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ABSTRACT

Title of Thesis: Mathematical Model of Temperature Profiles and Coking in a Crude Oil Heater Tube

Joseph C. Polimeni Master of Science in Chemical Engineering, 1983

> Thesis directed by: Dr. Gordon Lewandowski Professor of Chemical Engineering

A mathematical model to predict temperature profiles and coking of crude oil in furnace tubes is presented. The model assumes that the coking mechanism is due to a reaction in the laminar sublayer, whose rate depends upon the temperature profile. That profile is obtained by a numerical solution of the appropriate transport equations, with velocity profiles that may be laminar or turbulent, and including the temperature dependence of the crude oil properties. In addition, velocity and temperature profiles were adjusted when necessary to ensure closure of the heat and material balances. As a by-product of this study, a correction was found necessary to Nikuradse's formulation. of the turbulent velocity profile in order to ensure material balance closure. Comparisons are shown between the model and the limited published data.

MATHEMATICAL MODEL OF TEMPERATURE PROFILES AND COKING IN A CRUDE OIL HEATER TUBE

by Joseph C. Polimeni

Thesis submitted to the Faculty of the Graduate School of the New Jersey Institute of Technology in partial fulfillment of the requirements for the degree of Master of Science in Chemical Engineering 1983

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APPROVAL SHEET

Title of Thesis:

Mathematical Model of Temperature Profiles and Coking in a Crude Oil Heater Tube

Name of Candidate:

Joseph Cesare Polimeni Master of Science in Chemical Engineering, 1983

> Thesis directed by: Dr. Gordon Lewandowski Professor of Chemical Engineering

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VITA

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I. Introduction

Furnaces used to heat crude oil consist of banks of alloy steel tubes. The heat is transferred from the flame to the tubes by radiation and convection. During furnace operation, a layer of coke is formed on the inside of the tube walls. The thickness of this coke layer increases with time, and thereby increases the resistance to heat transfer across the tube wall. The increased resistance has two undesirable effects. First, in order to maintain a constant heat transfer rate, the outside tube wall temperature must increase (by increasing the furnace firing rate). Eventually (without decoking) the tube wall reaches the failure point, bulges, and ruptures. Secondly, there is a reduction of the radiant section efficiency. Much of the extra energy leaving the radient section can be recovered in the convection section, but this shift leads to further fouling of the convection tube bank and results in even further decreases in overall efficiency (1). Since furnaces and steam boilers consume approximately 75% of the energy used at petroleum refineries (2) coking can be a costly problem.

In addition, coking would clearly be a significant problem to overcome if synthetic fuels are processed. Fuels produced synthetically from coal contain a larger amount of aromatics and have a lower hydrogen to carbon atomic ratio (3). Both of these conditions make oil from coal more inclined to coking than conventional petroleum crude (4).

In order to assess the current state-of-the art

regarding coking predictive techniques, and to establish a data base, a thorough literature search was performed using the following computer data bases:

COMPENDEX-A machine readable version of "The Engineering Index" which provides abstracted information from the world's significant engineering and technological literature. The database contains all the information in the Engineering Index since 1970.

- FLUIDEX-A specialized database produced by the British Hydromechanics Research Association (BHRA). The database contains records from 1974 to present.
- DISSERTATION INDEX-A database which contains the subject, title, and author of virtually every American dissertation accepted at an accredited institution since 1861. Approximately 99% of all American dissertations are cited in this file. Masters thesis have been included since 1962.

The Dialog corporation allows searches through these databases. Key words are checked against each entries abstracts and classifications.

The following combinations of keywords were searched for in Compendex:

Coke or Coking and Reaction Kinetics Coke or Coking and Mathematical models Coke or Coking and Kinetics and Pyrolysis Coke or Coking and Cracking and Naphthas Naphthas and Cracking Naphthas and Pyrolysis Pyrolysis and Mathematical Models Crude Oil and Mass Transfer Petroleum and Mass Transfer Temperature Profile and Turbulent Flow Coking and Scale Formation (which turned out to be the most useful key words) Furthermore every article in the Oil and Gas Journal, Hydrocarbon Processing, and CEP which delt with coke or

coking since 1970 was checked.

The BHRA index was checked for: Coke or Coking Temperature Profile and Turbulent Flow

The Dissertation index was checked for: Coke or Coking and Mathematical Model

In addition to these searches which I performed myself, I contracted the Engineering Societies Library and the NJIT Library to do a literature search coking of crude oils and no additional information was found.

Industry, while recognizing the importance of coking on the economics of design and operation of furnaces, is usually satisfied with the use of estimated values of coking obtained from plant data (which is proprietary). Design equations which account for coking generally include an empirical fouling factor as part of the heat transfer coefficient (1). Although a better understanding of coking could be economically important, there exist no models to predict coking from a theoretical basis, and only one empirical model.

A. Coking from Gas Phase Reactions

Previous studies on coking have been mainly concerned with gas phase reactions, specifically the cracking of naphtha to produce ethylene. Although the coking of crude oil is not the same as coking of naphtha, some of the parameters which affect gas phase coking may also affect liquid phase coking.

Coke formation from a gas phase reaction is a combination of hetergeneous surface reactions (catalytic) and homogeneous gas phase reactions (5,6). The surface reaction is strongly dependent on the surface condition, which is a function of the bare metal composition, as well as the composition of reaction products that accumulate at the tube surface. These reaction products may be the result of inorganic reactions between the metal and gas constituents (such as water vapor, hydrogen sulfide, etc.), or the reaction products may include coke formation. If the hydrocarbon is relatively ash free, then the deposited coke should be low in metal content, and therefore inert. As such a layer covers the more catalytically active metal tube wall, reaction rates would decline. This has been observed in lab experiments by Albright & Tsai (5) and Newsome (7). However, in an industrial situation the hydrocarbon ash content may be significant, particularly when crude oil is involved. Therefore, the coke deposit may bring with it to the tube surface significant amounts of metal species. In that case, the coke deposit may actually enhance the reaction rate, and this has been

observed by Scarborough (8).

Different feed stocks display different coking rates (7). Certain unsaturated hydrocarbons have been found to be precursors; including acetylenic compounds, olefins, and aromatics (5). Coking also increases with the carbon-tohydrogen ratio (9).

In metal tubes, steam decreases the coking tendency of naphtha (7). This may be due to a reduction of the naphtha partial pressure, as well as oxidation of the coke. However, when a Vycor glass tube is used, steam has little effect on the coking rate (10).

Surface reactions are always decreased when hydrogen sulfide is used to pretreat the furnace tubes. However hydrogen sulfide is highly corrosive, especially at high temperatures (10).

Chen and Maddock (6) have derived a gas phase coking model which assumes that the coke formation reaction is essentially the cracking of hydrocarbons into coke at the tube wall surface. The coke precursors travel from the bulk of the process gas to the wall surface. At low temperatures, the overall coking rate is kinetically controlled and would be dependent upon the tube wall temperature. At temperatures above 850 C (temperatures of practical cracking operation), the coking rate is mass transfer controlled and proportional to the mass transfer coefficient. They propose that the coking rate may be determined as a function of Reynolds number and tube

diameter using a j-factor analogy for mass transfer.

Fernandez-Baujin and Solomon (11) propose an empirical equation to predict the coking rate, which assumes a twostep mechanism:

- 1. Mass transfer of coke precursors from the bulk of the gas to the walls of the tube.
- 2. Chemical reaction of coke precursors at the tube wall resulting in the formation and deposition of coke.

In gas phase coking it has been observed that there is a decrease in coking with an increase in mass flow rate, this may be explained by assuming that the coke is produced in the laminar region near the tube wall. The temperature in this layer is higher than the bulk temperature and hence the coking rate is high in this region. The conversion of coke precursors to coke in this region is called the film effect. Coking in small tubes and low mass velocities is primarily due to the film effect, while coking at high mass velocities is mainly due to high tube wall temperatures (12).

B. Coking from Crude Oil

A thorough literature search revealed that only Crittenden (1979) and Scarborough et al. (1979) have attempted to develop a method to predict the amount of coke obtained when heating crude oil.

1. Model of Crittenden and Kolaczkowski (1)

Crittenden and Kolaczkowski developed a coking model by combining empirical relationships which are used to predict fouling in heat transfer equipment with a two-step

kinetic model for coking. The equations are based upon the following schematic:



The tarry layer is where the coke precursors react and where tars and asphaltenes may diffuse back into the bulk fluid. Fluid shear in the tarry layer can also remove coke from the wall.

The deposition of the tarry layer is primarily kinetically controlled, not mass transfer controlled. The reaction order of the coking process is unknown so it was assumed that the reaction is pseudo-first order. They also assumed that the rate constant accounts for the mass transfer of the precursors from the bulk to the tarry layer. The conversion of the tarry layer to coke is also considered to be a first order reaction. The temperature dependence of these reactions is assumed to be represented by the Arrhenius equation. Crittenden, however, does not mention how to obtain the temperatures of the coke and tarry layers.

Coke removal by fluid shear is assumed to be linear with shear stress, as first proposed by Kern and Seaton in 1959.

The mass transfer terms for the coke precursors (which are not identified) are expressed by a j-factor analogy.

The final model contains seven constants which must be determined from data. None of the seven constants directly account for the type of oil, which would certainly affect the coking rate.

Crittenden could not find any published data on coking of crude oil, so he attempted to prove the validity of his equation by using gas oil data from Watkinson (13).

Watkinson's data was from gas oil at low temperatures (300 F), not crude oil at high temperatures. The substance Watkinson observed on the inside of the tube walls was soft and sooty, not hard like coke. Watkinson recirculated the gas oil and Crittenden's model clearly assumes the oil is once-through. Finally, Watkinson used a tube that was only 0.359 inch i.d., as compared to the 6 inch i.d. used in commercial heaters.

Watkinson found that the accumulation of coke stopped after a few days although there were still particulates in the oil. However, particulates do not solely contribute to coking. The presence of polycyclic aromatics, which are known coke precursors, were not tested for.

Crittenden reports good agreement between his equation and the Watkinson data. This would actually seem to bring doubt on the validity of Crittenden's model, although with

seven empirical constants the model may be able to fit almost any data.

2. Data of Scarborough et.al. (14)

Published data on coking of crude oil in furnace tubes is scarce. Apparently the only published data is by Scarborough et.al. who were attempting to establish empirically the relative rate of coke deposition as a function of bulk temperature, heat flux, mass velocity, and film temperature. These data were used to check the validity of the model presented in this paper. Therefore, an overview of the limitations and inconsistencies in their data follows.

The apparatus they used consisted of 304 stainless steel tubes .591 inches in diameter and 9 feet long. By comparison, industrial furnace tubes are usually 6 inches in diameter and at least 40 feet long (15). Although the results could be scaled up to industrial size, the actual scale-up factor is unknown, since the effect of the L/D ratio on coking is unknown. The length is much too short to comfortably neglect end-effects, and to study the pattern of coking downstream as compared to upstream.

The crude oil entered each tube at approximately 650 F, as a slip stream from a refinery. The slip stream was assumed to be of constant quality. However, the type of crude oil used was not reported. Each type of crude oil has a different amount of coke precursors, and therefore different types of crude oil will coke differently. In

order to ensure single-phase (liquid) flow, they used booster pumps. However, the actual slip stream has two phase (gas/liquid) flow.

The experiments were conducted in order to obtain relative coking rates, and therefore their data is insufficient for a proper mathematical model. Pressure drop, actual coke thickness as a function of length of the tube, and tube wall temperature for each thermocouple were not presented.

In order to better obtain the rate of coking, the amount of coke which is carried downstream should also have been determined, but was not.

The investigators reported most of the data in terms of thermal resistance and not coke thickness. They determined the thermal resistance by using the following equation:

> Thermal Resistance = (Thermocouple Temp)-Bulk Temp (Heat Flux)(Area)

The equation is valid if you measure the bulk temperature. However, the bulk temperature was not measured. A listing of their computer program reveals that they assumed a linear bulk temperature profile based upon the inlet and outlet temperatures. The bulk temperature may not follow a linear profile (as my model indicates: see Figure 47), and therefore the values of thermal resistance they report may be in error. This may also be the reason why one data set had an increase in thermal resistance but

no reported coke (14).

The actual coke thickness is a function of tube length, which would be very important for a coking model, but was only reported for one case. The coke thickness at the end of each experiment was reported as a range, which was generally equivalent to the average value +100%.

Each tube was surrounded by an electrically heated furnace, which was to provide a constant heat flux. The investigators connected thermocouples to the experimental tube at one foot increments. They did not mention, however, whether the thermocouples were inside the wall of the tube, or if the thermocouples were at the inside surface of the tube. The tube metal temperatures reported are only given at two of the 9 thermocouple positions and only given for some of the data.

Although the investigators report the bulk temperature measured at the inlet of the tube to be essentially constant, a set of sample data presented in one of their reports (16) shows considerable variations in the outlet bulk temperature. For a reported outlet bulk temperature of 684 F, the outlet temperature actually varied from 436 F to 715 F. The oscillation could have been due to the process controller they used (Leeds Northrop), since they reported having quite a bit of trouble with the controller (17). This is an indication that the heat flux was not constant.

There are some anomalous data reported. Since the heat flux was to be constant, and crude oil was being

heated, it is impossible for the tube metal temperature to decrease downstream, yet two reported cases showed this type of behavior. They did report having trouble supplying power to the heaters (18) and perhaps this was the cause of the anomalous behavior.

Some further anomalous behavior can be shown by comparing the data in Table 1:

TABLE 1: ANOMALOUS SCARBOROUGH DATA

Data Number	D2	D3	C2	C3	
Flow Rate	143	143	285	285	lbm/ft2-sec
Temperature in	650	640	660	645	F
Heat flux	56	45	59	44	kBtu/hr-ft2
Tube Metal Temp.	865	910	800	860	F
(at thermocouple	3				
at initial time)					

Clearly this data is inconsistent, the initial tube metal temperature for D2 cannot be less than D3, and the initial tube metal temperature for C2 cannot be less than C3.

They report a relationship between mass velocity, coking rate, and film temperature in the form of thermal resistance increases which they display in a figure. The figure, shown below, has very scattered data, and the lines drawn through the data were clearly not fit with least squares. By replotting the data and using least squares the correct relationship is shown in Figure 1a. Notice, for example, the relationship presented by the investigators for a flow rate of 4501bm/sec-ft2. There are two points present and instead of drawing a straight line



connecting the two points the investigators drew a horizontal line between the two points (Figure 1b). Also note that they do not report how they have determined the film temperature. Most likely they used a film coefficient, which is not accurately known. The data for a mass flow rate of 150 lbm/s-ft2 has been replotted two ways (Figure 1a). The solid line indicates a least squares fit with an Arrhenius-type equation, while the dotted line is a straight line fit with least squares.

C. Physical Properties of Crude Oil

Crude oil is a complex mixture of many different hydrocarbons. The distribution of the hydrocarbons varies with the source of the oil. Determining the actual composition of a particular crude oil is a formidable task. Therefore, crude oil is typed with a characterization factor which is based on the average molal boiling point and API gravity. Typically a high characterization factor (around 14) indicates a mixture of low molecular weight hydrocarbons, and a low characterization factor (around 10) indicates a mixture of high molecular weight hydrocarbons.

Viscosity may be expressed as a logarithmic function of temperature (17):

(B/T) y = A ewhere: $y = \text{kinematic viscosity } (\mu/\rho),$ centistokes T = absolute temperature, K A = (91.836 Tb -29.263)(C/(B*1.E6)) B = e (4.717 + 0.00526 Tb) B = e Tb = mid-boiling temperature of crude, K $C = \text{characterization factor}, \sqrt[3]{Tb/Sg}$ $Sg = \text{specific gravity}, \frac{141.5}{API + 131.5}$ API = API gravity

The average percent deviation from the actual viscosity is approximately ten percent.

Thermal conductivity and heat capacity of crude oil are linearly dependent upon API gravity and temperature. A correlation of the data in Nelson (20) has resulted in the following equations:

The density of crude oil can be represented by a nonlinear equation which depends upon API gravity and temperature. By regressing the data in Nelson (21) the following equation resulted:

 $\rho = 62.22 + 97.25 \times 10 \quad (API) - 204.2 \times 10 \quad (API) - 94.67 \times 10 \quad (T) - 83.61 \times 10 \quad (T)$ where: ρ = density, lbm/ft3 T = temperature, F

D. Thermal Conductivities of Stainless Steel and Coke

The following equation represents a linear fit to data (22) for the thermal conductivity of 304 stainless steel between 572 and 932 degrees F: $^{-3}$ $k = 8.52 + 4.17 \times 10^{-3}$ (T) where: k = thermal conductivity, BTU/hr-ft-F T = temperature, F For the thermal conductivity of coke, the following data is taken from a figure presented by Scarborough et. al. (14):

Tube	Thermal Resistance	Coke Thickness
Position	F/BTU-hr x 1E-3	inches
1	3.00	0.0022
2	4.06	0.0097
3	4.61	0.0120
4	5.06	0.0115
5	5.11	0.0151
6	5.28	0.0151
7	4.89	0.0138
8	4.28	0.0160

Using the equation:

Thermal Resistance = Coke Thickness (Thermal Conductivity)(Area) of Coke

where area is the inside surface area of the tube (1.46 ft2) the thermal conductivity of coke at each tube position can be calculated:

	Thermal	Conductivity
Tube	of	Coke
Position	BTU/	hr-ft-F
1	0.	00423
2	0.	1376
3	0.	1485
4	0.	1305
5	Ο.	1688
6	0.	1634
7	0.	1609
8	0.	2135
Aver	age 0.	1609

II. Mathematical Analysis

The rate of coking is a very strong function of temperature. Therefore, any coking model is only as good as the temperature profile used. Hence, a large portion of the present model is devoted to determine the temperature profiles for laminar and turbulent flow.

Consider a fluid flowing in a circular tube as shown below.



The following conditions will be imposed:

- (1) Temperature is a function of r and z.
- (2) The physical properties of the fluid: ρ - density, lbm/ft3 k - thermal conductivity, BTU/hr-ft-F Cp - heat capacity, BTU/lbm-F μ - viscosity, lbm/s-ft

are dependent upon the bulk temperature of the fluid, and are therefore functions of z. (This means that velocity will also change with z.)

- (3) The velocity profile is fully-developed (end effects are ignored).
- (4) Material balance closure is insured by making $\rho \langle \psi \rangle$ equal to a constant.
- (5) The fluid is Newtonian and incompressible.
- (6) Viscous dissipation and axial conduction may be neglected in the energy balance.

(7) Although coke build-up is an unsteady-state phenomenon, we will consider a small time segment (Δt) over which steady-state balances may be written.

With these considerations, the energy equation in cylindrical coordinates reduces to:

$$\rho C_{\rho} V_{z} \frac{\partial T}{\partial Z} = k \left[\frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial T}{\partial r} \right) \right]$$
(1)

Letting

$$\alpha = \frac{k}{\rho C_{P}}$$

equation (1) becomes:

$$V_{Z}\frac{\partial T}{\partial Z} = \alpha \left[\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right)\right]$$
⁽²⁾

A. Laminar Flow

For fully-developed laminar flow, Vz can be determined by the Hagen-Poiseuille equation:

$$V_{Z} = \frac{\Delta P R g_{e}}{4 \,\mu L} \left[1 - \left(\frac{r}{R}\right)^{2} \right]$$
(3)

This equation can be rewritten as:

$$V_{Z} = 2 \langle V_{Z} \rangle \left[1 - \left(\frac{r}{R}\right)^{2} \right]$$
⁽⁴⁾

where

$$\left\langle V_{Z}\right\rangle = \frac{\int_{0}^{R} V_{Z} r dr}{\int_{0}^{R} r dr} = \frac{\Delta P R^{2} g_{c}}{8 \mu L}$$
(5)

Equations (2), and (4) can then be used to determine the temperature profile.

B. <u>Turbulent Flow</u>

The empirical equations proposed by Nikuradse (23) for fully-developed turbulent flow are the ones chosen for this model. There are three equations proposed by Nikuradse. Each equation is applied in a different flow region.

The Nikuradse equations are:

$$\overline{\nabla}_{Z} = \vee^{*}(\Upsilon) \qquad (0 < \Upsilon < 5) \qquad (6)$$

$$\overline{V}_{Z} = V^{*} (5.0 \, \text{lm}(Y) - 3.05) (5 < Y < 30)$$
(7)

$$\overline{V}_{Z} = V^{*}(2.5 ln(Y) + 5.5) \quad (30 < Y)$$
 (8)

where

$$Y = \frac{(R-r) \, \sqrt{p}}{\mu} , \text{ dimensionless}$$
(9)

ana

$$V^* = \sqrt{\frac{T_o}{\rho} q_e}$$
(10)

 $au_{\dot{ ext{o}}}$ is the shear stress at the wall (24),

$$\tau_{o} = \frac{\Delta P R}{2 L}$$
(11)

The tube is assumed to be horizontal so the gravity term is neglected.

$$\Delta P = \frac{\rho f L(V_z)^2}{r g_c}$$
(12)

 $\langle V_Z \rangle$ is the average velocity f is the Fanning friction factor

The Fanning friction factor may be estimated over a wide range of Reynolds numbers with the Round equation (25).

$$f = \frac{1}{4} \left\{ 1.8 \ln \left(\frac{N_{RE}}{1.35 N_{RE}(\underline{\varepsilon}) + 65} \right) \right\}^{-2}$$
(13)

E is the roughness factor, for commercial steel pipe the value is 0.00015 ft.

$$N_{RE} = \frac{D \langle V_Z \rangle \rho}{\mu}$$
(14)

therefore

$$\bigvee^{*} = \langle \bigvee_{Z} \rangle^{-1} \sqrt{\frac{f}{2}}$$
 (15)

and

$$\frac{\mathsf{V}^{\star}}{\langle \mathsf{V}_{Z} \rangle} = \sqrt{\frac{f}{2}} \tag{16}$$

Once again, the average velocity $\langle Vz \rangle$ can be determined at any value of z by the integral:

$$\left\langle V_{Z}\right\rangle = \frac{\int_{0}^{R} V_{Z} r dr}{\int_{0}^{R} r dr}$$
(17)

The turbulent flow velocity profile includes eddies (26) which result in oscillations about the time-smoothed values. Following standard procedures (27), the turbulent energy flux is accounted for by assuming an eddy diffusivi-ty for heat transfer $(\epsilon_{\rm H})$:

$$\overline{V_{z}} \frac{\partial \overline{T}}{\partial z} = \frac{1}{r} \frac{\partial}{\partial r} \left[r \left(\alpha + \epsilon_{\mu} \right) \frac{\partial \overline{T}}{\partial r} \right]$$
(18)

(where the superscript bar denotes time-smoothed values)

The Reynolds analogy states that the eddy diffusivity for heat transfer and momentum transfer are equal:

$$\epsilon_{\mu} = \epsilon_{\mu} \tag{19}$$

The eddy diffusivity for momentum transfer (ϵ_m) can be determined by the equation:

$$\epsilon_{m} = l^{2} \frac{\partial V_{*}}{\partial r}$$
⁽²⁰⁾

The Prandtl mixing length (\mathcal{L}) can be approximated for the entire flow regime with the Van Driest Model (28):

$$\mathcal{L} = (\mathbf{R} - \mathbf{r}) \, \mathbf{K} \left[\mathbf{I} - \frac{\Gamma}{\mathbf{Y}} \right] \tag{21}$$

where

is the value of Y at the buffer layer-core interface. This value has been reported to be 26 (dimensionless).

K is an empirical proportionality factor (Deissler's constant), equal to 0.36 (dimensionless).
The thickness of the laminar sublayer (δ) has been estimated by Nikuradse (23) from the following equation:

$$Y = 5 = \delta \frac{\sqrt{*\rho}}{\mu}$$
(22)

C. Transition Flow

As an additional assumption in the model, for the Reynolds' number range of 2000 to 4000, the velocity profile is determined by a linear combination of the laminar and turbulent profiles using Reynolds' number as the weighting factor:

$$V_{Z \text{ transition}} = \left[\frac{4000 - N_{\text{RE}}}{2000}\right] V_{Z \text{ laminar}} + \left[\frac{N_{\text{RE}} - 2000}{2000}\right] \overline{V}_{Z \text{ turbulent}}$$
(23)

D. Bulk Temperature

The bulk temperature can be determined at any value of z (axial position) by the integral:

$$T_{\text{bulk}} = \frac{\int_{0}^{n} V_{Z} T r dr}{\int_{0}^{n} V_{Z} r dr}$$
(24)

E. Film Temperature



Assuming a linear temperature profile from the wall to one half the thickness of the laminar sublayer, a characteristic film temperature (Tf) can be calculated by:

$$T_{f} = \frac{\Delta g(\delta)}{2\pi R k} + T_{W}$$
⁽²⁵⁾

$$\frac{\Delta q}{\Delta z} = m C_p \frac{\Delta T_{\text{bulk}}}{\Delta z}$$
(26)

where q = rate of heat transfer through the wall<math>m = the mass flow rate of the crude oilCp = the heat capacity of the crude oil<math>k = the thermal conductivity of the crude oil $\Delta Tbulk = change in bulk temperature over axial$ $increment <math>\Delta z$

This definition of film temperature ensures closure of the energy balance.

F. Kinetic Rate Constant

The coking rate in the laminar sublayer was assumed to be zero order, with the kinetic rate constant determined from Scarborough's data (29):

Average Film Temperature (Degrees F)	Coking Rate (inches/hr)			
898	1.75 E-04			
888	1.55 E-04			
809	5.50 E-05			

These data are at the same linear velocity, and were fit to an Arrhenius expression (see Figure 2):

 $kc = 2797.7 \exp(-22518.3/Tf)$ (27)

- where Tf is the average film temperature in degrees Rankine.
 - and kc is the zero-order kinetic rate constant in inches/hr

22518.3 = E/R, and therefore the activation energy for coke formation (E) turns out to be 44743 BTU/lb-mole (or 24.85 kcal/gmole).

Note, however, that this correlation is heavily dependent on the data point at 809 F. Changes in the location of that point on Figure 2 can have a profound effect on the slope and intercept.

FIGURE 2 : COKING RATE



AVERAGE FILM TEMPERATURE IN ^OR

G. Skin Temperature



The adjacent figure depicts a layer of coke on the inside of a tube wall. Assuming that the heat flux, thermal conductivities, inside and outside radius of the tube, and thickness of the coke is known, the temperature of the outside tube wall (Ts) can be evaluated as follows:

$$T_{s} = \frac{\left[\frac{1}{R_{cone}} ln\left(\frac{r_{wall}}{r_{one}}\right) + \frac{1}{R_{sTEEL}} ln\left(\frac{r_{smin}}{r_{wall}}\right)\right]}{2 \pi} \frac{\Delta q}{\Delta z} + T_{c}$$
(28)

H. Boundary Conditions

Since the velocity profile equations assume fullydeveloped flow (no end effects), the inlet velocity profile is assumed to be fully-developed at the average inlet velocity specified by the problem.

However, for turbulent flow, the Nikuradse equations contain empirical constants. When the equation is integrated to find the average velocity, it may not always match the value determined by mass balance. Therefore, to ensure mass balance closure, an iterative procedure is used to determine a correction factor (η) which is used to * multiply V in equations 7 & 8 above. This procedure is discussed further in the chapter on Numerical Analysis.

The initial temperature profile is assumed to be flat at the initial value of bulk temperature specified by the problem.

At the wall, it was assumed that the temperature would be known at two points. The wall profile is then assumed to be linear using the two given values. This boundary condition was chosen instead of constant heat flux because the latter causes serious difficulties when using a numerical solution. A heat flux simply specifies the slope of the temperature profile at the wall:

$$q_{w} = \frac{-k(T_{w} - T_{r})}{(\delta/2)}$$

On the right hand side of this equation are two terms that may be independently fixed: Tw and Tf. Furthermore, the turbulent temperature profile can be very steep in the laminar sublayer, and hence Tf is very sensitive to the essentially empirical choice of δ . For these reasons, a stable solution in which we had confidence was not deemed possible with heat flux as a boundary condition.

Similarly, although the wall temperature is specified, it cannot be used directly as a boundary condition. The reason for this is that the temperature profile at the wall is very sensitive to the number of radial points used in the finite difference technique, and it is very easy to develop a profile at the wall that is inconsistent with the overall energy balance. Therefore, to ensure energy balance closure, the film temperature (Tf) is used as the effective boundary condition.

III. Numerical Analysis

In order to solve equation 18 by a finite difference technique, the region of interest must be put into the form of a grid.

			•		•		٠	٠	•	•	
	٠	•	٠	٠	٠	٠	٠	٠	٠	٠	
	٠	٠	٠	•	٠	٠	•	٠	٠	•	
	٠	٠	٠	•	٠	٠	٠	٠	٠	٠	
1	•	٠	٠		٠		٠	٠	•	٠	
<u>ر بار</u>		•		- •	+	-+-				•	CENTEP
2			•		•	•					

Note: The grid convention is that r(1) indicates the radial point next to the wall and r(n) indicates the radial point at the center of the tube.

Grid points in the first column are given the initial conditions, which are a flat temperature profile and a fully-developed velocity profile at the inlet average velocity.

As stated previously, the specified wall temperature is not used directly as a grid point, but rather the film temperature (Tf) is calculated in the middle of the laminar sublayer and used instead as the first row of grid points (closest to the wall). Specifying Tf involves a trial-anderror procedure as described in a subsequent section.

Each gridpoint has a temperature, velocity, and eddy diffusivity associated with it. Each column of gridpoints have a thermal conductivity, heat capacity, density, and viscosity with it, based on the bulk temperature for the previous column of grid points.

A. Laminar Flow

For Reynolds' numbers less than or equal to 2000, the velocity at each grid point is calculated using equation (4) with the average velocity determined by a material balance. Equation (2) is then used to calculate the temperature profile with the same finite difference formulas discussed below, but with $\epsilon_{\rm H}$ =0.

