238
11/17/77
uc-902

Lh. 1597 ORNL/TM-6016

MASTER

Analysis of Alkali Metal Boiler for Fluidized Bed Applications

R. L. Graves

OAK RIDGE NATIONAL LABORATORY
OPERATED BY UNION CARBIDE CORPORATION • FOR THE DEPARTMENT OF ENERGY

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

Printed in the United States of America. Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road, Springfield, Virginia 22161
Price: Printed Copy \$5.25; Microfiche \$3.00

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, contractors, subcontractors, or their employees, makes any warranty, express or implied, nor assumes any legal liability or responsibility for any third party's use or the results of such use of any information, apparatus, product or process disclosed in this report, nor represents that its use by such third party would not-infringe privately owned rights.

ORNL/TM-6016
Dist. Category UC-90f

Contract No. W-7405-eng-26

Engineering Technology Division

ANALYSIS OF ALKALI METAL BOILER FOR
FLUIDIZED BED APPLICATIONS

R. L. Graves

Date Published - November 1977

NOTICE: This document contains information of a preliminary nature. It is subject to revision or correction and therefore does not represent a final report.

NOTICE
This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Department of Energy, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

Prepared by
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37830
operated by
UNION CARBIDE CORPORATION
for the
DEPARTMENT OF ENERGY

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED *24*

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

CONTENTS

	<u>Page</u>
ABSTRACT	1
INTRODUCTION	1
ANALYSIS OF NATURAL CIRCULATION BOILER	2
Hydrodynamics	2
Heat Transfer	8
Input Data	12
Boiler Characteristics	14
Concluding Remarks on Vertical Tube Boiler	18
ANALYSIS OF HORIZONTAL TUBE BOILER	18
Pressure Drop in Forced Circulation	18
Forced Circulation Pumping Power	21
Liquid Metal Inventory	24
Critical Heat Flux	24
Recommendations	24
REFERENCES	25
NOMENCLATURE	26
Greek Symbols	28
APPENDIX A. LISTING OF COMPUTER PROGRAM FOR VERTICAL TUBE BOILER	29
APPENDIX B. LISTING OF COMPUTER PROGRAM FOR HORIZONTAL TUBE BOILER	37

ANALYSIS OF ALKALI METAL BOILER FOR FLUIDIZED BED APPLICATIONS

R. L. Graves

ABSTRACT

The analytical methods used to determine the operating characteristics of alkali metal boilers coupled specifically to fluidized bed furnaces are detailed. Calculation methods are provided for both natural circulation boilers used with deep beds and horizontal tube, forced circulation boilers used in conjunction with shallow fluidized beds. Typical steady-state operating characteristics for boilers of both types being investigated in conjunction with the ORNL alkali metal topping cycle study are provided also.

INTRODUCTION

Parametric studies of alkali metal boilers for use in fluidized bed furnaces were initiated to provide performance data for the boiler to be employed in the alkali metal vapor topping cycle power system under investigation at ORNL. The initial scope of the study involved the evaluation of fluidized bed furnaces operating at atmospheric pressure, pressures of 3-6 atm (0.3-0.6 MPa), and at higher pressures of 6-10 atm (0.6-0.10 MPa). From considerations of system cost and efficiency, the pressurized systems, especially the intermediate pressure systems, appeared to offer the greatest advantages. Since the pressurized systems allow fluidized bed depths on the order of 12 ft (3.66 m), a vertical tube, natural circulation boiler may be utilized. Hence the initial efforts in this study were centered on a natural circulation boiler.

A change in scope of the topping cycle study resulted in redirected efforts toward an atmospheric pressure furnace reference design. The shallow bed depth allowable in this type of furnace necessitates use of a horizontal tube, forced circulation boiler. This report includes details of the analysis of both boiler units.

ANALYSIS OF NATURAL CIRCULATION BOILER

Hydrodynamics

Analysis of the flow in the natural circulation boiler schematically illustrated in Fig. 1 is accomplished by satisfying the requirement that the sum of the pressure changes around the closed loop be equal to zero. The pressure changes along each segment of the circuit can be calculated by application of a simplified momentum equation as applied to a control volume,

$$\Sigma F = \frac{d}{dt} (mV)_{c.v.} + \Sigma \dot{m}_{ex} V_{ex} - \Sigma \dot{m}_i V_i, \quad (1)$$

where the pressure terms appear in the left-hand side. Since the analysis is for steady state, the momentum equation is further simplified to

$$\Sigma F = \Sigma \dot{m}_{ex} V_{ex} - \Sigma \dot{m}_i V_i. \quad (2)$$

In the downcomer, which has a constant area and which is not heated, the momentum balance is expressed as

$$A_d \Delta P + \int_0^{L_d} \tau_w \pi D_d dL_d - A_d \rho \frac{g}{f g_c} L_d = 0$$

so

$$\Delta P_d = \rho_f \frac{g}{g_c} L_d - \int_0^{L_d} \frac{\tau_w^4}{D_d} dL_d.$$

