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A User's Manual for the Computer Code OILPIP

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Abstract

The code OILPIP was written to solve the problem of calculating the temperature change of oil in a buried pipeline as it is transferred from one location to another. This problem arises in connection with the transfer of oil from one storage location to another in the Strategic Petroleum Reserve. Because the vapor pressure of the oil is sensitive to temperature, and the storage containers are pressure limited, it is necessary to estimate the exit temperatures of the oil as it leaves the pipeline. OILPIP is a quasi-one-dimensional axisymmetric code which employs the method of lines to solve the one dimensional heat convection equation for the oil in the pipeline, for a given flow rate history, and the coupled two-dimensional axisymmetric heat conduction equation in the surrounding soil.

Acknowledgment

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Contents

1. Introduction

The transfer of oil in the Strategic Petroleum Reserve takes place through a piping network involving pipelines of varying length (8 to 42 miles). Oil stored in underground caverns heats up over a period of time because of the geothermal gradient. Transfer of oil through a pipeline generally cools the oil because of conduction of heat to the pipe and its surroundings. If the temperature of the oil at the pipeline exit is above the level where its vapor pressure exceeds the safety limits of the storage tanks or storage vessels, then it must be cooled. It is therefore important to be able to estimate the temperature change of the oil as it passes through the pipeline. A typical burial depth for the pipelines is approximately three feet (to the top of the pipe).

A quasi-one-dimensional code has been written to estimate the oil temperature in the pipeline and the nearby surrounding soil. This user's manual describes the code, and provides instructions for its use.

2. Model

Assuming one-dimensional, incompressible flow in the pipeline, the average or bulk temperature, T, at any point, x, in the pipeline at the time, t, is given by the heat convection equation:

(EQ 1)

$$\frac{\partial T}{\partial t} = -v\frac{\partial}{\partial x}T + (T_w - T)\frac{2h_c}{\rho C r_o}$$

where T_w is the pipe wall temperature, ρ is the oil density, C is the oil specific heat, r_o is the pipe radius, h_c is the convective heat transfer coefficient, and v is the oil flow velocity. The convective heat transfer coefficient is given by [1] $h_c = \frac{0.023\rho C v}{Re^{0.2}Pr^{0.667}}$ where Re and Pr are the Reynolds and Prandtl numbers respectively.

The oil viscosity, μ, which is required for the evaluation of the Reynolds number, $Re = \frac{2\rho r_o v}{\mu}$, is taken to be, $\mu = 0.00771\left(\frac{40}{T_{av}}\right)^{1.218}$ lb/ft s, where T_{av} is the average of the oil and wall temperatures.

The flow velocity and initial temperatures are specified as input parameters. The temperature in the soil surrounding the pipe is assumed to be given by the one-dimensional radial heat conduction equation;

(EQ 2)

$$\frac{\partial T_s}{\partial t} = \frac{k_s}{\rho_s C_s}\left(\frac{\partial^2}{\partial r^2}T_s + \frac{1}{r}\frac{\partial T_s}{\partial r}\right)$$

where k_s is the thermal conductivity of the soil as the subscript, s, refers to the soil.

The initial soil temperature is assumed to be constant in space and is specified as an input parameter in the code. The wall temperature is related to the oil and soil temperatures by

(EQ 3)

$$\frac{\partial T_w}{\partial t} = (T - T_w)\frac{h_c}{f_p} - (T_w - T_s)\frac{k_s}{\Delta r f_p}$$

where $f_p = \rho_p C_p \delta$, is the product of the pipe material density, ρ_p, specific heat, C_p, and pipe-wall-thickness, δ. The soil temperature refers to the value a distance Δr from the pipe surface.

Equations 1 and 3 are solved by the method of lines using the Sandia mathematical equation solver DEABM found in the SLATEC [2] library. Equation 2 is solved with a tridiagonal algorithm.

3. Code Inputs

The following quantities are required as input to operate the code. Each of the values for these quantities are to be listed in the given order, in free format, in an input data file called DATA. If any consistent set of units besides the English (ft-lb-s) set are used, values of the oil viscosity and pipe material properties, which are currently embedded in the code, must be changed.

