Testing of and Model Development for Double-Walled Thermal Tubular

Topical Report

**R. M. Satchwell
L. A. Johnson, Jr.**

August 1992

Work Performed Under Contract No.: DE-FC21-86MC11076

For
U.S. Department of Energy
Office of Fossil Energy
Morgantown Energy Technology Center
Morgantown, West Virginia

By
Western Research Institute
Laramie, Wyoming

MASTER

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SUMMARY

Insulated tubular products have become essential for use in steam injection projects. In a steam injection project, steam is created at the surface by either steam boilers or generators. During this process, steam travels from a boiler through surface lines to the wellhead, down the wellbore to the sandface, and into the reservoir. For some projects to be an economic success, cost must be reduced and oil recoveries must be increased by reducing heat losses in the wellbore. With reduced heat losses, steam generation costs are lowered and higher quality steam can be injected into the formation.

To address this need, work under this project consisted of: the design and construction of a thermal flow loop, testing a double-walled tubular product that was manufactured by Inter-Mountain Pipe Company, and the development and verification of a thermal hydraulic numerical simulator for steam injection. Four different experimental configurations of the double-walled pipe were tested. These configurations included: (1) bare pipe case, (2) bare pipe case with an applied annular vacuum, (3) insulated annular pipe case, and (4) insulated annular pipe case with an applied annular vacuum. Both the pipe body and coupling were tested with each configuration.

The results of the experimental tests showed that the Inter-Mountain Pipe Company double-walled pipe body achieved a 98 percent reduction in heat loss when insulation was applied to the annular portion of the pipe. The application of insulation to the annular portion of the coupling reduced the heat losses by only 6 percent. In tests that specified the use of a vacuum in the annular portion of the pipe, leaks were detected and the vacuum could not be held.

From this work a new model for simulating the thermal hydraulics of saturated steam or hot water was developed. This model is capable of simulating the heat losses in surface lines from the boiler and through the wellbore to the reservoir sandface. This model extends the prediction of heat loss by allowing for a variety of surface pipe configurations and/or wellbore configurations to be simulated. The comparison of this new model to previously published models was performed. The new model can predict the field data over a larger range of operating parameters with better accuracy than any of the previously published models. Using this model, temperature, pressure, and steam quality at the reservoir sandface can be predicted with a high degree of accuracy and reliability. The information gained from these predictions can be used to design better well completion and provide better accuracy of steam flood performance.

INTRODUCTION

In light oil reservoirs, conventional oil recovery may extract up to 35 percent of the oil in the reservoir. In heavy oil reservoirs, a considerably larger fraction is left in-place. Thermal oil recovery techniques have demonstrated that a large amount of this unproduced heavy oil can be recovered. The major thermal recovery techniques in use are steam injection and in situ combustion.

Steam injection accounts for over 75 percent of the oil recovered using enhanced oil recovery (EOR) techniques. Efficient methods of transferring steam from the surface to the oil reservoir can reduce the cost of enhanced oil recovery. This can be achieved by reducing the heat losses in the injection string. Use of insulated tubulars can reduce the thermal losses and make the economics of steam EOR projects even more favorable.

The problem of controlling heat losses is one of considerable complexity. An insulated tubular design should produce a completion that will provide for minimum heat loss in the well. The selection of materials that will withstand the temperature extremes is also of major importance. The key to proper thermal recovery completions thus lies in an accurate knowledge of the temperatures and stresses involved. In addition, severe operating conditions that are imposed on completed injection wells should be considered. Temperatures must be kept at an acceptable level to avoid damage to or even failure of the casing.

To evaluate the feasibility of a hot fluid injection project, a good estimate of the heat carried by the injection fluid is extremely important. Knowing the temperature, pressure, and quality of the fluid at the formation is necessary to calculate heat content. However, at the present time, a physical method for measuring these bottom hole parameters is not available. A computer model must be used to estimate these parameters.

Inter-Mountain Pipe Company has developed a double-walled tubular which has the potential for being applicable in steam injection. However, laboratory verifications of the performance data were needed. These data include heat losses, temperature profiles, and other operating conditions. Western Research Institute (WRI) assembled a flow loop to develop a performance data base. The data are described in this report.

The primary objectives of this work were to: (1) evaluate Inter-Mountain Pipe's double-wall tubular for steam injection, and (2) develop a computer model to simulate the transient effect of steam injection under field conditions. These objectives were accomplished by building an instrumentated flow loop to test Inter-Mountain Pipe's product and developing a computer model to handle single- and double-walled tubing under a variety of conditions. The computer model was based on the Jensen and Sharma (1989) model, and includes the modeling efforts of Ramey (1962) and Satter (1963). Jensen and Sharma's model was modified to include boundary conditions not considered in the original work. The model developed includes several new theoretical and mathematical correlations, and an iteration scheme for pressure convergence. This makes it more comprehensive and versatile in solving the heat transfer problems associated with steam injection.

LABORATORY TESTING

Flow Loop Description

A steam flow loop was constructed at WRI's North Site facilities. The flow loop was designed such that heat loss in both the horizontal and vertical sections could be determined. The flow loop is shown schematically in Figure 1. The major components of the flow loop were: (1) a steam boiler, (2) a vertical flow section, (3) a horizontal flow section, and (4) a water recovery system. The tubular products used to build this flow loop were designed and fabricated by the Inter-Mountain Pipe Company.

Figure 1. Experimental Apparatus

The setup was designed as a closed flow loop system. Pressures and cross-sectional temperatures were monitored in each of the individual test sections, and recorded by the data acquisition system shown in Figure 2.

The setup was such that the steam generated from the boiler first flowed through the vertical test section and then through the horizontal test section, and into a water recovery system. Between the vertical and horizontal test sections, a sampling port was installed to drain and collect condensate. The electrical conductivities of the condensate and feed water were used to determine the average steam quality that existed between the two test sections.

The water recovery system incorporated a back-pressure regulator, a counter-current heat exchanger, a forced-air water chiller, and a condensate receiver with a float switch and a pump. The system provided a method for condensing the steam to water which was then pumped back to the boiler make-up water supply tank. The pressure controller and back-pressure regulator were incorporated in the system for three reasons. These reasons were: (1) to maintain a constant, overall system pressure, (2) to ensure that the steam was fully condensed into liquid after passing through the heat exchanger, and (3) to ensure that the condensate receiver was not pressurized.

The flow rate, temperature, and pressure of the water recovery system were continuously monitored to: (1) ensure complete condensation of the steam into water, (2) determine cold-water-equivalent flow rate, and (3) provide protection to the individual components that were sensitive to pressure and temperature.

Figure 2. Data Acquisition Schematic

Test Sections

Each test section (vertical and horizontal) was composed of an entrance, a test, and an exit subsection. Each of the sections was fabricated from Inter-Mountain Pipe's double-walled tubular product. The entrance subsection was about 153 inches long, with the test subsection being approximately 36 inches long. The length of the exit subsection was about 53 inches long. The subsection lengths were selected based on boundary layer theory, to establish stabilized flow conditions in each test section. The dimensions and configuration of the double-walled tubing body and associated coupling can not be shown because the design is proprietary. However, a generalized schematic of the pipe cross-section is shown in Figure 3.

Figure 3. Generalized Double-Walled Pipe Cross-Section

Inlet and exit fluid temperatures to the horizontal and vertical test sections were monitored using thermocouples TC1 and TC6, and TC8 and TC13, respectively. All thermocouple locations are shown in Figure 1. Thermocouples TC2 and TC3 in the horizontal test section and TC9 and TC10 in the vertical test section were positioned to measure the outside temperatures of the inner and outer tubing bodies, respectively of the double-walled tubes. The same configuration was implemented for measurements of the coupling temperatures, using thermocouples TC4 and TC5, and TC11 and TC12 in the horizontal and vertical test sections, respectively. Ambient temperatures were monitored for both the horizontal and vertical sections using thermocouples TC7 and TC14, respectively. Both absolute and differential pressures were monitored in the horizontal and vertical sections.

Experimental Procedure

Four different experimental configurations of the double-walled tubing were tested. These were: (1) no annular insulation, no vacuum; (2) no annular insulation, with vacuum; (3) annular insulation, no vacuum; and (4) annular insulation, with vacuum.

Each of the configurations was tested at steady-state flow conditions for a duration of 4 to 5 hours. Each experiment was initiated by stabilizing the boiler at 273°F (134°C). After stabilization, the valve between the boiler and flow loop was opened, allowing the steam to flow.

Typical experimental temperature profiles for the pipe body and pipe coupling, with and without insulation, are displayed in Figures 4, 5, 6, and 7, respectively. In all cases, steady-state stabilized temperature profiles were achieved in approximately one hour. The shape of the temperature histories were similar at all experimental conditions. In the case of the pipe bodies, Figures 4 and 5, the difference in temperature and the temperatures of the inner and outer walls were reduced by installing insulation in the annular portion of the pipe. As with the pipe couplings, Figures 6 and 7, little change in the temperatures was observed.

Figure 4. Pipe Body Temperature History with Insulation

Figure 5. Pipe Body Temperature History without Insulation

Figure 6. Pipe Coupling Temperature History with Insulation

Figure 7. Pipe Coupling Temperature History without Insulation

Flow was regulated manually with the use of a back-pressure regulator valve. The temperature and pressure were monitored at the inlet of the water recovery system. If the temperature at the inlet of the condensate barrel exceeded 180°F (82°C), then the regulator valve was further closed in order to reduce the temperature, which allowed the steam to completely condense. The condensate pump was controlled by a float switch. A turbine meter was employed to monitor the rate and the total volume of condensate pumped during each test period.

For testing configurations 2 and 4, a vacuum was applied to the annulus of the test sections. The testing procedure originally developed was to implement a pressure switch such that the vacuum pump would operate intermittently and maintain a pressure less than 0.1 torr in the annulus. However, the seals provided on the double-wall pipe could not hold a sufficient vacuum; thus, the vacuum pump ran continuously during the duration of all tests that used configurations 2 and 4.

A condensate sample from the flow loop and a feedwater sample from the boiler were taken approximately 30 minutes before each test was completed. The samples were allowed to cool, and electrical conductivities were measured and recorded. The data were used to compute the steam quality based on the water conductivity.

Experimental Results

A summary of the experimental test conditions is given in Table 1. The rate of heat injection through the flow loop during each test period ranged from 226,892 to 256,515 Btu per hour. The steam quality varied from 93.9 to 97.3 percent. The total cold-water-equivalent flow rate varied from 725 to 819 gallons per day. After the steady-state temperature profiles were achieved, the differential pressures were constant during the physical simulations.

Table 1. Experimental Test Conditions

Test No.	Steam Quality, %	Flow Rate, gal/day	Total Heat Injected, Btu/hr
1	94.1	819	251,330
2	93.9	790	242,061
3	97.3	816	256,515
4	96.7	725	226,892
5	95.2	807	249,723

Heat losses were computed with the following assumptions: (1) steady-state conditions existed in the test sections, (2) one-dimensional heat transfer in the radial direction, (3) negligible pipe wall thermal resistance, (4) convective heat transfer coefficient was constant, and (5) emissivity of steel was constant.

Based on these assumptions, the heat loss for each of the test sections and each test configuration was calculated using the temperature data given in Appendix A. A summary of the experimental results for the heat losses for several combinations of independent variables tested including the test section (either horizontal or vertical), the location (either pipe body or coupling), the insulation (installed or not installed), and the vacuum (with or without) is presented in Table 2.

Statistical analysis of the data was performed with respect to heat loss using coded data that represented the non-numerical data in matrix form. A matrix was developed using the independent variables (test number, test section, location, insulation, and vacuum) with respect to the dependent variable (heat loss). This matrix was developed with each independent variable having a normal distribution. For example, the coding of the insulation data was performed by assigning either a +1 or a -1, signifying that insulation was installed or not installed, respectively. After this coding was performed, both Pearson's product moment correlation coefficients

(Hines 1980) and Spearman's rank order correlation coefficients (Ullman 1972) were obtained from the analysis. Both methods were used to determine if any correlations existed between the heat loss and the other independent variables. No significant correlation was found between the test numbers and the test sections. This indicated that the physical simulations and testing procedures from test to test were performed in an unbiased manner. The analysis also showed that insulation and location terms were the only significant variables. There was no significant difference between the horizontal and vertical test sections.

Table 2. Experimental Heat Loss Summary

Test No.	Test Section	Location	Insulation	Vacuum	Heat Loss Measured, ^a Btu/hr	
1	Horizontal	Body	yes	no	65	^b
2	Horizontal	Body	yes	yes	65	^b
3	Horizontal	Body	no	yes	5035	
4	Horizontal	Body	no	no	4530	
5	Horizontal	Body	yes	no	144	
1	Horizontal	Coupling	no	no	4044	
2	Horizontal	Coupling	no	yes	4165	
3	Horizontal	Coupling	no	yes	4708	
4	Horizontal	Coupling	no	no	4226	
5	Horizontal	Coupling	yes	no	3384	
1	Vertical	Body	no	no	4875	
2	Vertical	Body	no	yes	4925	
3	Vertical	Body	yes	yes	144	
4	Vertical	Body	yes	no	145	
5	Vertical	Body	yes	no	144	
1	Vertical	Coupling	no	no	3621	
2	Vertical	Coupling	no	yes	3621	
3	Vertical	Coupling	no	yes	4226	
4	Vertical	Coupling	no	no	2573	
5	Vertical	Coupling	no	no	3412	

^a Measured in 3-foot pipe body or 6.75-inch coupling

^b Possible steam leak to annulus during test

All vacuum tests were intended to be performed at an absolute pressure of less than 0.1 torr. Perry's Chemical Engineering Handbook (Perry and Green 1984) states that pressure dependence of the thermal conductivities of gases is negligible between pressures of 1 torr to 10 atmospheres. Below pressures of 0.1 torr, the thermal conductivities of gases are almost proportional to absolute pressure and could be decreased by applying a higher vacuum. The insignificance of the vacuum variable can be attributed to the fact that a reasonable vacuum was never obtained in the annular space. Since, heat losses were not reduced and an increase in annulus pressure was observed, it appears that an adequate vacuum could not be maintained even though the vacuum pump ran continuously.

The results of the tests on the 3-foot test sections indicated that the insulated pipe body had an average heat loss rate of about 105 Btu per hour; whereas the uninsulated pipe body had an average heat loss rate of 4,703 Btu per hour, a 98 percent reduction in the overall heat loss. The 6-inch long insulated pipe coupling had a heat loss rate of 3,384 Btu per hour; whereas the uninsulated coupling averaged a heat loss rate of 3,575 Btu per hour, only a 6 percent reduction in the heat loss rate. This relatively minor reduction in the heat loss rate in the insulated coupling is a direct consequence of the major heat loss path through the metal to metal contact of the inner tube support steel ring located in the coupling.

If a new coupling design could incorporate an insulator support ring instead of the metal support ring, and/or a smaller cross-section area, then the heat losses could be reduced dramatically. Furthermore, if a positive seal system was designed which would support a vacuum of less than 0.1 torr, the heat losses could be reduced further.

NUMERICAL MODEL DESCRIPTION

General

The thermal hydraulics model presented in this paper calculates the heat losses in surface piping and the wellbore during steam injection. The model has been compared with other models and validated with field data. This model can be used as a tool to assist in designing steam injection systems and steam flood projects. The problem of estimating heat losses is of considerable complexity. Some of the phenomena involved in the modeling effort include: non-isothermal fluid flow, two-phase fluid flow, and transient heat losses.

This modeling effort was divided into two parts: (1) the analysis of the heat transfer process which leads to the predication of the overall heat transfer coefficient and heat loss, and (2) the analysis of pressure loss predictions. In the case of surface lines or wellbores, heat is transferred from or to a fluid by means of a differential temperature. All three heat transfer modes, conduction, convection, and radiation, can contribute to the heat transfer process in wells.

Literature Review

A number of investigators have presented models for wellbore heat loss during steam injection projects. The following discusses some of the more important contributions in the literature. These contributions are given in order of increased accuracy of prediction and sophistication.

One of the first studies of wellbore heat losses was by Moss and White (1959). Their method divided the well into a finite number of point sources or sinks (production or injection). Temperature was calculated as a function of time and depth using an exponential integral approach. Their model also included an iterative procedure to match the heat gained or lost to the surrounding formation. Errors inherent in their modeling effort were: (1)

the neglecting of radiation in the annulus, (2) neglecting the changes in fluid properties, (3) the use of the line source solution procedure, and (4) the assumption of a source of constant strength with time.

Ramey (1962) presented an approximate solution to the wellbore heat transmission problem for the injection of hot or cold fluids. His solution estimated the temperature of fluids, tubing, and casing as a function of depth and time. Ramey's solution assumed that heat transfer in the wellbore was steady state, while heat transfer to the earth was unsteady radial convection. Other assumptions in his model include: (1) formation and fluid properties were independent of depth and temperature, (2) radiation heat losses, frictional losses, and kinetic losses were negligible, and (3) the overall heat transfer coefficient was independent of depth.

Satter (1963) extended Ramey's model for use with saturated steam. In his solution method, fluid temperature and wellbore heat transfer coefficient were used in semi-analytical correlations to obtain steam quality as a function of depth and time. Satter improved Ramey's model by providing correlations for heat transfer coefficient and fluid properties as functions of depth. However, Satter's solution method was similar to Ramey's, in that changes in pressure with depth were neglected.

Leutwyler (1966) further developed the wellbore heat loss modeling effort by including the effects of radiation. However, the changes in pressure and fluid properties were not accounted for in this modeling effort. Leutwyler concluded that casing temperatures could be reduced by emissivity reducing coatings to the tubing, but the reduction in heat flow required a mechanical barrier such as insulation. These results also pointed out that increased annular pressures caused higher heat transfer rates. Other results of this work indicate that the application of an insulating cement sheath outside the casing could lower the heat losses, but would increase the casing temperature.