Introducing the familiar concept of the friction factor¹ gives

$$\tau_w = \frac{f \rho V^2}{8 g_c}. \quad (3)$$

Since boiling in the downcomer is suppressed by the insulating effect of the annulus formed by the sleeve, V_d and therefore f_d are

Fig. 1. Schematic representation of fluidized bed furnace-boiler.

essentially constant so that

$$\Delta P_d = \frac{g}{g_c} \rho_f L_d - \frac{\rho_f L_d f v_d^2}{2 D_d g_c} \quad (4)$$

In the heated riser, the hydrodynamics of the analysis are complicated by the two-phase flow which occurs in the boiling region. In the non-boiling section of the riser an expression similar to (4) is applicable.

The momentum equation in the boiling region, however, becomes

$$\Delta P_t = - \int_0^{L_t} \frac{f_t \rho_f V_o^2}{2 D_t g_c} dL_t - \frac{(\sum \dot{m}_{ex} V_{ex} - \sum \dot{m}_i V_i)}{g_c A_t} - \frac{g}{g_c} \int_0^{L_t} [(1 - \alpha) \rho_f + \alpha \rho_g] dL_t \quad (5)$$

The value of the two-phase fluid friction is conventionally evaluated by use of a factor, R , to modify the single phase fluid friction term. Perhaps the most familiar two-phase factor is that based on an experimental correlation by Lockhart and Martinelli,² whose work remains somewhat a milestone in two-phase flow analysis. The Lockhart-Martinelli two-phase multiplier is generally seen in graphical form for practical use as presented by Martinelli and Nelson.³ The generation of graphs for the average multiplier (as opposed to the local two-phase multiplier) requires knowledge of the heat input distribution along the boiling section of tube. Reasonably facile solutions for the natural circulation flow are possible by use of charts, such as those presented in Ref. 3 for a constant heat flux per tube length and those of Ref. 4 for a cosine function heat flux distribution. In general, however, two-phase friction multipliers are not readily evaluated for arbitrary heat flux distributions unless considerable effort is expended in generating the graphs.

Calculation of the momentum change term is facilitated by the following identity,

$$\frac{-\sum \dot{m}_{ex} V_{ex} + \sum \dot{m}_i V_i}{g_c A_t} = - \left[\frac{\dot{m}_t^2 (1 - x_{ex})^2}{\rho_f (1 - \alpha_{ex})} + \frac{\dot{m}_t^2 x_{ex}^2}{\rho_g \alpha_{ex}} \right] \frac{1}{g_c A_t^2} + \frac{\dot{m}_t^2}{g_c A_t^2 \rho_f} \quad (6)$$

where $\dot{m}_{ex} = \dot{m}_i = \dot{m}_t$. Martinelli and Nelson³ proposed graphical evaluation of this term also, which necessitated the assumption of a value for the slip ratio, V_g/V_f , in the two-phase flow region.

Evaluation of the hydrostatic head term,

$$-\frac{g}{g_c} \int [(1 - \alpha) \rho_f + \alpha \rho_g] dL_t \quad (7)$$

requires that the void fraction be known as a function of the boiler tube length. Charts for average void fraction are available only for a limited variety of heat flux distributions.⁴

In view of the deficiencies of the available calculation schemes for the parametric boiler analysis, a more general analytical procedure was desirable which would

1. Allow calculation of the two-phase multiplier where the heat flux distribution is arbitrary.
2. Eliminate assumptions concerning the slip ratio.
3. Minimize the use of graphs in the solutions which are usually trial and error.

