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SAND94-0022
Unlimited Release
Printed May 1994

Distribution
Category UC-126

THE BAYOU CHOCTAW OIL SHIPMENT TEST

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Abstract

In early October of 1993, an oil shipment of about 1 million barrels was made from the Bayou Choctaw Strategic Petroleum Reserve storage facility to St. James Terminal. During the shipment, oil temperatures and soil temperatures along the pipeline were recorded. The field data were used to make estimations of soil thermal properties, thermal conductivity and specific heat. These data were also used to validate and calibrate a heat transfer code, OILPIP, which has been used to calculate pipeline cooling of oil during a drawdown.

Acknowledgments

The report which follows is the culmination of a team effort. We would like to thank George Smith at St. James and J. C. Morris at Bayou Choctaw for their help and support. Lisa Nicholson of the Department of Energy in New Orleans and John Baudean of DynMcDermott were key members of the team that saw that the test materialized. Tom Hinkebein and Jim Todd provided review comments which greatly improved the quality of the manuscript. The personnel of the pipeline crew operating out of St. James facilitated instrumentation installation and data collection. These DynMcDermott personnel include, Bill Oakley, Dave, Tommy Breaux, J. O., Emma, and Donald.

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Executive Summary

This report is a technical description and assessment of a test in which about 1 MMbbl of crude oil was shipped from the Bayou Choctaw SPR storage facility to St. James Terminal. The purposes of the test were (1) to collect a data set to be used to validate and calibrate a heat transfer code (OILPIP, Russo, 1993), and (2) to collect a data set from which soil thermal properties (heat capacity and thermal conductivity) could be estimated.

The SPR Project has studied pipeline cooling and its utility in reducing the temperature of delivered oil (Bauer and Hinkebein, 1993). The predicted cooling for a pipeline depends on the analysis method (OILPIP) and the input parameters to the code. To establish confidence in the code, a data set was needed to compare measured temperatures with calculated temperatures. Oil property parameters for code input were obtained from SPR Project sources and from handbooks. The least confidence was placed on the soil thermal properties, in that they were estimated from textbook values. Thus a data set was needed to estimate soil thermal properties.

In early October of 1993, an oil shipment of about 1 MMbbl was made from the Bayou Choctaw SPR storage facility to St. James Terminal. During the shipment, oil temperatures and soil temperatures along the pipeline were recorded. These field data were then used to make estimations of soil thermal properties, heat capacity and thermal conductivity and were also used to validate and calibrate OILPIP.

The soil thermal conductivity and heat capacity were estimated at the valve stations along the pipeline. The thermal property estimates were obtained from the average of point measurements along the pipeline. The specific heat was found to be about 40% less and the thermal conductivity nearly 50% less than values used previously by Bauer and Hinkebein (1993).

Using these new estimates, revised heat transfer analyses of the oil shipment test compared within a few degrees to those measured in the field. It is concluded that the analysis method well represents the observed physical phenomena and that confidence may be placed in the analysis method.

The revised analysis predicts about 5°F less pipeline cooling for a simulated drawdown from Bayou Choctaw as compared to the Bauer and Hinkebein (1993) analyses. It is cautioned that the soil material properties determined herein for the Bayou Choctaw line may not apply to other pipelines and that their properties should be studied separately. As a result of this investigation, the pipeline cooling analyses completed for Bauer and Hinkebein (1993) will be revised.

Introduction

Crude oil stored in caverns in salt domes is subject to two geological factors that affect the subsequent storage of that oil in tanks. First, there is a characteristic tendency for naturally occurring gases to be absorbed in the crude oil, and second for oil to warm in response to geothermal heat. These two processes increase the bubble point of the stored oil above atmospheric pressure. Upon depressurization and storage of the oil in tanks at atmospheric pressure, these two factors act to increase the emission of gases and vapors from the oil. This increase in emissions can have potential safety and operational environmental impacts. Safety impacts follow from the release of combustible and toxic gases. Environmental impacts are the consequence of release of vapors and gases to the atmosphere. Bauer and Hinkebein (1993) addressed the geothermal heating of crude oil and considered those conditions applied to non-gassy crudes that lead to the violation of environmental standards. In Bauer and Hinkebein, the amount of cooling by pipeline transport of Strategic Petroleum Reserve (SPR) oil was quantified. The results of preliminary calculations indicate that pipeline transport is capable of providing significant cooling of oil in transit from site to terminal. These preliminary calculations were completed using OILPIP (Russo, 1993), a heat transfer code to compute the heat loss from the oil during pipeline transport. The two-dimensional, axisymmetric code is written to solve for the temperature of oil flowing in a pipeline. It is based on the assumptions that turbulent incompressible flow occurs in the pipe, and that heat transfer from the pipe and surrounding soil is by thermal conduction in the radial (away from the pipe center) direction.

Validation and calibration of OILPIP was warranted in order to consider the code results as part of an oil cooling scenario. This proof has taken the form of collecting a data set to attempt to validate and calibrate the code, and a data set to better estimate soil material properties to be used in the simulations.

A test was planned in which about 1 MMbbl of oil would be shipped from Bayou Choctaw to the tanks at St. James through a 36 inch diameter pipeline. The shipment was to be planned and run by DynMcDermott, the operations and maintenance contractors for the Department of Energy (DOE) SPR. Prior to the shipment, Sandia National Laboratories (SNL) completed a series of calculations to predict oil and soil temperatures at various locations along the pipeline for the conditions of the planned test. During the shipment, SNL monitored oil temperatures and soil temperatures at specific locations along the pipeline (valve stations). Following the test, soil temperature measurements were analyzed to estimate soil thermal properties. After reasonable estimates of soil properties were obtained, a new set of heat transfer calculations was completed of the as run test. Once the material properties were best understood, and the code workings validated, heat transfer calculations were repeated for a design drawdown for the Bayou Choctaw site.

Planning and Conduct of the Test

In order to provide the most meaningful data set possible to validate and calibrate the heat transfer code, it was desired to run a test which would simulate a drawdown. That is, hot oil would be pumped at the design rate for as long as possible. There are practical limits to the amount of oil that can be shipped. The tankage at St. James holds about 1 million barrels, which limits the amount of oil that can be shipped. The design flow rate from Bayou Choctaw to St. James is 480 MBD (thousand barrels/day). The intent of the test was to achieve the design rate as quickly as practical, maintain the 480 MBD flow rate (this allowed for about 50 hours of pumping) and then decrease the flow rate to zero when the test was completed. Because of engineering constraints, sour oil was to be used in the test.

A series of pretest analyses was completed in order to determine what sort of results were to be expected. The analyses were performed using the two-dimensional, axisymmetric computer code, OILPIP (Russo, 1993), written to compute the heat loss from the oil during pipeline transport. It is this code whose workings we are attempting to validate, and whose input parameters we are attempting to estimate with this test. The viscosity, μ (lb ft^{-1} s^{-1}), of the oil is assumed to vary with its temperature, T (°F) according to:

$$\mu = 0.00771\ (40 / T)^{1.218}$$

The transient energy equation is solved assuming that thermal conduction and diffusion in the flow direction are negligible compared to the convective heat transfer in that direction. Heat transfer from the oil to the pipe is calculated from a convective-heat transfer coefficient, h_c (BTU ft^{-2} s^{-1}), given by:

$$h_c = 0.023\ \rho\ c_o\ v / (Re^{0.2}\ Pr^{0.667})$$

where ρ is the oil density (lb ft^{-3}), c_o is the oil specific heat (BTU lb^{-1} $°F^{-1}$), v is the flow velocity (ft s^{-1}), and Re and Pr are the Reynolds and Prandtl numbers (both dimensionless). The temperatures in the oil and soil are written as output.

It was believed that the initial oil temperature flowing into the pipeline would be about 102°F. For the pretest analyses the soil temperature was estimated to range from 70 to 80°F with soil temperatures of 70, 75 and 80°F used in calculations. The oil and soil thermal properties used are listed in Table 1. These are the same values that were used by Bauer and Hinkebein (1993). Part of the reason for running the test was to establish better estimates of these properties. For the analysis, the pumping rate was linearly increased to 480 MBD in three hours, held at that rate for 48 hours, then the rate was linearly decreased to zero in 17 minutes. The inlet oil temperature was set at 102°F for the entire analysis.

The predicted effect on the delivered oil temperature by pumping 102°F oil from Bayou Choctaw to St. James using 70, 75, and 80°F initial soil temperatures is shown in Figure 1. All predictions have the same transit time for the "hot" oil traveling down the pipeline at constant velocity. This accounts for the sharp increase in delivered oil temperature beginning at about 15 hours after the start. The predicted temperature in each simulation increases at a decreasing

Table 1 - Thermal properties of oil and soil used in pre-test analyses.

Property	Oil	Soil
Density (lb/ft^3)	51.0	125.0
Specific heat (BTU/lb °F)	0.45	0.5
Thermal conductivity (BTU/ft sec °F)	2.11 x 10^{-5}	4.0 x 10^{-4}

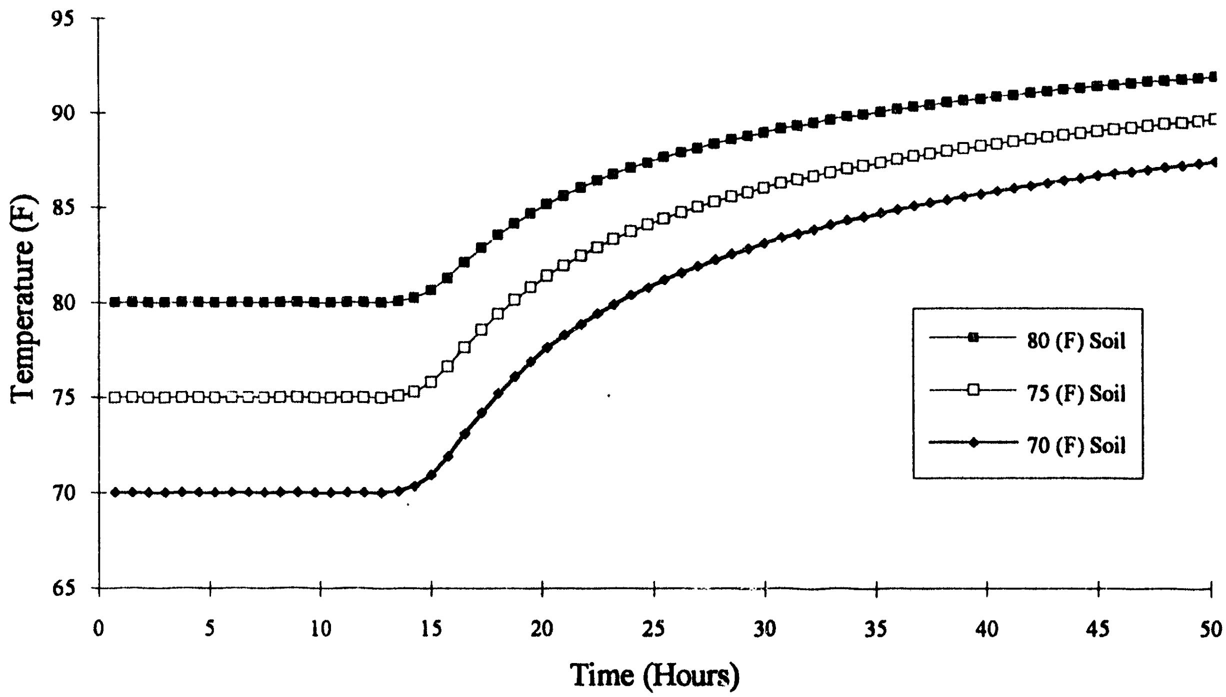


Figure 1 - Predicted oil temperatures using OILPIP at St. James for different initial soil temperatures.

rate until the oil flow is stopped at about 51 hours. The amount of oil cooling during transport, the difference between oil inlet temperature (102°F) and delivery temperature, decreases with increasing initial soil temperature. The input parameter which is varied from one calculation to another is the soil temperature, which is changed by 5°F from one calculation to the next. The delivered oil temperature, from one calculation to the next is less than 5°F. The results reported are consistent with those predicted by Bauer and Hinkebein (1993).

Figure 2 shows predictions of the temperature at the outside of the pipe at distances of 12.4, 24.8, and 37.2 miles from Bayou Choctaw for the 80°F initial soil temperature case. For each location the sudden rise in temperature indicates the arrival of the hot oil at that location. The farther a location is from the source, the less abrupt the temperature rise. This is in part because the oil is predicted to cool as it moves down the pipeline, thus the temperature difference between the oil and soil is less for greater distances down the pipeline.

Experimental Design

The purpose of the test was to collect a data set that could be used to measure the oil and soil temperature with increasing time as the oil was pumped from Bayou Choctaw to St. James. Data were collected at Bayou Choctaw, the seven main line valve (MLV) stations and at the pig trap area at St. James. The locations of valve stations along the Bayou Choctaw-St. James pipeline were determined from drawing DOE-SPR DWG #BC-0-511-001. The distance along the pipeline from Bayou Choctaw to each measurement location are listed in Table 2. At each of these locations access with a temperature probe was possible directly into the oil and the pipeline is

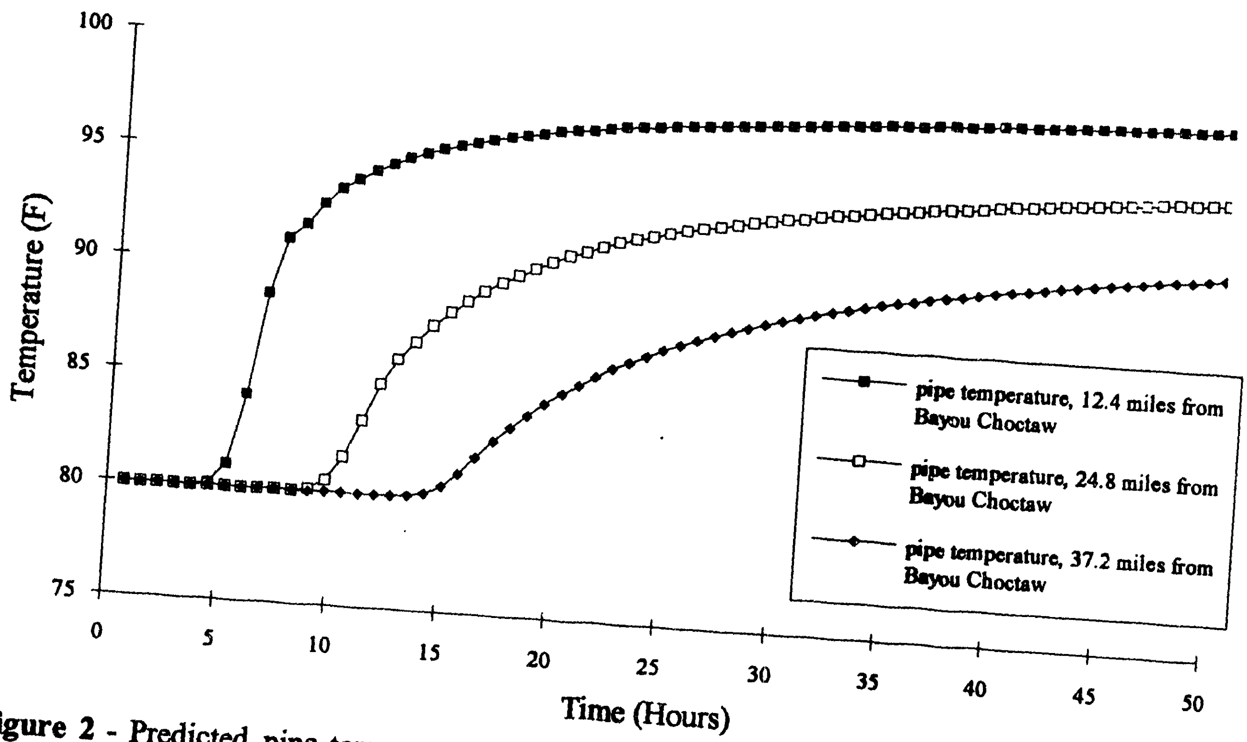


Figure 2 - Predicted pipe temperature using OILPIP at 12.4, 24.8 and 37.2 miles from Bayou Choctaw for an 80°F soil test case.

shallow enough (about 5 feet) that thermal sensing equipment could be installed in the soil immediately adjacent to the pipeline.

The test took place during the first weekend in October, 1993. Shortly after 9:00 p.m. on October 1, 1993, pumping began from Bayou Choctaw. The rate was linearly increased to about 275 MBD and after about 3 hours at this rate, an emergency shutdown was ordered. After the problems were mitigated (this took about 2 hours), the pumping was again initiated. At this point, the flow rate was linearly increased to about 460 MBD and held near that rate for about 50 hours (until a total of near 1 MMbbl was transported) followed by a shutdown. A graphical representation of the actual flow rate versus time is given in Figure 3. After the test, no oil was moved through the pipeline for about four days and then the oil was slowly pumped back to Bayou Choctaw.

Three probes were installed at each valve station. A complete description of the probes, their calibration, method of emplacement and exact position relative to the ground surface and the pipeline, are provided in Appendix A. Each probe consisted of ½" steel tubing within which an array of

Table 2 - Distances from Bayou Choctaw to the measurement locations.

Measurement location	Distance from Bayou Choctaw (miles)
Bayou Choctaw	0
MLV2	3.9
MLV3	5.0
MLV4	10.4
MLV5	18.0
MLV6	20.7
MLV7	24.6
MLV8	24.7
St. James	37.2

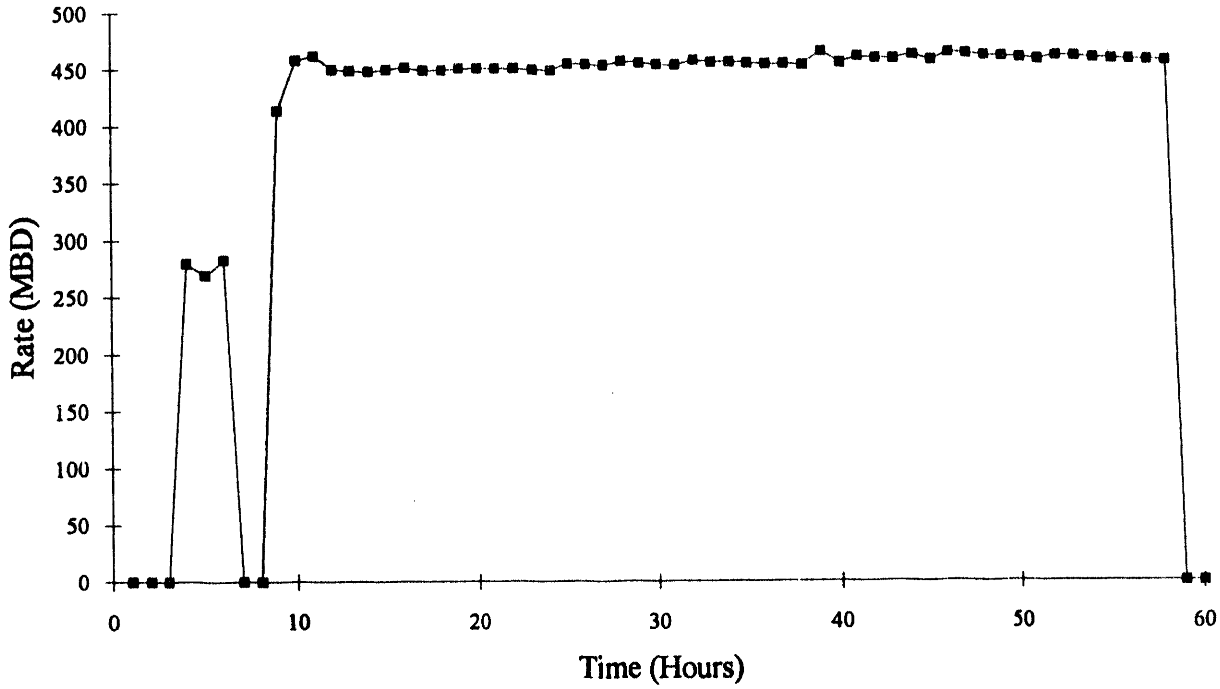


Figure 3 - Measured oil flow rate at the Bayou Choctaw meter skid during the pumping phase of the test.

thermistors was embedded in an epoxy resin potting compound. The thermistors were calibrated to an accuracy of ±0.02°F. Two of the probes had thermistors located approximately every foot along the length of the probe. These probes were pushed into the soil approximately 10 feet downstream from the valve station. Figure 4 illustrates a cross section through the pipeline at valve station 2, showing the position of the two soil probes relative to the pipeline. The third probe had only a single thermistor located near the bottom of the probe. It was inserted inside the oil pipeline through a 2" access pipe. The thermistor in the probe was positioned at the junction between the 2" access pipe and the 36" oil pipeline. In all, temperature measurements were made at 18 locations at each of the seven valve stations, 17 in the soil and 1 in the oil. At Bayou Choctaw, access to the oil pipeline was not possible. Oil temperature measurements were made by DynMcDermott at the Bayou Choctaw meter skid. Only one soil probe was emplaced at Bayou Choctaw. The bottom of this probe was emplaced at the top of the pipe at a depth of approximately 7.5 feet. At St. James, it was possible to insert a probe into the oil pipeline through an access pipe. As at Bayou Choctaw, only one soil probe was deployed, which hit the top of the pipeline at a depth of 6 feet. This soil probe was emplaced at a location where there was a great deal of piping, both above and below the ground surface. This piping conducted sufficient heat into and out of the soil to significantly impact the subsurface soil temperatures so the soil temperature data from this site were not used.

A battery-powered data logger was deployed at each of the nine measurement locations to monitor the oil and soil temperatures. Data were collected every 30 minutes for approximately 17 days before the oil shipment, every 15 minutes during the 2½ days that the oil was being shipped through the pipeline and then every 30 minutes for 8 days following the end of the test. In all, more than 200,000 temperature measurements were made at 148 temperature locations.

Typical Data

The soil temperature measured by the thermistors in the long probe deployed at valve station 2, located 3.92 miles downstream from Bayou Choctaw, are illustrated in Figure 5. Similar plots for the data from each measurement location are presented in Appendix B. Time 0 on the horizontal axis indicates the time at which oil began to be pumped through the pipeline. The data from the thermistor located 3 inches below the ground surface shows daily temperature oscillations with an amplitude of approximately 10°F. These data reflect atmospheric temperature variations reasonably well. The deeper thermistors, located from 3.25 to 12 feet below the surface, show only minimal effects of daily surface temperature oscillations. Before pumping began, the deeper thermistors show a general pattern of decreasing temperature with increasing depth. This is consistent with the fact that these observations were made in early fall when the ground temperatures at shallow depth still reflect the relative warmth of the summer season.

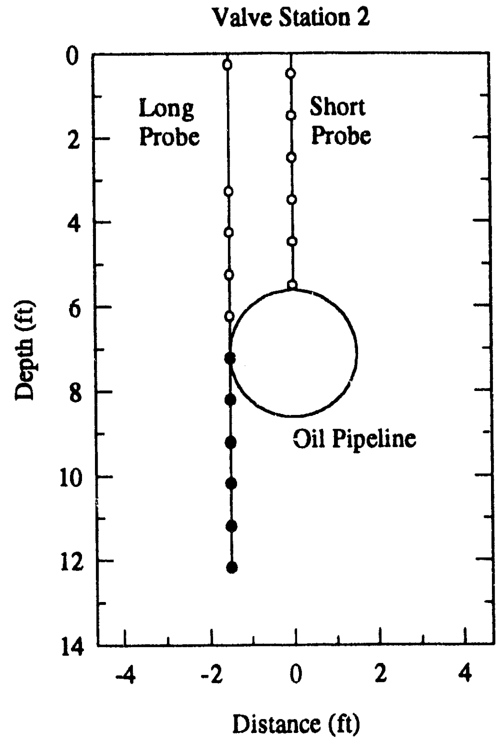


Figure 4 - Cross section through the soil probes at MLV2. This section is located about 10 ft downstream from the valve station. The symbols represent the temperature measurement positions. Filled symbols indicate measurement positions of data that were used in the thermal properties analysis.

Note that about 9 days before pumping began, the mean daily temperature observed by the thermistor located 3 inches below the surface was about 85°F but decreased to about 75°F 4 days before the test. This temperature drop is also observed at the thermistor located 3.25 feet below the surface but the amplitude of the drop is significantly reduced and delayed in time by a couple of days. This type of response to changes in surface temperature extends down to approximately the depth of the pipeline and is not observed below the pipeline. To avoid the effects of these surface temperature changes, only data collected below the pipeline were used to estimate the thermal properties of the soil. In Figure 4, the location of the data points used to estimate soil thermal properties are illustrated by filled circles.

When the oil pumping began at time 0 in Figure 5, temperatures recorded by the thermistors increased noticeably. To model the thermal properties of the soil, the desired temperature data is the amount by which the temperature of each thermistor increased in response to the presence of the warm oil in the pipeline. To determine this, a correction was applied to account for seasonal temperature effects. This correction was determined by fitting a straight line to the data acquired from each thermistor during the 16 day period prior to the initiation of pumping, extrapolating that line to times after the initiation of pumping and estimating what the temperature at each thermistor location would have been if pumping had not taken place. These predicted temperatures were subtracted from the observed temperatures to obtain an estimate of the warming effect of the presence of the oil.

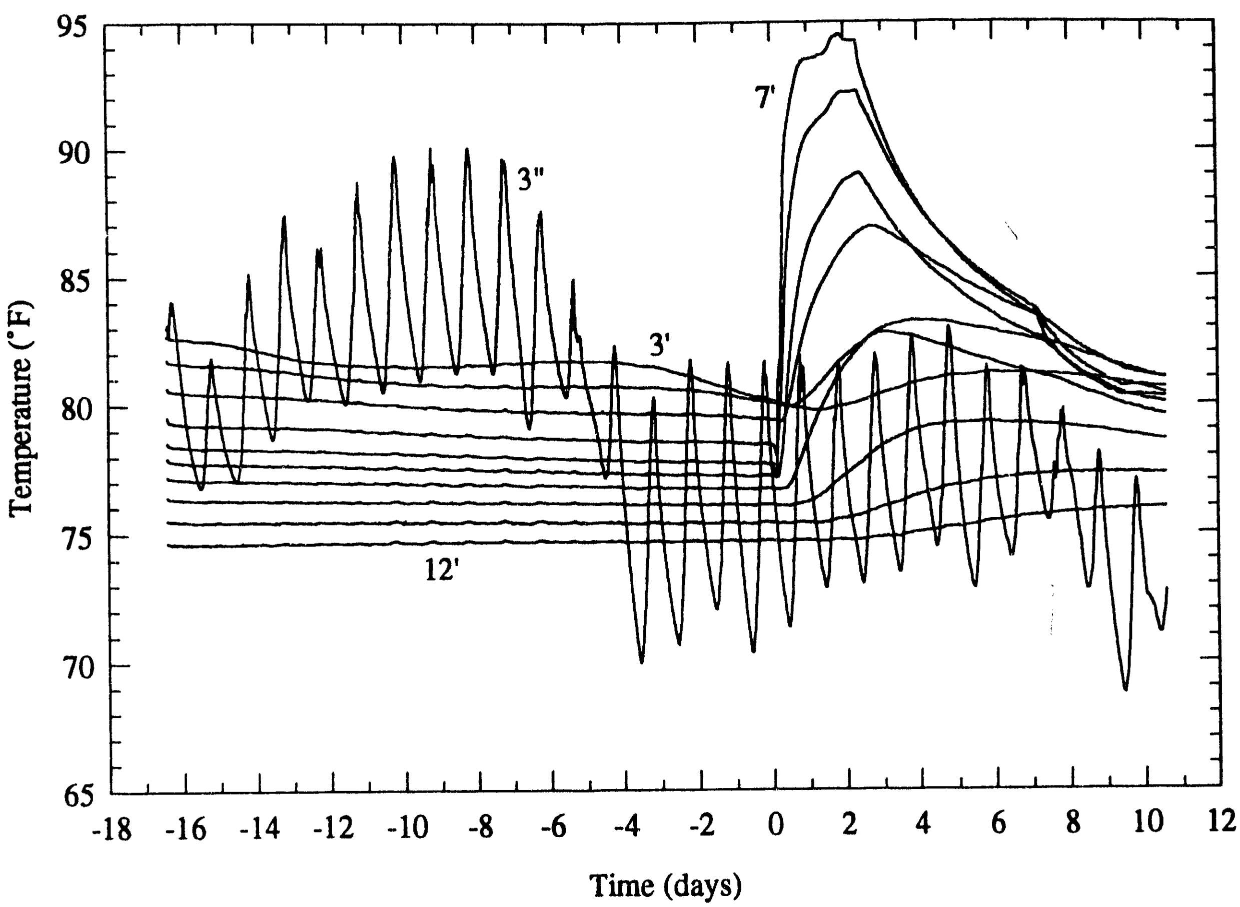


Figure 5 - Temperature as a function of time measured by the 11 thermistors in the long probe deployed at station MLV2. Time is measured relative to the time that oil pumping was initiated. Some of the curves are identified by the depth below the ground surface from which the data were obtained.

The corrected temperatures as a function of time for the 6 thermistors located below the pipeline at MLV2 are illustrated in Figure 6a. They indicate that the soil immediately adjacent to the pipeline warmed by approximately 17°F in response to the hot oil in the pipeline. When pumping ceased after 2.35 days, the soil immediately adjacent to the pipe started to cool, and had returned to within about 6°F of its normal temperature 4.5 days after pumping had ceased. The other thermistors, located at greater radial distances from the pipe, exhibited smaller temperature increases in response to the passage of the oil.