The contribution of Host and Flock (1966) attempted to account for frictional pressure losses, using a simple friction factor correlation. However, the frictional pressure loss model did not account for the type of flow regime or slip concept. Also neglected in their model effort were the effects of gravitational pressure changes. Their results indicated that friction could reduce heat losses, and the effect of friction on temperature and steam quality profiles was significant.

Earlougher's (1969) modeling efforts were similar to those of Satter. However, his model included the effect of pressure changes in the injection string and the effect of casing and cement on heat transfer. In Earlougher's model, the Hagedorn and Brown (1965) correlation was implemented to estimate friction pressure losses. This frictional pressure loss model assumes that the Reynold's number exceeds 1,000,000 and slip does not occur between the phases. Results from Earlougher's work indicate that pressure changes cannot be neglected in determining heat transfer, and that frictional pressure losses and gravitational pressure changes should be included.

The next significant modeling effort was by Farouq Ali (1981). His model used mass and momentum balances in the wellbore, and included heat balances in the wellbore and the surrounding medium. Unlike previous models, pressure calculations accounted for slip and the type of flow regime. Heat losses were treated rigorously, and the overall heat transfer coefficient accounted for a variety of well completion types. This model incorporated Pacheco and Farouq Ali's (1974) work and was further updated to include pressure losses and flow regimes using the correlations of Gould et al. (1974), Chierici et al. (1974), and Duns and Ros (1961). Farouq Ali's model yielded good agreement with field data. This work revealed that both the slip and flow regime concepts were essential in the calculation of pressure losses, which in turn were important in determining heat loss. Other results indicated that tubing paint or insulation can result in a significant reduction in heat losses.

The last model reviewed in this paper was that of Durrant and Thambynayagam (1986). Their model was based on material and momentum balances in the wellbore and a heat balance on the entire system, including the surrounding medium. Transient heat conduction was solved analytically by using Fourier and Laplace transforms. The Gould et al. (1974) and the Beggs and Brill (1973) pressure drop correlations were used to account for pressure losses. These correlations account for slip and different flow regimes.

As shown in the brief literature review, wellbore heat loss models have become more accurate and sophisticated using more advanced numerical solutions with a reduction in the many assumptions. However, discrepancies still exist between observed data and predicted results. The model modified in this study attempts to further improve the wellbore heat loss solution. These refinements were accomplished with the use of several theoretical, semi-theoretical, and mathematical correlations. This model also simulates the flow of steam from the boiler to the formation sandface under a variety of boundary conditions.

Model Description

The model reported here was originally developed by Jensen and Sharma (1989). Modifications to the original model were incorporated to include multiple tubing and casing strings, as well as the effects of a vacuum, and a convergence scheme for pressure. The model simulates the flow of saturated steam or hot water along a surface line and/or down a wellbore. The simulator can use a variety of surface line configurations that include buried or unburied, and insulated or uninsulated conditions. The wellbore modeling can include single- or double-walled tubing with or without insulation, multiple casing strings, different gases in the casing or tubing annuli with or without a vacuum, and multiple down hole formations. The simulator program is intended to be used with a file utility program and a full screen

editor. A listing of the source code of the simulator program is given in Appendix B.

The model is a finite difference simulation in length, for a specific time level. It has specifically been designed to simulate the flow of a hot-injection fluid from its source to the sandface. To simulate the transient effects, simulation runs are required for successive time steps. The model listed in Appendix B assumes that the injection fluid is either saturated steam or hot water. But the model is applicable to any hot-injection fluid as long as the correct thermal and physical properties are used.

For each control volume (length or depth) the heat loss and temperature or steam quality was first estimated. Then the pressure drop for each control volume was estimated using either the Lockhart and Martinelli (1949) correlation for two-phase saturated steam or the Moody friction factor (1944) and the Serghides (1984) correlation for single-phase flow. Iterations on pressure were performed until convergence was obtained. During the iteration process, fluid properties were continuously being updated. This pressure loss was used to modify the pressure in each control volume. If the saturated steam regime exists, the saturation temperature is updated according to the new saturation pressure by the use of a steam table. Depending on the fluid condition (saturated steam or hot water), the fluid properties are updated according to the new temperature and pressure by the use of correlations and look-up tables before moving to the next control volume.

A study was performed to determine the optimum control volume size. For a change in control volume size from 10 feet to 1 foot, the change in predicated results was approximately 10 percent. The change in predicated results was less than 1 percent when the control volume size was changed from 1 foot to 0.1 foot. Based on these results, a 1-foot control size was determined to be sufficient for the modeling effort.

For the estimation of heat loss and pressure change across one control volume, the fluid properties at the inlet of the control volume were used. These properties were assumed to be constant over the control volume. They were updated according to the outlet temperature and pressure from the control volume or used in calculating heat loss and pressure changes in the next control volume. To justify the assumptions of using inlet properties, a study was performed using an iterative loop which averaged the inlet and outlet fluid properties of the control volume. The results of the study indicated that, with a 1-foot control volume, the change in results was insignificant. The assumption of using inlet conditions was therefore valid.

The assumptions used in this model were: (1) heat is transferred radially away from the pipe, (2) fluid and heat flow are steady-state processes, except for heat loss in the wellbores, (3) the changes in physical and thermal properties are negligible for small intervals of pipe length, but are a function of axial distance, (4) heat transfer in the direction of fluid flow is attributed to only forced convection, and (5) the heat flux between two specified points is proportional to the temperature difference and inversely proportional to the overall specific thermal resistance.

The correlations used in this modeling effort were obtained from Jensen and Sharma (1987, 1989). These include heat transfer coefficients for the outside of surface pipes, film heat transfer coefficients for hot water flowing inside a surface pipe or down a well, and local film heat transfer coefficients for condensing steam flowing inside a surface line or down a well. Jensen and Sharma's (1987) work showed that the correlations used in this modeling effort were valid for vapor velocities from 20 to 1,000 feet per second, and steam qualities ranging from 0 to 99 percent.

For free convection in the annulus, the coefficients of heat transfer by radiation and convection were estimated using Willhite's (1967) correlations. The thermal conductivity, thermal diffusivity, and transient behavior of the surrounding formations were handled using the dimensionless time function developed by Ramey (1962) and Willhite (1967).

This new model accounts for pressure changes resulting from single-phase (hot water) and two-phase systems. From an independent study of friction factors by Jensen and Sharma (1987) and the Serghides (1984) friction factor, the correlation factor for single-phase flow was found to be best suited for this model.

Model Sensitivity Analysis

To evaluate model variation with parameter changes, several different cases were investigated with the numerical model. Heat loss, bottom hole temperature, bottom hole pressure, and steam quality were determined. Input parameters investigated were (1) single tubing versus dual tubing strings configurations, (2) insulation thickness, (3) injection rate (Rate), and (4) injection temperature (T_{inj}) and pressure (P_{inj}). Other parameters investigated, shown in Tables 3 and 4 but not discussed, included injected steam quality (SQ_{in}), and injection depth (Depth). Numerical results are consistent with the dynamics of the flow and existing discussions found in the literature.

A sensitivity study for a single tubing string was performed. The results are given in Table 3. Other parameters that were not investigated, but entered as input parameters included the heat transfer properties of steel, heat transfer properties of other insulating material other than the referenced material given in the Appendix C, heat transfer properties of surrounding formations, and surface pipe heat loss configurations.

The first three examples of Table 3 represent the effect of insulation thickness on steam quality (SQ) and total heat loss (HL). The results indicate that for constant heat input conditions, heat loss is reduced, resulting in higher steam qualities as the insulation thickness is increased. For example, an insulation thickness of 0.70 inches produced a 3.2 percent heat loss and a steam quality of 75.4 percent. Under the same conditions without any insulation, heat loss was determined to be 3.4 percent with a corresponding steam quality of 75.0 percent.

Table 3. Single Tubing String Sensitivity Study of Numerical Model Parameters^a

Insulation Thickness, inch	Rate, b/d	T _{inj} , °F	P _{inj} , psia	SQ _{inj} , %	Depth, feet	T _{depth} , °F	P _{depth} , psia	SQ _{depth} , %	HL %
0.70	350	484.9	600.0	80.0	400	487.6	601.2	75.4	3.2
0.50	350	484.9	600.0	80.0	400	487.6	601.2	75.3	3.3
0.00	350	484.9	600.0	80.0	400	487.6	601.2	75.0	3.4
0.70	300	484.9	600.0	80.0	400	487.7	602.1	74.6	3.7
0.70	250	484.9	600.0	80.0	400	487.8	602.8	73.5	4.4
0.70	350	484.9	600.0	70.0	400	487.6	601.5	65.4	3.4
0.70	350	484.9	600.0	90.0	400	487.6	601.5	85.4	3.0
0.70	350	466.2	500.0	80.0	400	468.2	500.0	75.8	3.0
0.70	350	444.3	400.0	80.0	400	445.5	398.7	76.3	2.7
0.70	350	484.9	600.0	80.0	500	487.6	601.5	74.2	4.0
0.70	350	484.9	600.0	80.0	600	487.7	601.8	73.1	4.7

^a performed with single tubing string (2.992-inch i.d. x 3.500-inch o.d.) in casing (4.950-inch i.d. x 5.500-inch o.d.) cemented in an 8.017-inch hole for 365 days

Injection rates were varied from 250 to 350 barrels per day of cold water. The results show that as the injection rate was increased, the temperature (T_{depth}) and steam quality (SQ_{depth}) at the bottom hole depth increased, resulting in a reduction in the net heat loss. There are two reasons for this reduced heat loss. First, the duration of time for which the injection fluid is exposed to the temperature difference between the injection fluid and the surrounding formations decreases with increasing flow rates, thus reducing the total heat loss per unit mass of steam. Second, the frictional pressure drop increases with increasing flow rates, reducing the rate of decline of the saturation temperature and pressure, resulting in a reduced heat flux per unit mass of steam.

Another phenomena predicted by the model is the existence of a critical flow rate below which adverse conditions persist, an interesting aspect of wellbore heat transfer not normally found in the literature. This phenomena shows that saturation pressures and temperatures are larger at the stated depth than under wellhead injection conditions. This condition is caused from the gravitational pressure increase being greater than the frictional pressure drop, causing the absolute pressure going down the well to increase. This increase in absolute pressure increases the saturation temperature, which in turn affects the fluid properties, such as density, viscosity, thermal conductivity, and latent heat of vaporization. The latent heat of vaporization decreases with increasing saturation temperature, causing the rate of steam condensation to increase as the pressure and temperature increase. This increase in condensation causes the pressure gradient to become even more dominant, thus creating an adverse spiral of events. In most of the cases examined, these conditions existed and this phenomena indeed occurred.

Further numerical modeling studies were performed using a double-walled tubing string. The results of this sensitivity study are given in Table 4. The parameters investigated include those given in Table 3, as well as different insulating configurations of the double-walled tubing. Insulating configurations used were air and/or insulation in the annulus and around the pipe.

The results obtained using the double-walled pipe were consistent with those using the single tubing string. However, by using insulation instead of air in the annulus of the double-walled tubing, a heat loss reduction of more than 50 percent (2.8 to 1.3 percent) was observed. The addition of insulation around the outer pipe resulted in only a minor reduction in the heat loss (1.3 to 1.2 percent).

Table 4. Double-Walled Tubing String Sensitivity Study of Numerical Model Parameters^a

Tubing Annulus Insulation Material	Rate, b/d	T _{inj} , °F	P _{inj} , psia	SQ _{inj} , %	Depth, feet	T _{depth} , °F	P _{depth} , psia	SQ _{depth} , %	HL %
insul ^b	350	484.9	600.0	80.0	400	487.6	601.2	78.1	1.3
air ^c	350	484.9	600.0	80.0	400	487.6	601.2	76.0	2.8
air-insul ^d	350	484.9	600.0	80.0	400	487.6	601.2	76.8	2.2
ins-ins ^e	350	484.9	600.0	80.0	400	487.6	601.2	78.3	1.2
insul ^b	300	484.9	600.0	80.0	400	487.7	602.8	77.8	1.5
insul ^b	250	484.9	600.0	80.0	400	487.8	602.8	77.3	1.8
insul ^b	350	466.2	500.0	80.0	400	468.2	500.0	78.2	1.3
insul ^b	350	444.3	400.0	80.0	400	445.5	398.8	78.4	1.2
insul ^b	350	484.9	600.0	70.0	400	487.6	601.4	68.1	1.4
insul ^b	350	484.9	600.0	90.0	400	487.6	601.6	88.1	1.2
insul ^b	350	484.9	600.0	80.0	500	487.7	602.0	87.6	1.5
insul ^b	350	484.9	600.0	80.0	600	487.8	602.3	87.1	1.8

^a performed with double-walled tubing string (2.992-inch i.d. x 3.500-inch o.d. inner string) and (4.950-inch i.d. x 5.500-inch o.d. outer string) in casing (8.017-inch i.d. x 8.625-inch o.d.) cemented in a 11.00-inch hole for 365 days

^b insulation in the double-walled tubing annulus

^c air in the double-walled tubing annulus

^d air in double-walled tubing annulus and 2 inches of insulation around outer tubing string

^e insulation in double-walled tubing annulus and 2 inches of insulation around outer tubing string

To determine the effects of time and to provide a comparison of the single tubing string to the double-walled tubing string, numerical simulations were performed with constant input parameters for various completion cases to a depth of 4,000 feet. The completion cases were:

Case A - Single tubing string (2.992 inches x 3.500 inches) with casing (8.017 inches x 9.625 inches) cemented in an 11.000-inch hole;

Case B - Single tubing string (2.992 inches x 3.500 inches) with 2.0 inches of external insulation, with casing (8.017 inches x 8.625 inches) cemented in an 11.000-inch hole;

Case C - Double-walled tubing string (inner pipe - 2.992 inches x 3.500 inches, outer pipe - 4.950 inches x 5.500 inches) with casing (8.017 inches x 8.625 inches) cemented in an 11.000-inch hole;

Case D - Double-walled tubing string (inner pipe - 2.992 inches x 3.500 inches, outer pipe - 4.950 inches x 5.500 inches) with annular insulation, with casing (8.017 inches x 8.625 inches) cemented in an 11.000-inch hole;

Case E - Double-walled tubing string (inner pipe - 2.992 inches x 3.500 inches, outer pipe - 4.950 inches x 5.500 inches) with annular insulation, with 2.0-inch external insulation, with casing (8.017 inches x 8.625 inches) cemented in an 11.000-inch hole;

The results of these cases are shown in Figures 8 and 9 for heat losses and steam quality as a function of time, respectively.

To provide a comparison of each case, the average heat loss and average steam quality of the 1000 day injection period were computed using a trapezoid computational method. In Figure 8, the difference in heat loss of Case D (annular insulated double-walled tubing string) compared to Case A

Figure 8. Case Studies of Heat Losses

Figure 9. Case Studies of Steam Quality

(single tubing string) is reduced by approximately 30 percent during the entire injection period. At the heat injection rate of 1502.2 Btu per second, the use of Case D tubing completion results in a heat loss reduction of 38.937×10^{10} Btu. If propane were used as fuel at a cost of \$2.76 per pound (\$0.65 per gallon) and a net heat of combustion of 19,944 Btu per pound, a fuel savings of more than \$5.3 million dollars could be realized. Comparing Case B (insulated single tubing string) to Case D with the same parameters, a fuel savings of more than \$2.8 million could be realized using the annular-insulated double-walled tubing string.

A case-by-case depiction of reducing this heat loss as a function of steam quality is illustrated in Figure 9. In Figure 9, an average increase of steam quality of 44 percent, using the trapezoid computational method, is obtained when comparing Case D to Case A. This increased steam quality would result in increased production rates as well as higher ultimate recoveries.

Other significant results shown in both Figures 8 and 9 are little net change in heat loss and steam quality by using external insulation (Case E to Case D). Another interesting result is a small difference in steam quality and heat loss between the non-insulated double-walled tubing string and the insulated single tubing string.

Model Verification

The task of measuring steam quality at various depths in a wellbore is a complex and separate project by itself. However, published field data for steam temperature was used for the validation of this model and also as a comparison to previously published models.

The new model developed for this project predicts the field data better than the two previously published models, as shown in Figure 10. Figure 10 shows the steam temperature as a function of depth using the data from Well No. 61-0, Martha Bigpond Field, Oklahoma as reported by Bleakley (1964).

During this field project, steam was injected at 80 percent quality at a rate of 4,850 pounds per hour through 2-inch tubing for a period of 5 days. As shown in Figure 10, the predictions of the Farouq Ali (1981) model deviate away from the field data at a depth of 800 feet, and continue to increase in error to the total depth of the well. The Durrant and Thambynayagam (1986) model maintains a constant error from the surface to total depth. Even though the steam temperatures predicted by the other models differ by only a small amount from the measured steam temperatures, the differences will be greater for the predicted saturation pressures. For example, at a saturation temperature of 380°F (193°C), a difference in temperature of 4°F (2.2°C) equivalent to a difference of 10 psia in the saturation pressure. A comparison of these models to the new model shows that the steam qualities differ by more than 30 percent at steam qualities lower than 0.35. These differences may be attributed to two-phase frictional pressure predictions and the physical and thermal property correlations used.

Figure 10. Numerical Model Comparisons

CONCLUSIONS AND RECOMMENDATIONS

Heat losses were determined for four different configurations of the double-walled tubular product provided by the Inter-Mountain Pipe Company. A flow loop was constructed to develop a data base for the evaluation of the thermal properties of the pipe. Also performed in this work, was the development of a thermal hydraulics simulator.