B. Turbulent Flow

Two of the turbulent flow velocity profile equations contain empirical constants (equations 7 & 8). When an average is determined from this profile using equation 17, there is no guarantee that the material balance will be satisfied. In order to ensure material balance closure, V in equations (7 & 8) is replaced by 77 V,

$$\overline{V}_{Z} = \eta \, \vee^{*} (5.0 \, l_{\rm n} (\Upsilon) - 3.05) \tag{29}$$

$$\overline{\nabla}_{z} = \eta \, \vee^{*} (2.5 \, \ln(\Upsilon) + 5.5) \tag{30}$$

Where η is determined by trial-and-error using the secant method. In this method, two initial guesses are made for η (usually between 1.1 and 1.4). The turbulent velocity profile is calculated using equations 6, 29, and 30, and the average velocity is calculated using equation 17. The next value of η is then determined as follows:

$$G = \langle V_Z \rangle_{actual} - \langle V_Z \rangle_{calculated} = 0$$
 (31)

$$\eta_{i+2} = \eta_{i+1} - \frac{G_{i+1}}{\left(\frac{G_{i+1} - G_i}{\eta_{i+1} - \eta_i}\right)}$$
(32)

until $|G| \leq$ convergence criterion

This procedure is followed for each column of grid points. Resulting values of η are discussed in a later section of this dissertation.

The average velocity is determined by solving equation 17 with the trapezoidal rule. The trapezoidal rule is chosen for two reasons:

- 1. Either an odd or an even number of radial segments can be chosen.
- 2. The terms to be evaluated for the numerator and the denominator are plotted in Figure 3. It is clear that the area can be represented well by a linear type of integration method such as the trapezoidal rule.

Expanding equation 18:

$$\frac{1}{r} \left[r \alpha \frac{\partial \overline{T}}{\partial r^2} + \alpha \frac{\partial \overline{T}}{\partial r} + r \epsilon_{\mu} \frac{\partial \overline{T}}{\partial r^2} + \epsilon_{\mu} \frac{\partial \overline{T}}{\partial r} + r \frac{\partial \overline{T}}{\partial r} \frac{\partial \epsilon_{\mu}}{\partial r} \right] = \overline{V_2} \frac{\partial \overline{T}}{\partial Z}$$
(33)

combining like partial terms:

$$\left(\alpha + \epsilon_{\mu} + r \frac{\partial \epsilon_{\mu}}{\partial r}\right) \frac{\partial \overline{T}}{\partial r} + r \left(\alpha + \epsilon_{\mu}\right) \frac{\partial^{2} \overline{T}}{\partial r^{2}} = r \overline{V}_{Z} \frac{\partial \overline{T}}{\partial Z}$$
(34)

The partial derivatives were approximated using the Crank-Nicolson method (30). This method was used rather than (e.g.) a forward difference technique, because the Crank-Nicolson method 2 can converge using much larger axial increments (10 times). Since each length increment requires about 1 cpu second to run on a Univac 90/80-4, a 10 foot tube would require 1000 cpu seconds using forward difference as opposed to only 10 cpu seconds using Crank-Nicolson. This saving in computer time would increase for each time segment over which the temperature profiles are calculated along the entire length. The forward difference technique would also display severe temperature instabilities near the wall, with fluid temperatures oscillating and even becoming higher than the wall temperature. The region near the wall is most critical from the standpoint of coking kinetics.

Using Crank-Nicolson, the expressions for the partial derivatives are:

$$\frac{\partial T}{\partial Z} = \frac{T_{(n+1,m)} - T_{(n,m)}}{\Delta Z}$$
(35)

.

$$\frac{\partial \overline{T}}{\partial r} = \frac{1}{4\Delta r} \left(T_{(n+1,m+1)} - T_{(n+1,m-1)} + T_{(n,m+1)} - T_{(n,m-1)} \right)$$
(36)

_

$$\frac{\partial^2 T}{\partial r^2} = \frac{1}{2(\Delta r)^2} \left(T_{(n+1,m+1)} - 2 T_{(n+1,m)} + T_{(n+1,m-1)} + T_{(n,m+1)} - 2 T_{(n,m)} + T_{(n,m-1)} \right)$$
(37)

where the following convention for subscripts was used:

n is for the z coordinate (axial direction); n=1 is the point closest to the tube inlet

m is for the r coordinate (radial direction); m=1 is the point closest to the wall. m=M is the point at the center.

$$\beta_{m} = \left(\frac{\Delta Z}{4\Delta r}\right) \left(\frac{\alpha_{n} + \epsilon_{\mu m}}{V_{z_{lym}} r_{m}}\right)$$
(38)
(39)

Let

$$\gamma_{m} = \frac{\Delta Z}{2\left(\Delta r\right)^{2}} \left(\frac{\alpha_{n} + \epsilon_{\mu_{m}}}{V_{z_{n}m}} \right)$$
(40)

$$\xi_{m} = \frac{\Delta Z}{4\Delta r V_{Z_{nm}}} \left(\frac{\partial \epsilon_{\mu}}{\partial r} \right)_{m}$$
(40)
(41)

where

$$\frac{\partial \epsilon_{\mu}}{\partial r} = \frac{\epsilon_{\mu(n,m+1)} - \epsilon_{\mu(n,m-1)}}{2\Delta r}$$

and

$$\epsilon_{\mu(n,m)} = \ell_{(n,m)}^{2} \left[\frac{\overline{\nabla}_{Z(n,m+1)} - \overline{\nabla}_{Z(n,m)}}{\Delta r} \right]$$
(42)

(Note: the eddy diffusivity along the centerline approaches zero, and so was set equal to the value at the next radial grid point.)

$$\mathcal{L}_{(n,m)} = (R - r_{(m)}) 0.36 \left[1 - \frac{26}{Y_{(n,m)}} \right]$$
(43)
$$Y_{(n,m)} = (R - r_{(m)}) V_{(n)}^{*} \frac{\rho_{(n)}}{\mu_{(n)}}$$
(44)

$$\bigvee_{(n)}^{*} = \langle \bigvee_{Z} \rangle \sqrt{\frac{f_{(n)}}{2}}$$
(45)

Substituting into equation 34:

$$\beta_{m} \left(T_{(n+l_{j},m+l)} - T_{(n+l_{j},m-1)} + T_{(n_{j},l_{j}+l)} - T_{(n_{j},m-1)} \right) +$$

$$\gamma_{m} \left(T_{(n+l_{j},m+l)} - 2 T_{(n+l_{j},m)} + T_{(n+l_{j},m-1)} + T_{(n_{j},m+l)} - 2 T_{(n_{j},m)} + T_{(n_{j},m-1)} \right) +$$

$$\xi_{m} \left(T_{(n+l_{j},m+l)} - T_{(n+l_{j},m-1)} + T_{(n_{j},m+1)} - T_{(n_{j},m-1)} \right) - T_{(n+l_{j},m)} + T_{(n_{j},m)} = 0$$

$$(46)$$

Combining like terms:

$$T_{(n+1,m+1)}\left(\beta_{m}+\gamma_{m}+\xi_{m}\right)+T_{(n+1,m)}\left(-2\gamma_{m}-1\right)+T_{(n+1,m+1)}\left(-\beta_{m}+\gamma_{m}-\xi_{m}\right)$$

$$=-T_{(n,m+1)}\left(\beta_{m}+\gamma_{m}+\xi_{m}\right)-T_{(n,m)}\left(-2\gamma_{m}+1\right)-T_{(n,m-1)}\left(-\beta_{m}+\gamma_{m}-\xi_{m}\right)$$
(47)

Equation 47 is valid at all points except those along the centerline, where 1/r is undefined. Using L'Hôpitals' rule

at the centerline:

$$\lim_{T \to 0} \left(\frac{1}{T} \frac{\partial T}{\partial Y} \right) = \left(\frac{\partial^2 T}{\partial Y^2} \right)_{T=0}$$
(48)

$$\frac{\alpha + \epsilon_{H}}{\gamma} \frac{\partial \bar{\tau}}{\partial r} = \left(\alpha + \epsilon_{H} \right) \left(\frac{\partial \bar{\tau}}{\partial r^{2}} \right)_{r=0}$$
(49)

Substituting into equation (18):

$$(\alpha + \epsilon_{\mu})\left(2\frac{\partial\overline{T}}{\partial r^{2}}\right) + \frac{\partial\overline{T}}{\partial r}\frac{\partial\epsilon_{\mu}}{\partial r} = \overline{V_{z}}\frac{\partial\overline{T}}{\partial \overline{Z}}$$
(50)

Defining

$$\gamma_{m} = \Delta Z \left(\frac{\alpha_{n} + \epsilon_{H_{n}}}{(\Delta r)^{2} V_{Z_{N}m}} \right)$$
(51)

Equation 50 may be rewritten in terms of Crank-Nicolson finite difference expressions:

$$\gamma_{m}' \left(T_{(n+i_{j},m+i)} - 2 T_{(n+i_{j},m)} + T_{(n+i_{j},m-i)} + T_{(n_{j},m+i)} - 2 T_{(n_{j},m)} + T_{(n_{j},m-i)} \right) + \xi_{m} \left(T_{(n+i_{j},m+i)} - T_{(n+i_{j},m+i)} - T_{(n_{j},m-i)} \right) - T_{(n+i_{j},m)} + T_{(n_{j},m)} = 0$$
(52)

Combining like terms:

$$T_{(n+i,m+i)}(\gamma_{m}' + \xi_{m}) + T_{(n+i,m)}(-2\gamma_{m}' - 1) + T_{(n+i,m-i)}(\gamma_{m}' - \xi_{m})$$

$$= -T_{(n,m+i)}(\gamma_{m}' + \xi_{m}) - T_{(n,m)}(-2\gamma_{m}' + 1) - T_{(n,m-i)}(\gamma_{m}' - \xi_{m})$$
(53)

By symmetry, ξ_m , at the centerline is equal to zero because $\frac{\partial \epsilon_{\mu}}{\partial r} = 0$; therefore equation 53 can be written as:

$$T_{(n+1,m+1)}(\gamma_{m}') + T_{(n+1,m)}(-2\gamma_{m}'-1) + T_{(n+1,m-1)}(\gamma_{m}')$$

= $-T_{(n,m+1)}(\gamma_{m}') - T_{(n,m)}(-2\gamma_{m}'+1) - T_{(n,m-1)}(\gamma_{m}')$ (54)

also by symmetry:

$$T_{(n+1,m-1)} = T_{(n+1,m+1)}$$
(55)

$$T_{(n_1, m-1)} = T_{(n_1, m+1)}$$
(56)

placing equations 55 and 56 into 54:

$$T_{(n+1)m}(-2\gamma_{m}-1) + T_{(n+1)m}(2\gamma_{m}') = -T_{(n_{1}m)}(-2\gamma_{m}+1) - T_{(n_{1}m-1)}(2\gamma_{m}')$$
(57)

When solving for the first unknown temperature next to the wall equation 47 can be simplified since the temperature next to the wall is a boundary condition.

$$T_{(n+i)m_{1}}(-2\gamma_{m}-1)+T_{(n+i)m+i_{1}}(\beta_{m}+\gamma_{m}+\xi_{m})$$

$$= -T_{(2,i)}(-\beta_{m}+\gamma_{m}-\xi_{m})-T_{(i,i)}(-\beta_{m}+\gamma_{m}-\xi_{m})$$

$$-T_{(n,m+i)}(\beta_{m}+\gamma_{in}+\xi_{m})-T_{(n,m)}(-2\gamma_{m}+1)$$
(58)

Solving for the temperature profile using a tridiagonal matrix: Consider 5 radial values:

For clarity let $Am = \beta_m + \gamma_m + \xi_m$ $Cm = -2\gamma_m - 1$ $Dm = -\beta_m + \gamma_m - \xi_m$ $Em = -T_{(n,m+1)}A_m - T_{(n,m-1)}D_m$

making these substitutions into equation 47 we obtain

Also, let

Fm =
$$-2\gamma'_{m} - 1$$

Gm = $2\gamma'_{m}$
Hm = $-(-2\gamma'_{m} + 1)T_{(n,m)} - T_{(n,m-1)}(2\gamma'_{m})$

Equation 57 with these substitutions becomes:

$$T Fm + T Gm = Hm (59)(n+1,m) (n+1,m-1)$$

Finally, let
$$Im = -T$$
 $Dm - T$ $Dm - T$ Am
(2,1) (1,1) (n,m+1)
 $-T$ (n,m) (-2 $\gamma m + 1$)

and with this substitution equation 58 is now:

$$T Cm + T Am = Im$$
 (60)
(n+1,m) (n+1,m+1)

(Reminder: "n" refers to the z coordinate, and "m" the r coordinate) $\label{eq:coordinate}$

The tridiagonal matrix is set up for n=1 as follows (Remember at the first radial grid point the film temperature is known):

(m)

2	(C2)T (2,2)	(A2)T (2,3)	0	0	= I2 EQ.60
3	(D3)T (2,2)	(C3)T (2,3)	(A3)T (2,4)	0	= E3 EQ.58
4	0	(D4)T (2,3)	(C4)T (2,4)	(A4)T (2,5	= E4 EQ.58 5)
5	0	0	(G5)T(2,4)	(F5)T(2,	5)= H5 EQ.59

The N-1 equations and N-1 unknowns are solved by using a standard tridiagonal matrix algorithm (31).

C. Transition Flow

In the Reynolds' number range from 2000 to 4000, the velocity profile is determined using the equations for laminar and turbulent flow, as described above, and equation 23.

D. Bulk Temperature

In calculating the bulk temperature, equation 24 is solved using the trapezoidal rule. This appears to be an effective method as indicated by Figures 3 and 4.

Equation 24 with the finite difference approximations to the trapezoidal rule is:

$$T_{bulk} = \frac{\sum_{j=1}^{M-1} V_{Z}(n, j) T_{(n, j)} Y_{(j)}}{\sum_{j=1}^{M-1} V_{Z}(n, j) Y_{(j)}}$$
(61)



FIGURE 3 : NUMERATOR FOR AVERAGE VELOCITY AND DENOMINATOR FOR BULK TEMPERATURE

FIGURE 4 : NUMERATOR FOR BULK TEMPERATURE



Film Temperature

The initial value of the film temperature is taken to be the same as the wall temperature. After obtaining the temperature profile, the bulk temperature is determined, and equation 26 is used to calculate Δq . Then, a new film temperature is calculated using equation 25. The procedure is repeated until the film temperature converges.

F. Kinetic Rate Constant

Once the profile for the entire length of the tube has been determined, the coke is layered using equation 27. The user supplies the value for the time increment during which the coke is deposited. The amount of coke (in inches) then reduces the inside tube radius for the next time increment. The calculations are then repeated for the crude oil temperature profile along the entire tube length, more coke is deposited, and so on.

G. Skin Temperature

The outside skin temperature of the tube is determined using equation 28. The skin temperature is calculated after the film temperature (and therefore the temperature profile) has converged.

H. Boundary Conditions and Stability

The initial boundary conditions (at z=0) is a flat temperature profile equal to the average inlet bulk temperature, and a fully-developed velocity profile based on the

average inlet velocity. However, the second boundary condition on temperature, at the wall, presented special problems.

All finite difference methods have the potential for instability. When the wall temperature is used as a boundary condition, the method will not converge for a typical case (such as series D4) unless there are 2000 equal radial segments. Naturally 2000 radial segments is ridiculous, assuming that no round-off error is encountered, 900 cpu seconds would be required for a 9 foot tube, as opposed to only 9 cpu seconds using 30 radial segments (with 1 ft axial segments, and using the Crank-Nicolson method). In an attempt to correct this situation, the Crank-Nicolson equations were re-derived so that only the first few radial segments closest to the wall were small while the segments in the bulk liquid were relatively large This change, however, resulted in temperature oscillations, and in some cases fluid temperatures higher than the wall temperature, unless the size of the axial increment was reduced to 0.01 ft. This was the same problem encountered using the forward difference technique. In addition a heat balance done on each axial segment revealed that the heat balance was not closing. The pattern followed is shown in Figure 32.

In an effort to solve both the problems of stability and heat balance closure, the program was changed to utilize the film temperature rather than the wall tempera-



ture as the boundary condition. The initial guess for the film temperature is the wall temperature. The bulk temperature is then determined from the temperature profile, and a heat balance is used to determine the film temperature as described in equations 25 and 26. This procedure is iterated by successive substitution until the film temperature converges. If instead of a linear temperature profile assumed for the laminar sublayer, a parabolic profile is used, the calculated film temperature is the same but it requires 10 more iterations to converge. Hence, a linear profile is used in the program.

Therefore, the temperature next to the wall, which causes all the stability problems, is determined in a way which causes virtually no stability problems. For 40 radial segments, an axial segment of 0.5 feet is sufficient for stability and accuracy.

The proper number of radial segments to use was found by plotting the final bulk temperature (for series D4) using a variety of radial segments. Figure 33 indicates that 40 is the proper number of radial segments for accuracy and speed. The size of the axial segment was not found to affect the bulk temperature appreciably. However, decreasing the axial segment in half required twice as much computer time to calculate the temperature profile. For a nine foot tube with series D4, 40 radial segments, and an axial segment of 0.5 feet, the program requires about 30 cpu seconds to calculate the temperature profile for the entire length.



Since many calculations are required in this program, the entire program was re-written with double precision. The results were essentially the same (the bulk temperature differed slightly in the fourth decimal place). Since double precision requires much more memory and more time to run, the program used is the single precision version.

The program uses tolerance values for the film temperature and for the calculation of η . The tolerances were chosen to be the smallest that can be used without causing oscillation. If tolerances smaller than the present values are used for the series run in this dissertation, oscillation occurs, and no results are obtained.

IV. Description of Computer Program

A. <u>General Description</u>

After the crude oil parameters and tube dimensions are read, the velocity profile, temperature profile, and other important quantities (NRe, Bulk Temperature, etc.) are calculated starting from the first length segment and continuing downstream until reaching the end of the tube. At each length segment the physical properties of the crude oil are updated. Time is not incremented at each length segment. Time is incremented when all the calculations for an entire length have been completed.

Once an entire length has been completed, a uniform coke layer is added to the inside of the tube. The amount of coke is determined based upon the film temperature and the time increment. The velocity and temperature distributions are then calculated based upon the new value of the flow area.

This program requires the temperature of the inside of the tube wall at each length increment, constant heat flux is not necessary. The program assumes that the temperature and velocity profiles initially entering the tube are flat.

In order to save memory requirements the velocity and temperature profile arrays contain only 2 columns. Column 1 contains the past length segment values, column 2 contains the present values. Once all the calculations for a length segment are complete the arrays are reset with subroutine RESET (i.e. the present value in column 2

becomes the past value and is placed in column 1).

B. Program Specifics

Figure 5 shows the hierarchy diagram for the program. The flow chart for the MAIN program is shown in Figure 6. The MAIN program is responsible for calling the second level subroutines and incrementing the length and time. The main routine also insures that the temperature profile follows a heat balance by calling subroutine TADJ which adjusts the temperature next to the wall. This will be discussed further below.

MAIN starts by calling subroutine INIT (Figure 7), which initializes flags and important variables. Main then calls subroutine READER (Figure 8), which reads in the API gravity and mid-boiling temperature of the crude, the mass flow rate, inlet temperature, and wall temperature. In addition, it reads the specified number of radial and axial segments, the time increment, and variables used to control the printing of results. Once these variables are read in with READER, INIT sets the initial temperature array to the bulk temperature of the crude oil entering. Finally INIT calls PRN1 (Figure 9), which prints some of the important data read in subroutine READER.

Once INIT is complete and control is back to MAIN, a loop which counts the number of axial segments is begun. The first step of this loop is to call PHYP (Figure 10), which calculates the physical properties (density, thermal

conductivity, heat capacity etc.) of the crude oil based upon the bulk temperature of the previous length segment. The viscosity is calculated by calling function VISC (Figure 11). Once the physical properties are determined, routine PHYP determines the average velocity by performing a mass balance using the mass flow rate and the crosssectional area of flow. The flow area is not necessarily the cross-sectional area of the tube, because as the coke layer builds up the flow area is restricted. Once the average velocity is calculated, the Reynolds number and laminar sublayer thickness are calculated. Routine PHYP also determines the thickness of the laminar sublayer using the equations given previously. Once the thickness of the laminar sublayer is determined, the size of each radial segment is determined by subtracting one half of the laminar sublayer from the radius of flow, and then dividing by the number of specified radial segments.

The temperature of the wall for a particular length segment is calculated using WALLT (Figure 12), which takes two known wall temperatures specified in the data and assumes a linear profile. This profile is then extrapolated to cover the entire tube length.

RENVL (Figure 13) is a routine which decides which flow regime is applicable and calls the appropriate velocity subroutine. Laminar flow is considered to have a Reynolds number less than 2000, turbulent flow greater than 4000, and the transition region is between 2000 and 4000. If the Reynolds number is under 2000, RENVL calls

subroutine LAMAR (Figure 14), which calculates the velocity profile using equation 4. If the Reynolds number is greater than 4000, RENVL calls TURB (Figure 15), which uses two guesses (1.0 and 1.4) to the velocity correction factor, η , and then calls VPP (Figure 20), which determines the velocity profile using equations 6, 29, and 30; TVAVG (Figure 17), which determines the average velocity using the trapezoidal rule (Subroutine TRAP Figure 18); and SECANT (Figure 19), which performs the trial-and-error to obtain the appropriate value of η in order to close the material balance on $\langle Vz \rangle$. SECANT determines the next guess for the velocities to match. Once they match within a specified tolerance, control is given back to the main routine.

If the Reynolds number is between 2000 and 4000, subroutine TRANS is called (Figure 21), which calculates both the laminar profile (by calling LAMAR) and the turbulent profile (by calling TURB). The transition velocity profile is then based on a linear combination of both profiles, using a weighting factor which is proportional to the Reynolds number (see equation 23).

Once the velocity profile is determined control is restored to MAIN. The next step is to call TEMP (Figure 22), which calls EDDY and then TCRANK.

EDDY (Figure 23) determines the values of the eddy diffusivity for each radial point. If the flag, KTFLG, is

equal to zero then the flow is laminar and the eddy diffusivity for each radial segment is zero. For turbulent flow, the eddy diffusivity is calculated as described in the numerical section.

Once EDDY has been called, routine TEMP calls TCRANK (Figure 24), which sets up the terms for the tridiagonal matrix described in the numerical section. Once the appropriate terms are placed in the tridiagonal matrix, the matrix is solved with TRIDAG (Figure 25).

Once the temperature profile is determined, control is passed back to the main routine where QCALC is called (Figure 26), which determines the heat flux for the axial segment the program. QCALC calls BULKT (Figure 27), a subroutine to determine the bulk temperature using the trapezoidal integration method. Once the bulk temperature for the present axial segment is known, QCALC performs a heat balance to determine what the heat flux should be. The first guess for the temperature of the laminar sublayer is the same as the wall temperature, and a new value is generated by TADJ, (Figure 28), which uses the heat flux calculated in QCALC and a linear profile to determine the film temperature. It then iterates back to TEMP until convergence is reached on Tf. Once the temperature converges, SKIN is called (Figure 29) which calculates the temperature of the outside of the tube wall.

The program prints the results with routine PRN2 (Figure 16). Array IPRN and variable NPRN are used to limit the computer printout. The results for each axial

segment for the entire tube length will be printed, but only at the time increments specified. For example: If the total time of the test is 200 hours, and you want the coke to be layered at 100 and at 200 hours. There are three time segments (initial, 100 and 200 hours), but say only the value for the initial time and at 200 hours are desired. NPRN has the number of time increments to be printed, in this case NPRN is two. Array IPRN will have 2 values which correspond to the desired time increment. In this case IPRN(1) would equal zero (for the initial time segment) and IPRN(2) would equal two (for the value at 200 hours).

Once a length segment is completed, the V and T arrays are changed with RESET (Figure 30) so that the second column becomes the first. Once an entire length is completed the time is incremented by an amount, DTIME. If the total time is reached the program ends, otherwise subroutine NEWINT (Figure 31) is called which calculates the average film temperature, and then the coke thickness using the specified kinetic rate constant. NEWINT also determines the new flow area, and initializes variables for the next time segment.

In the next time segment, the temperature at the cokecrude oil interface is considered to be the same as the initial temperature at the tube wall-crude oil interface.







SUBACUTINE INIT (T. V. S. H. G. GL. DI. AMB. DR. ANGA. TAVE, API. 1 TO. NELVT. FUR. TIMET. AFIAST. ATTLE. 701. 783. MSES. 1. 1 TC3.TC4.DTINE.TTINE.CGRETE.TINE.IPAN.MPMI.BOVT.BINA BINENSIGN T13.549.V(2.549.B(363.IPAN.2069 EFERST IS THE FLAG WHILE INDICATES WHITHES IT IS THE FIRST TIME THEOREM THE PHOGRAM & VALUE OF 0 THEIGATES TRACT IT IS THE FLAST TIME & VALUE OF 1 INDICATES THAT THAT IT HAS ALREADE COME THEOREM ONE & SECRET IFINT OF HIS ALREADE COME THEOREM ONE & SECRET ETTLE IS THE FLAG VEICE (MOICATES LANIMAR OR THROUGHT FLOW 10 FOR LANIMAR 1 FOR THEMILINES IT IS INSTALLY SET TO LEDO CTTLE-4 T IS THE LEMETE DOMESTICAN INFELALLY SET TO & FT Z.0.8 T188+8.8 THE INITIAL CORE TRICINERS IS THE CONTELS.S CALL SEADERCTINEY, TVALL.01. MP. 328. APT 1 . TB. MPLOT. MSES, 32, TCI. TCA. 371M, TTIME, 2 . IFAM. MPMM. 2007. 2199 RAD - RAD /12 RIN - RAD ROUT = ROUT /12 DO 75 I=1,50 ŝ V(1,1)=0.0 V(2,1)= 0.0 <u>!</u>__ 75 ----20 300 1=1,50 T(1,1)- TINIT **!**____ .(300) -CALCULATE CROER SECTIONAL AREA IREA-8.14157-9880-238 CALCULATE THE FLOW MATE FROM ALMOST"S & TO LANAS THE INITIAL AVERAGE TEMP IS TIMIT THE-THEF TRATINIT TRATIL *** FIRE IS & SERENTFINE VERCE FRINTS OVE INFORMATION INFORMATION VALUE POLE NOT CLAME FOR IACS INCOMMENT. CALL PHOLERAD.H.SR.BE.APT.TB.Q3 RETURN

.

FIGURE 7: FLOWCHART OF SUBROUTINE INIT

FIGURE 8: FLOWCHART OF SUBROUTINE READER



FIGURE 9: FLOWCHART OF SUBROUTINE PRN1



FIGURE 10: FLOWCHART OF SUBROUTINE PHYP





FIGURE 1° FLOWCHART OF SUBROUTINE WALLT


FIGURE 13: FLOWCHART OF SUBROUTINE RENVL



FIGURE 14: FLOWCHART OF SUBROUTINE LAMAR



FIGURE 15: FLOWCHART OF SUBROUTINE TURB



FIGURE 16; FLOWCHART OF SUBROUTINE PRN2



FIGURE 17: FLOWCHART OF SUBROUTINE TVAVG

• •









FIGURE 20: FLOWCHART OF SUBROUTINE VPP







FIGURE 22: FLOWCHART OF SUBROUTINE TEMP





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FIGURE 23: FLOWCHART OF SUBROUTINE EDDY





FIGURE 26: FLOWCHART OF SUBROUTINE QCALC

ويها الوابوس والالمرو والمسور الراسينييني متتصبب الامتراد التراك والمراجعات



FIGURE 27: FLOWCHART OF SUBROUTINE BULKT



FIGURE 28: FLOWCHART OF SUBROUTINE TADJ



FIGURE 29: FLOWCHART OF SUBROUTINE SKIN









V. Results and Discussion

The program was executed with the data from Scarborough presented in Table 2. Only data which included initial wall temperatures were used. The data from series A2 and A3, however, were discarded since the wall temperature decreases downstream which is an impossible condition.

The Scarborough data, however, was taken at constant heat flux, and the program uses wall temperature as a boundary condition. An analytical solution could use the heat flux boundary condition very easily, however, the constant heat flux boundary condition poses problems for the numerical analysis. In order to use constant heat flux, and solve equation 18 numerically, one must know the wall temperature or film temperature, and then iterate to determine the correct profile in the laminar sublayer. This method would have posed serious stability problems, and so was not used.

The overall results are presented and compared with Scarborough's in Table 3. Heat flux as a function of tube length, as predicted by the program, is compared with the Scarborough data in Figures 34 through 39. The initial high heat flux predicted by the program, evident in Figures 34 through 39, can be attributed to the initial discontinuity in the temperature profile. Table 3 presents the percent difference between the average heat flux predicted by the program, and the Scarborough data. The difference in values can be attributed to the

following:

1. Some of the Scarborough data, as discussed in the introduction, is inconsistent and anomalous. Table 1, for example, presents values from Scarborough which indicate that for constant flow rate, increasing the heat flux decreases the tube temperature. Furthermore, the bulk temperatures, which were reported as constant, actually varied. In one case, for a reported outlet bulk temperature of 684 F the temperature actually varied from 436 F to 715 F. This is an indication that the heat flux was not constant.

2. The expressions for the eddy diffusivity (equations 19 through 21) are empirical. There is no guarantee that these expressions will be accurate for the conditions used by Scarborough. The value of the eddy diffusivity can have a great effect on the bulk temperature and the heat flux.

The values predicted by the program for outlet bulk temperature generally compare within three percent.

At low flow rates (143 lbm/ft2-s) the program predicts the amount of coke within 1.7 percent. At a flow rate of 285 lbm/ft2-s the program and Scarborough differ by, in one case 17 percent, and in another 261 percent. At a flow -4rate of 430 lbm/ft2-s the program predicts 11 X 10 feet of coke, however, Scarborough reports no coke for this data series. The difference is an indication that coking is not just kinetically controlled, but may also be a function of

mass transfer and mechanical effects. At higher velocities, some coke may actually scour from the tube wall.