A model for the two-phase flow friction multiplier, as proposed by Lottes and Flinn,⁴ appeared to be satisfactory for implementation in a computer program. The model and its derivation are briefly presented below. The basic assumption in the development of the model is that for two-phase flow,

$$\tau_w \propto V_f^2$$

or

$$(\tau_w)_{t.p.} = \frac{f \rho_f V_f^2}{8 g_c} \quad (8)$$

From continuity for two-phase flow

$$\frac{V_f}{V_o} = \frac{1 - x}{1 - \alpha} \quad (9)$$

so that by substituting Eq. (9) into Eq. (8)

$$(\tau_w)_{t.p.} = \left(\frac{1-x}{1-\alpha} \right)^2 \frac{\rho_f f V_o^2}{8g_c},$$

which gives rise to a local two-phase friction multiplier

$$R = \left(\frac{1-x}{1-\alpha} \right)^2.$$

The relation between x and α is readily obtainable from the data correlated by Lockhart and Martinelli.² It should be noted that the limited void fraction data for liquid metals does indeed follow the Lockhart-Martinelli correlation as seen in Ref. 5 and Ref. 6. A third-order polynomial was fitted to the void fraction data to provide α as a function of x .

Other two-phase friction models are available, such as those by Levy⁷ and Marchaterre⁸ for example, which would be quite suitable for computer calculation. However, the correlations between quality and void fraction and the two-phase multiplier which were reported by Lockhart, Martinelli, and Nelson^{2,3} have yet to be surpassed in their agreement with the available experimental data over a broad range of boiling conditions. This fact is apparent from the evidence presented in Ref. 5. Such was also the conclusion of Dukler et al.,⁹ as noted by Tong,¹⁰ who also expressed much confidence in the Lockhart-Martinelli-Nelson results. Furthermore, the pressure drop predicted by the Lockhart-Martinelli-Nelson method has been demonstrated as accurate for bubble, slug, and annular flow regimes,¹¹ eliminating the need for introducing a new pressure drop model for each possible flow pattern. Thus, a conclusive argument for the Lottes-Flinn model is that its pressure drop multiplier is in good agreement (0 to +10% error) with the Lockhart-Martinelli-Nelson multiplier when the void fraction-quality data of the latter investigators is used. The reasonable accuracy of the Lottes-Flinn model is, therefore, demonstrated implicitly.

Since a relation between x and α is available (which inclusively accounts for proper values of slip), evaluation of the momentum change, Eq. (6), is possible for a given value of mass flow rate. The hydrostatic head, Eq. (7), can similarly be expressed as a function of x .

Finally, a fitting loss factor was introduced to account for pressure losses resulting from flow through tees and from sudden expansions and contractions in the flow passages. The fitting pressure drops were expressed as

$$\Delta P_{\text{loss}} = \Sigma K \frac{\rho_f V_o^2}{2g_c} \quad (11)$$

Having expressions for the pressure changes in the legs of the loop, the natural circulation flow rate could be found by satisfying the following inclusive relation from Eqs. (4), (6), (7), and (10).

$$\begin{aligned} \frac{\rho_f g L_d}{g_c} - \frac{f_d \rho_f V_d^2 L_d}{2D_d g_c} - \left[\frac{\dot{m}_t^2 (1 - x_{\text{ex}})^2}{\rho_f (1 - \alpha_{\text{ex}})} + \frac{\dot{m}_t^2 x_{\text{ex}}^2}{\rho_g \alpha_{\text{ex}}} \right] \frac{1}{g_c A_t^2} + \frac{\dot{m}_t^2}{g_c A_t^2 \rho_f} \\ - \frac{g}{g_c} \int_0^{L_t} [(1 - \alpha) \rho_f + \alpha \rho_g] dL_t - \frac{\rho_f V_o^2 f}{2D_t g_c} \int_0^{L_t} \frac{(1 - x)^2}{(1 - \alpha)^2} dL_t \\ - \frac{\rho_f V_o^2 f L_{sc}}{2D_t g_c} - \frac{\rho_f g L_{sc}}{g_c} - \Sigma K \frac{\rho_f V_o^2}{2g_c} = 0 \quad (12) \end{aligned}$$

A value of V_o , i.e., $\dot{m}_t$, which will be a solution to Eq. (12), can be found by iteration if

1. The flow quality, x , can be related to the boiling section length, L_t .
2. The heated length continuing subcooled liquid, L_{sc} , can be found.
3. The downcomer velocity, V_d , can be related to the velocity of subcooled liquid in the boiler tubes, V_o .

These conditions can be met by use of heat transfer and energy relations as described below.

Heat Transfer

The quality in the boiler tubes can be related to the tube length through the first law of thermodynamics which, for this case, simplifies to

$$\dot{Q} = \sum \dot{m}_{ex} h_{ex} - \sum \dot{m}_i h_i \quad (13)$$

since viscous work, kinetic energy, and potential energy changes are very small relative to $\dot{Q}$ and are negligible for our purpose here. Assuming that boiling point will start when the saturation temperature is reached, this becomes (for boiling region in tubes)

$$\dot{Q} = \dot{m}_t x h_{fg}$$

and differentiating with respect to tube length,

$$\frac{dx}{dL_t} = \frac{d\dot{Q}}{dL_t} \frac{1}{\dot{m}_t h_{fg}} \quad (14)$$

Therefore, if $d\dot{Q}/dL_t$ is known, then condition 1 can be met.