The results of the flow loop showed that:

1. Of the variables tested, only location (coupling or body) and insulation (installed or not installed) were found to affect heat losses. Other insignificant variables tested included: test number, test section (horizontal or vertical), and vacuum (applied or not applied).
2. By applying insulation in the annular portion of the double-walled pipe, pipe body heat loss rates were reduced by 98 percent as compared to the uninsulated cases.
3. In the 3-feet-long test section, the average heat loss rate of the insulated pipe body was 105 Btu per hour.
4. The insulated pipe coupling heat loss rates were considerably higher than the pipe body. The heat loss rates were reduced by only 6 percent when the insulation was applied to the coupling.
5. Tests requiring a vacuum of 0.1 torr in the annulus were not achieved because of leaks. A vacuum of 1.0 psia was not effective in reducing the heat loss rate which was consistent with the literature.

The pipe body with insulation in the annular portion of the pipe was effective in reducing the heat losses during the physical simulations. However, the coupling heat losses need to be reduced to at least a value comparable to pipe body.

The coupling heat losses can be reduced by: (1) incorporating a thermal resistant support, instead of the presently used carbon steel support ring, and/or (2) by incorporating a smaller cross-section area in the new or existing ring. The change in cross-section area may be accomplished with the use of knife edges. An alternate solution would require a new design which would eliminate the metal to metal contact between the two pipes in the coupling area.

A modification of the seals used in the coupling design is recommended. The seal modification is required to ensure that the steam does not leak into the annular portion of the pipe. In addition, a positive (pressure-vacuum) seal would also allow a vacuum to be maintained in the annular portion of the pipe. By lowering and maintaining the annular pressure at a vacuum less than 0.1 torr, further improvements in heat loss rates should be possible.

A new model for simulating the thermal hydraulics of saturated steam, or hot water from the heat source (steam generator or boiler) to the sandface of a reservoir was developed. The model extends the understanding of the various modes of heat transfer to the wellbore thermal hydraulics problem. The model includes two-phase frictional pressure drop calculations which allow for slip and local two-phase fluid film heat transfer coefficients. The model also has provisions that allow for a variety of surface pipe and wellbore boundary conditions to be incorporated.

Sensitivity studies showed that the heat loss experienced by the injection fluid decreased with an increase in either injection rate, insulation thickness, or injection time. The model predicts that a minimum injection rate exists below which severe heat loss occurs. The depth at which these adverse effects occur can be determined using the model.

The predictions of the model were compared with those of previous models and with actual steam temperature field data. The new model compares excellently with the previous published models in a specified range of operating conditions. In the case of evaluation with actual field data, this new model predicted the field data over a wider range of operating ranges with better accuracy than any of the previously published models.

ACKNOWLEDGEMENTS

The authors express appreciation to the United States Department of Energy (Cooperative Agreement Number DE-FC21-86MC11076) and to Inter-Mountain Pipe Company for funding of this work. Special thanks are extended to Mr. Thayne Routh for his assistance in modifying the model.

DISCLAIMER

Mention of specific brand names or models of equipment is for information only and does not imply endorsement of any particular brand.

REFERENCES

- Beggs, H.D., and Brill, J.P., 1973, A Study of Two-Phase Flow in Inclined Pipes. J. Pet. Tech., 25(5): 607-617.
- Bleakley, W.B., 1964, Here Are Case Histories of Two Thermal Projects. Oil and Gas J., October 26, 123-130.
- Chierici, G.L., Ciucci, G.M., and Sclocchi, G., 1974, Two-Phase Flow in Oil Wells - Predictions of Pressure Drop. J. Pet. Tech., 26(8): 927-938.
- Durrant, A.J., and Thambynayagam, R.G.M., 1986, Wellbore Heat Transmission and Pressure Drop for Steam/Water Injection and Geothermal Production, A Simple Solution Technique. SPE Reservoir Engineering, 1(2): 148-162.
- Duns, H. Jr., and Ros, N.C., 1961, Vertical Flow of Gas and Liquid Mixtures in Wells. Proc., Sixth World Pet. Congress, Frankfurt, Sec. II, Paper 22-PD6, 451-465.
- Earlougher, R.C. Jr., 1969, Some Practical Considerations in the Design of Steam Injection Wells. J. Pet. Tech., 21(1): 79-86.
- Farouq Ali, S.M., 1981, A Comprehensive Wellbore Steam/Water Flow Model for Steam Injection and Geothermal Applications. J. Pet. Tech., 33(10): 527-534.
- Gould T.L., Tek, M.R., and Katz, D.L., 1974, Two-Phase Flow Through Vertical. Inclined, or Curved Pipe. J. Pet. Tech., 26(8): 915-926.
- Hagedorn, A.R., and Brown, K.E., 1965, Experimental Study of Pressure Gradients Occurring During Continuous Flow in Small Diameter Conduits. J. Pet. Tech., 17(4): 475-484.
- Hines, William W. and Montgomery, D.C., 1980, Probability and Statistics in engineering and Management Science, 2nd edition. John Wiley and Sons, New York.
- Host, P.H., and Flock, D.L., 1966, Wellbore Behavior During Saturated Steam Injection. J. Cdn. Pet. Tech., 5(4): 184.
- Jensen, T.B., and Sharma, M.P., 1989, Thermal Hydraulics of Wellbore and Surface Lines During Steam/Hot Water Injection - Part I: Theoretical Model. J. Eng. Resour. Tech., 111(2): 55-63.

- Jensen, T.B., and Sharma, M.P., 1987, Analysis of Friction Factor and Equivalent Diameter Correlations. Presented at the ASME Petroleum Division ETCE Conference, February 15-20, Dallas, TX.
- Leutwyler, K., 1966, Casing Temperature Studies in Steam Injection Wells. J. Pet.Tech., 18(9): 1157-1162.
- Lockhart, R.W., and Martinelli, R.C., 1949, Proposed Correlation of Data for Isothermal Two-phase, Two Component Flow in Pipes. Chemical Engineering Progress, 45(1): 39-48.
- Moody, L.F., 1944, Friction Factors for Pipe Flow. Trans A.S.M.E., 66: 671.
- Moss, J.T., and White, P.D., 1959, How to Calculate Temperature Profiles in a Water-Injection Well. Oil and Gas J., 57(11): 174.
- Pacheco, E.F., and Farouq Ali, S.M., 1974, Wellbore Heat Losses and Pressure Drop in Steam Injection. J. Pet.Tech., 26(8): 915-926.
- Perry, R.H., and Green, D.W., 1984, Perry's Chemical Engineering Handbook, 6th Edition. McGraw Hill Book Company, New York.
- Ramey, H.J. Jr., 1962, Wellbore Heat Transmission. J. Pet.Tech., 14(4): 427-435.
- Satter, A, 1963, Heat Losses During Flow of Steam Down a Wellbore. J. Pet.Tech., 15(7): 845-851.
- Serghides. C.K., 1984, Estimate Friction Factors Accurately. Chemical Engineering, March 4, 63-64.
- Ullman, N.R., 1972, Statistics: An Applied Approach. Xerox College Publishing, Mass.
- Willhite, G.P., 1967, Over-All Heat Transfer Coefficients in Steam and Hot Water Injection Wells. J. Pet.Tech., 19(5): 607-615.

APPENDIX A
Experimental Data

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Table 1 : Flowloop Run #1

Test Conditions:

Vertical Test Section - no insulation - no vacuum - no coupling insulation

Horizontal Test Section - with insulation - no vacuum - no coupling insulation

Time	TC1	TC2	TC3	TC4	TC5	TC6	TC7	TC8	TC9	TC10	TC11	TC12	TC13	TC14	Cond
0	66	58	58	58	59	64	61	242	61	88	61	70	92	63	65
5	275	62	140	106	256	275	61	275	78	225	119	253	276	63	66
10	272	66	142	144	259	273	62	273	92	226	155	258	273	65	64
15	268	71	143	163	258	269	62	269	103	226	173	258	269	66	81
20	271	77	146	173	262	272	63	272	112	230	183	261	272	66	114
25	279	82	152	180	268	280	64	280	121	238	191	269	280	68	131
30	275	88	154	187	266	275	64	275	128	237	197	267	276	69	133
35	268	92	154	190	262	269	64	269	133	233	199	262	269	70	125
40	271	96	157	190	263	271	63	272	136	235	199	264	272	68	126
45	279	100	163	194	270	280	64	280	140	242	202	271	280	66	143
50	275	103	164	196	267	275	64	275	143	240	205	268	276	68	143
55	266	106	162	196	261	266	65	266	144	234	205	261	267	70	130
60	271	108	164	195	264	272	66	272	146	238	203	264	272	73	134
65	280	110	169	196	271	280	63	281	147	244	204	272	281	71	151
70	275	111	168	198	268	275	62	275	148	242	206	269	276	66	147
75	265	112	165	197	260	266	60	266	147	235	205	261	267	65	133
80	272	113	167	195	264	272	59	272	146	238	203	265	273	65	138
85	280	113	171	196	272	281	58	281	146	245	205	273	281	59	155
90	274	114	169	199	268	275	63	275	147	241	207	268	275	68	148
95	266	115	167	197	261	266	66	267	147	235	205	261	267	73	136
100	271	116	168	196	263	271	65	271	147	238	204	264	272	71	138
105	279	116	172	197	271	280	63	280	148	244	205	272	280	67	155
110	275	117	172	200	268	275	64	275	149	242	207	269	276	69	151
115	267	117	169	199	262	268	67	268	149	236	207	262	268	71	140
120	269	117	169	197	263	270	65	270	150	237	205	263	271	69	138
125	278	117	173	198	270	279	62	279	149	244	206	271	280	67	154
130	275	118	173	200	269	276	64	276	150	243	207	270	277	69	154
135	268	118	170	200	263	269	67	269	150	238	207	264	269	73	142
140	268	118	169	197	262	269	66	269	150	236	206	262	269	70	137
145	277	119	173	199	270	278	63	278	150	243	206	270	278	68	152
150	276	119	174	201	270	277	66	277	151	243	207	271	277	72	156
155	270	119	171	201	265	270	67	270	151	239	208	265	271	70	146
160	267	119	169	199	261	268	63	268	151	236	205	262	269	69	137
165	276	119	173	198	269	277	68	277	151	242	207	269	277	71	151
170	277	119	174	201	270	277	65	278	151	244	209	271	278	68	159
175	271	119	172	201	265	271	64	272	151	239	208	266	272	68	149
180	265	119	169	200	259	266	65	266	151	235	206	260	266	70	138
185	274	119	172	198	267	275	68	275	151	241	206	268	275	71	150

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Table 1 : Flowloop Run #1 (cont.)

Test Conditions:

Vertical Test Section - no insulation - no vacuum - no coupling insulation

Horizontal Test Section - with insulation - no vacuum - no coupling insulation

Time	TC1	TC2	TC3	TC4	TC5	TC6	TC7	TC8	TC9	TC10	TC11	TC12	TC13	TC14	Cond
190	278	119	175	200	271	279	66	279	151	245	208	272	279	69	174
195	272	119	172	201	266	272	64	272	151	240	208	267	273	68	161
200	264	119	169	200	260	265	65	265	151	234	207	260	265	69	146
205	272	119	171	197	265	273	68	273	151	239	207	266	273	70	157
210	280	119	175	199	273	280	66	281	151	246	208	273	281	70	179
215	273	119	173	201	268	274	64	274	151	241	208	268	275	67	165
220	265	119	169	200	260	265	64	265	151	235	207	261	266	68	150
225	271	119	171	198	264	272	66	272	151	239	206	265	272	70	156
230	280	119	175	198	272	280	68	280	151	245	208	273	281	71	175
235	274	120	173	201	268	275	66	275	152	242	208	269	275	70	167
240	266	119	170	201	261	267	64	267	151	236	208	262	267	68	153
245	270	119	171	199	264	271	65	271	151	238	205	264	271	68	155
250	279	119	174	199	271	279	66	280	151	245	207	272	280	70	173
255	275	120	173	201	269	275	68	275	152	242	208	269	276	71	169
260	265	120	170	199	261	266	65	266	151	236	208	261	266	67	152
265	272	119	171	199	265	272	65	272	151	239	206	265	273	68	158
270	280	119	175	200	273	280	65	281	151	246	207	273	281	70	181
275	273	120	173	200	268	274	68	274	152	242	209	268	275	71	167
280	265	120	169	200	260	266	66	266	152	235	207	260	267	70	149
285	274	119	172	199	267	274	64	275	151	241	206	267	275	68	163
290	278	120	175	201	272	279	65	279	152	245	208	272	280	69	182
295	271	120	172	201	266	272	67	272	152	240	209	267	272	71	164
300	267	120	169	199	261	267	68	267	151	236	207	261	268	71	149
305	275	120	173	198	268	276	65	276	151	242	207	269	276	69	165
310	277	120	174	201	271	278	64	278	152	244	207	271	278	68	177
315	270	120	172	201	265	271	65	271	152	239	208	266	271	69	162
320	268	120	170	199	261	268	67	268	151	236	207	262	269	70	151
325	276	119	173	198	269	277	68	277	151	243	207	270	278	71	168
330	276	120	174	200	270	277	67	277	152	244	209	271	278	71	175
335	200	120	170	201	256	201	65	259	151	232	208	252	241	69	152

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Table 2 : Flowloop Run #2

Test Conditions:

Vertical Test Section - no insulation - with vacuum - no coupling insulation

Horizontal Test Section - with insulation - with vacuum - no coupling insulation

Time	TC1	TC2	TC3	TC4	TC5	TC6	TC7	TC8	TC9	TC10	TC11	TC12	TC13	TC14	Cond
0	202	73	134	153	210	203	65	248	119	210	168	202	203	69	62
5	194	77	124	151	196	200	64	228	121	199	161	197	196	68	64
10	185	80	122	148	191	188	64	220	122	190	160	193	192	65	66
15	178	82	120	144	183	174	64	215	122	181	156	183	184	68	68
20	278	85	143	141	250	279	66	279	122	232	151	248	279	68	68
25	273	88	157	162	264	273	67	274	127	235	176	265	274	69	114
30	265	92	156	176	258	265	66	265	131	230	186	258	266	71	115
35	269	95	158	182	261	269	65	269	133	233	192	261	270	66	119
40	276	98	163	187	269	277	65	277	137	239	196	269	278	69	135
45	276	101	165	192	270	277	65	277	140	240	202	270	277	67	144
50	268	103	163	194	262	268	66	268	142	235	203	263	268	68	132
55	269	105	164	193	262	269	66	269	143	235	204	262	270	68	130
60	277	107	168	195	270	278	67	278	144	242	205	270	278	70	146
65	276	109	169	196	270	276	66	277	146	242	207	271	277	70	151
70	267	110	164	196	262	267	66	267	147	235	207	263	268	71	137
75	270	111	166	195	264	271	65	271	147	238	204	264	271	71	139
80	279	112	170	197	272	279	64	280	148	244	207	272	280	67	155
85	275	113	170	198	269	275	65	275	149	242	208	270	276	67	153
90	265	114	166	198	260	265	65	265	149	235	207	261	266	68	137
95	272	114	169	196	266	272	66	273	148	239	206	266	273	68	144
100	280	115	173	197	273	280	67	281	149	245	207	273	281	69	161
105	274	115	171	199	268	274	67	274	150	241	209	269	275	70	153
110	264	116	167	196	260	265	67	265	149	234	208	260	265	70	137
115	273	116	170	196	266	273	66	274	149	240	206	267	274	70	147
120	279	116	173	198	273	280	65	280	149	245	209	273	280	67	163
125	273	116	171	198	268	273	65	274	150	241	209	268	274	67	153
130	264	116	167	198	260	265	65	265	150	235	207	260	266	68	138
135	273	116	170	197	267	273	67	274	149	240	206	267	274	70	149
140	279	117	173	197	273	279	67	280	150	245	208	273	280	70	164
145	273	117	171	198	268	273	65	273	150	241	209	268	274	69	154
150	264	117	168	197	260	265	66	265	150	234	207	260	266	67	139
155	273	117	169	197	266	273	65	273	150	240	206	267	274	68	149
160	279	117	173	198	273	280	66	280	150	245	208	273	280	69	165
165	273	117	171	199	268	273	68	273	151	241	209	268	274	70	155
170	264	117	168	197	260	265	67	265	150	235	208	260	266	70	140
175	273	117	171	195	266	273	67	273	150	240	206	267	274	70	149
180	279	117	174	198	273	280	66	280	150	245	208	273	280	68	165
185	273	117	172	198	268	274	66	274	151	241	209	268	274	68	155

rms/WRI 92

Table 2 : Flowloop Run #2 (cont.)