The model presented does not include mass transfer for the following reasons:

1. A literature search revealed no published data on the mass transfer of coke precursors in crude oil.

2. There is not enough data presented by Scarborough to determine the mass transfer coefficient from data.

The velocity profile generated at various points downstream in the tube is shown in Figure 40. The value of the correction factor, η , for the Nikuradse equations (equations 29 and 30) is plotted for a typical series (D4) in Figure 41 as a function of length downstream. Figure 42 is a plot of the log of Reynolds number versus η . This is clearly a linear relationship. Fitting with least squares results in the following equation:

 $\eta = 2.97 - 0.144 \ln(Nre)$

 $(0.9 < \eta < 1.1 \text{ for } 4X10^5 < \text{Nre} < 1.7X10^6)$

The temperature profile at various lengths downstream for series D4 is presented in Figure 43. The dramatic effect of coke is illustrated by comparing Figures 44 and 45 which show temperatures of the outside tube wall with and without coke. Although the model predicts the outside tube wall temperature to be the highest at the entrance of the tube, this may be due to the initial discontinuity in the temperature profile.

The importance of updating the physical properties as the bulk temperature changes is illustrated in Figures 46 and 47 which shows the increase in average velocity, and bulk temperature respectively, as the fluid travels downstream.

The size of the time increment does not have an effect on any of the cases examined. This is a result of the small effect that coking has on the film temperature. Therefore, the fluid temperature profile and coking rate only needs to be calculated at an initial time, and the outside tube temperature can be determined directly from the coking rate and run time.

TABLE 2: THE DATA USED FOR COMAPRISON WITH SCAREOROUGH

Data	Bulk	Mass Flow	Wall	Temperature
Name	Temperature	Rate	at 3	ft at 6 ft
	Inlet, F	Lbm/ft2-s	F	F
C2	660	285	800	830
D2	650	143	865	980
B3	650	430	805	810
C3	645	285	860	885
D3	640	143	910	920
D4	640	143	820	830

TABLE 3: COMPARISON OF RESULTS

Scarborough

Data	Name	Bulk Temperature Out in F	Average Heat Flux in BTU/hr-ft2	Coke Thickness 4 in ft (X 10)
C2		710	59000	1.9
D 2		750	59000	5.8
в3		677	44000	0
C3		684	44000	8.3
D3		720	45000	18.
D4		693	29000	8.8

Program Results

Data Na	me]	Bulk Temperature Out in F	Average Heat Flux in BTU/hr-ft2	Coke Thickness 4 in ft (X 10)
C2		706	54000	5.2
D2	•	733	50000	5.9
B3		692	72000	11.
C3	,	713	78000	30
D3	1	704	37000	18.
D4	•	676	21000	8.8

Percent	Difference	Between	Program and Sc	arborough
Data Na	me Bul Tem Out	k perature	Average Hea Flux	t Coke Thickness
C2 D2 B3 C3 D3	-0. -2. 2. 4. -2.	6 3 2 4 2 5	-8.5 -15 64 77 -17 -27	17 1.7 N/A 261 0 0
D4	- <i>Z</i> .		-21	0

















FIGURE 41 : VELOCITY CORRECTION FACTOR FOR SERIES D4











TUBE WITH COKE LAYER (0.01 inches) FOR SERIES D4 FIGURE 45:


VI. Conclusions

Coking of furnace tubes by crude oil was modeled from an analytical standpoint. To the author's knowledge no analytical equations exist which accomplish this. The major consideration of this model was to obtain the temperature of the laminar sublayer as accurately as possible since this is where the coking reaction is believed to occur (12). The temperature profile of crude oil as it passes through a furnace tube was modeled by solving the transport equations by the Crank-Nicolson method. Internal checks are in the program to ensure closure of the mass and heat balances. The program requires the wall temperature to be specified at two points, but does not require the temperature to be constant.

This model appears to work well at low flow rates. However, since there are very little published data available, the model cannot be given a complete test. The model does not perform well at high flow rates, when transfer of coke from the wall back to the bulk fluid may occur.

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VII. Recommendations

- Clearly there is a need for useful data on coking.
 The data should include accurate measurements of tube wall temperature, bulk temperature, actual coke thickness along the entire length of the tube, and the presence of coke in the outlet oil.
- 2. Actual industrial conditions such as heating the crude from ambient temperatures should be used.
- 3. The coking characteristics of different types of crude oil should be studied.
- 4. The mathematical model presented here should include mass transfer terms. Once enough data is available the mass transfer terms could be evaluated.
- 5. The actual kinetics involved with coking should be studied, including the catalytic effect of the tube wall.

Nomenclature

A –	Term in the viscosity equation
API -	API gravity
в –	Term in the viscosity equation
C -	Characterization factor
Cp -	Heat capacity, BTU/1bm-F
E -	Coking activation energy
f -	Fanning friction factor
G –	function used in secant method
k -	thermal conductivity, BTU/hr-ft-F
L -	Prandtl mixing length, ft.
L -	Length, ft
m —	Mass flow rate, 1bm/s
Nre -	Reynolds number, dimensionless
P -	Pressure drop, 1bm/ft-s2
q -	Heat flux, BTU/s-ft-F
r -	Radial coordinate
R -	Radius of flow, ft
r -	Radial increment, ft
т –	Temperature, F
Tbulk-	Bulk temperature, F
Tc -	Temperature at coke-crude oil interface, F
Tf -	Temperature of the laminar sublayer, F
Ts -	Temperature of the outside wall of the tube, F
Tw -	Temperature of the inside wall of the tube, F
Tb -	Mid boiling point of crude oil, F
Vz -	Velocity in z direction, ft/s

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- Vz Time-smoothed velocity in the z-direction (in turbulent flow), ft/s
- $\langle Vz \rangle$ Average velocity, ft/s

$$V^* = \sqrt{\frac{T_o}{\rho}} g_e$$
$$Y = \frac{(R - r) V^* \rho}{\mu}$$

z - axial increment, ft

GREEK NOTATION

$$\alpha = \frac{k}{\rho C_{p}}$$

 Γ - Value of Y at the buffer layer-core interface

$$\gamma_{m} = \frac{\Delta Z}{2\left(\Delta r\right)^{2}} \left(\frac{\alpha_{m} + \epsilon_{\mu_{m}}}{V_{z_{m}}}\right)$$

$$\gamma_{m} = \Delta Z \left(\frac{\alpha + \epsilon_{\mu}}{(\Delta r)^{2} V_{z}} \right)$$

 ϵ - Roughness factor, ft

 ϵ_{μ^-} Thermal eddy diffusivity, ft2/s

- $\epsilon_{\rm M}$ Momentum eddy diffusivity, ft2/s
- μ Viscosity, lbm/ft-s

$$\beta_{M} = \left(\frac{\Delta Z}{4\Delta r}\right) \left(\frac{\alpha_{M} + \epsilon_{HM}}{V_{z_{M}} r_{M}}\right)$$

- ρ Density, lbm/ft3
- $\mathcal{T}_{\rm o}$ Shear stress at the tube wall, 1bm/s2-ft

$$\xi_{\rm M} = \frac{\Delta Z}{4\Delta r V_{\rm Z_{\rm M}}} \left(\frac{\partial \epsilon_{\rm H}}{\partial r}\right)_{\rm M}$$

SUBSCRIPTS

- n denotes axial direction
- m denotes radial direction

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APPENDIX A

LISTING OF THE COMPUTER PROGRAM

(THE VARIABLE DICTIONARY IS ON THE LAST PAGES OF THE PROGRAM)

1.0000	C*************************************	***
2.0000	C*************************************	***
3.0000	C***** **	***
4.0000	C**** COKING PROGRAM BY **	* * *
5.0000	C**** JOE POLIMENI **	***
6.0000	C*****	***
7.0000	C***** FOR PARTIAL FULFILMENT OF **	***
8 0000	CANANA REQUIREMENTS OF MASTER OF SCIENCE	***
9 0000	C***** IN CHEMICAL ENGINEERING AT MILT **	***
10 0000		***
11 0000		* * *
12 0000		***
13 0000		* * *
13.0000		***
14.0000	· · · · · · · · · · · · · · · · · · ·	***
13.0000		
10.0000		
17.0000		
18.0000		
19.0000		
20.0000		
21.0000	DIMENSION V(2,50), T(2,50), R(50)	
22.0000	DIMENSION ED(50), Y(50), FILMT(100), IPRN(200)	
23.0000	C	
24.0000	C	
25.0000	C	
26.0000	C *** INIT IS A SUBROUTINE WHICH DOES THE FOLLOWING	
27.0000	C 1) INITIALIZES THE FLAGS	
28.0000	C 2) SETS VARIABLES TO ZERO	
29.0000	C 3) CALL SUBROUTINE READER WHICH READS	
30,0000	C IMPORTANT DATA	
31.0000	C 4) CALLS SUBROUTINE PRN1 WHICH PRINTS	
32.0000	C IMPORTANT DATA	
33.0000	C	
34.0000	CALL INIT(T,V,R,N,Q,Q1,DZ,RAD,DR,AREA,TAVG,API,	
35.0000	1 TB, HFLUX, FLUX, TINIT, KFIRST, KTFLG, TB1, TB2, NSEG, Z,	1
36.0000	2 TC3, TC6, DTIME, TTIME, COKETK, TIME, IPRN, NPRN, ROUT, F	łΙΝ,
37.0000	3 IP)	
38.0000	50 CONTINUE	
39.0000	C	
40.0000	C *** BEGIN A LOOP WHICH COUNTS THE Z INCREMENT	
41.0000	C NSEC IS THE NUMBER OF Z SEGMENTS	
42.0000	C	
43.0000	DO 200 $I = 1$, NSEG	
44.0000	C	
45.0000	C *** PHYP IS A SUBROUTINE WHICH CALCULATES:	
46.0000	C 1) THE PHYSICAL PROPERTIES OF THE CRUDE	
47.0000	C OIL BASED ON TAVG	
48.0000	C 2) THE AVERAGE VELOCITY AND REYNOLDS NUMBER	
49.0000	C 3) THE THICKNESS OF THE LAMINAR SUB LAYER	
50.0000	C 4) THE RADIAL POSITIONS	

51.0000 C CALL PHYP(TAVG, API, AREA, Q, AX, RHO, CP, AVGV, 52.0000 53.0000 1 HFLUX, FLUX, DZ, N, R, VIS, TB, RENN, RAD, THICK, TAUO) 54.0000 C 55.0000 C 56.0000 C 57.0000 C INCREMENT THE LENGTH 58.0000 Z = Z + DZ59.0000 C 60.0000 C RESET NEW BULK TEMPERATURE TO OLD BULK TEMPERATURE 61.0000 TB1 = TB262.0000 C 63.0000 C *** WALL T IS A SUBROUTINE WHICH ASSIGNS 64.0000 C THE WALL TEMPERATURE TO EACH Z INCREMENT 65.0000 C 66.0000 CALL WALLT(TW1, TW2, T, Z, DZ, TC3, TC6, TWAVG) 67.0000 C 68.0000 C *** RENVL IS A SUBROUTINE WHICH CALLS THE PROPER 69.0000 C VELOCITY PROFILE SUBROUTINE FOR THE 70.0000 C REYNOLDS NUMBER OF INTEREST 71.0000 C CALL RENVL(VIS, AVGV, RAD, RHO, RENN 72.0000 73.0000 1 , V.R., N, KFIRST, DR, DZ, KTFLG, Y, TAUO) 74.0000 C 75.0000 C 76.0000 C *** TEMP IS A SUBROUTINE WHICH CALLS THE 77.0000 C SUBROUTINE TO CALCULATE THE EDDY DIFFUSIVITY AND CALLS THE SUBROUTINE WHICH CALCULATES THE 78.0000 C 79.0000 C TEMPERATURE PROFILE 80.0000 C 81.0000 999 CALL TEMP(T,V,DZ,DR,CP,RHO,AK,R,N,FLUX 82.0000 1, KTFLG, Y, ED, Z, TW1, TW2, RAD) 83.0000 C 84.0000 C 85.0000 C *** QCALC IS A SUBROUTINE WHICH DOES TWO THINGS: 1) IT CALLS A SUBROUTINE 'BULKT' 86.0000 C WHICH CALCULATES THE BULK TEMPERATURE 87.0000 C 88.0000 C 2) IT CALCULATES Q BY M*CP*DELTA T 89,0000 C CALL GCALC(TB1, T, R, V, AVGV, AX, DZ, N, RHO 90.0000 1 , OMCP, TB2, CP, RAD) 91.0000 92.0000 TAVG=TB1 BTOL = .193.0000 94.0000 TH = T(2, 1)95.0000 C 96,0000 C FIND OUT WHAT T NEXT TO THE WALL SHOULD HAVE BEEN CALL TADJ(T, OMCP, DZ, AK, RAD, R, TW2) 97.0000 98.0000 C 99.0000 C SAFETY SO THAT THE RADIAL SEGMENT NEXT TO THE 100.0000 C WALL DOES NOT STAY THE WALL TEMPERATURE 101.0000 C MAKING IT THE WALL TEMPERATURE IS ONLY DONE TO 102.0000 C INCREASE THE SPEED OF CONVERENGENCE CHECK=ABS(T(2,1)-TH) 103.0000 IF (CHECK.GT.BTOL) GO TO 999 104.0000

105.0000 C 106.0000 C 107.0000 C CALL THE SUBROUTINE TO DETERMINE THE SKIN TEMPERATURE 108.0000 CALL SKIN(QMCP, TWAVG, RAD, ROUT, RIN, TSKIN, DZ) 109.0000 C *** RESET IS A SUBROUTINE WHICH SHIFTS ARRAYS SUCH 110.0000 C THAT THE NEW VALUES WILL BECOME THE NEXT INCREMENT'S 111.0000 C OLD VALUES 112.0000 C 113.0000 C *** PRN2 IS A SUBROUTINE WHICH PRINTS THE RADIAL VALUES 114.0000 C THE VELOCITY, TEMPERATURE, AND EDDY DIFFUSIVITY 115.0000 C FOR EACH Z SEGMENT 116.0000 C 117.0000 C 118.0000 C PRINT DECISION 119.0000 DO 901 J=1.NPRN IF (IP.EQ.IPRN(J)) CALL PRN2(V,T,R,TB1,TB2,RHO,CP 120.0000 121.0000 1. AK. AVGV. RENN. Z. VIS, N. I. ED. G. OLDT, DZ. RAD, THICK. 122.0000 2 TIME, GMCP, TSKIN, TW1, TW2) 123.0000 901 CONTINUE. 124.0000 C 125.0000 555 CONTINUE 126.0000 C PUT THE FILM TEMPERATURE INTO THE ARRAY FILMT 127.0000 FILMT(I) = T(2,1)128.0000 C 129.0000 C 130.0000 CALL RESET (T,N) CALL RESET (V,N) 131.0000 132.0000 C 133.0000 C THE FIRST TIME HAS ALREADY BEEN ACCOMPLISHED 134.0000 KFIRST = 1135.0000 C 136.0000 200 CONTINUE 137.0000 C 138.0000 C INCREMENT THE TIME 139.0000 TIME=TIME+DTIME 140.0000 C 141.0000 C 142.0000 C INCREMENT THE PRINTER FLAG 143.0000 IP = IP + 1144.0000 C CHECK TO SEE IF TTIME (THE TOTAL TIME) HAS BEEN REACHED 145.0000 C IF IT HAS END 146.0000 IF(TIME.GT.TTIME) GO TO 111 147.0000 C 148.0000 C *** THE COMPLETE LENGTH HAS BEEN COMPLETED *** 149.0000 C COKE IS LAYERED ON THE TUBE AND THE PROCESS IS REPEATED 150.0000 C 151.0000 C CALL NEWINT(T,V,R,N,DZ,RAD,DR,AREA,TAVG, 152.0000 153.0000 1 TB, TINIT, KFIRST, TB1, TB2, Q, Q1, NSEG, Z, 154.0000 2 COKETK, DTIME, FILMT, KTFLG, TC3, TC6, TIME) 155.0000 C 156.0000 GO TO 50 157.0000 C 158.0000 111 CONTINUE

159.0000 STOP 160.0000 END 161.0000 C 162.0000 C 163.0000 SUBROUTINE INIT (T,V,R,N,G,G1,DZ,RAD,DR,AREA,TAVG,API, 1 TB, HFLUX, FLUX, TINIT, KFIRST, KTFLG, TB1, TB2, NSEG, Z, 164.0000 2 TC3.TC6, DTIME, TTIME, COKETK, TIME, IPRN, NPRN, ROUT, RIN, 165.0000 166.0000 3 IP) 167.0000 C 168.0000 C THIS SUBROUTINE INITIALIZES IMPORTANT VARIABLES, 169.0000 C FLAGS AND CALLS 'READER' WHICH READS IN IMPORTANT 170.0000 C DATA FROM A FILE 171.0000 C 172.0000 DIMENSION T(2,50),V(2,50),R(50),IPRN(200) 173.0000 C 174.0000 C 175.0000 C KFIRST IS THE FLAG WHICH INDICATES WHETHER IT IS THE 176.0000 C FIRST TIME THROUGH THE PROGRAM & VALUE OF 0 INDICATES 177.0000 C THAT IT IS THE FIRST TIME & VALUE OF 1 INDICATES THAT 178.0000 C THAT IT HAS ALREADY GONE THROUGH ONE DZ SEGMENT 179.0000 KFIRST=0 180.0000 C 181.0000 C XTFLG IS THE FLAG WHICH INDICATES LAMINAR OR 182.0000 C TURBULENT FLOW (0 FOR LAMINAR 1 FOR TURBULENT) 183.0000 C IT IS INITALLY SET TO ZERO 184,0000 XTFLG = 0185.0000 C 186.0000 C 187.0000 C Z IS THE LENGTH DOWNSTREAM INITIALLY SET TO 0 FT 188.0000 Z = 0.0189.0000 C 190.0000 C SET THE TIME TO ZERO 191.0000 TIME = 0.0192.0000 C 193.0000 C SET THE PRINT COUNTER TO ZERO 194.0000 IP = 0195.0000 C 196.0000 C THE INITIAL COKE THICKNESS IS ZERO COKETK=0.0 197.0000 198.0000 C 199.0000 C CALL THE PROGRAM WHICH READS THE DATA CALL READER(TINIT, TWALL, Q1, NF, RAD, API 200.0000 1 ,TB,HFLUX,NSEG,DZ,TC3,TC6,DTIME,TTIME, 201.0000 2 IPRN, NPRN, ROUT, RIN) 202.0000 203.0000 C 204,0000 C CONVERT THE RIN AND ROUT TO FEET 205.0000 RIN=RAD/12. ROUT=ROUT/12. 206.0000 207.0000 C SET THE VELOCITY MATRIX TO ZERO DO 75 I=1,50 208.0000 209.0000 V(1, I) = 0.0V(2, 1) = 0. 210.0000 CONTINUE 211.0000 75 RAD=RAD/12. 212.0000

213,0000 C 214.0000 N=NF+1215.0000 C 216.0000 C INITIALIZE THE TEMPERATURE MATRIX TO TINIT 217.0000 C 213.0000 DO 300 I=1,50 219.0000 T(1, I) = TINIT220.0000 300 CONTINUE 221.0000 C 222.0000 C 223.0000 C CALCULATE CROSS SECTIONAL AREA 224.0000 AREA=3.14159*RAD*RAD 225.0000 C 226.0000 C CALCULATE THE FLOW RATE FROM LLBM/FT"2 S TO LBM/S 227.0000 Q=Q1*AREA 228.0000 C 229.0000 C THE INITIAL AVERAGE TEMP IS TINIT 230.0000 C TAVG=TINIT 231.0000 232.0000 TB1=TINIT TB2 = TB1233.0000 234.0000 C 235,0000 C *** PRN1 IS A SUBROUTINE WHICH PRINTS OUT IMPORTANT INFORMATION WHICH DOES NOT CHANGE FOR EACH 236.0000 C INCREMENT 237.0000 C 238.0000 C CALL PRN1(RAD, N, DR, DZ, API, TB, Q, TC3, TC6, 239.0000 1 DTIME, TTIME) 240.0000 241.0000 RETURN 242.0000 END 243.0000 C 244.0000 C 245.0000 SUBROUTINE READER(TINIT, TWALL, Q, NF, RAD, API 1 , TB, HFLUX, NSEG, DZ, TC3, TC6, DTIME, TTIME, 246.0000 2 IPRN, NPRN, ROUT, RIN) 247.0000 248.0000 DIMENSION IPRN(200) 249.0000 C 250.0000 C THIS ROUTINE READS IMPORTANT DATA 251.0000 C 252,0000 C THIS ROUTINE IS CALLED BY SUBROUTINE INIT 253.0000 C 254.0000 C 255.0000 C READ THE INITIAL TEMPERATURE READ(5,100) TINIT 256.0000 257.0000 C 258.0000 C READ THE FLOW RATE IN LBM/FTA2 SEC READ(5,100) Q 259.0000 260.0000 C 261.0000 C READ THE NUMBER OF RADIAL SEGMENTS READ(5,200) NF 262.0000 263.0000 C 264.0000 C READ THE RADIUS IN INCHES READ(5,250) RAD 265.0000 266.0000 C

267.0000 C READ THE API GRAVITY READ(5,250) API 268.0000 269.0000 C 270.0000 C READ THE TE VALUE 271.0000 READ(5,250) TB 272.0000 C 273.0000 C READ THE OUTSIDE WALL RADIUS 274.0000 READ(5,250) ROUT 275.0000 C 276.0000 C READ THE NUMBER OF Z SEGMENTS IN ONE PASS 277.0000 READ(5,300) NSEC 278.0000 C 279.0000 C READ THE VALUE OF DZ 280.0000 READ(5,350) DZ 281.0000 C 282.0000 C READ THE TERMOCOUPLE TEMPERATURES (DEGREES F) 283.0000 READ(5,250) TC3 284.0000 READ(5,250) TC6 285.0000 C 286.0000 C READ THE TIME INCREMENT IN HOURS 287.0000 READ(5,400) DTIME 288.0000 C 289,0000 C READ THE TOTAL TIME IN HOURS 290.0000 READ(5,400) TTIME 291.0000 C 292,0000 C READ AND WRITE THE DATA NUMBER READ(5,11) DATN 293.0000 WRITE(6,12) DATN 294.0000 295.0000 C 196.0000 C READ THE PARAMETERS FOR PRINTING DECISION 297,0000 C I.E. WHAT LENGTHS SHOULD BE PRINTED READ(5,902) NPRN 298.0000 DO 901 I=1,NPRN 299.0000 READ(5,902) IPRN(I) 300.0000 301.0000 901 CONTINUE 302.0000 C 303.0000 C 304.0000 100 FORMAT(F7.1) 305.0000 200 FORMAT(12) 306.0000 250 FORMAT(F10.5) 307.0000 300 FORMAT(13) 308.0000 350 FORMAT(E20.5) 309.0000 400 FORMAT(F8.1) 310.0000 902 FORMAT(I3) 311.0000 11 FORMAT(A4) 312.0000 12 FORMAT(1H0, 'THIS IS DATA NUMBER ',A4) 313.0000 C 314.0000 RETURN 315.0000 END 316.0000 C 317.0000 C SUBROUTINE NEWINT(T,V,R,N,DZ,RAD,DR,AREA,TAVG, 318.0000 319.0000 1 TB, TINIT, KFIRST, TB1, TB2, Q, Q1, NSEG, Z, 2 COKETK, DTIME, FILMT, KTFLG, TC3, TC6, TIME) 320.0000

321.0000 C 322.0000 C 323.0000 C THIS ROUTINE IS SIMILIAR TO 'INIT' HOWEVER 324.0000 C THIS ROUTINE DOES NOT CALL READER AND THIS ROUTINE 325.0000 C IS RESPONSIBLE FOR CALCULATING THE AMOUNT OF COKE 326.0000 C WHICH HAS BEEN DEPOSITED. IT ALSO CALCULATES 327,0000 C THE NEW INSIDE RADIUS OF FLOW 328.0000 C THE ROUTINE ALSO CALCULATES THE AVERAGE FILM TEMPERATURE 329.0000 C FOR ONE COMPLETE TIME SEGMENT 330.0000 C DIMENSION T(2,50),V(2,50),R(50) 331.0000 332.0000 DIMENSION FILMT(100) 333.0000 C XTFLG = 0334.0000 335.0000 KFIRST=0 336.0000 Z = 0.0337.0000 C 338.0000 C SET THE VELOCITY MATRIX TO ZERO 339.0000 DO 75 I=1,50 340.0000 V(1,I) = 0.0341.0000 V(2, I) = 0.0342.0000 75 CONTINUE 343,0000 C 344.0000 C CALCULATE THE AVERAGE FILM TEMPERATURE AVGFT 345.0000 C 346.0000 ADD=0.0347.0000 DO 200 I=1.NSEG 348.0000 ADD = ADD + FILMT(I)349.0000 200 CONTINUE 350.0000 AVGFT=ADD/NSEG 351,0000 C 352.0000 C 353.0000 C THIS IS THE SECTION WHICH DETERMINES THE COKE LAYER 354.0000 C THICKNESS IN INCHES. SEE TEXT FOR DERIVATION OF EQUATION 355.0000 C 356,0000 TK=(3483,68*EXP(-22727.74/(AVGFT+460))) 357.0000 C 358.0000 C MUST INCLUDE TIME WHEN CONSIDERING COKE THICKNESS 359.0000 C TMP=TIME-DTIME 360.0000 361.0000 WRITE(6,991) TMP 11 363.0000 1 1H0, ' THE ENTIRE LENGTH FOR TIME ', F6.1, ' HOURS HAS ۰, 2 'BEEN COMPLETED') 364.0000 365.0000 COKETK=TK*DTIME/12.+COKETK 366.0000 C WRITE(6,992) AVGFT, TIME, COKETK 367.0000 368.0000 992 FORMAT(1H0, 'THE AVERAGE FILM TEMPERATURE FOR THE LENGT HIS'. 1 F9.2, ' DEGREES F'/1X, 'THE COKE THICKNESS BASED ON', 369.0000 2 'THIS TEMPERATURE AT TIME ', F6.1, ' IS ', 370.0000 371.0000 3 E14.5,' FT',1H1)

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372.0000 C CALCULATE THE NEW VALUE FOR THE RADIUS
373.0000
             RAD=RAD-(TK*DTIME/12.)
374.0000
              DO 300 I=1,50
 375.0000
              T(1, I) = TINIT
376.0000
              T(2, I) = 0.0
 377.0000 300 CONTINUE
378.0000 C
 379.0000 C CALCULATE THE AREA AND FLOW RATE
380.0000
              AREA=3.14159*RAD*RAD
381.0000
               Q=Q1*AREA
382.0000
              TAVG=TINIT
 383.0000
              TB1=TINIT
384.0000
               TB2=TB1
385.0000 C
386.0000
              RETURN
 387.0000
              END
388.0000 C
 389.0000 C
 390.0000 C
              SUBROUTINE PHYP(TAVG, API, AREA, Q, AK, RHO, CP, AVGV,
 391.0000
 392.0000
             1 HFLUX, FLUX, DZ, N, R, VIS, TB, RENN, RAD, THICK, TAUO)
 393.0000 C
 394.0000 C THIS SUBROUTINE CALCULATES THE PHYSICAL PROPERTIES
 395.0000 C OF CRUDE OIL (DENSITY, THERMAL CONDUCTIVITY, HEAT CAPACIT
Y)
 396.0000 C EQUATIONS FOR DENSITY THERMAL CONDUCTIVITY AND
 397.0000 C HEAT CAPACITY ARE FROM DATA GIVEN IN NELSON, W.L.
 398.0000 C PETROLEUM REFINERY ENGINEERING, MCGRAW-HILL, 4TH ED. 1959
 399.0000 C
 400.0000 C
 401.0000 C THIS ROUTINE ALSO CALCULATES THE AVERAGE VELOCITY
 402.0000 C USING A MASS BALANCE
 403.0000 C THE REYNOLDS NUMBER
 404.0000 C AND THE THICKNESS OF THE LAMINAR SUBLAYER
 405.0000 C IT THEN DETERMINES THE RADIAL PROFILE
 406.0000 C
 407.0000
             DIMENSION R(50)
 408.0000 C
 409.0000 C
              CALCULATE THE DENSITY
              SG=.99864+1.56152E-03*API-3.278E-04*API*API
 410.0000
 411.0000
             1 -1.5195E-04*TAVG-1.342E-07*TAVG*TAVG
 412.0000
              RHO = SG * 62.3
 413.0000 C
 414.0000 C
 415.0000 C
 416.0000 C
              THERMAL CONDUCTIVITY
 417.0000
              AK = (6.48+(0.0455*API)-(0.00237*TAVG))/360000.
 418.0000 C
 419.0000 C
              ** HEAT CAPCITY **
 420.0000
              CP=3.34998E-1+(2.16414E-3*API)+(5.86636E-4*TAVG)
 421.0000 C
 422.0000 C CALCULATE THE NEW AVERAGE VELOCITY BASED UPON
 423.0000 C THE ADJUSTED VALUE OF THE DENSITY
 424.0000 C
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425.0000 C IT IS THE EQUATION OF CONTINUTITY 426.0000 AVGV=Q/RHO/AREA 427.0000 C 428.0000 C 429.0000 C CALCULATES THE REYNOLDS NUMBER 430.0000 C VIS=VISC(API, TE, TAVG, RHO) 431.0000 432.0000 RENN=RAD*2. *AVGV*RHO/VIS 433.0000 C 434.0000 C FF IS THE FANNING FRICTION FACTOR 435,0000 C THE FRICTION FACTOR IS CALCULATED BY THE ROUND EQUATION 436.0000 C 437.0000 FF=((((1.8*ALOG(RENN/(1.35*RENN*(1.5E-04/2./RAD)+6.5))) **(-2.))/4.) 438.0000 C 439,0000 C CALCULATE THE THICKNESS OF THE LAMINAR SUBLAYER 440.0000 C TAUO=FF*RHO/2.*AVGV*AVGV 441.0000 THICK=5, *VIS/(SQRT(RHO*TAUO)) 442.0000 443.0000 THICK=THICK/2. 444.0000 C 445.0000 C CALCULATE THE RADIAL PROFILE 446.0000 C 447.0000 C NF IS THE NUMBER OF RADIAL SEGMENTS AFTER 448.0000 C THE FIRST RADIAL SEGMENT NF=N-1 449.0000 450.0000 R(1) = RAD - THICK451.0000 R2=R(1)/FLOAT(NF)452.0000 DO 200 I=2,NF 453.0000 IM = I - 1454.0000 R(I) = R(IM) - R2455.0000 200 CONTINUE R(N) = 0.0456.0000 457.0000 NP = N + 1458.0000 NRM = N - 1459.0000 R(NP) = R(NRM)RETURN 460.0000 461.0000 END 462.0000 C 463.0000 C FUNCTION VISC(API, TBE, TAVG, RHO) 464.0000 465.0000 C 466.0000 C THIS FUNCTION CALCULATES THE VISCOSITY FOR THE 467.0000 C CRUDE OIL 468.0000 C 469.0000 C THE EQUATIONS ARE FROM AMIN, M.B., AND MADDOX, R.N., 470.0000 C HYDROCARBON PROCESSING, VOL59, N12 DEC1980, P131-135 \$71.0000 C 472,0000 C THIS FUNCTION IS USED BY SUBROUTINE PHYP 473.0000 C T=TAVG 474.0000 TB=TBB 475.0000 CONVERT T FROM F TO K 476.0000 C 477.0000 T=273.15+((5./9.)*(T-32.))