The fluidized bed temperature is essentially constant along the tube length. Employing the concept of the overall heat transfer coefficient we obtain

$$\frac{d\dot{Q}}{dL_t} = \frac{U_b dA_s}{dL_t} (T_b - T_s) \quad (15)$$

after utilizing the simplifying assumption that change in the saturation temperature, T_s , in the boiler tubes has a negligible effect. Combining Eqs. (14) and (15) yields a relation between flow quality and tube length in the section of the boiling tubes immersed in the fluidized bed.

In the freeboard area above the bed, heat is transferred to the boiler tubes from the combustion gases. An overall heat transfer coefficient is again employed. Let

$$\Theta = T_g - T_s$$

$$d\theta = dT_g$$

so

$$d\dot{Q} = U_g \theta dA_s = -\dot{m}_a C_{p_a} d\theta \quad (16)$$

$$\frac{d\theta}{\theta} = -\frac{U_g dA_s}{\dot{m}_a C_{p_a}} = -\frac{NU_g \pi D_o dL_t}{\dot{m}_a C_{p_a}}$$

Integrating yields

$$\frac{\theta_2}{\theta_1} = \exp \left(-\frac{U_g N \pi D_o L_t}{\dot{m}_a C_{p_a}} \right), \quad (17)$$

where station 1 is at the bed surface and station 2 is at the top of the boiler tubes and where L_t is the length of boiler tube exposed in the freeboard. Knowing the variation of T_g with the tube length allows calculation of $d\dot{Q}/dL_t$ from Eq. (16). An expression relating flow quality to tube length above the bed follows as

$$\frac{dx}{dL_t} = \frac{\pi D_o U_g}{\dot{m}_t h_{fg}} \left[(T_b - T_s) \exp \left(-\frac{U_g \pi L_t N D_o}{\dot{m}_a C_{p_a}} \right) \right]. \quad (18)$$

Integration of Eqs. (14) and (18) yields the final expressions for quality as a function of tube length. In the fluidized bed then

$$x = \frac{U_b \pi D_o L_t (T_b - T_s)}{\dot{m}_t h_{fg}} \quad (19)$$

$$0 \leq L_t \leq (L_b - L_{sc})$$

and in the freeboard

$$x = \frac{\beta_1}{\beta_2} e^{\beta_2 L_t} + x_o - \frac{\beta_1}{\beta_2} , \quad (20)$$

where

$$\beta_1 = \frac{\pi D_o U (T_b - T_s)}{\dot{m}_t h_{fg}}$$

$$\beta_2 = - \frac{U \pi N D_o}{\dot{m}_a C_{p_a}}$$

$$x_o = \frac{U_b \pi D_o (L_b - L_{sc}) (T_b - T_s)}{\dot{m}_t h_{fg}}$$

$$(L_b - L_{sc}) \leq L_t \leq L_{tt}$$

As discussed above, an expression is needed to determine the length of tube required to heat the subcooled liquid to the saturation temperature. This is accomplished via an energy balance similar to Eq. (16).

Let

$$\Theta_b = T_b - T_f ;$$

then

$$\frac{d\dot{Q}_{sc}}{dL_{sc}} = U_b \pi D_o \Theta_b = - \dot{m}_t C_p \frac{d\Theta_b}{dL_{sc}} \quad (21)$$

and

$$dL_{sc} = \frac{-\dot{m}_t C_p}{U_b \pi D_o} \frac{d\Theta_b}{\Theta_b}$$

so for the fluid temperature to reach saturation temperature the length required is

$$L_{sc} = \frac{\dot{m}_t C_p}{U_b \pi D_o} \ln \frac{(T_b - T_i)}{(T_b - T_s)} \quad (22)$$