NPR is the number of time steps between printouts. The length of each time step is specified by the input variable DT which controls the integration of EQ 2. If the time step chosen is too large for an accurate or stable solution the code will adjust it to a shorter value.

NVFLO is the number of time-flow-velocity pairs in the flow rate profile. The flow rate is linearly interpolated between these values. For example, if a flow rate is to start at zero at time equal to zero, rise to 5 ft/s in 100 seconds and remain at that value for 100,000 seconds, NVFLO would be set to 3, and values of 0.,0. 100.,5. and 100100.,5. would be provided for TFLO(I) and VFLO(I) for I=1 to 3. Because the code cannot treat values of velocity equal to zero (the Reynolds Number appears in the denominator of several expressions) the initial value of VFLO(1) will be set to a small number (0.01) internally.

TSOIL is the initial temperature of the soil surrounding the buried pipe.

TOIL is the oil temperature at the pipe inlet.

RHOIL is the oil density.

CPOIL is the oil specific heat.

AKO is the oil thermal conductivity.

RHOS is the average bulk density of the soil around the pipe.

CPS is the soil specific heat.

AKS is the soil thermal conductivity.

RAD is the pipe inner radius.

DT is the desired computational time step duration.

TEND is the end time of the calculation.

AL is the length of the soil in the radial direction to be considered (see Appendix A).

ALZ is the length of the pipeline to be modeled.

DELP is the pipe thickness (in feet in the default English system).

The velocity history profile is read in last by reading in NVFLO pairs of values of

TFLO time points at which the flow velocity is defined, and

VFLO flow velocity values.

If a single flow rate, V, is desired, set NVFLO to 1 with TFLO(1)=0. and VFLO(1)=V

A sample data set is shown in Appendix B

4. Code Output

After printing the input data to the screen as it is read, the code prints the radial temperature profile in the soil at the pipe exit to the screen every NPR time steps. The time (in hours) is printed and then two columns representing the radial position and soil temperature at that position follow. At the same time points, the pipe wall temperature at 4 locations along the pipe, and the oil outlet, and tank, temperatures are written onto unit 3 for post processing.

After the final time step the above information is also printed and written. In addition an array of soil temperatures at 6 positions along the pipe direction, and their positions (miles axially and feet radially) are written on unit 4.

If the oil being transported in the pipeline is being deposited into an empty vessel, the temperature in the vessel will reflect the temperature history of the oil being deposited. In general this is a lower value than the oil temperature at the pipe outlet at the conclusion of the transport process because the oil is initially cooled by the pipeline, particularly at early times in the flow. The value of the final temperature in the vessel (tank temperature) is also printed and written to unit 4. A sample of the code output data is also listed in Appendix B.

5. Results

A series of calculations were performed for a pipeline of various lengths for three different soil thermal conductivities. The oil filled pipeline was assumed to be 2.5 ft in diameter and its center was buried 4.5 feet below the surface so that AL was equal to 9.0. Oil properties were as given in the sample data set in Appendix B. The initial oil and ground temperatures were assumed to be 70 °F and the inlet oil temperature was 120 °F. Figure 1 shows the steady state temperature (after 20 days of flow) at the outlet for the different pipeline lengths for soil thermal conductivities of 4×10^{-4}, 2×10^{-4}, and 0.5×10^{-4} Btu/ft s °F. As expected, for any soil conductivity the final outlet temperature decreases with increasing length, and, for any length, increases with decreasing soil thermal conductivity. The calculations of Appendix A show that as the thickness of the soil layer around the pipe increases the outlet oil temperature also increases as does the time to reach steady state.