Figure 6b illustrates the temperature of the soil as a function of radial distance from the pipe for the time period during which the oil was being pumped. These data indicate that the soil temperature increase due to the warming effect of the oil drops off rapidly with distance from the pipe. The soil 3 feet from the pipe had experienced only a minimal amount of warming by the time the oil pumping ceased.

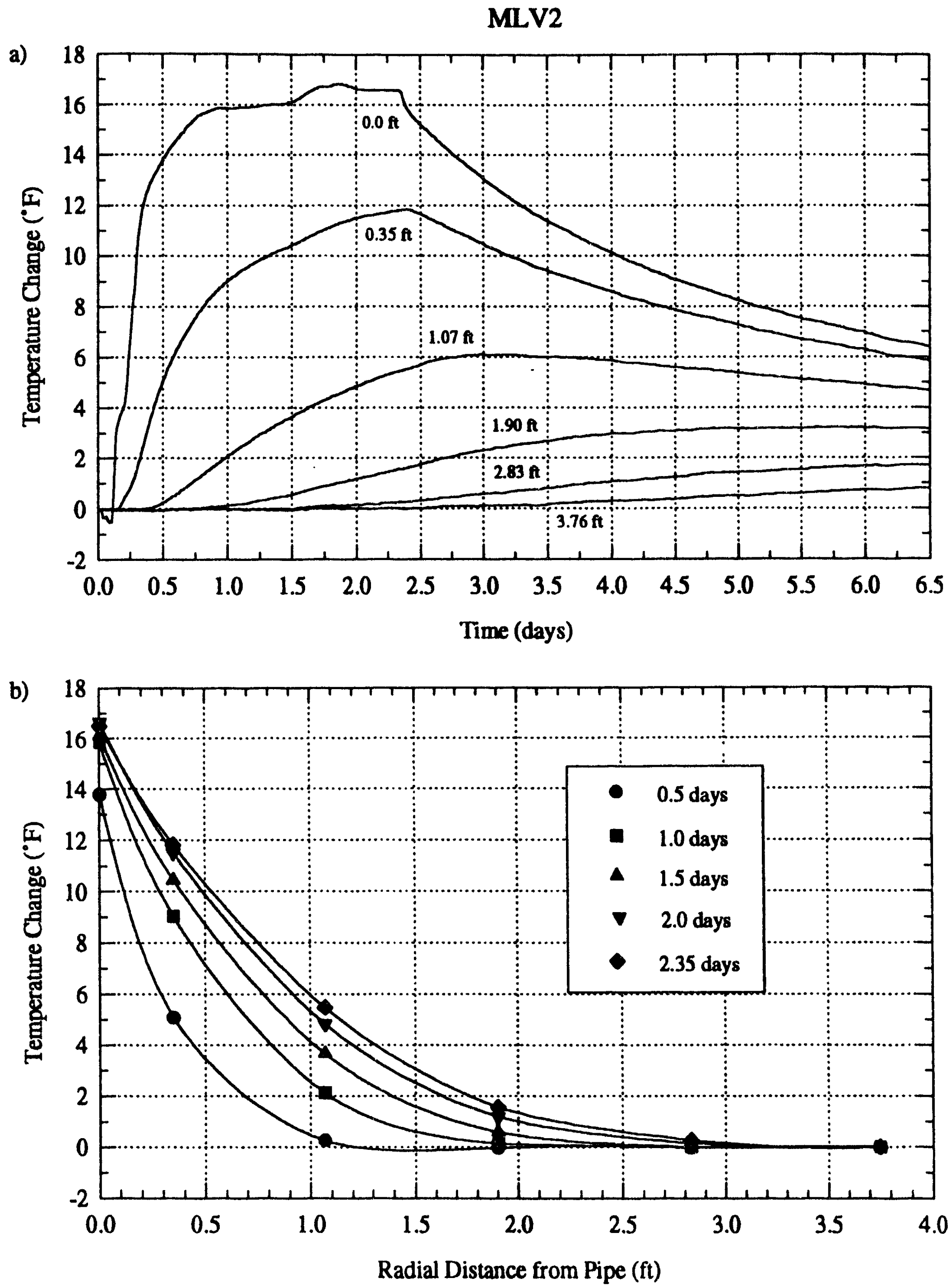


Figure 6 - Amount by which the measured temperatures at MLV2 increased in response to the presence of the warm oil a) as a function of time and b) radial distance from the pipeline wall. Temperature data are from the thermistors in the long probe below the pipeline. Temperatures have been corrected for seasonal temperature effects. In a) the curves are labeled with the radial distance from the pipeline wall to the measurement location. In b), the symbols are the data and the curves are cubic splines fit to the data.

Thermal Modelling for Soil Property Estimation

The OILPIP code requires that the thermal conductivity of the soil, K, and the product of the soil density and the soil specific heat, ρc, be known independently of each other. The approach adopted here is to use the soil temperature measurements to estimate the thermal diffusivity of the soil, κ, where $\kappa = K/\rho c$. Then K is estimated independently using the soil temperature measurements and estimates of the heat flux from the pipeline, q. The product of the soil density and specific heat, ρc, is then calculated from κ and K.

Thermal Diffusivity

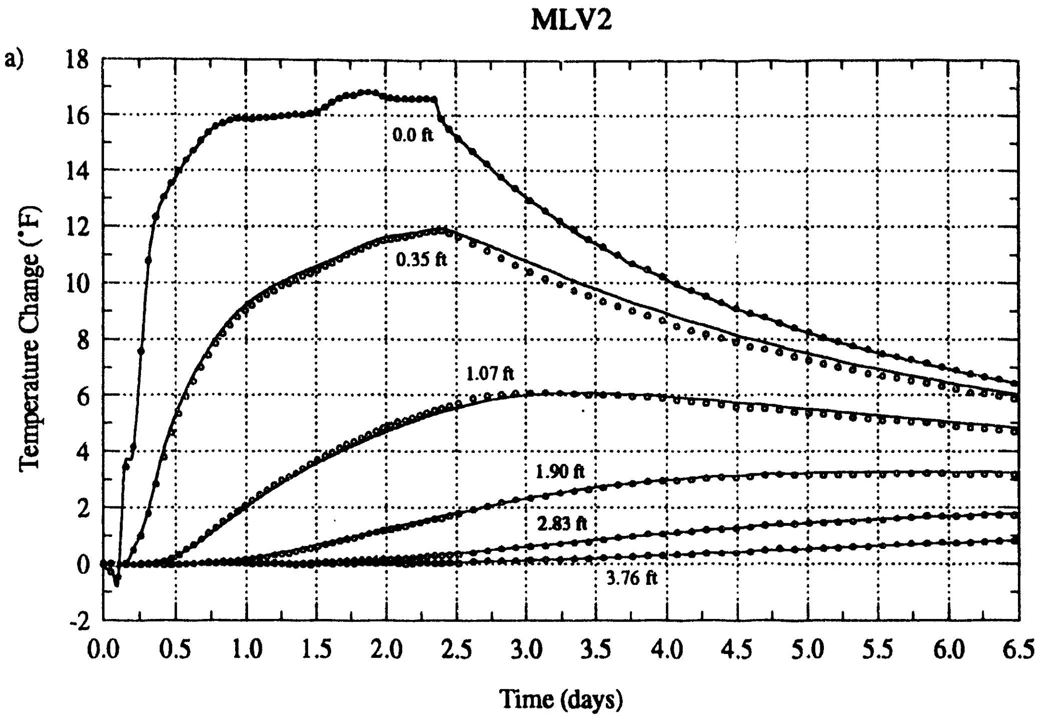
The warming effect on the soil surrounding the pipe can be described by the transient thermal diffusion equation in cylindrical coordinates

$$\frac{\partial T}{\partial t} = \kappa\left(\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r}\right) \tag{1}$$

where T is the amount by which the temperature of the soil around the pipe increased in response to the presence of the hot oil, t is time, κ is the thermal diffusivity of the soil surrounding the pipe and r is radial distance from the center line of the pipe. The initial condition is $T=0$ for all r. The boundary conditions are that $T_{r=\infty}=0$ for all time and $T=f(t)$ at $r=r_0$. The constant r_0 is the radial distance from the center line of the pipeline to the temperature observation point which is closest to the pipe wall and $f(t)$ describes the temperature as a function of time measured at r_0. While r_0 is equal to the radius of the pipeline at several of the measurement locations, it is up to an inch away from the pipeline wall at a few of the stations. This analysis assumes that all heat transport is directed radially away from the pipeline, there is no heat produced in the soil and that the pipeline is buried in an infinite, homogeneous, isotropic medium.

The approach is to seek a value of κ that results in the best fit between the measured temperature as a function of both time and radius, and the temperature calculated according to Equation 1. In Figure 7, the measured temperature as a function of time and radial distance from the pipe, measured at station MLV2, is compared with the theoretical temperatures calculated according to Equation 1 using a value of κ of 4.95×10^{-6} ft^2/s. That the fit is quite good suggests that the assumptions made in the analysis are reasonable. Similar plots for the eight measurement locations where thermal property estimation were possible are presented in Appendix B. The thermal diffusivity of the soil at each measurement location is tabulated in Table 4 and illustrated in Figure 8.

To illustrate the relationship between thermal diffusivity and soil temperature, soil temperature vs radial distance from the pipeline wall at two different soil thermal diffusivities is illustrated in Figure 9. The two data sets that are plotted represent the observed and modeled temperatures from measurement locations MLV3, the station where the highest thermal diffusivity was observed, and MVL6, the station with the lowest thermal diffusivity, right at the end of the time during which oil was being pumped. Because the amount by which the temperature of the soil increased at each location was different, the temperature data in Figure 9 have been normalized by the temperature measurement closest to the pipe in both cases. Note that the thermal effect of the warm oil extends out to considerably greater radial distances from the pipe at the station with the high thermal diffusivity compared to the station with the low diffusivity.



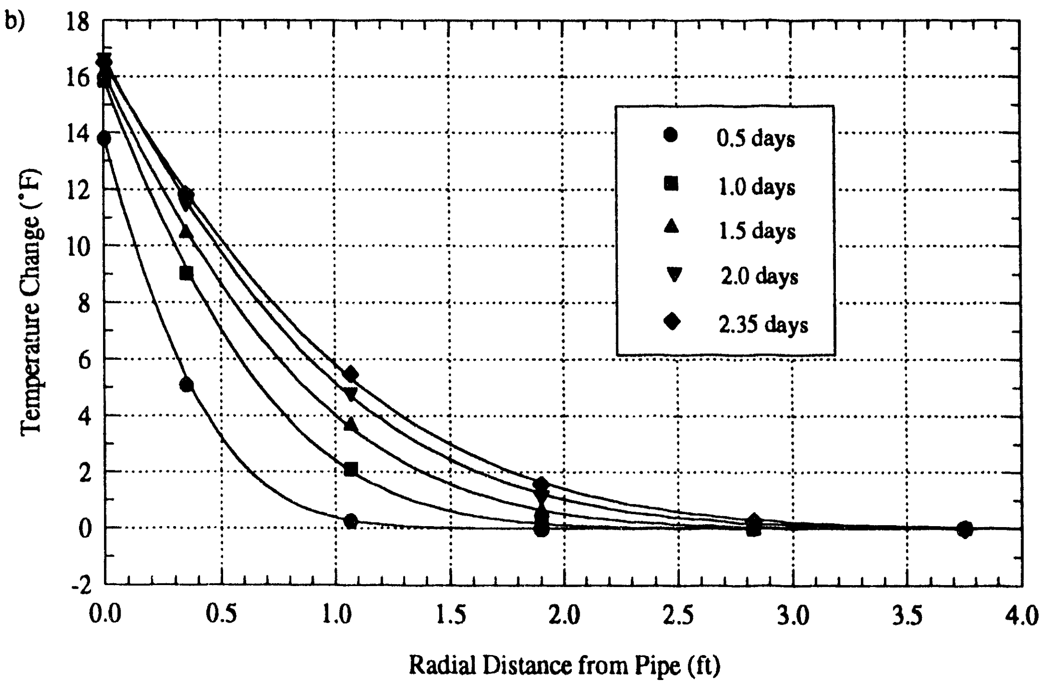


Figure 7 - Amount by which the measured temperatures at MLV2 increased in response to the presence of the warm oil a) as a function of time and b) radial distance from the pipeline wall. The symbols represent the data and the curves represent the predicted temperature calculated according to Equation 1. In a) only every fifth data point is plotted and the curves are labeled with the radial distance from the pipeline wall to the measurement location.

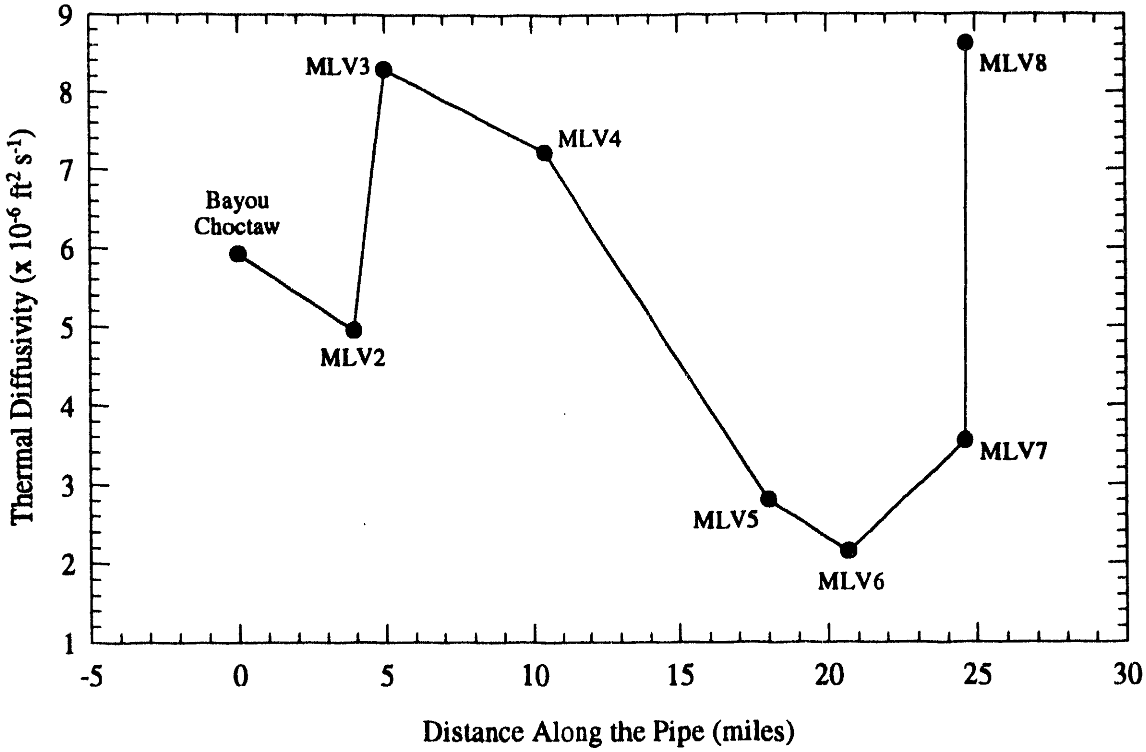


Figure 8 - Thermal diffusivity at each of the eight measurement locations.

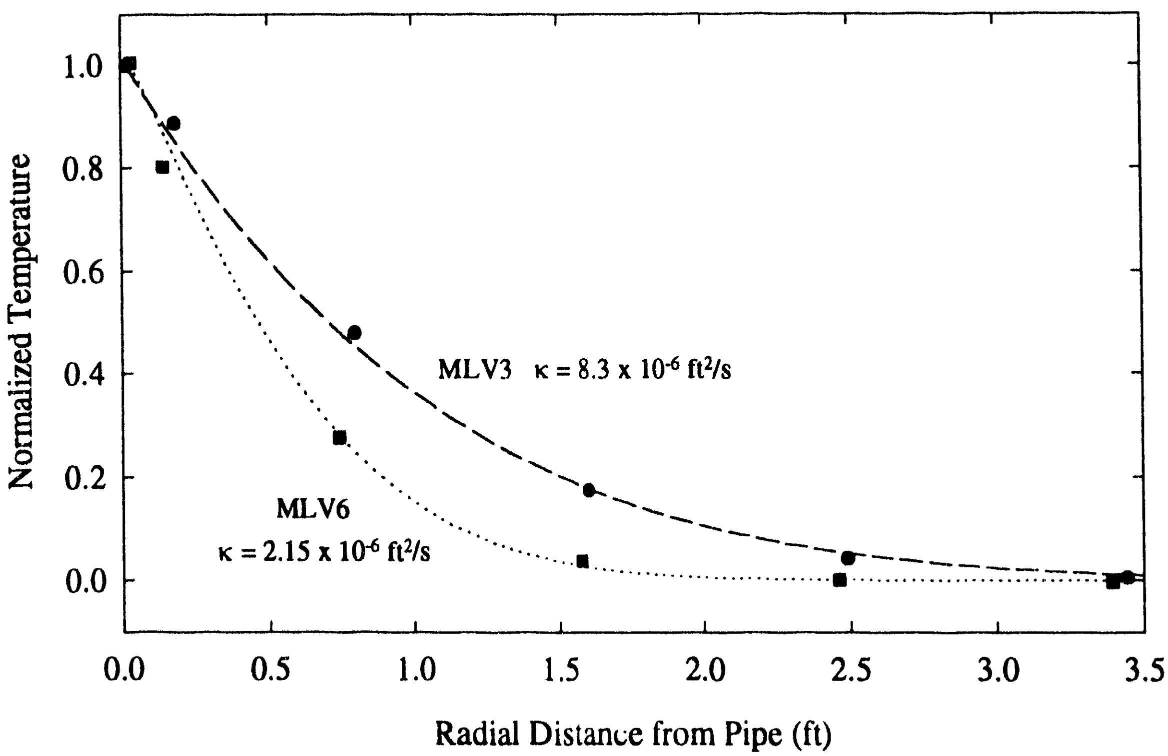


Figure 9 - Temperature as a function of radial distance from the pipeline at stations MLV3 and MLV6. Symbols represent the measured values and the curves the models. The temperature data have been normalized by the modeled pipeline wall temperature.

Soil Thermal Conductivity

The thermal conductivity of the soil, ***K***, can be determined at each measurement location from Fourier's Law of Heat Conduction

$$q = K \frac{dT}{dr} \qquad (2)$$

where q is the heat flux per unit area from the pipe and dT/dr is the radial temperature gradient in the soil surrounding the pipe, measured at the pipe wall. To determine K, estimates of q and dT/dr at the pipe wall are needed.

Heat Flux From the Pipe

Consider the heat flux out of the pipe as the oil flows along. Conservation of energy requires that the heat flux out of the oil equal the decrease in energy content of the oil. This is described mathematically by

$$\int_S \vec{q} \cdot \vec{n}\, dS = -\int_V \frac{\partial}{\partial t} \rho_o c_o T\, dV \qquad (3)$$

where

V is the volume of a packet of oil,
S is the outer surface of V,
$\vec{q}$ is a vector describing the heat flux per unit area on S,
$\vec{n}$ is the outwardly directed unit vector on S,
ρ_o is the density of the oil,
c_o is the specific heat of the oil,
T is the temperature in V, and
t is the time.

The term on the left represents the net heat flux out of the oil while the term on the right represents the net decrease in energy content of the oil. Consider a disk-shaped packet of oil, V, with radius r and thickness dx, obtained by taking two closely spaced cross sections of the pipe. Assume that the oil in V is well mixed (ie., its temperature is independent of radial position), all the heat flux is directed radially outward and is uniformly distributed around the circumference of the pipe, and that the material properties of the oil are homogeneous, isotropic and independent of temperature. Under these conditions Equation 3 can be written

$$q\, 2\pi r\, dx = -\rho_o c_o \frac{dT}{dt} \pi r^2\, dx \qquad (4)$$

or

$$q = -\rho_o c_o \frac{r}{2} \frac{dT}{dt} \tag{5}$$

where q is now the magnitude of the heat flux vector which is radially directed out of the pipe. Since $dt = dx/v$, where v is the velocity of the oil in the pipe, then

$$q = -\frac{1}{2} \rho_o c_o v r \frac{dT}{dx} \tag{6}$$

In order to calculate the flux from the pipe, values of dT/dx, the rate at which the oil cooled as it moved down the pipeline, must be determined. Figure 10a illustrates the temperature of the oil at each measurement location, as a function of time. The data from Bayou Choctaw were obtained from DynMcDermott while the data from the other locations were measured by probes inserted into the pipeline as previously described. Figure 10b illustrates the temperature of 5 packets of oil which left Bayou Choctaw at different times, as they moved down the pipe. For example, 5 hours after the test started, the temperature of the oil going into the pipeline at Bayou Choctaw was 94°F. By the time that packet of oil reached MLV2, it had cooled to about 91°F and by the time it reached St. James, it had cooled to 77°F. To calculate dT/dx in Equation 6, a 2nd order polynomial was fit to the temperature vs distance data and the derivative with respect to distance calculated at each valve station. Using a quadratic equation to model the temperature vs distance data is equivalent to assuming that the heat flux from the pipe decreases linearly with distance along the pipe. Then the flux from the pipe at each measurement location, as a function of time, was calculated according to Equation 6, using the thermal and geometric parameters in Table 3.

Note that the oil temperature data from valve station 3 were omitted from the analysis. This was done because the data were inconsistent with the data from the other stations. For example, Figure 10a indicates that 30 hours after pumping started and again at the end of the test, the temperature of the oil at MLV3 was actually cooler than it was at MLV4, implying that the oil warmed as it moved down the pipe. Also notice that the temperature data from MLV3 are quite

Table 3 - Oil thermal properties and pipeline geometric factors used in the calculation of heat flux from the pipeline.

Oil density	ρ_o	53.3 lb ft^{-3}
Oil specific heat	c_o	0.45 BTU lb^{-1} $°F^{-1}$
Pipe radius	r	1.5 ft
Oil velocity	v	4.39 ft s^{-1}

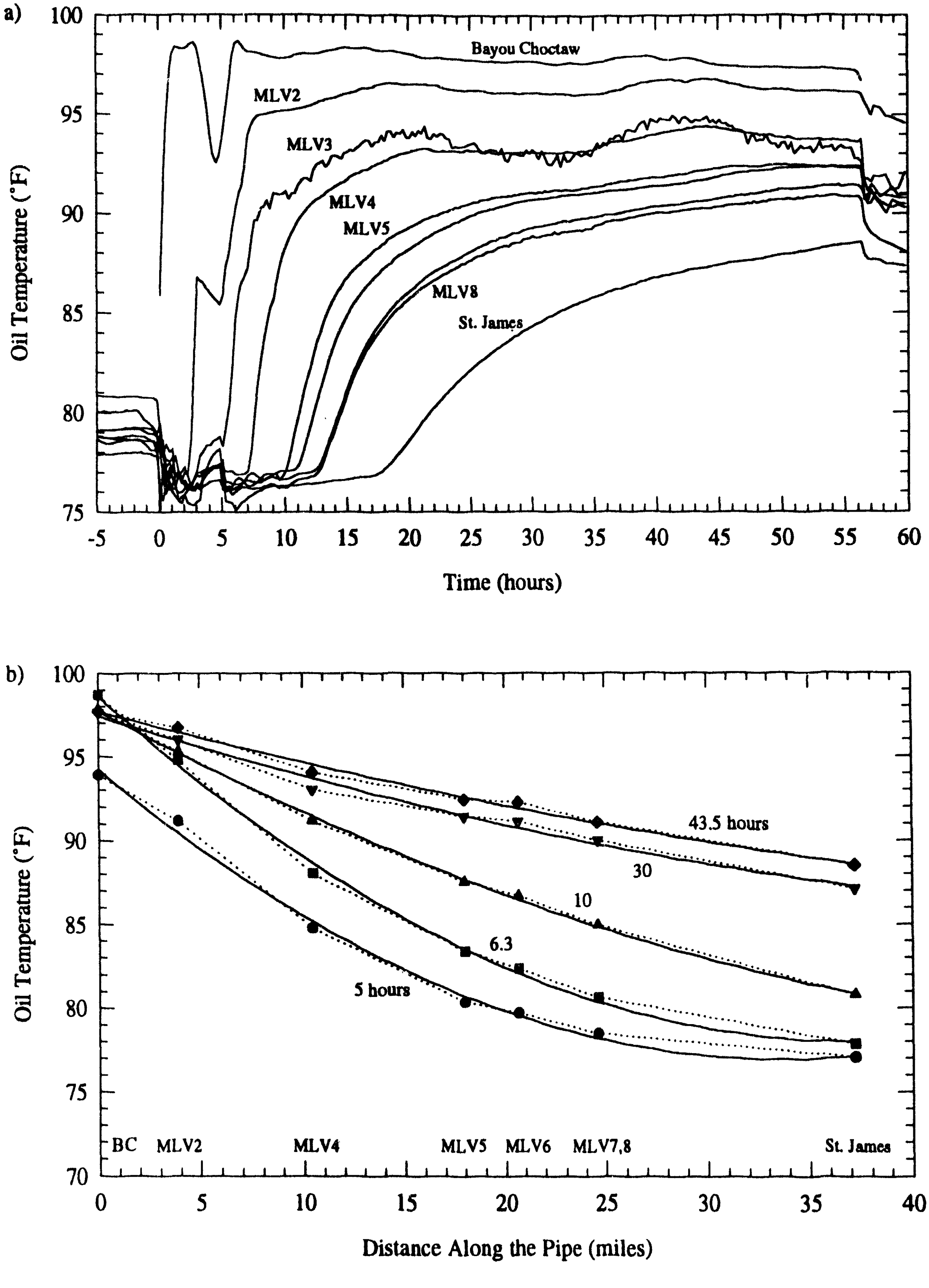


Figure 10 - a) Oil temperature as a function of time during the test. b) Temperature vs distance along the pipe for 5 individual packets of oil that left Bayou Choctaw, 5, 6.3, 10, 30 and 43.5 hours after pumping began.

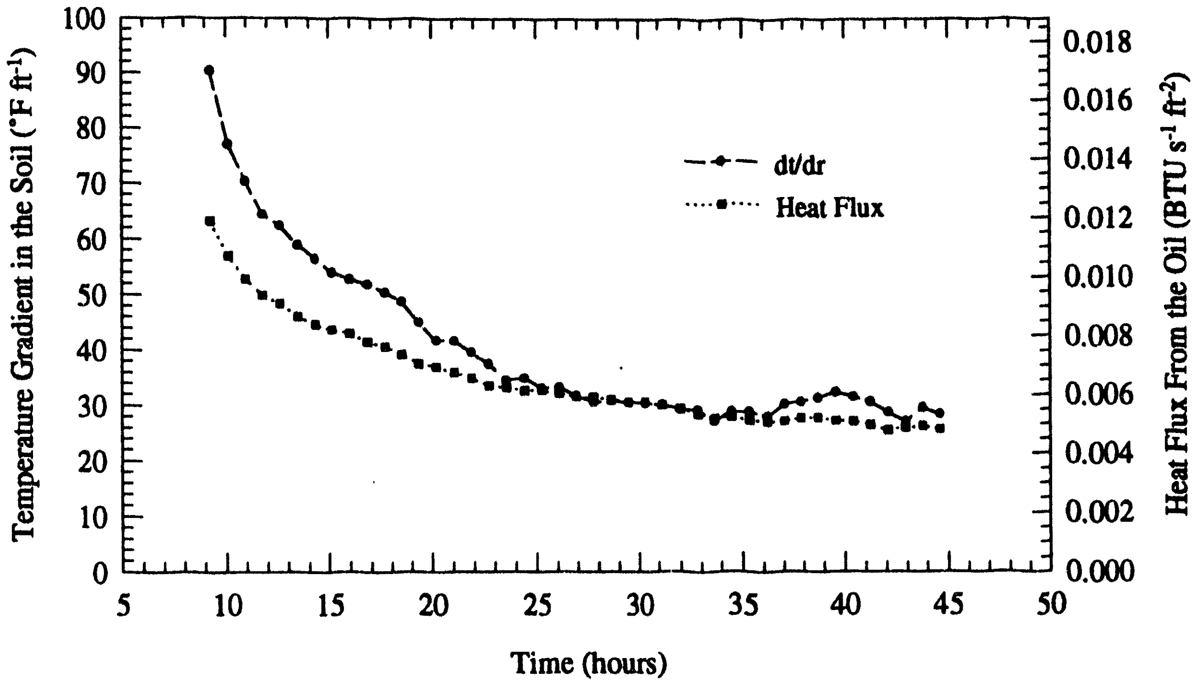
noisy compared to the data from the other valve stations. It is possible, but it has not been confirmed, that the thermistor was cracked during fabrication, shipping or installation of the probe. Also, the oil temperature data from Stations 7 and 8, which are only 0.15 miles apart, were averaged.

Radial Temperature Gradients in the Soil

The radial temperature gradient in the soil at the pipe wall at each valve station, as a function of time, was obtained from the numerical model used to determine the thermal diffusivity of the soil around the pipe. The modelling results were used rather than the actual measurements because the radial spacing of the observations is sufficiently large as to preclude accurate determination of the temperature gradient at the pipe wall. Since the modelled and measured temperatures agree so well (Figure 7b) it is reasonable to assume that the model accurately represents the actual gradients also.