Unfortunately, a new unknown, T_i , has appeared which represents the temperature of the subcooled liquid resulting from the mixing of the make-up liquid and the saturated liquid returning via the downcomer. The evaluation of this temperature requires application of a continuity equation for the entire boiler and the energy equation at the make-up liquid inlet. The problem of continuity is complicated by the sleeve which surrounds the downcomer in each tube bundle. The flow in the resulting annulus is treated as a flow parallel to the boiler tubes and subject to the same pressure drop as across the boiler tubes. The vapor formed in the annulus is assumed to leave the boiler with that vapor formed in the main boiler tubes. Thus the continuity relation for the boiler is

$$x_{ex} \dot{\Sigma m}_t + x_{a_{ex}} \dot{m}_{ma} = \dot{m}_{feed} \quad (23)$$

and, thus,

$$\dot{m}_d = (1 - x_{ex}) \dot{\Sigma m}_t + (1 - x_{a_{ex}}) \dot{m}_{ma} \quad (24)$$

The energy equation at the make-up feed inlet can be written as

$$(\dot{m}_d - \dot{m}_{ma}) h_f + \dot{m}_{feed} h_{feed} = \dot{\Sigma m}_t C_p T_i ;$$

substituting Eqs. (23) and (24) for $\dot{m}_d$ and $\dot{m}_{feed}$,

$$[(1 - x_{ex}) \dot{\Sigma m}_t - x_{a_{ex}} \dot{m}_{ma}] h_f + x_{ex} \dot{\Sigma m}_t h_{feed} + x_{a_{ex}} \dot{m}_{ma} h_{feed} = \dot{\Sigma m}_t C_p T_i \quad (25)$$

For a given value of mass flow rate, $\dot{m}_t$, Eqs. (22) and (25) can be iteratively solved for L_{sc} and T_i . Having all of the required relations

in hand, the calculation procedure is now outlined. The computer code performs the calculations in the manner enumerated below.

1. Values for $\dot{m}_t$ and $\dot{m}_a$ are assumed.
2. Values for L_{sc} and T_i are calculated by iterating on T_i until Eqs. (19), (20), (22), and (25) are satisfied.
3. By satisfying the requirement that the pressure drop through the annulus is equal to that through the boiler tubes, $\dot{m}_a$ can be found for the assumed value of $\dot{m}_t$. This is also done by iteration, and requires repetition of step 2 for each iteration.
4. A value of $\dot{m}_d$ is calculated from Eq. (24).
5. The condition set forth by Eq. (12) is checked. New guesses for $\dot{m}_t$ are made, each requiring repetition of steps 2 - 5, until Eq. (12) is satisfied.

Input Data

Use of the computer code requires input data such as the properties of the boiling substance, boiler tube geometry, heat transfer coefficients, etc. The more significant of these parameters are given more detailed attention below.

The thermodynamic properties of the alkali metals were taken from the NRL^{12,13} data which was later extrapolated to lower temperatures by ORNL. The transport properties which were utilized had been collated by Hoffman et al.^{14,15}

Third-order polynomials were fitted to data of void fraction, α , as a function of the logarithm of the flow quality, x , which were obtained from data of void fraction as a function of the Lockhart-Martinelli correlation parameter. At 2000°R (1111°K) saturation temperature, the resulting expressions were

$$\alpha = 0.999373 + 5.53601 \times 10^{-2} \ln x - 9.93718 \times 10^{-3} (\ln x)^2 - 3.0889 \times 10^{-4} (\ln x)^3 \quad (26)$$

for cesium and

$$\alpha = 0.99973 + 2.88343 \times 10^{-2} \ln x - 1.15127 \times 10^{-2} (\ln x)^2 - 2.81755 \times 10^{-4} (\ln x)^3 \quad (27)$$

for potassium. The coefficients of determination for the polynomials are 0.999827 for cesium and 0.999308 for potassium.

The friction factor expression was found in Ref. 1 and was increased by a factor of about 1.4 to yield values for the Darcy friction factor which corresponds to a relative pipe roughness of approximately 0.0001 or less (very smooth) on the Moody diagram. The resulting expression was

$$f = 0.68 [\log_{10} (Re_h)]^{-2.2}, \quad (28)$$

where f is defined in terms of fluid shear in Eq. (3).

The heat transfer coefficient between the fluidized bed and the submerged boiler tubes is advantageously high. Values of 50–60 Btu/hr-ft²-°R (284–341 W/m²-°K) are reported in Ref. 16.

Nusselt numbers for parallel flow through tube bundles have been documented by Kays.¹⁷ The resulting heat transfer coefficient between the combustion gases and tube bundle was on the order of 2.6 Btu/hr-ft²-°R (14.76 W/cm²-°K) for the 1.0 in. (2.54 cm) tubes equally spaced on 2.0 in. (5.08 cm) centers with a gas velocity of 6.0 ft/sec (1.82 m/sec). The fluidized bed design point combustion temperature was chosen as 2210°R (1228°K) for the parametric study. The basic layout of the furnace-boiler and its combustion characteristics have been described in a related report.¹⁸ For the parametric study, the effects of a bed depth variation of 10–15 ft (3.0–4.6 m) were investigated. Effects of variations in the available static liquid head were also studied as was the influence of the various tube sizes on the performance of the boiler.

