),

3. Agronomy research site (site located 2-1/2 miles southwest

of the propane storage-research site).

These data were compared for internal consistency. This comparison is found in Chapter VI.

Tank pressures were monitored and recorded on weekly circular charts. The sole purpose of the charts was to be an immediate indication of leakage in the system. However, the daily maximum and minimum pressure for the 250-, 1000-, and 2800-gallon tanks has been transferred to punched cards for use with the computer. All records are on file in the School of Chemical Engineering.

CHAPTER V

DERIVATION OF HEAT TRANSFER MODEL

The basic assumptions necessary to describe a feasible heat trans-
fer model include the heat transfer mechanism, liquid temperatures,
ambient temperatures and the storage vessels. Each of these factors
will be examined separately.

The mechanism for external heat transfer to or from a tank is a
combination of radiation and convective heat transfer. Radiation is
the mode for transfer of energy from the sun to the storage vessels.
Convection is the mode for transfer of energy from wind to the tanks.
Also, for simplicity, outside heat losses due to rain, snow, etc. were
ignored. This assumption is, in fact, a safety factor in that the
liquid temperature would be actually less than the calculated value.

The internal heat transfer is assumed to be only conduction.
Transfer of energy due to convection inside the tanks was ignored. Net
heat transfer is defined as the net energy input to the tanks. Energy
is conveyed as discussed above, by radiation and convection. In addi-
tion, radiation from the ground to the tanks must be considered. Note
that input from each of these sources may be either positive, negative
or zero.

The temperature of the liquid in the storage container is dependent
upon the specific heat and heat of vaporization of the liquid, net heat
transfer and time of day. The time factor, however, can be eliminated

from this list since time and ambient temperatures are so related that
the use of ambient temperature data contains an implied time dependence.
The factors which determine liquid temperature are not independent of
each other, and none can be assumed as constants. However, all of them
can be set up as functions of temperature alone.

The model could have been based on sun radiation values rather
than on ambient temperatures. Actual values of sun radiation could
have been continuously measured and recorded. Temperatures predicted
by such a model would reflect the effects of cloud coverage. However,
sun radiation values, if available at all, are generally daily averages,
which obscure cloud cover effects on the tank temperatures. Therefore
the following assumption was made: Ambient temperatures are related to
sun radiation in such a way that ambient temperature data are sufficient
to predict liquid temperatures in the storage vessels.

The storage vessel is assumed to be so positioned that the wind
blows only in the axial direction. Also, the vessel is modeled as an
infinitely long cylinder (end effects are neglected).

The following mathematical derivation describes the heat transfer
to and from the storage vessels. The resulting equation relates ambi-
ent temperature to liquid temperatures for various tank geometries.
Additional assumptions will be discussed as they are required. A
complete nomenclature list is given in Chapter VIII.

Derivation

To model the energy transfer to and from a propane storage tank,
an energy balance was made on an arbitrarily thin shell of fluid, Δr.
There are three discontinuities which may be encountered depending upon

the direction taken when the differential equation is integrated. These discontinuities are the vapor-liquid interface, vapor-solid (tank shell) interface, and the liquid-solid interface. The liquid-solid interface was included in the derivation under "tank shell." However, the other two discontinuities were ignored, because a differential equation covering these would be intractable. The tank was assumed completely filled with liquid (actual liquid volumes were at least 89% of tank volumes). The following derivation is then made using Figure 11.
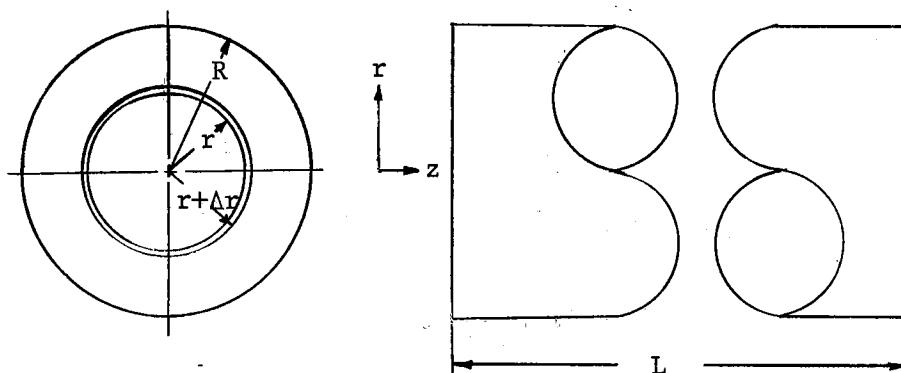
Figure 11. Tank Model

Energy input at r over time interval $\Delta\theta$ (neglecting end effects):
$-K(\partial T/\partial r)A\Delta\theta$ where $A = 2\pi rL$.

Energy output at $r + \Delta r$ over time interval $\Delta\theta$:
$-K(\partial T/\partial r)A\Delta\theta - K(\partial/\partial r)(A\partial T/\partial r)\Delta\theta\Delta r$.

Energy in the tank at θ:

    (a) Propane (see Appendix A):

        $(C_v(T) + (\Delta H_v V/(V_g - V_l))\ln(T))2\pi r\Delta rL\rho$

    (b) Tank shell: $\rho C_p 2\pi r\Delta rL(T)$

Energy in tank at $\theta + \Delta\theta$:

(a) Propane: $(C_v(T)\rho + (\Delta H_v V/(V_g - V_1))\ln(T))\rho(2\pi r\Delta rL) +$

$(\partial/\partial\theta)(C_v(T)\rho + (\Delta H_v V/(V_g - V_1))\ln(T))\rho(2\pi r\pi rL\Delta\theta)$

(b) Tank shell: $C_p 2\pi r\Delta rL(T)\rho + (\partial/\partial\theta)(C_p 2\pi r\Delta rL(T))\Delta\theta\rho$

From an energy balance, input - output + generation = accumulation, and from the fact that no energy is generated:

$$K(\partial/\partial r)(A\partial T/\partial r)\Delta\theta\Delta r = 2C_p\pi r\Delta rL(\partial T/\partial\theta)\Delta\theta\rho + 2C_v(\partial T/\partial\theta)$$

$$(\pi r\Delta rL\Delta\theta)\rho + ((\Delta H_v V/T(V_g - V_1))$$

$$(\partial T/\partial\theta))2\pi r\Delta r\Delta\theta L\rho$$

dividing by $2\pi r\Delta r\Delta\theta LK$,

$$(\partial^2 T/\partial r^2) + 1/r(\partial T/\partial r) = ((C_p + C_v)/K + (\Delta H_v V/KT(V_g - V_1)))$$

$$(\partial T/\partial\theta)\rho \qquad\qquad 4.$$

The physical properties of the liquid are assumed to be independent of time, θ. If these properties are dependent upon temperature, the partial differential equation becomes highly nonlinear in nature and intractable. For simplicity, C_v, C_p, K, V_g, V_1, ρ and ΔH_v are all assumed to be independent of temperature for narrow ranges of temperature. Thus, define $\alpha = \rho(C_p + C_v)/K$ and $\gamma = (\Delta H_v V/K(V_g - V_1))\rho$. Then the differential equation becomes

$$(\partial^2 T/\partial r^2) + 1/r(\partial T/\partial r) = (\alpha + \gamma/T)(\partial T/\partial\theta)$$

Boundary and initial conditions for the storage vessels are:

$$\text{at } \theta > 0, \; r = 0, \; (\partial T/\partial r) = 0 \qquad\qquad 5.$$

at $\theta \leq 0$, for all r, $T = T_o$ 6.

at $\theta > 0$, r $= R$, $-K(\partial T/\partial r)_R A =$ 7.

AB$(T - T_a)$, see Appendix A, Part B

However, the differential equation is still nonlinear and cannot be solved analytically. By assuming that the ratio of γ/T is constant throughout the temperature range, $\alpha + \gamma/T$ can be redefined as κ. Then,

$$(\partial^2 T/\partial r^2) + 1/r(\partial T/\partial r) = \kappa(\partial T/\partial \theta)$$ 8.