Test Conditions:

Vertical Test Section - no insulation - with vacuum - no coupling insulation

Horizontal Test Section - with insulation - with vacuum - no coupling insulation

Time	TC1	TC2	TC3	TC4	TC5	TC6	TC7	TC8	TC9	TC10	TC11	TC12	TC13	TC14	Cond
190	264	118	168	198	260	265	66	265	151	235	207	260	266	68	140
195	273	118	171	197	267	273	67	274	150	240	206	267	274	69	150
200	279	118	174	197	273	280	68	280	150	245	208	273	280	70	165
205	273	118	172	198	268	273	69	274	151	241	209	268	274	70	155
210	265	118	168	197	260	265	68	265	150	235	207	260	266	70	140
215	273	118	171	197	267	274	67	274	150	241	207	267	275	70	151
220	278	118	174	198	273	279	66	279	150	245	207	273	280	69	165
225	273	118	172	198	267	273	66	273	151	241	208	268	274	69	154
230	264	118	168	198	260	265	66	265	151	234	206	260	266	70	140
235	273	118	171	197	267	273	66	273	150	240	206	267	274	70	149
240	279	118	174	198	273	280	67	280	150	245	207	273	280	70	166
245	273	118	172	199	268	273	68	274	151	241	210	268	274	71	155
250	264	118	168	197	260	265	69	265	151	235	209	261	266	70	142
255	271	118	171	196	265	272	67	272	150	239	206	265	273	70	147
260	280	118	174	197	273	280	66	281	150	246	207	273	281	70	165
265	274	118	172	198	269	274	66	275	151	242	209	269	275	70	157
270	267	118	170	198	262	268	67	268	151	237	207	263	268	69	146
275	268	118	170	197	263	269	66	269	150	237	205	263	270	69	143
280	200	118	171	197	255	201	66	259	150	179	205	256	213	71	147

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Table 3 : Flowloop Run #3

Test Conditions:

Vertical Test Section - with insulation - with vacuum - no coupling insulation

Horizontal Test Section - no insulation - with vacuum - no coupling insulation

Time	TC1	TC2	TC3	TC4	TC5	TC6	TC7	TC8	TC9	TC10	TC11	TC12	TC13	TC14	Cond
0	59	59	59	59	59	59	57	63	61	62	61	58	60	61	61
5	59	59	59	59	59	59	57	63	61	62	61	58	60	61	61
10	61	59	59	59	60	56	57	125	61	62	61	59	67	62	59
15	255	70	213	93	254	255	57	255	64	196	98	59	255	233	54
20	264	82	223	127	264	264	61	264	68	203	132	61	265	247	111
25	273	93	232	139	273	273	60	273	72	211	152	61	273	259	129
30	281	105	240	138	281	280	60	281	76	217	166	60	281	269	151
35	274	114	237	142	275	274	62	274	81	216	175	62	274	266	146
40	268	121	233	139	268	268	60	268	85	215	180	61	268	261	136
45	272	127	237	138	272	272	62	272	89	219	183	62	272	265	141
50	280	133	244	139	280	280	60	280	94	225	186	62	280	272	160
55	274	137	242	139	275	275	62	275	98	224	190	62	275	268	156
60	265	140	234	136	266	265	63	266	100	218	191	63	266	259	138
65	271	142	240	138	272	272	62	272	103	223	191	62	272	264	147
70	280	143	246	135	280	280	66	280	105	229	191	64	280	271	168
75	274	145	243	138	275	274	63	275	107	227	194	63	275	268	163
80	265	146	236	139	266	265	64	265	108	220	194	63	266	259	144
85	272	147	241	139	272	272	65	272	110	225	193	63	273	264	154
90	280	148	247	136	280	280	63	281	111	231	194	64	281	271	175
95	274	148	243	137	275	274	63	274	112	228	195	63	275	267	166
100	265	148	236	136	265	265	64	265	112	221	194	63	266	259	146
105	273	148	242	139	273	273	64	274	113	227	193	64	274	265	161
110	280	149	247	135	280	280	64	280	113	232	194	64	280	271	189
115	273	150	242	137	273	273	64	273	114	228	195	64	273	266	166
120	265	149	236	137	266	266	64	266	114	222	194	63	266	259	148
125	274	149	243	136	274	274	64	275	115	228	193	63	275	266	165
130	279	150	247	134	279	279	66	279	115	232	195	65	280	271	188
135	273	150	242	134	273	273	65	273	115	228	196	65	273	266	159
140	266	150	236	135	266	266	64	266	116	222	195	64	267	260	144
145	274	150	243	135	275	275	64	275	115	229	194	64	275	267	157
150	278	150	246	135	279	279	64	279	116	232	195	64	279	271	170
155	272	150	242	136	273	273	65	273	116	228	196	64	273	266	158
160	265	149	236	136	266	266	67	266	116	222	195	65	266	259	143
165	274	149	243	136	275	274	66	275	116	228	194	65	275	267	156
170	279	150	247	135	279	279	66	279	117	232	195	64	280	272	170
175	272	150	242	135	273	273	65	273	117	228	196	65	273	266	157
180	265	149	236	136	265	265	65	266	117	222	195	64	266	259	143
185	274	149	242	134	274	274	65	274	117	228	194	64	275	267	155

rms/WR192

Table 3 : Flowloop Run #3 (cont.)

Test Conditions:

Vertical Test Section - with insulation - with vacuum - no coupling insulation

Horizontal Test Section - no insulation - with vacuum - no coupling insulation

Time	TC1	TC2	TC3	TC4	TC5	TC6	TC7	TC8	TC9	TC10	TC11	TC12	TC13	TC14	Cond
190	279	150	247	136	280	279	65	280	117	233	195	66	280	272	169
195	273	150	242	138	273	273	65	273	117	229	196	65	274	266	159
200	265	149	236	136	266	266	66	266	117	223	194	65	266	259	144
205	274	149	242	134	274	274	65	274	117	229	194	65	275	267	156
210	279	149	247	134	279	279	65	279	118	233	196	65	280	271	170
215	272	150	242	135	273	273	66	273	117	228	196	65	273	266	159
220	266	149	236	136	266	266	65	266	118	223	195	65	267	259	144
225	274	149	243	137	275	275	65	275	118	229	194	65	275	267	158
230	278	150	246	136	279	279	66	279	118	233	195	66	279	272	170
235	272	150	242	139	273	272	65	273	118	228	196	65	273	265	159
240	266	150	236	130	266	266	62	266	117	223	194	63	267	259	144
245	275	149	243	136	275	275	65	275	116	229	194	66	275	267	158
250	278	150	246	153	279	278	65	279	117	232	195	66	279	271	170
255	272	150	241	198	273	272	66	272	117	228	196	66	273	266	158
260	266	150	237	197	267	266	65	267	118	223	194	66	267	260	145
265	275	150	243	195	275	275	67	275	118	229	193	66	276	267	159
270	278	150	246	196	279	278	67	279	118	232	195	66	279	271	170
275	271	150	241	196	272	272	67	272	118	228	196	67	272	266	158
280	267	150	238	195	268	268	66	268	118	224	194	66	268	261	146
285	276	150	244	195	276	276	67	277	118	230	193	66	277	269	162
290	277	150	245	196	278	277	66	278	119	232	195	66	278	271	170
295	270	150	240	196	271	270	67	271	119	227	196	67	271	264	157
300	269	150	238	194	269	269	68	269	118	225	194	66	270	261	149
305	278	150	246	194	278	278	66	279	119	232	193	67	279	270	167
310	275	150	244	196	276	276	68	276	119	231	196	68	276	268	168
315	269	150	239	195	270	269	67	269	119	226	195	67	270	262	156
320	270	150	239	194	270	270	66	271	119	226	194	67	271	262	152
325	280	150	247	194	281	280	66	281	119	233	194	67	281	272	172
330	274	150	243	195	275	274	67	274	119	230	195	68	275	267	165
335	268	150	238	195	269	268	67	269	119	225	196	66	269	262	153
340	269	150	239	193	269	269	65	270	118	225	193	65	270	261	150
345	278	150	246	194	279	279	67	279	118	232	194	66	279	270	167
350	275	150	244	195	276	275	66	276	118	230	195	67	276	268	167
355	269	150	239	195	270	270	66	270	119	226	195	67	270	263	155
360	265	150	235	193	265	265	67	265	118	222	194	67	266	258	145
365	273	149	242	192	274	274	66	274	119	228	193	67	275	266	159
370	279	150	247	194	279	279	67	279	119	233	194	67	280	271	174
375	272	150	242	195	273	273	67	273	119	229	195	67	273	266	162

rms/WR192

Table 4 : Flowloop Run #4

Test Conditions:

Vertical Test Section - with insulation - no vacuum - no coupling insulation

Horizontal Test Section - no insulation - no vacuum - no coupling insulation

Time	TC1	TC2	TC3	TC4	TC5	TC6	TC7	TC8	TC9	TC10	TC11	TC12	TC13	TC14	Cond
0	58	58	58	58	58	58	60	148	60	60	59	59	58	60	70
5	276	69	227	80	-454	276	58	276	62	205	94	188	276	60	55
10	274	88	229	128	-454	274	59	274	66	206	133	220	274	61	53
15	210	100	196	146	-454	210	59	254	71	199	147	199	222	61	58
20	269	111	228	159	262	268	61	269	75	207	158	230	269	62	106
25	270	120	231	170	264	270	61	270	80	211	169	235	270	61	112
30	278	128	239	179	272	278	60	279	85	217	176	244	279	62	126
35	275	136	239	186	270	274	62	275	89	219	183	246	275	62	129
40	265	141	233	188	261	265	61	266	92	214	186	241	266	61	119
45	273	144	239	189	268	273	61	274	96	220	187	246	274	61	126
50	279	148	245	193	275	279	62	280	99	226	189	252	280	62	141
55	272	151	240	194	268	272	61	272	102	221	192	248	272	62	133
60	266	152	236	193	262	266	62	267	104	218	191	244	267	63	123
65	275	153	243	194	270	275	62	276	106	225	190	250	276	63	135
70	278	155	244	196	274	278	61	278	108	227	192	253	278	63	144
75	272	156	240	197	268	272	62	272	109	223	194	249	272	64	136
80	265	155	235	196	261	265	61	266	110	219	193	244	266	63	126
85	275	156	242	195	270	275	62	275	111	226	192	250	275	64	137
90	278	157	245	197	274	278	61	279	112	229	194	254	279	63	147
95	272	158	241	197	268	273	64	273	112	225	195	251	273	64	139
100	265	157	236	197	262	265	62	266	113	220	194	245	266	64	129
105	272	157	241	195	267	272	63	273	113	225	192	249	273	64	134
110	280	157	247	197	275	280	62	280	114	231	194	255	280	64	149
115	274	158	243	198	270	274	62	274	114	227	195	252	275	64	143
120	268	158	238	198	264	268	62	268	114	222	195	248	268	64	134
125	269	157	238	196	264	269	62	269	114	223	193	246	269	64	131
130	278	158	245	196	273	278	64	278	114	229	193	253	279	65	144
135	276	158	244	198	272	276	62	277	114	229	195	253	277	64	147
140	270	158	240	198	267	271	62	271	115	224	195	250	271	64	138
145	265	157	235	197	261	265	63	265	114	220	194	245	266	64	129
150	274	157	242	195	269	274	63	274	115	227	193	250	275	64	139
155	279	158	246	198	275	279	62	279	114	231	195	255	279	64	151
160	273	159	242	199	269	273	64	273	115	226	196	252	274	65	143
165	265	158	236	198	262	266	63	266	115	221	195	247	266	65	133
170	271	158	240	196	267	271	62	272	115	225	193	248	272	64	136
175	280	158	247	198	276	280	62	281	115	231	194	255	281	64	151
180	275	159	243	199	271	275	63	275	115	228	195	253	275	65	147
185	268	159	239	199	265	268	63	269	115	223	195	249	269	65	138

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Table 4 : Flowloop Run #4 (cont.)

Test Conditions:

Vertical Test Section - with insulation - no vacuum - no coupling insulation

Horizontal Test Section - no insulation - no vacuum - no coupling insulation

Time	TC1	TC2	TC3	TC4	TC5	TC6	TC7	TC8	TC9	TC10	TC11	TC12	TC13	TC14	Cond
190	269	158	238	197	264	269	63	269	115	223	194	247	270	65	134
195	278	158	245	198	273	278	63	279	115	230	193	253	279	65	148
200	276	159	245	200	272	276	63	276	115	229	195	254	277	65	150
205	270	159	240	200	267	271	63	271	115	225	196	250	271	65	141
210	267	158	237	197	263	267	64	267	115	222	194	246	268	66	133
215	276	159	244	198	271	276	63	277	116	229	194	253	277	66	146
220	277	159	246	198	274	277	61	278	115	230	195	255	278	64	154
225	272	160	241	199	268	272	63	272	114	226	195	251	273	64	145
230	265	159	236	198	261	265	62	265	114	220	194	246	265	63	134
235	274	159	242	196	269	273	61	274	113	227	192	250	275	63	144
240	279	159	247	197	275	279	61	279	114	231	194	255	280	62	157
245	273	160	242	198	269	273	62	274	113	227	195	252	274	63	149
250	267	159	237	197	263	267	62	267	114	222	194	248	268	63	140
255	270	158	239	195	265	270	61	270	114	224	193	248	271	63	139
260	279	159	246	197	274	279	62	280	113	231	193	254	280	63	154
265	275	159	244	199	271	275	62	276	113	228	195	253	276	63	153
270	270	160	240	199	266	270	62	270	113	224	194	249	270	63	144
275	267	159	238	197	263	267	63	268	112	222	193	246	268	64	137
280	276	159	244	197	272	276	63	277	111	228	193	252	277	63	150
285	277	160	246	199	273	277	63	278	111	229	194	254	278	64	158
290	271	160	241	200	268	271	63	272	111	225	195	250	272	64	148
295	265	159	236	198	261	265	63	266	111	220	193	245	266	63	138
300	274	159	243	197	270	274	62	275	111	227	192	250	275	63	148
305	278	160	247	199	275	278	62	279	112	230	194	255	279	63	161
310	273	160	242	199	269	273	63	273	112	226	194	251	273	64	152
315	265	160	237	197	262	265	62	266	112	220	194	246	266	64	141
320	271	159	241	197	267	271	63	272	112	225	192	249	272	64	145
325	280	160	248	198	276	280	62	281	113	231	193	255	281	64	161
330	275	160	244	199	271	275	63	275	113	227	195	253	275	64	156
335	269	160	239	199	266	269	63	270	113	223	194	249	270	64	147
340	268	159	238	197	263	268	63	268	113	222	193	246	268	64	140
345	277	159	245	197	272	277	62	277	113	229	193	252	278	64	153
350	277	160	245	200	273	277	63	277	113	229	194	254	278	64	159
355	271	160	241	200	268	271	63	272	112	225	195	251	272	64	150
360	265	159	236	198	261	265	63	265	112	220	194	246	266	64	139
365	274	159	243	198	270	274	63	275	113	227	193	250	275	64	149
370	279	160	247	198	275	279	63	279	113	231	194	255	280	64	162
375	273	160	243	200	269	273	64	274	113	226	195	252	274	64	153
380	266	160	237	199	263	266	63	267	112	221	194	247	267	65	143
385	271	159	240	197	266	271	63	271	112	224	192	248	271	65	144
390	280	159	247	198	275	280	63	280	112	231	193	255	281	65	160
395	200	157	210	194	230	200	64	265	112	219	191	235	249	65	138

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Table 5 : Flowloop Run #5

Test Conditions:

Vertical Test Section - with insulation - no vacuum - no coupling insulation

Horizontal Test Section - with insulation - no vacuum - with coupling insulation

Time	TC1	TC2	TC3	TC4	TC5	TC6	TC7	TC8	TC9	TC10	TC11	TC12	TC13	TC14	Cond
0	213	58	146	58	123	213	58	215	80	164	79	134	216	60	67
5	270	62	214	93	251	270	59	270	82	209	120	215	270	60	115
10	267	67	213	129	252	267	59	267	85	209	147	224	267	61	118
15	275	72	220	150	262	275	61	275	88	215	163	236	275	62	134
20	278	78	224	166	268	278	60	278	90	219	174	244	278	61	149
25	269	83	218	176	261	268	60	269	94	216	180	241	269	62	137
30	269	88	219	180	260	269	61	270	96	217	183	242	270	62	135
35	278	93	227	184	268	277	60	278	99	224	186	249	278	62	152
40	276	97	227	188	268	276	61	276	102	224	190	250	276	63	157
45	266	101	220	190	260	266	62	266	104	218	190	245	266	63	141
50	272	104	225	190	264	272	61	272	106	222	190	247	272	64	147
55	280	107	233	191	271	280	64	280	107	228	193	253	280	64	165
60	274	109	228	194	267	274	61	274	109	225	194	251	274	64	158
65	266	111	222	193	259	266	63	266	110	218	195	245	266	64	141
70	274	112	229	193	266	274	61	274	111	225	193	250	275	64	155
75	279	114	233	194	271	278	63	279	112	229	193	254	279	64	168
80	271	114	228	195	265	271	62	272	113	224	195	250	272	64	157
85	267	115	224	195	260	267	61	268	114	221	194	246	268	64	145
90	276	116	232	194	268	276	62	276	114	228	193	252	277	65	161
95	277	117	233	196	271	277	62	278	114	229	195	254	278	64	168
100	270	117	227	197	264	270	62	270	113	224	196	250	270	64	155
105	268	118	226	195	261	268	61	269	113	222	193	247	269	63	148
110	277	119	233	195	269	277	62	278	112	229	192	253	278	63	164
115	276	119	233	196	270	276	61	277	113	228	195	253	277	63	168
120	269	119	227	197	264	269	62	270	113	223	194	249	270	63	156
125	268	119	226	196	261	268	62	269	112	222	193	247	269	63	149
130	277	119	233	195	269	277	62	277	113	228	193	252	278	63	166
135	277	120	233	197	270	277	63	277	113	229	195	254	277	64	171
140	269	120	227	198	264	269	62	269	112	223	194	249	270	64	157
145	269	120	227	197	262	269	62	269	113	222	194	247	269	63	151
150	278	120	234	196	270	278	62	278	114	229	194	253	278	64	168
155	276	120	233	198	270	276	62	276	114	228	195	254	277	64	171
160	267	120	226	198	262	267	63	267	114	222	195	248	268	64	156
165	272	120	229	196	264	272	63	272	114	225	194	249	272	64	159
170	280	120	236	197	272	280	62	280	115	231	195	255	281	65	182
175	274	120	232	198	268	274	63	275	115	227	196	253	275	65	170
180	266	120	225	198	261	266	63	266	115	221	196	247	266	65	155
185	272	120	229	196	265	272	63	272	115	225	194	249	272	65	160

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Table 5 : Flowloop Run #5 (cont.)