Approximate values of the fitting losses were taken from Ref. 4 and Ref. 19. An additional loss was introduced for the vapor separator. Experiments at ORNL have demonstrated that the separator pressure drop is on the order of 0.5 psi (0.0034 MPa).

Boiler Characteristics

The results of the initial computer runs revealed that the natural circulation flow rate was quite high, consequentially producing a low exit quality (3-4%) for the alkali metal. Additional pressure drop in the liquid lines was accomplished by slight changes in the geometry of the downcomer. The data presented here are in reference to the boiler configuration illustrated in Fig. 2.

Performance maps of the boiler for cesium and potassium are presented in Figs. 3 and 4 respectively. The probable operating ranges for the respective boilers are indicated on the figures. These ranges of heat flux correspond to overall heat transfer coefficients of 45-65 Btu/hr-ft²-°F (255-369 W/m²-°K) in the fluidized bed. Since the coefficient is much lower in the freeboard area, over 98% of the effective heating is typically accomplished in the fluidized bed zone.

The effect of the heat flux (in the fluidized bed) on the natural circulation flow rate is shown in Figs. 5 and 6 for cesium and potassium respectively. Also presented are the pressure drop derivatives with respect to flow velocity at the various operating points. These derivatives were calculated in order to determine whether the stability criterion according to Leddineg²⁰ had been satisfied. The Leddineg criterion, which is one of the more fundamental checks for stability, states that at a given operating point,

$$\frac{\partial(\Delta P)_{ex}}{\partial V_o} + \frac{\partial(\Delta P)_{fr}}{\partial V_o} \leq 0 . \quad (29)$$

This particular boiler configuration is seen to be quite stable, primarily due to the large liquid driving head and the artificial pressure drop incorporated into the liquid lines in the lower end of the boiler. Furthermore, the stability increases at higher heat flux since, at the subsequently higher flow quality, the two-phase multiplier and void fraction are less sensitive to a change in the flow velocity. This characteristic is not a function of the boiler geometry only, however, but depends also on the specific alkali metal and the saturation pressure at which the boiler is operating.

Fig. 2. Arrangement of vertical tube boiler, 25 ft (7.62 m) main vertical tubes.

Fig. 3. Performance map of vertical tube cesium boiler.

Fig. 4. Performance map of vertical tube potassium boiler.

Fig. 5. Characteristics of natural circulation boiler - cesium.

Fig. 6. Characteristics of natural circulation boiler - potassium.

The two-phase friction is the dominant factor in the pressure drop at the higher heat fluxes, thus reducing the circulation rate. The lower limit on the potassium operating curve results from the very low degree of subcooling which occurs for potassium at a low heat input. The low subcooling leads to boiling in the horizontal branches in the bottom of the boiler, a condition which could not be tolerated since the flow distribution to the vertical tubes would be disrupted.

Concluding Remarks on Vertical Tube Boiler

The analysis of the vertical tube boiler was halted when the program emphasis was shifted from a pressurized fluidized bed furnace to an atmospheric pressure unit. The atmospheric furnace limits the depth of the fluidized bed to 3 or 4 ft (0.91 or 1.22 m), necessitating that the boiler be a horizontal tube, forced circulation unit. The following items were regarded to be important toward the completion of the vertical tube boiler analysis but were necessarily left for future work.

1. Off-design operation.
2. Transient response of boiler during start-up.
3. Methods of control.

ANALYSIS OF HORIZONTAL TUBE BOILER

Pressure Drop in Forced Circulation

Although perhaps there are fewer worries with flow oscillations and instabilities in forced circulation than in a natural circulation boiler, the added cost of recirculation pumps coupled with some additional, though small, parasitic power losses associated with the pumps generally makes the horizontal tube unit less desirable. This is in addition, of course, to the numerous drawbacks inherent in the atmospheric pressure furnace used in conjunction with the horizontal tube boiler.¹⁸

The general layout of the horizontal tube unit is shown in Fig. 7. The pressure drop resulting from the two-phase flow is dominant in this

Fig. 7. Layout of horizontal tube boiler.

system since there is no large gravity head. The correlations of Lockhart, Martinelli, and Nelson^{2,3} were used in conjunction with a pressure drop model of Lottes and Flinn to determine the fluid frictional losses in the two-phase region. The accuracy of this model has been verified elsewhere in this report. The determination of the flow quality along the tube length is the integral part of the calculation as this allows determination of the void fraction correlated by Lockhart, Martinelli and Nelson.^{2,3} These two sets of data are required to compute the two-phase friction multiplier. The other pressure change terms which were included were the following.