Normalizing the variable T, $\eta = (T - T_a)/(T_o - T_a)$, equation 8 becomes

$$(\partial^2 \eta/\partial r^2) + 1/r(\partial \eta/\partial r) = \kappa(\partial \eta/\partial \theta)$$

with boundary and initial conditions:

at $\theta \leq 0$, for all r, $\eta = 1$ 9.

at $\theta > 0$, r $= 0$, $(\partial \eta/\partial r) = 0$ 10.

at $\theta > 0$, r $= R$, $-K(\partial \eta/\partial r) = \beta \eta$ 11.

Let $\eta = R(r)\phi(\theta)$ be a solution to this equation.

$$R''(r)\phi(\theta) + (1/r)R'(r)\phi(\theta) = R(r)\phi'(\theta)$$ 12.

$$(R'' + R'/r)/R = \kappa\phi'/\phi = -a^2$$

where a is an unknown constant. Then,

$$R'' + R'/r + {}^2R = 0$$

and

$$\kappa\phi'/\phi = -a^2 .$$

Solutions to these equations are:

$$R = C_1 J_0(ar) + C_2 Y_0(ar)$$

and

$$\phi = C_3 \exp(-a^2\theta/\kappa).$$

Therefore, the overall solution is:

$$\eta = \exp(-a^2\theta/\kappa)(C_1' J_0(ar) + C_2' Y_0(ar)) \qquad 13.$$

Using boundary condition three, $(\partial\eta/\partial r) = 0$, at $r = 0$, $\theta > 0$,

$$(\partial\eta/\partial r) = 0 = \exp(-a^2\theta/\kappa)(C_1'(-a)J_1(ar) - C_2' Y_1(ar))_r = 0$$

$$0 = -C_1' J_1(0) - C_2' Y_1(0)$$

where $J_1(0) = 0$ and $Y_1(0) = \infty$, thus $C_2' = 0$; therefore,

$$\eta = \exp(-a^2\theta/\kappa)(C_1' J_0(ar)) \qquad 14.$$

Using boundary condition two, $\theta > 0$, $r = R$,

$$-K(\partial\eta/\partial r)\Big|_R = \beta\eta$$

$$(\partial\eta/\partial r) = \exp(-a^2\theta/\kappa)(-aC_1' J_1(ar))$$

$$-K(\partial\eta/\partial r)_R = \exp(-a^2\theta/\kappa)(aKC_1' J_1(ar))\Big|_R$$

$$\exp(-a^2\theta/\kappa)(aKC_1' J_1(aR)) = \exp(-a^2\theta/\kappa)(\beta C_1' J_0(aR))$$

$$aKJ_1(aR) = \beta J_0(aR)$$

therefore,

$$(aJ_1(aR))/J_0(aR) = \beta/K \qquad 15.$$

There are several values for constant a, so a should have been denoted

a_n. And

$$\eta = \sum_{n=0}^{\infty} \exp(-a_n^2\theta/\kappa)(C_1'J_0(ar)) \ .$$

Using the Sturm-Liouville equation to check for orthogonality:

$$r^2R'' + rR' + a^2r^2R = 0 \ .$$

$$g_0 = r^2 \qquad P(r) = \exp(\ r/r^2 dr) = r$$

$$g_1 = r \qquad g(r) = g_2(r)/g_0(r) = 0$$

$$g_2 = 0 \qquad R(r) = g_3(r)P(r)/g_0(r) = (r^2/r^2)r = r$$

$$g_3 = r^2$$

Thus, the equation is orthogonal. Orthogonality implies that there is only one value for C_1'. Using the initial condition, at $\theta \leq 0$, at all r, $\eta = 1$ and multipling the equation by $J_0(a_nr)$ and $R(r) = r$.

$$\int_0^1 rJ_0(a_nr)dr = \int_0^1 \sum_{n=0}^{\infty} rC_1'J_0(a_nr)dr \ ,$$

recalling that there is only one value for C_1' and integrating,

$$C_1' = (2J_1(a_n))/(a_n^4(J_1^2(a_n)) + a_n^2J_0^2(a_n)) \qquad\qquad 16.$$

Thus,

$$\eta = \sum_{n=0}^{\infty} \exp(-a_n^2\theta/\kappa)(2J_1(a_n)/(a_n^2(a_n^2J_1^2(a_n) + J_0^2(a_n))))J_0(a_nr) \qquad 17.$$

or

$$T = (T_0 - T_a)\sum_{n=0}^{\infty} \exp(-a_n^2\theta/\kappa)(2J_1(a_n)/a_n^2(a_n^2J_1^2(a_n) + J_0^2(a_n)))$$

$$(J_0(a_nr)) + T_a \qquad\qquad 18.$$

where a_n are obtained from roots of equation 15.

CHAPTER VI

RESULTS

Data Treatment

Ambient Temperatures

Ambient temperature is the key independent variable. Ambient temperature data from the Stillwater airport were used to compute tank liquid temperatures for two reasons. First, ambient temperature data for most locations can be assumed to come from the local United States Weather Bureau station; and secondly, the Stillwater station is located approximately one mile north of the propane storage site.

Air temperatures were also monitored at the Agronomy research station located 1-1/2 miles southwest of campus and at the propane storage site. A comparison of these data with the Weather Bureau data showed a root-mean-square temperature difference of 10.7 and 6.3°F respectively. No explanation can be offered for the difference between the Agronomy and Stillwater airport values. The difference between the site values and those from the Stillwater airport can be attributed to the use of unshielded thermocouples at the research site.

Liquid Temperatures

Reliable calculation of liquid temperature from ambient temperatures requires a comparison of the computed values with those actually

measured. Tank liquid temperatures were continuously measured at three different locations in the storage vessels. The maximum and minimum values of these temperatures were each averaged to obtain a maximum and minimum value for the storage vessel for each day. The upper thermocouple was located near the liquid-vapor interface. During the daily cycling of temperatures, the interface in some tanks would become lower and the thermocouple would be measuring vapor temperatures. When the temperature from the upper thermocouple was found to be 10°F higher than the average of the other two temperatures, it was not included in the calculation of the maximum daily average temperature. This reduced the possibility of using an erroneous temperature value in determining the propane liquid temperatures.

Modification of Model

One of the major assumptions necessary for an analytical solution to the partial differential equation discussed in Chapter V was constant physical and thermodynamic properties. The assumption of constant properties over a temperature range of 100°F is easily realized as being unrealistic. To lessen the effect on the computed liquid temperature, a new value for each property is calculated each time a new ambient temperature is used. Even though some error is introduced when the propane properties are calculated at the ambient temperature, the magnitude of this error is less than that which would be introduced by assuming constant properties.

The second assumption was that the ratio γ/T remained constant. Since the ratio is not constant, a new value of γ/T is calculated each time a new ambient temperature is used.

Computer Program

A program based on the heat transfer model derived in Chapter V to calculate tank liquid temperatures was written for the IBM-360 computer. The required input data are listed in Table IV. The program considers tank geometry when calculating tank temperatures from the necessary input data. If measured liquid temperatures are available, they are compared to the computed ones and the percentage deviation and root-mean-square temperature differences between the two are determined.

TABLE IV

INPUT DATA FOR COMPUTER PROGRAM

Necessary Data:

1. Daily maximum and minimum ambient temperatures.

2. Tank dimensions--overall length and diameter.

3. Paint emissivity factor.

4. Properties of stored liquid-critical temperature and critical pressure, molecular weight and specific heat constants.

5. Total wind velocity for each day.

Supplemental Data:

1. Actual tank temperatures--for comparison between calculated and measured values.

The computer program calculates the physical and thermodynamic properties of air and the stored liquid. The properties of air were taken from Eckert and Drake (4). These data were fitted to equations linear in temperature to predict the properties of air. The specific heat of the stored liquid is determined from $C_p = A + BT + CT^2 + DT^3$

(6). Other relationships were obtained from Reid and Sherwood (8): density is calculated using the Watson method (10); thermal conductivity by the method proposed by Sheffy and Johnson (9) and heat of vaporization by the Kirchhoff equation (5). All relationships are shown in Appendix A, part C.