478.0000 TB=273.15+((5)/9.)*(TB-32.))479.0000 C 480.0000 C CONVERT T FROM F TO R 481.0000 TBR=TBB+459.67 482.0000 C 483.0000 C CALCULATE SPECIFIC GRAVITY AT 60 DEGREES F (S) 484.0000 S=141.5/(API+131.5)485.0000 C 486.0000 C CALCUALTE THE CHARACTERIZATION FACTOR 487.0000 C=(TBR**(1,/3,))/S 488.0000 C 489.0000 C CLACULATE THER TERMS IN THE VISCOSITY EQUATION 490.0000 B = E X P (4, 717 + (0, 00526 * TB))491,0000 $A = (91, 836 \times (TB \times (-0, 175)) - 29, 263) \times (C/B)$ 492.0000 C 493.0000 C CALCUALTE THE VISCOSITY IN CENTISTOKES 494.0000 ANU=A*EXP(B/T) 495.0000 C 496.0000 C CONVERT TO LBM/FT S 497.0000 VISC=ANU*RHO*10.764E-6 498,0000 C 499.0000 C RETURN 500.0000 501,0000 END 502.0000 C 503.0000 C 504.0000 C 505.0000 SUBROUTINE WALLT(TW1,TW2,T,Z,DZ,TC3,TC6,TWAVG) DIMENSION T(2,50) 506.0000 507.0000 C 508.0000 C IF THE WALL TEMPERATURE VARIES YOU NEED THIS 509.0000 C SUBROUTINE TO CALCULATE THE WALL TEMPERATURE AT 510.0000 C VARIOUS POINTS IN THE PIPE 511.0000 C THIS VERSION OF THE ROUTINE USES TWO WALL TEMPERATURES 512.0000 C ONE TEMPERATURE AT 3 FT AND ONE AT 6 FT 513.0000 C IT THEN FITS THESE TWO POINTS TO A LINE 514.0000 C AND THE TEMPERATURE AT ANY OTHER POINT IS ASSUMED 515.0000 C TO BE REPRESENTED BY THIS LINEAR FUNCTION 516.0000 C 517.0000 C 518.0000 C 519.0000 C SET UP THE WALL TEMPERATURES 520.0000 SLOP = (TC6 - TC3)/3. 521.0000 B=TC3-SLOP*3. 522.0000 C 523.0000 C TW1 = B + SLOP * (Z - DZ)524.0000 TW2 = B + SLOP * Z525.0000 526,0000 C 527.0000 C CALCULATE THE AVERAGE WALL TEMP FOR THIS INCREMENT 528.0000 TWAVG = (TW1 + TW2)/2.529.0000 C 530,0000 C FIRST GUESS 531,0000 $T(2,1) = B + SLOP \times Z - .1$

532.0000 C 533.0000 RETURN 534.0000 END 535.0000 C 536.0000 C 537,0000 C 538.0000 SUBROUTINE RENVL (VIS, AVGV, RAD, RHO, RENN 539.0000 1 , V, Ŕ, N, KFIRST, DR, DZ, KTFLG, Y, TAUO) 540.0000 C 541.0000 C THIS SUBROUTINE IS CALLED BY THE MAIN PROGRAM 542.0000 C THIS ROUTINE IS A DECISION ROUTINE 543.0000 C IT CALLS THE APPROPRIATE VELOCITY CALCULATION ROUTINE 544.0000 C DEPENDING UPON THE VALUE OF THE REYNOLDS NUMBER 545.0000 C 546.0000 C 547.0000 DIMENSION V(2,50), R(50), Y(50) 548.0000 C 549.0000 C 550.0000 C NOW CHECK THE REYNOLDS NUMBER AND USE THE 551.0000 C APPROPRIATE SUBROUTINE TO CALCULATE THE VELOCITY 552,0000 C 553.0000 C LAMINAR FLOW 554.0000 IF (RENN.GT.2000.) GO TO 300 555.0000 C 556.0000 C *** LAMAR IS A SUBROUTINE WHICH DETERMINES 557.0000 C THE VELOCITY PROFILE FOR LAMINAR FLOW 558.0000 C 559.0000 CALL LAMAR(V, AVGV, R, RAD, N) RETURN 560.0000 561.0000 C 562.0000 C TRANSITION REGION 563.0000 300 IF (RENN.GT.4000.) GO TO 400 564.0000 C *** TRANS IS A SUBROUTINE WHICH CALCULATES THE 565.0000 C VELOCITY PROFILE IN THE TRANSITION REGION BY USING A WEIGHTED AVERAGE (WEIGHED BY THE 566.0000 C VALUE OF THE REYNOLDS NUMBER) BASED ON A LAMINAR 567.0000 C 568.0000 C FLOW PROFILE AND A TURBULENT FLOW PROFILE 569.0000 C 570.0000 CALL TRANS(V, R, RAD, AVGV, N, RENN, KFIRST, 571.0000 1 DR, DZ, VIS, KTFLG, RHO) 572.0000 RETURN 573.0000 C 574.0000 C IF THE VELOCITY HAS NOT BEEN ALREADY CALCULATED IT IS 575,0000 C TURBULENT 576.0000 C 577.0000 C FIRST SET THE TURBULENT FLAG KTFLG 578.0000 400 KTFLG=1 579.0000 C 580,0000 C *** TURB IS A SUBROUTINE WHICH CALCULATES THE 581.0000 C VELOCITY PROFILE FOR TURBULENT FLOW IT ALSO CALCULATES THE CORRECT PRESSURE DROP 582.0000 C FOR THE FLOW RATE SPECIFIED 583.0000 C 584.0000 C CALL TURB(V, R, RAD, RHO, DZ, VIS, N, DR, AVGV, 585.0000

586.0000 1 KFIRST, KTFLG, Y, RENN, TAUO) RETURN 587.0000 END 588.0000 589.0000 C 590.0000 C 591.0000 C 592.0000 SUBROUTINE LAMAR (V, AVGV, R, RAD, N) 593.0000 C 594.0000 C CALCULATE THE VELOCITY PROFILE FOR LAMINAR FLOW 595.0000 DIMENSION V(2,50),R(50) 596.0000 C 597.0000 C 598.0000 C CALCULATE NEW VALUE OF V 599.0000 DO 100 I=1,N 600.0000 V(2,I) = 2.*AVGV*(1.-(R(I)/RAD)**2.)601.0000 100 CONTINUE 602.0000 RETURN 603.0000 END 604.0000 C 605.0000 C 606.0000 C 607.0000 C 608.0000 SUBROUTINE TURB(V, R, RAD, RHO, DZ, VIS, N, 608.0000SUBROUTINE TURB(V,R,RAD,RHO,DZ,VIS,609.00001 DR,AVGV,KFIRST,KTFLG,Y,RENN,TAUO) 610.0000 C 611.0000 C THIS ROUTINE TAKES. THE AVERAGE VELOCITY AND SOLVES 612.0000 C FOR THE PROPER PRESSURE AND HENCE THE TURBULENT 613.0000 C VELOCITY PROFILE 614.0000 C 615.0000 C THIS ROUTINE IS CALLED BY 616.0000 C 1) SUBROUTINE RENVL \$17.0000 C 2) SUBROUTINE TRANS 618,0000 C 619.0000 DIMENSION V(2,50), R(50), Y(50) 620.0000 C 621.0000 C 622.0000 C ETA IS THE VELOCITY CORRECTION FACTOR 623.0000 C MAKE TWO INITIAL GUESSES TO ETA FOR THE 624.0000 C SECANT METHOD 625.0000 ETAG1=1.0 626.0000 ETAG2 = 1.4627.0000 C 428.0000 C SET THE TOLERANCE TO BE USED BY THE SECN METHOD 629.0000 C AND THE FLAG USED BY THE SECANT ROUTINE 630.0000 $ATOL = 1 \cdot E - 02$ 631.0000 IFLG=0 632.0000 C 633.0000 C CALCULATE THE VELOCTLY PROFILE USING THE GUESSES 634.0000 C 635.0000 C *** VPP IS A SUBROUTINE WHICH CALCULATES THE 636.0000 C TURBULENT FLOW VELOCITY PROFILE 637.0000 C *** TVAVG IS A SUBROUTINE WHICH CALCULATES THE 638.0000 C AVERAGE VELOCITY FOR THE TURBULENT FLOW PROFILE 639.0000 Č

640.0000 100 CALL VPP(R,V,ETAG1,RAD,RHO,DZ,VIS,N,Y,RENN, 641.0000 1 TAUO, AVGV, KFIRST) 642.0000 CALL TVAVG(V,N,R,DR,AVGV1,RAD) 643.0000 C 644.0000 CALL VPP(R,V,ETAG2,RAD,RHO,DZ,VIS,N,Y,RENN, 645.0000 1 TAUO, AVGV, KFIRST) 646.0000 CALL TVAVG(V,N,R,DR,AVGV2,RAD) 647.0000 C 648.0000 C 649.0000 C THE SECANT ROUTINE NEEDS THE FUNCTION IN TERMS 650.0000 C OF F(X)=0 . 651.0000 C -652.0000 F1 = AVGV - AVGV1653.0000 F2 = AVGV - AVGV2654.0000 C 655.0000 CALL SECAN (ETAG1, ETAG2, X3, F1, F2, ATOL, IFLG) 656.0000 IF(IFLG.EQ.1) GO TO 200 657.0000 C 658.0000 C TRY AGAIN 659.0000 ETAG1=ETAG2 660.0000 ETAG2 = X3661.0000 GO TO 100 662.0000 200 ETA=X3 663.0000 CALL VPP(R, V, ETA, RAD, RHO, DZ, VIS, N, Y, RENN, 664.0000 1 TAUO, AVGV, XFIRST) 665.0000 C 666.0000 WRITE(6,43)ETA 667.0000 43 FORMAT(1H0,'ETA IS ',E11.4) 668.0000 CALL TVAVG(V,N,R,DR,AVGV,RAD) 669.0000 RETURN 670.0000 END 671.0000 C 672.0000 C 673.0000 · SUBROUTINE VPP(R,V,ETA,RAD,RHO,DZ,VIS,N,Y,RENN, 674.0000 1 TAUO, AVGV, KFIRST) 675.0000 C THIS SUBROUTINE EVALUATES THE VELOCITY PROFILE FOR 676.0000 C TURBULENT FLOW 677.0000 C 678.0000 C THIS ROUTINE IS CALLED BY SUBROUTINE TURB 679.0000 C 680.0000 DIMENSION V(2,50),R(50),Y(50) 681.0000 C 682.0000 C 683.0000 FF=(((1.8*ALOG(RENN/(1.35*RENN*(1.5E-04/2./RAD)+6.5))) **(-2,))/4.) 684.0000 VA=AVGV*SQRT(FF/2.) 685.0000 C 686.0000 C CALCULATE SP 687.0000 DO 100 I=1,N 688.0000 S=RAD-R(I)689.0000 C CALCULATE SP AND PUT IN AN ARRAY TO BE USED LATER 690.0000 C IN THE EDDY EQUATION 691.0000 SP=S*VA*RHO/VIS 692,0000 Y(I) = SP

693.0000 100 CONTINUE 694.0000 C 695.0000 C THE EQUATIONS USED BY THIS ROUTINE TO EVALUATE 696.0000 C THE VELOCITY PROFILE ARE FROM 697.0000 C GEANKOPLIS, C.J.; "TRANSPORT PROCESSES AND UNIT OPERATION 5." 698.0000 C ALLYN AND BACON, BOSTON, MASS., P127, (1978) 699.0000 C 700.0000 DO 200 I=1,N 701.0000 IF(Y(I), LE, 5, 0) V(2, 1) = VA * Y(I)702.0000 IF(Y(I).GT.5.0.AND,Y(I).LE.30.0) 703.0000 1 V(2,I)=VA*ETA*(5,0*ALOG(Y(I))-3.05) 704.0000 IF(Y(I).GT.30.0) V(2,I)=VA*ETA*(2.5*ALOG(Y(I))+5.5) 705.0000 200 CONTINUE 706.0000 IF(KFIRST.EQ.1) GO TO 300 707.0000 DO 400 I=1,N 708.0000 V(1, I) = V(2, I)709.0000 400 CONTINUE 710.0000 300 CONTINUE 711.0000 RETURN 712.0000 END 713.0000 C 714.0000 C 715.0000 C 716.0000 C 717.0000 C 718.0000 C SUBROUTINE TVAVG(V,N,R,DR,AVGV,RAD) 719.0000 720.0000 C 721.0000 C THIS ROUTINE CALCULATES THE AVERAGE VELOCITY FOR THE 722.0000 C TURBULENT FLOW PRFILE 723.0000 C 724.0000 C THIS ROUTINE IS CALLED BY 725.0000 C 1) SUBROUTINE TURB 726.0000 C 2) SUBROUTINE TRANS 727.0000 C 728.0000 DIMENSION V(2,50),R(50),F(50) 729.0000 C THERE ARE N+2 TERMS BECAUSE THE WALL AND THE 730.0000 C CENTER VALUES OF F ARE ZERO 731.0000 N2 = N + 2732.0000 DO 100 I=1,N 733.0000 F(I+1) = V(2, I) * R(I)734.0000 100 CONTINUE 735.0000 F(1) = 0.0736.0000 F(N2)=0.0737.0000 CALL TRAP(N2, R, F, RESULT, RAD) ANUM=RESULT 738.0000 739.0000 DO 200 I=1,N 740.0000 F(I)=R(I) 741.0000 200 CONTINUE 742.0000 F(1) = 0.0743.0000 F(N2)=0.0744.0000 CALL TRAP(N2, R, F, RESULT, RAD) 745.0000 AVGV=ANUM/RESULT

746.0000 RETURN 747.0000 END 748.0000 C 749.0000 C 750.0000 SUBROUTINE TRAP(N,R,F,ATRAP,RAD) 751.0000 DIMENSION R(50), F(50) 752.0000 C 753.0000 C THIS SUBROUTINE PERFORMES THE TRAPAZOIDAL RULE 754.0000 C FOR THE INTEGRAL OF F DX 755.0000 C' THIS ROUTINE IS CALLED BY: 756.0000 C 1) SUBROUTINE BULKT 757.0000 C 2) SUBROUTINE TVAVG 758.0000 C 759.0000 C 760.0000 ATRAP = ((F(1) + F(2)) * (RAD - R(1)) / 2, 0)NM=N-1 761.0000 762.0000 DO 100 I=2,NM 763.0000 IP = I + 1764.0000 IM = I - 1765.0000 C TERM = ((F(I) + F(IP)) * (R(IM) - R(I)) / 2, 0)766.0000 767.0000 ATRAP=ATRAP+TERM 768.0000 100 CONTINUE 769.0000 RETURN 770.0000 END 771.0000 C 772.0000 C 773.0000 C 774.0000 C 775.0000 C 776.0000 C 777.0000 C 778.0000 SUBROUTINE SECAN(X1,X2,X3,F1,F2,ATOL,IFLG) 779.0000 C 780.0000 C PERFORMS SECANT ITERATION WHERE X3 IS THE NEXT GUESS 781.0000 C IF THE TOLERANCE IS MET THE FLAG (IFLG) IS SET TO 1 782.0000 C THIS ROUTINE IS CALLED BY SUBROUTINE TURB 783.0000 C 784.0000 C SAFETY IN CASE F1-F2=0 785.0000 IF (F1.NE.F2) GO TO 100 IFLG=1786.0000 RETURN 787.0000 788.0000 100 X3=X2-(F2/((F2-F1)/(X2-X1))) 789.0000 C IF X3 AND X2 DIFFER BY LESS THAN THE SPECIFICED 790,0000 C TOLERENCE (ATOL) SET THE FLAG (IFLG) TO'I 791.0000 IF (ABS(X3-X2).LE.ATOL) IFLG=1 792.0000 X4=X3-X2 RETURN 793.0000 END 794.0000 795.0000 C 796.0000 C 797.0000 C 798.0000 C SUBROUTINE TEMP (T,V,DZ,DR,CP,RHO,AK,R,N,FLUX 799.0000

 800.0000
 1, KTFLG, Y, ED, Z, TW1, TW2, RAD)

 801.0000
 DIMENSION T(2, 50), V(2, 50),
 DIMENSION T(2,50),V(2,50),R(50),ED(50) 802.0000 DIMENSION Y(50) 803.0000 C 804.0000 C CALCULATE THE WALL TEMPERATURE BASED ON THE DISTANCE 805.0000 C DOWNSTREAM 806.0000 C 807.0000 C 808.0000 C CALCULATE THE EDDY DIFFUSIVITY IF LAMINAR FLOW 809.0000 C THE EDDY SUBROUTINE WILL MAKE THE ED ARRAY ZERO 810.0000 CALL EDDY(T,V,R,ED,N,KTFLG,Y,RAD) 811.0000 C 812.0000 C 813.0000 C 814.0000 C CALCULATE THE TEMP PROFILE BY THE CRANK NICOLSON 815.0000 C METHOD CALL THE TCRANK SUBROUTINE 816.0000 C 817.0000 C *** TCRANK IS A SUBROUTINE WHICH DETERMINES 818.0000 C THE TEMPERATURE PROFILE USING THE CRANK 819.0000 C NICKOLSON METHOD TO SOLVE THE PDE'S 820.0000 C 821.0000 CALL TCRANK(T,V,R,AK,RHO,CP,ED,N,DZ) 822.0000 RETURN 823.0000 END 824.0000 C 825.0000 C 826.0000 C 827.0000 C 828.0000 SUBROUTINE TCRANK(T,V,R,AK,RHO,CP,ED,N,DZ) 829.0000 C THIS ROUTINE CALCULATES THE TEMPERATURE PROFILE BY 830.0000 C FOR TURBULENT FLOW 831.0000 C \$32.0000 C FOR A THROUGH DESCRIPTION OF THIS ROUTINE PLEASE SEE 833.0000 C THE TEXT OF THE REPORT INCLUDED WITH THIS PROGRAM 834.0000 C 835.0000 C THIS ROUTINE SOLVES A PARTIAL DIFFERENTIAL EQUATION 836.0000 C BY THE CRANK NICOLSON METHOD 837.0000 C
 838.0000
 DIMENSION TR1(50),TR3(50),TR2(50),D(50)

 839.0000
 DIMENSION T(2,50),V(2,50),R(50),AN(50)
 840.0000 DIMENSION AL(50), B(50), G(50), ED(50) 841.0000 DIMENSION E(50) 842.0000 NM = N - 1843.0000 NP = N + 1844.0000 ALPHA=AK/RHO/CP 845.0000 C 846.0000 C CALCULATE THE B,G,D TERMS 847.0000 DO 100 I = 2.NM848.0000 IM = I - 1849.0000 IP=I+1DR=R(IM)-R(I) 850.0000 B(I) = DZ/DR/4./V(2,I)/R(I)*(ALPHA+ED(I))851.0000