1. Momentum change.
2. Hydrostatic head in vertical section (two-phase).
3. Hydrostatic head in downcomer (liquid).
4. Fluid friction in entrance section (liquid).
5. Entrance fitting loss and vapor separator loss.

The liquid frictional pressure drop in the downcomer is negligible and was not included. The resulting expression for the pressure change around

the loop was

$$\begin{aligned} \Delta P = & - \frac{f \rho_f V_o^2 (L_e + L_{sc})}{2 D_t g_c} - \left[\frac{\dot{m}_t^2 (1 - x_{ex})^2}{\rho_f (1 - \alpha_{ex})} + \frac{\dot{m}_t^2 x_{ex}^2}{\rho_g \alpha_{ex}} \right] \frac{1}{g_c A_t^2} \\ & + \frac{\dot{m}_t^2}{g_c A_t^2 \rho_f} - \frac{g}{g_c} \int_0^{L_v} [(1 - \alpha) \rho_f + \alpha \rho_g] dL_v + \frac{\rho_f g L_d}{g_c} \\ & - \frac{\rho_f V_o^2 f}{2 D_t g_c} \int_{s=0}^{s=2L_h + L_v - L_{sc}} \frac{(1 - x)^2}{(1 - \alpha)^2} ds - \frac{K \rho_f V_o^2}{2 g_c} \end{aligned} \quad (30)$$

The flow quality may be related to the tube length by the equation

$$x = \frac{U_b \pi D_o L_h (T_b - T_s)}{\dot{m}_t h_{fg}} \quad (31)$$

since the heat flux is constant along the heated sections of tube. The void fraction, then, was readily obtainable from the curve fits to the Lockhart-Martinelli correlation of void fraction, Eqs. (26) and (27).

The heated length of tube required to bring the working fluid to boiling was found by the relation

$$L_{sc} = \frac{\dot{m}_t C_p}{U_b \pi D_o} \ln \frac{(T_b - T_i)}{(T_b - T_s)} \quad (32)$$

The entrance temperature of the fluid must be found by iterating on Eq. (32) and the following:

$$x_e = \frac{U_b \pi D_o (T_b - T_s)}{\dot{m}_t h_{fg}} (2L_h + L_v - L_{sc}) \quad (33)$$

$$T_i = [(1 - x_e) h_f + x_e h_{feed}] / C_p \quad (34)$$

As with the natural circulation analysis, the calculations were performed via the ORNL-IBM 360/91 computing system.

Forced Circulation Pumping Power

Unless very low exit quality of the alkali metal is desired, the pumping power for the recirculation pumps is very small. This power is actually on the same order of magnitude as the thermal energy spent in driving the natural circulation in the vertical tube boiler. The pumping power per kW(t) output of the boiler is shown in Figs. 8 and 9 for cesium

Fig. 8. Pumping power for cesium boiling loop, 1540°F (1111°K), 36 in. (91 cm) vertical section.

Fig. 9. Pumping power for potassium boiling loop, 1540°F (1111°K), 36 in. (91 cm) vertical section.

and potassium, respectively. The power shown applies only to the heated loop and does not include the pressure drop incurred in the liquid feed line or exit vapor line.

The tube layout results in tubes which have significantly different lengths, especially different in the vertical section. For a given mass

flow, the shorter tubes will, of course, have a lower pressure drop. For a given pressure drop, the variation in exit quality which would exist was of interest. The results of the investigation are depicted in Fig. 10. No related problems were anticipated from this behavior.

Fig. 10. Variation of quality at exit of horizontal boiler tubes as function of vertical section length, 12 ft (3.66 m) horizontal section, equal ΔP through tubes.

Liquid Metal Inventory

The size of the liquid metal inventory was required for a complete reference design of the furnace-boiler. The mass of the alkali metal in the boiler tubes during operation could be calculated via the expression

$$A_t \frac{g}{g_c} \rho_f L_{sc} + \int_{s=0}^{s=2L_h+L_v-L_{sc}} [(1-\alpha)\rho_f + \alpha\rho_g] ds, \quad (35)$$

which provided the mass of alkali metal in the heated portion of each boiler tube. The liquid metal inventory in the unheated boiler tubing was necessarily added to obtain the total inventory. It was found that only a very small mass of alkali metal was present in the boiling regions in the tubes at a given instant relative to those parts of the tube containing liquid. At 25% exit quality the mass of cesium in the heated loop would be typically 3.7 lbm (1.68 kg) per 0.8 in. (2.03 cm) ID tube. A similar case for potassium would yield an inventory of 1.30 lbm (0.59 kg) per tube.