The initial condition of the differential equation in Chapter V states that internal tank temperature is dependent upon the temperature of the preceeding day, T_0. Instead of using a fixed temperature value for the initial condition the computer program uses a ratio between the maximum ambient temperature of the preceeding day and the minimum ambient temperature of the day in question. This procedure is based on Baird's suggested relationship between liquid temperature and the average temperature of the ten preceeding days (3). The effects of this assumption are such that they die out in one or two days.

Curve-Fit Program

The regression coefficients for Baird's proposed equation of

$$T_L = B(1)T_{BO} + B(2)T_C + \ldots + B(12)T_{B10} + B(13) \qquad 19.$$

were determined using a non-linear regression analysis program. The coefficients were determined from ambient and all tank liquid temperatures. Coefficients were determined for three ambient temperature sources. The coefficients of Baird's equation were then determined for each individual tank.

Baird's equation was next modified by adding tank geometry and the Prandtl number as variables. The new equations were

$$T_L = B(1)T_{BO} + B(2)T_C + \ldots + B(12)T_{B10} + B(13)(L/D) + B(14) \qquad 20.$$

$$T_L = (B(1)_{BO} + B(2)T_C + \ldots + B(12)T_{B10} + B(13))(L/D) + B(14) \qquad 21.$$

$$T_L = (B(1)T_{BO} + B(2)T_C + \ldots + B(12)T_{B10} + B(13))(L/D)$$

$$EXP(B(14)^2/(L/D)) \qquad 22.$$

$$T_L = (B(1)T_{BO} + B(2)T_C + \ldots + B(12)T_{B10} + B(13))(L/D)$$

$$EXP(B(14)^2Pr/(L/D)) \qquad 23.$$

where L/D is geometry of the tank (length/diameter) and Pr is the Prandtl's number which is a function of T_C.

Finally, a comparison of the liquid temperature calculated from these equations to values computed from the heat transfer model and to the measured data completes the basic data treatment.

Discussion of Results

Experimental Error

An estimate of the experimental error included in the measured liquid temperature data follows. The accuracy of the thermocouples was ± 0.75°F, that of reading temperatures from the chart paper (estimated over 20 points) was ± 0.20°F and finally, the accuracy of the recorder was ± 0.10°F. These total to a maximum of ± 1.05°F. So a deviation of 1.05°F is the maximum experimental error that could be included in each recorded temperature value.

Curve-Fit Program

Regression coefficients for equations 19, 20, 21, 22 and 23 are shown in Table V. Each set of weather data was used to determine

TABLE V

REGRESSION COEFFICIENTS

Equation No.:	B(1)	B(2)	B(3)	B(4)	B(5)
Overall:					
Airport--19a	-0.0775	0.8588	0.2453	-0.1385	0.2244
Site--19b	0.1147	0.6331	0.0912	0.0207	0.0016
Agronomy--19c	2.2508	-1.0778	-0.2863	0.6890	0.0316
Individual:					
100--19d	0.0125	0.9899	0.2248	0.3235	0.5731
250--19e	-0.1436	0.9898	0.2153	-0.2667	0.3718
1000--19f	0.0319	0.7645	0.2449	-0.1587	0.2432
1800--19g	0.3136	0.5884	0.1742	0.1239	-0.1178
2800--19h	0.2266	0.6002	0.1911	0.1508	-0.1835
20	-0.0095	0.8600	0.2457	-0.1386	0.2245
21	-0.0086	0.1729	0.0496	-0.0358	0.0556
22	0.0007	0.0863	0.0248	-0.0140	0.0228
23	0.0005	0.0871	0.0247	-0.0139	0.0228

TABLE V (CONTINUED)

Equation No.:	B(6)	B(7)	B(8)	B(9)	B(10)
Overall:					
Airport--19a	-0.2962	0.4516	-0.3144	0.3947	-0.3816
Site--19b	-0.0026	0.0342	0.0740	0.0120	0.0281
Agronomy--19c	-0.0460	0.3745	-0.1836	0.2268	0.1722
Individual:					
100--19d	-0.5098	0.6316	-0.6388	0.5282	-0.5345
250--19e	-0.3522	0.4956	-0.4651	0.4728	-0.5033
1000--19f	-0.2669	0.4141	-0.3329	0.3978	-0.3780
1800--19g	-0.0284	0.1810	0.1364	0.1229	-0.1097
2800--19h	0.0181	0.1592	0.0966	0.1304	-0.0611
20	-0.2966	0.4521	0.3146	0.3947	-0.3816
21	-0.0659	0.0955	-0.0742	0.0848	-0.0833
22	-0.0298	0.0456	-0.0320	0.0403	-0.0389
23	-0.0297	0.0455	-0.0317	0.0398	-0.0383

TABLE V (CONTINUED)

Equation No.:	B(11)	B(12)	B(13)	B(14)
Overall:				
Airport--19a	0.4009	-0.1960	-0.7144	--
Site--19b	-0.0397	-0.0049	-0.7142	--
Agronomy--19c	0.1464	0.4665	-25.5896	--
Individual:				
100--19d	0.7614	-0.2789	-2.5492	--
250--19e	0.5848	-0.2734	3.7196	--
1000--19f	0.4064	-0.2161	3.1646	--
1800--19g	0.0164	-0.0075	-7.0034	--
2800--19h	-0.0438	-0.0440	-3.0600	--
20	0.4011	-0.1960	0.9207	-4.7990
21	0.0908	-0.0436	-0.0867	44.8241
22	0.0407	-0.0201	-0.0482	1.7954
23	0.0404	-0.0199	-0.0912	2.1003

coefficients for equation 19. Also, coefficients were obtained for
applying equation 19 to individual tanks. Equation 19 was used with
coefficients 19a, 19d, 19e, 19f, 19g and 19h, and equations 20 through
23 were used with their respective coefficients to calculate the li-
quid temperatures for each tank. These temperatures were compared to
the actual measured temperatures and the root-mean-square temperature
differences calculated. All results are shown in Table VI.

TABLE VI

ROOT-MEAN-SQUARE TEMPERATURE DIFFERENCES

Tank Size	Equation 19		Equation				Heat Transfer Model
	Ind.	Overall	20	21	22	23	
100	1.49	7.18	4.53	7.87	9.97	6.38	5.73
250	0.56	2.75	2.71	3.11	5.42	5.34	4.73
1000	0.82	1.34	7.10	8.47	9.25	20.06	3.89
1800	1.60	4.78	7.88	6.07	3.28	7.99	5.29
2800	1.53	5.39	7.24	8.66	5.08	13.65	5.31

The temperatures from the equations obtained through the non-
linear regression curve-fit on individual tanks are much closer to
measured values than any of the other computed temperatures. Column
two, the values from the overall equation, shows that the use of
Baird's equation is limited to describing the tank temperatures of tanks
larger than 100 pounds. It must be noted that Baird's equation (with
the regression coefficients described in this paper) cannot be presumed
to apply to tanks larger than 2800 gallons. Modification of this
equation by adding length-diameter ratio further restricted the use of

the equation, see column 3, 4 and 5. Similarly, adding the Prandtl number as a variable, column 6, almost completely negated the usefulness of the equation.

Figures 12-16 exhibit a comparison between the measured liquid temperatures and the values calculated from the theoretical heat transfer model and equations 19a and 19d through 19h.

One disadvantage for the regression equations is the number of consecutive daily temperatures required to predict one liquid temperature. Also, since the liquid temperature is based on consecutive ambient temperatures, an abrupt change in ambient temperature would have either a lesser or a greater effect than it should have on the predicted temperature. On the other hand, if the regression equations are used, these consecutive temperatures are the only necessary input information.