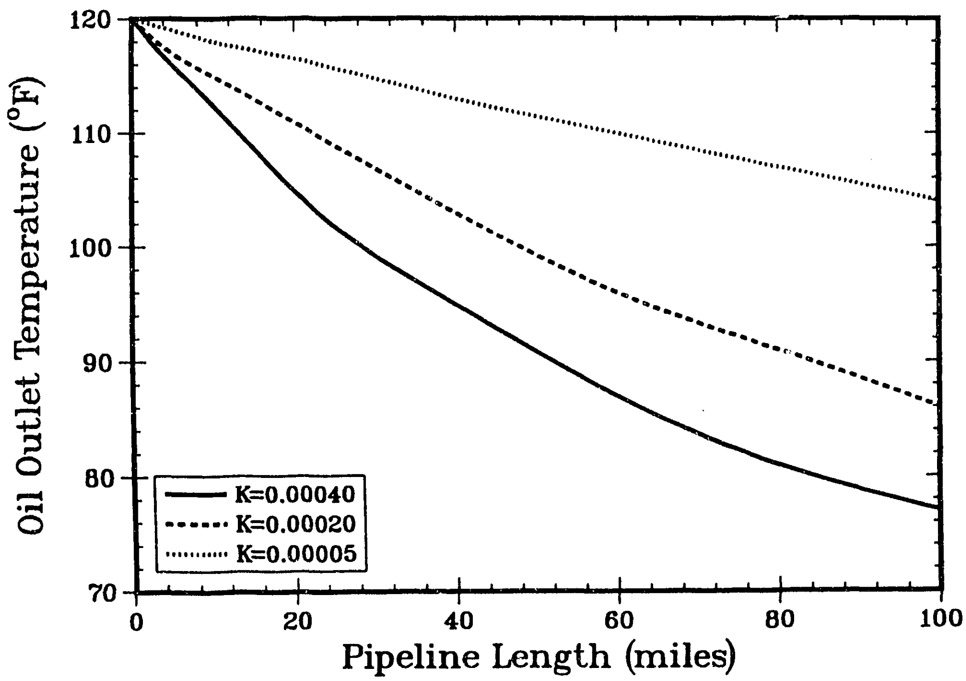

Figure 1.Calculated outlet oil temperatures, after 20 days, for different pipeline lengths and soil thermal conductivities. Inlet temperature was 120 °F and burial depth was 4.5 ft.

6. References

1. F. Kreith, *Principles of Heat Transfer,* International Textbook Co., Scranton, PA, 1960, p. 347.

2. K.W. Fong et al. "Formal Conventions of the SLATEC Library," SIGNUM Newsletter, V19 No. 1, Jan. 1984, pp 17-22.

Appendix A

Effective Radius Calculation

The main body of this report is concerned with the calculation of temperature changes in oil flowing through buried pipelines and has assumed that the buried pipeline could, as a first approximation, be modeled as an axisymmetric pipe surrounded by soil out to some specified radius, at which the temperature was known. This axisymmetric model avoids the complexity of a three-dimensional calculation and mesh generation, but introduces an uncertainty in what outer soil radius should be used to approximate the burial depth of the pipe. A first approximation might use the burial depth of the pipe (typically the top of the pipe is 3 ft. below the surface for SPR pipelines) as the bounding radius and the average atmospheric temperature as the bounding temperature. This is clearly not a conservative approximation if the maximum steady state temperature is of interest. This appendix describes a calculation to determine the axisymmetric radius that will best model the true three-dimensional geometry. The value chosen will be that which yields the same heat transfer, in the steady state, as the true geometry for the same temperature difference. A cross section of the idealized buried pipe problem is shown in Figure 1.

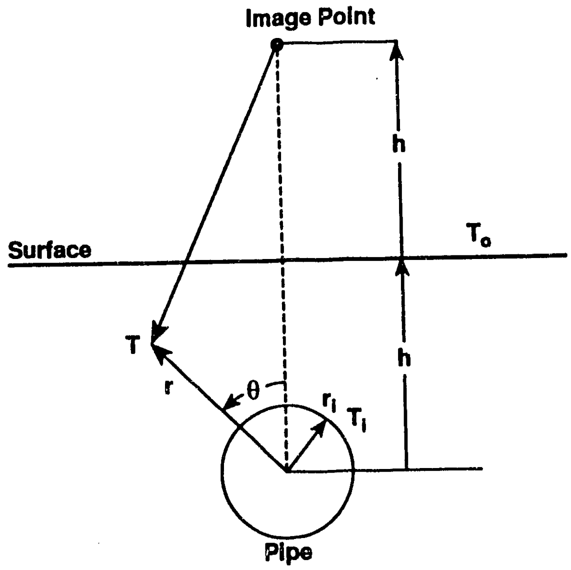

Figure 2. Geometry of a buried pipe cross section

In the soil, the steady heat conduction equation, with constant thermal conductivity, reduces to Laplace's equation, $\nabla^2 T = 0$. The solution in cylindrical coordinates of a constant temperature cylinder near a constant temperature plane can be found by the method of images.