Test Conditions:

Vertical Test Section - with insulation - no vacuum - no coupling insulation

Horizontal Test Section - with insulation - no vacuum - with coupling insulation

Time	TC1	TC2	TC3	TC4	TC5	TC6	TC7	TC8	TC9	TC10	TC11	TC12	TC13	TC14	Cond
190	280	120	236	197	272	280	63	280	115	231	195	256	281	65	187
195	274	120	231	198	268	274	62	274	115	227	196	253	275	65	170
200	265	120	224	198	260	265	63	265	115	220	195	247	266	65	153
205	273	120	230	196	266	273	62	273	114	226	194	251	274	65	162
210	280	120	236	197	272	280	63	280	114	231	195	256	280	65	186
215	273	120	231	198	267	273	63	274	114	226	196	252	274	65	168
220	265	121	224	198	260	265	63	266	114	220	195	246	266	65	151
225	274	120	231	196	267	274	63	275	114	227	194	251	275	65	164
230	279	120	235	197	272	279	63	279	114	230	195	255	279	64	186
235	273	120	230	198	267	273	62	273	114	226	195	252	273	64	167
240	266	120	224	198	260	266	62	266	115	220	195	246	267	64	152
245	274	120	231	196	267	274	62	275	115	227	194	251	275	64	166
250	279	120	235	197	272	279	63	279	115	230	195	256	279	64	189
255	272	120	230	198	266	272	63	272	115	225	196	252	272	64	167
260	267	120	225	197	261	267	62	267	115	221	194	247	268	64	154
265	276	120	233	196	268	276	62	276	115	228	194	252	277	64	169
270	277	120	234	198	271	277	63	278	115	230	195	255	278	64	183
275	271	120	229	198	265	271	63	271	115	224	196	251	271	64	166
280	268	120	226	197	261	268	62	268	115	222	195	247	269	64	155
285	277	119	233	196	269	277	62	277	116	229	194	253	278	64	172
290	277	120	234	198	271	277	63	277	115	229	196	255	277	65	180
295	270	120	228	199	265	270	63	270	115	224	195	251	271	66	165
300	268	120	226	197	262	268	63	268	114	222	194	247	269	65	155
305	277	120	234	197	269	277	63	277	115	229	194	253	278	65	172
310	277	120	234	198	271	277	62	277	115	229	196	254	277	65	182
315	269	120	227	199	264	269	62	269	116	223	196	250	270	65	164
320	270	120	227	197	263	270	63	270	116	223	194	248	270	64	159
325	278	120	235	197	271	278	62	279	115	230	194	254	279	65	178
330	276	120	233	198	270	276	63	276	115	228	196	254	276	65	179
335	267	120	226	198	262	268	63	268	116	222	196	249	268	65	161
340	271	120	228	197	264	271	63	271	116	224	194	249	271	65	162
345	279	120	235	197	272	279	62	280	116	231	195	255	280	65	192
350	275	120	232	199	269	275	62	275	116	228	196	253	275	65	177
355	266	120	225	198	261	267	63	267	116	222	196	248	267	66	160
360	272	120	229	197	265	272	63	272	116	225	194	249	272	65	165
365	280	120	236	197	272	280	66	281	115	231	195	256	281	67	199
370	275	120	232	199	269	275	63	275	116	228	197	253	275	66	177
375	267	120	226	199	262	267	63	267	116	222	196	248	268	66	162
380	271	120	228	197	264	271	63	271	116	225	194	249	271	66	163
385	279	120	236	197	272	279	63	280	116	231	195	255	280	66	197
390	200	120	218	195	234	220	63	264	117	220	192	236	248	66	162

rms/WRI 92

APPENDIX B
Computer Code

```

*****
*
* Program name:  WRISIM
* Distributed under license by Western Research Institute
* Environment:   i486
* Compiler:      Microsoft Fortran, version 4.1
* Data:         December 1991
*
* Copyright Western Research Institute
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*****
*
* WRISIM is a thermal hydraulics simulator for simulation
* of flow of saturated steam or hot water along a surface
* line and/or down a wellbore. The simulator allows a
* variety of surface line configurations (buried, not
* buried, insulated, not insulated, etc.) and wellbore
* completions (single or double wall tubing, insulation or
* no insulation, multiple casing strings, choice of gas in
* casing and tubing annuli, multiple downhole formations,
* etc.). The simulator is a stand-alone program, but is
* intended to be used with the full screen editor program
* THSIMS.
*
*****

```

\$STORAGE:2

```

*
* Declaration of variables and common blocks and
* initialization of data.
*
  REAL WS,D,A,D12,D1,A1,U2(5000),KF(5000),ALPH(5000),UI1,UI2,T,RCI,
  CLEN,DEPTH,P,TV,X,E1,E2,PS,TIME,XF1,XF2,L1,AN1,AN2,RINS,DB,TM,WV,
  CGG,RW(5000),DO1,U1,K22,KCEM(5),D22,DEP,KS,K21,ALPHA(5),D11,DF(5),
  CLC(5),ID(5),OD(5),KC(5),TF(5),KHF(5),K12,K11,DW(5),SINA2,U,M,
  CD21,DEL,DEZ,EINS,ECI,TCI,TINS,HIN,HRATE,SINA1,HL,DLO,DZO,H,DX,
  CDELTAP,RO1,RL1,RG1,LV1,HW1,ESL,D21B,D22B,K21B,ET1,ET2,KDTINS
  INTEGER J,L,C,XX,FX1,ISL,N,M1,J1,JJJ,
  C NCOUNT,I,NUM,K,NPC,NFAC,NPAG,NTWO,NHEAD,GINTUB,GINCAS
  CHARACTER*12 FII,FIO
  CHARACTER*15 FLUID(2)
  CHARACTER*43 TITLE
  CHARACTER*63 TEXT(2)
  CHARACTER*31 TEXT2(2)
  LOGICAL DT
  COMMON /DTUB/ DT,D22A,D21B,D22B,K21B,ET1,ET2,KDTINS,GINTUB,
  C GINCAS,UDT,PDT,PCAS
  COMMON /COMM1/ U2,ALPH,RW,RINS,RCI,TIME,DEL,DEZ
  COMMON /COMM2/ KF,TM,GG,EINS,ECI,ESL,TTINS
  COMMON /COMM3/ TCI,TINS,TTB1,TTB2
  COMMON /FREAD/ ALPHA,LC,ID,OD,KC,TF,KHF,DW,N,M1,U1,
  C K22,KCEM,D22,DEPTH
  COMMON /LREAD/ L,LEN,WV,D11,D12,E1,ISL,K11,K12,T,DB,
  C KS,J1,X,P,TV,M,D21,E2,K21,AN2,AN1
  COMMON /SATS/ DELTAP,DX,RO1,RL1,RG1,LV1,HW1
  COMMON /MISC/ FII,FIO,TITLE,NPCSL,NPCWB
  DATA FLUID/'SATURATED STEAM','HOT WATER'/

```

```

DATA TEXT/
C'THE FLUID REACHES THE WELLHEAD WITH THE FOLLOWING PROPERTIES:',
C'THE CONDITIONS UPON INJECTION INTO THE RESERVOIR ARE AS FOLLOWS'/
DATA TEXT2/'POINT IS LOCATED AT A LENGTH OF',
C          'POINT IS LOCATED AT A DEPTH OF'/
NCOUNT = 0
*
* Calling subroutine TREAD for input of required data.
*
      CALL TREAD(UI1,D,D1,DO1,HIN,HRATE)
      NHEAD = 0
      NQUIT = 0
*
* Calculation of casing and cement string(s) total
* thermal resistivity for each depth step.
*
      WS = M
      XF1 = X
      UI2 = U1
      IF (L.EQ.2.OR.L.EQ.3) THEN
        DF(1) = TF(1)
        DO 93 I = 2,M1
          DF(I) = DF(I-1) + TF(I)
93      CONTINUE
        NUM = INT(DEPTH/DEZ)
        DO 94 I = 1,NUM
          U2(I) = 0
          DEP = FLOAT(I)*DE.
          IF (N.EQ.1) THEN
            FIX1 = 1
            GOTO 98
          ENDIF
          DO 95 J = 1,N
            IF (DEP.LE.LC(J)) FIX1 = J
95      CONTINUE
          DO 96 K = 1, FIX1-1
            U2(I) = U2(I) + ALOG(OD(K)/ID(K))/KC(K) +
C              ALOG(ID(K-1)/OD(K))/KCEM(K)
96      CONTINUE
93      U2(I) = U2(I) + ALOG(OD(FIX1)/ID(FIX1))/KC(FIX1) +
C              ALOG(DW(FIX1)/OD(FIX1))/KCEM(FIX1)
          DO 89 J = 1,N
            IF (DEP.LE.LC(J)) RW(I) = DW(J)/2.
89      CONTINUE
          DO 97 J = 1,M1
            IF (DEP.LE.DF(J)) THEN
              KF(I) = KHF(J)
              ALPH(I) = ALPHA(J)
              GOTO 94
            ENDIF
97      CONTINUE
94      CONTINUE
        ENDIF
        A = 0.7853982*D**2
        A1 = 0.7853982*D1**2
*
* Calling subroutine PRINT to initialize output data file
* and echo input data to the output file.
*
      CALL PRINT(L,J1,D1,DO1,LEN,D,DEPTH,TV,P,XF1,WS,HRATE,

```

```

      C          AN1,AN2,NPAG,WV)
*
*   Initializing variables
*
      XX = 0
      C = 0
      SINA2 = -SIN(.017453*AN2)
      SINA1 = SIN(.017453*AN1)
      DLO = DEL
      DZO = DEZ
      NFAC = 0
      L1 = 0.
*
*   Detemination of type of simulation to be performed:
*
*   L = 1 => Only surface line simulation
*       2 => Only wellbore simulation
*       3 => Both surface line and wellbore simualtion
*
*   J1 = 1 => Injection fluid is saturated steam
*       2 => Injection fluid is hot water
*
      IF(L.EQ.1.OR.L.EQ.3)THEN
        IF(J1.EQ.1)GOTO 50
        IF(J1.EQ.2)GOTO 85
      ELSE
        IF(J1.EQ.1)GOTO 150
        IF(J1.EQ.2)GOTO 195
      ENDIF
*
*   Surface line simulation for saturated steam.
*
50  WRITE(8,60)
     NHEAD = 0
     CALL COUNT(6,NCOUNT,NPAG,NHEAD,0)
70  IF((L1+DEL).GT.LEN)DEL = LEN - L1
     L1 = L1 + DEL
     C = C + 1
     XX = XX + 1
     J1 = 1
     CALL TWOP(TV,P,C,XF1,XF2,L1,D1,DO1,UI1,WS,SINA1,A1,E1,DEL,U,
C      1,NTWO,ISL,WV)
     NTWO = 0
*   IF(TV.LT.20..OR.(P-1.5*DELTAP).LT.10.)THEN
     IF(TV.LT.20..OR.P.EQ.0.)THEN
       WRITE(8,200)
       WRITE(8,61)
       GOTO 210
     ENDIF
     IF(L1.GE.LEN)THEN
       CALL HLOSS(1,TV,XF2,HIN,J1,H,HL)
       WRITE(8,181)L1,P,TV,XF2,HL,U
       WRITE(8,61)
       CALL COUNT(2,NCOUNT,NPAG,NHEAD,0)
       PHL = 100.*HL
       WRITE(8,33)TEXT(1),FLUID(1),P,TV,XF2,PHL
       CALL COUNT(10,NCOUNT,NPAG,NHEAD,0)
       IF(L.EQ.1)GOTO 210
       L1 = 0.
       C = 0

```



```

      XX = 0
      GOTO 150
    ENDIF
    XF1 = XF2
    IF (XX.GE.NPCSL) THEN
      CALL HLOSS (1, TV, XF2, HIN, J1, H, HL)
      WRITE (8, 181) L1, P, TV, XF2, HL, U
      CALL COUNT (1, NCOUNT, NPAG, NHEAD, 2)
      XX = 0
      IF (NHEAD.EQ.1) THEN
        WRITE (8, 60)
        NHEAD = 0
      ENDIF
    ENDIF
    IF (XF2.LT.0.0001) THEN
      CALL HLOSS (1, TV, XF2, HIN, J1, H, HL)
      WRITE (8, 181) L1, P, TV, XF2, HL, U
      WRITE (8, 61)
      CALL COUNT (2, NCOUNT, NPAG, NHEAD, 0)
      GOTO 80
    ENDIF
    IF ((2.*XF2-XF1).LT.0..AND.C.NE.1) THEN
      DEL = .99*DLO*XF2/(XF1-XF2)
      NFAC = 1
      XX = XX - 1
    ENDIF
    GOTO 70
80  WRITE (8, 32) FLUID (2), TEXT2 (1), L1
    CALL COUNT (5, NCOUNT, NPAG, NHEAD, 0)
*
*   Surface line simulation for hot water.
*
85  WRITE (8, 30)
    NHEAD = 0
    CALL COUNT (6, NCOUNT, NPAG, NHEAD, 0)
100 IF (NFAC.EQ.2) THEN
    DEL = DLO
    NFAC = 0
  ENDIF
  IF (NFAC.EQ.1) THEN
    DEL = DLO-DEL
    NFAC = 2
  ENDIF
  IF ((L1+DEL).GT.LEN) DEL = LEN - L1
  L1 = L1 + DEL
  C = C + 1
  XX = XX + 1
  J1 = 2
  CALL HOTW (TV, P, C, L1, UI1, WS, SINA1, D1, DO1, A1, E1, DEL, U, 1, ISL,
C      WV, DELTAP)
  IF (TV.LT.20..OR.(P-1.25*DELTAP).LT.10.) THEN
    WRITE (8, 180)
    WRITE (8, 29)
    GOTO 210
  ENDIF
  IF (L1.GE.LEN) THEN
    CALL HLOSS (1, TV, XF2, HIN, J1, H, H')
    WRITE (8, 180) L1, P, TV, HL, U
    WRITE (8, 29)
    CALL COUNT (2, NCOUNT, NPAG, NHEAD, 0)

```

```

    PHL = 100.*HL
    WRITE(8,31)TEXT(1),FLUID(2),P,TV,PHL
    CALL COUNT(9,NCOUNT,NPAG,NHEAD,0)
    IF(L.EQ.1)GOTO 210
    L1 = 0.
    C = 0
    XX = 0
    GOTO 195
ENDIF
IF (XX.GE.NPCSL) THEN
    CALL HLOSS(1,TV,XF2,HIN,J1,H,HL)
    WRITE(8,180)L1,P,TV,HL,U
    CALL COUNT(1,NCOUNT,NPAG,NHEAD,1)
    XX = 0
    IF(NHEAD.EQ.1) THEN
        WRITE(8,30)
        NHEAD = 0
    ENDIF
ENDIF
GOTO 100
*
* Wellbore simulation for saturated steam.
*
150 WRITE(8,160)
    L = 2
    NHEAD = 0
    CALL COUNT(6,NCOUNT,NPAG,NHEAD,0)
    NFAC = 0
170 IF((L1+DEZ).GT.DEPTH)DEZ = DEPTH - L1
    L1 = L1 + DEZ
    C = INT(L1/DZO)
    XX = XX + 1
    J1 = 1
    CALL TWOP(TV,P,C,XF1,XF2,L1,D,DO1,UI2,WS,SINA2,A,E2,DEZ,U,
C          2,NTWO,ISL,WV)
    NTWO = 0
    IF(TV.LT.20..OR.(P-1.5*DELTAP).LT.10.) THEN
        WRITE(8,200)
        WRITE(8,161)
        GOTO 210
    ENDIF
    IF(L1.GE.DEPTH) THEN
        CALL HLOSS(1,TV,XF2,HIN,J1,H,HL)
        WRITE(8,183)L1,P,TV,XF2,TCI,HL,U
        WRITE(8,161)
        CALL COUNT(2,NCOUNT,NPAG,NHEAD,0)
        PHL = 100.*HL
        WRITE(8,33)TEXT(2),FLUID(1),P,TV,XF2,PHL
        CALL COUNT(10,NCOUNT,NPAG,NHEAD,0)
        GOTO 210
    ENDIF
    XF1 = XF2
    IF(XF2.LT.0.0001) THEN
        CALL HLOSS(1,TV,XF2,HIN,J1,H,HL)
        WRITE(8,183)L1,P,TV,XF2,TCI,HL,U
        WRITE(8,161)
        CALL COUNT(2,NCOUNT,NPAG,NHEAD,0)
        GOTO 190
    ENDIF
    IF(XX.GE.NPCWB) THEN