 852.0000
 G(I)=DZ/2./DR/DR/V(2,I)*(ALPHA+ED(I)).

 853.0000
 DEDR=(ED(IP)-ED(I-1))/2./DR

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854,0000 E(I)=DZ/4./DR/V(2,I)*DEDR
855.0000 100 CONTINUE.
856.0000 C
857,0000 C CALCULATE TERMS FOR THE CENTER
                                   G(N) = DZ/1./DR/DR/V(2,N) * (ALPHA+ED(N))
858.0000
859.0000 C
860,0000 C SET THE TRIDIAGONAL MATRIX TO ZERO
861.0000
                             DO 200 I=1,NM
                                TR1(I)=0.0
862.0000
863.0000
                                TR2(I)=0.0
                                TR3(I) = 0.0
864.0000
865,0000
                                D(I)=0.0
866.0000 200 CONTINUE
867.0000 C
868,0000 C TERMS FOR THE FIRST EQUATION
                                TR2(1)=(-1.)*(2.*G(2)+1)
869.0000
870.0000
                                 TR3(1) = G(2) + B(2) + E(2)
871.0000
                                D(1) = -T(2, 1) * (G(2) - B(2) - E(2)) - T(1, 3) * (B(2) + G(2) + E(2)) - C(2) + C(2
872.0000
                              1 T(1,2)*(1-2.*G(2))-T(1,1)*(G(2)-B(2)-E(2))
                                                                                                                                                         •
873.0000 C
874.0000 C LAST EQUATION
                                 NM2 = N - 2
875.0000
876.0000
                                  TR1(NM)=2.*G(N)
877.0000
                                TR2(NM) = (-1,)*(1,+2,*G(N))
                                   D(NM) = -1, T(1, N) * (-2, *G(N) + 1, ) - 2, *T(1, NM) *G(N)
878.0000
879.0000 C
880,0000 C ALL OTHER EQUATIONS
881.0000
                                DO 250 I=3,NM
                                IM = I - 1
882.0000
883.0000
                                IP = I + 1
                                TR1(IM) = G(I) - E(I) - B(I)
884.0000
                                TR2(IM) = (-1.)*(2.*G(I)+1)
885.0000
886.0000
                                TR3(IM) = B(I) + G(I) + E(I)
                                D(IM) = -T(1, IP) * (B(I) + G(I) + E(I)) - T(1, I) * (1, -2, *G(I)) -
887.0000
                              1 T(1,IM)*(G(I)-E(I)-B(I))
888.0000
889.0000 250 CONTINUE
890.0000
                                IF = 1
891.0000
                                  CALL TRIDAG(IF, NM, TR1, TR2, TR3, D, AN)
892.0000 C
893.0000 C SET SOLUTION VECTOR TO T(2,1)
                         DO 900 I=2,N
894.0000
                                 IM = I - 1
895.0000
896.0000
                                 T(2,I) = AN(IM)
                                  IF(T(2, I), LT, T(1, I)) T(2, I) = T(1, I)
 897.0000
 898.0000 900 CONTINUE
 899.0000 C
900.0000 C SYMMETRY
901.0000
                               NP = N + 1
902.0000
                                 T(2,NP) = T(2,NM)
                                RETURN
 903.0000
904.0000
                                END
905.0000 C
906.0000 C
 907.0000 C
```

908.0000 SUBROUTINE TRIDAG(IF,L,A,B,C,D,V) DIMENSION A(50), B(50), C(50), D(50), V(50), BETA(50) 909.0000 DIMENSION GAMMA(50) 910.0000 911.0000 C . 912.0000 C COMPUTE INTERMEDIATE ARRAYS BETA AND GAMMA 913.0000 BETA(IF) = B(IF)GAMMA(IF)=D(IF)/BETA(IF) 914.0000 915.0000 IFP1 = IF + 1916.0000 DO 1 I=IFP1,L BETA(I) = B(I) - A(I) * C(I-1) / BETA(I-1)917.0000 GAMMA(I) = (D(I) - A(I) * GAMMA(I-1)) / BETA(I)918,0000 1 919.0000 C 920.0000 C COMPUTE THE FINAL SOLUTION VECOTR V 921.0000 V(L) = GAMMA(L)922.0000 LAST=L-IF 923.0000 DO 2 K=1,LAST 924.0000 I = L - K925.0000 2 V(I) = GAMMA(I) - C(I) * V(I+1) / BETA(I)RETURN 926.0000 927.0000 END 928,0000 C 929.0000 C 930.0000 C SUBROUTINE BULKT(T,V,R,TB2,N,RAD) 931.0000 932.0000 C 933.0000 C' THIS SUBROUTINE CALCULATES THE BULK TEMPERATURE DIMENSION T(2,50),V(2,50),R(50) 934.0000 DIMENSIONF(50) 935.0000 936.0000 C 937.0000 C F AT THE WALL AND THE CENTER IS ZERO 938.0000 C THERE ARE N+2 F TERMS 939.0000 N2 = N + 2N1 = N + 1940.0000 DO 100 I=1,N 941.0000 F(I+1)=T(2,I)*V(2,I)*R(I)942.0000 943.0000 100 CONTINUE F(1) = 0.0944.0000 F(N2)=0.0945.0000 946.0000 CALL TRAP(N2, R, F, RESULT, RAD) 947.0000 ANUM=RESULT DO 200 I=1,N 948.0000 F(I+1) = V(2, I) * R(I)949.0000 950.0000 200 CONTINUE 951.0000 F(1) = 0.0F(N2) = 0.0952.0000 CALL TRAP(N2, R, F, RESULT, RAD) 953.0000 954.0000 TB2=ANUM/RESULT 955.0000 RETURN END 956.0000 957.0000 C 958,0000 C 959.0000 C 960.0000 C 961,0000 C

962.0000 C 963.0000 C 964.0000 SUBROUTINE PRN1 (RAD, N, DR, DZ, API, TB, Q, TC3, TC6, 965.0000 1 DTIME, TTIME) 966.0000 C 967.0000 C THIS ROUTINE PRINTS THE VALUES WHICH ARE CONSTANT 968.0000 C THROUGHTOUT THE LENGTH OF THE PIPE 969.0000 C 970.0000 C 971.0000 C THIS ROUTINE IS CALLED BY SUBROUTINE INIT 972.0000 C 973.0000 WRITE(6,10) 974.0000 WRITE(6,20) 975.0000 WRITE(6,100) RAD,N,DZ 976.0000 WRITE(6,110) TC3,TC6 977.0000 WRITE(6,125) Q 978.0000 WRITE(6,200) API, TB 979.0000 WRITE(6,401) DTIME, TTIME *****/ 981.0000 1 1H0, *********** COKING PROGRAM ********** ****!/ 982.0000 2 1%, ********** BY ********* *****/ 1X, '************ JOSEPH POLIMENI ********* 983.0000 3 ****'/ 4 984.0000 ***') 985.0000 20 FORMAT(1H0'THE DATA FOR THIS SERIES IS AS FOLLOWS: ') 986.0000 100 FORMAT(1H0, 'THE PIPE RADIUS IS ', F9.5,' FEET'/ 1 1X, 'THE NUMBER OF RADIAL SEGMENTS IS ', 12/1X, 987.0000 988.0000 3 'THE LENGTH SEGMENT IS ', F9.5, 'FEET') 989.0000 110 FORMAT(1X, 'TEMP AT THERMOCOUPLE 3 IS ', F4.0, ' F', 1 ' TEMP AT THERMOCOUPLE 6 IS ', F4.0, ' F') 990.0000 991.0000 125 FORMAT(1X, 'THE INITIAL FLOW RATE IS ', F10.5, ' LEM/SEC' 3 992.0000 200 FORMAT (1H0, 'THE OIL PROPERTIES: '/1X, 993.0000 1 'THE API GRAVITY IS ', F9.3/1X, 2 'THE 50% BOILING TEMP, IS ', F9.3, ' F') 994.0000 995.0000 401 FORMAT(1H0, 'THE INCREMENTAL TIME WILL BE ', F6.1, ' HOUR S'/ 1 1X, 'THE TOTAL TIME WILL BE ', F6.1, ' HOURS'/1H1) 996.0000 997.0000 C 998.0000 RETURN END 999.0000 1000.0000 C 1001.0000 C 1002.0000 C SUBROUTINE PRN2(V,T,R,TB1,TB2,RHO,CP,AK,AVGV, 1003.0000 1004.0000 1 RENN, Z, VIS, N, I, ED, Q, OLDT, DZ, RAD, THICK, TIME, 2 OMCP, TSKIN, TW1, TW2) 1005.0000 1006.0000 C PRINT THE VALUES WHICH CHANGE AT EACH LENGTH SEGMENT 1007.0000 C 1008.0000 C

1009.0000 C THIS ROUTINE IS CALLED BY THE MAIN PROGRAM 1010.0000 C 1011.0000 DIMENSION V(2,50),T(2,50),R(50) 1012.0000 DIMENSION ED(50) 1013.0000 C 1014.0000 C 1015.0000 0 = 0.01016.0000 C 1017.0000 OZ = Z - DZ1018.0000 WRITE(6,75) TIME 1019.0000 WRITE(6,100) 02,Z 1020.0000 WRITE(6,300)TE1 1021.0000 WRITE(6,305) RHO, VIS, AK, CP 1022.0000 WRITE(6,350) RENN 1023.0000 WRITE(6,400) AVGV,TB2 1024.0000 WRITE(6,450) TSKIN 1025.0000 C GA=GMCP*3600*1/DZ/(2.*3.14156*RAD) 1026.0000 1027.0000 WRITE(6,600) QA 1028.0000 WRITE(6,470) 1029.0000 WRITE(6,490) 1030.0000 WRITE(6,495) RAD,0,0,TW1,TW2,0 1031.0000 NP = N + 1DO 711 J=1,N 1032.0000 1033.0000 WRITE(6,500) R(J),V(1,J),V(2,J),T(1,J),T(2,J),ED(J) 1034.0000 711 CONTINUE 1035.0000 *****'/ 1H0, ' THE PRESENT TIME IS ', F9.1, ' HOURS'/ 1036.0000 1 1037.0000 2 ***** 1038.0000 100 FORMAT(1H0, 'THE PAST LENGTH SEGMENT IS ', F9.5,' FEET'/ 1039.0000 1 1X, 'THE PRESENT LENGTH SEGMENT IS ', F9.5, ' FEE T') *****'/ 1041.0000 1 1X,' THE PHYSICAL PROPERTIES ARE BASED O N THE'. ' BULK TEMPERATURE OF '/2X, 'THE PAST LENGTH SEGMENT 1042.0000 2 ۰, 'WHICH IS ', F5.1, ' F'/1H0) 1043.0000 3 1044.0000 305 FORMAT(1X, 'THE DENSITY IS ', F9.3, ' LBM/FT3'/ 1X, 'THE VISCOSITY IS ',E12.5,' LEM/FT-S'/ 1045.0000 1 1046.0000 2 1X, 'THE THERMAL CONDUCTIVITY IS ', E12.5.' BTU/S-FT-F'/ 1047.0000 3 1X, 'THE HEAT CAPACITY IS ', F9.5, 'BTU/LEM-F') *****'/ 1049.0000 1 1X, 'THE AVERAGE VELOCITY FOR THE PRESENT LENGTH IS ', 1050.0000 2 E12.5,' FT/S'/ 1051.0000 1HO, 'THE BULK TEMPERATURE FOR THE PRESENT LENGTH 4 IS ', 1052.0000 5 F11.5, ' DEGREES F')

*****/ 1054.0000 1H0, 'THE REYNOLDS NUMBER IS ', F9.2) 1 1055.0000 450 FORMAT(1H0, 'THE OUTSIDE TUBE WALL TEMPERATURE IS ', 1056.0000 1 E12.5, 'DEGREES F') ***** 1058.0000 5 ********************************* ********!/ 1 1H0,3X, 'RADIUS',12X, 'VELOCITY',18X, 'TEMPERATURE' 1059.0000 ,7%,'EDDY DIFFUSIVITY'/ 1060.0000 2 1061.0000 3 1X,14X, 'PREVIOUS', 5X, 'PRESENT', 7X, 'PREVIOUS', 5X, 1062.0000 4 'PRESENT', 5X, 'PRESENT') 1063.0000 490 FORMAT(1X,4X,'FT',8X,' FT/S ',6X,' FT/S ',8X, 1064.0000 1 'DEGREES F', 4X, 'DEGREES F', 4X, 'FT2/S') 1065.0000 495 FORMAT(1H0,F10.7,2X,E10.4,2X,E10.4,6X,F9.4,3X,F9.4, 1066.0000 1 3X,E10.4,' *** WALL ***') 1067.0000 500 FORMAT(1X,F10.7,2X,E10.4,2X,E10.4,6X,F9.4,3X,F9.4, 1068.0000 1 3X,E10.4) 1069.0000 600 FORMAT(1X, 'THE HEAT FLUX FOR THIS LENGTH SEGMENT IS ', E20.5. 1070.0000 1 ' BTU/HR FT2') 1071.0000 C 1072,0000 C 1073.0000 WRITE(6,991) ۰. 1075.0000 ********************************* 1 ***'/1%. 2 *********************************** 1076.0000 ***', 1077.0000 3 ************************************* ***'/1H1) 1078.0000 RETURN 1079.0000 END 1080.0000 C 1081.0000 C 1082.0000 C 1083.0000 C 1084.0000 C 1085.0000 C 1086,0000 C 1087.0000 C SUBROUTINE RESET (X,N) 1088.0000 1089,0000 C THIS SUBROUTINE SET ANYTHING IN THE SECOND ROW TO 1090.0000 C THE FIRST ROW IE NEW VALUES OF VELOCITY OR 1091.0000 C TEMPERATURE BECOMES OLD VALUES 1092.0000 C 1093.0000 C THIS ROUTINE IS CALLED BY THE MAIN PROGRAM 1094.0000 C 1095.0000 DIMENSION X(2,50) NP = N + 11096.0000 1097.0000 DO 100 I=1,NP 1098.0000 X(1, I) = X(2, I)

1099.0000 100 CONTINUE 1100.0000 RETURN 1101.0000 END 1102.0000 C 1103.0000 C 1104.0000 C 1105.0000 SUBROUTINE TRANS(V, R, RAD, AVGV, N, RENN, KFIRST, 1106.0000 1 DR, DZ, VIS, KTFLG, RHO) 1107.0000 C 1108.0000 C THIS ROUTINE CALCULATES THE VELOCITY PROFILE IN THE 1109.0000 C TRANSITION ZONE BY USING A WEIGHTED AVERAGE BETWEEN 1110.0000 C REYNOLDS NUMBERS 2000-4000 1111.0000 C 1112.0000 C THIS ROUTINE IS CALLED BY SUBROUTINE RENVL 1113.0000 C 1114.0000 DIMENSION VLAM(2,50), VTURB(2,50), V(2,50) 1115.0000 DIMENSION R(50) 1116.0000 C 1117.0000 C 1118.0000 C FIRST CALCULATE THE LAMINAR FLOW PROFILE 1119.0000 CALL LAMAR(V, AVGV, R, RAD, N) 1120.0000 DO 20 IJ=1,N 1121.0000 VLAM(2,IJ) = V(2,IJ)1122.0000 20 CONTINUE 1123.0000 IF (KFIRST.EQ.1) GO TO 25 1124.0000 C 1125.0000 C CALCULATE THE TURBULENT FLOW PROFILE 1126.0000 25 CONTINUE 1127.0000 CALL TURB(V, R, RAD, RHO, DZ, VIS, N, DR, AVGVT, 1128.0000 1 KFIRST, KTFLG, Y, RENN, TAUO) 1129.0000 C 1130.0000 C CALCULATE THE WEIGHTS LWT = 2. - (RENN / 2000.)1131.0000 1132.0000 TWT = (RENN / 2000.) - 1.1133.0000 NP = N + 11134.0000 DO 100 I=1,N 1135.0000 $V(2,I) = LWT \times VLAM(2,I) + TWT \times V(2,I)$ 1136.0000 100 CONTINUE 1137.0000 C 1138.0000 C CALCULATE THE AVERAGE VELOCITY 1139.0000 CALL TVAVG(V,N,R,DR,AVGVT,RAD) 1140.0000 C 1141.0000 C NORMALIZE TO FORCE PROFILE TO GIVE AVGV 1142.0000 DO 200 I=1,NP 1143.0000 V(2, I) = V(2, I) * AVGV / AVGVT1144.0000 200 CONTINUE 1145.0000 RETURN 1146.0000 END · 1147.0000 C 1148.0000 C 1149.0000 SUBROUTINE EDDY(T,V,R,ED,N,KTFLG,Y,RAD) 1150.0000 C 1151.0000 C THIS ROUTINE DETERMINES THE EDDY DIFFUSIVITY FOR 1152.0000 C EACH RADIAL SEGMENT

1153.0000 C 1154.0000 C THIS ROUTINE IS CALLED BY SUBROUTINE TEMP 1155,0000 C DIMENSION T(2,50),V(2,50),R(50),ED(50) 1156.0000 1157.0000 DIMENSION Y(50) 1158.0000 C 1159.0000 C CHECK FOR TURBULENT FLOW 1160.0000 C IF LAMINAR SET ED ARRAY TO ZERO AND RETURN 1161.0000 IF(KTFLG.EQ.1) GO TO 20 1162.0000 DO 10 I=1,2001163.0000 ED(I)=0.01164.0000 10 CONTINUE 1165.0000 RETURN 1166.0000 20 CONTINUE 1167.0000 C 1168.0000 C SET DIELSER CONSTANT 1169.0000 DK=0.36 1170.0000 C 1171.0000 C CALCULATE PRANDTLE MIXING LENGTH 1172.0000 NM = N - 11173.0000 NP = N + 11174.0000 DO 100 I=1,NM 1175.0000 IM = I - 11176.0000 IP = I + 11177.0000 C 1178.0000 C CALCULATE THE DISTANCE FROM THE WALL 1179.0000 S=RAD-R(I) 1180.0000 C 1181.0000 C CALCUALTE THE MIXING LENGTH 1182.0000 C 1183.0000 C SAFETY SO EXP IS NOT EXCEEDED 1184.0000 IF(Y(I), GT, 50,) Y(I) = 50.1185.0000 AL = DK * S * (1, -(1, /EXP(Y(1)/26,)))1186.0000 C 1187.0000 C CALCULATE DV/DR 1188.0000 DVDR = (V(2, IP) - V(2, I)) / ((R(I) - R(IP)))1189.0000 ED(I)=AL*AL*1*DVDR 1190.0000 C 1191.0000 C INCLUDE A SAFETY FEATURE SO THAT 1192.0000 C NEGATIVE EDDY DIFFUSIVITIES ARE AVOIDED 1193.0000 IM = I - 11194.0000 IF(ED(I), LE, 0, 0) = ED(I) = ED(IM)1195.0000 100 CONTINUE 1196.0000 ED(N) = ED(NM)1197.0000 ED(NP) = ED(N)1198.0000 RETURN 1199.0000 END 1200.0000 C 1201.0000 C 1202.0000 C 1203.0000 SUBROUTINE GCALC(TB1,T,R,V,AVGV,AK,DZ,N,RHO 1204.0000 1 , GMCP, TB2, CP, RAD) 1205.0000 C 1206.0000 C THIS ROUTINE CALCULATES Q

1207.0000 C 1208.0000 C THIS ROUTINE IS CALLED BY THE MAIN PROGRAM 1209.0000 C 1210.0000 DIMENSION T(2,50),R(50),V(2,50) 1211.0000 CALL BULKT(T,V,R,TB2,N,RAD) 1212.0000 DELT=TB2-TB1 1213.0000 C 1214.0000 PI=3,14159 1215.0000 GMCP=AVGV*PI*RHO*(R(1)**2.)*DELT*CP 1216.0000 RETURN 1217.0000 END 1218.0000 C 1219.0000 C 1220.0000 C 1221.0000 SUBROUTINE TADJ(T, OMCP, DZ, AK, RAD, R, TW2) 1222.0000 C 1223.0000 C THIS ROUTINE CALCULATES WHAT THE TEMPERATURE 1224.0000 C NEXT TO THE WALL SHOULD BE BASED UPON THE 1225.0000 C Q CALCULATED BY M*CP*DELTA T 1226.0000 C 1227.0000 C THIS ROUTINE IS CALLED BY 1228.0000 C MAIN PROGRAM 1229.0000 C 1230.0000 DIMENSION T(2,50), R(50) 1231.0000 TERM=2.*3.14159*DZ*AK*RAD 1232.0000 T(2,1) = OMCP / TERM * (R(1) - RAD) + TW21233.0000 RETURN 1234.0000 END 1235.0000 C 1236,0000 C 1237.0000 SUBROUTINE SKIN(OMCP, TWAVG, RAD, ROUT, RIN, TSKIN, DZ) 1238.0000 C 1239.0000 C 1240.0000 COKEX=0.161 1241.0000 STEELK=8.52+4.17E-03*TWAVG 1242.0000 G=GMCP*3600. 1243.0000 TSKIN=Q*((1/COKEK)*ALOG(RIN/RAD)+(1/STEELK)*ALOG(ROUT/ RIN)) 1 /2./3.14159/DZ+TWAVG 1244.0000 1245.0000 RETURN 1246.0000 END 1247.0000 C 1248.0000 C 1249.0000 C 1250,0000 C 1251.0000 C 1252.0000 C 1253.0000 C 1254.0000 C 1255.0000 C 1256.0000 C 1257.0000 C 1258,0000 C 1259.0000 C *** VARIABLE DICTIONARY FOR ENTIRE PROGRAM *** `

1260.0000 C 1261.0000 C A-INITIAL LIMIT OF INTEGRATION 1262.0000 C __ ADD-SUM OF ALL FILM TEMPERATURES FOR A PARTICULAR 1263.0000 C TIME SEGMENT. 1264.0000 C AK-THERMAL CONDUCTIVITY OF CRUDE OIL AL-PRANDTLE MIXING LENGTH 1265.0000 C 1266,0000 C API-API GRAVITY 1267.0000 C AREA-AREA OF FLOW 1268.0000 C ATOL-TOLERENCE FOR SECANT METHOD 1269.0000 C AVGFT-AVERAGE OF ALL FILM TEMPERATURES FOR A PARTICULAR 1270.0000 C TIME SEGMENT 1271.0000 C AVGV-AVERAGE VELOCITY 1272 0000 C BTOL-TOLERENCE FOR TEMPERATURE NEXT TO WALL 1273.0000 C 1274.0000 C C-CHARACTERIZATION FACTOR 1275.0000 C CHECK-THE ABSOLUTE VALUE OF THE DIFFERENCE BETWEEN THE LAST VALUE OF THE TEMPERATURE NEXT TO THE 1276.0000 C WALL AND THE CURRENT VALUE OF THE TEMPERATURE 1277.0000 C 1278.0000 C NEXT TO THE WALL 1279,0000 C COKETK-COKE THICKNESS 1280.0000 C CP-HEAT CAPACITY OF THE CRUDE OIL 1281.0000 C DATN-NAME OF DATA SET 1282.0000 C DELT-DIFFERENCE BETWEEN PRESENT BULK TEMPERATURE AND 1283.0000 C PAST LENGTH BULK TEMPERATURE 1284.0000 C DTIME-TIME INCREMENT 1285.0000 C DVDR-FORWARD DIFFERENCE APPROXIMATION TO THE PARTIAL DERIVATIVE OF VELOCITY WITH RESPECT TO R 1286.0000 C 1287.0000 C DZ-LENGTH INCREMENT ETA-CORRECTION FACTOR FOR VELOCITY PROFILE 1288.0000 C 1289.0000 C ETAG1-FIRST GUESS OF ETA -- USED BY SECANT METHOD 1290.0000 C ETAG2-SECOND GUESS OF ETA -- USED BY SECANT METHOD 1291.0000 C F1-VALUE OF F(ETAG1) USED BY SECANT METHOD 1292.0000 C F2-VALUE OF F(ETAG2) USED BY SECANT METHOD 1293.0000 C FF-FANNING FRICTION FACTOR 1294.0000 C FILMT-ARRAY WHICH CONTAINS THE VALUE OF THE TEMPERATURE NEXT TO THE WALL FOR EACH 1295.0000 C 1296.0000 C LENGTH SEGMENT 1297.0000 C IFLG-FLAG, INDICATES WHETHER THE SECANT METHOD HAS 1298.0000 C CONVERGED OR NOT: 0 MEANS NOT CONVERGED YET, 1 INDICATES THAT IT HAS CONVERGED 1299.0000 C IP-PRINTER VARIABLE, USED TO INDICATE IF ALL THE 1300.0000 C 1301.0000 C VALUES PERTAINING TO A PARTICULAR TIME SEGMENT SHOUL D 1302.0000 C BE PRINTED. 1303.0000 C IPRN-PRINTER ARRAY, CONTAINS WHICH PARTICULAR TIME SEGMEN TS. WILL HAVE ALL THE VALUES PERTAINING TO IT PRINTED 1304.0000 C 1305,0000 CKFIRST-FLAG, 0 INDICATES FIRST TIME THROUGH, 1 INDICATES IT HAS ALREADY BEEN THROUGH THE ENTIRE LENGTH ONCE. 1306.0000 C 1307.0000 C KTFLG-FLAG, WHICH INDICATES LAMINAR OR TURBULENT FLOW 1308.0000 C O INDICATES LAMINAR, 1 INDICATES TURBULENT 1309.0000 C LWT-A WEIGHT FACTOR USED WHEN IN TRANSITION REGION A LINEAR FUNCTION OF REYNOLDS NUMBER, THIS 1310.0000 C VARIABLE GIVES THE WEIGHT TO THE LAMINAR PROFILE 1311.0000 C

1312.0000 C NF-NUMBER OF RADIAL SEGMENTS 1313.0000 C NP-N+1 1314.0000 C NPRN-PRINTER VARIABLE, USED TO INDICATE THE TOTAL AMOUNT OF 1315,0000 C TIME SEGMENTS WHICH WILL HAVE ALL THE VALUES PERTAIN ING 1316.0000 C TO IT PRINTED 1317.0000 C NRM-N-1 1318.0000 C NSEG-NUMBER OF LENGTH SEGMENTS IN ONE TIME PERIOD 1319.0000 C Q-FLOW RATE IN LBM/FT2-SEC 1320.0000 C Q1-FLOW RATE IN LBM/S 1321.0000 C GMCP-HEAT FLUX CALCULATED BY M*CP*DELTA T 1322,0000 C R2-SIZE OF RADIAL SEGMENT 1323.0000 C RAD-INSIDE RADIUS OF FLOW (IF THERE IS NOT COKE 1324.0000 C THIS IS THE INSIDE RADIUS OF THE TUBE) 1325.0000 C RENN-REYNOLDS NUMBER 1326.0000 C RHO-DENSITY OF THE CRUDE OIL (PRESENT LENGTH SEGMENT) 1327,0000 C ROUT-OUTSIDE TUBE RADIUS 1328.0000 C SG-SPECIFIC GRAVITY OF CRUDE OIL 1329,0000 C TAUO-SHEAR STRESS AT THE WALL OF THE TUBE 1330.0000 C TE1-BULK TEMPERATURE AT PREVIOUS LENGTH INCREMENT 1331,0000 C TB2-BULK TEMPERATURE AT CURRENT LENGTH INCREMENT 1332,0000 C TC3-TEMPERATURE AT THERMOCOUPLE NUMBER 3 1333.0000 C TC6-TEMPERATURE AT THERMOUCOUPLE NUMBER 6 1334,0000 C TH-HOLDS THE VALUE OF T NEXT TO THE WALL 1335.0000 C THICK-ONE HALF OF THE THICKNESS OF THE LAMINAR SUBLAYER 1336,0000 C TIME-CURRENT TIME 1337.0000 C TINIT-INITIAL TEMPERATURE (BULK TEMPERATURE OF CRUDE OIL . 1338,0000 C INTO TUBE) 1339.0000 C TK-AMOUNT OF COKE DEPOSITED FOR ONE TIME SEGMENT. 1340.0000 C TTIME-FINAL TIME 1341.0000 C TB-FIFTY PERCENT BOLING POINT 1342.0000 C TB1-BULK TEMPERATURE AT PREVIOUS LENGTH INCREMENT 1343.0000 C TB2-BULK TEMPERATURE AT CURRENT LENGTH INCREMENT 1344,0000 C TH-HOLDS THE VALUE OF T NEXT TO THE WALL 1345.0000 C TW1-TEMPERATURE AT FLUID SOLID (TUBE WALL OR COKE LAYER) 1346.0000 C INTERFACE AT PREVIOUS LENGTH SEMGMENT 1347.0000 C TW2-TEMPERATURE AT FLUID SOLID INTERFACE AT PRESENT LENG TH 1348.0000 C SEGMENT 1349.0000 C TWAVG-AVERAGE TEMPERATURE AT FLUID SOLID INTERFACE 1350.0000 C (AVERAGE BASED ON PAST LENGTH SEGMENT AND PRESENT LENGTH SEGMENT) 1351.0000 C 1352.0000 C TWT-A WEIGHT FACTOR USED WHEN IN TRANSITION REGION 1353.0000 C A LINEAR FUNCTION OF REYNOLDS NUMBER USED TO 1354.0000 C DETERMINE HOW MUCH OF THE VELOCITY PROFILE 1355,0000 C IS TURBULENT 1356.0000 C 1357.0000 C V-ARRAY CONTAINING THE VELOCITY PROFILE: 1358.0000 C V(1,X) CONTAINS THE PAST LENGTH SEGMENT VELOCITY PRO FILE 1359.0000 C V(2,X) CONTAINS THE CURRENT LENGTH SEGMENT VELOCITY 1360.0000 C PROFILE 1361.0000 C VA-DIMENSIONLESS VELOCITY
1362.0000 C VIS-VISCOSITY OF CRUDE OIL 1363.0000 C VLAM-ARRAY USED TO CONTAIN THE LAMINAR FLOW VELOCITY
 1364.0000 C
 PROFILE.

 1365.0000 C
 PROFILE

 1366.0000 C
 Z-LENGTH
 .

1367.

APPENDIX B

INPUT FORMAT FOR PROGRAM

HOW TO USE THE PROGRAM

You will need to know the following

- 1. The wall temperature for the entire length of the tube (or make a linear assumption as described below).
- 2. The initial crude oil temperature.
- 3. The flow rate.
- 4. The inside and outside radius of the tube.
- 5. The API gravity and mid boiling point of the crude oil

THE WALL TEMPERATURE

Subroutine WALLT determines the wall temperature at a particular length. In its present form, the subroutine takes the wall temperature at 3 and 6 feet downstream, and uses the two values to assume a linear profile for the entire length of the tube. If the temperature profile is different from this the user must change the way TW1 and TW2 are calculated (TW1 is the tube wall temperature at the past axial segment, TW2 is the tube wall temperature at the present axial segment). For example:

The lines to be changed in subroutine WALLT are:

SLOP = (TC6 - TC3)/3. B = TC3 - SLOP*3. TW1 = B + SLOP * (Z-DZ)TW2 = B + SLOP * Z

say we know the wall temperature at 2 and 7 feet downstream and we still want a linear profile. Then TC6 would represent the temperature at 7 feet, and TC3 would represent the temperature at 3 feet. The first two lines

would be changed to the following: SLOP = (TC6 - TC3)/5.B = TC3 - SLOP*5DATA ENTRY FORMAT The data is entered with cards or a data file. CARD 1 The initial bulk temperature in F The format for this card is F7.1 example: column 1 2 3 4 5 6 7 6 4 0 . 0 would indicate that the initial bulk temperature is 640 F. CARD 2 The flow rate in lbm/ft2-s The format for this card is F7.1 example: column 1 2 3 4 5 6 7 4 3 . 0 1 would indicate that the flow rate is 143 lbm/ft2-s. CARD 3 * A Value The User Chooses * The number of radial segments The format for this card is I2 example: column 1 2 4 0 would indicate 40 radial segments