(EQ 4)

$$T = \frac{(T_i - T_o)}{ln\left(\frac{r_i}{\sqrt{r_i^2 + (2h)^2 - 4r_ih\cos\theta}}\right)} ln\left(\frac{r_i}{r_1}\right) + T_o$$

where T_i is the cylinder temperature and T_o is the ground plane temperature. The distance r_1 is given by: $r_1 = \sqrt{r^2 + (2h)^2 - 4rh\cos\theta}$, and θ is the angle measured from the vertical. The total heat per unit length flowing out of the pipe in the axisymmetric case, q, is;

(EQ 5)

$$q = \frac{(T_i - T_o)\ (2\pi K)}{ln\left(\frac{r_o}{r_i}\right)}$$

where K is the thermal conductivity of the soil and r_o is the effective outer radius of the soil. The total heat per unit length flowing out of the pipe in the geometry of Figure 1 is:

(EQ 6)

$$q = (T_o - T_i) K \int_0^{2\pi} \frac{\left(1 - \frac{r_i}{r_{1i}}\right)}{ln\left(\frac{r_i}{r_{1i}}\right)} + \frac{2hr_i\cos\theta}{r_{1i}^2 ln\left(\frac{r_i}{r_{1i}}\right)} d\theta$$

where r_{1i} is the value of r_1 evaluated at the pipe surface. Equating the values of q and simplifying we obtain

$$ln\left(\frac{r_o}{r_i}\right) = \frac{\pi}{\int_0^{2\pi} \left(\frac{\left(2\left(\frac{h}{r_i}\right)^2 - \frac{h}{r_i}\cos\theta\right)}{R^2 ln(R)}\right) d\theta} \quad \text{(EQ 7)}$$

where

(EQ 8)

$$R^2 - 1 = 4\left(\left(\frac{h}{r_i}\right)^2 - \frac{h}{r_i}\cos\theta\right)$$

The value of $\frac{r_o}{r_i}$ can be found by the numerical integration of EQ 7. Note that the ratio of effective radius to pipe radius is a function of the parameter $\frac{h}{r_i}$ only, and is independent of soil properties. A plot of $\frac{r_o}{r_i}$ versus $\frac{h}{r_i}$ is shown in Figure 2.

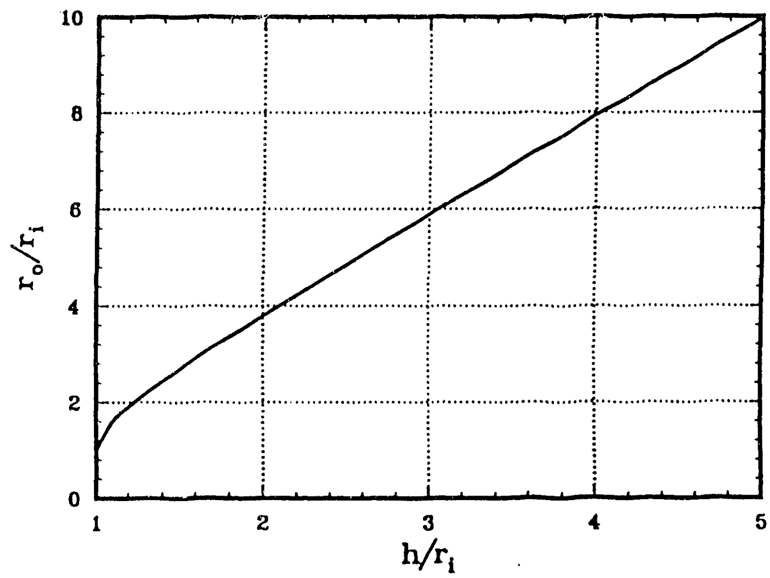

Figure 3. Effective radius ratio as a function of depth parameter from EQ 7.

It is seen that the slope of the effective radius ratio curve approaches 2 for large burial depth ratios, so that is a convenient rule of thumb.