Heat Transfer Model

The theoretical heat transfer model requires more input information than the regression equations, but the resulting liquid temperatures include both a minimum and a maximum value reached in a 24 hour period. Advantages of the heat transfer model are that it is not limited to one type of tank geometry and the fluid stored in the tank can be varied. As evidence, the model was used to calculate the temperatures of anhydrous ammonia stored in railroad cars of varying paint color (Baird's data). The results are compared to Baird's results and the measured liquid temperatures in Figure 17. The model results yield a root-mean-square temperature difference of $4.37^{\circ}F$ while Baird's results have a root-mean-square temperature difference of $3.81^{\circ}F$. This
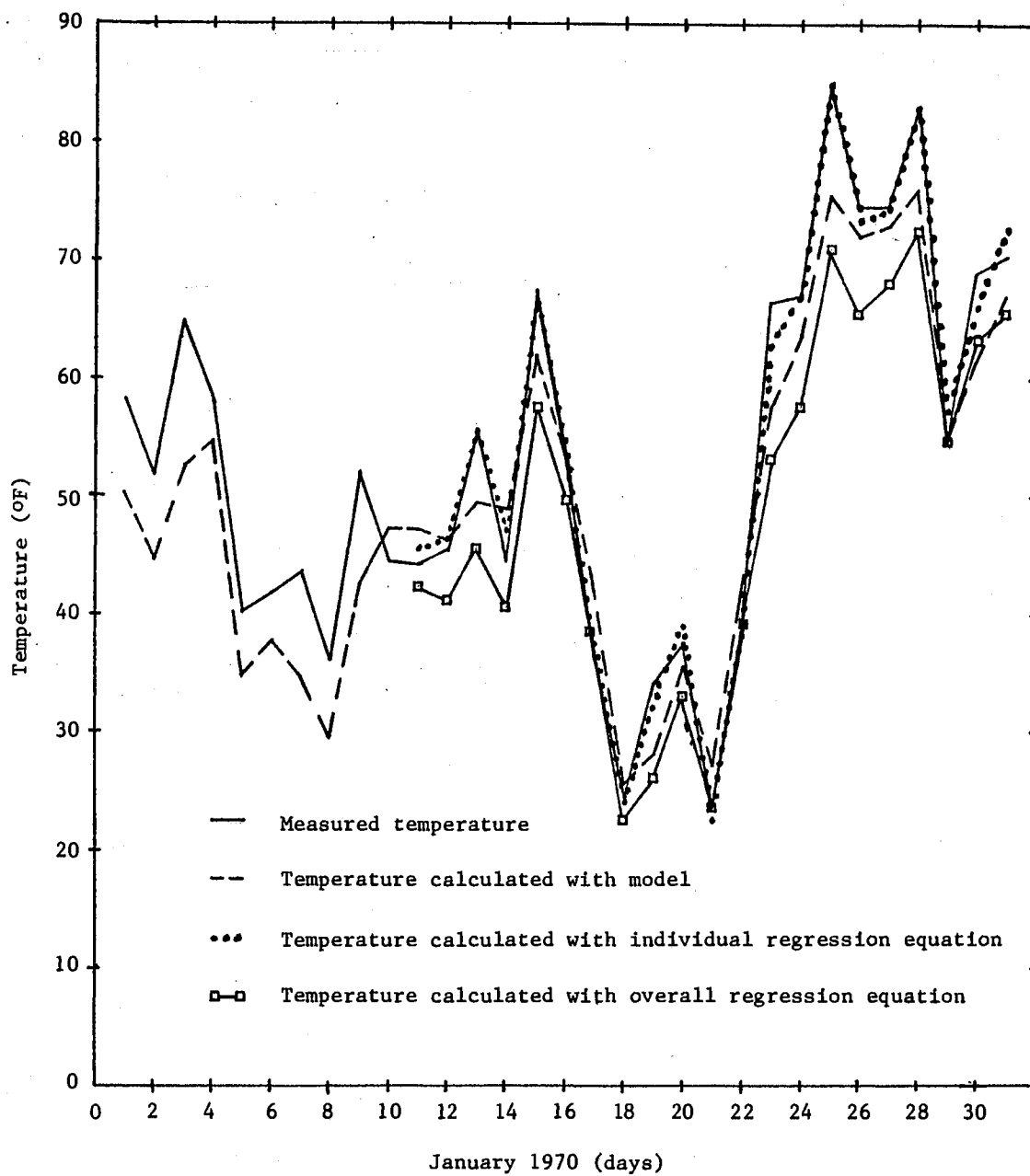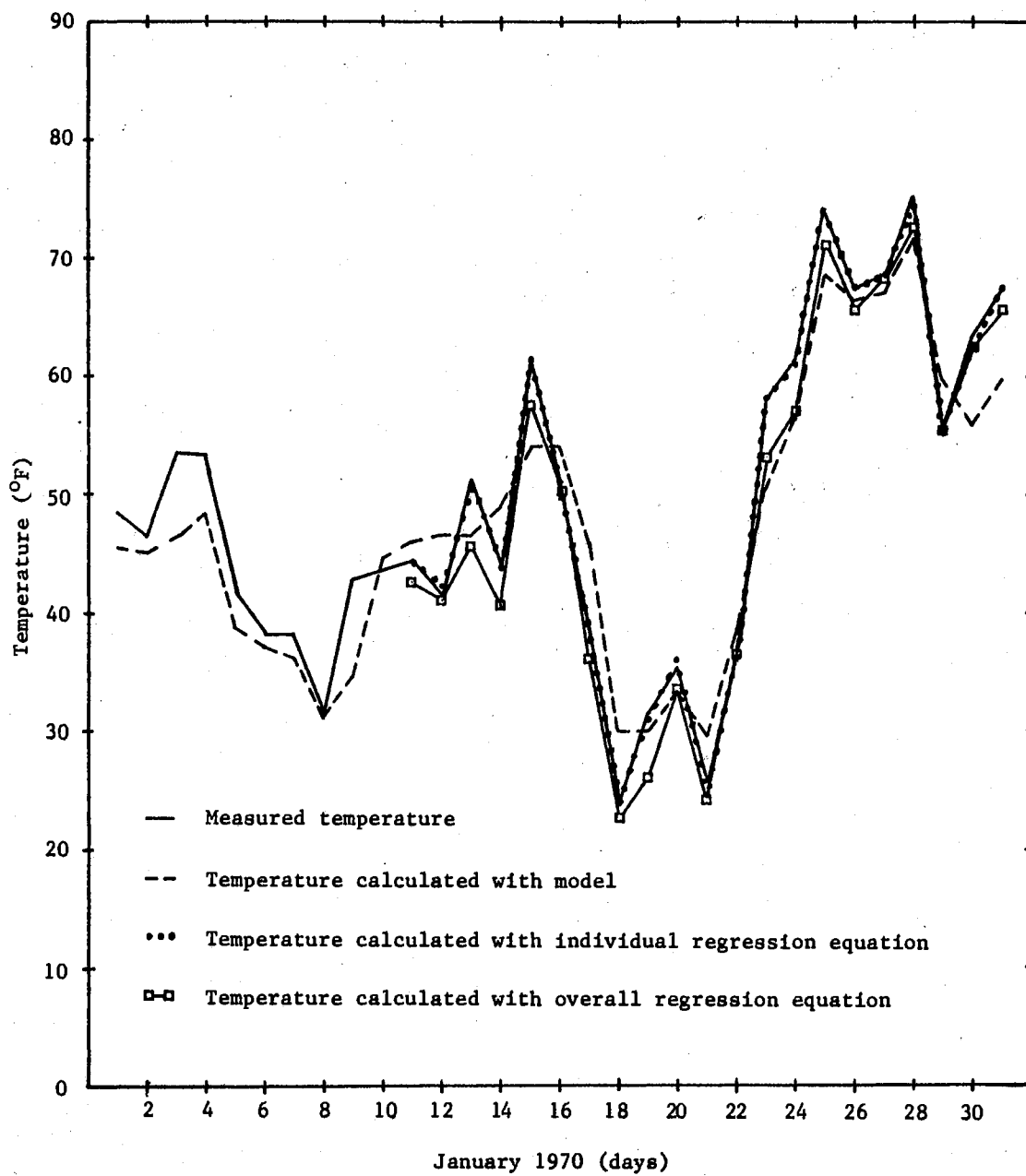
Figure 12. Propane Temperatures—100 Pound Tank
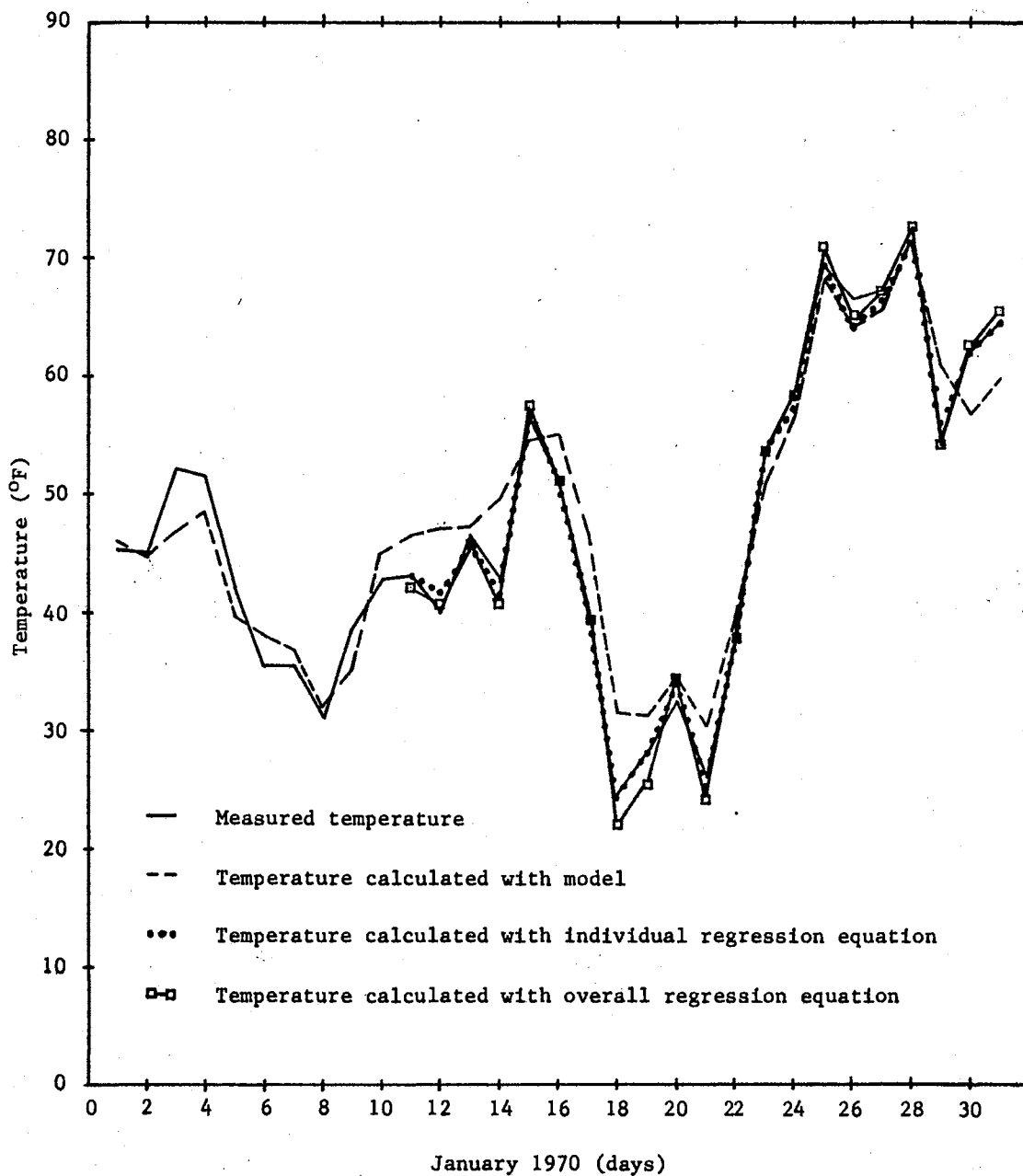
Figure 13. Propane Temperatures—250 Gallon Tank