Inside radius of tube in inches The format for this card is F10.5 example: column 1 2 3 0 3 . would indicate 0.3 inches CARD 5 API gravity of the crude oil The format for this card is F10.5 example: column 1 2 3 4 2 9 . 6 would indicate an API gravity of 29.6 CARD 6 Mid-point boiling temperature of crude oil in F. The format for this card is F10.5 example: 2 3 column 1 4 5 1 7 0 . 0 would indicate a mid-point boiling temperature of 701 F. CARD 7 Outside radius of tube in inches. The format for this card is F10.5 example: column 2 3 1 0 5 . would indicate an outside tube wall radius of 0.5 inches.

CARD 4

CARD 8 * A Value the User Chooses * The number of axial segments The format for this card is I3 example: column 1 2 3 8 1 would indicate 18 axial segments CARD 9 The value of z in feet. The format for this card is E20.5 example: column 1 2 3 5 0 would indicate that each axial increment is 0.5 feet. CARD 10 The temperature of the tube wall three feet downstream in F The format for this card is F10.5 example: column 2 3 4 5 1 2 8 ο. 0 would indicate that the temperature of the tube wall three feet downstream is 820 F. CARD 11 The temperature of the tube wall six feet downstream in F The format for this card is F10.5 example: column 1 2 3 4 5 8 3 0 0 would indicate that the temperature of the tube wall six feet downstream is 830 F.

* A User Chosen Value * The time increment in hours. The format for this card is F8.1 example: column 1 2 3 4 9 3 \cap would indicate that the time increment is 93 hours. CARD 13 The total time in hours. The format for this card is F8.1 example: column 1 2 3 4 3 0 9 . would indicate that the total time is 93 hours. CARD 14 The data number. This is only a name to give to the data. This is useful when running many data sets at one time. The format for this card is A4 example: column 1 2 3 4 D 4

CARD 12

would indicate that the name of this series is D4. CARDS USED TO CONTROL PRINTING

The program prints the results with routine PRN2. Array IPRN and variable NPRN are used to limit the computer printout. The results for each axial segment for the entire tube length will be printed, but only at the time increments specified. For example: If the total time of the test is 200 hours, and you want the coke to be layered at 100 and at 200 hours. There are three time segments (initial, 100 and 200 hours), but say only the value for

the initial time and at 200 hours are desired. NPRN has the number of time increments to be printed, in this case NPRN is two. Array IPRN will have 2 values which correspond to the desired time increment. In this case IPRN(1) would equal zero (for the initial time segment) and IPRN(2) would equal two (for the value at 200 hours).

CARD 15

The value of NPRN (the number of entire length segments to print). The format for this card is I3 example: column 1 2 3 2

would indicate that the results for two time increments will be printed.

CARD 16 ETC.

The number of cards here will depend upon the value of CARD 15. If the value on CARD 15 is one, then only one card will follow CARD 15. Assume that CARD 15 has the value two on it, we will need two more cards after CARD 15.

The time increment to print the results for. Format for this card is I3 example: column 1 2 3 0

indicates that the initial time segment results should be printed.

CARD 17

The time increment to print the results for.

Format for this card is I3

example: column 1 2 3

indicates that the second time segment results should be printed.

APPENDIX C SAMPLE PRINTOUT FROM PROGRAM

THIS IS DATA NUMBER DA ******** . BY ********* JOSEPH POLIMENS **************** ********* ----------THE DATA FOR THIS SERIES IS AS FOLLOWS: THE PIPE RÁDIUS IS 0.02500 FEET THE NUMBER OF RADIAL SEGMENTS IS 41 THE LENGTH SEGMENT IS 0.50DDJ FEET TERP AT THERMOCOUPLE 3 IS 820. F TEMP AT THERMOCOUPLE 6 IS 830. F THE INITIAL FLOW RATE IS 0.28078 LBM/SEC THE OIL PROPERTIES: THE API GRAVITY IS 29.600 THE SOX BOILING TEMP. IS 707.000 F -----THE INCREMENTAL TIME WILL BE 191.0 HOURS .

NORMALLY THE PROGRAM PRINTS THE RESULTS FOR EACH AXIAL SEGMENT. IN ORDER TO CONSERVE SPACE, ONLY THE RESULTS FROM 0.5, 1.0, 4.5, AND 9.0 FEET WITH AND WITHOUT COKE HAVE BEEN INCLUDED.



	TINE IS	DO HOURS			
*****	******	***********	*******		•
THE PAST LE	NGTH SEGMENT	15).00000	FEET		
	CENGIA JEGAE				······································
THE PHYSIC THE PAST L	AL PROPERTIES	ARE BASED ON	THE BULK TEMP	PERATURE OF	
THE DENSITY	-15	TR#/F#3			. <u>.</u>
THE VISCOSI	TY IS 0.1151	0E-03 LBM/FT-	-04 BILLS-ET-4		
THE HEAT CA	PACITY IS C	774 SOBTU/LBM	- F		
******	*** ********	******	****		
THE REYNOLD	S NUMBER IS	62119.83			*********
****	*****	********			
THE AVERAGE	VELOCITY FOR	THE PRESENT	LENGTH IS 0.3	7912E 01 FT/	s
THE VELOCIT	Y CORRECTION	FACTOR IS U.	1 390 2E 01		
THE BULK TE	MPERATURE FOR	THE PRESENT	LENGTH IS 64	3.86035 DEGR	EES F
THE OUTSIDE	TUBE WALL TE	MPERATURE IS	G.85194E-030E	GREES F	
THE BEAT PL	UK FUR IHIS L	ENGTH SEGMENT	15 L	1.38307E US B	TU/HR FTZ
********	*****	*******	(4 44 44), 444,449 ,944,	******	******
RAD IU S	VEL	.0CIJY	TEMP	ERATURE	EDDY DIFFUSIVITY
FT	FTVS	FT75	DEGREES F	DEGREES F	FTZ/S
0.0250000	.0000E 00	00 3 COOO	810.0000	811-6665	-00001 00
0.0249438	.3395E 00	-3895E 00	640.0000	777.5623	V3817E-07
0.0236966	+2955E 01	-2048E UT	640.0000	654-0842	-4185E+04
0.0230730	.3139E 01	.3339E 01	640.0000	650-3616	•2233E-03
0.0224494	.3272E 01	.3272E 01	640.0000	648-0452	•3053E+03
0.0212322	.3460E 01	-3760E 01	640.0000	040+4438 645-2659	-3877E-03
0.0205786	.3531E 01	-3531E 01	640.0000	644.3618	.5533E-03
D.01995.50	- 3594E 01	-3594E 01	640.0000	643.6479	.6364E-03
0.0187078	- 3698E 01	- 3698F 01	640.0000	642.5981	•7195E→U3 -8027E→03
0.0186842	-3743E 01	-3743E 01	640.0000	642.2019	.8859E-03
0.0174606	-3783E 01	-3783E 01	640.0000	641.8667	•9691E-03
0.0162370	- 3856F 01	*28218 UT	640.0000 	041.5806	+105ZE-02
0.01558.98	.3888E 01	.3888 E 01	640.0000	641.1196	.1219E-02
0.0.14 96 62	.3918E D1	.3918E 01	640.0000	640.9319	.1302E-02
0 0 14 34 26" 0 013 71 00	3947E 01	- 3947E 01	640.0000	640.7664	-1386E-02
0.0130954	. 3999E 01	-3999E 01	640.0000	640.4912	-1552E+02
0.0124718	.4023E 01	-4023E 01	640.0000	640.3757	.1636 E-02
0.0118482	.4046E 01	-4046E 01	640.0000	640.2739	.1719E-02
0.01060.11	4089E 01	4065E 01	640.0000	04U+1031	+10U2E-U2
0.0099775	.4107E 01	.4109E 01	640.0000	640.0417	.1969E-02
0.0093539	.4128E 01	.4#28E 01	640.0000	640.0000	+2053E-02
0.00873.03	.4140E UT	-4146E UT	640.0000	640.0000 640.0000	•2130E=02
0.0074831	.4181E 01	.4181E 01	640.000Q	640.0000	-2303E-02
0.0068595	-4198E 01	-4198E 01	640.0000	640.0000	-2386E-02
0.0056173	•4614E U1 •42796 01	4214E 07	840.0000 640.0000	640-0000 640-0000	• 2407E-02
0.0049887	.4244E 01	4244E 01	640.0000	640.0000	.263₹E-02
0 -004 36 51	4258E 01	-4258E 01	640.0000	640.0000	-2720E-02
u.0037415	.4273E 01	.4273E 01	640-0000	640.0000	. 2803E-02
0.0024943	.4299E 01	.4299 E 01	640.0000	640.0000	.2970E-02
0.00.18707	.4312E 01	4312E 01	640.0000	640.0000	.3053E=02
0.0012471	-4325E 01	-4825E 01	640.0000	640.0000	-3136E-02
0.0000000	+4349E 01	.4349E 01	640.0000	640.0000	.3220E-02

****	*****	****}*******	* *** * * * * * *		
THE PRESENT	TINE IS	0-0 HOURS			·
** ***(* ** ** **	** *****	*****	* *** * * * * * *		
THE DACT CEN	ETH CEENENT	TE 0 50000			······································
THE PRESENT	LENGTH SEGM	ENT IS 1.000	OQ FEET		
*******	** *****	******			
THE PHYISICA	L PROPERTIE	S ARE BASED ON	THE BULK TEMP	ERATURE OF	
THE PAST LE	NG.TH SEGMEN	WHICH IS 643	• 9 F		
THE VISCOSIT	Y 15 0.115	9 L9M/FT3 10E-03 L8M/FT-1	5		· · · · · · · · · · · · · · · · · · ·
THE THERMAL	CONDUCTIVIT	Y IS 0-17528E	-04 BTU/S-FT-F		
THE HEAT CAP	ACITY IS	0.774509T0/L8M	- F		······································
****	** *** *****	**********	* *** ** *** *		
THE REYNOLDS	NUMBER IS	62149.83			
****	******		********		
THE AVERAGE	VELOCITY FO	R THE PRESENT I	ENGTH 15 0.3	7912E 01 FT/	S
THE VELOCITY	CORRECTION	FACTOR IS 0.	13902E 01		
THE BULK TEM	PERATURE FO	R THE PRESENT I	LENGTH IS 64	7.64843 DEGR	EES F
THE DUTS INC.	10 de - 01 fr - 1				
THE HEAT FLU	X FOR THIS	LENGTH SEGMENT		.37590E 05 8	TU/HR FT2
			*************	******	***************
RADIUS	VE	LOCITY	TERP	ERATURE	EDDY DIFFUSIVITY
FT	FT/S	PRESENT FT/S	DEGREES F	DEGREES F	PRESENT FT2/S
0.0250000	- 0000E 00	-0000E 00.	811.6665	813.3333	-0000E 00 *** WAL
0.0243202	- 2648E 01	-2648E 01	662-1560	672.7727	-4185E-04
0.0236966	. 2955E 01	-2955E 01	654.0842	663.5967	-1425E-03
0.0224494	-3272E 01	-3272E 01	648-0452	655.64.72	•2233E=03
0.0218258	+3375E 01	-3875E 01	646.4438	-653-2527	-3877E=05
0.0205786	• 340UE UT	•346)E UT	645.2659	651.3782	-4705E-03
0.01 9 95 53	- 3594E 01	-3594E 01	543-6479	648.6057	•6364E=03
0.0193314	.3649E 01	.3649E 01	643.0720	647.5476	•7195E-03
0.018/0/8	+ 3698E UI	53698E 01	642.5981	646.6460	18027E-03
0.0174606	• 3783E 01	-3783E 01	641_8667	645.1956	+00392003 _9691F≠83
0.0168370	.3821E 01	.3821E 01	641.5806	644 - 6074	.1052E-02
0.0162134	-3856E 01	-3856E 01	641.3342	644.0916	-1136E-02
0.0122898	- 3888E 01	-3888E 01 -3918E 01	647.1196	643.6377	+1219E-02
0-0143426	-3947E 01-	-3947 E 01	640.7664		+1386E#02
0.0137190	.3973E 01	-3973E 01	640.6206	642.5686	-1469E-02
0.01309.54	.3999E 01	.3999E 01	640.4912	642-2905	.1552E+02
0.0124718	+4023E 01	-4023E 01	640.3757	642.0442	• 1636 E-02
0.0112246	+4068E 01	-4068E 01	640,1851	641.6345	18025-02
0.01060.11	-4089E 01	4089E 01	340,1084	641.4651	.1886 E-02
0.009.9775	-4109E 01	-4707E 01	640-0417	-641.3167	.1969E=02
0.0093539	-4128E 01	-4128E 01	640.0000	641.1714	-2053E-02
0.0081067	+4140E UT	•4340 E UJ •4166 E 81	640.0000	041.0095 440.8404	.2130E-UZ
0.0074831	-4181E 01	-4481E 01	640.0000	640.7488	. 2303E-02
0.006 85 95	.4198E 01	4198E 01	640.0000	640.6455	.2386E-02
0 004 23 50	- 4214F 01	4216 F 01	640-0000	A40.5583	24695-02

640.0000

640.0000

640.0000

640.0000 640.0000 640.0000

840.0000

640.0000

640.0000

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640.0000

640.5583

640.4854

640.4253

640.3770

640.3389

640.3103 640.2898

640.2766 640.2693 640.2671 640.2671

-2553E-02 -2637E-02

.2720E-02

-2803E-02

-2887E-02 -2970E-02

-3053E-02

3136E-02

•3220E=02

.3220E-02

0.0056123

0.0049887 0.0043651 0.0037415

0.0031179 0.0024943

0.0018707

0.0012471

0.0006235

0.000.000.0

.4229E 01

.4258E 01

+4273E_01

•4286E 01 •4299E 01 •4312E 01 •4325E 01 •4337E 01

.4349E 01

-4229E 01

+4258E 01

.4258E 01 .4273E 01 .4286E 01 .4299£ 01 .4312E 01 .4325E 01 .4325E 01

.4349E 01

and the second . THE PRESENT TIME IS -0-0-HOURS-****** THE PAST LENGTH SEGMENT IS THE PRESENT LENGTH SEGMENT IS 4.00000 FEET 4.50000 FEET ******** THE PHYSICAL PROPERTIES ARE BASED ON THE BULK TEMPERATURE OF THE PAST LENGTH SEGNENT WHICH IS 657.9 F THE DENSITY IS 37.390 LBW/FT3 THE VISCOSITY IS 0.10542E-D3 LBM/FT-S THE THERMAL CONDUCTIVITY IS 0.17421E-04 BTU/S-FT-F _ · THE HEAT CAPACITY IS 0.78402BTU/LBM-F **[****** THE REYNICLOS NUMBER 15 67823.00 THE AVERAGE VELOCITY FOR THE PRESENT LENGTH IS 0.38246E O1 FT/S The velocity correction factor is 0.13753E 01 THE BULK JEMPERATURE FOR THE PRESENT LENGTH IS 659.44482 DEGREES F THE OUTSIDE TUBE WALL TEMPERATURE IS 0.841 TOE OBDEGREES F THE HEAT FLUX FOR THIS LENGTH SEGMENT IS 0.15912E 05 BTU/HR ET2 RATURE ED DY DIEEUSIWITY RADIUS VELOCITY TEMPERATURE PREVIOUS PREVIOUS PRESENT £Τ FT/S FTYS DEGREES F DEGREES F. FT2/S 0.0250000 -0000E 00--0000E-00----823.3333 824-9998--0000E 00 --- WALL -3421E 00 -2676E 01 0.02494:85 -3424E 00 -2679E 01 811.9392 -3244 E+07 809.7014 0.0243248 694.6499 -4497E-04 0.02370.11 .2984E 01 .2987E 01 ----680-9524 682-5947 1416E=03 0.0230774 \$3169E 01 .3172E 01 675.7827 673.9963 -2222E-03 0.0224537 .3301E 01 -3804E 01 669.3523 671.1997 -3040E-03 0.02183 00 -3404E 01 -3407E 01-665.9390 667.7998--386ZE-03 0.02120 62 .3489E 01 -3492E 01 663.2852 665.1318 +4688E-03 0.0205825 .3561E 01 -3564E 01 661.1443 662.9626 .5515E+03 0.0199538 - 3623E 01 .6344E-03 3626E 01 659.3713 661.1558 0.01933.51 .3881E 01 657.8735 659.6250 .7173E-03 0.0187114 .3727E 01 .3730E 01 .8003E-03 656.5925 658.3081 0.0180877 -3775E 01 .3771E 01 655.4824 657.1643 .8833E-03 0-0174640 .3812E 01 -3815 F 01 654.5095 656.1653 •9663E-03 . 3850E 01 0.01684,02 .3853E 01 655.2852 653.6538 -1049E-02 0.0162165 3884E 01 3887E 01 652.8962 654.5054 0.0155928 .3917E 01 .3920E 01 653.8103 652.2246 .1216E-02 .3947E 01 0.0149691 -3950E 01 653.1885 -1299E-02 651.6273 0.01434.54 -3975E 01 -3978E 01 651-0950 -1382E-02 652.6299 0.0137217 .4002E 01 .4005E 01 650.6216 652.1260 -1465E-02 0.0130980 .4027E 01 650.1970 .403) E 01 651.6738 -1548E-02 .4051E 01 .4074E 01 0.0124742 0.0118505 .4054E 01 .4077E 01 649-8201 649-4871 651.2639 .1632E-02 -1715E-02 -4099E 01 .4096E 01 0.01122 68 649.1917 650.5571 .1798E-02 .1881E-02 650.2554 0.0106031 -4117E 01 648.9319 -4140E 01 0.0099794 -4137E 01 648.7043 649.9836 1964 E=02 0.00935.57 .4156E 01 .4359E 01 648-4915 649.7537 .2048E+02 649.5798 649.4219 0.0087320 .4175E 01 .4178E 01 648.2737 -2131F-02 .4195E 01 0.0081082 .4192E 01 648-0874 .2214E-02 0.0074845 .4209E 01 .4212E 01 647.9272 649.2810 .2297E-02 0.0068608 -4225E 01 -4229E 01 647.7891 649-1572 2380E=02 0.0062371 .4242E 01 .4245E 01 647.6716 649.0496 .2464 E-02 0.0056134 .4257E 01 .4260E 01 647.5742 648.9556 \$2547E-02 0.004 98 97 4272E D1 -4275E OT 647:4935 648.8762 .2630E-02 0.0043660 .4287E 01 .4289E 01 .2713E-02 647.4268 648.8113 .4301E 01 0.0037427 .4304E 01 647.3735 648.7590 -2796E-02 0.0031185 .4314E 01 -4317E 01 647-3320 648.7188 LZ880E-02 0-0024948 .4327E 01 .4331E 01 647-2998 648.6907 -2963E-02 0+0018711 .4340E 01 .4343E 01 647.2776 648.6719 \$3046E-02 648.6606 0.0012474 -4353E-01 4356E 01 647.2644 -3130E-02 0.0006737 .4365E 01 .4368E 01 647-2585 648.6563 .3212E-02 .4377E 01 0.0000000 .4380E 01 647.2585 648.6550 .3212E-02

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	1142 79	UNU RUUKS	-		
:	*** *******	*******	*******	1	·
E PAST LE E PRESENT	NGTH SEGMENT LENGTH SEGMI	15 8.50000 ENT (S 9.000	FEET Oo feet		, ,
******	***		* *** * * * * * *		
HE PHYSIC	AL PROPERTIES	5 ARE BASED ON	THE BULK TEMP	ERATURE OF	
NE PASI L	ENGIN SEGMEN	1 MHECH 12 012	• 9 F		
HE DENSITY	15 37.064	LB#7FT3			
HE VISCOSI He thermal	TY IS 0.9690 CONDUCTIVITY	52E-04 LOM/FT- 1 IS 0.17317E	S -04 BTU/S-FT-F		· _
TE HEAT CA	PACITY IS	1.798298TU7LBM	- ;	• ••••••••••••••••••••••••••••••••••••	
******	*** *** ** ***	*********	* ********		·····
HE REYNOLD	S NUMBER'IS	73740.13		-	
****	*********	*****	<i></i>		
HE AVERAGE	VELOCITY FOR	THE PRESENT	LENGTH IS 0.3 13614E 01	8582E 01 FT/	s
	WOEDATHOE FOI	THE DECENT	1 ENCTN TO	5 83014	
HE UNLA IL	APERAIURE FUI	AND PRESENT	0/	3.03711 DEGR	ELJ F
FE DUTSIDE	UX FOR THIS I	ENGTH SEGMENT	U-85962E-038E IS 0	GREES F 19247E 05.8	TU/HR FT2
*******	*******	****	**********	**********	**************
	Ue 1	00174		EDATHAE	CARY ATECHANISM
	PREVIOUS	PRESENT	PREVIOUS	PRESENT	PRESENT
FT	FT/S	FT/S	DEGREES F	DEGREES F	FT2#S
0-02500-00	-0000E 00	.0800E 00	838-3333	839.9998	-0000E 00 *** WALL
0 + 0 2 4 3 2 88	• 2707E 01	.2911E 01	823-4290 716-9509	825+3779. 719+9675	•2779E+07 •4801E-04
0237050	- 3016E 01	-3020E 01	701.2744	703.7136	-1408E-03
0.0224574	• 3333E 01	-3805E 01	687.7551	093+3977 689+8516	-2234E-03 -3030E-03
0%0218335 0%0218335	-3436E 01	-3440E 01	683.7356	685.7659	-3857E+03
0.0205859	- 3592E 01	-3523E UT	680 +5 930 678-0464	682.5784 679.9968	• 4 67 5 E=03
0.01 996 21	-3654E 01	-3658E 01	675.9312	677.8516	.6328E-03
	77000 04	-3713E 01	674.3445	676.0330	•7156E-03
0.0193383	• J709E UJ	.JYDEE UI	671-2813	673-1177	./964E-03
0.0193383 0.0187145 0.0180906	- 3758E 01	ASSUZE UT	670-1196	671.9304	•9642E-03
0.0193383 0.0187145 0.0180906 0.0174668	- 3758E 01 - 3803E 01 - 3844E 01	.3807E 01			101 70 07
0 • 0 19 33 83 0 • 0 18 71 45 0 • 0 18 09 06 0 • 0 17 46 68 0 • 0 16 84 30	.3709E 03 .3758E 01 .3803E 01 .3844E 01 .3881E 01	.3807E 01 .3847E 01 .3885E 01	669.0977	670.8835	• 104/ETU2
0.0193383 0.0187145 0.0180906 0.0174668 0.0168430 0.0168430 0.0162192 0.0155954	- 3709E 01 - 3758E 01 - 3803E 01 - 3844E 01 - 3881E 01 - 3916E 01 - 3948E 01	.3807E 01 .3847E 01 .3885E 01 .3919E 01 .3952E 01	669.0977 668.1943 667.3887	670.8835 669.9553 669.1318	1130E-02
0.0193383 0.0187145 0.0187145 0.0174668 0.0174668 0.0168430 0.0162192 0.0155954 0.0149715	- 3709E 03 - 3758E 01 - 3803E 01 - 3884E 01 - 3881E 01 - 3915E 01 - 3948E 01 - 3978E 01	.3807E 01 .3847E 01 .3885E 01 .3919E 01 .3952E 01 .3982E 01	669.0977 668.1943 667.3887 666.6707	670.8835 669.9553 669.1318 668.3962	-1047E=02 -1130E=02 -1213E=02 -1296E=02
0.0193383 0.0193387 0.0187145 0.0180906 0.0174668 0.0168430 0.0168430 0.0162192 0.0155954 0.0149715 0.0149715 0.0149775	- 3709E 03 - 3758E 01 - 3803E 01 - 3844E 01 - 3916E 01 - 3948E 01 - 3978E 01 - 4006E 01	.3807E 01 .3847E 01 .3885E 01 .3919E 01 .3952E 01 .3982E 01 .4010E 04	669.0977 688.1943 667.3887 666.6707 666.0293	670.8835 669.9553 669.1318 668.3962 667.7375	• 104 / E+02 • 1130 E=02 • 1213 E=02 • 1296 E+02 • 1379 E+02 • 1379 E+02
0 • 019 33 83 0 • 018 71 45 0 • 018 0906 0 • 017 46 68 0 • 016 84 30 0 • 016 84 30 0 • 016 21 92 0 • 015 59 54 0 • 014 97 15 0 • 014 37 75 0 • 013 72 39 0 • 013 10 01	- 3709E 03 - 3758E 01 - 3803E 01 - 3844E 01 - 3916E 01 - 3948E 01 - 3978E 01 - 4006E 01 - 4003E 01	.3807E 01 .3847E 01 .3885E 01 .3919E 01 .3952E 01 .3982E 01 .4010E 04 .4037E 01 .4062E 01	669.0977 668.1943 667.3887 666.6707 666.0293 665.4529 664.9353	670.8835 669.9553 669.1318 668.3962 667.7375 667.1489 666.6218	• 1047E=02 • 1130E=02 • 1213E=02 • 1296E=02 • 1379E≑02 • 1462E=02 • 1565E=02
J.0193383 J.0193387 J.0187145 J.0180906 J.0174668 J.0162192 J.0155954 J.0155954 J.0155954 J.0155954 J.0155755 J.0149715 J.0149715 J.0137239 J.0137239	- 3709E 03 - 3758E 01 - 3803E 01 - 3844E 01 - 3916E 01 - 3948E 01 - 3978E 01 - 4006E 01 - 4003E 01 - 4059E 01	- 3807E 01 - 3847E 01 - 3845E 01 - 3919E 01 - 3952E 01 - 4010E 01 - 40037E 01 - 4003E 01 - 4005E 01	669.0977 668.1943 667.3887 666.6707 666.0293 665.4529 665.4529 664.9353 664.675	670.8835 669.9553 669.1318 668.3962 667.7375 667.7375 667.4489 666.6218 666.1519	• 104 / E+02 • 1130 E=02 • 1213 E=02 • 1296 E=02 • 1379 E≑02 • 1462 E=02 • 1565 E=02 • 1628 E=02
J.0193383 J.0193387 J.0180906 J.0174668 J.0168430 J.0155954 J.0155954 J.0155954 J.0149715 J.0149715 J.014975 J.0137239 J.0137239 J.0137239 J.0137239 J.0137239	- 3709E 03 - 3758E 01 - 3803E 01 - 3844E 01 - 3948E 01 - 3948E 01 - 3978E 01 - 4006E 01 - 4059E 01 - 4083E 01 - 4105E 01 - 4105E 01	- 3807E 01 - 3847E 01 - 3845E 01 - 3919E 01 - 3952E 01 - 4010E 01 - 40037E 01 - 40037E 01 - 4005E 01 - 4109E 01 - 4109E 01	669.0977 668.1943 667.3887 666.6707 666.0293 665.4529 665.4529 664.9353 664.4675 664.0408	670.8835 669.9553 669.1318 668.3962 667.7375 667.7489 666.6218 666.1519 666.1519 665.7383	• 104 / E+02 • 1130 E=02 • 1213 E=02 • 1296 E=02 • 1379 E≠02 • 1462 E=02 • 1545 E=02 • 1628 E=02 • 1731 E+02 • 1731 E+02
$\begin{array}{c} 0.0193385\\ 0.0193387\\ 0.0187145\\ 0.0174668\\ 0.0168430\\ 0.0168430\\ 0.0168430\\ 0.0155954\\ 0.0155954\\ 0.0149715\\ 0.0149715\\ 0.0149715\\ 0.0137239\\ 0.01$	- 3709E 03 - 3758E 01 - 3803E 01 - 3844E 01 - 3948E 01 - 3948E 01 - 3978E 01 - 4005E 01 - 4059E 01 - 4083E 01 - 4105E 01 - 4127E 01 - 4148E 01	.3807E 01 .3847E 01 .3847E 01 .3919E 01 .3952E 01 .4010E 01 .4010E 01 .4057E 01 .4057E 01 .4056E 01 .4109E 07 .4109E 01 .4152E 01	669.0977 688.1943 667.3887 666.6707 666.0293 665.4529 664.9353 664.4675 664.0408 663.6570 663.3105	670.8835 669.9553 669.9553 669.1318 668.3962 667.7375 667.7489 666.6218 666.5218 666.1519 665.7383 665.3704	• 104 / E+02 • 1130 E=02 • 1213 E=02 • 1296 E=02 • 1379 E≠02 • 1462 E=02 • 1545 E=02 • 1628 E=02 • 1731 E+02 • 1795 E=02 • 1877 E=02
0.0193383 0.0193383 0.01974668 0.0174668 0.0162430 0.0155954 0.0149715 0.0149715 0.0137239 0.0131001 0.01374363 0.0118525 0.0118525 0.0118525 0.0118525	- 3709E 03 - 3758E 01 - 3803E 01 - 3844E 01 - 3948E 01 - 3948E 01 - 3978E 01 - 4006E 01 - 4059E 01 - 4083E 01 - 4105E 01 - 4148E 01 - 4168E 01	.3807E 01 .3847E 01 .3847E 01 .3919E 01 .3952E 01 .4010E 01 .4037E 01 .4037E 01 .4037E 01 .4037E 01 .4038E 01 .4131E 01 .4352E 01 .4372E 01	669.0977 688.1943 667.3887 666.6707 666.0293 665.4529 664.9353 664.475 664.0408 663.6570 863.3105 662.9971	670.8835 669.9553 669.9553 669.1318 668.3962 667.7375 667.7489 666.6218 666.1519 665.7383 665.7383 665.3704 665.0464	• 104 / E=02 • 1213E=02 • 1296 E=02 • 1379 E=02 • 1462 E=02 • 1545 E=02 • 1628 E=02 • 1731 E=02 • 1795 E=02 • 1877 E=02 • 1961 E=02