A comparison of calculations for oil temperature loss through two different pipeline lengths is shown in Figures 3 and 4. In each figure the calculated exit temperature is shown for assumed outer radii of 4.5 and 9 feet. The pipeline length is 8 miles for the 30 inch dia. pipe shown in Figure 3. The change in effective radius has little effect for this shorter pipe. The 40 inch dia. pipe shown in Figure 4 is 43.6 miles long and it is seen that not only does the temperature take longer to reach steady state but the final temperature is significantly higher. All of these calculations were done assuming an outer temperature of 70 ^{o}F.

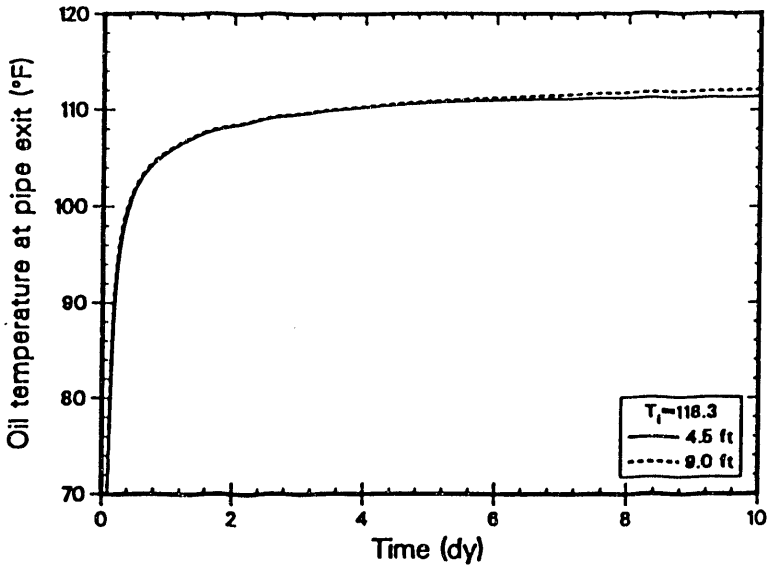

Figure 4. Calculated exit temperature for a 30 inch pipeline.

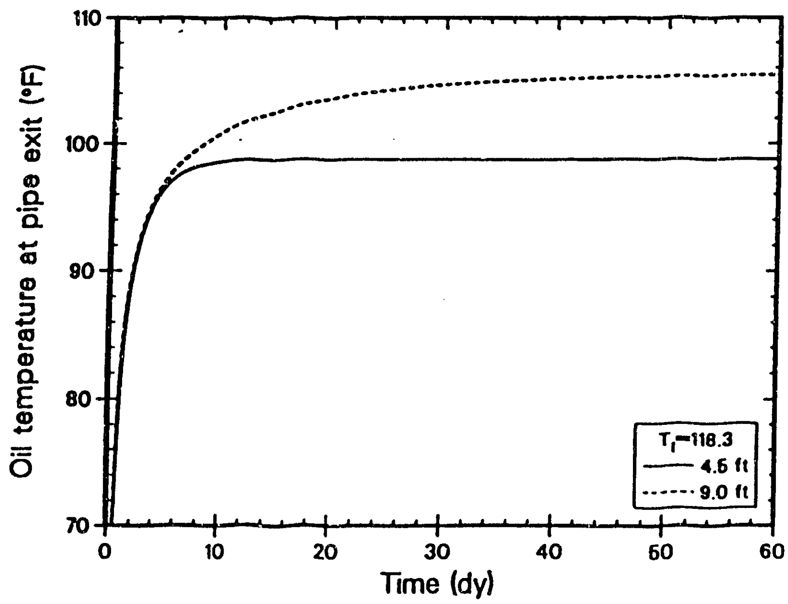

Figure 5. Calculated exit temperature for a 40 inch pipeline.

Appendix B

Samples of Input and Output Data

The following is an example of an input file, DATA, for the code OILPIP.