Soil Thermal Properties

To obtain the best possible estimate of the thermal conductivity at each site, the thermal conductivity of the soil is calculated at a number of different points in time throughout the test and an average taken. At each valve station the heat flux from the pipe as a function of time is divided by the temperature gradient in the surrounding soil, also as a function of time, to determine the thermal conductivity of the soil, ***K***. Figure 11a illustrates the heat flux from the pipe and the radial temperature gradient in the soil around the pipe at station MLV2, as a function of time. Figure 11b shows the calculated thermal conductivity of the soil at MLV2, also as a function of time. Since the thermal conductivity of the soil is not expected to vary as a function of time, the two curves in Figure 11a should overlap each other perfectly and a horizontal line is expected in Figure 11b. This is not entirely the case; particularly during the early part of the test. This is likely due to the fact that the calculated radial temperature gradient responded to changes in the input oil temperature more quickly than did the calculated flux from the pipe. This is because the flux from the pipe is smoothed somewhat since it is calculated by fitting a quadratic curve to oil temperatures all along the pipe while the temperature gradient comes from data from each individual station, one station at a time. This implies that the analysis technique is valid only after some sort of quasi-equilibrium state is obtained, and only so long as the input oil temperature remains fairly constant. As can be seen in Figure 10a, the oil temperature data from Bayou Choctaw collected after about 10 hours into the test, show two gentle "humps", the first from approximately 12 to 25 hours and the second from approximately 35 to 45 hours. These small input oil temperature increases (about 1°F) reflect the increased atmospheric temperature associated with daylight hours. The intervening interval, from 25 to 35 hours, is characterized by the most stable input oil temperature. This time interval corresponds to the nighttime hours when the oil in surface pipes at Bayou Choctaw was not being warmed by the sun. These temperature increases due to warming by the sun are evident in the temperature gradient data from MLV2 illustrated in Figure 11a but are not evident in the heat flux data shown in the same figure. For the data from Bayou Choctaw and MLV2 the time interval from approximately 25 to 35 hours into the test was considered the most stable for estimating the thermal conductivity of the soil and the data from that time interval were averaged to obtain the best estimate for the thermal conductivity. For stations from MLV3 to St. James, the temperature gradient data do not show any influence due to the second temperature rise, from 35 to 45 hours, so the thermal conductivity from approximately 25 hours until the end of the test were averaged to obtain the best estimates of the thermal conductivity at those sites. Plots



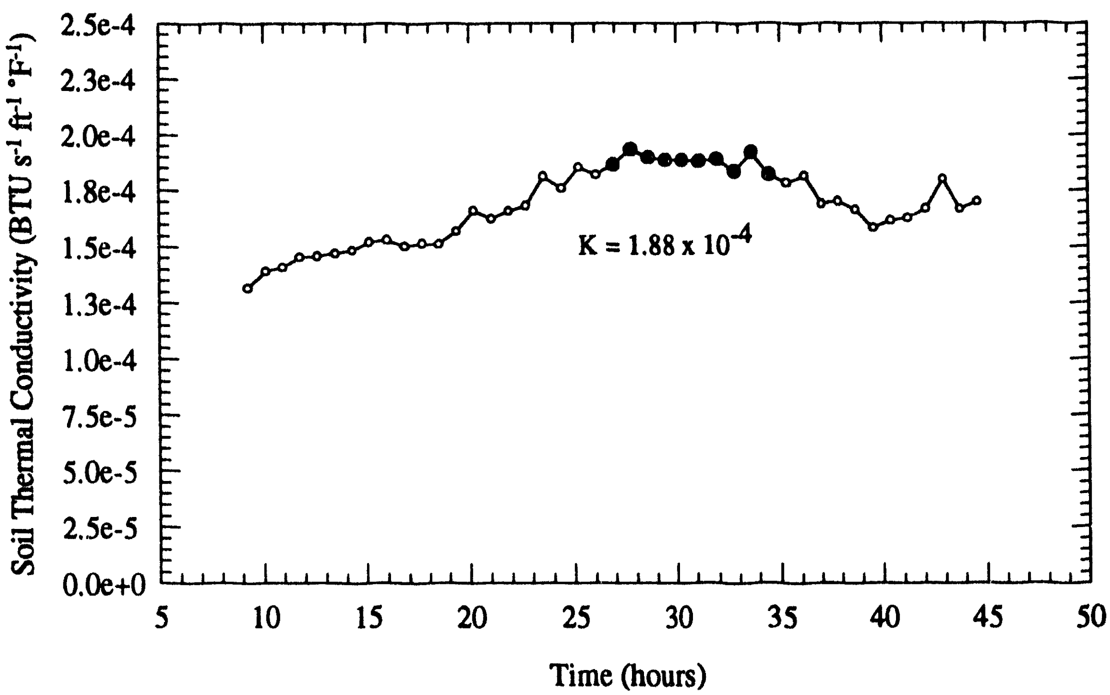


Figure 11 - Thermal conductivity analysis for data from MLV2. a) Temperature gradient in the soil at the pipe wall and heat flux from the pipe, as a function of time. b) Thermal conductivity of the soil. In b), filled circles represent data points that were averaged to obtain the best estimate of the thermal conductivity of the site.

similar to those in Figure 11 are presented in Appendix B for each of the eight measurement locations where thermal properties were estimated.

Given K and the diffusivity κ, the product ρc for the soil can be determined from the relation $\kappa=K/\rho c$. In the analysis of oil temperatures using OILPIP, the individual values of ρ and c are unimportant, only their product appears in all the relevant equations. A value of ρ of 125 lb ft^{-3} is assumed and the value of c calculated. The results of the analysis for all the stations are given in Table 4. The thermal conductivity of the soil at each measurement location is illustrated in Figure 12.

Table 4 - Soil thermal properties determined from soil temperature analysis

Station	Diffusivity (ft^2 s^{-1})	Thermal Conductivity (BTU s^{-1} ft^{-1} °F^{-1})	Specific Heat (BTU lb^{-1} °F^{-1})
MLV1	5.92×10^{-6}	2.13×10^{-4}	0.288
MLV2	4.95×10^{-6}	1.88×10^{-4}	0.304
MLV3	8.29×10^{-6}	3.34×10^{-4}	0.322
MLV4	7.21×10^{-6}	2.61×10^{-4}	0.290
MLV5	2.80×10^{-6}	1.17×10^{-4}	0.334
MLV6	2.15×10^{-6}	1.06×10^{-4}	0.394
MLV7	3.55×10^{-6}	1.50×10^{-4}	0.338
MLV8	8.61×10^{-6}	2.61×10^{-4}	0.243
Mean	5.44×10^{-6}	2.04×10^{-4}	0.314

Relationships of Soil Properties to Soil Types

The soils along the oil pipeline were studied by reviewing soil surveys for St. James, Assumption, Ascension, and Iberville Parishes (USDA and LAES, 1973, 1978, 1976, 1977). It was hoped that a correlation could be made between the soil thermal properties and soil types. An inherent problem with this study is that the soil data in the surveys has been judged by experts as accurate and representative for depths of 0-36", a reasonable extrapolation for depths to 60" and guess work for greater depths. The temperature data collected as part of this report spans depths from the surface down to about 12 feet. The temperature data is least affected by daily temperature fluctuations for depths greater than about 50", depths for which extrapolations of soil type are suspect.

The pipeline was traversed on soil survey maps. Essentially all of the soil along the pipeline is poorly drained loamy and clayey soil deposited from historic floods of the Mississippi River. During instrument installation and removal it was observed that the soil was soft and wet

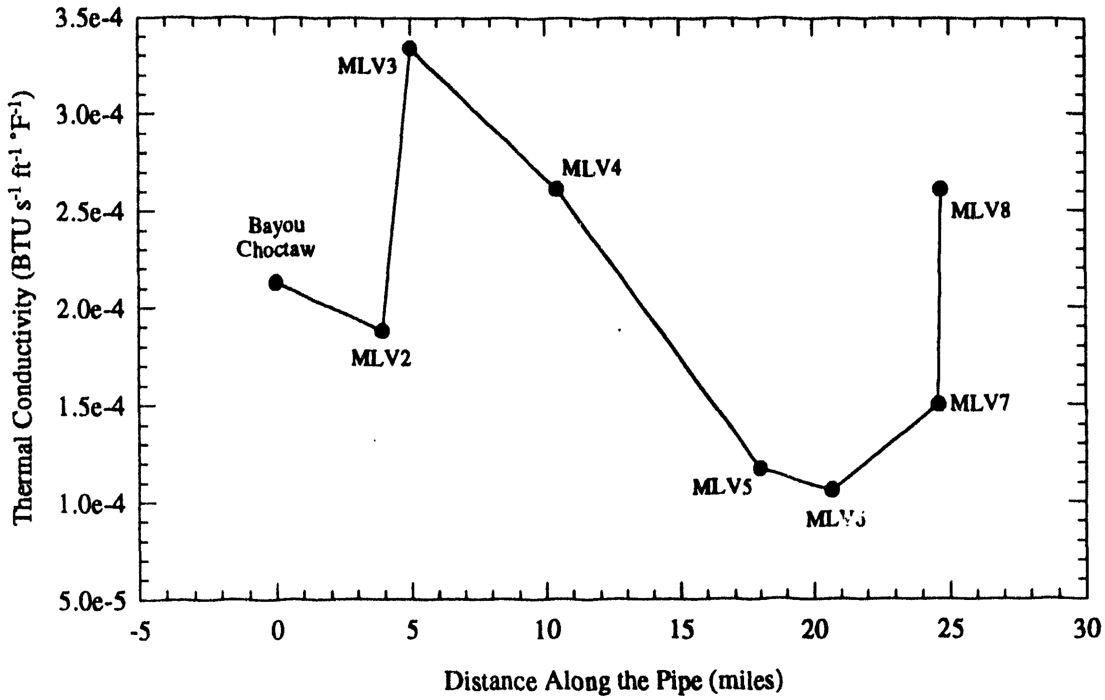


Figure 12 - Soil thermal conductivity as a function of distance along the pipeline.

(saturated) for depths greater than 1-2 feet. No apparent correlation between soil thermal properties and soil types could be made because of the apparent overall homogeneity of the soil along the pipeline.

Test Re-Analysis

The test was reanalyzed using OILPIP with estimates of soil thermal properties as determined from above, and measured oil flow rate and temperature measurements. The oil and soil properties used in the analysis are listed in Table 5.

The oil density listed is an average value for sour crude oil stored at Bayou Choctaw, the oil specific heat and density are the same values used elsewhere in this report. The flow rate used in the analysis was derived from the actual flow rate (Figure 13). In the figure the actual and modeled flow rates are given. The model linearly interpolates between two input flow rate values for times when the flow rate is not specified.

The initial soil temperature is an average value for the soil at the start of the test. The model assumes that the oil transport pipe is buried in a soil of initially uniform temperature. The temperature measurements with depth all indicate that a temperature gradient exists in the soil profile. Shallow depths show influence of daily temperature fluctuations. Neither this gradient nor the daily temperature fluctuations are considered in the analysis method.

Oil inlet temperatures at Bayou Choctaw used in the analyses, as compared to the measured oil temperatures are shown in Figure 14. In the simulations, for each time when the flow rate

Table 5 - Comparison of "old" and "new" thermal properties

Property	"Old"	"New"	Units
Oil density	51.0	53.3	lb./ft^3
Oil specific heat	0.45	0.45	BTU/lb. °F
Oil thermal conductivity	2.11 x 10^{-5}	2.11 x 10^{-5}	BTU/ft. s °F
Soil density	125.0	125.0	lb./ft^3
Soil specific heat	0.5	0.314	BTU/lb. °F
Soil thermal conductivity	4.0 x 10^{-4}	2.04 x 10^{-4}	BTU/ft s °F

was changed, a representative value for the inlet temperature (from the measured values) was selected for the analysis and used until another change in flow rate was made.

In Figure 15 the calculated oil temperature is compared with the measured oil temperature at St. James for the "as run" simulation. (Measured oil temperatures compared to calculated oil temperatures at each valve station are plotted in Appendix C.) The measured values at this location are an integrated response for the entire pipeline. For a time of "0" the measured 80+°F

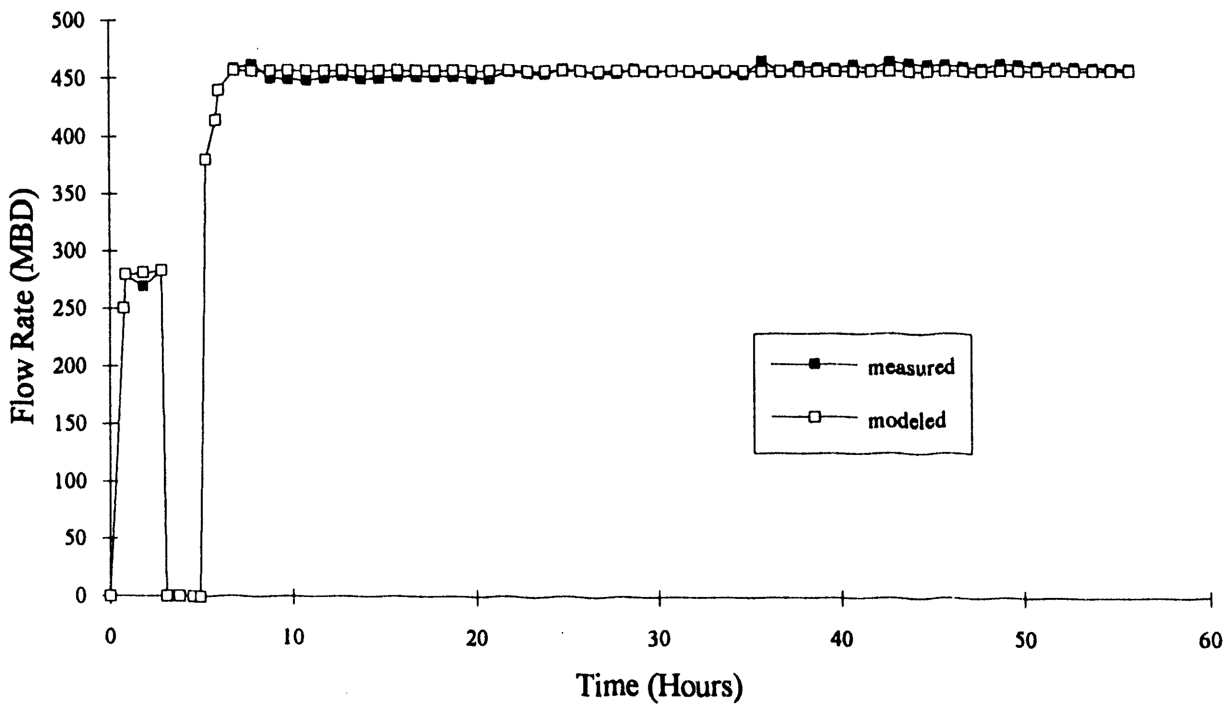


Figure 13 - Measured and modeled oil flow rates for the "as run" test and analysis.

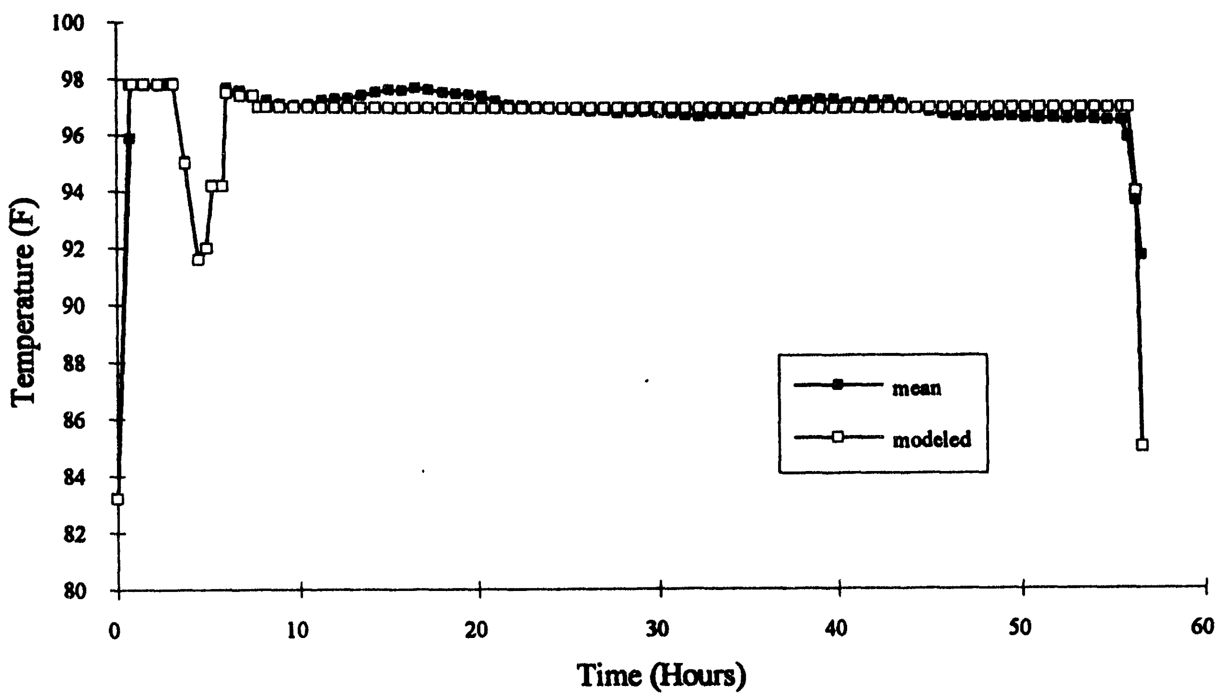


Figure 14 - Measured (mean value) and modeled temperatures for the "as run" test and analysis.

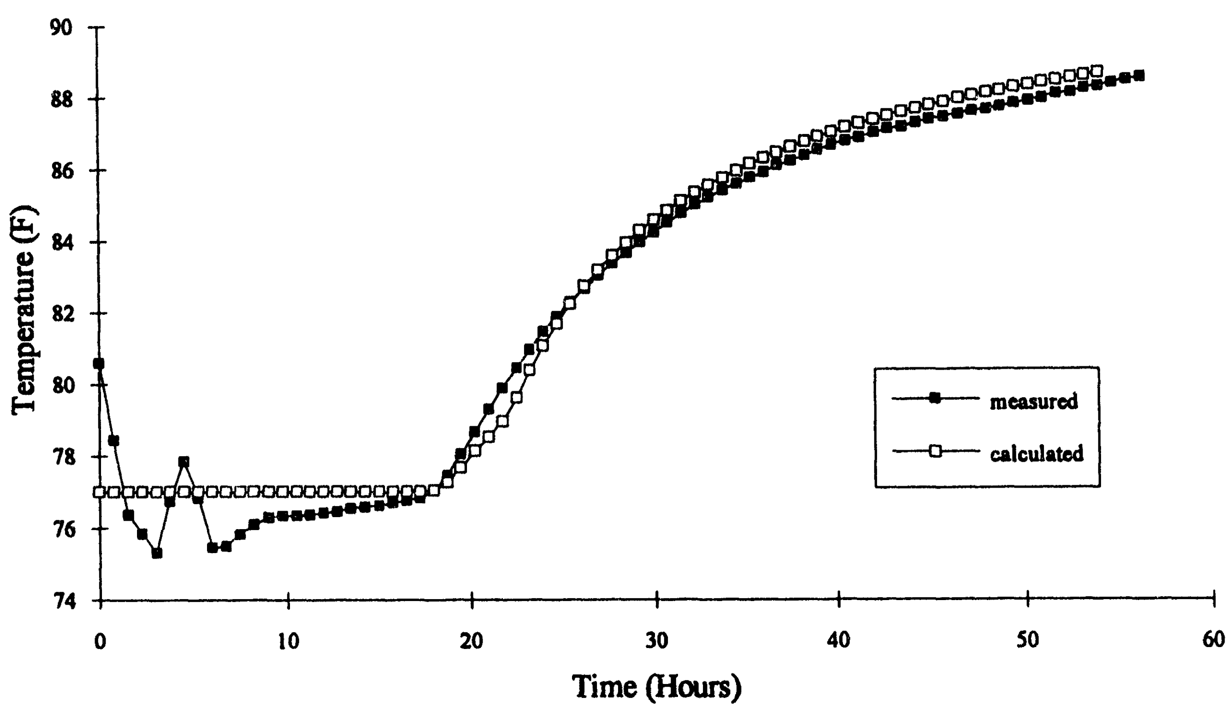


Figure 15 - Comparison of measured and calculated delivered oil temperatures at St. James using the mean value of the estimated soil thermal properties.

temperature of the oil is the oil temperature at the top of the pipe diameter for stagnant conditions. As the oil is pumped, it circulates within the pipe. The oil temperature is not uniform along the pipeline, as evidenced by the near 3°F variation in oil temperature as it arrives at St. James. Recall that the test includes a near two hour shut down in pumping at about a time of 7 hours. At about 18 hours into the test the hot oil is observed to first arrive at St. James. The oil temperature continues to increase but at a decreasing rate. For the test duration, about 50 hours of pumping, the delivered oil temperature does not attain a constant value with time, nor does the cooling rate of the oil attain steady state.

The calculated temperatures are nearly constant, near 77°F, for the first 18 hours of the analysis, reflective of the input of 77°F uniform soil temperature surrounding the pipeline. For times greater than about 25 hours (7-8 hours after the initial hot oil passes St. James), the calculated response exceeds the measured values. For times greater than about 30 hours it appears that the slopes of the measured and calculated responses are nearly equal.

Drawdown Re-Analysis

In order to give a current assessment of oil transport cooling efficiency for the Bayou Choctaw line, heat transfer calculations using "new" material properties (the same ones used to compare with measured test values) were completed. For the two analyses the inlet oil temperature was assumed to be 110°F, and the pumping rate was set at 480 MBD. A comparison of material properties used in the two sets of analyses is given in Table 5. "Old Material Properties" are those properties obtained from handbooks and used in Bauer and Hinkebein (1993). The soil thermal properties listed show there to be a near 40% decrease in specific heat and a near 50% decrease in thermal conductivity for values used now and previously.

The results of this analysis and the results using "old" material properties are shown in Figure 16. The major difference of importance between the two calculated responses is that there is predicted to be about 5°F less cooling using the "new" material properties for extended times.

Discussion and Conclusions

A 1 million barrel oil transfer was made from Bayou Choctaw to St. James Terminal in early October for the purposes of code validation/calibration, and soil material property estimation.

A set of soil thermal properties was determined through temperature measurements of the oil and soil during the transfer. The property estimates were the average of eight point measurements along the pipeline.

Using material properties estimated from the test and using the heat transfer code to calculate oil and soil temperatures, measured oil temperatures for longer times (greater than about 30 hours of pumping) are well represented by the calculations. Thus confidence has been established in the analysis method and in the ability to apply the method to a physical situation.

The soil material properties determined herein for the Bayou Choctaw line do not necessarily apply to other pipelines. The soil thermal properties for other SPR pipelines should be studied separately.

The results of this test have provided a data set of estimated soil thermal properties for the Bayou Choctaw to St. James oil line. The estimated properties differ from earlier estimates that were used in SAND93-0005 (Bauer and Hinkebein, 1993). It was determined, through analysis (Figure 1), that by varying the initial soil temperature 10°F, the calculated delivered oil

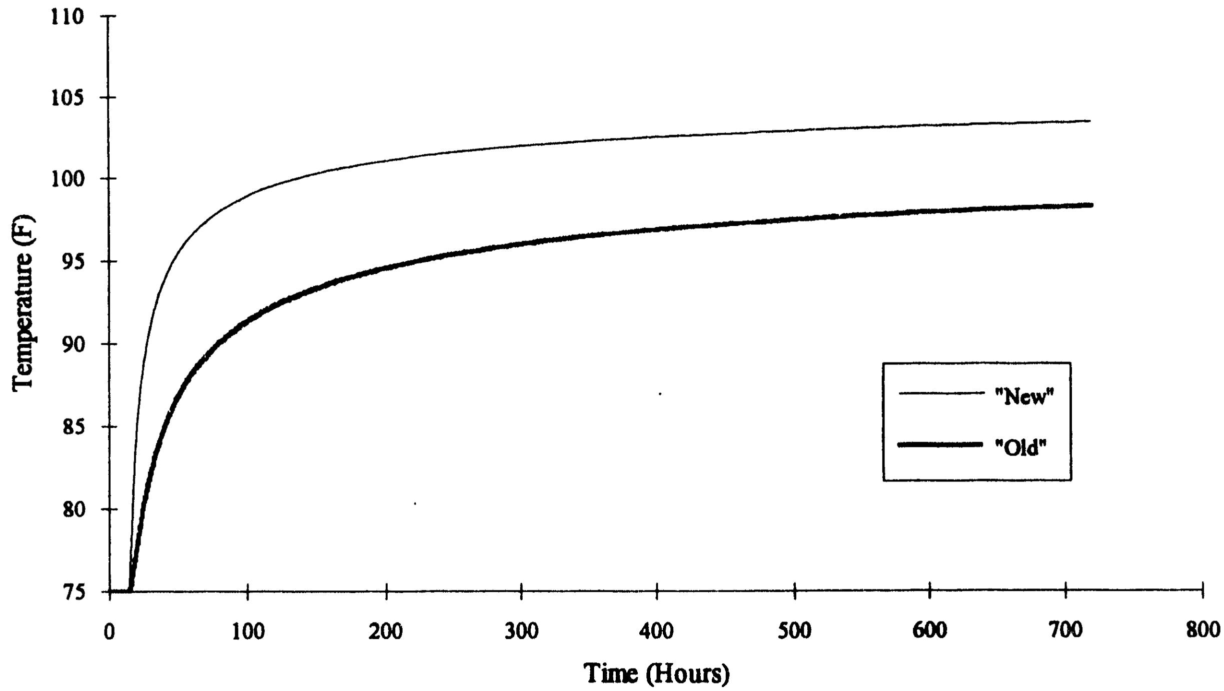


Figure 16 - Predicted temperatures of delivered oil at St. James resulting from a drawdown from Bayou Choctaw at a rate of 480 MBD.

temperature at a given time changed by only 5°F. This prediction is important in using the code predictions as part of the strategy to cool oil for a drawdown. A drawdown could be ordered at any time of the year, and seasonal soil temperature variations may be as much as 10°F. It should also be noted, however, that the greater the oil temperature (the oil temperature at a site will continue to increase due to geothermal heating), the less important the seasonal temperature variations.

The calculated response for a drawdown from Bayou Choctaw to St. James using the newly estimated soil thermal properties differs from that in Bauer and Hinkebein (1993). Less cooling (5°F) is predicted for a drawdown using "new" soil thermal properties. In light of this, the pipeline cooling analyses completed for Bauer and Hinkebein (1993) will be revisited.

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APPENDIX A

Oil and Soil Temperature Probe Construction

List of Figures

List of Tables

Oil and Soil Temperature Probe Considerations

In this appendix, an overview of the materials and methods used for the construction of the temperature probes which measured the oil and soil temperatures along the pipeline between Bayou Choctaw Strategic Petroleum Reserve storage facility and St. James Terminal are presented.

Oil temperature probes were constructed in a fashion similar to an existing version of oil temperature probe provided by J. Baudean of DynMcDermott (Watson 1989). This design takes advantage of the existing pipeline riser pipes, flanges, and valves at each valve station for installation.

A tool commonly used to locate the exact position of pipe buried near the surface was chosen to make pilot holes that the soil probes were later emplaced in. The tool consists of several lengths of approximately 5/8" diameter rod which can be threaded together or to a "T" handle. The bottom length of rod has a spiked tip to penetrate the soil. The "T" handle is used to drive the tool into the soil. Since much of the soil is saturated and free from any large rocks, this tool can easily be forced into and back out of the ground to the desired ~15' depths by a single person. When used, this tool is forced into the ground in the vicinity of the pipeline. Contact with the pipeline is readily apparent as the movement of the tool stops abruptly. The apex of the pipeline is found by repeated attempts until the position at which the most shallow contact with the pipeline is found. Placement of the long temperature probes, alongside the pipeline, is determined relative to the apex point. The pilot hole that remains after removing the tool will accommodate a tube up to ~1/2" diameter. Therefore, 1/2" tubing was chosen to house the thermistors of the temperature probes, in particular 1/2" stainless steel tubing with a wall thickness of .049" was used.

The precision thermistors used for both the soil and the oil temperature probes were Fenwal Electronics Inc. P/N 135-105QAG-J01. These thermistors are nominally 1 megohm at room temperature. Prior to use, the thermistors were calibrated in a temperature controlled water bath at 7 temperatures over the range of 15 - 50 °C (59 - 122 °F). The calibration procedure uses a temperature standard with an absolute accuracy of ±0.02°F. The data collection systems are also capable of resolving temperatures to within ±0.02°F.

The cable chosen for the thermistor connections was Alpha Wire Corp. #3496C. It was chosen for two reasons, (1) it had the largest number of 28 AWG conductors in a cable bundle which would still fit inside the 1/2" x .049" W.T. tube, and (2) availability. The #3496C cable is a six twisted pair shielded cable. By design, all thermistors on a particular soil temperature probe share a common return conductor, so this cable would allow up to 11 thermistors to be installed in each probe.