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0.0193383 0.0193383 0.0187145 0.0188906 0.0162192 0.0155954 0.0155954 0.0155954 0.0155954 0.0149715 0.0149715 0.0149715 0.0149715 0.0149739 0.0137239 0.0137239 0.0137239 0.011286 0.0174857 0.0093572 0.0093572 0.0093572 0.0093572 0.0093572 0.0093572 0.0093572 0.0093572 0.0093572 0.0093572 0.0093572 0.0093572 0.0095572 0.00955734 0.00955734 0.0055314757 0.005557 0.005557 0.005557 0.005557 0.005557 0.005557 0.005557 0.005557 0.0055757 0.0055757 0.0055757 0.0055757 0.005575757 0.005575757 0.005575757 0.005575757 0.0055757575757 0.00557575757575757575757575757575757575	- 3709E 03 - 3758E 01 - 3803E 01 - 3844E 01 - 3948E 01 - 3948E 01 - 3948E 01 - 3978E 01 - 4006E 01 - 40059E 01 - 4059E 01 - 4105E 01 - 4127E 01 - 4168E 01 - 4168E 01 - 4187E 01 - 4223E 01 - 4223E 01 - 4257E 01 - 423E 01 - 4205E 01 - 4205E 01 - 423E 01	- 3807E 01 - 3847E 01 - 3847E 01 - 3982E 01 - 3982E 01 - 4010E 01 - 4010E 01 - 4037E 01 - 4037E 01 - 4036E 01 - 4139E 01 - 4191E 01 - 4191E 01 - 4297E 01 - 4227E 01 - 4227E 01 - 4227E 01 - 4292E 01 - 4292E 01 - 4207E 01 - 4207	669.0977 688.1943 667.3887 666.6707 666.0293 665.4529 664.9353 664.4675 664.4675 664.4675 664.4675 664.4675 663.6570 663.6570 662.7266 662.7266 662.5164 662.3247 662.1528 662.1528 661.7517 661.6533	670.8835 669.9553 669.9553 669.9553 667.7375 667.7375 667.7489 666.6218 666.1519 665.7383 665.3704 665.3704 665.3704 664.5056 664.5056 664.2493 664.30305 663.8438 663.6846 663.5498 663.4377 663.4452	• 104 / E+02 • 1130E=02 • 1296E+02 • 1296E+02 • 1462E=02 • 1462E=02 • 1565E=02 • 1628E=02 • 1795E=02 • 1795E=02 • 1795E=02 • 1877E=02 • 2044E=02 • 2126E=02 • 2293E=02 • 2293E=02 • 2542E=02 • 265E=02

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THE ENTIRE LENGTH FOR TIME 0.0 HOURS HAS BEEN COMPLETED

THE AVERAGE FILM TEMPERATURE FOR THE LENGTH IS 809.30 DEGREES F. THE COKE THICKNESS BASED ON THUS TEMPERATURE AT TIME 191.0 IS 0.87890E-03 FT1

THE PRESENT	TIME IS	191NO HOURS		•	
					· ·
	• • # # # # # # # # # # # # # # # # # #	•=====================================	* *******		
THE PAST LEN	IGTH SEGMENT	15 0.00000	FEET		
INC PRESENT	LENGIN SEGNI	IN T 15 0-500	UU FEET		
********	*****	*****	********		
THE PHYSICA	T PROPERTIES	ARE BASED ON	THE-BULK TENP	ERATURE OF	
	JEBAEN	- #REEN 15 04U.	*U P		,
THE DENSITY	IS 37.719 IV IS 0.115	/ LBM/FT3 10F-D3 (BM/FT-	<i>د</i>		
THE THER MAL	CONDUCTIVITY	15 0.17528E	-04-870/S=FT=F		
THE HEAT CAP	ACITY IS (.774508TU/LBM	- F		
***	*****	**********	*****		— — — — — — — — — — — — — — — — — — —
THE REYNOLDS	S NUMBER IS	59935.89			- ·
THE AVERAGE	VELOCITY FOI	THE PRESENT	********* LENGTH IS N-3	79128 01 57 4	
HE VELOCITI	CORRECTION	FACTOR IS 0.	138672-01	THE VITIT	
THE BULK DEP	PERATURE FOI	THE PRESENT	LENGTH IS 64	4-36743 DEGRI	EES F
HE OUTS IDE	TUBE WALL TE	INPERATURE IS	0.10783E 040E	GREES F	
THE HEAT FLL	IX FOR THIS L	ENGTH SEGMENT	15 0	.41810E 05 B1	U/HR ET2
******	*****	************	* ********	***********	*****
RADIUS	VFI	00119	TCED	FRATINE -	
	PREVIOUS	PRESENT	PREVIOUS	PRESENT	PRESENT
FT	FT/S	FT/S	DEGREES F	DEGREES E	FTZVS
0-024 12 11	.0000E 00	-0000-00	810.0000	811-4445	-00005 00 +++ 4444
0.02406.53	.3417E 00	.3417E 00	640.0000	774.6858	-3868E+07
0.0234636	-2628E 01	-2628E 01	640.0000	665.1677	-4179E=04
0.0222604	. 2733E UT	.2735 E UT	640.000Q 640.0000	020.0923 651.8730	+1382E-03
0.0216587	-3271E OT			- 649-2400	-2959E#03
0.02105.71	.3375E 01	+3375E 01	640-0000	647.4150	.3758E-03
0.0204555	.3460E 01	-3167E 01	640.0000	646-0691	.4559E-03
0.01925/22	.3594E 01	.3594E 01	640.0000	644.2158	-6166E-03
0.0186566	.3649E 01	.3649E 01	640.0000	643.5535	.6971E-03
0.01804.89	- 3699E 01	-3899E 01	640.0000	643.03.68	.7777E=03
0.01744:73	+ 3744E UT	-3744£ UT .3785£ 01	640+0000 640-0000	642.5493 647 1676	•8582E=03
0.0162440	- 3822E 01	-3822E 01	640-0000	641.8320	.1020E-02
0-0156424	-3857E 01	-3857E 07	640-0000	641.5474	.1100E-02
0.0150408	• 3890E D1	-3890E 01	640.0000	641.3000	-1181E-02
0.0138375	- 3949E 01 -	-3949E 01	640.0000	041.0835 ····· 640.8933 ·····	-12021-UZ
	. 3975E 01	.3975E 01	640.0000	640.7256	.1423E-02
0.01323.59	.400.1E 01	-4001 E 01	640.0000	640.5767	-1504E-02
0.0132359		18756 64	640.0000	640.4453	-1584E-02
0.0132359 0.0126342 0.0120326	-4025E 01	+4023E UT	((0,0000	4/0	
0.0132359 0.0126342 0.0120326 0.0114310	-4025E 01 -4048E 01	-4025E 01	640.0000	640.3296	.1665E+UZ
0.0132359 0.0126342 0.0120326 0.0114310 0.0108293 0.0102277	-4025E 01 -4048E 01 -4073E 01 -4091E 01	.4025E 01 .4048E 01 .4070E 01 .4091E 01	640-0000 640-0000 640-0000	640.3296 640.2285 640.1409	• 1665 E≠02 •1746 E=02 •1827 E=02
0.0132359 0.0126342 0.0120326 0.0114310 0.0108293 0.0102277 0.0096261	- 4025E 01 - 4048E 01 - 4073E 01 - 409/1E 01 - 4113E 01	.4025£ 01 .4048E 01 .4070£ 01 .4091E 01 .4111E 01	640.0000 640.0000 640.0000 640.0000	640.3296 640.2285 640.1409 640.0642	• 166>E+02 • 1746E=02 • 1827E=02 • 1908E+02
0.0132359 0.0126342 0.0120326 0.0114310 0.0108293 0.01082977 0.0096261 0.0090244	-4025E 01 -4048E 01 -4073E 01 -4097E 01 -4113E 01 -4130E 01 -4130E 01	.4025£ 01 .4048£ 01 .4070£ 01 .4091£ 01 .4111E 01 .4130£ 01	640.0000 640.0000 640.0000 640.0000 640.0000	640.3296 640.2285 640.1409 640.0642 640.0000	• 1665 E≠02 • 1746 E=02 • 1827 E=02 • 1908 E≠02 • 1989 E≠02 • 1989 E≠02
$\begin{array}{c} 0.013 23 59 \\ 0.01263 42 \\ 0.01203 26 \\ 0.01143 10 \\ 0.010 82 93 \\ 0.010 82 93 \\ 0.010 82 61 \\ 0.00962 61 \\ 0.00902 44 \\ 0.008 42 28 \\ 0.007 82.12 \end{array}$	-4025E 01 -4048E 01 -4075E 01 -4077E 01 -4113E 01 -4130E 01 -4149E 01 -4167E 01	.4023£ 01 .4048E 01 .4070£ 01 .4091E 01 .4111E 01 .4130£ 01 .4149E 01 .4167E 01	640.0000 640.0000 640.0000 640.0000 640.0000 640.0000 640.0000	640.3296 640.2285 640.1409 640.0642 640.0000 640.0000 640.0000	.1665 E+02 .1746 E=02 .1827 E=02 .1908 E=02 .2069 E=02 .2069 E=02 .2150 E=02
$\begin{array}{c} 0.013 23 59 \\ 0.01263 42 \\ 0.01203 26 \\ 0.01143 10 \\ 0.010 82 93 \\ 0.010 82 93 \\ 0.010 82 61 \\ 0.00962 61 \\ 0.00902 44 \\ 0.008 42 28 \\ 0.007 82.12 \\ 0.007 721 95 \\ \end{array}$	-4025E 01 -4048E 01 -4077E 01 -4077E 01 -4117E 01 -4130E 01 -4149E 01 -4167E 01 -4184E 01	.4023£ 01 .4048E 01 .4070£ 01 .4091E 01 .4111E 01 .4130£ 01 .4149E 01 .4167£ 01 .4184E 01	640.0000 640.0000 640.0000 640.0000 640.0000 640.0000 640.0000 640.0000 640.0000	640.3296 640.2285 640.1409 640.0642 640.0000 640.0000 640.0000	.1665E+02 .1746E=02 .1827E-02 .1908E+02 .1989E+02 .2069E-02 .2150E+02 .2150E+02 .2231E=02
$\begin{array}{c} 0.013 23 59 \\ 0.01263 42 \\ 0.01203 26 \\ 0.01143 10 \\ 0.010 82 93 \\ 0.010 82 93 \\ 0.010 82 93 \\ 0.010 82 61 \\ 0.00962 61 \\ 0.00902 44 \\ 0.008 42 28 \\ 0.007 82 12 \\ 0.0007 82 12 \\ 0.0006 61 79 \\ 0.00661 79 \\ \end{array}$	-4025E 01 -4048E 01 -4079E 01 -4079E 01 -4113E 01 -4130E 01 -4149E 01 -4167E 01 -4184E 01 -4201E 01	.4025£ 01 .4048E 01 .4070£ 01 .4091E 01 .4111E 01 .4130£ 01 .4149E 01 .4167£ 01 .4184£ 01 .4201£ 01	640.0000 640.0000 640.0000 640.0000 640.0000 640.0000 640.0000 640.0000 640.0000 640.0000	640.3296 640.2285 640.1409 640.0642 640.0000 640.0000 640.0000 640.0000 640.0000	.1665 E+02 .1746 E=02 .1827 E=02 .1908 E=02 .2069 E=02 .2150 E=02 .231 E=02 .231 E=02
$\begin{array}{c} 0.013 23 59 \\ 0.01263 42 \\ 0.01203 26 \\ 0.01143 10 \\ 0.010 82 93 \\ 0.010 82 93 \\ 0.010 82 93 \\ 0.010 82 93 \\ 0.00962 61 \\ 0.00902 44 \\ 0.008 42 28 \\ 0.007 82 12 \\ 0.0007 82 12 \\ 0.0007 82 17 \\ 0.00661 79 \\ 0.00661 63 \\ 0.004 4 56 \\ 0.005 4 \\ 0.005$	- 4025E 01 - 4048E 01 - 4073E 01 - 4073E 01 - 4113E 01 - 4130E 01 - 4149E 01 - 4167E 01 - 4167E 01 - 4201E 01 - 4217E 01	.4023£ 01 .4048E 01 .4070£ 01 .4091E 01 .4130£ 01 .4130£ 01 .4167£ 01 .4184£ 01 .4201£ 01 .4201£ 01	$\begin{array}{c} 640.0000\\ 640.000\\ 640.00$	640.3296 640.2285 640.1409 640.00642 640.0000 640.0000 640.0000 640.0000 640.0000 640.0000 640.0000	.1665 E+02 .1746 E=02 .1827 E=02 .1908 E=02 .2069 E=02 .2150 E=02 .2231 E=02 .231 E=02 .239 E=02
$\begin{array}{c} 0.0.13 23 59 \\ 0.01263 42 \\ 0.01203 26 \\ 0.01143 10 \\ 0.010 82 93 \\ 0.010 82 93 \\ 0.010 82 93 \\ 0.00962 61 \\ 0.00962 61 \\ 0.009 02 44 \\ 0.008 42 28 \\ 0.007 82 12 \\ 0.0007 82 12 \\ 0.000 61 79 \\ 0.006 61 79 \\ 0.005 41 46 \\ 0.005 41 46 \\ 0.005 41 30 \\ \end{array}$	- 4025E 01 - 4048E 01 - 4077E 01 - 4077E 01 - 4117E 01 - 4130E 01 - 4149E 01 - 4167E 01 - 4167E 01 - 4201E 01 - 4217E 01 - 4232E 01 - 4232F 01	.4023£ 01 .4048E 01 .4070£ 01 .4091E 01 .4130E 01 .4130E 01 .4167E 01 .4167E 01 .4201£ 01 .4201£ 01 .4232E 01 .4267E 01	$\begin{array}{c} 640.0000\\ 640.0000\\ 640.0000\\ 640.0000\\ 640.0000\\ 640.0000\\ 640.0000\\ 640.0000\\ 640.0000\\ 640.0000\\ 640.0000\\ 640.0000\\ 640.0000\\ 640.0000\\ \end{array}$	640.3296 640.2285 640.1409 640.00642 640.0000 640.0000 640.0000 640.0000 640.0000 640.0000 640.0000 640.0000 640.0000	.1665 E+02 .1746 E=02 .1827 E=02 .1908 E=02 .2069 E=02 .2150 E=02 .231 E=02 .231 E=02 .239 Z E=02 .255 E=02 .255 E=02
$\begin{array}{c} 0.013 23 59 \\ 0.01263 42 \\ 0.01203 26 \\ 0.013 43 10 \\ 0.010 82 93 \\ 0.010 82 93 \\ 0.010 82 93 \\ 0.00962 61 \\ 0.00962 44 \\ 0.008 42 28 \\ 0.007 82.12 \\ 0.0005 41 82 \\ 0.007 82.12 \\ 0.006 61 79 \\ 0.006 61 63 \\ 0.005 41 46 \\ 0.004 81 30 \\ 0.004 21 13 \\ \end{array}$	- 4025E 01 - 4048E 01 - 4073E 01 - 4073E 01 - 4113E 01 - 4130E 01 - 4149E 01 - 4167E 01 - 4167E 01 - 4201E 01 - 4217E 01 - 4232E 01 - 4247E 01 - 4262E 01	.4023£ 01 .4048E 01 .4070£ 01 .4091E 01 .4130E 01 .4130E 01 .4167E 01 .4167E 01 .4201£ 01 .4221E 01 .4232E 01 .4267E 01 .4267E 01	$\begin{array}{c} 640.0000\\ 640.000\\ 640.000\\ 640.000\\ 640.000\\ 640.0000\\ 640.0000\\ 640.0000\\ 640$	640.3296 640.2285 640.1409 640.0062 640.0000 640.0000 640.0000 640.0000 640.0000 640.0000 640.0000 640.0000 640.0000 640.0000	- 1665 E+02 - 1746 E=02 - 1827 E=02 - 1908 E=02 - 2069 E=02 - 2150 E=02 - 231 E=02 - 231 E=02 - 239 2 E=02 - 2473 E=02 - 2554 E=02 - 2554 E=02 - 265 E+02
$\begin{array}{c} 0 & 0.13 & 23 & 59 \\ 0 & 0.12 & 63 & 42 \\ 0 & 0.12 & 03 & 26 \\ 0 & 0.11 & 43 & 10 \\ 0 & 0 & 10 & 82 & 93 \\ 0 & 0 & 10 & 82 & 93 \\ 0 & 0 & 0 & 902 & 44 \\ 0 & 0 & 09 & 02 & 44 \\ 0 & 0 & 09 & 02 & 44 \\ 0 & 0 & 09 & 02 & 44 \\ 0 & 0 & 09 & 02 & 44 \\ 0 & 0 & 00 & 902 & 44 \\ 0 & 0 & 00 & 902 & 44 \\ 0 & 0 & 00 & 902 & 44 \\ 0 & 0 & 00 & 61 & 63 \\ 0 & 0 & 0 & 61 & 63 \\ 0 & 0 & 0 & 41 & 30 \\ 0 & 0 & 0 & 42 & 11 \\ 0 & 0 & 0 & 360 & 97 \\ \end{array}$	- 4025E 01 - 4048E 01 - 4073E 01 - 4073E 01 - 4130E 01 - 4130E 01 - 4149E 01 - 4167E 01 - 4201E 01 - 4217E 01 - 4217E 01 - 4227E 01 - 4262E 01 - 4276E 01	.4023£ 01 .4048E 01 .4070£ 01 .4091E 01 .4130£ 01 .4130£ 01 .4167£ 01 .4167£ 01 .4201£ 01 .4201£ 01 .4232£ 01 .4267£ 01 .4267£ 01 .4267£ 01	$\begin{array}{c} 640.0000\\ 640.000\\$	640.3296 640.2285 640.1409 640.0062 640.0000 640.0000 640.0000 640.0000 640.0000 640.0000 640.0000 640.0000 640.0000 640.0000	- 1665 E+02 - 1766 E=02 - 1827 E=02 - 1908 E=02 - 2069 E=02 - 2150 E=02 - 231 E=02 - 231 E=02 - 239 2 E=02 - 2473 E=02 - 2554 E=02 - 265 E+02 - 2715 E=02
$\begin{array}{c} 0.0132359\\ 0.0126342\\ 0.0126342\\ 0.0120326\\ 0.01120326\\ 0.0112277\\ 0.0096261\\ 0.0096261\\ 0.0096244\\ 0.0084228\\ 0.0078212\\ 0.0078212\\ 0.0078212\\ 0.0078145\\ 0.0066179\\ 0.0030081\\ 0.0030081\\ 0.003081\\ 0.003081\\ 0.003081\\ 0.003081\\ 0.003081\\ 0.003081\\ 0.003081\\$	- 4025E 01 - 4048E 01 - 4073E 01 - 4073E 01 - 4130E 01 - 4130E 01 - 4149E 01 - 4167E 01 - 4167E 01 - 4201E 01 - 4217E 01 - 4227E 01 - 4262E 01 - 4289E 01 - 4289E 01	.4023£ 01 .40248 01 .4070£ 01 .4091E 01 .4130£ 01 .4130£ 01 .4167£ 01 .4167£ 01 .4232£ 01 .4232£ 01 .4247£ 01 .4247£ 01 .4262£ 01 .4289£ 01 .4289£ 01	$\begin{array}{c} 640.0000\\ 640.000\\ 640.000\\ 640.0000\\ 640.000\\ 6$	640.3296 640.2285 640.1409 640.0642 640.0000 640.0000 640.0000 640.0000 640.0000 640.0000 640.0000 640.0000 640.0000 640.0000 640.0000 640.0000	- 1665 E+02 - 1766 E=02 - 1827 E=02 - 1988 E=02 - 2069 E=02 - 2150 E=02 - 231 E=02 - 231 E=02 - 231 E=02 - 239 2 E=02 - 2473 E=02 - 2554 E=02 - 2554 E=02 - 2554 E=02 - 2715 E=02 - 2797 E=02 - 2797 E=02
$\begin{array}{c} 0.0132359\\ 0.0126342\\ 0.0126342\\ 0.0120326\\ 0.01120326\\ 0.01120377\\ 0.0096261\\ 0.0096261\\ 0.0096244\\ 0.0084228\\ 0.0078212\\ 0.0078212\\ 0.0078212\\ 0.0078195\\ 0.0066179\\ 0.007208\\ 0.001600\\ 0.001600\\ 0.001600\\ 0.00160\\ 0.000\\ 0.00$	- 4025E 01 - 4048E 01 - 4073E 01 - 4073E 01 - 4130E 01 - 4130E 01 - 4149E 01 - 4167E 01 - 4167E 01 - 4201E 01 - 4217E 01 - 4227E 01 - 4262E 01 - 4267E 01 - 4289E 01 - 4303E 01 - 4102E 01 - 4102E 01 - 4289E 01 - 4289E 01 - 4303E 01 - 4102E 01 - 4202E 01 - 4202	.4025£ 01 .4025£ 01 .4070£ 01 .4091£ 01 .4130£ 01 .4130£ 01 .4167£ 01 .4167£ 01 .4201£ 01 .4201£ 01 .4227£ 01 .4227£ 01 .4262£ 01 .4262£ 01 .4289£ 01 .4289£ 01 .4303£ 01	$\begin{array}{c} 640.0000\\ 640.000\\ 640.0000\\ 640.000\\ 64$	640.3296 640.2285 640.1409 640.0642 640.0000 640.0000 640.0000 640.0000 640.0000 640.0000 640.0000 640.0000 640.0000 640.0000 640.0000 640.0000 640.0000	- 1665 E+02 - 1766 E=02 - 1827 E=02 - 1908 E=02 - 2069 E=02 - 2150 E=02 - 231 E=02 - 231 E=02 - 231 E=02 - 237 E=02 - 2473 E=02 - 265 E=02 - 265 E=02 - 2715 E=02 - 2797 E=02 - 2877 E=02 - 2877 E=02 - 297 E=02
$\begin{array}{c} 0.013 23 59\\ 0.01263 42\\ 0.01203 26\\ 0.011 43 10\\ 0.010 82 93\\ 0.010 22;77\\ 0.00962 61\\ 0.00902 44\\ 0.008 42 28\\ 0.007 82.12\\ 0.007 21 95\\ 0.006 61 79\\ 0.006 61 79\\ 0.006 61 79\\ 0.005 41 46\\ 0.005 41 46\\ 0.005 41 46\\ 0.004 81 30\\ 0.005 41 46\\ 0.003 60 97\\ 0.003 60 97\\ 0.003 00 81\\ 0.002 40 65\\ 0.001 80 48\\ 0.001 20 32\\ \end{array}$	- 4025E 01 - 4048E 01 - 4073E 01 - 4073E 01 - 4113E 01 - 4130E 01 - 4149E 01 - 4167E 01 - 4167E 01 - 4201E 01 - 4217E 01 - 4227E 01 - 4262E 01 - 4267E 01 - 4289E 03 - 4303E 01 - 4316E 01 - 4328E 01	-4025£ 01 -4025£ 01 -4070£ 01 -4091£ 01 -4130£ 01 -4149£ 01 -4167£ 01 -4167£ 01 -4201£ 01 -4201£ 01 -4227£ 01 -4227£ 01 -4262£ 01 -4262£ 01 -4289£ 01 -4303£ 01 -4316£ 01 -4328£ 01	$\begin{array}{c} 640.0000\\ 640.000\\ 640.000\\ 640.000\\ 640.000\\ 640.0000\\ 640.0000\\ 640.0000\\ 640$	640.3296 640.2285 640.1409 640.0642 640.0000 640.0000 640.0000 640.0000 640.0000 640.0000 640.0000 640.0000 640.0000 640.0000 640.0000 640.0000 640.0000 640.0000 640.0000	- 1665 E+02 - 1766 E=02 - 1827 E=02 - 1908 E=02 - 2069 E=02 - 2150 E=02 - 231 E=02 - 231 E=02 - 231 E=02 - 237 E=02 - 2473 E=02 - 265 E ±02 - 2715 E=02 - 2715 E=02 - 2797 E=02 - 2877 E=02 - 2957 E=02 - 2957 E=02 - 2957 E=02 - 2957 E=02

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THE PRESENT TIME IS 19160 HOURS

THE AVERAGE VELOCITY EOR THE PRESENT LENGTH IS 0.379,12E 01 FT/S THE VELOCITY CORRECTION FACTOR IS 0.13867E 01

THE BULK TEMPERATURE FOR THE PRESENT LENGTH IS 648.60253 DEGREES F

THE OUTSIDE TUBE WALL TEMPERATURE IS 0.10718E 04DEGREES F THE HEAT FLUX FOR THIS LENGTH SEGMENT IS D.40543E 05 BTU/HR FT2 +

RADIUS	VELOCITY		TENPERATURE		EDDY DIEFUSIVITY	
	PREVIOUS	PRESENT	PREVIOUS	PRESENT	PRESENT	
FT	FT/S	FTYS	DEGREES F	DEGREES F.	FT2/S	
0.0241211	.0000E 00	.0001 E 00	811.6665	813.3333	-0000E 00 WALL	
0.0240653	.3417E 00	13717E 00	774-6858	777.4731	-3868E-07	
0.0234636	.2628E D1	-2528E 01	665-1677	676-6687	-41795-04	
0.0228620	- 2953E 01	.2953E 01	656-0923	666. 5217	-1 38 2 8-03	
0.0222604	.3138E 01	.3338E 01	651.8730	661.2532	2165E-03	
0.02165:87	.3271E 01	.3271 E 01	649.2430	657.6609	2959E-03	
0.0210571	. 3375E 0.1	.3875E 01	647.4150	654.9839	-3758E-03	
0.0204555	.3460E 01	.3460E 01	646.0691	652.8845	.4559E+03	
0.0198538	.3532E 01	.3532£ 01	645.0347	651.1831	.5362E-03	
0.0192522	.3594E 01	.3594E 01	644.2158	649.7722	-6166E-03	
0.01865 (6	.3649E 01	.3549E 01	643.5535	648.5828	-6971E-03	
0 .01804 89	.3699E 01	.3899E.01	643.0068	647.5679	.7777E-03	
0.0174473	-3744E 01	-3744E 01	642.5493	646.6929	-8582E-03	
0.0168457	.3785E D1	.3785E 01	642-1624	645.9326	• 9 390 E-0 3	
0.0162440	.3822E 01	.3822E 01	641.8320	645.2681	-1020E-02	
0.0156424	. 3857E 01	.3857E 01	641.5474	666.6851	-1100E-02	
0.01504 68	.3890E 01	.3890E 01	641.30 03	644.17.11	-1 18 TE-02	
0.0144394	.3920E 01	.3920E 01	641.0833	643.7173	-1262E-02	
0.0138375	. 3949E 01	.3949E 01	640.8933	643-3152	1342E=02	
0.0132359	.3975E 01	.3975E 01	640.7256	642.9587	-1423E+02	
0-0126342	.4001E 01	.400TE 01	640.5767	642.6433	-1504E-02	
0.01203 26	4025E DT	-4025E 01	640.4453	642.3638	1584E+02	
0.01143.10	+4048E 01	.4048E 01	640.3296	642-3160	-1665E-02	
0.0108293	.4070E 01	.4070E 01	640.2285	641.8970	.1746E-02	
0.01022 77	-4094E 01	- 4091E 01	640-1409	641.7039	-1827E-02	
0.009626	.4114E 01	-4311E 01	640.0642	641-5342 -	.1908E-02	
0.0090244	.4130E D1	.4130E 01	640.0000	641.3833	.1989E-02	
0.00842.28	.4149E 01	.4149£ 01	640.0000	641.1965	-2069E-02	
0.0078212	.4167E 01	.4167E 01	640.0000	641.0349	.2150E-02	
0.0072195	.4184E 01	.4184E 01	640.0000	640.8958	.2231E-02	
0.0066179	.4201E 01	.4201E 01	640.0000	640.7771	.2311E-02	
0.006.0163	-4217E 01	.4217E 01	640.0000	640.6765	.2392E-02	
0.0054146	.4232E 01	.4232E 01	640.0000	640.5920	+2473E=02	
0.0048130	+4247E 01	.4247E 01	640.0000	640.5222	.2554E-02	
0.0042113	.4262E D1	.4262E 01	640.0000	640.4651	• 2 6 3 5 E - 0 2	
0.0036097	.4276E 01	.4276E 01	640.0000	. 640.4199	-2715E-02	
0.003008	.4289E DT	-4289E 01	640.0000	640.3853	-2797E-02	
U +UUZ 40 65	43U3E 01	.4803E U1	640.0000	640.3604	.2877E+02	
U-UUT8048	.4316E 01	-4316E 01	640.0000	640.3438	-2957E-02	
0.0012032	-4328E 01	-4328E 01	640.0000	640.3345	.3039E-02	
0.0006016	-434JE 01	-4341 E 01	640.0000	640.3311	.3119E-02	
0.0000000	-4353E 01	.4353E 01	640.0000	640.3308	•311.9E-02	
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THE PRESENT						
	TINE IS	191-0-HOURS				
****	*****	*****	*******			
THE PAST LE	NGTH SEGMENT	15 4-00000	FFET		· · · · · · · · · · · · · · · · · · ·	
THE PRESENT	LENGTH SEGNE	NT 45 4.500	DO FEET			
********	*******	**********	*******			
THE PHYISIC	AL PROPERTIES	ARE BASED ON	THE BULK TENA	ERATURE OF		
THE PAST L	ENGTH SEGMENT	WHECH IS 656	•8 F	· · · · · ·		
THE DENS ITY	15 37.410	EBWAFT3				
THE VISCOSI	1.T 15 0.1000 CONDUCTIVITY	UE-US LBM/FT- ' TS 0.174286	-04 811/5-57-5			
THE HEAT CA	PACITY IS 0	783428TU/L88	#F			
*****	**********	**********	*******			
THE REYNOLD	S NUMBER IS	65081.18				
****	**********	***	********			
THE AVERAGE	VELOGITY FOR	TAE PRESENT	LENGTH IS 0.3	8225E 01 FT/	'S	
THE VELOCIT	T CORRECTION	FACIOR IS U.	1 3724E 01		····	
THE BULK TE	MPERATURE FOR	THE PRESENT	LENGTH IS 65	8.24023 DEGR	EES F	
					•	
THE NEAT FL	UNE WALL TE	HPERATURE IS ENGIN SEGMENT	15 030E	GREES F	TU/HR ET?	
			•			
*****	******	**********	*********	**********	******	****
RAD 1US	VEL	00114	TEMP	ERATURE	EDDY DIFFUSIV	177
	PREVIOUS	PRESENT	PREVIOUS	PRESENT	PRESENT	
* 1	F175	FT#S	DEGREES F	DEGREES F	FT2/S	
0.024 12 11-	.0000E 00	-0000E 00	823.3333		-0000E 00	VALL
0.02406.97	.344ZE 00	.3744E 00	810.9133	813.1841	.3346E-07	
U.U.2.340.79	. 2672E 01	-2674E 01	690.5640	691.6123	.4231E-04	
0.0222644	.3165E 01	.3168E 01	671 - 6 268	673.2405	+1373ETU3 -2155E403	
0.0216627	.3298E 01	.3301E 01	667.1924	669.0298	-2946E-03	
0.0210610	-340ZE-01	-3404E-01	664.1282		-3743E=03	
	7/070 04					
0.0204592	-3487E 01	-3561 F 01	661.7751	641.7432	53475-03	
0.0198575	.3487E 01 .3558E 01 .3621E 01	.3561 E 01	661 •7751 659•9019 658•2563	661.2632	-5343E-03	
0.0198575 0.0192557 0.0186540	.3487E 01 .3558E 01 .3621E 01 .3676E 01	-3561 E 01 -3624E 01 -3679E 01	661 •7 751 659•9019 658•2563 656•7954	661.2632 659.6252 658.3059	.5343E-03 .6146E-03 .6949E-03	
0.0198575 0.0198575 0.0192557 0.0186540 0.0180523	.3487E 01 .3558E 01 .3621E 01 .3676E 01 .3725E 01	.3561 E 01 .3524E 01 .3679E 01 .372BE 01	661.7751 659.9019 658.2563 656.7954 655.5662	661.2632 659.6252 658.3059 657.1470	•5343E-03 •6146E-03 •6949E-03 •7753E-03	
0.0204592 0.0198575 0.0192557 0.0186540 0.0186523 0.0174505	.3487E 01 .3558E 01 .3621E 01 .3676E 01 .3725E 01 .3770E 01	.3567 E 01 .3567 E 01 .3679 E 01 .3728 E 01 .3773 E 01 .3716 E 01	661 • 7 751 659 • 9 019 658 • 2 563 656 • 7 954 655 • 5 662 654 • 5 154 653 • 6042	661.2632 659.6252 658.3059 657.1470 656.7257	• 5343E-03 • 6146E-03 • 6949E-03 • 7753E-03 • 8556E-03	