60 1 83.0 113.2 51.0 0.45 2.11e-5 125.0 0.50 4.0e-4

1.25 30.0 3.11148e4 3.0 58080.0 0.08333

0.0 4.2755

The corresponding output wall temperature history is written onto unit 3 as:

0.50	107.76	83.06	83.00	83.00	83.00	83.00
1.00	109.58	88.62	83.00	83.00	83.00	83.00
1.50	110.27	97.43	83.39	83.00	83.00	83.00
2.00	110.66	101.09	87.01	83.02	83.00	83.00
2.50	110.91	103.02	91.89	83.52	83.00	83.00
3.00	111.09	104.22	95.19	85.73	83.00	83.00
3.50	111.24	105.05	97.39	88.70	83.00	83.01
4.00	111.35	105.67	98.93	91.24	83.05	83.10
4.50	111.44	106.15	100.07	93.23	83.35	83.60
5.00	111.52	106.54	100.96	94.78	84.16	84.73
5.50	111.58	106.86	101.66	96.01	85.34	86.19
6.00	111.64	107.13	102.25	97.00	86.65	87.67
6.50	111.69	107.36	102.74	97.81	87.91	89.03
7.00	111.74	107.57	103.15	98.48	89.07	90.24
7.50	111.78	107.75	103.50	99.04	90.11	91.29
8.00	111.82	107.90	103.81	99.54	91.03	92.21
8.50	111.85	108.04	104.07	99.98	91.85	93.02
8.65	111.86	108.08	104.15	100.10	92.08	93.25

The final soil temperature array is written onto unit 4 as:

	0.0	2.2	4.4	6.6	8.8	11.0
1.25	111.86	108.08	104.15	100.10	96.03	92.08
1.26	111.16	107.39	103.49	99.48	95.47	91.61
1.28	110.43	106.68	102.81	98.85	94.90	91.13
1.30	109.68	105.95	102.11	98.20	94.33	90.65
1.31	108.91	105.19	101.39	97.53	93.74	90.17
1.33	108.10	104.42	100.65	96.86	93.15	89.69
1.35	107.28	103.62	99.90	96.17	92.55	89.22
1.37	106.42	102.80	99.13	95.48	91.96	88.75
1.39	105.55	101.96	98.35	94.78	91.36	88.28
1.41	104.64	101.10	97.55	94.07	90.77	87.83
1.43	103.72	100.22	96.75	93.36	90.18	87.39
1.46	102.78	99.34	95.94	92.65	89.60	86.96
1.48	101.81	98.43	95.12	91.94	89.03	86.54
1.51	100.83	97.52	94.30	91.24	88.47	86.15
1.53	99.84	96.60	93.48	90.55	87.93	85.78
1.56	98.83	95.68	92.67	89.87	87.41	85.42
1.59	97.82	94.76	91.86	89.21	86.91	85.09
1.62	96.80	93.84	91.07	88.57	86.44	84.79
1.66	95.78	92.94	90.30	87.95	85.99	84.51
1.69	94.77	92.04	89.55	87.37	85.58	84.26
1.73	93.77	91.17	88.83	86.81	85.20	84.04
1.77	92.78	90.32	88.13	86.29	84.85	83.84
1.81	91.82	89.50	87.48	85.81	84.53	83.67
1.85	90.88	88.72	86.86	85.36	84.25	83.53
1.89	89.98	87.98	86.29	84.96	84.00	83.40
1.94	89.11	87.28	85.77	84.60	83.79	83.30
1.99	88.30	86.64	85.30	84.29	83.61	83.22
2.04	87.54	86.05	84.87	84.02	83.46	83.16
2.10	86.83	85.51	84.50	83.79	83.34	83.11

2.15	86.19	85.04	84.18	83.60	83.25	83.08
2.21	85.61	84.63	83.91	83.44	83.17	83.05
2.28	85.10	84.27	83.68	83.32	83.12	83.03
2.34	84.66	83.97	83.50	83.22	83.08	83.02
2.41	84.28	83.72	83.36	83.15	83.05	83.01
2.48	83.96	83.52	83.25	83.10	83.03	83.01
2.56	83.70	83.37	83.17	83.06	83.02	83.00
2.64	83.49	83.25	83.11	83.04	83.01	83.00
2.72	83.33	83.16	83.06	83.02	83.00	83.00
2.81	83.20	83.09	83.04	83.01	83.00	83.00
2.90	83.09	83.04	83.02	83.00	83.00	83.00
3.00	83.00	83.00	83.00	83.00	83.00	83.00

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