At each of the seven valve stations two soil temperature probes and one oil temperature probe were deployed. The short soil temperature probe is approximately 6.5 ft in length (Figure 1), and measures soil temperatures directly above the pipeline down to the pipeline itself. The long soil probe is approximately 13.5 ft in length (Figure 2), and measures soil temperatures along the side of the pipeline both above and below the pipeline centerline depth. The actual pipeline depth varied from valve station to valve station, (the top of pipeline was ~5' - 6' at the seven valve stations, somewhat deeper at both terminals) so when installed, the probes were inserted relative to the pipeline depth rather than ground level. Considering the available number of conductors and the depth of the pipeline, a spacing between thermistors of approximately one foot was chosen. So with one foot spacing, it was possible for the short probes to contain six thermistors,

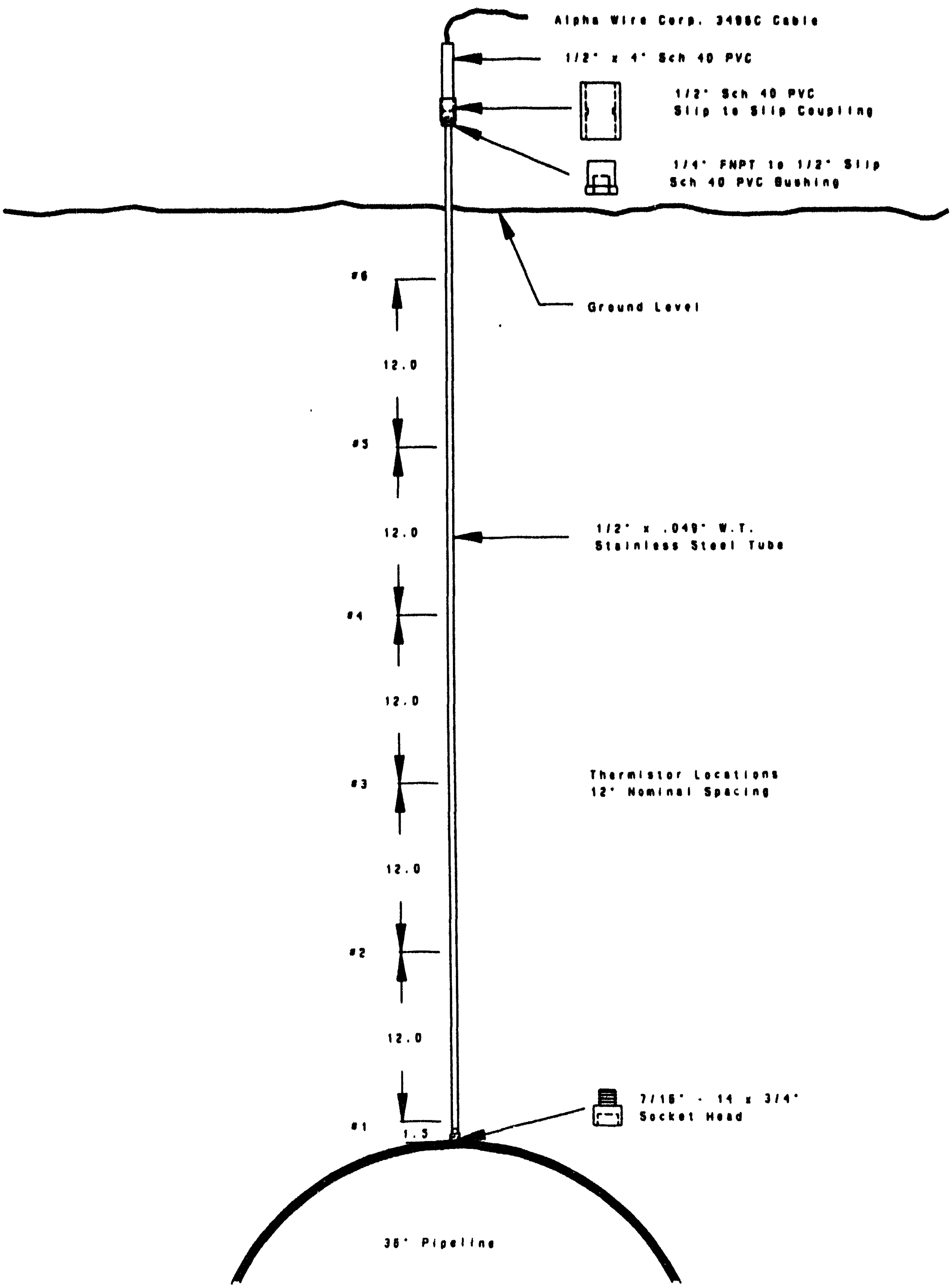

Figure A-1 - Short Soil Temperature Probe.

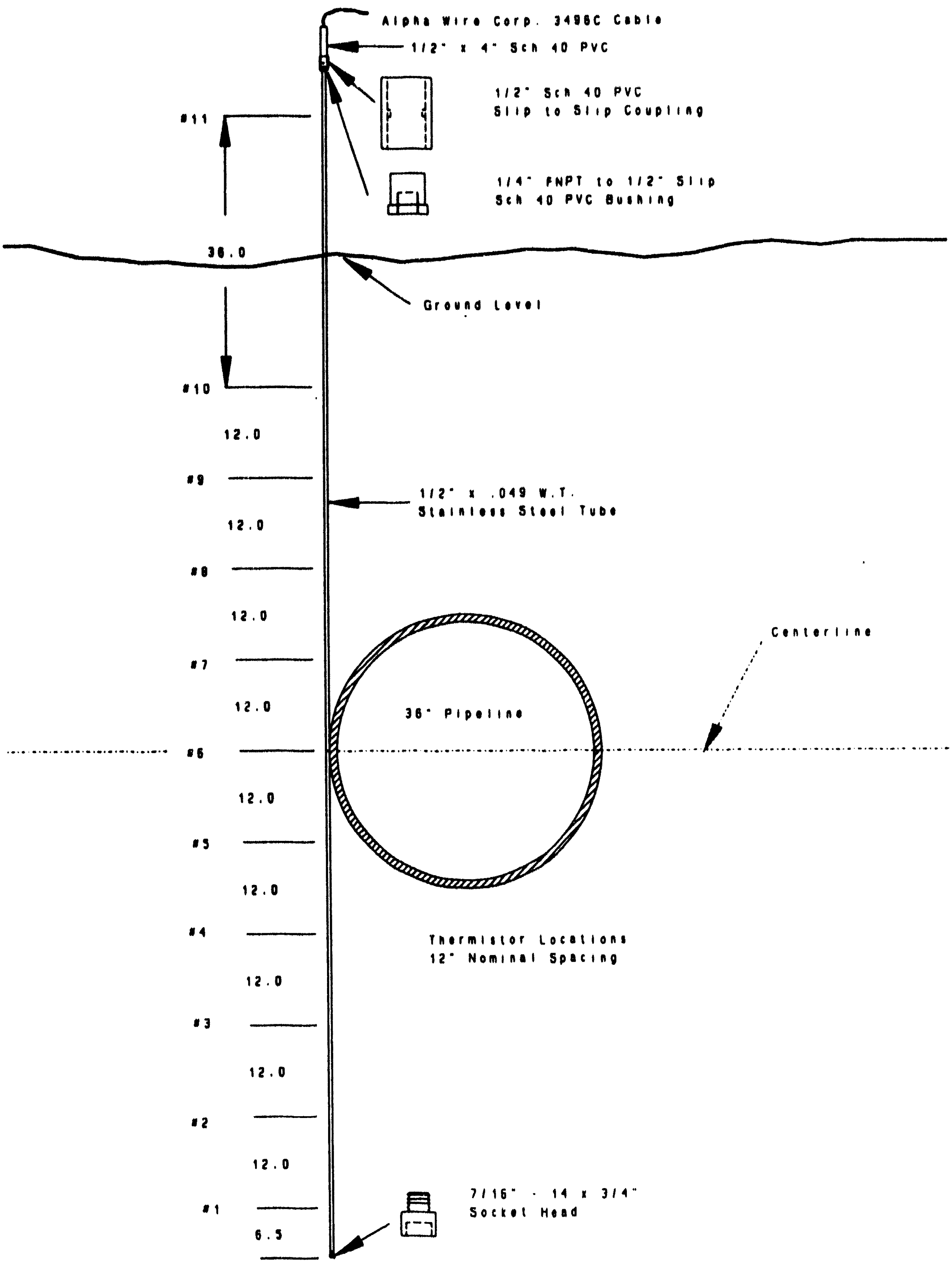

Figure A-2 - Long Soil Temperature Probe.

while the long probes contained 11. This spacing also conveniently allowed at least one thermistor to monitor air temperature at many of the valve stations.

Because of the variation in depth of the pipeline, particularly at the St. James Terminal, three different lengths of probes were made to measure the oil temperature (Figure 3). Oil temperature probes consisted of a single thermistor located at the bottom of the probe. These probes were installed into the pipeline through the existing riser pipes at each valve station such that the tip of the temperature probe was positioned at the junction between the riser pipe and the main pipeline. The probes were not inserted into the pipeline itself for fear that they would be sheared off by the flowing oil during the test. This was accomplished by first measuring the length of the riser pipe from the top of the pipeline to the top of the flange at each valve station (Table 10). The length of the oil temperature probe extending below the riser flange was adjusted to the length of the riser pipe, and fixed into place with the 1/2"FNPT-1/2" tube Swagelok adapter at the top of the bell reducer.

Soil Temperature Probe Construction

Soil temperature probes were constructed by first attaching the thermistors to the cable using solder and shrink tubing. Once all the thermistors were attached to the cable, the cable was stretched along the outside of the length of stainless steel tubing used for the housing and held in place with tape. The outside of the tubing was marked to identify each thermistor location. This procedure accounts for variations in the actual spacing from the desired one foot spacing of the thermistors. Next, while the cable was still taped to the outside of the stainless steel tubing, ~12" of buss wire was wrapped around the conductors of the bottom thermistor and stretched tightly passed the end of the tubing. The location of the end of the tubing was marked on the buss wire. The tape was removed from the cable and thermistors and the cable was then fed inside the tubing until the point marked on the buss wire was again aligned with the bottom end of the 1/2" stainless steel tubing. The buss wire was then folded back over the outside of the tubing and clamped into place.

The thermistors were then potted inside the 1/2" stainless steel tubing with 3M Electrical Insulating Resin. This was done to displace the air, (and the moisture in the air) and to increase and even out the thermal conductivity of the probe. To avoid pockets of trapped air, the resin was injected from the bottom of the probe while the probe was oriented roughly vertical. The injection was accomplished by pressurizing a volume of the resin placed in a vessel constructed from PVC pipe and fittings, which was in turn was attached to the 1/2" stainless steel tubing by a short length of flexible hose. The injection process required a pressure of ~20 psi obtained from "house" compressed air.

Although the resin used above is a waterproof material, the bond between the stainless steel tubing and the resin, particularly where the tubing has not been cleaned properly, is not a reliable method to seal the probes from the saturated soils and humidity present along the pipeline. So the stainless steel tubing was threaded with 1/4" NPT threads at the top of each temperature probe. A 1/4" FNPT x 1/2" Slip PVC bushing was screwed onto those threads wrapped with Teflon tape. A 4" length of 1/2" schedule 40 PVC was attached to the bushing using a schedule 40 PVC slip-to-slip coupling, PVC primer, and PVC cement. The inside of the 4" length of 1/2" PVC pipe was thoroughly cleaned using PVC primer then allowed to dry. Finally, a 4" waterproof seal was made by filling the entire length of the 1/2" PVC pipe with resin. To seal the bottom end of the probes, the already cured resin on the inside of the tubing was drilled out to

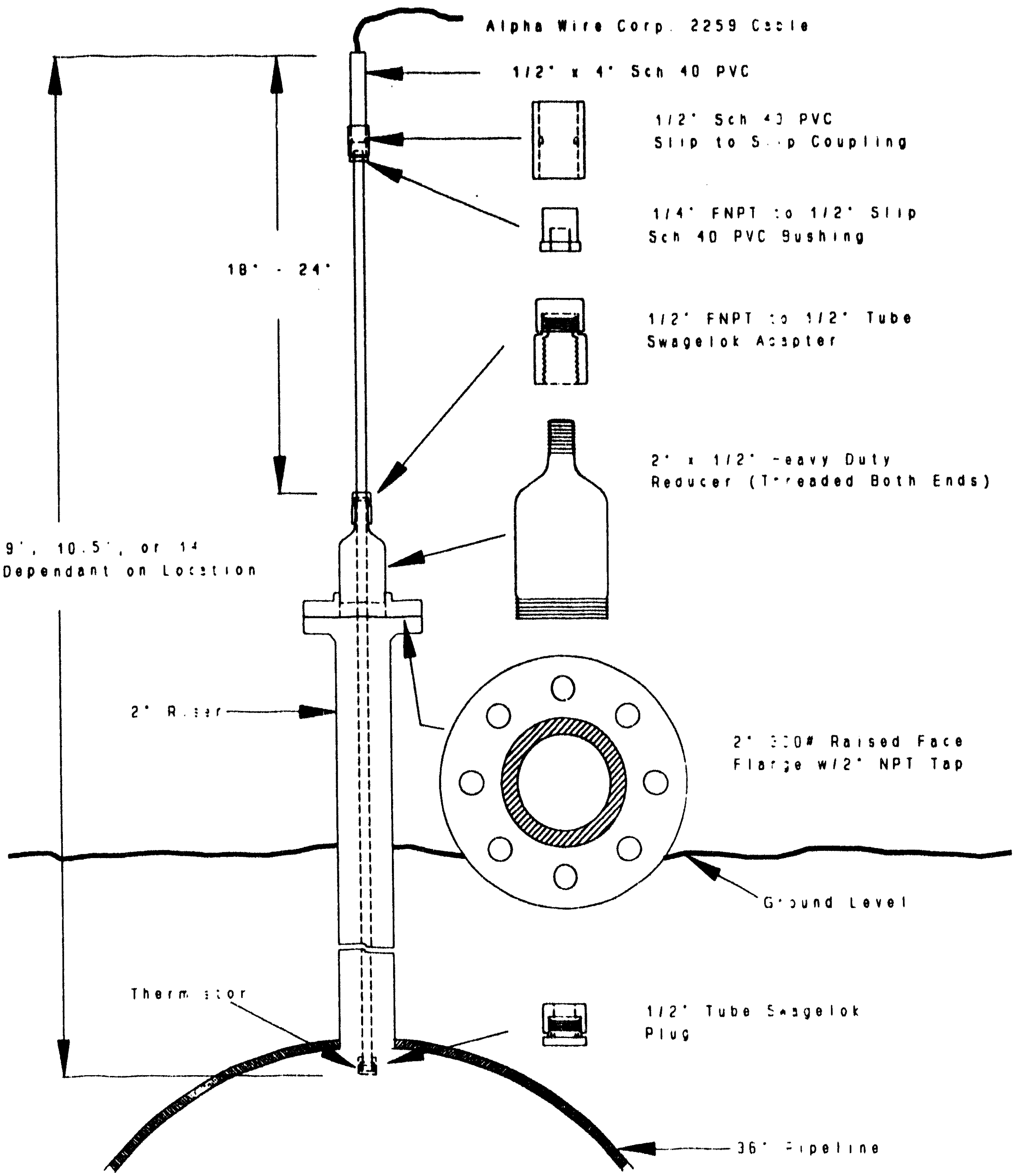

Figure A-3 - Oil Temperature Probe.

a depth of ~1". Next, 7/16"-14 machine threads were tapped into the inside of the tubing. A 7/16"-14 x 3/4" socket head bolt was then glued into the end of the stainless steel tubing using Hardman Wet Surface Epoxy.

Since the pipeline depth was deeper at both terminals than at the seven valve stations, only one soil probe was used at each terminal. These probes were installed directly above the pipeline and resembled the short probes in every respect except the total length and total number of thermistors.

Oil Temperature Probe Construction

Oil temperature probes were constructed in a fashion similar to the soil temperature probes. The single thermistor was attached to Alpha Wire Corp. #2259 two conductor shielded cable using solder and shrink tubing. Buss wire was wrapped around the conductors of the cable just above the thermistor. The cable was then fed inside the stainless steel tubing and positioned using the buss wire so that the thermistor was within ~1/8" from the bottom end of the tubing. Insulating resin was injected into the probe as described above. However, before the resin had fully cured, the resin injection hose and buss wire end were removed from the end of the stainless steel tubing and a 1/2" Swagelok plug was installed. This was done when the resin was still pliable to prevent damage to the thermistor from the crushing action of the Swagelok plug. At the top of each oil temperature probe, the stainless steel tubing was threaded with 1/4" NPT threads. A 1/4" FNPT x 1/2" slip bushing, 1/2" slip to slip coupling, and 4" length of 1/2" schedule 40 PVC were cleaned and glued together with PVC primer and cement. The PVC parts were not attached to the probe however, until actually installed in the field. This allowed the probes to be shipped in a more compact fashion without the flanges and bell reducers installed. Once the oil temperature probes were installed by the site pipeline crew, the PVC portion of the assembly was attached and potted with insulating resin.

Tables 1 through 9 provide the actual locations (in feet) of each thermistor on the soil probe(s) as installed at the seven valve stations and two end terminals. Negative values in ground surface locations indicate that the thermistor is above the ground level. Negative values for locations relative to center line of pipe indicate that the thermistor is below the centerline of the pipe.

Table 1 Bayou Choctaw

Depth Below Ground Surface	Height Above Top of Pipe
-1.41	9.07
-0.43	8.09
0.57	7.09
1.57	6.09
2.57	5.09
3.54	4.13
4.53	3.14
5.54	2.13
6.53	1.14
7.54	0.13

Table 2 Valve Station MLV2

Long Probe

Depth Below Ground Surface	Height Above Center Line of Pipe	Radial Distance from Pipe Wall
0.27	6.85	5.52
3.27	3.85	2.64
4.25	2.88	1.74
5.25	1.88	0.90
6.23	0.90	0.25
7.23	-0.10	0.00
8.21	-1.08	0.35
9.21	-2.08	1.07
10.18	-3.05	1.90
11.19	-4.06	2.83
12.17	-5.04	3.76

Short Probe

Depth Below Ground Surface	Height Above Top of Pipe
0.48	5.15
1.48	4.15
2.48	3.15
3.48	2.15
4.48	1.15
5.50	0.13

Table 3 Valve Station MLV3

Long Probe

Depth Below Ground Surface	Height Above Center Line of Pipe	Radial Distance from Pipe Wall
0.65	6.16	4.84
3.63	3.18	2.01
4.63	2.18	1.14
5.58	1.22	0.43
6.56	0.24	0.02
7.56	-0.76	0.18
8.54	-1.74	0.80
9.52	-2.72	1.61
10.50	-3.70	2.49
11.51	-4.71	3.44
12.48	-5.68	4.37

Short Probe

Depth Below Ground Surface	Height Above Top of Pipe
0.19	5.11
1.20	4.10
2.20	3.10
3.18	2.13
4.18	1.13
5.18	0.13

Table 4 Valve Station MLV4

Long Probe

Depth Below Ground Surface	Height Above Center Line of Pipe	Radial Distance from Pipe Wall
-0.17	7.48	6.13
2.81	4.50	3.24
3.79	3.52	2.33
4.77	2.54	1.45
5.77	1.54	0.65
6.76	0.55	0.10
7.75	-0.44	0.06
8.75	-1.44	0.58
9.73	-2.42	1.34
10.77	-3.46	2.27
11.77	-4.46	3.20

Short Probe

Depth Below Ground Surface	Height Above Top of Pipe
0.73	5.08
1.73	4.08
2.73	3.08
3.72	2.09
4.70	1.11
5.69	0.13

Table 5 Valve Station MLV5

Long Probe

Depth Below Ground Surface	Height Above Center Line of Pipe	Radial Distance from Pipe Wall
-0.69	6.54	5.21
2.31	3.54	2.35
3.29	2.56	1.47
4.27	1.58	0.68
5.26	0.59	0.11
6.24	-0.39	0.05
7.24	-1.39	0.54
8.25	-2.40	1.33
9.25	-3.40	2.21
10.23	-4.38	3.13
11.25	-5.40	4.10

Short Probe

Depth Below Ground Surface	Height Above Top of Pipe
-0.75	5.10
0.24	4.11
1.23	3.13
2.23	2.13
3.24	1.11
4.23	0.13

Table 6 Valve Station MLV6

Long Probe

Depth Below Ground Surface	Height Above Center Line of Pipe	Radial Distance from Pipe Wall
0.01	5.28	3.99
2.98	2.31	1.26
3.97	1.32	0.50
4.98	0.31	0.03
5.96	-0.67	0.14
6.96	-1.67	0.74
7.98	-2.69	1.58
8.96	-3.67	2.46
9.95	-4.66	3.39
10.93	-5.64	4.33
11.92	-6.63	5.29

Short Probe

Depth Below Ground Surface	Height Above Top of Pipe
-1.34	5.14
-0.35	4.15
0.65	3.15
1.65	2.15
2.65	1.15
3.67	0.13

Table 7 Valve Station MLV7

Long Probe

Depth Below Ground Surface	Height Above Center Line of Pipe	Radial Distance from Pipe Wall
-0.19	5.44	4.14
2.77	2.48	1.40
3.76	1.49	0.61
4.75	0.50	0.08
5.72	-0.47	0.07
6.72	-1.47	0.60
7.73	-2.48	1.40
8.72	-3.47	2.28
9.73	-4.48	3.22
10.73	-5.48	4.18
11.71	-6.46	5.13

Short Probe

Depth Below Ground Surface	Height Above Top of Pipe
-1.38	5.13
-0.38	4.13
0.63	3.13
1.60	2.15
2.63	1.13
3.65	0.10

Table 8 Valve Station MLV8

Long Probe

Depth Below Ground Surface	Height Above Center Line of Pipe	Radial Distance from Pipe Wall
-2.25	7.98	6.62
0.79	4.94	3.66
1.79	3.94	2.71
2.79	2.94	1.80
3.77	1.96	0.97
4.75	0.98	0.29
5.75	-0.02	0.00
6.73	-1.00	0.30
7.74	-2.01	1.01
8.73	-3.00	1.85
9.69	-3.96	2.73

Short Probe

Depth Below Ground Surface	Height Above Top of Pipe
-0.79	5.02
0.19	4.04
1.17	3.06
2.17	2.06
3.13	1.10
4.13	0.10

Table 9 St. James Terminal

Depth Below Ground Surface	Height Above Top of Pipe
-5.18	11.08
-3.20	9.10
-2.22	8.13
-1.21	7.11
-0.22	6.13
0.76	5.15
1.76	4.15
2.78	3.13
3.77	2.14
4.78	1.13
5.78	0.13

Table 10 Length of Riser Pipe at each Valve Station

Valve Station #	Length (in feet)
MLV2	8.00
MLV3	7.75
MLV4	8.33
MLV5	6.92
MLV6	6.25
MLV7	6.50
MLV8	6.50

References

Watson, N., 1989, "Pipeline Leak Investigation, 36" Bayou Choctaw Crude Oil Pipeline", Strategic Petroleum Reserve Publication D506-02202-04.

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APPENDIX B

Soil Temperatures and Modelling Results at Each Measurement Location

List of Figures

Soil Temperatures and Modelling Results at Each Measurement Location

In this appendix, plots illustrating the temperatures observed at each measurement location and describing the results of the thermal modelling for soil properties estimation are presented. Six plots are included for most of the nine measurement locations. The first two illustrate the temperature as a function of time for the long and short probes deployed in the soil. Only temperature measurements obtained below the ground surface are included. Since only one probe was deployed at Bayou Choctaw and St. James, there is only one plot for each of those sites.

The next two plots illustrate the corrected ground temperature as a function of time and as a function of radial distance from the pipe wall. The temperature data have been corrected for seasonal effects by having temporal trends in the data that existed before the initiation of pumping subtracted from the data. Application of these corrections means that the corrected temperatures reflect the amount by which the temperature of the soil around the pipe was increased due to the presence of the warm oil in the pipe. Only data from the long probe below the centerline of the oil pipeline are included. These are the data that were used to estimate the soil thermal properties. Also included on these two plots are the theoretical temperature distributions calculated using the thermal diffusivity which resulted in the best fit between the observed and theoretical temperatures. At Bayou Choctaw, temperature data obtained above the pipe were used in the analysis since there was no data from below the pipe. At St. James, the soil temperature data was of insufficient quality to be used for soil thermal property analysis due to interference from surface temperature effects (see Figure B-25). These data were obtained from relatively shallow depths (less than 6 feet depth) at a location where there appeared to be a considerable amount of piping in the ground.

The fifth plot at each measurement location illustrates both the heat flux from the pipe and the radial temperature gradient in the soil measured at the pipe wall, as a function of time. Note that the two vertical axes, temperature gradient and heat flux, were chosen such that the ratio of the axes is equal to the calculated thermal conductivity. In an ideal world, the two curves would plot directly on top of each other. The last of the six plots at each measurement location illustrates the thermal conductivity of the soil as a function of time obtained by taking the ratio of the temperature gradient and heat flux curves in the fifth plot. Since the thermal conductivity of the soil is not expected to be time dependent, this plot would be a horizontal line in a perfect world. The points illustrated with filled circles were averaged to obtain the best estimate of the soil thermal conductivity at the site.

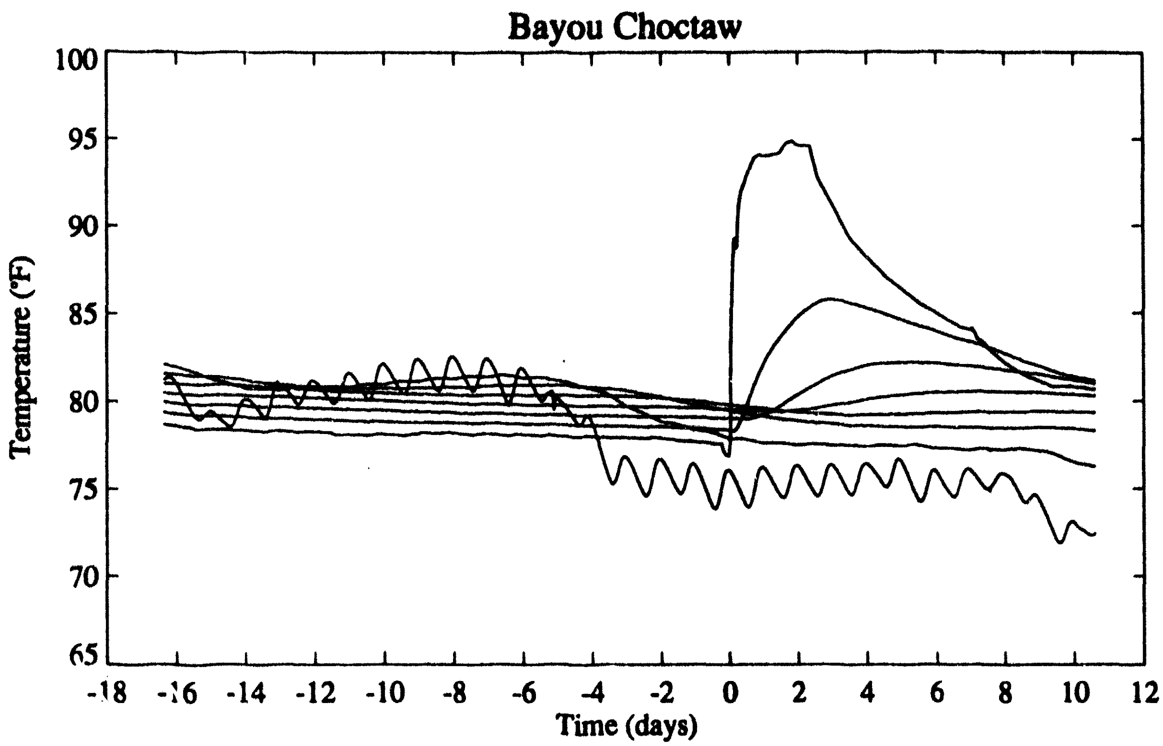


Figure B-1 - Temperature as a function of time recorded by the subsurface thermistors in the probe at Bayou Choctaw.