```

```

CALL HLOSS (1,TV,XF2,HIN,J1,H,HL)
WRITE (8,183) L1,P,TV,XF2,TCI,HL,U
CALL COUNT (1,NCOUNT,NPAG,NHEAD,4)
XX = 0
IF (NHEAD.EQ.1) THEN
    WRITE (8,160)
    NHEAD = 0
ENDIF
ENDIF
IF ((2.*XF2-XF1).LT.0..AND.C.NE.1) THEN
    DEZ = .99*DZO*XF2/(XF1-XF2)
    NFAC = 1
    XX = XX - 1
ENDIF
GOTO 170
190 WRITE (8,32) FLUID (2),TEXT2 (2),L1
    CALL COUNT (5,NCOUNT,NPAG,NHEAD,0)
*
* Wellbore simulation for hot water.
*
195 WRITE (8,120)
    L = 2
    NHEAD = 0
    CALL COUNT (6,NCOUNT,NPAG,NHEAD,0)
205 IF (NFAC.EQ.2) THEN
    DEZ = DZO
    NFAC = 0
ENDIF
IF (NFAC.EQ.1) THEN
    DEZ = DZO-DEZ
    NFAC = 2
ENDIF
IF ((L1+DEZ).GT.DEPTH) THEN
    DEZ = DEPTH - L1
    IF (DEZ.LT.0.01) NQUIT = 1
ENDIF
L1 = L1 + DEZ
C = INT (L1/DZO)
XX = XX + 1
J1 = 2
CALL HOTW (TV,P,C,L1,UI2,WS,SINA2,D,DO1,A,E2,DEZ,U,2,
C          ISL,WV,DELTAP)
IF (TV.LT.20..OR.(P-1.5*DELTAP).LT.10.) THEN
    WRITE (8,200)
    WRITE (8,121)
    GOTO 210
ENDIF
IF (L1.GE.DEPTH.OR.NQUIT.EQ.1) THEN
    CALL HLOSS (1,TV,XF2,HIN,J1,H,HL)
    WRITE (8,182) L1,P,TV,TCI,HL,U
    WRITE (8,121)
    CALL COUNT (2,NCOUNT,NPAG,NHEAD,0)
    PHL = 100.*HL
    WRITE (8,31) TEXT (2),FLUID (2),P,TV,PHL
    CALL COUNT (9,NCOUNT,NPAG,NHEAD,0)
    GOTO 210
ENDIF
IF (XX.GE.NPCWB) THEN
    CALL HLOSS (1,TV,XF2,HIN,J1,H,HL)
    WRITE (8,182) L1,P,TV,TCI,HL,U

```

```

      CALL COUNT(1,NCOUNT,NPAG,NHEAD,3)
      XX = 0
      IF (NHEAD.EQ.1) THEN
        WRITE(8,120)
        NHEAD = 0
      ENDIF
    ENDIF
  GOTO 205
29  FORMAT(2X,59('-'))
30  FORMAT(//,2X,59('-'),/,2X,'LENGTH',3X,'PRESSURE',2X,'TEMPERATURE'
C,4X,'HEAT LOSS',3X,'HEAT TRANSFER',/,3X,'FEET',6X,'PSIA',7X,
C'deg F',7X,'FRACTION',5X,'COEFFICIENT',/,2X,59('-'))
31  FORMAT(///,5X,A63,/,8X,A17,' AT:',/,8X,'PRESSURE =',5X,F7.1,
C' PSIA',/,8X,'TEMPERATURE =',3X,F6.1,' deg F',/,
C 8X,'HEAT LOST =',3X,F6.1,' PERCENT')
32  FORMAT(///,5X,'THE ',A17,/,5X,A33,F6.0,' FEET')
33  FORMAT(///,5X,A63,/,8X,A17,' AT:',/,8X,'PRESSURE =',5X,F7.1,
C' PSIA',/,8X,'TEMPERATURE =',3X,F6.1,' deg F',/,8X,'STEAM QUAL',
C'ITY =',2X,F5.3,/,8X,'HEAT LOST =',5X,F6.1,' PERCENT')
60  FORMAT(//,2X,70('-'),/,2X,'LENGTH',2X,'PRESSURE',2X,'TEMPERATURE'
C,2X,'STEAM QUALITY',2X,'HEAT LOSS',2X,'HEAT TRANSFER',/,3X,'FEET'
C,5X,'PSIA',7X,'deg F',8X,'FRACTION',5X,'FRACTION',3X,'COEFFICIE',
C'NT',/,2X,70('-'))
61  FORMAT(2X,70('-'))
120 FORMAT(//,2X,73('-'),/,2X,'DEPTH PRESSURE TEMPERATURE'
C,2X,'CASING TEMP.',4X,'HEAT LOST',3X,'HEAT TRANSFER',/,3X,'FEET'
C,4X,'PSIA',9X,'deg F',8X,'deg F',9X,'FRACTION',4X,'COEFFICIENT',
C/,2X,73('-'))
121 FORMAT(2X,73('-'))
160 FORMAT(//,2X,77('-'),/,2X,'DEPTH PRESSURE TEMPERATURE'
C,1X,'STEAM QUALITY CASING TEMP. HEAT LOST HEAT ',
C'TRANSFER',/,2X,'FEET',4X,'PSIA',6X,'deg F',7X,'FRACTION',7X,
C'deg F',5X,'FRACTION',2X,'COEFFICIENT',/,2X,77('-'))
161 FORMAT(2X,77('-'))
180 FORMAT(2X,F5.0,5X,F7.2,5X,F7.2,7X,F5.3,8X,F7.3)
181 FORMAT(2X,F5.0,3X,F7.2,5X,F7.2,8X,F5.3,8X,F5.3,7X,F6.3)
182 FORMAT(2X,F5.0,4X,F7.2,5X,F7.2,6X,F7.2,9X,F5.3,8X,F6.3)
183 FORMAT(2X,F5.0,1X,F7.2,4X,F7.2,7X,F5.3,7X,F7.2,6X,F5.3,6X,F6.3)
200 FORMAT(///,8X,'PRESSURE OR TEMPERATURE IS APPROACHING ZERO',
C //,15X,'*** SIMULATION TERMINATED ***')
210 CLOSE(8,STATUS='KEEP')
      STOP
      END
      SUBROUTINE COUNT(N,NCOUNT,NPAG,NHEAD,NSUB)
*
*****
*
* Subroutine COUNT keeps track of the number of lines
* written to the current output file page. When the total
* number of lines reaches 50, a form feed character is
* written, and a new page header including page number is
* inserted.
*
*****
*
* Declaration of variables.
*
      INTEGER N,NCOUNT,NPAG,IYR,IMON,IDAY,IHR,IMIN,ISEC,I100TH,NHEAD,NS
      CHARACTER*3 FF
      FF = CHAR(12)

```

```

NCOUNT = NCOUNT + N
IF (NCOUNT.GE.50) THEN
  IF (NSUB.EQ.1) WRITE (8,1)
  IF (NSUB.EQ.2) WRITE (8,2)
  IF (NSUB.EQ.3) WRITE (8,3)
  IF (NSUB.EQ.4) WRITE (8,4)
  NPAG = NPAG + 1
  NCOUNT = 4
  IF (NPAG.NE.1) WRITE (8,10) FF
  CALL GETDAT(IYR,IMON,IDAY)
  CALL GETTIM(IHR,IMIN,ISEC,I100TH)
  WRITE (8,20) NPAG,IMON,IDAY,IYR,IHR,IMIN,ISEC
  NHEAD = 1
ENDIF
1  FORMAT (2X,59('-'))
2  FORMAT (2X,70('-'))
3  FORMAT (2X,73('-'))
4  FORMAT (2X,78('-'))
10 FORMAT (1X,A3)
20 FORMAT (/ ,2X,'WRI THERMAL HYDRAULICS, DECEMBER 19'
C'91',29X,'PAGE ',I2,/,65X,I2,'-',I2,'-',I4,/,67X,I2,':',I2,':',
CI2,/)
RETURN
END
SUBROUTINE HLOSS (NMS,T,XF2,HIN,J1,H,HL)
*
*****
*
* Subroutine HLOSS estimates the heat lost from the injection *
* fluid as a fraction of the initial heat content of the *
* injection fluid. The heat contents are estimated from fluid *
* enthalpies.
*
*****
*
* Declaration of variables.
*
REAL T,XF2,X,HW,HS,H,HL,HIN
X = (T-32.)/1.8
IF (J1.EQ.1) THEN
  IF (X.LT.130.) HW = 4.2*X
  IF (X.LT.310..AND.X.GT.130.) HW = 4.2*X + .003*(X-130.)**2.
  IF (X.GT.310.) HW = 4.2*X + .003*(X-130.)**2. + .0008*(X-310.)**3.
  HS = 2500. + 1.88*X - 3.7E-6*X**3.2
  H = (XF2*HS + (1.-XF2)*HW)*.4308
ENDIF
IF (J1.EQ.2) THEN
  IF (X.LT.130.) HW = 4.2*X
  IF (X.LT.310..AND.X.GT.130.) HW = 4.2*X + .003*(X-130.)**2.
  IF (X.GT.310.) HW = 4.2*X + .003*(X-130.)**2. + .0008*(X-310.)**3.
  H = HW*.4308
ENDIF
IF (NMS.EQ.0) HIN = H
IF (NMS.NE.0) HL = 1. - H/HIN
RETURN
END
SUBROUTINE PRINT (L,J,D1,DO1,LEN,D,DEPTH,TV,P,XF1,WS,HRATE,
CA1,A2,NPAG,WV)
*
*****

```

```

*
* Subroutine PRINT first opens the current output file and
* then echoes the input data to this output file. Depending
* on the current input data, only data regarding the current
* simulation is printed.
*
*****
*
* Declaration of variables and common blocks.
*
      REAL D1,DO1,LEN,D,DEPTH,TV,P,XF1,WS,U2(5000),ALPH(5000),DP4,WV,
      CRW(5000),RINS,RCI,TIME,KF(5000),TM,GG,DP,DP2,DP3,DP1,DEL,DEZ,
      CECI,EINS,A1,A2,ESL,D21B,D22B,K21B,ET1,ET2,KDTINS
      INTEGER L,J,NPAG,NHEAD,GINTUB,GINCAS
      CHARACTER*12 FII,FIO
      CHARACTER*15 FLUID(2)
      CHARACTER*43 TITLE
      LOGICAL DT
      COMMON /DTUB/ DT,D22A,D21B,D22B,K21B,ET1,ET2,KDTINS,GINTUB,
      C          GINCAS,UDT,PDT,PCAS
      COMMON /COMM1/ U2,ALPH,RW,RINS,RCI,TIME,DEL,DEZ
      COMMON /COMM2/ KF,TM,GG,EINS,ECI,ESL,TTINS
      COMMON /MISC/ FII,FIO,TITLE,NPCSL,NPCWB
      DATA FLUID/'SATURATED STEAM','HOT WATER'/
*
* Open current output data file.
*
      OPEN(8,FILE=FIO,ACCESS='SEQUENTIAL')
      CLOSE(8,STATUS='DELETE')
      OPEN(8,FILE=FIO,ACCESS='SEQUENTIAL',STATUS='NEW')
*
* Convert diameters to inches units
*
      DP = D*12.
      DP1 = D1*12.
      DP2 = 24.*RINS-2.*TTINS
      DP3 = 24.*RCI
      DP4 = DO1*12.
      DP5 = D21B
      DP6 = D22B
*
* Initializing page counter and printing page header.
*
      NPAG = 0
      CALL COUNT(57,1,NPAG,NHEAD,0)
*
* Echoing input data.
*
      WRITE(8,10)TITLE
      IF(L.EQ.2)GOTO 20
      WRITE(8,30)DP1,DP4,LEN,DEL,A1,TM,WV
      IF(L.EQ.1)GOTO 25
20  IF(.NOT.DT)WRITE(8,40)DP,DP2,TTINS,DP3,DEPTH,DEZ,A2,GG
      IF(DT)WRITE(8,50)DP,DP5,DP6,DP2,TTINS,DP3,DEPTH,DEZ,A2,GG
25  IF(L.NE.1)THEN
          WRITE(8,60)FLUID(J),WS,TV,P,TIME,HRATE
          IF(J.EQ.2)WRITE(8,70)XF1
      ELSE
          WRITE(8,80)FLUID(J),WS,TV,P,HRATE
          IF(J.EQ.2)WRITE(8,70)XF1

```

```

ENDIF
WRITE(8,85)
CALL COUNT(57,1,NPAG,NHEAD,0)
10  FORMAT(/,5X,'TITLE:      ',A43,/,
C   5X,'INPUT VARIABLES',/,5X,15('='),/)
30  FORMAT(5X,'SURFACE LINE',/,5X,12('='),/,5X,'INNER DIAMETER ',
C27('.'),3X,F5.2,2X,'INCHES',/,5X,'OUTER DIAMETER ',27('.'),3X,
CF5.2,2X,'INCHES',/,5X,'LENGTH ',35('.'),1X,F7.1,2X,'FEET',/,5X,
C'STEP SIZE FOR SURFACE LINE ',15('.'),2X,F6.1,2X,'FEET',/,5X,
C'ANGLE OF INCLINATION (FROM HORIZONTAL) ',3('.'),2X,F6.1,2X,'DEGR'
C,'EES',/,5X,'SURFACE TEMPERATURE ',22('.'),3X,F5.1,2X,'DEGREES F',
C/,5X,'AVERAGE SURFACE WIND VELOCITY ',12('.'),3X,F5.1,2X,'MPH',/)
40  FORMAT(5X,'WELLBORE (SINGLE WALL TUBING)',/,5X,29('='),/,
C 5X,'TUBING INNER DIAMETER ',20('.'),3X,F5.2,2X,'INCHES',/,
C 5X,'TUBING OUTER DIAMETER ',20('.'),3X,F5.2,2X,'INCHES',/,
C 5X,'INSULATION THICKNESS ',21('.'),3X,F5.2,2X,'INCHES',/,
C 5X,'CASING INNER DIAMETER ',20('.'),3X,F5.2,
C2X,'INCHES',/,5X,'DEPTH ',36('.'),1X,F7.1,2X,'FEET',/,5X,'STEP S',
C'IZE FOR WELLBORE ',19('.'),2X,F6.1,2X,'FEET',/,5X,'ANGLE OF INC',
C'LINATION (FROM HORIZONTAL) ',3('.'),2X,F6.1,2X,'DEGREES',/,5X,
C'GEOTHERMAL GRADIENT ',22('.'),1X,F7.5,2X,'DEGREES F/FEET',/)
50  FORMAT(5X,'WELLBORE (DOUBLE WALL TUBING)',/,5X,29('='),/,
C 5X,'INNER TUBING ID ',26('.'),3X,F5.2,2X,'INCHES',/,
C 5X,'INNER TUBING OD ',26('.'),3X,F5.2,2X,'INCHES',/,
C 5X,'OUTER TUBING ID ',26('.'),3X,F5.2,2X,'INCHES',/,
C 5X,'OUTER TUBING OD ',26('.'),3X,F5.2,2X,'INCHES',/,
C 5X,'INSULATION THICKNESS ',21('.'),3X,F5.2,2X,'INCHES',/,
C 5X,'CASING INNER DIAMETER ',20('.'),3X,F5.2,
C2X,'INCHES',/,5X,'DEPTH ',36('.'),1X,F7.1,2X,'FEET',/,5X,'STEP S',
C'IZE FOR WELLBORE ',19('.'),2X,F6.1,2X,'FEET',/,5X,'ANGLE OF INC',
C'LINATION (FROM HORIZONTAL) ',3('.'),2X,F6.1,2X,'DEGREES',/,5X,
C'GEOTHERMAL GRADIENT ',22('.'),1X,F7.5,2X,'DEGREES F/FEET',/)
60  FORMAT(5X,'OTHER INPUT VARIABLES',/,5X,21('='),/,5X,'THE',
C' INJECTION FLUID IS ',A17,/,5X,'MASS FLOWRATE',
C1X,28('.'),3X,F5.2,2X,'LBM/SEC',/,5X,'TEMPERATURE',1X,30('.'),
C2X,F6.1,2X,'DEGREES F',/,5X,'PRESSURE',1X,33('.'),2X,F6.1,2X,
C'PSIA',/,5X,'INJECTION TIME',1X,27('.'),1X,F7.1,2X,'DAYS',/,
C5X,'HEAT INJECTION RATE',1X,22('.'),1X,F7.1,2X,'BTU/SEC')
70  FORMAT(5X,'STEAM QUALITY',1X,28('.'),3X,F5.3)
80  FORMAT(5X,'OTHER INPUT VARIABLES',/,5X,21('='),/,5X,'THE',
C' INJECTION FLUID IS ',A17,/,5X,'MASS FLOWRATE',1X,28('.'),
C3X,F5.2,2X,'LBM/SEC',/,5X,'TEMPERATURE',1X,30('.'),2X,F6.1,
C2X,'DEGREES F',/,5X,'PRESSURE',1X,33('.'),2X,F6.1,2X,'PSIA',
C/,5X,'HEAT INJECTION RATE',1X,22('.'),1X,F7.1,2X,'BTU/SEC')
85  FORMAT(/,5X,'NOTE: HEAT TRANSFER COEFFICIENTS ARE EXPRESSED IN',
C11X,'Btu/hr-ft-degF')
100 FORMAT(A1)
WRITE(8,110)
110 FORMAT(/,5X,'SIMULATION RESULTS FOR INJECTION:',/,5X,33('='))
RETURN
END
SUBROUTINE TREAD(UI1,D,D1,D99,HIN,HRATE)

```

```

*
*****
*
* Subroutine TREAD reads input data from the current input file *
* which is specified on the command line. Some data processing *
* is performed (e.g. estimation of surface line and tubing *
* thermal resistances). *
*