Figure 14. Propane Temperatures--1000 Gallon Tank

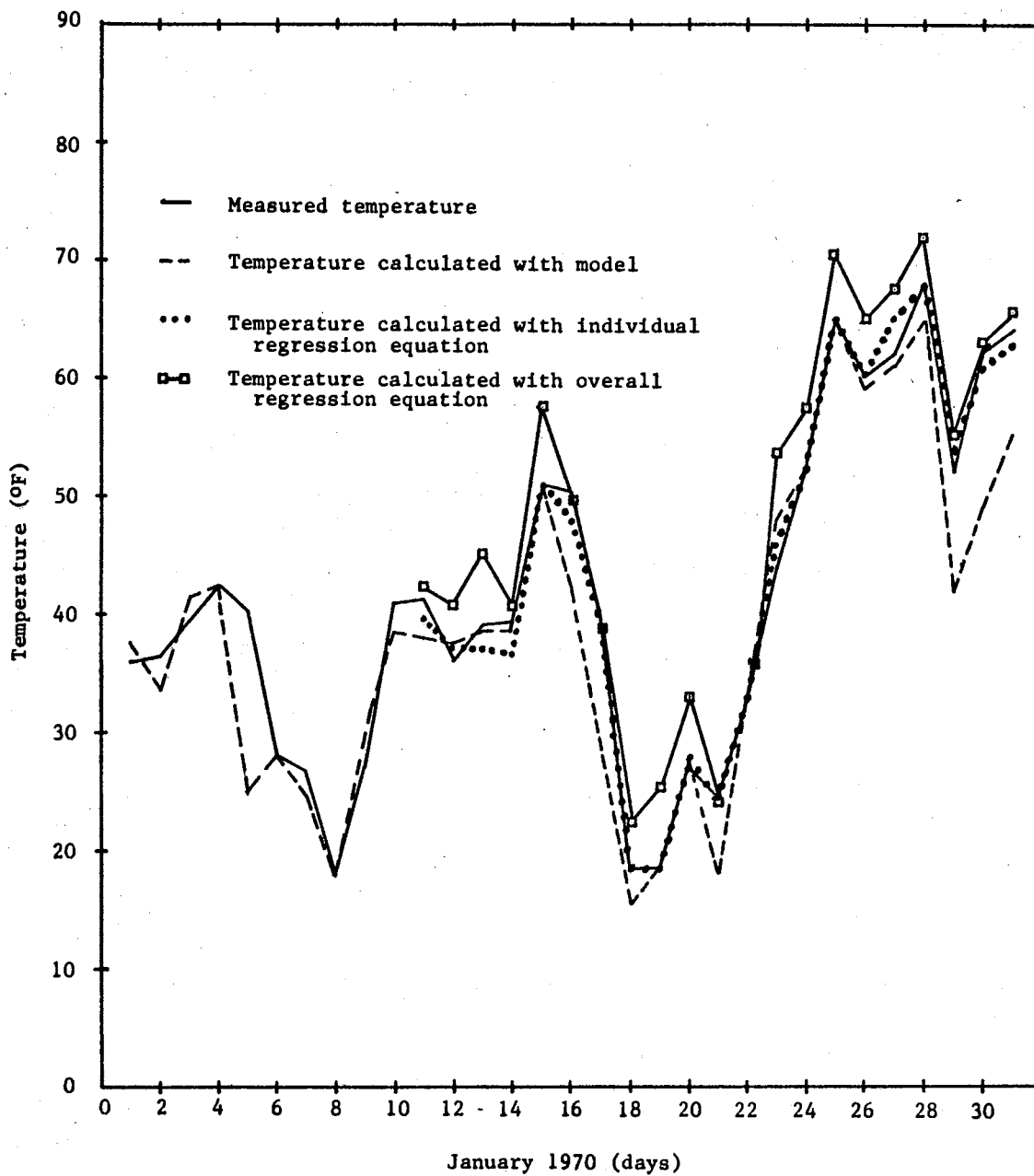Figure 15.   Propane Temperatures—1800 Gallon Tank
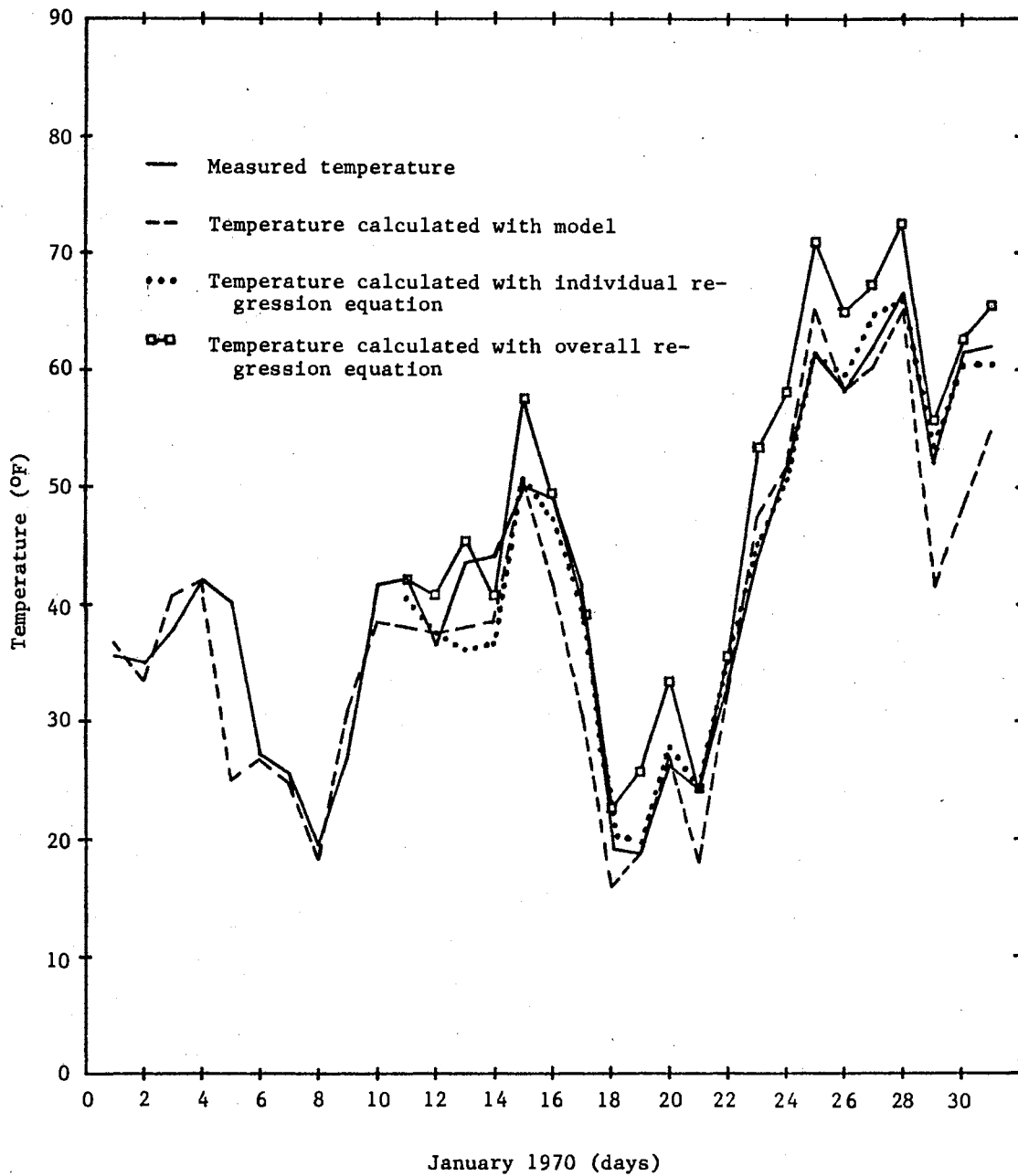
Figure 16. Propane Temperatures--2800 Gallon Tank
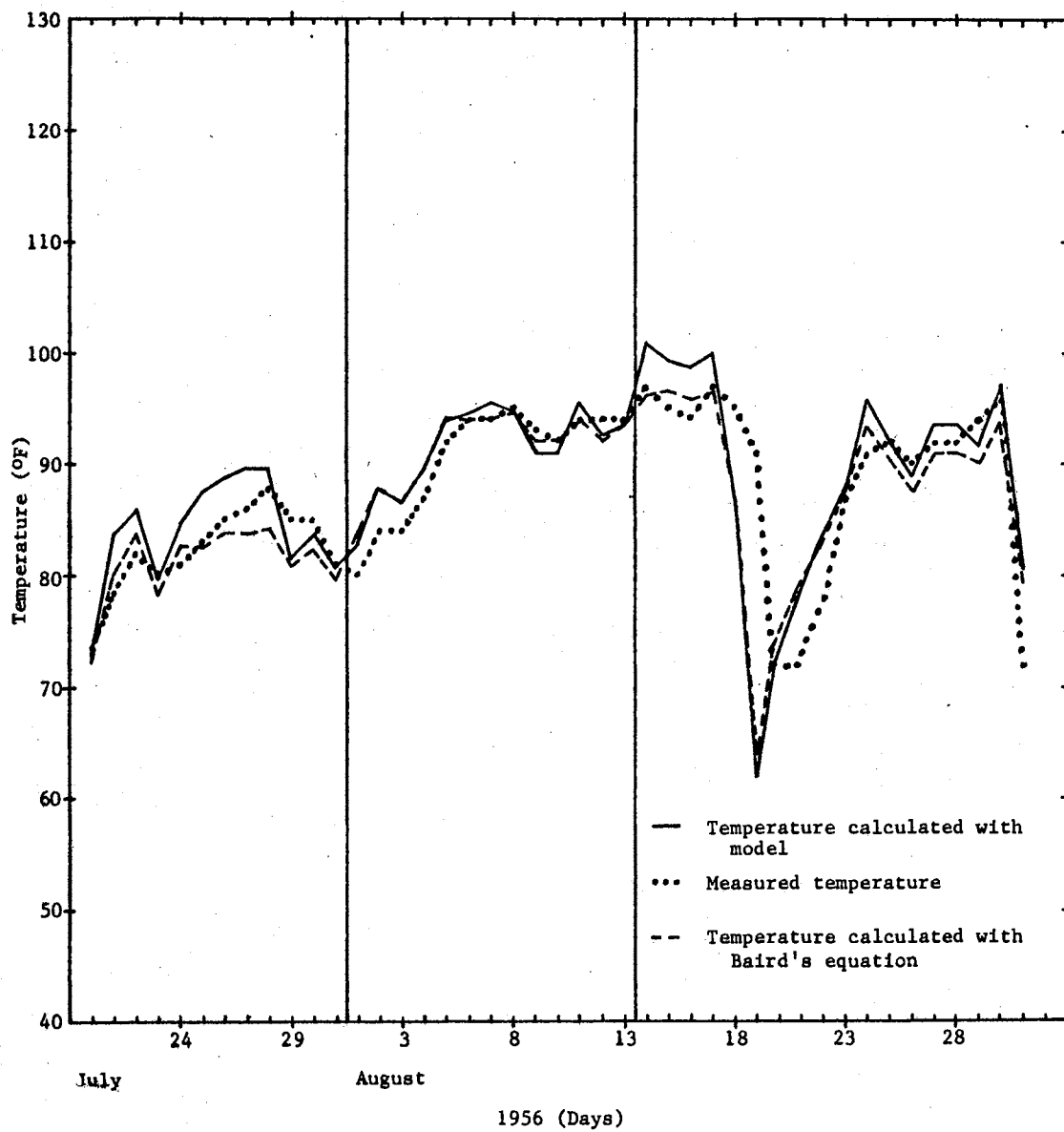
Figure 17. Ammonia Temperatures for Baird's 1956 Tests

agreement is considered quite good, especially since the model was not derived for ammonia storage.