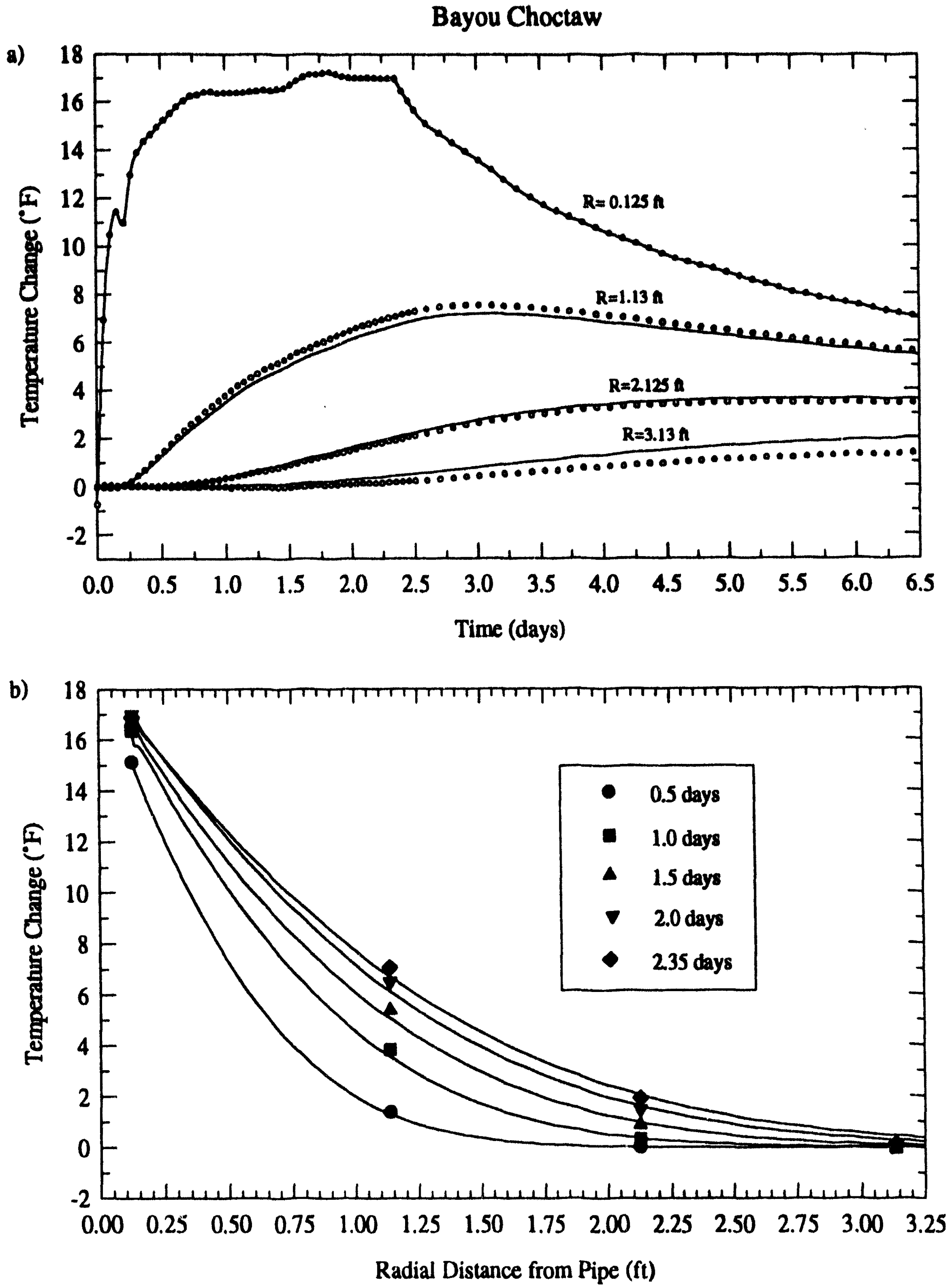


Figure B-2 - Bayou Choctaw. a) Corrected temperature as a function of time and b) corrected temperature as a function of radial distance from the pipeline wall. Symbols represent the data and the curves represent the theoretical model using a thermal diffusivity of 5.92×10^{-6} ft^2/s.

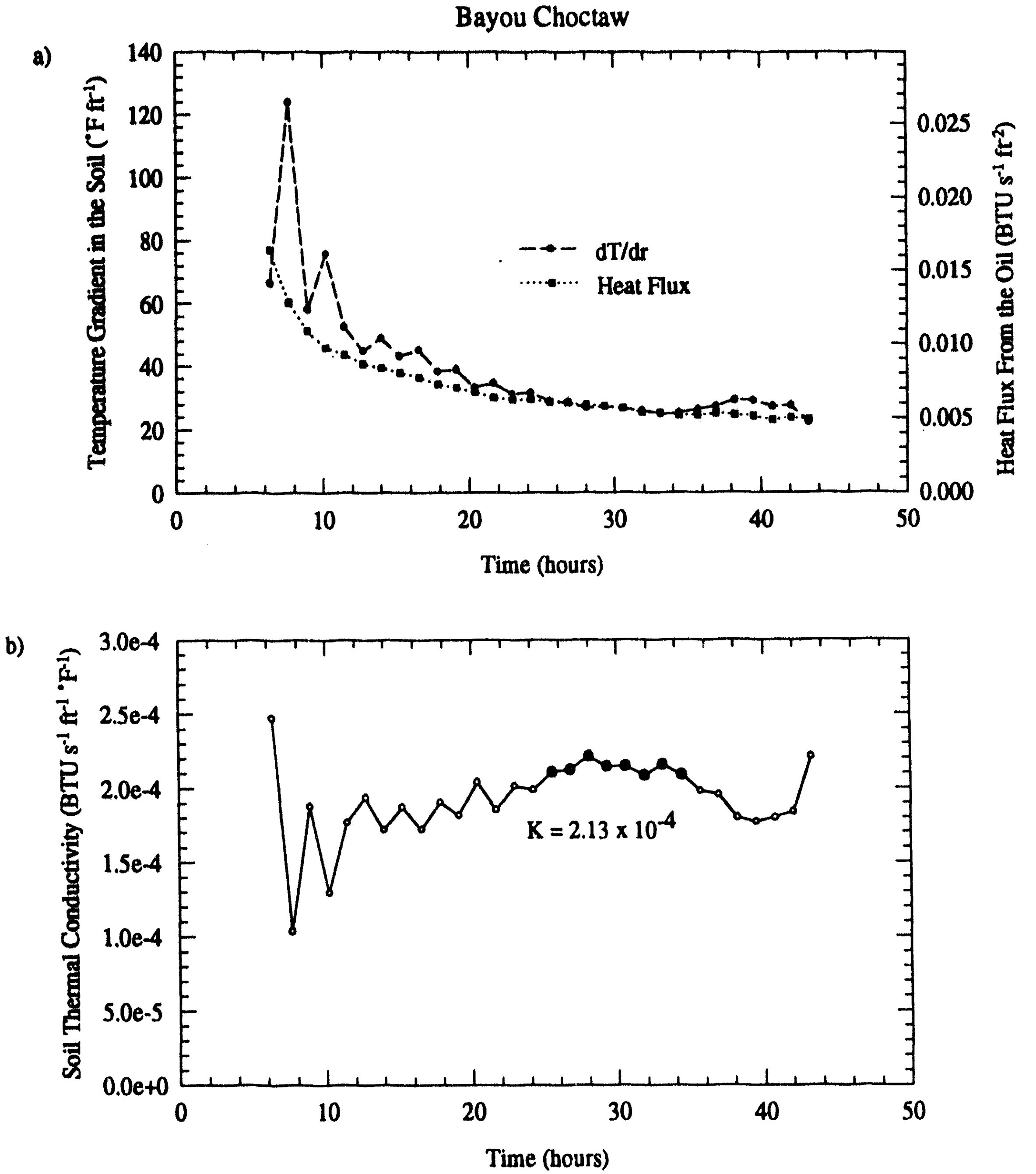


Figure B-3 - Bayou Choctaw. a) Radial temperature gradient measured in the soil at the pipeline wall and the heat flux from the pipe as a function of time. b) Soil thermal conductivity determined from the temperature gradient and flux in a). In b) the filled symbols indicate data that was averaged to obtain representative thermal conductivity for the site.

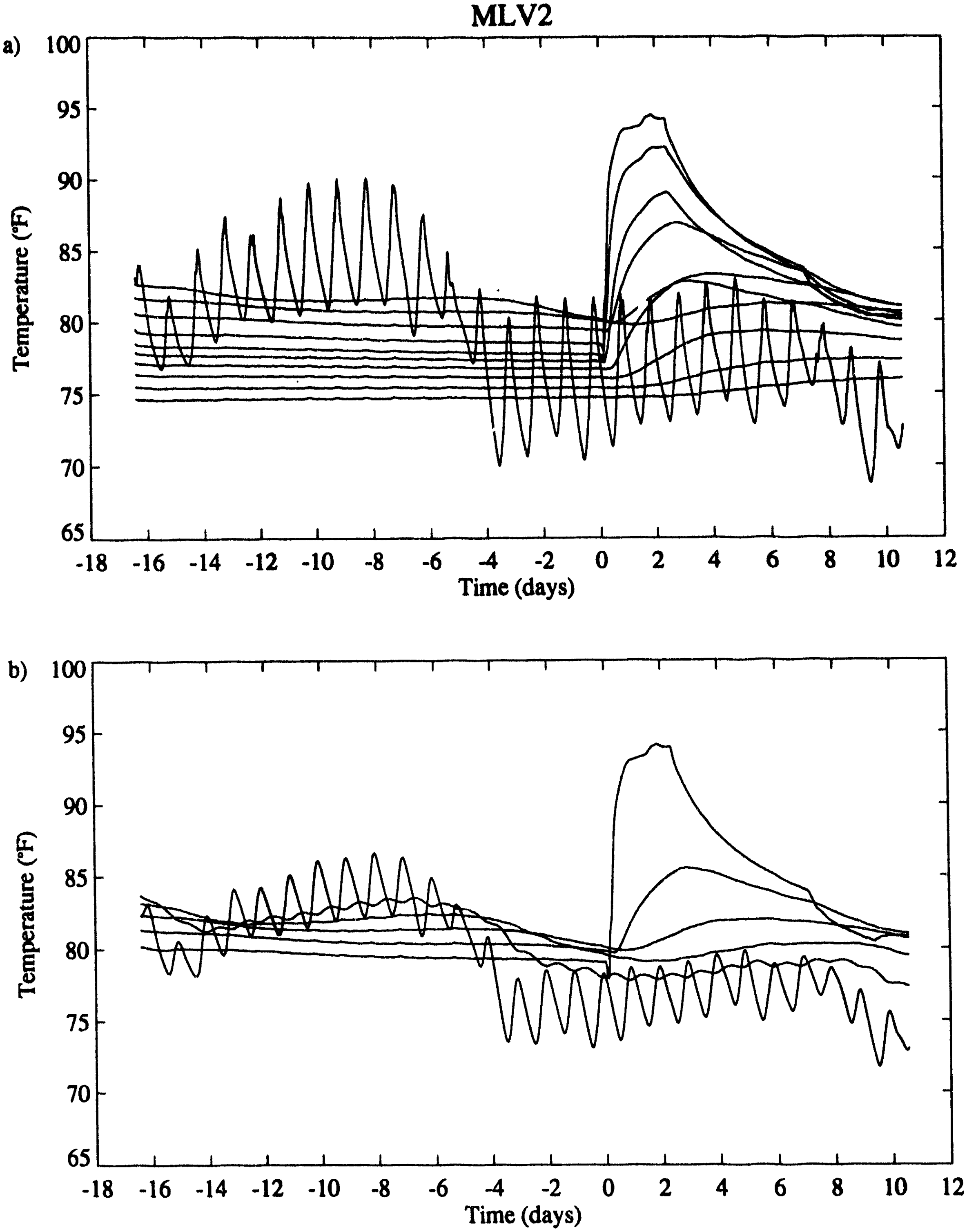


Figure B-4 - Temperature as a function of time recorded by the subsurface thermistors in the a) long probe and b) short probe at station MLV2.

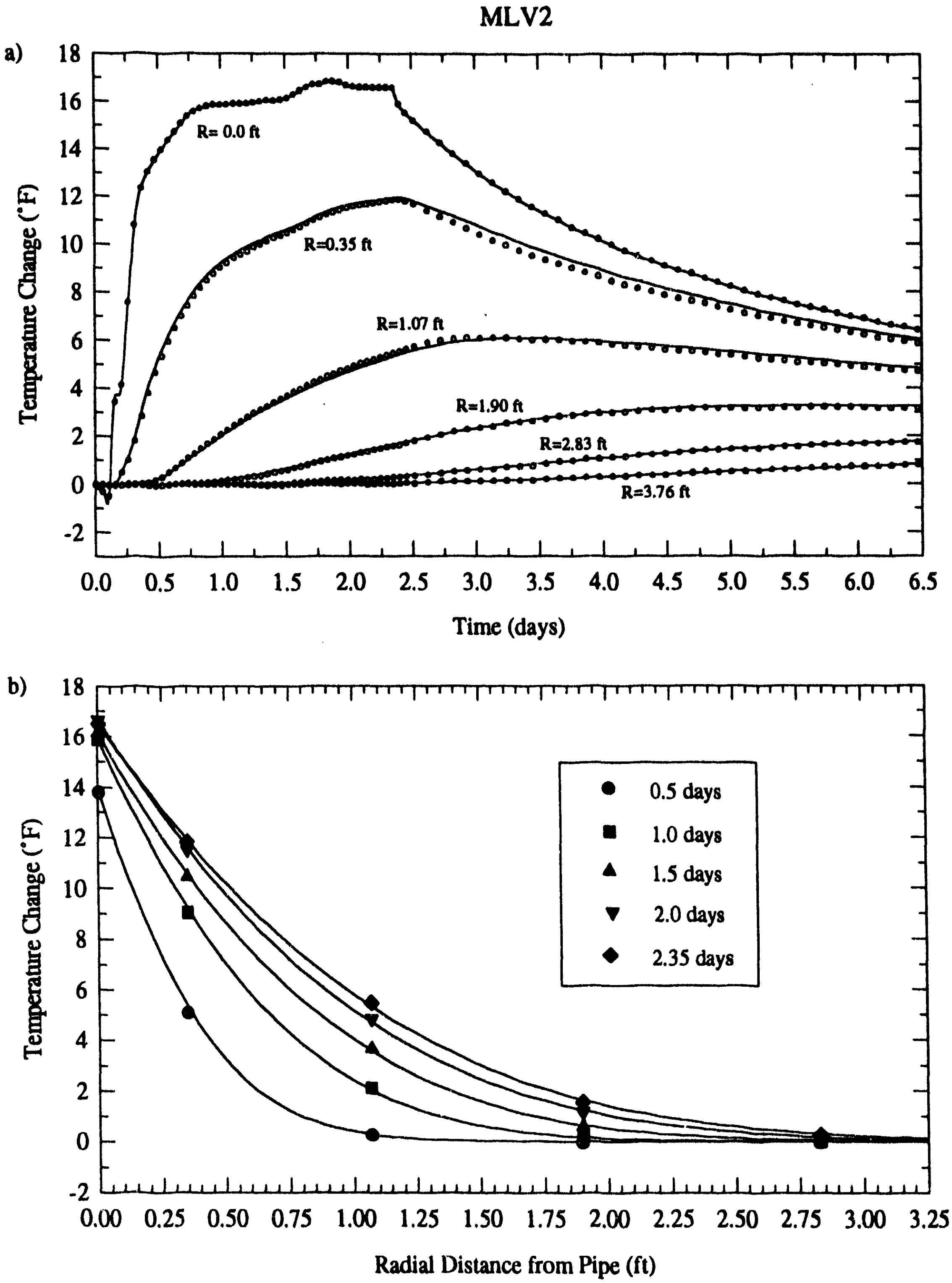


Figure B-5 - MLV2. a) Corrected temperature as a function of time and b) corrected temperature as a function of radial distance from the pipeline wall. Symbols represent the data and the curves represent the theoretical model using a thermal diffusivity of 4.95×10^{-6} ft^2/s.

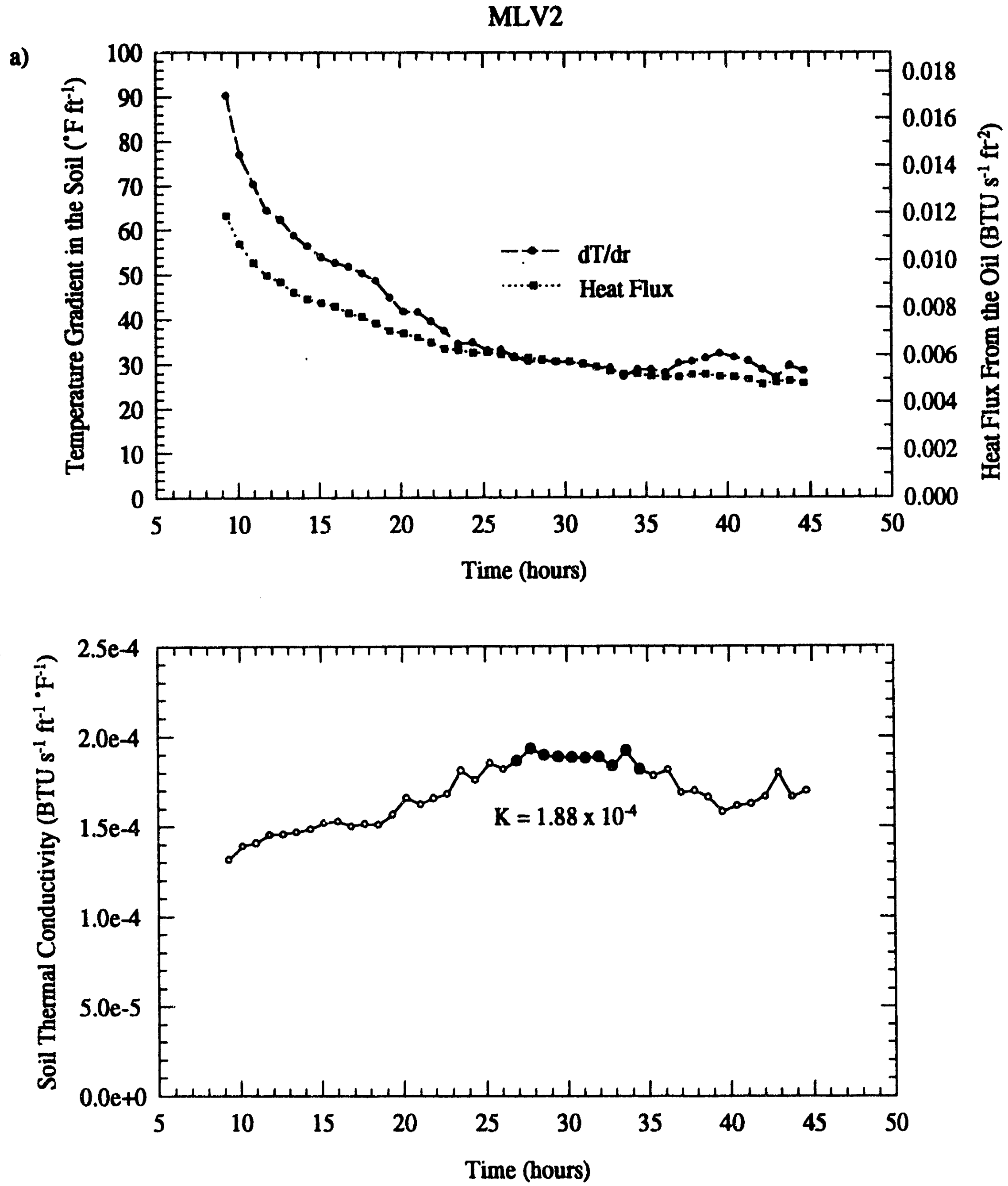


Figure B-6 - MLV2. a) Radial temperature gradient measured in the soil at the pipeline wall and the heat flux from the pipe as a function of time. b) Soil thermal conductivity determined from the temperature gradient and flux in a). In b) the filled symbols indicate data that was averaged to obtain representative thermal conductivity for the site.

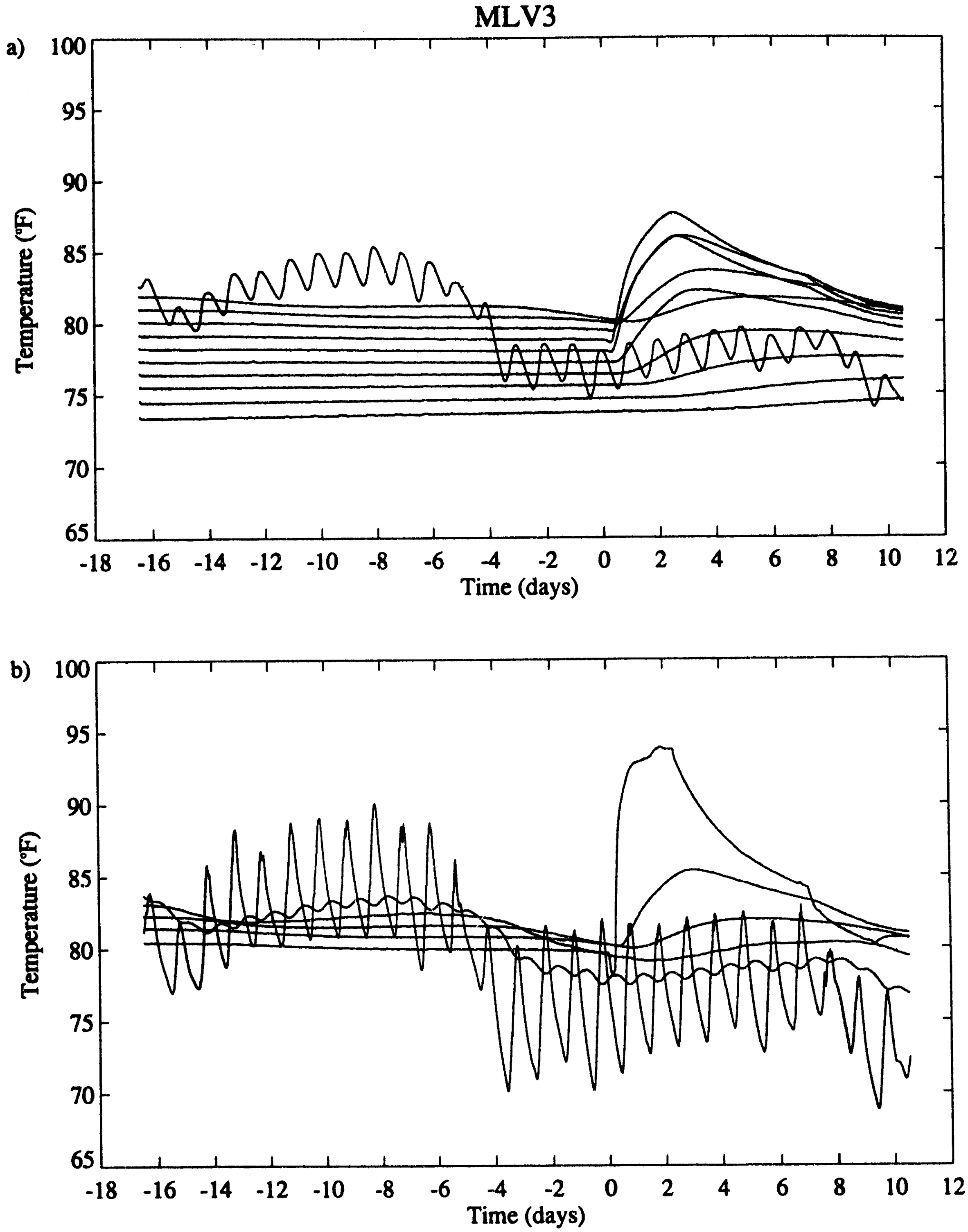


Figure B-7 - Temperature as a function of time recorded by the subsurface thermistors in the a) long probe and b) short probe at station MLV3.

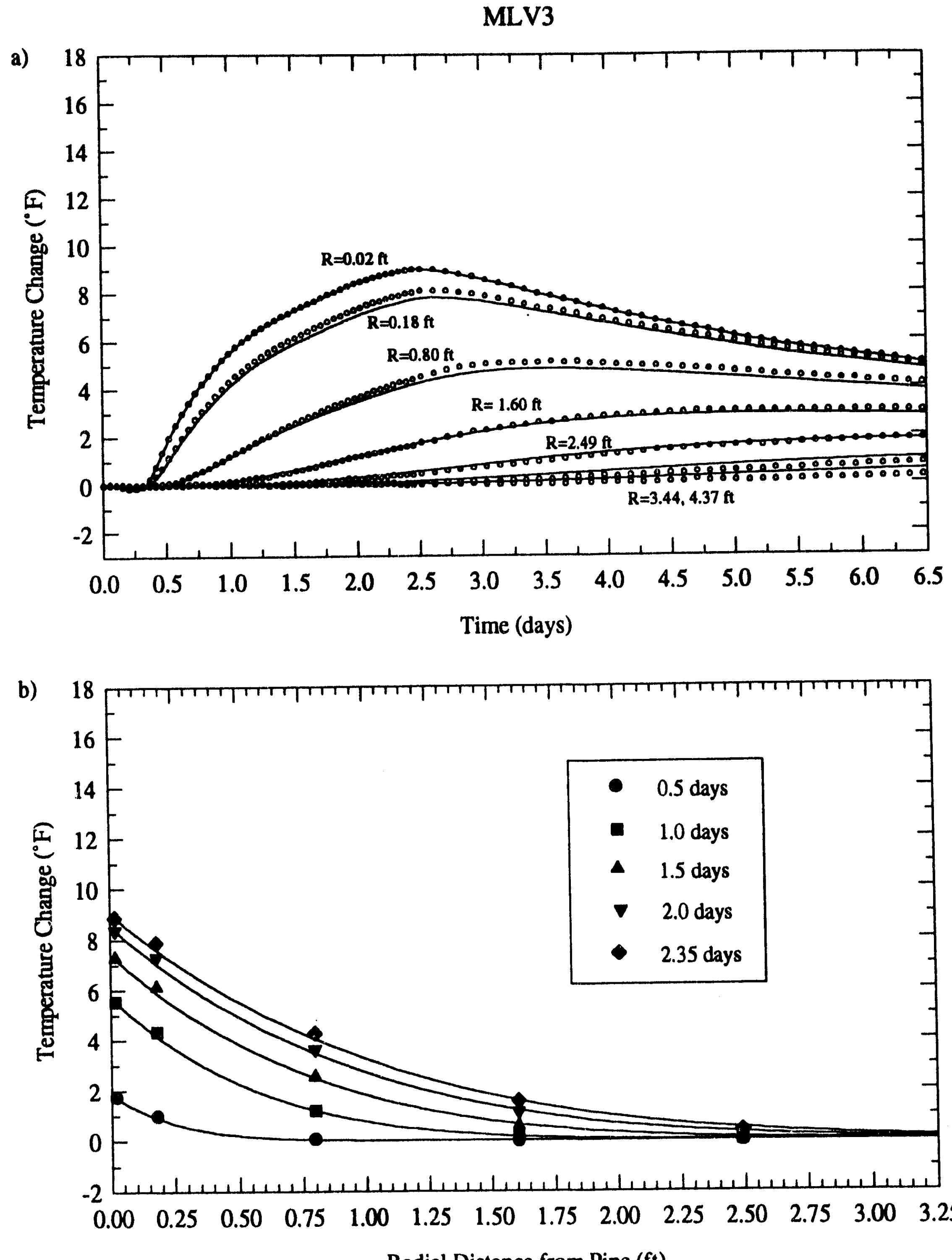


Figure B-8 - MLV3. a) Corrected temperature as a function of time and b) corrected temperature as a function of radial distance from the pipeline wall. Symbols represent the data and the curves represent the theoretical model using a thermal diffusivity of 8.29 x 10^{-6} ft^2/s.

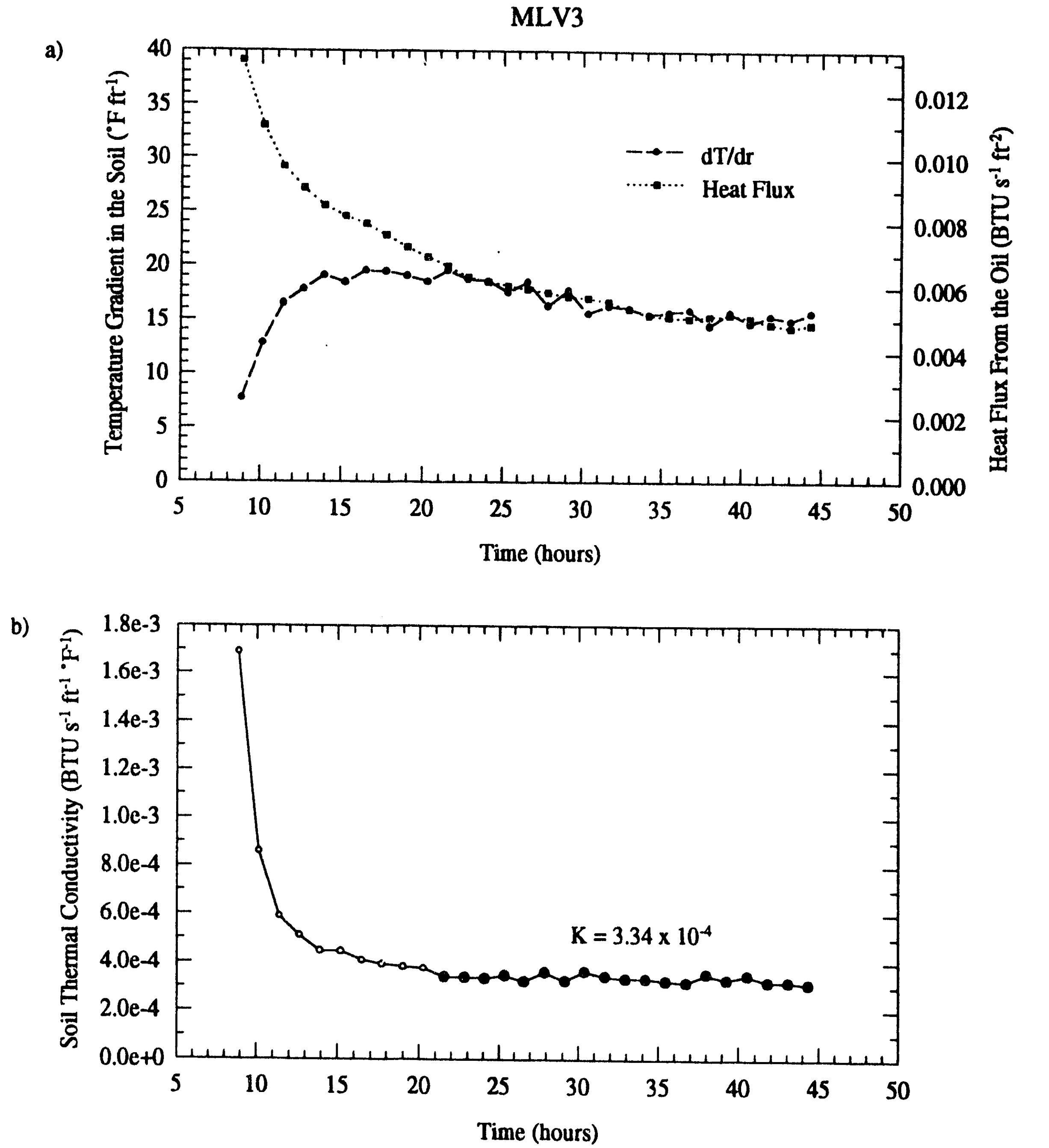


Figure B-9 - MLV3. a) Radial temperature gradient measured in the soil at the pipeline wall and the heat flux from the pipe as a function of time. b) Soil thermal conductivity determined from the temperature gradient and flux in a). In b) the filled symbols indicate data that was averaged to obtain representative thermal conductivity for the site.