```

```

*****
*
* Declaration of variables and common blocks.
*
  REAL LEN,D11,D12,D13,D21,D22,K11,K12,K21,E1,E2,K22,WV,T,H,TIME,
  CUI1,P,TV,X,M,DEPTH,ALPHA(5),TEMP2,D,D99,AN1,AN2,D1,GG,DEZ,
  CTM,LC(5),ID(5),OD(5),KC(5),TF(5),KHF(5),U2(5000),RW(5000),
  CKF(5000),KCEM(5),DW(5),KS,ALPH(5000),DEP,U1,RCI,RINS,DB,DEL,
  CECI,EINS,ESL,TX,HW,HS,HL,TINS,D21B,D22B,K21B,ET1,ET2,KDTINS
  INTEGER I,K,L,FIX1,NUM,M1,J1,ISL,N,NDEF,NCAS,NFORM,
  C NSAT,NCHECK,NL,GINTUB,GINCAS
  CHARACTER*12 FII,FIO
  CHARACTER*43 TITLE
  LOGICAL DT
  COMMON /DTUB/ DT,D22A,D21B,D22B,K21B,ET1,ET2,KDTINS,GINTUB,
  C GINCAS,UDT,PDT,PCAS
  COMMON /COMM1/ U2,ALPH,RW,RINS,RCI,TIME,DEL,DEZ
  COMMON /COMM2/ KF,TM,GG,EINS,ECI,ESL,TTINS
  COMMON /FREAD/ ALPHA,LC,ID,OD,KC,TF,KHF,DW,N,M1,U1,
  C K22,KCEM,D22,DEPTH
  COMMON /LREAD/ L,LEN,WV,D11,D12,E1,ISL,K11,K12,T,DB,
  C KS,J1,X,P,TV,M,D21,E2,K21,AN2,AN1
  COMMON /MISC/ FII,FIO,TITLE,NPCSL,NPCWB
*
* Open file FII (specified on the comand line) for
* reading of input data. Read input data unformatted.
*
  OPEN(6,FILE=FII,ACCESS='SEQUENTIAL')
  READ(6,*)LEN , DEPTH , DEL , DEZ
  READ(6,*)NPCSL , NPCWB , M , P
  READ(6,*)X , TV , TIME , TM
  READ(6,*)WV , GG , N , M1
  READ(6,*)D11 , D12 , T , DB
  READ(6,*)AN1 , E1 , ESL , K11
  READ(6,*)K12 , KS , D21 , D22
  READ(6,*)K21 , ET1 , D21B , D22B
  READ(6,*)K21B , ET2 , TTINS , K22
  READ(6,*)EINS , AN2 , E2 , NDT
  READ(6,*)GINTUB , GINCAS , KDTINS , PDT
  READ(6,*)ID(1) , OD(1) , DW(1) , LC(1)
  READ(6,*)KC(1) , KCEM(1) , ECI , ID(2)
  READ(6,*)OD(2) , DW(2) , LC(2) , KC(2)
  READ(6,*)KCEM(2) , ID(3) , OD(3) , DW(3)
  READ(6,*)LC(3) , KC(3) , KCEM(3) , ID(4)
  READ(6,*)OD(4) , DW(4) , LC(4) , KC(4)
  READ(6,*)KCEM(4) , ID(5) , OD(5) , DW(5)
  READ(6,*)LC(5) , KC(5) , KCEM(5) , TF(1)
  READ(6,*)KHF(1) , ALPHA(1) , TF(2) , KHF(2)
  READ(6,*)ALPHA(2) , TF(3) , KHF(3) , ALPHA(3)
  READ(6,*)TF(4) , KHF(4) , ALPHA(4) , TF(5)
  READ(6,*)KHF(5) , ALPHA(5)
  READ(6,'(A12)')FIO
  READ(6,'(A43)')TITLE
  CLOSE(6,STATUS='KEEP')
*
* Set logical and integer flags.
* Convert diameters and flowrate to proper units.
*
  DT = .FALSE.
  IF (NDT.EQ.2)DT = .TRUE.

```



```

D22A = D22
M = 0.004055*M
L = 3
IF(LEN.LT.1.)L = 2
IF(DEPTH.LT.1.)L = 1
IF(L.EQ.2)GOTO 41
D1 = D11/12.
ISL = 1
IF(T.GT..01) ISL = 2
IF(DB.GT..01) ISL = 3
IF(ISL.EQ.2)GOTO 30
IF(ISL.EQ.3)GOTO 31
D99 = D12/12.
*
* Calculate initial thermal resistance of surface line
*
    UI1 = ALOG(D12/D11)/K11
    GOTO 41
30  D13 = D12 + 2.*T
    D99 = D13/12.
    UI1 = ALOG(D12/D11)/K11 + ALOG(D13/D12)/K12
    GOTO 41
31  TEMP2 = 12.*DB/D12 + SQRT((12.*DB/D12)**2. - 1.)
    UI1 = ALOG(D12/D11)/K11 + ALOG(TEMP2)/KS
41  J1 = 1
    IF(X.LT..0001) J1 = 2
    IF(J1.EQ.2)GOTO 60
    TV = 132.924*P**.21 - 22.
*
* Calculate initial heat content of injection fluid
*
60  CALL HLOSS(0,TV,X,HIN,J1,H,HL)
    HRATE = HIN*M
*
* Calculate initial thermal resistance of wellbore
*
    IF(L.EQ.1)GOTO 130
    IF(DT)THEN
        D = D21/12.
        RINS = D22/24.
        U1 = ALOG(D22/D21)/K21
        UDT = ALOG(D22B/D21B)/K21B
        IF(TTINS.GT..00001)
C          UDT = UDT + ALOG((D22B+2.*TTINS/12.)/D22B)/K22
        RINS = (D22B+2.*TTINS)/24.
    ELSE
        D = D21/12.
        RINS = D22/24.
        U1 = ALOG(D22/D21)/K21
        IF(TTINS.GT..00001)U1 = U1 + ALOG((D22+2.*TTINS/12.)/D22)/K22
        RINS = (D22+2.*TTINS)/24.
    ENDIF
    DO 91 I = 1,N
        ID(I) = ID(I)/12.
        OD(I) = OD(I)/12.
        DW(I) = DW(I)/12.
91  CONTINUE
    LC(1) = DEPTH
    RCI = ID(1)/2.
    IF(M1.EQ.1)TF(1) = DEPTH

```

```

130 RETURN
END
SUBROUTINE TWOP (T,P,C,XF1,XF2,L1,D,DO,UI,WS,SINA,A,E,DELTA,
C
R,L,NT,ISL,WV)
*
*****
*
* Subroutine TWOP performs simulation for two-phase saturated
* steam. The pressure drop is estimated from the Lockhart and
* Martinelli correlation. The heat losses are based on the
* total thermal resistance as described by T.B. Jensen,
* M.S. Thesis, University of Wyoming, December 1986.
* The subroutine iterates on pressure and steam quality until
* these converge within a specified tolerance.
*
*****
*
* Declaration of variables and common blocks and
* initialization of data blocks.
*
REAL T,P,XF1,XF2,L1,D,UI,WS,SINA,A,MUL,MUG,REL,REG,U,K,VE1,VE2,
CAA(24),XF,QL,QG,FTD,E,PG,PF,PM,RG2,RL2,ROM,TCI,TINS,LL,LG,X,ROLD,
CKF(5000),TM,GG,EINS,ECI,RG1,RL1,LV1,XFA,FL,FG,LV2,HW1,HW2,DXDZ,
CDELTAP,DX,XF2N,P2N,RO1,RO2,R,FI,TOLD,P2,RLA,RGA,WV,DO,H,ESL
INTEGER C,L,II,NT,NUMIT,NCONT,ISL
COMMON /COMM2/ KF,TM,GG,EINS,ECI,ESL,TTINS
COMMON /COMM3/ TCI,TINS,TTB1,TTB2
COMMON /SATS/ DELTAP,DX,RO1,RL1,RG1,LV1,HW1
DATA AA/3.7162,.018813,-.60121,3.7158,.018824,.39877,4.4454,
C.015826,-.59103,4.445,.015832,.40897,4.445,.01698,-.61213,
C4.446,.01684,.38785,5.195,.0148,-.60915,5.1915,.01483,.3905/
NUMIT = 0
TOLD = T
X = (T+460.)/1.8
*
* Calculation fluid properties for first call to TWOP for
* estimation of (dx/dz).
*
IF(C.LE.1.OR.NT.EQ.1)THEN
P2 = .995*P
XF2 = .995*XF1
RL1=20.0739*(1.+1.9227*(1.-X/647.3)**.3333+.8631*(1.-
C X/647.3)**.6667+.0669*(1.-X/647.3)**1.3333)
IF(T.LT.260.33)LV1=1075.73-1.07488*(X-273.15)
IF(T.GE.260.33)LV1=938.58*(1.-.000015*(X-400.))**2)
X = (T-32.)/1.8
RG1 = 1.6787*P/((1.012-4.461E-4*X+2.98E-6*X**2.-1.663E-8*X**3.)
C *(T+459.67))
RO1 = 1./(XF1/RG1+(1.-XF1)/RL1)
IF(X.LT.130.)HW1 = 1.8094*X
IF(X.GE.130..AND.X.LT.310.)HW1=1.8094*X+.0013*(X-130.)**2
IF(X.GE.310.)HW1=1.8094*X+.0013*(X-130.)**2+.00034*(X-310.))**3.
DXDZ = -.01*XF1/DELTA
*
* Estimation of (dx/dz).
*
ELSE
P2 = P - DELTAP
IF(P2.LE.0)THEN
P=0

```

```

        GOTO 110
    ENDIF
    XF2 = XF1 - DX
    DXDZ = DX/DELTA
ENDIF
*
* Iteration loop for estimation of pressure and steam quality.
*
* First step - calculation of fluid properties.
*
10  T = 132.924*P2**.21-22.
    X = (T+460.)/1.8
    RL2=20.0739*(1.+1.9227*(1.-X/647.3)**.3333+.8631*(1.-
C    X/647.3)**.6667+.0669*(1.-X/647.3)**1.3333)
    MUG = .00802*(1.+0.0006*(X-273.15)**1.4)
    IF(T.LT.260.33) LV2=1075.73-1.07488*(X-273.15)
    IF(T.GE.260.33) LV2=938.58*(1.-.000015*(X-400.))**2)
    X = (T-32.)/1.8
    MUL = 100./(2.1482*(X-8.435+(8078.4+(X-8.435)**2.))**.5)-120.)
    RG2 = 1.6787*P/((1.012-4.461E-4*X+2.98E-6*X**2.-1.663E-8*X**3.)
C    *(T+459.67))
    RLA = (RL1+RL2)/2.
    RGA = (RG1+RG2)/2.
    XFA = (XF1+XF2)/2.
*
* Calling subroutine THCSAT for estimation of film heat transfer
* coefficient of either hot water or saturated steam. This
* subroutine in turn calls TOTTHC which estimates the overall
* thermal resistance for wellbore systems.
*
    CALL THCSAT(WS,RGA,RLA,D,SINA,MUL,MUG,XFA,T,UI,U,C,L1,L,DXDZ)
*
* For surface line simulation, call subroutine SLINER for
* estimation of convective and radiative heat losses from
* the pipe. Then estimate total thermal resistance.
*
* For the wellbore simulation -
* estimate total thermal resistance.
*
    IF(L.EQ.1) THEN
        CALL SLINER(ISL,C,U,10000.,10000.,T,TM,R,ROLD,WV,DO,ESL)
        FI = R*((T+TOLD)/2. - TM)
    ELSE
        R = 6.2832/U
        FI = R*((T+TOLD)/2.-TM-GG*(L1-DELTA/2.))
    ENDIF
*
* Estimate change in steam quality based on overall
* thermal resistance.
*
    RO2 = 1./(XF2/RG2+(1.-XF2)/RL2)
    IF(X.LT.130.) HW2 = 1.8094*X
    IF(X.GE.130..AND.X.LT.310.) HW2=1.8094*X+.0013*(X-130.))**2
    IF(X.GE.310.) HW2=1.8094*X+.0013*(X-130.))**2+.00034*(X-310.))**3.
    XF2N = (XF1*LV1+HW1-HW2-FI*DELTA/(3600.*WS)+
C    .37018*(P2-P)/(RO2+RO1))/LV2
    IF(XF2N.GT.1.) XF2N = .9999999
    IF(XF2N.LT.0.) THEN
        XF2N = .000001
        NCONT = 1

```

```

      ENDIF
*
* Estimate pressure changes - frictional and gravitational.
*
      XFA = .5*(XF1+XF2N)
      REG = XFA*WS*D/(A*MUG*.000672)
      REL = (1.-XFA)*WS*D/(A*MUL*.000672)
      IF (REG.LT.1000..AND.REL.LT.1000.) II = 0
      IF (REG.LT.1000..AND.REL.GE.1000.) II = 6
      IF (REG.GE.1000..AND.REL.LT.1000.) II = 12
      IF (REG.GE.1000..AND.REL.GE.1000.) II = 18
      CALL FRFAC(D,E,REL,LL)
      CALL FRFAC(D,E,REG,LG)
      X = SQRT((LL*(1.-XFA)*WS)**2/RL2)/(LG*(XFA*WS)**2/RG2))
      FL = AA(1+II)*EXP(AA(2+II)*X)*X**AA(3+II)
      FG = AA(4+II)*EXP(AA(5+II)*X)*X**AA(6+II)
      PF=(2.*FL**2*LL*(1.-XFA)**2/(RL2+RL1)+2.*FG**2*LG*XFA**2/
C      (RG1+RG2))* (WS/A)**2/(D*32.2)
      P2N = P - DELTA*(PF+RO2*SINA)/144.
      IF (P2N.LE.0) THEN
        P=0
        GOTO 110
      ENDIF
*
* Convergence check and update of primary variables.
*
      IF (NCONT.EQ.1) GOTO 20
      IF (ABS(XF2-XF2N).GT.3.E-5.OR.ABS(P2-P2N).GT.2.E-2) THEN
        NUMIT = NUMIT + 1
        IF (NUMIT.GT.10) THEN
          WRITE(8,101)
          GOTO 20
        ENDIF
        P2 = P2N
        XF2 = XF2N
        DXDZ = (XF2-XF1)/DELTA
        GOTO 10
      ENDIF
20  XF2 = XF2N
    T = 132.924*P2N**.21 - 22.
*
* Estimate accelerational pressure change.
*
      K = (RL2/RG2)**.07
      VE1 = (XF1/RG1 + K*(1.-XF1)/RL1)*(XF1 + (1.-XF1)/K)
      VE2 = (XF2/RG2 + K*(1.-XF2)/RL2)*(XF2 + (1.-XF2)/K)
      PM = (WS/A)**2*(VE1-VE2)/32.2
      P = P2 - PM/144.
      IF (P.LE.0) THEN
        P=0
        GOTO 110
      ENDIF
*
* Update fluid properties for subsequent calls to TWOP.
*
      HW1 = HW2
      LV1 = LV2
      RO1 = RO2
      RL1 = RL2
      RG1 = RG2

```

```

      DELATAP = P2N - P
      DX = XF2N - XF1
101  FORMAT('/', 'CONVERGENCE NOT OBTAINED IN PRESSURE/', '/',
      C      'STEAM QUALITY CALCULATION', '/')
110  RETURN
      END
      SUBROUTINE HOTW(T,P,C,L1,UI,WS,SINA,D,DO,A,E,DELTA,R,L,ISL,
      C      WV,DELTAP)
*
*****
*
* Subroutine HOTW performs simulation for hot water flowing
* either in a surface line or down a wellbore. The frictional
* pressure drop is estimated from the Moody correlation. The
* heat losses are based on the total thermal resistance as
* described by T.B. Jensen, M.S. Thesis, University of Wyoming,
* December 1986.
*
*****
* Declaration of variables and common blocks.
*
      REAL T,L1,P,UI,WS,SINA,D,A,RL,MUL,KW,FTD,HW,PRW,TM,GG,TCI,X,U,DO,
      CTF,KF(5000),R,CP,A1,PF,PG,E,FF,RE,UL,RI,EINS,ECI,TINS,TOLD,WV,
      CROLD,H,ESL
      INTEGER C,L,ISL
      COMMON /COMM2/ KF,TM,GG,EINS,ECI,ESL,TTINS
      COMMON /COMM3/ TCI,TINS,TTB1,TTB2
*
* Estimation of fluid properties.
*
      X = (T+460.)/1.8
      RL=20.0739*(1.+1.9227*(1.-X/647.3)**.3333+.8631*(1.-
      C X/647.3)**.6667+.0669*(1.-X/647.3)**1.3333)
      KW = .3975*(1.-.0000086*(X-410.))**2)
      CP = 1.+1.E-10*(X-310.))**4
      X = (T-32.)/1.8
      MUL = 100./(2.1482*(X-8.435+(8078.4+(X-8.435)**2.))**.5)-120.)
      RE = WS*D/(A*MUL*.000672)
      IF(RE.LT.1000.)HW = 4.36*KW/D
      IF(RE.GE.1000.)HW = .03*RE**.8*(CP*MUL/KW)**.3*KW/D
      RI = D/2.
*
* For surface line simulation, call subroutine SLINER for
* estimation of convective and radiative heat losses from
* the pipe. Then estimate overall thermal resistance and
* change in temperature of the flowing hot water.
*
* For the wellbore simulation, call subroutine TOTTHC for
* estimation of overall thermal resistance change in
* temperature of the flowing hot water.
*
      IF(L.EQ.1)THEN
        CALL SLINER(ISL,C,UI,HW,RI,T,TM,R,ROLD,WV,DO,ESL)
        T = T - DELTA*R*(T-TM)/(3600.*WS*CP)
      ELSE
        UI = UI + 1./(HW*RI)
        TF = TM + GG*L1
        CALL TOTTHC(UI,C,TF,T,U)
        R = 6.2832/U