Temperatures calculated from the theoretical heat transfer model were also compared with measured temperatures. The root-mean-square temperature differences were computed. The root-mean-square temperature differences for the model reported in Table VI are for January 1970. To more fully evaluate the theoretical model, the root-mean-square temperature difference was calculated over the data for the whole test period (August 4, 1969 through September 12, 1970). These results are shown in Table VII. In all cases except for the 1000 gallon tank, the

TABLE VII

YEARLY ROOT-MEAN-SQUARE TEMPERATURE DIFFERENCES USING STILL-
WATER AIRPORT AMBIENT TEMPERATURE DATA

Tank Size (pounds or gallons)	Overall Value	Minimum Temperature Value	Maximum Predicted Value
100	4.03	3.35	4.62
250	4.47	3.11	5.50
1000	5.08	4.03	5.94
1800	4.21	3.54	4.73
2800	4.37	4.08	4.64

yearly root-mean-square temperature difference is lower than that given for January. One possible explanation for this is that the 1000-gallon tank had a minute, undetectable leak which caused the liquid-vapor interface to cross the thermocouples, causing erroneous liquid temperature readings.

Finally, the source of ambient temperature data did not affect the
Bessel constants in the heat transfer equation derived in Chapter V.
Of the first three Bessel constants, only the first one is important.
In fact, only the first term of the series expansion of equation 18 is
required. The second and third terms are on the order of 1.0 and 0.1
compared to 100.0 for the first term.

CHAPTER VII

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

From the previous discussion of results, two conclusions can be
reached. For calculating liquid temperatures in tanks of size 100
pounds, 250-, 1000-, 1800-, and 2800-gallons, the individual regression
equation produces the best results; i.e., equation 19,

$$T_L = B(1)T_{BO} + B(2)T_C + \ldots + B(12)T_{B10} + B(13)$$

with coefficients 19d through 19h from Table V is best. If an equation
considering tank geometry and/or the fluid physical and thermodynamic
properties is desired, the heat transfer model

$$T = T_a + (T_0 - T_a) \sum_{n=0}^{\infty} \exp(-a_n^2 \theta / \kappa)(2J_1(a_n))/(a_n^2(a_n^2 J_1^2(a_n) + J_0^2(a_n)))J_0(a_n r)$$

can be used to predict tank temperatures with reasonable accuracy,
$\pm 5.0^{\circ}F$.

Recommendations

The heat transfer model derived in Chapter V is recommended for
predicting liquid temperatures of LPG in a storage vessel. These pre-
dicted values can then be used to calculate filling density of the

storage vessel.

Future Work

For a future study, the following items should be noted:

1. Existing level gages on both the cargo and home storage tanks are not precise enough that liquid levels in the storage vessels can be measured accurately. Sight glasses, even though they present a possible safety problem, are a device for measuring liquid levels accurately.

2. From a safety viewpoint, it would be better to have the pressure lines under ground. In this test, they were laid next to the thermocouple conduit and were a continuous problem.

3. In modelling, the radiation factor needs more exploration. The present heat transfer model is adequate except on bright, sunny days.

CHAPTER VIII

NOTATION

Symbols that have been used in the derivation discussed in the text of this report are listed below:

A = area in square feet

a_n = unknown constants from the Bessel equation

β = $(h'e_T + TC_p/\mu\langle v \rangle)$ = assumed constant

C_1', C_1, C_2, C_3 = arbitrary constants

C_v, C_p = specific heat in Btu/lb-^{o}R

D_T = tank diameter in feet

e_T = emissivity factor

h' = radiation coefficient in Btu/hr-ft^2-^{o}R

ΔH_v = heat of vaporization in Btu/lb.

J_0 = Bessel function of the first kind of zero order

J_1 = Bessel function of the first kind of order one

K = thermal conductivity in Btu/hr-ft^2-^{o}R/ft of length

κ = γ/T = assumed constant

L = length of tank in feet

L/D = tank length over tank diameter ratio, dimensionless

η = $(T - T_a)/(T_0 - T_a)$ = dimensionless temperature variable

ρ = density in lb/ft^3.

Pr = $\mu C_p/K$ = Prandtl's number, dimensionless

q, Q = heat in Btu/hr.

r = tank radius in feet

Re = $D_T<v>\rho/\mu$ = Reynold's number, dimensionless

T = liquid temperature in $^\circ R$

T_a = ambient temperature in $^\circ R$

T_0 = reference temperature in $^\circ R$

T = shear stress in $lb/ft\text{-}hr^2$

μ = viscosity in $lb/ft\text{-}hr$

U = internal energy in Btu/hr

V_g = volume of gas in ft^3

V_L = volume of liquid in ft^3

V = $V_g + V_L$ = total volume in ft^3

$<v>$ = wind velocity in ft/hr

W = PV work in Btu/hr

Y_0 = Bessel function of second kind, zero order

Y_1 = Bessel function of second kind, first order

θ = time in hours

π = 3.14159

α = $(C_p + C_v)/K$ = assumed constant

γ = $\Delta H_v V/K(V_g - V_L)$ = assumed constant

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APPENDIX A

MODEL DERIVATION

APPENDIX A

MODEL DERIVATION

Part A--Derivation of Heat Content of Tank

First law of thermodynamics for a closed system is

$$Q = U + W$$

where Q is heat, U is internal energy, and W is work compressing the vapor (W = PV).

Total derivative of first law:

$$dQ = \frac{\partial U}{\partial T}dT + \frac{\partial W}{\partial T}dT$$

$$dQ = \frac{\partial U}{\partial T}dT + \frac{\partial (PV)}{\partial T}dT$$

$$dQ = \frac{\partial U}{\partial T}dT + V\frac{\partial P}{\partial T}dT + \frac{\partial V}{\partial T}dT$$

Assuming volume remains constant,

$$dQ = \frac{\partial U}{\partial T}dT + V\frac{\partial P}{\partial T}\partial T$$

Using definition of constant volume specific heat, $C_V = \frac{\partial U}{\partial T}$, then

$$dQ = C_V dT + V\frac{\partial P}{\partial T}dT$$

Using Clapeyron equation, $\dfrac{\partial P}{\partial T} = \dfrac{\Delta H_V}{T(V_g - V_L)}$,

$$\left(\dfrac{\partial P}{\partial T}\right)_V = \dfrac{\Delta H_V}{T(V_g - V_L)}$$

$$V\left(\dfrac{\partial P}{\partial T}\right)_V dT = \dfrac{\Delta H_V}{(V_g - V_L)} \dfrac{V}{T} dT$$

and

$$dQ = C_V dT + \dfrac{\Delta H_V}{(V_g - V_L)} \dfrac{V}{T} dT$$

$$\int_0^Q dQ = \int_0^T \left(C_V + \dfrac{\Delta H_V}{(V_g - V_L)} \dfrac{V}{T}\right) dT$$

$$Q = C_V T + \dfrac{\Delta H_V}{(V_g - V_L)} V \ln T$$

Part B—Derivation of Boundary Conditions

Boundary condition at r = R is composed of radiation and convection heat transfer.

Radiation

Since the surface area of the propane tank is very small in comparison with the atmosphere, only the emissivity of the tank has to be considered. So

$$q\Big|_R = h'A(T - T_A)e_T$$

where h' is radiation coefficient of heat transfer, $A = \pi D(D+L)$ is surface area of the tank, e_T is emissivity factor for the tank, and $(T-T_A)$ is temperature difference between tank and atmosphere.

Convection

Check for turbulence flow around the tank. For the sake of simplicity, assume flow over tank is in axial direction only. Then,

$$R_E = D_T <v> \rho / \mu$$

where D_T is diameter of propane tank (ft.), $<v>$ is average wind velocity (ft./hr.), ρ is density of air = 0.0808 lb_m/ft (average value), and μ is viscosity of air = 0.04477 $lb_m/ft-hr$ (average value).

Average wind velocity over the months of July, August, and September, 1969, Stillwater, Oklahoma, was 20.1 miles/hr.

$$R_E = D_T \frac{(1.06 \times 10^5)(8.08 \times 10^{-2})}{4.48 \times 10^{-2}} = 1.91 \times 10^5 D_T$$

Since D_T varies from 1.5 to 6.6 feet, R_E will vary from 2.9×10^5 to 13.0×10^5. By choosing the criteria for turbulence flow around the tanks similar to that for flow around submerged objects, the flow would be turbulent in nature.