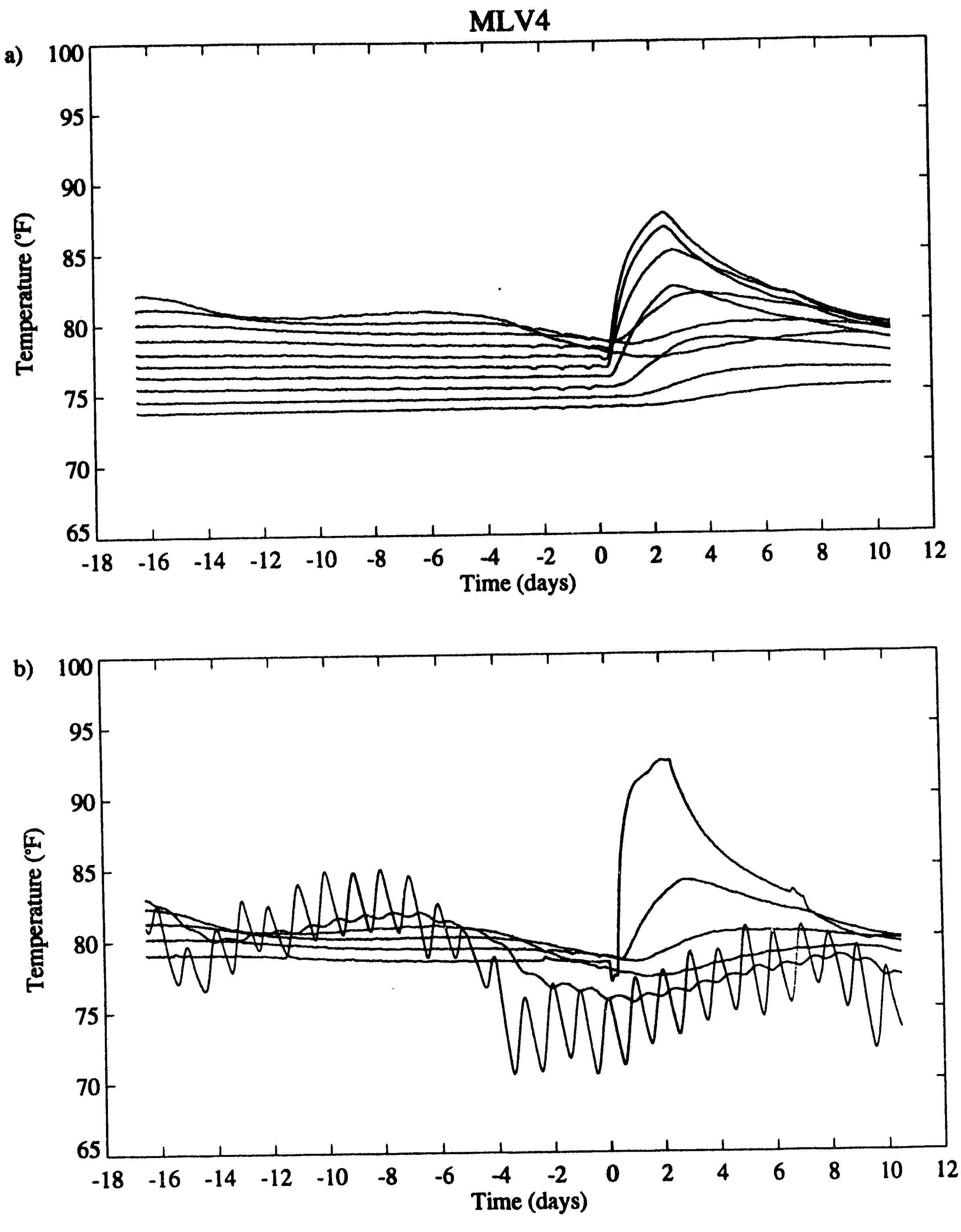


Figure B-10 - Temperature as a function of time recorded by the subsurface thermistors in the a) long probe and b) short probe at station MLV4.

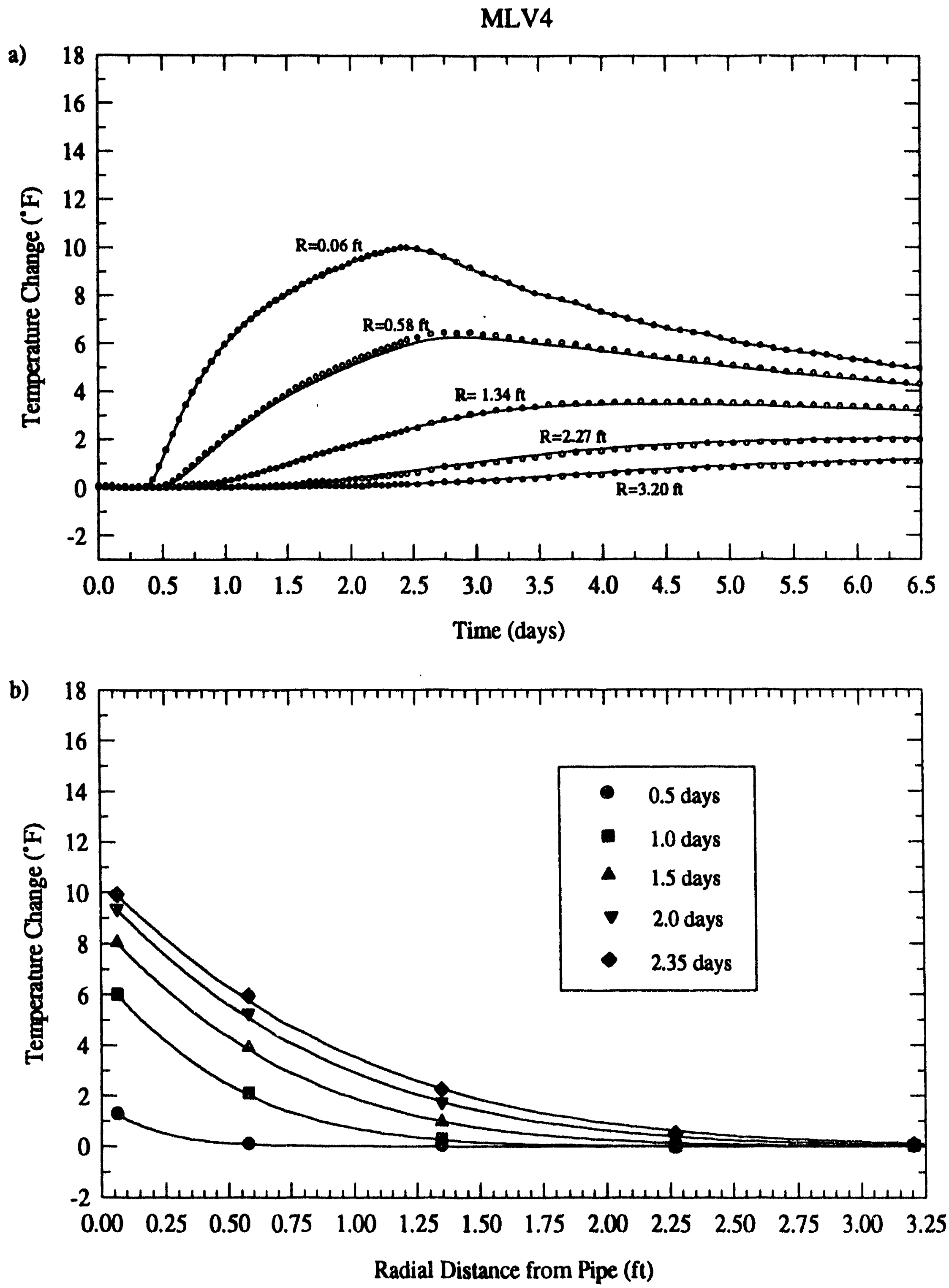


Figure B-11 - MLV4. a) Corrected temperature as a function of time and b) corrected temperature as a function of radial distance from the pipeline wall. Symbols represent the data and the curves represent the theoretical model using a thermal diffusivity of 7.21×10^{-6} ft^2/s.

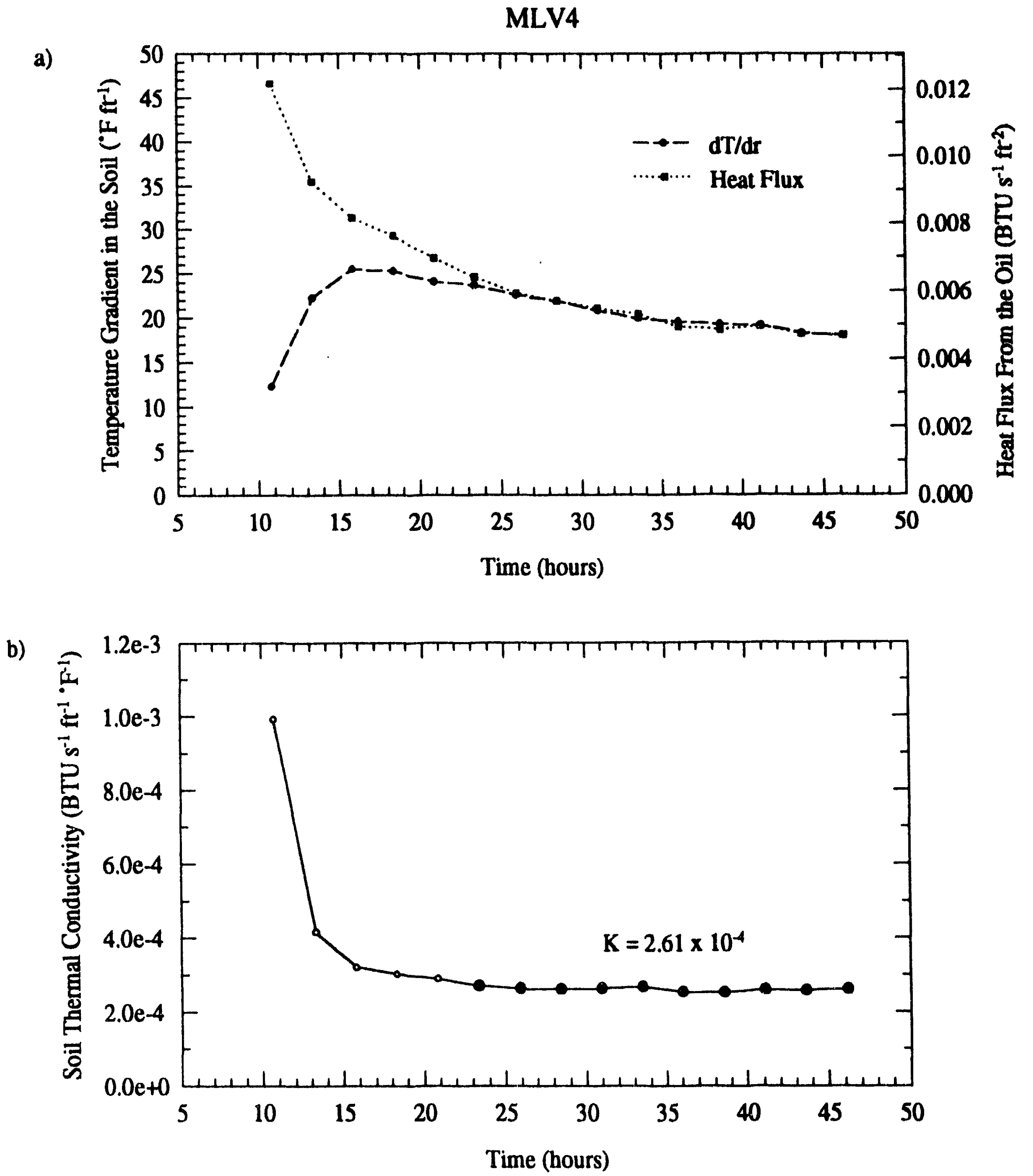


Figure B-12 - MLV4. a) Radial temperature gradient measured in the soil at the pipeline wall and the heat flux from the pipe as a function of time. b) Soil thermal conductivity determined from the temperature gradient and flux in a). In b) the filled symbols indicate data that was averaged to obtain representative thermal conductivity for the site.

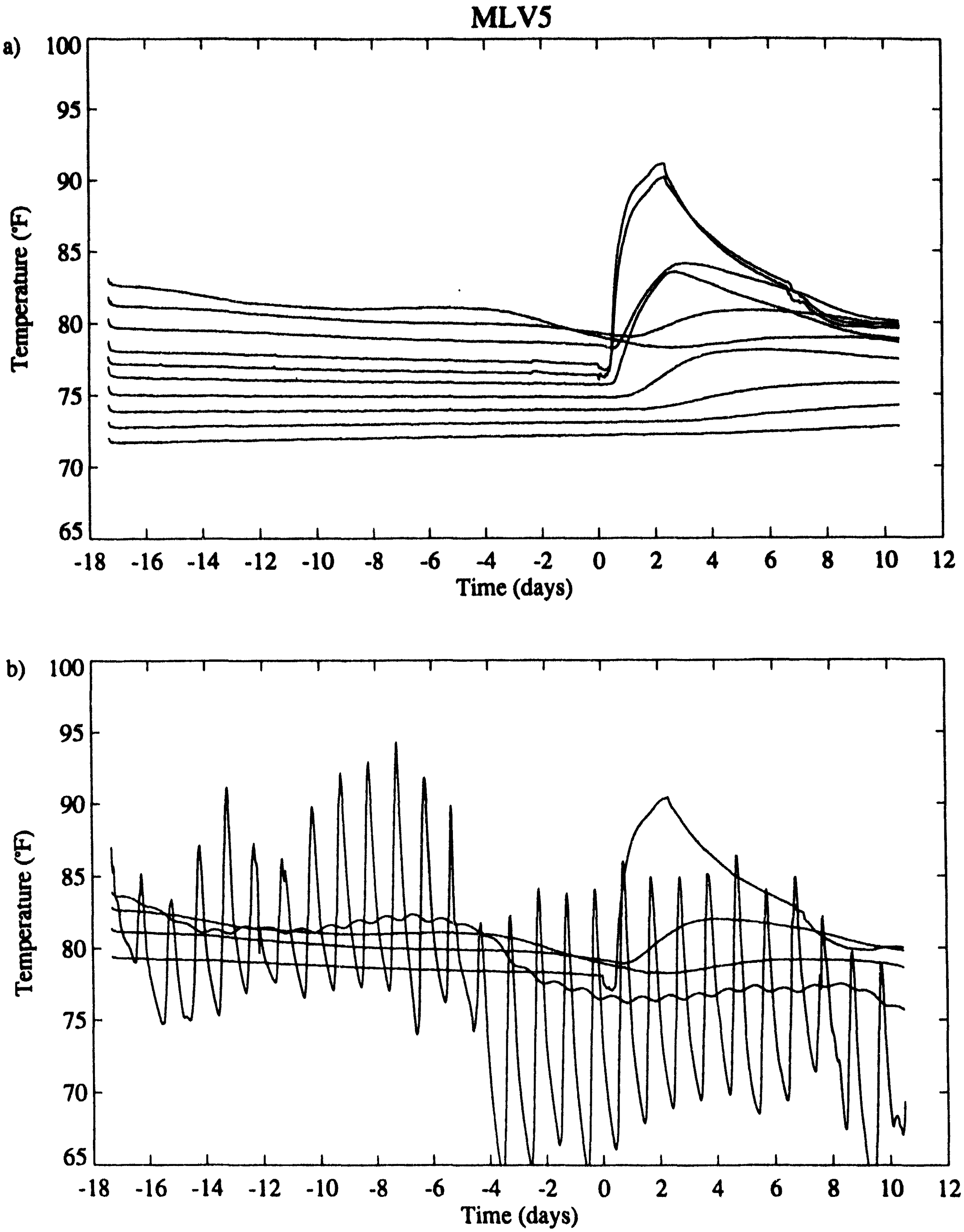


Figure B-13 - Temperature as a function of time recorded by the subsurface thermistors in the a) long probe and b) short probe at station MLV5.

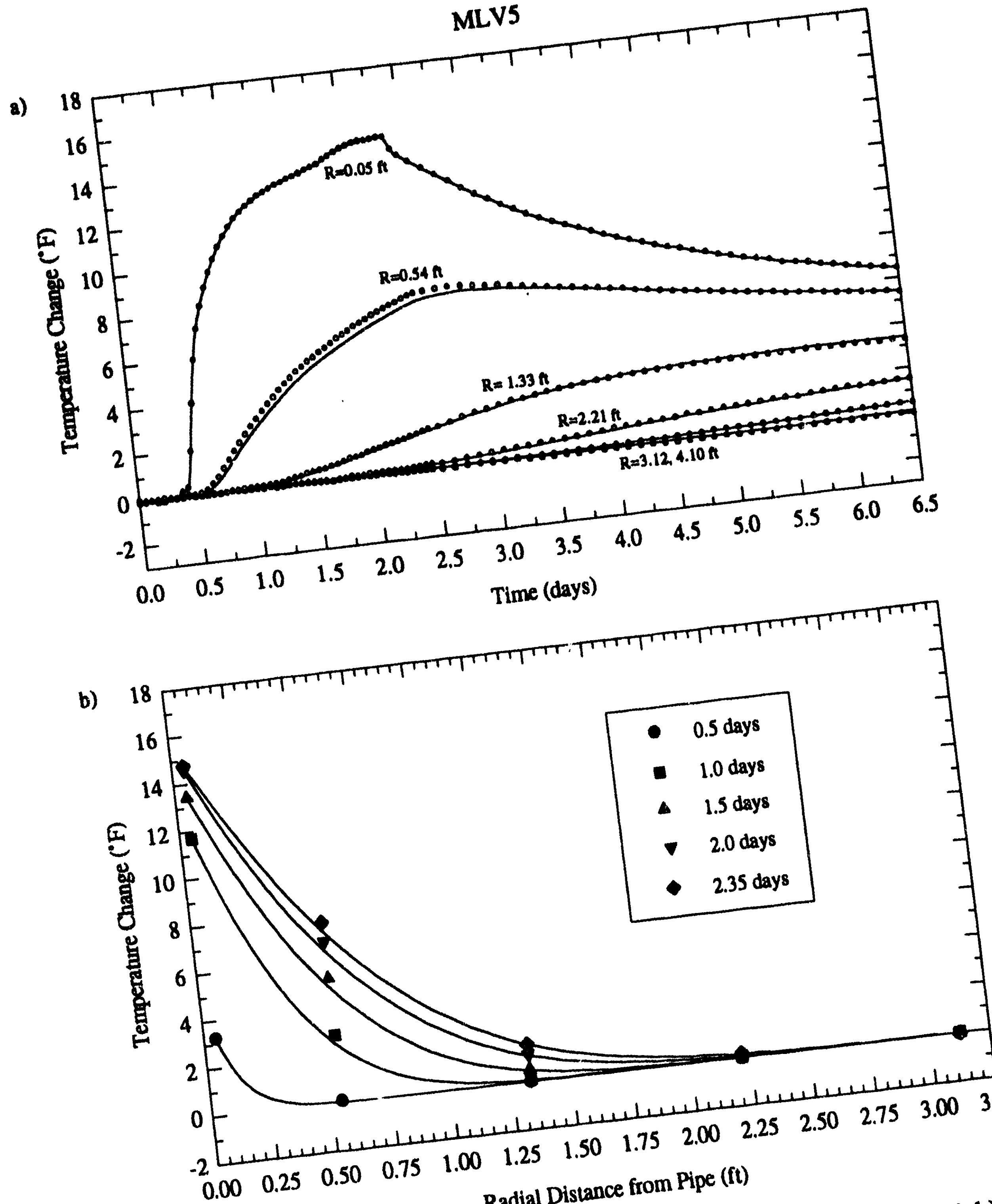


Figure B-14 - MLV5. a) Corrected temperature as a function of time and b) corrected temperature as a function of radial distance from the pipeline wall. Symbols represent the data and the curves represent the theoretical model using a thermal diffusivity of 2.80 x 10^{-6} ft^2/s.

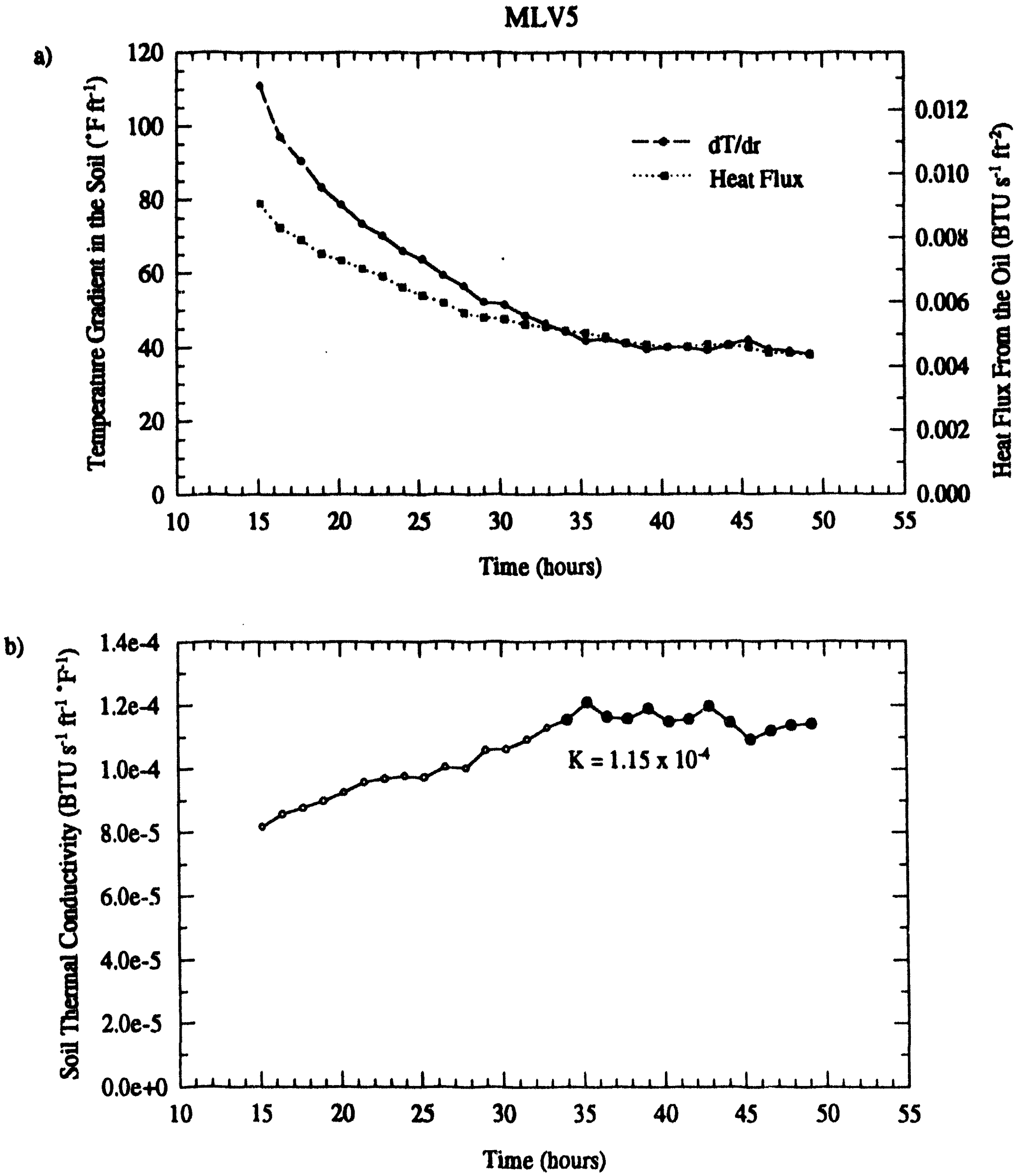


Figure B-15 - MLV5. a) Radial temperature gradient measured in the soil at the pipeline wall and the heat flux from the pipe as a function of time. b) Soil thermal conductivity determined from the temperature gradient and flux in a). In b) the filled symbols indicate data that was averaged to obtain representative thermal conductivity for the site.

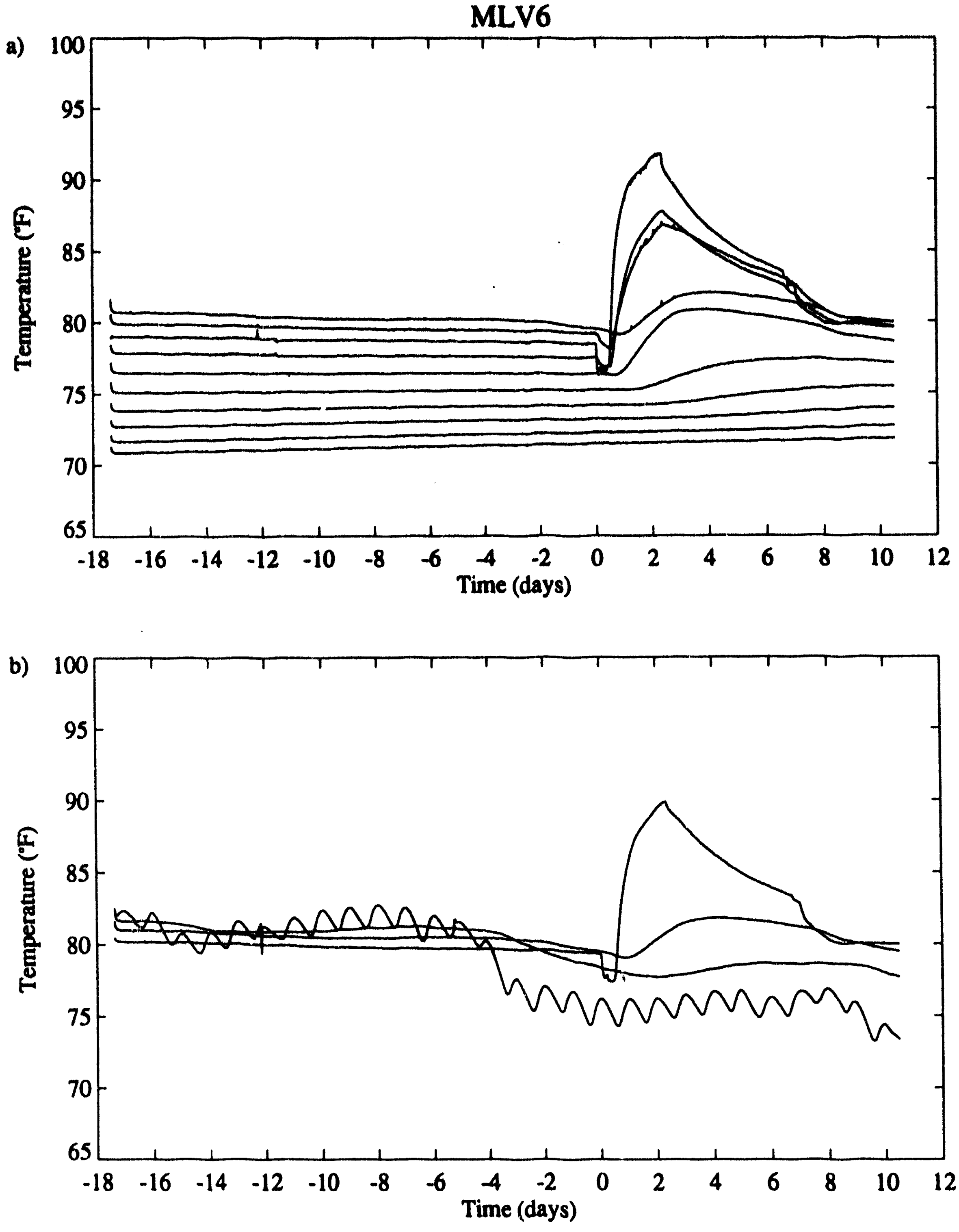


Figure B-16 - Temperature as a function of time recorded by the subsurface thermistors in the a) long probe and b) short probe at station MLV6.