0.0204592 0.0198575 0.0192557 0.0186540 0.0180523 0.0174505 0.0168488 0.0162470	- 3487E 01 - 3558E 01 - 3621E 01 - 3676E 01 - 3725E 01 - 3770E 01 - 3811E 01 - 3848E 01	-3567E 01 -3567E 01 -3679E 01 -3773E 01 -3773E 01 -3814E 01 -3857E 01	661 • 7751 659•9019 658•2563 656•7954 655•5662 655•5662 655•5154 653•6042 652•8088	661.2632 659.6252 658.3059 657.1470 656.1257 655.2253 654.4265	• 5343E-03 • 6146E-03 • 6949E-03 • 7753E-03 • 8556E-03 • 9362E-03 • 1017E+02	
0.0198575 0.0198575 0.01985757 0.0186540 0.0186540 0.0188523 0.0174505 0.0168488 0.0162470 0.0156453	- 3487E 01 - 3558E 01 - 3621E 01 - 3676E 01 - 3725E 01 - 3770E 01 - 3811E 01 - 3848E 01 - 3883E 01	-3567E 01 -3567E 01 -3679E 01 -3773E 01 -3773E 01 -3814E 01 -3857E 01 -3886E 01	661 • 7751 659•9019 658•2563 656•7954 655•5662 655•5662 655•5154 653•6042 652•8088 652•1096	661.2632 659.6252 658.3059 657.1470 656.7257 655.2253 654.4265 653.7151	• 5343 E-03 • 6146 E-03 • 6949 E-03 • 7753 E-03 • 8556 E-03 • 9362 E-03 • 1017 E-02 • 1097 E-02	
0.0198575 0.0198575 0.0192557 0.0186540 0.0186540 0.0186540 0.0174505 0.0168488 0.0162470 0.0156453 0.0150435 0.0150435	- 3487E 01 - 3558E 01 - 3621E 01 - 3676E 01 - 3725E 01 - 3770E 01 - 3811E 01 - 3848E 01 - 3883E 01 - 3916E 01	-3561 E 01 -3561 E 01 -3679E 01 -3773E 01 -3773E 01 -3814E 01 -3857E 01 -3918E 01 -3918E 01	661 • 7751 659•9019 658•2563 656•7954 655•5662 655•5662 655•5154 653•6042 652•8088 652•8088 652•1096 651•4929	661.2632 659.6252 658.3059 657.1470 656.7257 655.2253 654.4265 653.0774	- 5343 E-03 - 6146 E-03 - 6949 E-03 - 7753 E-03 - 8556 E-03 - 9362 E-03 - 1017 E-02 - 107 E-02 - 1177 E-02	
0.02045 92 0.01985 75 0.01925 57 0.01865 40 0.01865 23 0.0174505 0.01684 88 0.01624 70 0.01564 53 0.01564 35 0.01444 18 0.01384 01	. 3487E 01 .3558E 01 .3671E 01 .3676E 01 .3770E 01 .3770E 01 .3811E 01 .3848E 01 .3883E 01 .3916E 01 .3946E 01	-3561 E 01 -3567 E 01 -3679 E 01 -3773 E 01 -3773 E 01 -3814 E 01 -3857 E 01 -3918 E 01 -3949 E 01 -3949 E 01	661.7751 659.9019 658.2563 656.7954 655.5662 654.5154 653.6042 652.8088 652.1096 651.4929 650.9466	661.2632 659.6252 658.3059 657.1470 656.7257 655.2253 654.4265 653.7151 653.0774 652.5078	- 5343 E-03 - 6146 E-03 - 6949 E-03 - 7753 E-03 - 8556 E-03 - 9362 E-03 - 1017 E-02 - 107 E-02 - 1177 E-02 - 1258 E-02 - 135 E-02	
0.02045 92 0.01985 75 0.01925 57 0.01865 40 0.01865 40 0.01865 23 0.0174505 0.01684 88 0.01624 70 0.01564 53 0.01564 35 0.01444 18 0.01323 83	- 3487E 01 - 3558E 01 - 3621E 01 - 3676E 01 - 3770E 01 - 3811E 01 - 3848E 01 - 3883E 01 - 3946E 01 - 3946E 01 - 3975E 01 - 4001E 01	-3561 E 01 -3561 E 01 -3679E 01 -3773E 01 -3773E 01 -3814E 01 -3857E 01 -3918E 01 -3949E 01 -3949E 01 -3977E 01 -4004E 01	661 • 7751 659•9019 658•2563 656•7954 655•5662 655•5662 654•5154 652•8088 652•8088 652•1096 651•4929 650•9466 650•4583 650•0247	661.2632 659.6252 658.3059 657.1470 656.7257 655.2253 654.4265 653.0774 652.5078 651.9946 651.5330	- 5343 E-03 - 6146 E-03 - 6949 E-03 - 7753 E-03 - 8556 E-03 - 9362 E-03 - 1017 E-02 - 107 E-02 - 1177 E-02 - 1258 E-02 - 1339 E-02 - 1419 E-02	
0.0198575 0.0198575 0.0186540 0.0186540 0.0186540 0.0174505 0.0174505 0.0168488 0.0162470 0.0156453 0.0156453 0.0156455 0.0144418 0.0132383 0.0132385	- 3487E 01 - 3558E 01 - 3621E 01 - 3676E 01 - 3725E 01 - 3770E 01 - 3811E 01 - 3848E 01 - 3848E 01 - 3848E 01 - 3946E 01 - 3946E 01 - 3975E 01 - 4001E 01 - 4027E 01	-3561 E 01 -3561 E 01 -3679E 01 -3773E 01 -3773E 01 -3814E 01 -3857E 01 -3918E 01 -3949E 01 -3949E 01 -4004E 01 -4004E 01	661 • 7751 659•9019 658•2563 656•7954 655•5662 654•5154 652•8088 652•8088 652•1096 651•4929 650•9446 650•4583 650•0247 649•6404	661.2632 659.6252 658.3059 657.1470 656.7257 655.2253 654.4265 653.0774 652.5078 651.9946 651.5330 651.1150	- 5343 E-03 - 6146 E-03 - 6949 E-03 - 775 E-03 - 8556 E-03 - 9362 E-03 - 1017 E-02 - 1097 E-02 - 1177 E-02 - 1258 E-02 - 1339 E=02 - 1419 E-02 - 1500 E-02	
0.02045 92 0.01985 75 0.01865 40 0.01865 40 0.01865 23 0.017450 5 0.01684 88 0.01624 70 0.01564 35 0.01564 35 0.01444 18 0.01323 83 0.01263 66 0.01203 48 0.01123 48	- 3487E 01 - 3558E 01 - 3621E 01 - 3676E 01 - 3725E 01 - 3811E 01 - 3848E 01 - 3848E 01 - 3848E 01 - 3946E 01 - 3946E 01 - 4001E 01 - 4027E 01	-3561 E 01 -3561 E 01 -3679E 01 -3728E 01 -3773E 01 -3814E 01 -3857E 01 -3918E 01 -3949E 01 -3949E 01 -4004E 01 -4054E 01 -4054E 01	661 .7751 659.9019 658.2563 656.7954 655.5662 654.5154 652.8088 652.8088 652.1096 651.4929 650.9446 650.4583 650.4247 649.2998	661.2632 659.6252 658.3059 657.1470 656.7257 655.2253 654.4265 653.0774 652.5078 651.5330 651.1150 650.7375	- 5343 E-03 - 6146 E-03 - 6949 E-03 - 775 E-03 - 8556 E-03 - 9362 E-03 - 1017 E-02 - 1097 E-02 - 1177 E-02 - 1258 E-02 - 1339 E-02 - 1419 E-02 - 1580 E-02 - 1580 E-02	
$\begin{array}{c} 0.02045 \ 92\\ 0.01985 \ 75\\ 0.01925 \ 57\\ 0.01865 \ 40\\ 0.01865 \ 40\\ 0.01805 \ 23\\ 0.017450 \ 5\\ 0.01684 \ 88\\ 0.01624 \ 70\\ 0.01564 \ 35\\ 0.01504 \ 35\\ 0.01323 \ 83\\ 0.01323 \ 83\\ 0.01263 \ 66\\ 0.01203 \ 48\\ 0.01143 \ 31\\ 0.01083 \ 13\\ \end{array}$	- 3487E 01 - 3558E 01 - 3621E 01 - 3676E 01 - 3770E 01 - 3811E 01 - 3848E 01 - 3848E 01 - 3848E 01 - 3946E 01 - 3946E 01 - 4001E 01 - 4051E 01 - 4074E 01 - 4096E 01	-3561 E 01 -3562 E 01 -3679E 01 -3773E 01 -3773E 01 -3814E 01 -3857E 01 -3918E 01 -3949E 01 -4004E 01 -4032 01 -4054E 01 -4054E 01 -4059E 01	661 • 7751 659•9019 658•2563 656•7954 655•5662 654•5154 652•8088 652•8088 652•1096 651•4929 650•9446 650•4583 650•0247 649•2998 648•7299	661.2632 659.6252 658.3059 657.1470 656.1257 655.2253 654.4265 653.7151 653.0774 652.5078 651.9946 651.5330 651.1150 650.7375 650.3977	- 5343 E-03 - 6146 E-03 - 6949 E-03 - 775 E-03 - 8556 E-03 - 9362 E-03 - 1017 E-02 - 1097 E-02 - 1258 E-02 - 1339 E-02 - 1419 E-02 - 1580 E-02 - 1580 E-02 - 1661 E-02 - 1762 E-02	
0.02045 92 0.01985 75 0.01925 57 0.01865 40 0.01805 23 0.017450 5 0.01684 88 0.01624 70 0.01564 53 0.01564 35 0.01444 18 0.01323 83 0.01323 83 0.01263 66 0.01203 48 0.01143 31 0.01022 96	- 3487E 01 - 3558E 01 - 3671E 01 - 3676E 01 - 3770E 01 - 3811E 01 - 3848E 01 - 3848E 01 - 3848E 01 - 3946E 01 - 3946E 01 - 4051E 01 - 4051E 01 - 4074E 01 - 4076E 01 - 4076E 01	-3561 E 01 -3561 E 01 -3679E 01 -3773E 01 -3773E 01 -3851E 01 -3857E 01 -3918E 01 -3918E 01 -3977E 01 -4004E 01 -4031E 01 -4031E 01 -40399E 01 -4119E 01	661 • 7751 659•9019 658.2563 656•7954 655•5662 654•5154 652•8088 652•8088 652•1096 651•4929 650•9446 650•0247 649•6404 649•2998 648•7292 648•7292 648•4973	661.2632 659.6252 658.3059 657.1470 656.1257 655.2253 654.4265 653.7151 653.0774 652.5078 651.9946 651.5330 651.1150 650.7375 650.3977 650.0913 649.8125	- 5343 E-03 - 6146 E-03 - 6949 E-03 - 7753 E-03 - 8556 E-03 - 9362 E-03 - 1017 E-02 - 1097 E-02 - 1177 E-02 - 1258 E-02 - 1339 E-02 - 1580 E-02 - 1580 E-02 - 1580 E-02 - 1742 E-02 - 1822 E-02	
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$\begin{array}{c} 0.02045 \ 92\\ 0.01985 \ 75\\ 0.01925 \ 57\\ 0.01865 \ 40\\ 0.01805 \ 23\\ 0.017450 \ 5\\ 0.01684 \ 88\\ 0.01504 \ 35\\ 0.01504 \ 35\\ 0.01504 \ 35\\ 0.01444 \ 18\\ 0.01323 \ 83\\ 0.01263 \ 66\\ 0.01203 \ 48\\ 0.01143 \ 31\\ 0.01023 \ 48\\ 0.01023 \ 48\\ 0.01023 \ 48\\ 0.001023 \ 48\\ 0.001023 \ 48\\ 0.001023 \ 48\\ 0.001023 \ 48\\ 0.001023 \ 48\\ 0.001023 \ 48\\ 0.001023 \ 48\\ 0.001023 \ 48\\ 0.001023 \ 48\\ 0.001722 \ 9\\ 0.00902 \ 61\\ 0.008 \ 42 \ 44\\ 0.007 \ 82 \ 26\\ 0.007 \ 72 \ 29\\ 0.006 \ 61 \ 97\\ 0.005 \ 41 \ 57\\ 0.004 \ 81 \ 39\\ 0.004 \ 81 \ 89\\ 0.004 \ 81 \ 89\\ 0.004 \ 81 \ 89\\ 0.004 \ 81 \ 89\\ 0.004 \ 81 \ 89\\ 0.004 \ 81 \ 89\\ 0.004 \ 81 \ 89\\ 0.004 \ 81 \ 89\\ 0.004 \ 81 \ 89\\ 0.004 \ 81 \ 89\\ 0.004 \ 81 \ 89\\ 0.004 \ 81 \ 89\\ 0.004 \ 81 \ 89\\ 0.004 \ 80\ 89\ 80\ 89\\ 0.004 \ 80\ 80\ 80\ 80\ 80\ 80\ 80\ 80\ 80\ 8$. 3487E 01 .3558E 01 .3578E 01 .3725E 01 .3725E 01 .37270E 01 .3811E 01 .3848E 01 .3916E 01 .3946E 01 .3946E 01 .4007E 01 .4007E 01 .4074E 01 .4074E 01 .4175E 01 .4156E 01 .4156E 01 .4226E 01 .4226E 01 .4257E 01 .4287E 01	-3561 E 01 -3561 E 01 -35728 E 01 -3773E 01 -3773E 01 -3814E 01 -3857E 01 -3918E 01 -3918E 01 -3949E 01 -4004E 01 -4032E 01 -4077E 01 -4077E 01 -4195E 01 -4195E 01 -4275E 01 -4290E	661.7751 659.9019 658.2563 656.7954 655.5662 655.5662 653.6042 652.8088 652.1096 651.4929 650.9446 650.9446 650.9446 650.9446 649.2998 648.7292 648.4973 648.2957 648.4973 648.2957 648.4973 647.5859 647.4583 647.2587 647.1909 647.1309	661.2632 659.6252 658.3059 657.1470 656.7257 655.2253 654.4265 653.7157 653.0774 652.5078 651.9946 651.9946 651.5330 651.5330 651.775 650.3977 650.0913 649.8125 649.5598 649.5598 649.3350 649.1851 649.231 648.9231 648.6313 648.6313 648.6313	- 5343 E-03 - 6749 E-03 - 6749 E-03 - 6753 E-03 - 8556 E-03 - 9362 E-03 - 1077 E-02 - 1177 E-02 - 1258 E-02 - 1339 E-02 - 1580 E-02 - 1580 E-02 - 1580 E-02 - 1582 E-02 - 1661 E-02 - 1742 E-02 - 1983 E-02 - 2064 E-02 - 225 E-02 - 238 6 E-02 - 255 E-02 - 258 E-02	
$\begin{array}{c} 0.02045 \ 92\\ 0.01985 \ 75\\ 0.01925 \ 57\\ 0.01865 \ 40\\ 0.01805 \ 23\\ 0.017450 \ 5\\ 0.01684 \ 88\\ 0.01564 \ 53\\ 0.01564 \ 53\\ 0.01564 \ 53\\ 0.01564 \ 53\\ 0.01444 \ 18\\ 0.01323 \ 83\\ 0.01263 \ 66\\ 0.01203 \ 48\\ 0.01143 \ 31\\ 0.01023 \ 48\\ 0.01023 \ 48\\ 0.01023 \ 48\\ 0.01023 \ 48\\ 0.00162 \ 79\\ 0.00902 \ 61\\ 0.007 \ 82 \ 26\\ 0.007 \ 82 \ 20\\ 0.007 \ 82 \ 20\\ 0.007 \ 82 \ 20\\ 0.007 \ 82 \ 20\\ 0.007 \ 82 \ 20\\ 0.007 \ 82 \ 20\\ 0.007 \ 82 \ 20\\ 0.007 \ 82 \ 20\\ 0.007 \ 82 \ 20\\ 0.007 \ 82 \ 20\\ 0.007 \ 82 \ 20\\ 0.007 \ 82 \ 20\\ 0.007 \ 82 \ 20\\ 0.007 \ 82 \ 20\\ 0.007 \ 82 \ 20\\ 0.007 \ 82 \ 20\\ 0.007 \ 82 \ 20\\ 0.007 \ 82 \ 20\\ 0.005 \ 41 \ 57\\ 0.004 \ 81 \ 37\\ 0.004 \ 81 \ 87\\ 0.005 \ 81 \ 81 \ 81\ 81\ 81\\ 0.005 \ 81 \ 81\ 81\ 81\ 81\ 81\ 81\ 81\ 81\ $. 3487E 01 . 3558E 01 . 3558E 01 . 3676E 01 . 3770E 01 . 3770E 01 . 3811E 01 . 3848E 01 . 3883E 01 . 3916E 01 . 3946E 01 . 3975E 01 . 4001E 01 . 4027E 01 . 4074E 01 . 4074E 01 . 4177E 01 . 4175E 01 . 4175E 01 . 4192E 01 . 4257E 01 . 4257E 01 . 4287E 01 . 4287E 01 . 4287E 01 . 4287E 01 . 4287E 01 . 4287E 01 . 4301E 01	-3561 E 01 -3561 E 01 -35728 E 01 -3773E 01 -3773E 01 -3814E 01 -3857E 01 -3918E 01 -3918E 01 -3918E 01 -3949E 01 -4032E 01 -4032E 01 -4077E 01 -4195E 01 -4195E 01 -4195E 01 -4275E 01 -4290E	661.7751 659.9019 658.2563 656.7954 655.5662 655.5662 653.6042 652.8088 652.1096 651.4929 650.9446 650.9446 650.9446 650.9446 650.9446 649.2998 648.7292 648.4973 648.2957 648.4973 648.2957 648.4973 647.5859 647.5859 647.4583 647.3521 647.1909 647.1309 647.1309 647.0828	661.2632 659.6252 658.3059 657.1470 656.7257 655.2253 654.4265 653.7157 653.0774 652.5078 651.9946 650.7375 650.9913 649.8125 649.9350 649.9350 649.9231 648.9231 648.9231 648.6313 648.6313 648.5586 648.4983 648.4997	5343 E-03 $6146 E-03$ $6949 E-03$ $7753 E-03$ $8556 E-03$ $9362 E-03$ $1017 E-02$ $1177 E-02$ $1258 E-02$ $1339 E-02$ $1500 E-02$ $1500 E-02$ $1580 E+02$ $1580 E+02$ $1661 E-02$ $182 E-02$ $258 E-02$ $2064 E-02$ $225 E-02$ $2305 E-02$ $2305 E-02$ $2364 E-02$ $225 E-02$ $2364 E-02$ $2547 E-02$ $2547 E-02$ $2547 E-02$ $2709 E+02$	
$\begin{array}{c} 0.02045 \ 92\\ 0.01985 \ 75\\ 0.01925 \ 57\\ 0.01805 \ 23\\ 0.017450 \ 5\\ 0.01684 \ 88\\ 0.01624 \ 70\\ 0.01564 \ 53\\ 0.01564 \ 53\\ 0.01564 \ 53\\ 0.01564 \ 53\\ 0.01444 \ 18\\ 0.01323 \ 83\\ 0.01243 \ 66\\ 0.01203 \ 48\\ 0.01143 \ 31\\ 0.01023 \ 48\\ 0.01022 \ 96\\ 0.00902 \ 61\\ 0.0084244\\ 0.00782 \ 26\\ 0.00782 \ 26\\ 0.00782 \ 209\\ 0.00961 \ 74\\ 0.00541 \ 57\\ 0.00481 \ 37\\ 0.00541 \ 57\\ 0.00481 \ 39\\ 0.00541 \ 57\\ 0.00481 \ 39\\ 0.00481 \ 39\\ 0.00481 \ 39\\ 0.003 \ 0087\\ 0.002 \ 40.69\\ \end{array}$. 3487E 01 . 3558E 01 . 3558E 01 . 3676E 01 . 3770E 01 . 3770E 01 . 3811E 01 . 3848E 01 . 3883E 01 . 3916E 01 . 3946E 01 . 4001E 01 . 4027E 01 . 4051E 01 . 4074E 01 . 4074E 01 . 4177E 01 . 4156E 01 . 4175E 01 . 4192E 01 . 4257E 01 . 4301E 01 . 4315E 01 . 4315E 01	-3561 E 01 -3561 E 01 -35679E 01 -3773E 01 -3773E 01 -3814E 01 -3857E 01 -3918E 01 -3918E 01 -3949E 01 -4004E 01 -4032E 01 -4032E 01 -4077E 01 -4195E 01 -4195E 01 -4195E 01 -4255E 01 -4255E 01 -4290E 01 -4201E 0	661.7751 659.9019 658.2563 656.7954 655.5662 655.5662 653.6042 652.8088 652.1096 651.4929 650.9446 650.9446 650.9446 650.9446 649.2998 648.7292 648.4973 648.2957 648.4973 648.2957 648.4973 647.5859 647.5859 647.5859 647.5859 647.1309 647.0947 647.0176	661.2632 659.6252 658.3059 657.1470 656.7257 655.2253 654.4265 653.7157 653.0774 652.5078 651.9946 652.5078 649.3350 649.3350 649.49231 648.9231 648.9231 648.9231 648.6313 648.6313 648.4983 648.4983 648.4497 648.4497 648.4131	- 5343 E-03 - 6749 E-03 - 6749 E-03 - 7753 E-03 - 8556 E-03 - 9362 E-03 - 1077 E-02 - 1097 E-02 - 1177 E-02 - 1258 E-02 - 1339 E-02 - 1500 E-02 - 1580 E+02 - 1580 E+02 - 1580 E+02 - 1661 E-02 - 1742 E-02 - 1983 E-02 - 2064 E-02 - 2144 E+02 - 225 E-02 - 238 6 E-02 - 238 6 E-02 - 2547 E-02 - 2628 E-02 - 2789 E-02 - 27	
$\begin{array}{c} 0.02045 \ 92\\ 0.01985 \ 75\\ 0.01925 \ 57\\ 0.01865 \ 40\\ 0.01805 \ 23\\ 0.017450 \ 5\\ 0.01684 \ 88\\ 0.01564 \ 53\\ 0.01564 \ 53\\ 0.01564 \ 53\\ 0.01564 \ 53\\ 0.01564 \ 53\\ 0.01444 \ 18\\ 0.013 \ 24 \ 35\\ 0.01444 \ 18\\ 0.013 \ 24 \ 35\\ 0.0123 \ 48\\ 0.01143 \ 31\\ 0.010 \ 23 \ 48\\ 0.01143 \ 31\\ 0.010 \ 23 \ 48\\ 0.010 \ 23 \ 48\\ 0.0010 \ 27 \ 96\\ 0.00902 \ 61\\ 0.00902 \ 61\\ 0.008 \ 42 \ 44\\ 0.007 \ 82 \ 26\\ 0.007 \ 82 \ 209\\ 0.006 \ 61 \ 91\\ 0.005 \ 41 \ 57\\ 0.004 \ 81 \ 39\\ 0.004 \ 81 \ 39\\ 0.004 \ 81 \ 39\\ 0.004 \ 81 \ 39\\ 0.004 \ 81 \ 39\\ 0.004 \ 81 \ 39\\ 0.004 \ 81 \ 39\\ 0.004 \ 81 \ 39\\ 0.004 \ 81 \ 39\\ 0.004 \ 81 \ 39\\ 0.004 \ 81 \ 39\\ 0.004 \ 81 \ 39\\ 0.004 \ 81 \ 39\\ 0.004 \ 81 \ 39\\ 0.004 \ 81 \ 39\\ 0.004 \ 81 \ 39\\ 0.004 \ 81 \ 39\\ 0.004 \ 81 \ 39\\ 0.004 \ 81 \ 39\\ 0.002 \ 40 \ 69\\ 0.001 \ 80\ 52\ 52\ 52\ 52\ 52\ 52\ 52\ 52\ 52\ 52$. 3487E 01 . 3558E 01 . 3576E 01 . 3770E 01 . 3770E 01 . 3770E 01 . 3811E 01 . 3848E 01 . 3883E 01 . 3916E 01 . 3975E 01 . 4001E 01 . 4027E 01 . 4051E 01 . 4074E 01 . 4074E 01 . 4175E 01 . 4175E 01 . 4175E 01 . 4226E 01 . 4257E 01 . 4301E 01 . 4315E 01 . 4341E 01	-3561 E 01 -3561 E 01 -3679E 01 -3773E 01 -3773E 01 -3886E 01 -3918E 01 -3918E 01 -3949E 01 -4004E 01 -4032E 01 -4054E 01 -4054E 01 -4054E 01 -4159E 01 -4159E 01 -4159E 01 -4259E 01 -4255E 01 -4255E 01 -4260E 01 -4275E 01 -4290E 01 -431E 01 -431E 01 -431E 01 -4344E 01	661.7751 659.9019 658.2563 656.7954 655.5662 655.5662 653.6042 652.8088 652.1096 651.4929 650.9446 650.9446 650.9446 649.2998 648.7292 648.4973 648.2957 648.4973 648.2957 648.4973 648.4973 647.5857 647.585 647.585 647.585 647.585 647.1909 647.1309 647.0828 647.0176	661.2632 659.6252 658.3059 657.1470 656.7257 655.2253 654.4265 653.7157 655.071 655.071 655.071 653.071 653.071 653.071 653.071 653.071 653.071 655.078 651.9946 651.9946 651.07375 650.0913 649.5998 649.5998 649.3500 649.7375 649.0471 648.9231 648.9231 648.9231 648.5586 648.4983 648.4983 648.4983 648.4983 648.4983 648.4983 648.4983 648.4983 648.4983 648.4983 648.4983 648.4983 648.4983 648.43848 648.38	5343 E-03 $6146 E-03$ $6949 E-03$ $7753 E-03$ $8556 E-03$ $9362 E-03$ $107 E-02$ $117 E-02$ $1258 E-02$ $1339 E-02$ $1500 E-02$ $1500 E-02$ $1500 E-02$ $1661 E-02$ $1742 E-02$ $182 2 E-02$ $2064 E-02$ $225 E-02$ $2305 E-02$ $2305 E-02$ $2305 E-02$ $225 E-02$ $2386 E-02$ $225 E-02$ $2467 E-02$ $2267 E-02$ $2709 E+02$ $2709 E+02$ $2709 E+02$	
$\begin{array}{c} 0.0204592\\ 0.0198575\\ 0.0192557\\ 0.0180523\\ 0.0180523\\ 0.0174505\\ 0.0168488\\ 0.0162470\\ 0.0156453\\ 0.0156453\\ 0.0156453\\ 0.0150435\\ 0.0144418\\ 0.0132383\\ 0.0124366\\ 0.0120348\\ 0.0114331\\ 0.0102348\\ 0.0102348\\ 0.0102348\\ 0.0102296\\ 0.090261\\ 0.0090261\\ 0.0090261\\ 0.0090261\\ 0.0090261\\ 0.0090261\\ 0.0084244\\ 0.00782209\\ 0.0096279\\ 0.0090261\\ 0.0084244\\ 0.00782209\\ 0.0084244\\ 0.00782209\\ 0.0066174\\ 0.0054157\\ 0.0048137\\ 0.0024069\\ 0.0018052\\ 0.001805\\ 0.001805\\ 0.001805\\ 0.001805\\ 0.001805\\ 0.001805\\ 0.001805\\ 0.001805\\ 0.001805\\ 0.001805\\ 0.001805\\ 0.00180\\ 0.001805\\ 0.00180\\$. 3487E 01 . 3558E 01 . 3576E 01 . 3770E 01 . 3770E 01 . 3811E 01 . 3848E 01 . 3883E 01 . 3916E 01 . 3916E 01 . 3975E 01 . 4001E 01 . 4027E 01 . 4051E 01 . 4076E 01 . 4177E 01 . 4137E 01 . 4156E 01 . 4276E 01 . 4226E 01 . 4257E 01 . 4257	-3561 E 01 -3561 E 01 -3679E 01 -3773E 01 -3773E 01 -3773E 01 -3886E 01 -3918E 01 -3918E 01 -3918E 01 -3949E 01 -4054E 01 -4054E 01 -4054E 01 -4054E 01 -4077E 01 -4195E 01 -4195E 01 -4255E 01 -4245E 01 -4255E 01 -4260E 01 -4275E 01 -4290E 01 -431E 01 -431E 01 -4356E 01	661.7751 659.9019 658.2563 656.7954 655.5662 655.5662 655.5662 652.8088 652.1096 651.4929 650.9446 650.9446 650.9446 650.9446 647.2998 648.2957 648.2957 648.2957 648.2973 648.2973 648.2973 647.5859 647.5859 647.5585 647.5585 647.521 647.1309 647.0828 647.0828 647.0828 647.0828 647.0988 646.9880	661.2632 659.6252 658.3059 657.1470 656.7257 655.2253 654.4265 653.7151 653.0778 651.9946 649.330 649.3350 649.1851 649.231 648.9231 648.9231 648.4933 648.4933 648.4983 648.4983 648.4983 648.3848 648.3652 648.3535	5343 E-03 $6146 E-03$ $6949 E-03$ $7753 E-03$ $8556 E-03$ $9362 E-03$ $1017 E-02$ $1177 E-02$ $1258 E-02$ $1339 E-02$ $1500 E-02$ $1580 E+02$ $1580 E+02$ $1580 E+02$ $225 E-02$ $2064 E-02$ $2364 E-02$ $2364 E-02$ $2364 E-02$ $2364 E-02$ $2364 E-02$ $2386 E-02$ $2386 E-02$ $2467 E-02$ $2547 E-02$ $2648 E-02$ $2709 E+02$ $2789 E+02$ $2789 E+02$ $2789 E+02$ $2870 E-02$ $290 E+02$ $230 5 E-02$ $2789 E+02$ $2789 E+02$ $2789 E+02$ $2789 E+02$ $2870 E-02$ $290 E+02$ $290 E+02$ $290 E+02$ $303 0 E-02$	
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THE PRESENT	TIME IS	19160-HOUNS	·····		
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THE DACT IF	NGTH SECHENT	15 8-50000			
THE PRESENT	LENGTH SEGME	NT IS 9-000	DOFEET		
	*** ***3 * *** **	***}*	********		
THE PHYSIC	AL PROPERTIES	ARE BASED ON	THE BULK TEN	PERATURE OF	
			•••		
THE DERSITY	15 37-102	LUN/FIT3	·		
THE VISCOSI	TY 15 0.9789 CONDUCTIVITY	1E-D4 LBM/FT- IS 0.17329E	S -04 BTU/S-FT-	F	'
THE HEAT CA	PACITY IS D	79223BTUTER	-1	· · · · · · · · · · · · · · · · · · ·	
********	*********	**********	********		
THE REINGLD	S NUMBER IS	70472.31			
*****	***********	**********	*****	·	
THE AVERAGE	VELOCITY FOR	THE PRESENT	L'ENGTH IS O.	38542E 01 FT	/s
THE VELVELL	LURRECTION	EACTOR 15 U.	13391E 01		······
THE BULK TE	MPERATURE FOR	THE RRESENT	LENGTH 15 67	13.92822 DEGI	REES F
THE OUTS IDE	TUBE WALL TE	MPERATURE IS	0.95621E 038	GREES F	
	UN FUR THIS L	CHOIR SEBRENI	13 1	J. 10323E UJ t	DIU/NK F#2
~## <i>##########</i> ########################	**********	******	************	**********	*********************
RADIUS	VEL	OCITY	TEMF	ERATURE	EDDY DIFFUSIVITY
FT	FT/5	FTIS	DEGREES F	DEGREES F	FT2/S
0.024 12 11	.00000 00	.0003E 00	838-3333	839.9998	
0.0240736	- 3469E DD	-3472E 00	824.4517	826.0464	-2888E-07
0.0228699	-3010E 01	-2904E 01	697.6826	700-1038	+509E=04
0+0222681	-3195E 01	-3199E 01	690-1980	692.1934	-2146E-03
0.0210644	-3432E 01	-3435E DT	681-2678	685, 1865	-2936E-03
0.0204625	.3516E 01	-3520E 01	678.2588	680.2434	-4530E-03
0.0198607	.3588E 01	-3592E 01	675.7871	677.8936	-5330E-03
0.0186570	. 3706E 01	-3709E 01	672.1875	673.5690 674.1008	-6137.E-U3
0.01805 52	.3755E 01	.3759E 01	670.7712	672.6104	177356-03
0.01745 33	. 3800E 01	-3803£ 01	669.5298	671.3306	-8538E±03
0.0167696	- 3840E 01	•3844E 01	668-4397	670.2151	-9341E-03
-0.0156478-	- 3913E UT	-3082E UT	00/+4//>	009+2334 	-1014E=02
0.01504.59	. 3945E Q1	-3949 E 01	665.8665	667.5918	.1175E-02
0.0144441	. 3979E 01	.3979E 01	665.1912	666.9006	•1256E+02
0.0132404	.4004E 01	.4006E 01	664-5842 664-0410	666.2859	-1336E-02
0.0126386	.4056E 01	.4067 E 01	663.5522	665.2427	-14/02-02
0.0120367	- 4080E 01	-4084E 01	663-T111	664-8040	.1577E-02
0.01083 30	4125E 01	-4107E 01	662+1144 667-3577	664.4128	-1658E+02
0.0102312	4146E 01	4150E 01	662.0330	663 7627	1814F-02
0.0096294	.4166E 0T	.4370E 01	661.7380	663.4998 -	-1899E-02
0.0090275	-4185E UT	4189E 01	661.4734	663.2698	-1979E-02
0.0078238	4221E 01	-4225E 01	661.1160	662.8076	-2 UD U E - UZ
0.0072220	.4239E 01	.4242E 01	660.9602	662.6282	- 2224 E-02
0.0066207	.4255E 01	4259E 01	560.8243	662.4739	-2302E-02
0.0054165	4286E 01	-4290E 01	660-7024	662.3437 862.2388	•2382E-02
0.0048146	.4301E 01	-4805E 01	660.5063	662.1506	•2542E+02
0-0042128	-4316E 01	-4319E 01	660.4314	662.0786	-2623E-02
0.0030091	-4344E 01	-4347E 01	660.3276		•2705E-02
0.0024073	-4357E 01	-4360E 01	660.2939	661.9385	•2864E-02
0-0012054	4370E 01	+4873E 01	660,2710	661.9150	-2945E-02
0.0006017	.4395E 01	-4398E 01	660.2510	001.9006 00 661_8953	-JU4>E-02
0.0000000	.4406E 01	-4413E 01	660.2505	661.8950	-3106E-02
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