Now by assuming that there is no velocity or temperature gradient between the laminar sublayer and the free stream,

$$\frac{Q|_R}{T} = \frac{KA}{\mu <v>} (T - T_A)$$

$$Q|_R = \frac{TKA}{\mu <v>} (T - T_A)$$

Using the definition of Prandtl number, P_R, as $C_p \mu / K$,

$$Q|_R = \frac{T C_p A}{P_R <v>} (T - T_A)$$

Combining radiation and convection terms,

$$\mathcal{U}\,Q\big|_R = h'Ae_T(T - T_A) + \frac{TC_pA}{P_R\langle v\rangle}(T - T_a)$$

$$Q\big|_R = (h'e_T + \frac{TC_p}{P_R\langle v\rangle})A(T - T_A)$$

$$\text{Let}\quad \beta = (h'e_T + \frac{TC_p}{P_R\langle v\rangle})$$

$$\text{Then}\quad Q\big|_R = \beta(T - T_A)A$$

Part C--Properties of Air and Stored Liquid

Properties of Air

$$C_p = \frac{1.8}{28.97}(6.713 + 4.697 \times 10^{-3}T + 1.147 \times 10^{-6}T^2$$

$$+ 4.696 \times 10^{-6}T^3)$$

$$P_R = 0.739 \times 10^{-9.41 \times 10^{-5}T}$$

$$\mu = 4.02 \times 10^{-6}T^{0.796}$$

$$\rho = 0.440\,T^{-1.022}$$

Properties of Stored Liquid

Watson Equation:

$$Z_c = 0.371 - 0.0343\,\log\left[\frac{P_{cr}/14.7}{T_{cr}/T_B) - 1}\right]$$

$$\rho = 62.37M[1.20 + \{(5.563 - 11.03Z_c)/(1 - T/T_{cr})\}$$

$$EXP(.8Z_c + .31)]/[(82.06)(14.7)Z_cT_{cr}/1.8P_{cr}]$$

Sheffy and Johnson Equation:

$$K = 3.6524\left[\frac{1-.00126(T-T_M)}{T_M{}^{.216}M^{.3}}\right]$$

Kirchhoff:

$$H_V = 1.4124TT_{cr}\log\left[\frac{P_{cr}/14.7}{T_{cr}-T}\right]$$

where

Z_c is critical compressibility factor

P_{cr} is critical pressure of stored liquid in psig

T_{cr} is critical temperature of stored liquid in $^O R$

T_B is boiling temperature of stored liquid in $^O R$

T_M is melting temperature of stored liquid in $^O R$

M is molecular weight of stored liquid.

APPENDIX B

TEMPERATURE DATA

TABLE VIII

AMBIENT TEMPERATURE DATA FOR JANUARY, 1970

Date	Minimum[a] Temperature($^{\circ}$F)	Maximum[a] Temperature($^{\circ}$F)	Wind Velocity[b] (miles / day)
01-01-70	18.0	42.0	904.0
01-02-70	18.0	35.0	928.0
01-03-70	19.0	45.0	972.0
01-04-70	21.0	46.0	13.0
01-05-70	19.0	24.0	120.0
01-06-70	10.0	29.0	314.0
01-07-70	12.0	25.0	394.0
01-08-70	4.0	20.0	472.0
01-09-70	7.0	36.0	525.0
01-10-70	30.0	38.0	646.0
01-11-70	28.0	38.0	791.0
01-12-70	28.0	37.0	853.0
01-13-70	20.0	41.0	861.0
01-14-70	27.0	39.0	904.0
01-15-70	28.0	55.0	964.0
01-16-70	31.0	42.0	59.0
01-17-70	16.0	32.0	131.0
01-18-70	8.0	15.0	301.0
01-19-70	8.0	19.0	379.0
01-20-70	17.0	27.0	407.0
01-21-70	12.0	17.0	511.0
01-22-70	22.0	33.0	612.0

TABLE VIII (CONTINUED)

Date	Minimum[a] Temperature($^{\circ}$F)	Maximum[a] Temperature($^{\circ}$F)	Wind Velocity[b] (miles / day)
01-23-70	31.0	50.0	717.0
01-24-70	32.0	55.0	758.0
01-25-70	49.0	67.0	814.0
01-26-70	35.0	63.0	882.0
01-27-70	37.0	65.0	906.0
01-28-70	47.0	67.0	111.0
01-29-70	28.0	43.0	256.0
01-30-70	22.0	54.0	336.0
01-31-70	32.0	59.0	416.0

[a]Data measured at the Stillwater Airport.

[b]Data measured at the Agronomy research site.

TABLE IX

LIQUID PROPANE TEMPERATURES(^{o}F) MEASURED AT THE RESEARCH SITE
DURING THE MONTH OF JANUARY, 1970[a]

Date	100 Pound Tank	250 Gallon Tank	1000 Gallon Tank	1800 Gallon Tank	2800 Gallon Tank
01-01-70	58.0	48.4	45.1	36.0	35.5
01-02-70	51.4	46.4	45.0	36.3	35.3
01-03-70	64.8	53.5	51.8	39.5	38.1
01-04-70	58.2	53.2	51.5	42.7	42.2
01-05-70	40.1	41.8	41.9	40.1	40.1
01-06-70	41.2	38.3	35.2	27.2	27.2
01-07-70	43.2	38.4	35.5	25.7	25.6
01-08-70	36.1	31.6	30.8	19.0	19.6
01-09-70	52.0	42.8	38.7	27.0	26.9
01-10-70	44.5	43.2	42.7	41.1	41.5
01-11-70	44.1	43.7	42.9	41.2	42.0
01-12-70	45.5	41.4	40.0	36.0	36.5
01-13-70	55.6	51.0	46.5	39.0	38.5
01-14-70	44.5	43.5	42.7	39.1	39.0
01-15-70	67.2	61.0	56.5	51.0	50.1
01-16-70	52.5	50.7	50.7	50.1	48.9
01-17-70	35.8	38.6	39.2	40.1	41.3
01-18-70	24.2	23.8	24.6	18.2	19.2
01-19-70	33.8	31.4	28.4	18.3	18.8
01-20-70	37.5	35.4	32.5	26.2	26.1
01-21-70	23.5	25.8	26.0	24.1	24.3

TABLE IX (CONTINUED)

Date	100 Pound Tank	250 Gallon Tank	1000 Gallon Tank	1800 Gallon Tank	2800 Gallon Tank
01-22-70	38.5	37.5	36.7	34.0	33.7
01-23-70	66.1	57.2	53.2	44.0	43.2
01-24-70	66.8	61.4	58.2	52.2	52.0
01-25-70	84.7	74.2	69.2	65.0	61.5
01-26-70	74.1	67.2	64.0	60.0	58.1
01-27-70	74.1	68.8	65.4	62.0	61.9
01-28-70	82.6	75.2	72.4	67.8	66.5
01-29-70	57.2	55.1	54.7	52.0	52.0
01-30-70	69.0	63.1	62.0	61.9	61.3
01-31-70	70.2	67.6	64.5	64.5	62.0

[a]Average of the maximum thermocouple readings during each day.

VITA

Ryan DeLacy Moats, Jr.

Candidate for the Degree of

Master of Science

Thesis: THE EFFECTS OF AMBIENT TEMPERATURE ON LIQUID TEMPERATURE IN PROPANE STORAGE AND CARGO TANKS

Major Field: Chemical Engineering

Biographical:

Personal Data: Born in Kansas City, Kansas, March 27, 1941, the son of Mr. and Mrs. Ryan D. Moats, Sr.; married Judith Jane Laidig, February 21, 1963; have three sons, Ryan D. III, David L., and Michael S.

Education: Graduated from Wyandotte High School, Kansas City, Kansas, in May 1959; received the Bachelor of Science degree from the University of Kansas, Lawrence, Kansas, in 1964 with a major in chemical engineering; completed the requirements for Master of Science degree at Oklahoma State University in May 1971.

Professional Experience: Associate engineer, Thiokol Chemical Corporation, June 1964 to July 1965; Chemical engineer, Atlas Chemical Industries, Inc., August 1965 to September 1968; Graduate teaching assistant, School of Chemical Engineering, Oklahoma State University, 1969-1970 and 1970-1971.