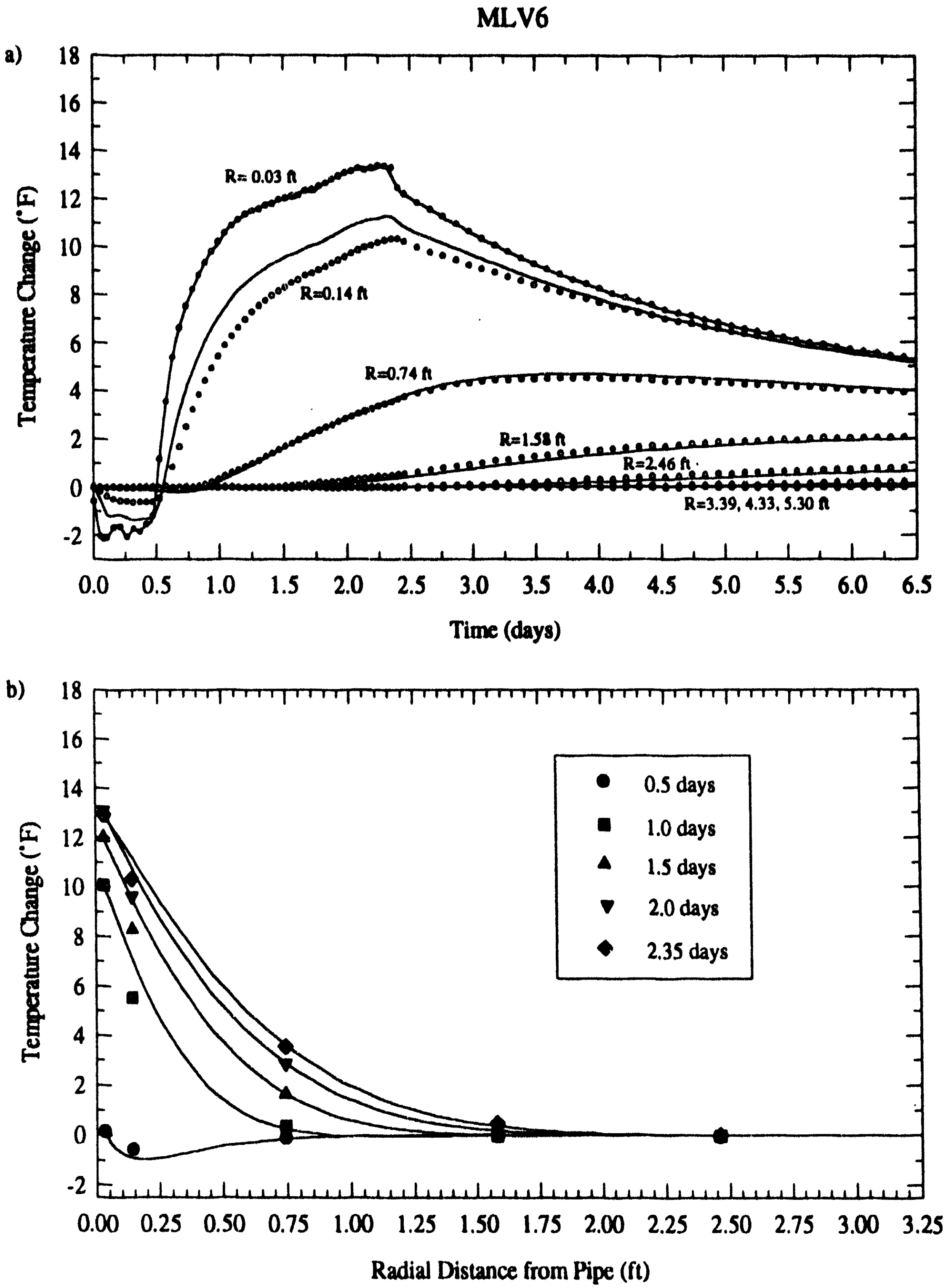


Figure B-17 - MLV6. a) Corrected temperature as a function of time and b) corrected temperature as a function of radial distance from the pipeline wall. Symbols represent the data and the curves represent the theoretical model using a thermal diffusivity of 2.15×10^{-6} ft^2/s.

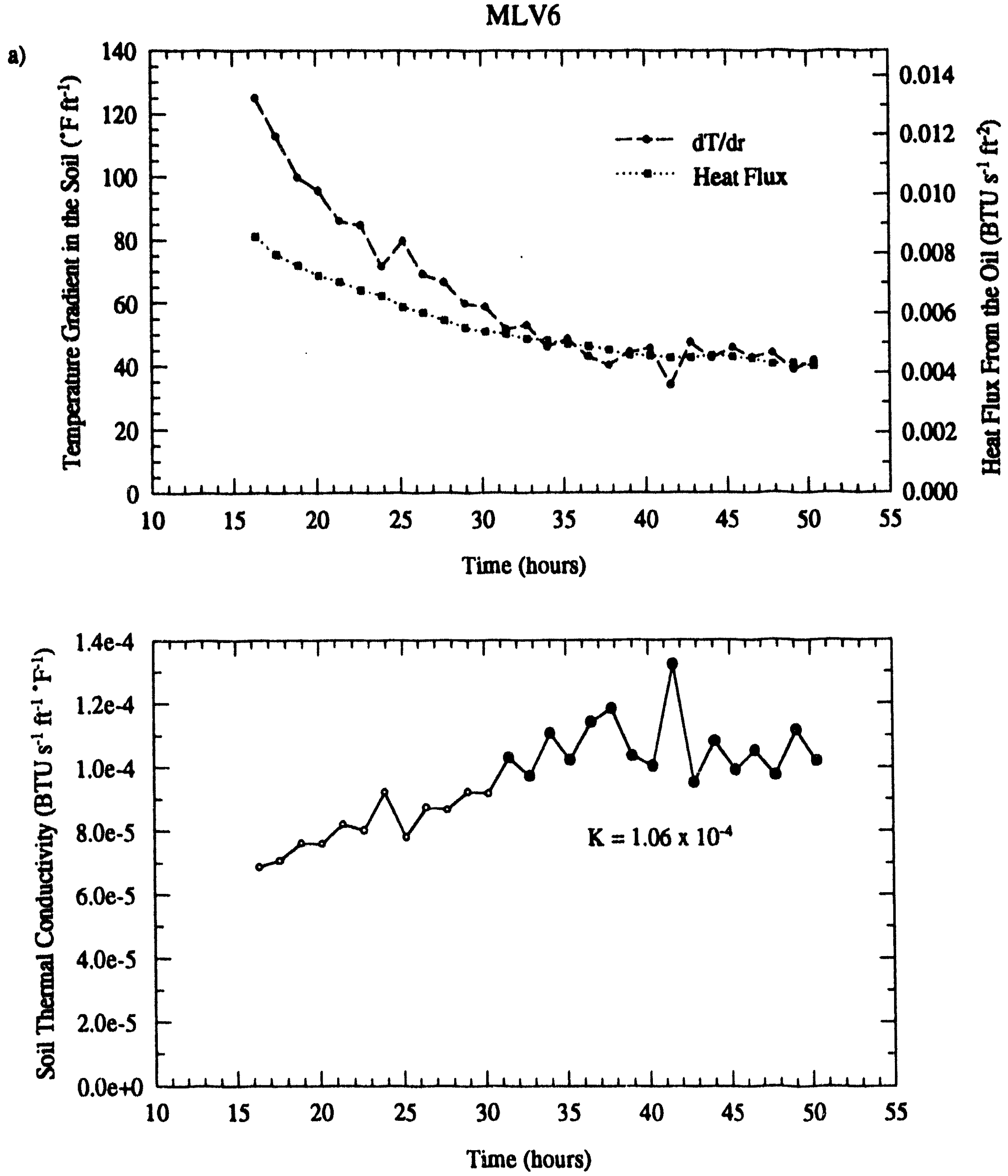


Figure B-18 - MLV6. a) Radial temperature gradient measured in the soil at the pipeline wall and the heat flux from the pipe as a function of time. b) Soil thermal conductivity determined from the temperature gradient and flux in a). In b) the filled symbols indicate data that was averaged to obtain representative thermal conductivity for the site.

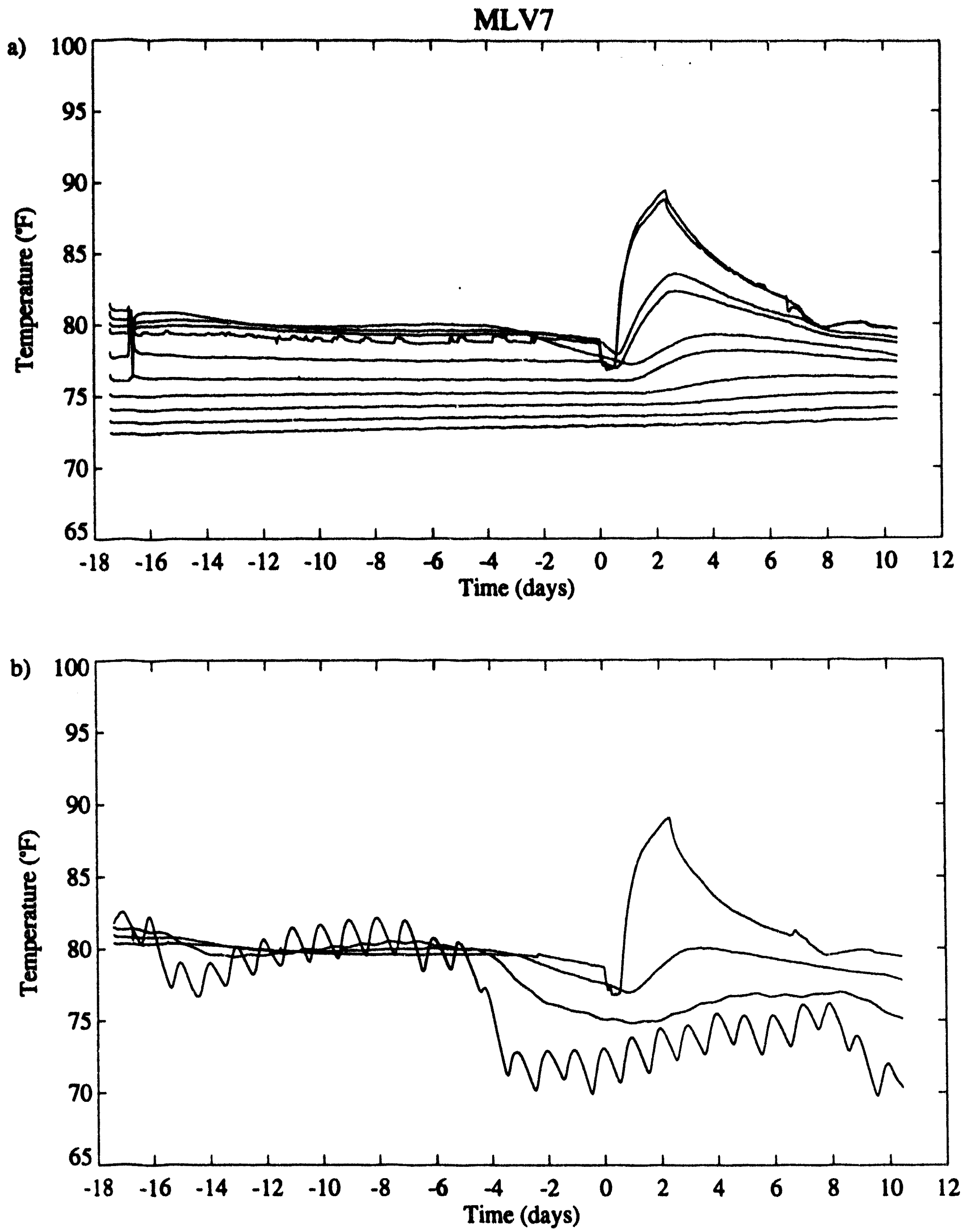


Figure B-19 - Temperature as a function of time recorded by the subsurface thermistors in the a) long probe and b) short probe at station MLV7.

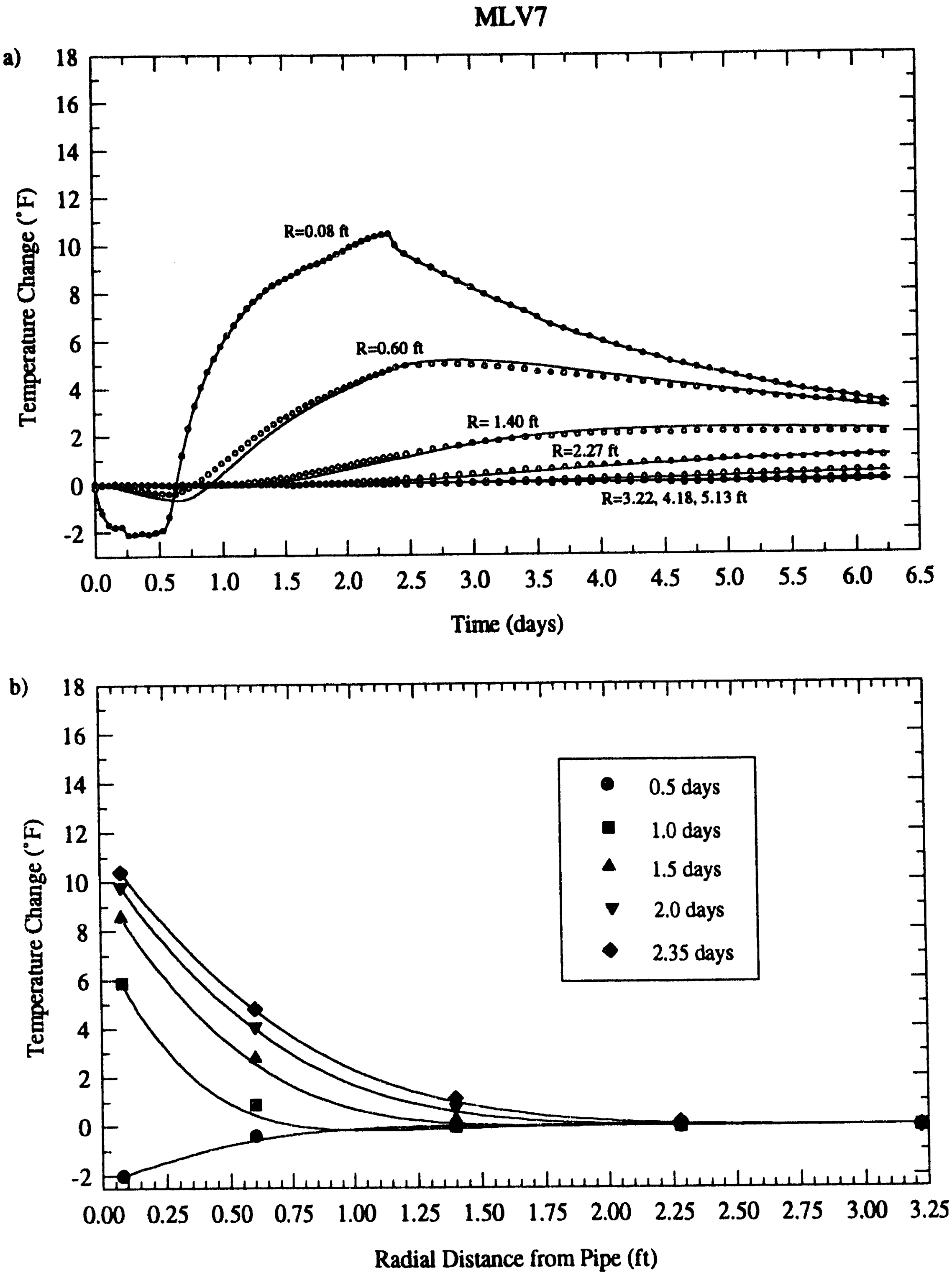
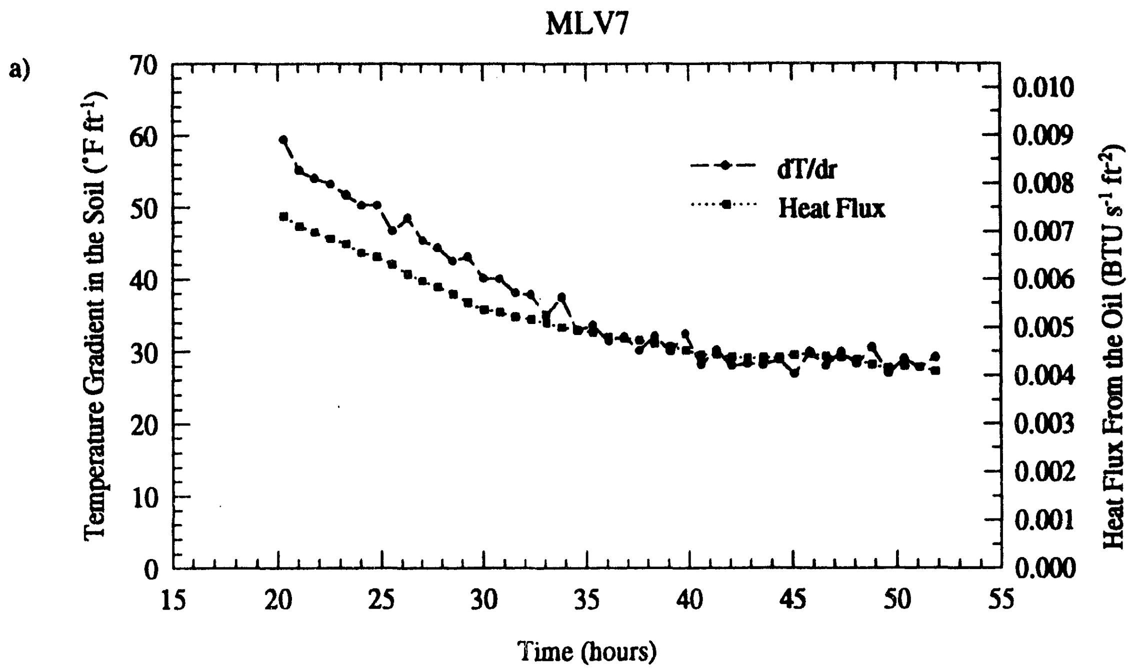


Figure B-20 - MLV7. a) Corrected temperature as a function of time and b) corrected temperature as a function of radial distance from the pipeline wall. Symbols represent the data and the curves represent the theoretical model using a thermal diffusivity of 3.55×10^{-6} ft^2/s.



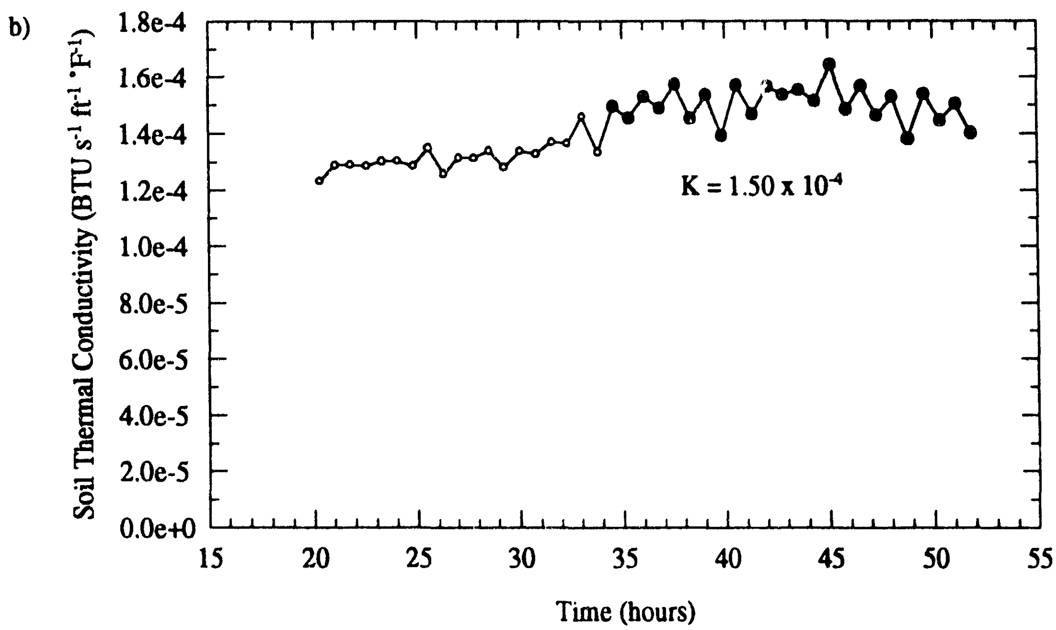


Figure B-21 - MLV7. a) Radial temperature gradient measured in the soil at the pipeline wall and the heat flux from the pipe as a function of time. b) Soil thermal conductivity determined from the temperature gradient and flux in a). In b) the filled symbols indicate data that was averaged to obtain representative thermal conductivity for the site.

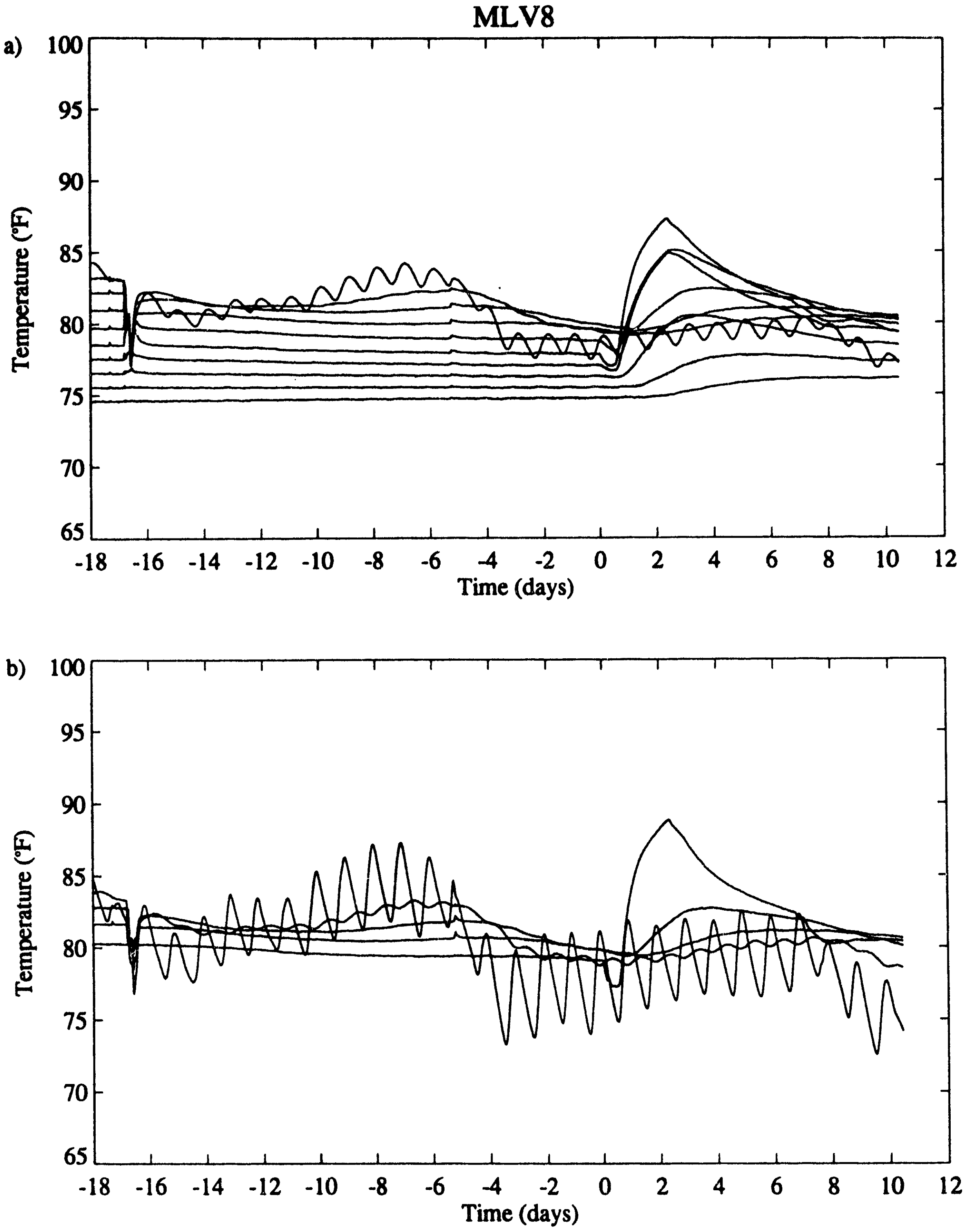


Figure B-22 - Temperature as a function of time recorded by the subsurface thermistors in the a) long probe and b) short probe at station MLV8.

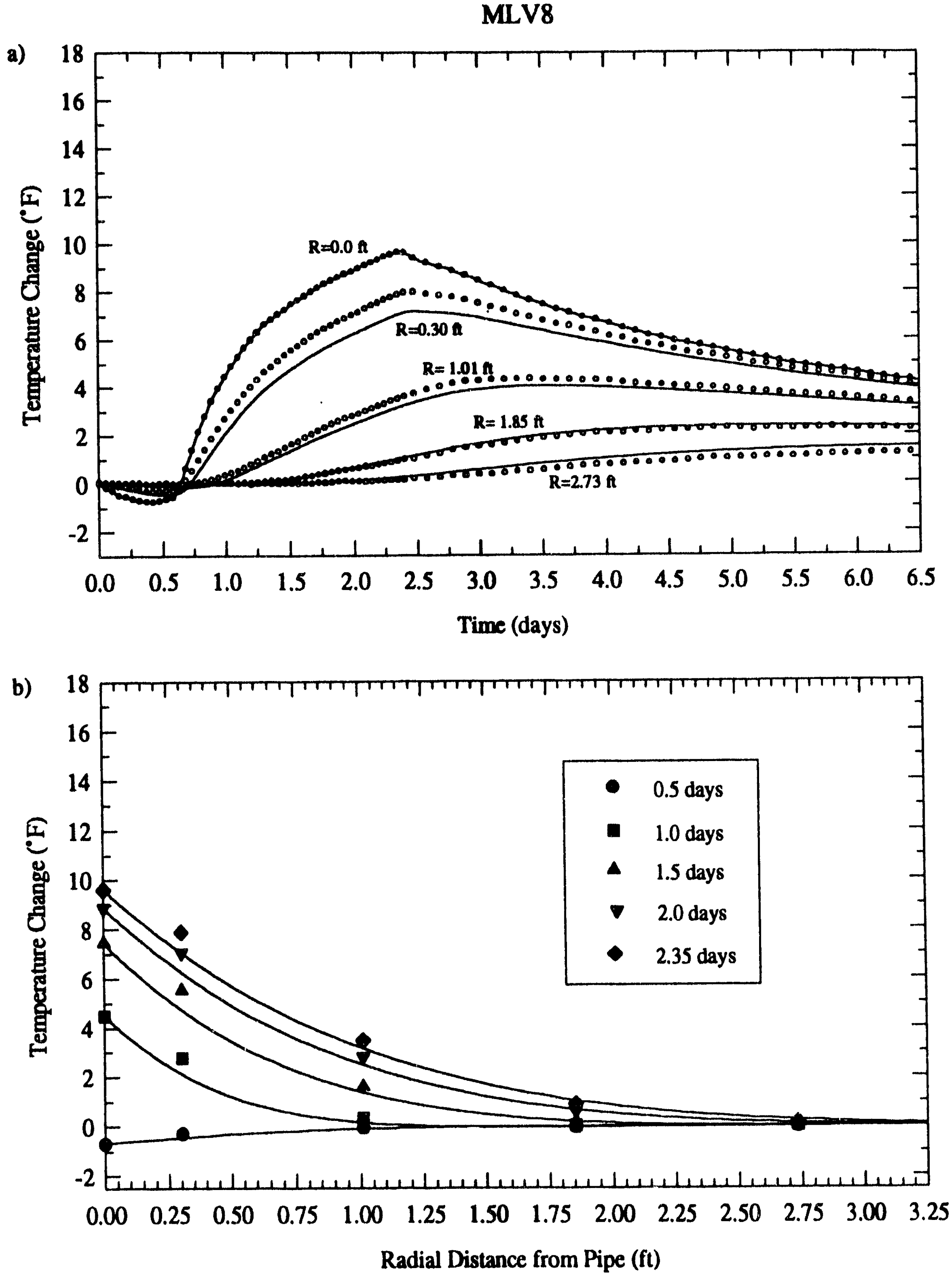
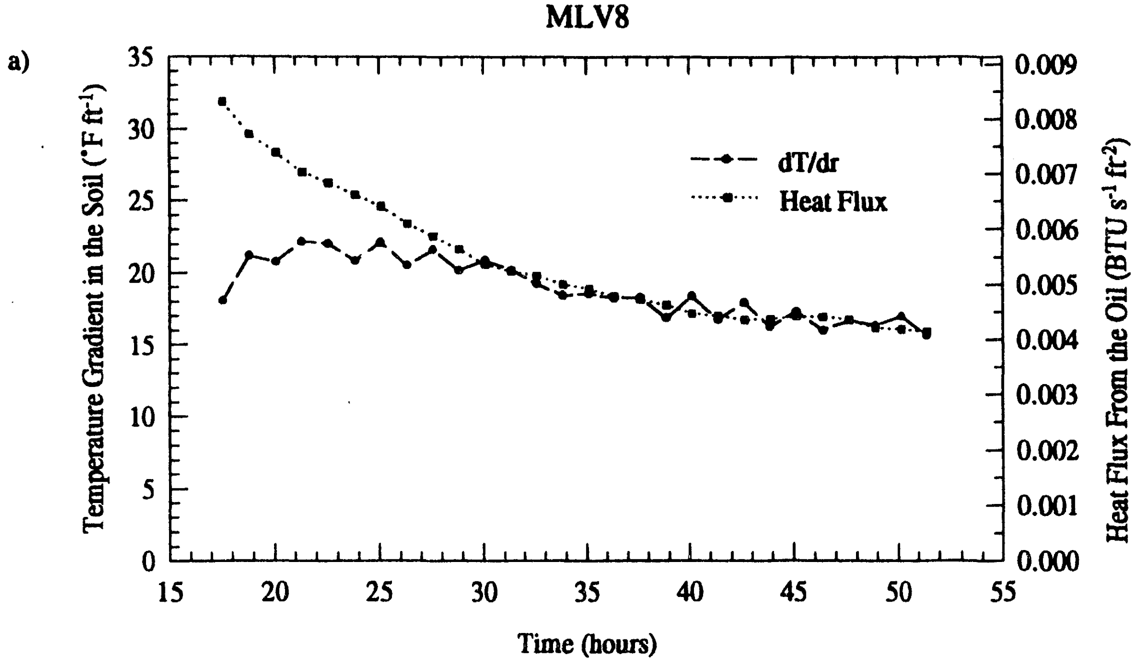


Figure B-23 - MLV8. a) Corrected temperature as a function of time and b) corrected temperature as a function of radial distance from the pipeline wall. Symbols represent the data and the curves represent the theoretical model using a thermal diffusivity of 8.61×10^{-6} ft^2/s.

a)



b)

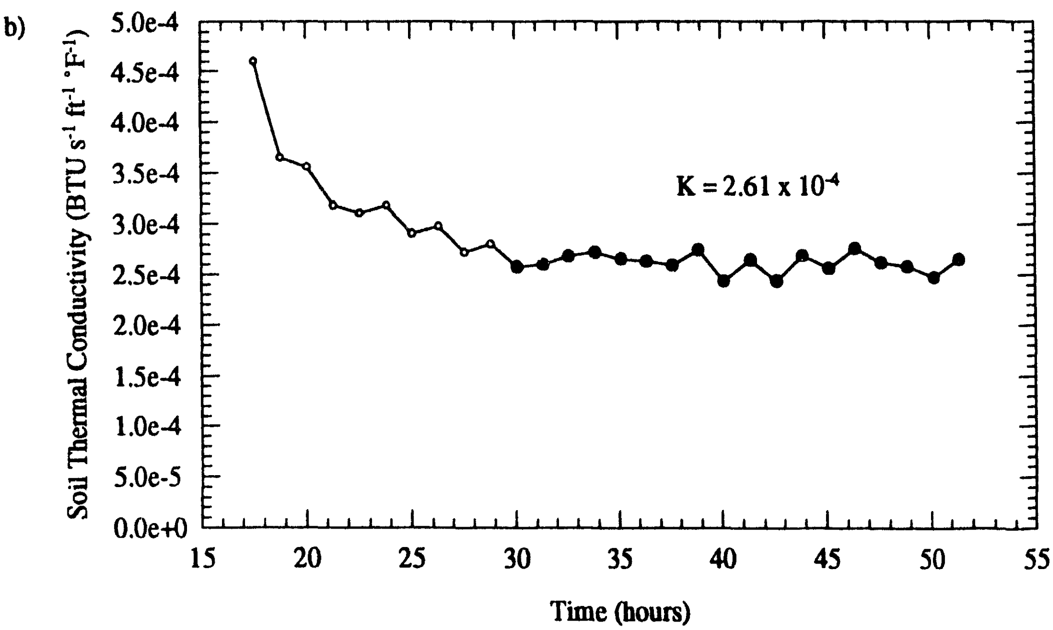


Figure B-24 - MLV8. a) Radial temperature gradient measured in the soil at the pipeline wall and the heat flux from the pipe as a function of time. b) Soil thermal conductivity determined from the temperature gradient and flux in a). In b) the filled symbols indicate data that was averaged to obtain representative thermal conductivity for the site.