```

```

      T = TF - 3600.*WS*GG*CP/R + (T-TM-GG*(L1-DELTA)+
C      3600.*WS*GG*CP/R)*EXP(-R*DELTA/(3600.*WS*CP))
      ENDIF
*
* Estimate frictional and gravitational pressure drop.
*
      CALL FRFAC(D,E,RE,FF)
      DELTAP = DELTA*(FF*(WS/(RL*A))**2*RL/(D*16.1) + RL*SINA)/144.
      P = P - DELTAP
      RETURN
      END
      SUBROUTINE SLINER(ISL,C,UI,HW,RI,T,TM,R,ROLD,WV,DO,ESL)
*
*****
* Subroutine SLINER estimates the convective and radiative
* heat transfer coefficients for the outside of the surface
* line. If the wind velocity is non-zero, correlations for
* forced convection are used to estimate the convection heat
* transfer coefficient, otherwise, correlations for free
* convection are used. Tubing (or insulation) and average
* ambient temperatures are used to estimate the radiative
* heat transfer coefficient.
*****
* Declaration of variables.
*
      REAL UI,HW,RI,T,TM,R,ROLD,WV,DO,ESL,TINS,H
      INTEGER ISL,C
      ROLD = 6.2832/(UI+1./(HW*RI))
      IF (ISL.NE.3) THEN
        IF (C.LE.1) THEN
          IF (ISL.EQ.1) TINS = .9*(T-TM) + TM
          IF (ISL.EQ.2) TINS = .4*(T-TM) + TM
        ELSE
          TINS = T - (T-TM)*R/ROLD
        ENDIF
        IF (WV.GT..1) THEN
          H = .4899*(WV/DO)**.5+.3334*WV**.6667/DO**.3333
        ELSE
          H = .2068*((TINS-TM)/DO)**.25
        ENDIF
        H = H + 1.71E-9*ESL*((TINS+460)**2+(TM+460)**2)*(TINS+TM+920)
        R = 6.2932/(UI+1./(HW*RI)+2./(H*DO))
      ELSE
        R = ROLD
      ENDIF
      RETURN
      END
      SUBROUTINE TOTTHC(U1,C,TA,T,U)
*
*****
* Subroutine TOTTHC estimates the total heat transfer
* coefficient for flow down a wellbore. Different relation-
* ships are used depending on the wellbore completion
* configuration (e.g. single or double wall tubing).
* Furthermore, transient heat transfer to the surrounding
* formations is estimated (based on a dimensionless solution

```

```

* of the heat diffusivity equation) and included as a      *
* transient part of the overall heat transfer coefficient.  *
* The subroutine iterates on casing annulus (and tubing     *
* annulus if double wall tubing filled with gas) temperatures *
* until these converge within a specified tolerance.        *
*                                                            *
*****
*
* Declaration of variables and common blocks and
* initialization of data blocks.
*
      REAL U2(5000),KF(5000),ALPH(5000),FS(10,14),RCI,TCIN,T,RW(5000),
      CRINS,U1,TA,TIME,U,TV,B,GR,F,HR,TS(10),RS(14),DEL,DEZ,WV,ESL,
      CEINS,ECI,TCI,U3,TD,FTD,RBAR,T1,T2,T3,T4,T5,TINSN,TM,GG,TINS,
      CD21B,D22B,K21B,ET1,ET2,KDTINS
      INTEGER I,J,K,L,C,NITER,MAXITER,GINTUB,GINCAS
      LOGICAL DT
      COMMON /DTUB/ DT,D22A,D21B,D22B,K21B,ET1,ET2,KDTINS,GINTUB,
      C GINCAS,UDT,PDT,PCAS
      COMMON /COMM1/ U2,ALPH,RW,RINS,RCI,TIME,DEL,DEZ
      COMMON /COMM2/ KF,TM,GG,EINS,ECI,ESL,TTINS
      COMMON /COMM3/ TCI,TINS,TTB1,TTB2
      DATA RS/100.,50.,20.,10.,5.,2.,1.,.5,.2,.1,.05,.02,.01,.0/
      DATA TS/.2,.2,.5,1.,2.,5.,10.,20.,50.,100./
      DATA FS/.313,.423,.616,.802,1.02,1.36,1.65,1.96,2.39,2.73,
      C.313,.423,.617,.803,1.02,1.37,1.66,1.97,2.39,2.73,.314,.424,
      C.629,.806,1.03,1.37,1.66,1.97,2.40,2.74,.316,.427,.623,.811,
      C1.04,1.38,1.67,1.99,2.42,2.75,.318,.430,.629,.820,1.05,1.40,
      C1.69,2.00,2.44,2.77,.323,.439,.644,.842,1.08,1.44,1.73,2.05,
      C2.48,2.81,.330,.452,.666,.872,1.11,1.48,1.77,2.09,2.51,2.84,
      C.345,.473,.698,.910,1.15,1.52,1.81,2.12,2.54,2.86,.373,.511,
      C.745,.958,1.20,1.56,1.84,2.15,2.56,2.88,.396,.538,.772,.984,
      C1.22,1.57,1.86,2.16,2.57,2.89,.417,.568,.790,1.00,1.24,1.58,
      C1.86,2.16,2.57,2.89,.433,.572,.802,1.01,1.24,1.59,1.87,2.17,
      C2.57,2.89,.438,.578,.806,1.01,1.25,1.59,1.87,2.17,2.58,2.89,
      C.445,.588,.811,1.02,1.25,1.59,1.88,2.17,2.58,2.90/
*
* Guestimate tubing and casing temperatures if first call
* to subroutine TOTTC.
*
      IF(C.LE.1)THEN
        TCI = 100.
        TINS = 690.
        TTB1 = 710.
        TTB2 = 700.
      ENDIF
      MAXITER = 10
      NITER = 0
*
* Iteration loop for estimation of annuli temperatures.
*
      1 NITER = NITER + 1
*
* Estimation of heat transfer across casing annulus.
* Estimation of properties and effective heat transfer
* coefficient of fluid in casing annulus through call to
* subroutine HTCANN.
*
      CALL HTCANN(GINCAS,RINS,RCI,TINS,TCI,EINS,ECI,PCAS,HR2)
      U3 = U1 + 1./(HR2*RINS) + U2(C)

```

```

      IF (.NOT.DT) GOTO 99
*
* Estimation of heat transfer across double tubing annulus.
* Estimation of properties and effective heat transfer
* coefficient of fluid in tubing annulus through call to
* subroutine HTCANN.
*
      IF (GINTUB.NE.4) THEN
        RT1 = D22A/24.
        RT2 = D21B/24.
        CALL HTCANN (GINTUB, RT1, RT2, TTB1, TTB2, ET1, ET2, PDT, HR1)
        U5 = 1. / (HR1*RT1)
        U4 = UDT + U5
      ELSE
        U5 = ALOG (D21B/D22A) / KDTINS
        U4 = UDT + U5
      ENDIF
      U3 = U3 + U4
*
* Estimation of transient heat transfer coefficient
* in surrounding formations.
*
* Step 1 - Calculate dimensionless time
*
99  TD = ALPH (C) * TIME / RW (C) ** 2.
*
* Step 2 - Look up dimensionless formation heat transfer
* parameter (FTD) based on dimensionless time and RBAR.
*
      IF (TD.GE.100.) THEN
        FTD = .5*ALOG (TD) + .403
      ELSE
        RBAR = 6.2832*U3*KF (C)
        DO 10 I = 1, 14
          IF (RBAR.GT.RS (I)) THEN
            L = I
            GOTO 30
          ENDIF
10      CONTINUE
30      DO 20 J = 1, 10
          IF (TD.LT.TS (J)) THEN
            K = J
            GOTO 40
          ENDIF
20      CONTINUE
40      IF (L.LT.2) T1 = 0.
          IF (L.GE.2) T1 = (RBAR-RS (L)) / (RS (L-1)-RS (L))
          IF (K.LT.2) T2 = 0.
          IF (K.GE.2) T2 = (TD-TS (K)) / (TS (K-1)-TS (K))
          FTD = FS (K, L) - T1*(FS (K, L) - FS (K, L-1)) - T2*(FS (K, L)
C          -FS (K-1, L)) - T1*T2*(FS (K, L) - FS (K-1, L-1))
          ENDIF
*
* Add transient heat transfer coefficient to overall heat
* transfer coefficient.
*
      U = U3 + FTD/KF (C)
      IF (NITER.GE.MAXITER) GOTO 50
*
* Estimate new iteration level temperatures for single wall

```



```

* tubing based on fractional heat transfer resistances.
*
  IF(.NOT.DT) THEN
    TCIN = TA + (T-TA)*(U2(C)+FTD/KF(C))/U
    TINSN = T - (T-TA)*U1/U
    DTMAX = AMAX1(ABS(TCIN-TCI),ABS(TINSN-TINS))
    TTB1N = TTB1
    TTB2N = TTB2
*
* Estimate new iteration level temperatures for double wall
* tubing based on fractional heat transfer resistances.
*
    ELSE
      TCIN = TA + (T-TA)*(U2(C)+FTD/KF(C))/U
      TINSN = TA + (T-TA)*(1./(HR2*RINS)+U2(C)+FTD/KF(C))/U
      TTB1N = T - (T-TA)*U1/U
      TTB2N = T - (T-TA)*(U1+U5)/U
      DTMAX1 = AMAX1(ABS(TCIN-TCI),ABS(TINSN-TINS))
      DTMAX2 = AMAX1(ABS(TTB1N-TTB1),ABS(TTB2N-TTB2))
      DTMAX = AMAX1(DTMAX1,DTMAX2)
    ENDIF
*
* Update casing and tubing temperatures.
*
    IF(DTMAX.GT..002) THEN
      TCI = TCIN
      TINS = TINSN
      TTB1 = TTB1N
      TTB2 = TTB2N
      GOTO 1
    ENDIF
*
* End of iteration loop - update casing and tubing temperatures.
*
50  TCI = TCIN
    TINS = TINSN
    TTB1 = TTB1N
    TTB2 = TTB2N
    RETURN
  END
  SUBROUTINE FRFAC(D,E,RE,F)
*
*****
*
* Subroutine FRFAC estimates friction factors
*
*****
*
  REAL D,E,RE,F,A,B,C
  IF(RE.LT.1000.) THEN
    F = 16./RE
  ELSE
    A = -2.*ALOG10(E/(3.7*D) + 12./RE)
    B = -2.*ALOG10(E/(3.7*D) + 2.51*A/RE)
    C = -2.*ALOG10(E/(3.7*D) + 2.51*B/RE)
    F = ((A-(B-A)**2/(C-2.*B+A))**(-2))/4.
  ENDIF
  RETURN
  END
  SUBROUTINE HTCANN(GAS,RI,RO,TI,TO,EI,EO,P,HANN)

```

```

*
*****
*
* Subroutine HTCANN estimates an effective heat
* transfer coefficient for free convection and
* radiation in a tubing or casing annulus filled
* with a specified gas.
*
*****
*
* Declaration of variables and initialization of data.
*
      REAL RI,RO,TI,TO,EI,EO,HANN,DC(12),MC(9),KC(9),PC(9),BC(4)
      REAL TAVG,TK,DENSANN,MJUANN,KANN,PRANN,KANNE,GRANN,BANN
      INTEGER GAS,K
      DATA DC/3.901, -.015, 2.417E-5,-1.366E-8,
C          3.9988,-.01575,2.661E-5,-1.6009E-8,
C          4.7733,-.01548,2.153E-5,-1.0867E-8/
      DATA MC/1.744E-6, 6.265E-8, -2.405E-11,
C          5.1101E-6,4.0508E-8,1.8036E-12,
C          1.0E-6, 4.92E-8, -1.0E-11/
      DATA KC/-3.042E-4,9.868E-5,-3.339E-8,
C          .001804,8.8496E-5,-2.839E-8,
C          -.00847,8.45E-5,-5.0E-9/
      DATA PC/0.8201,-5.177E-4,4.857E-7,
C          0.7909,-.0003413,3.1607E-7,
C          0.8933,-5.609E-4,4.429E-7/
      DATA BC/0.01125,-4.3956E-5,7.1036E-8,-4.0463E-11/
      G = 9.81
*****
*
* Estimating density, viscosity, thermal conductivity,
* Prandtl number, and coefficient of thermal expansion
* for gas in annulus. Metric units.
*
*****
* GAS: 1: AIR; 2: NITROGEN; 3: CARBON DIOXIDE
*****
      TAVG = .5*(TI+TO)
      TK = (TAVG-32.)/1.8 + 273.15
      K = (GAS - 1)*4 + 1
      DENSANN = DC(K) + DC(K+1)*TK + DC(K+2)*TK**2 + DC(K+3)*TK**3
      K = (GAS - 1)*3 + 1
      MJUANN = MC(K) + MC(K+1)*TK + MC(K+2)*TK**2
      KANN = KC(K) + KC(K+1)*TK + KC(K+2)*TK**2
      PRANN = PC(K) + PC(K+1)*TK + PC(K+2)*TK**2
      BANN = BC(1) + BC(2)*TK + BC(3)*TK**2 + BC(4)*TK**3
*****
*
* Estimating Grashof number, effective radiation
* and convection, and overall effective heat transfer
* coefficient in annulus. (See Willhite, J. Pet. Tech.,
* May 1967, pp 607-615). For pressures less than
* atmospheric, the effective thermal conductivity in
* the annulus is estimated as a straight line function
* of pressure.
*
*****
      GRANN = ((RO-RI)*0.3048)**3.*DENSANN**2.*G*BANN*(TI-TO)/
C          MJUANN**2

```

```

      F = ((460.+TI)**2+(460.+TO)**2)*(920.+TO+TI)
      KANNE = 0.049*KANN*(GRANN*PR)**0.3333*PRANN**0.047*0.57782
      IF(P.LT.5.2) KANNE = KANNE*(P/5.2)
      HANN = 1.713E-9*F/(1./EI+RI*(1./EO-1.)/RO)
      C      + KANNE/(RI*ALOG(RO/RI))
      RETURN
      END
      SUBROUTINE THCSAT(WS, RG, RL, D1, S, ML, MG, X, T, UI, U, C1, L1, L, DXDZ)
*
*****
*
* Subroutine THCSAT estimates the film heat transfer
* coefficient of saturated steam. This film coefficient
* is based on steam quality, steam quality gradient, and
* flow rates along with other steam proerties (density,
* viscosity, etc.). The subroutine also calls the
* subroutine TOTTC for estimation of the overall heat
* transfer coefficient.
*
*****
*
* Declaration of variables and common blocks.
*
      REAL A, B, C, F, RG, RL, ML, MG, RET, D1, FF, FM, CPW, EINS, ECI, DXDZ, WV, ESL,
      CKW, PR, HW, U, UI, WS, X, T, FT, SI, FA, RI, TM, TF, GG, L1, KF(5000), S, RE
      INTEGER C1, L
      COMMON /COMM2/ KF, TM, GG, EINS, ECI, ESL, TTINS
*
* Estimate frictional, accelerational and
* gravitational components.
*
      IF(X.LT..03)GOTO 10
      A = .81057*WS**2/(RG*D1**4)
      RET = 1894.7*WS/(D1*MG)
      B = ML/MG
      C = RG/RL
      F = (1.-X)/X
      FF = .045*A*RET**(-.2)*(X**1.8+5.7*B**.0523*(1.-X)**.47*X**
      C      1.33*C**.261+8.11*B**.105*(1.-X)**.94*X**.86*C**.522)
      FM = .5*A*D1*DXDZ*(2.*(1.-X)*C**.67+(1./X-3.+2.*X)*C**1.33+
      C      (.75*X-1.)*C**.33+(2.5-1.25/X-1.25*X)*C**1.66+.5*(X-1.)*C)
      IF(FM.LT.0.)FM = 0.
      FA = -8.05*S*(RL-RG)*D1*(1.-1./(1.+F*C**.67))
10  CPW = 1. + 1.E-10*((T+460.)/1.8-310.)**4
      KW = .3975*(1.-.0000086*((T+460.)/1.8-410.))**2)
*
* Calculate film heat transfer coefficient. Use hot water
* film heat transfer coefficient if steam quality is less
* than 3%.
*
      IF(X.LT..03)THEN
      RE = WS/(D1*ML*.000528)
      IF(RE.LT.1000.)HW = 4.36*KW/D1
      IF(RE.GE.1000.)HW = .03*RE**.8*(CPW*ML/KW)**.65*KW/ML
      ELSE
      HW = 95.131*((FF+FM+FA)*RL)**.5*(CPW*ML/KW)**.65*KW/ML
      ENDIF
*
* Estimate overall heat transfer coefficient.
*

```

```
RI = D1/2.  
U = UI + 1./ (HW*RI)  
IF (L.NE.1) THEN  
  TF = TM + GG*L1  
  CALL TOTTHC (UI,C1,TF,T,U)  
ENDIF  
RETURN  
END
```

APPENDIX C
Materials Description

MATERIALS DESCRIPTION

Pipe Dimensions

Construction material.....	carbon steel
Inside diameter of inner pipe.....	2.992 inches
Outside pipe of inner pipe.....	3.500 inches
Inside diameter of outer pipe.....	4.950 inches
Outside diameter of outer pipe.....	5.500 inches
Insulation thickness (when used).....	1.450 inches
Pipe test section length.....	36.00 inches
Coupling test section length.....	6.75 inches
Total test section length (pipe and coupling).....	42.75 inches

Heat Transfer Properties

Convective heat transfer coefficient.....	0.8806 Btu/hr-ft ² -°F
Emissivity of carbon steel.....	0.60
Insulation, thermal conductivity	
120.....	0.0214 Btu/hr-ft-°F
140.....	0.0224 Btu/hr-ft-°F
160.....	0.0233 Btu/hr-ft-°F
180.....	0.0243 Btu/hr-ft-°F
200.....	0.0253 Btu/hr-ft-°F
Air, thermal conductivity	
120.....	0.0481 Btu/hr-ft-°F
140.....	0.0499 Btu/hr-ft-°F
160.....	0.0516 Btu/hr-ft-°F
180.....	0.0533 Btu/hr-ft-°F
200.....	0.0549 Btu/hr-ft-°F

END

**DATE
FILMED**

11/26/93