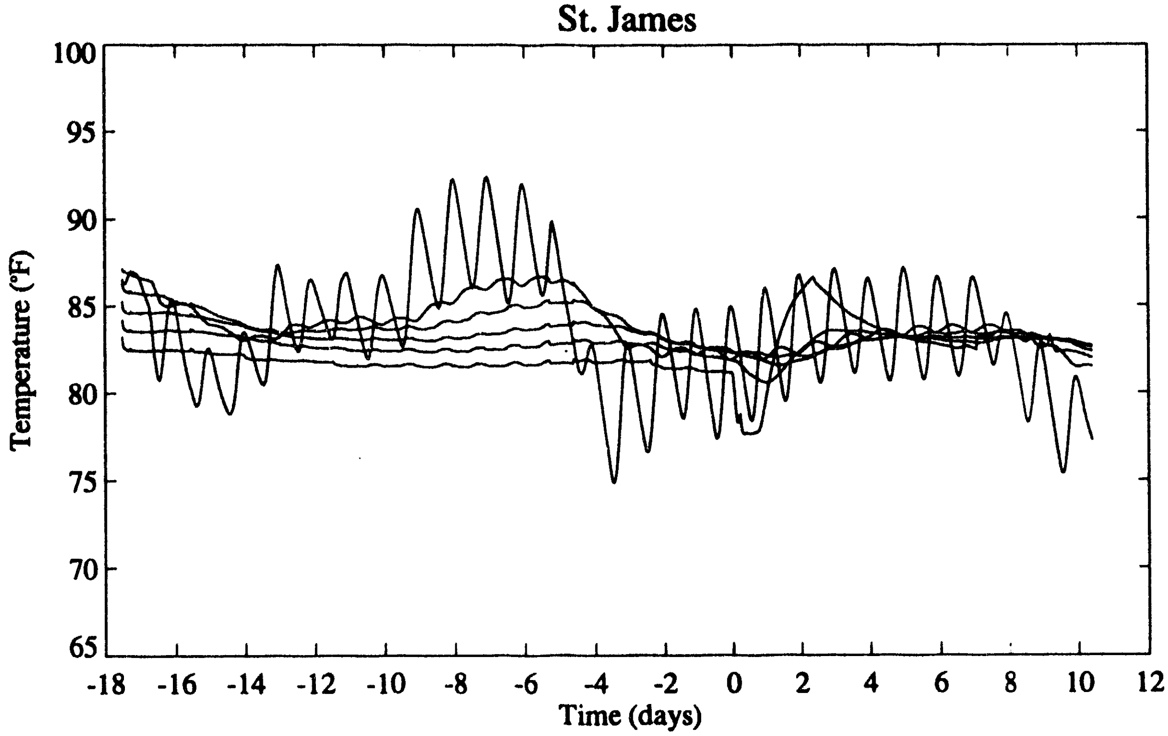


Figure B-25 - Temperature as a function of time recorded by the subsurface thermistors in the probe at St. James.

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APPENDIX C

Measured and Calculated Oil and Soil Temperatures at Each Valve Station

List of Figures

Measured and Calculated Oil and Soil Temperatures at Each Valve Station

In this appendix, plots illustrating the calculated oil temperatures, the calculated temperature at the outside of the pipe, and the measured oil temperature at each valve station are presented. For all calculations, the mean value of soil thermal properties, as determined as part of this report, were used. For all of the valve stations, at any given time, the calculated temperatures are within a few of the measured values during the pumping phase of the test. The estimated soil thermal properties were observed to vary widely from one location to the next (Table 4). This variation, however, does allow for an accurate determination of the mean value of the estimated properties, as evidenced by the "good" match of calculated values to measured values all along the line.

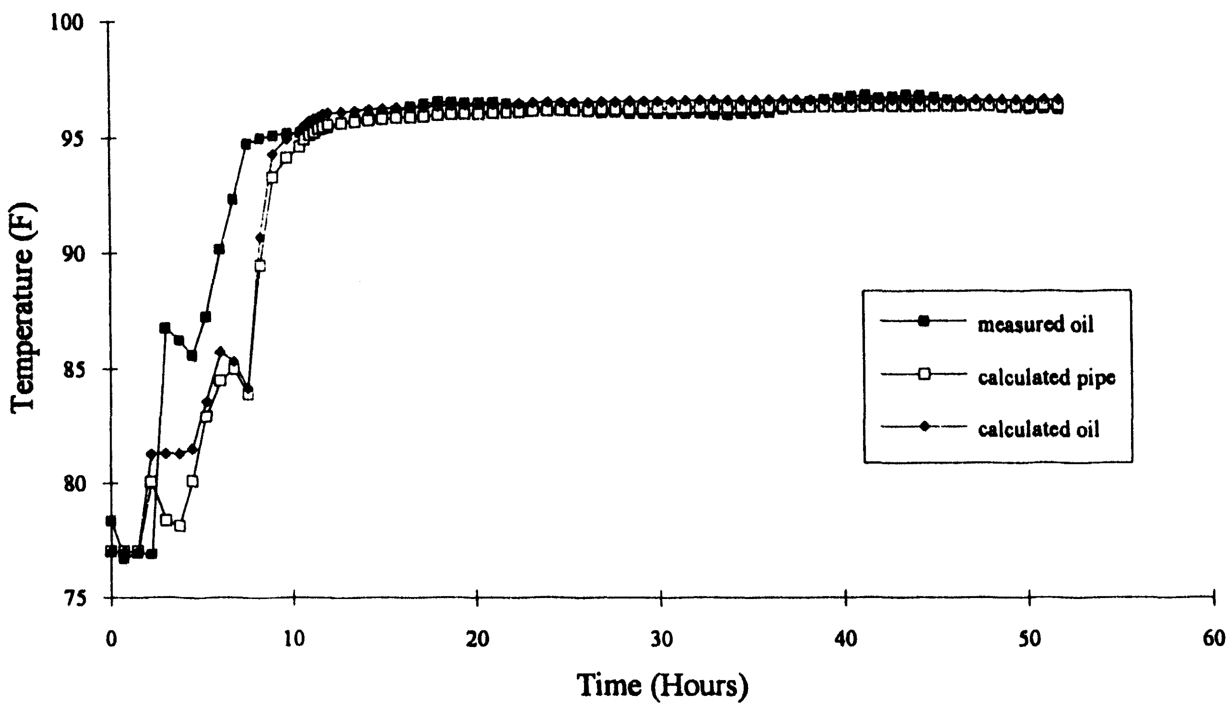

Figure C-1 - Comparison of measured and calculated oil temperatures at MLV2 located 3.9 miles from Bayou Choctaw.

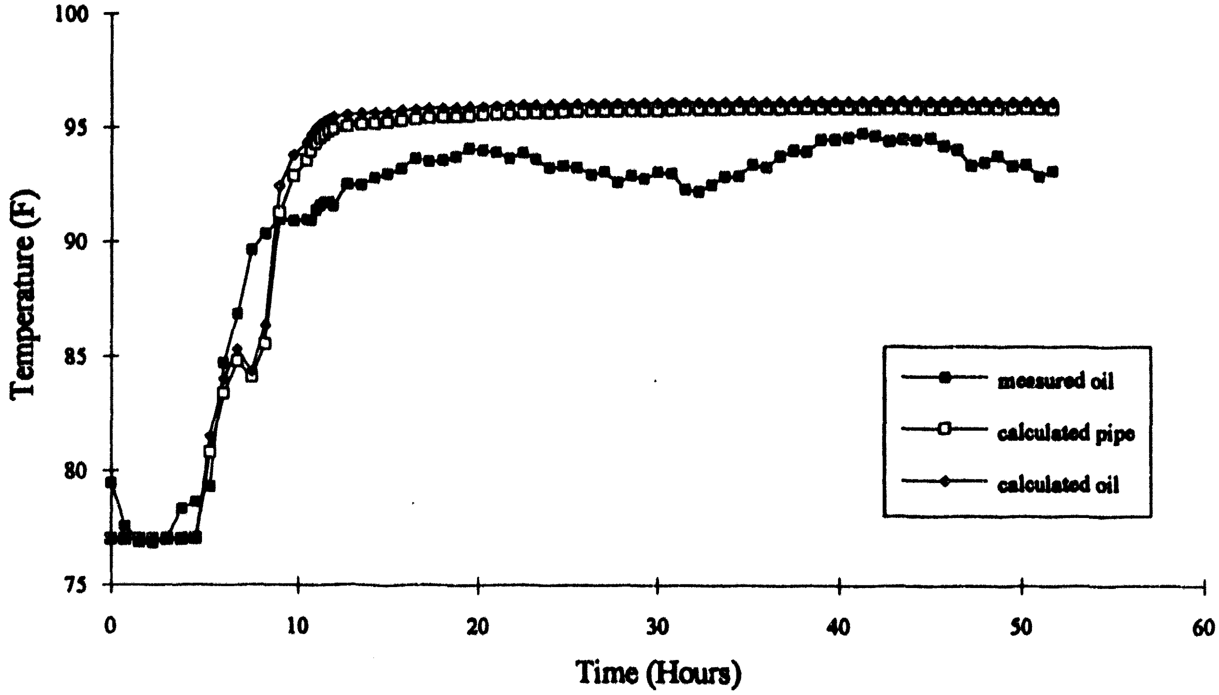

Figure C-2 - Comparison of measured and calculated oil temperatures at MLV3 located 5.0 miles from Bayou Choctaw.

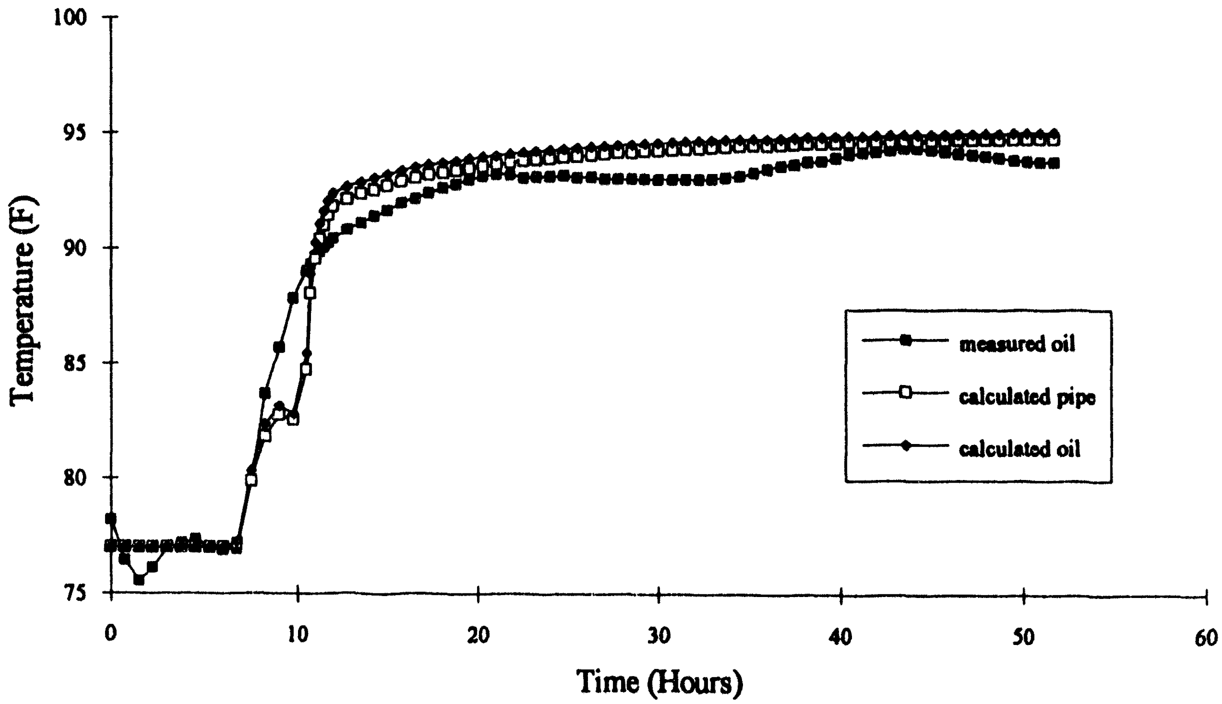

Figure C-3 - Comparison of measured and calculated oil temperatures at MLV4 located 10.4 miles from Bayou Choctaw.

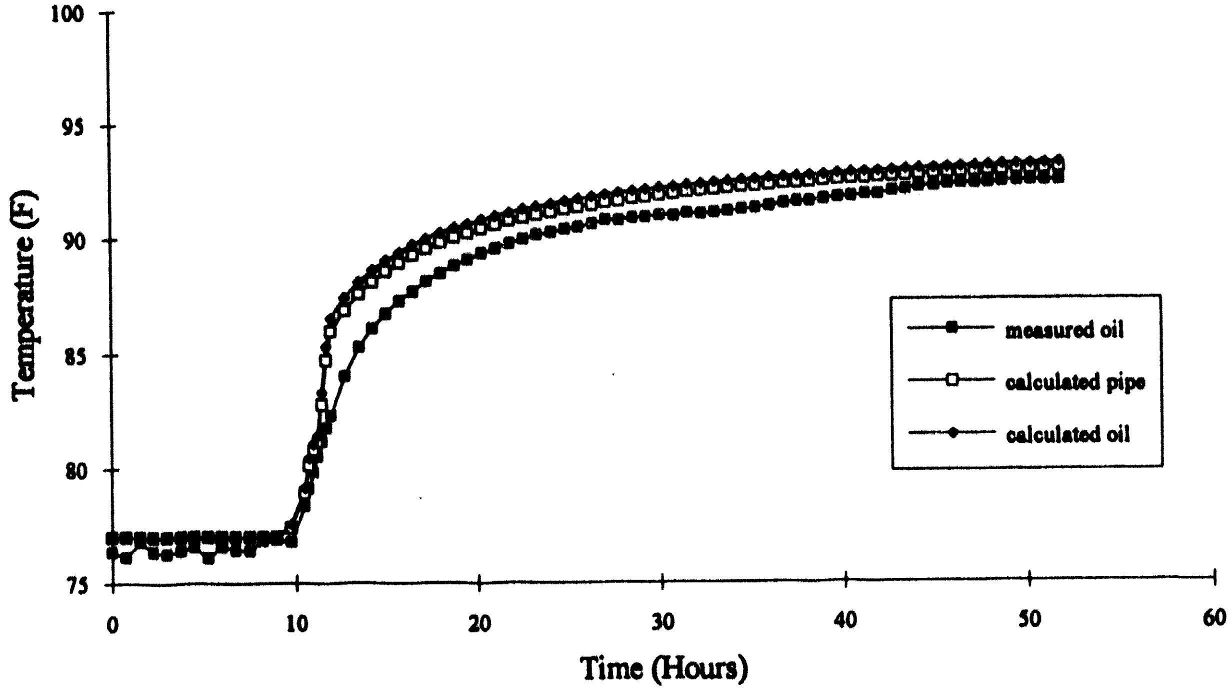

Figure C-4 - Comparison of measured and calculated oil temperatures at MLV5 located 18.0 miles from Bayou Choctaw.

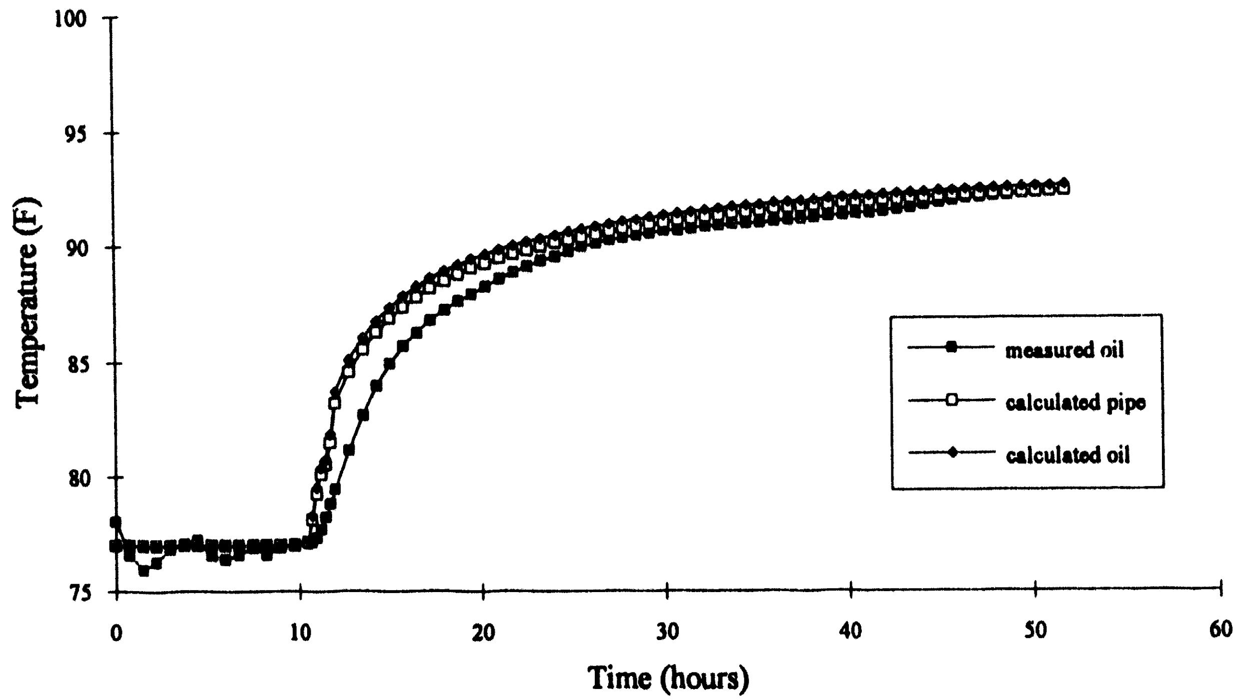

Figure C-5 - Comparison of measured and calculated oil temperatures at MLV6 located 20.7 miles from Bayou Choctaw.

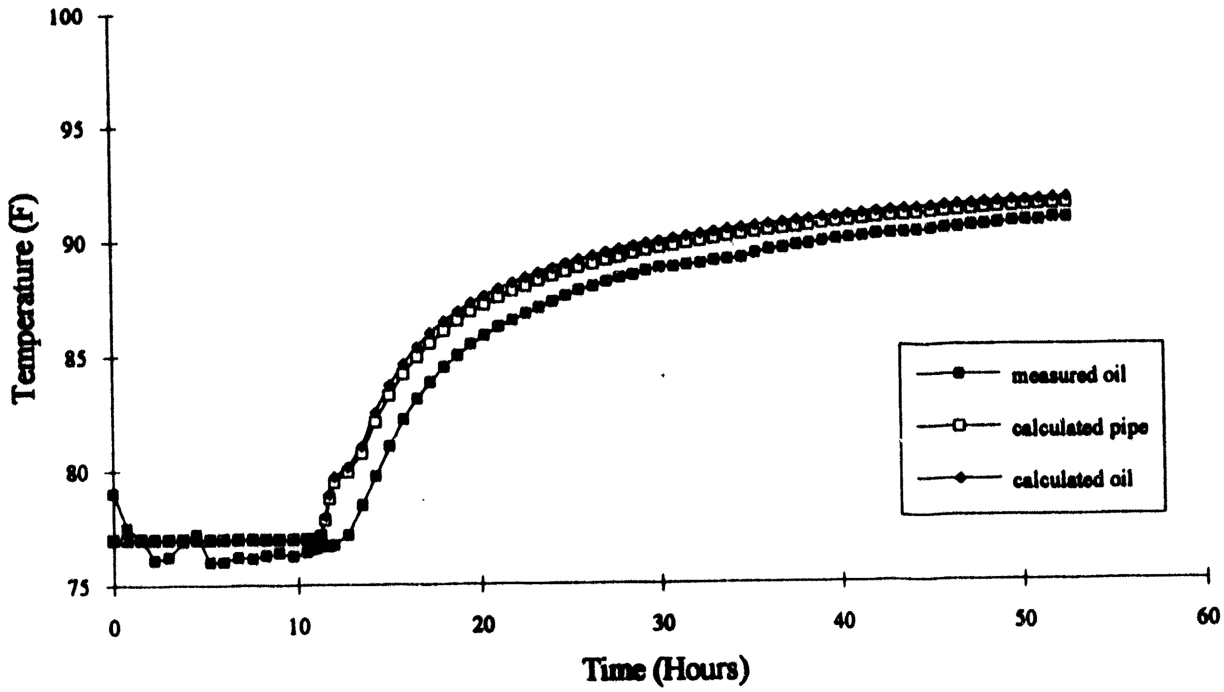

Figure C-6 - Comparison of measured and calculated oil temperatures at MLV7 located 24.6 miles from Bayou Choctaw.

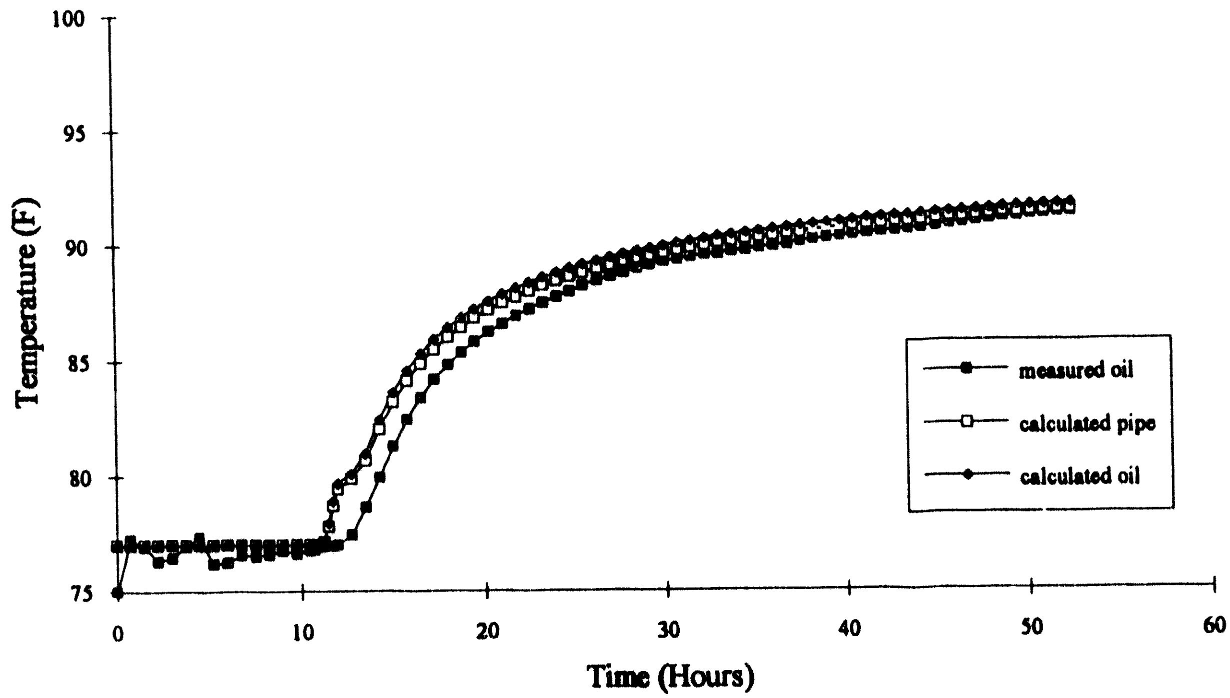

Figure C-7 - Comparison of measured and calculated oil temperatures at MLV8 located 24.7 miles from Bayou Choctaw.

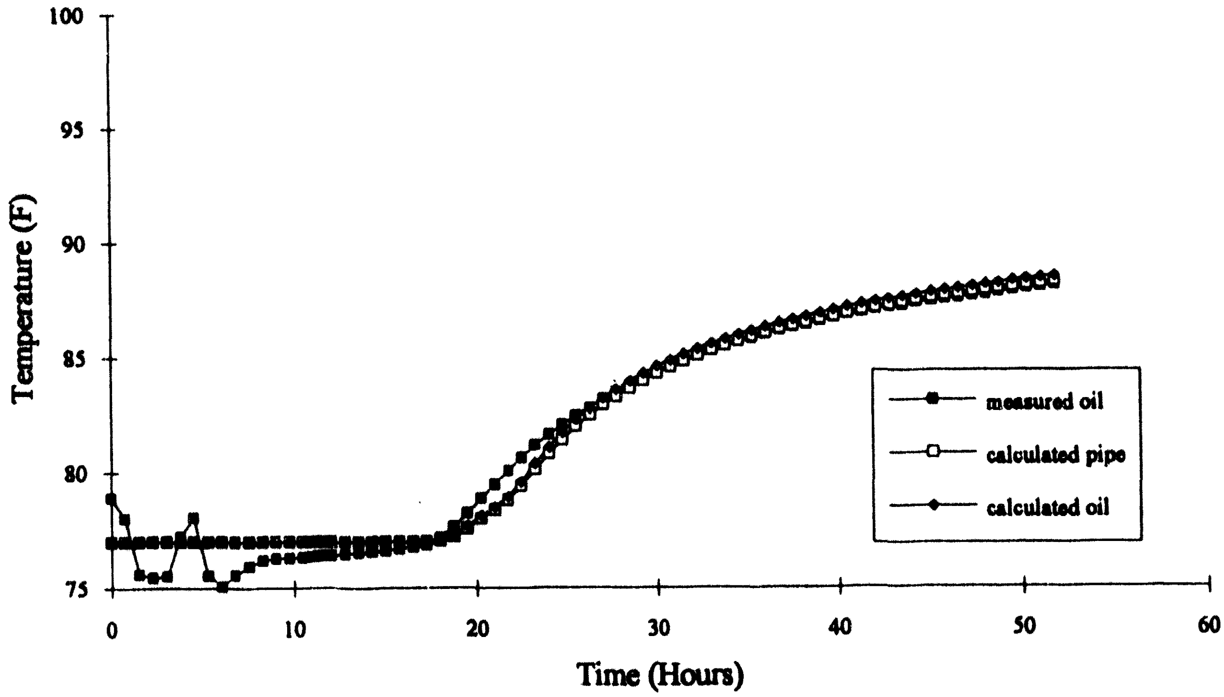

Figure C-8 - Comparison of measured and calculated oil temperatures at St. James located 37.2 miles from Bayou Choctaw.

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6100 (MS 0701) R. W. Lynch
6113 (MS 0706) J. K. Linn (10)
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