Critical Heat Flux

Although it is unlikely that a potential tube burnout condition exists since the temperature in a fluidized bed is limited, values for the critical heat flux were obtained from the literature as a precaution. The critical heat fluxes cited in Refs. 10, 21, and 22 were greater than the anticipated furnace heat flux of 10,500 Btu/hr-ft² (33,100 W/m²) by, at least one order of magnitude at qualities on the order of 20%.

Recommendations

The degree of detail required for the reference design did not require complete analysis of transient behavior or off-design operation. These would likely be the next steps in the analysis to aid in the eventual design and construction of a pilot plant. The analytical methods described here could also be refined by the introduction of variable

alkali metal properties. The reference design for the atmospheric pressure furnace and alkali metal topping cycle is described in Refs. 23 and 24.

REFERENCES

1. F. M. White, *Viscous Fluid Flow*, McGraw-Hill Book Company, New York, 1974.
2. R. W. Lockhart and R. C. Martinelli, "Proposed Correlation of Data for Isothermal Two-Phase, Two-Component Flow in Pipes," *Chemical Engineering Progress* 45(1) (January 1949).
3. R. C. Martinelli and D. B. Nelson, "Prediction of Pressure Drop During Forced Circulation Boiling of Water," *Trans. ASME* (August 1948).
4. P. A. Lottes, *Nuclear Reactor Heat Transfer*, ANL-6469 (December 1961).
5. J. Costa and P. Charlety, "Forced Convection Boiling of Sodium in a Narrow Channel," *Liquid Metal Heat Transfer and Fluid Dynamics*, ASME, New York, 1970.
6. H. K. Fauske and M. A. Grolmes, "Pressure Drop and Forced Convection Flashing Sodium," *Liquid Metal Heat Transfer and Fluid Dynamics*, ASME, New York, 1970.
7. S. Levy, "Steam Slip - Theoretical Prediction from Momentum Model," *Trans. ASME, Ser. C, J. Heat Transfer* 82 (1960).
8. J. F. Marchaterre, "Two-Phase Frictional Pressure Drop Prediction from Levy's Momentum Model," *Trans. ASME, Ser. C, J. Heat Transfer* 83 (1961).
9. A. E. Dukler et al., "Frictional Pressure Drop in Two-Phase Flow: A Comparison of Existing Correlations for Pressure Loss and Holdup," *AIChE Journal* 10 (January 1964).
10. L. S. Tong, *Boiling Heat Transfer and Two-Phase Flow*, John Wiley and Sons, New York, 1965.
11. O. Baker, "Simultaneous Flow of Oil and Gas," *Oil and Gas Journal* 53 (July 26, 1954).
12. C. T. Ewing et al., *High Temperature Properties of Cesium*, NRL-6246 (Sept. 24, 1965).
13. C. T. Ewing et al., *High Temperature Properties of Potassium*, NRL-6233 (Sept. 24, 1965).
14. H. W. Hoffman and T. T. Robin, Jr., *A Preliminary Collation of the Thermodynamic and Transport Properties of Cesium*, ORNL-TM-1755 (1967).
15. H. W. Hoffman and B. Cox, *A Preliminary Collation of the Thermodynamic and Transport Properties of Potassium*, ORNL-TM-2126 (1968).
16. J. F. Davidson and D. Harrison (Eds.), *Fluidization*, Academic Press, London, 1971.

17. W. M. Kays, *Convective Heat and Mass Transfer*, McGraw-Hill Book Company, New York, 1966.
18. G. Samuels, "Coal-Fired Alkali Metal Design Study," *Technical Progress Report for Period January 1, 1977-March 31, 1977*, ORNL/TM-5885 (1977).
19. J. E. Baker and J. W. Michel, *Pressure Changes with the Flow of Water Through Tees*, Report K-998, Carbide and Carbon Chemicals Company, Division of Union Carbide Corporation (1953).
20. Y. Hsu and R. W. Graham, *Transport Processes in Boiling and Two-Phase Systems*, Hemisphere Publishing Company, Washington, 1976.
21. J. R. Peterson, *High Performance Once-Through Boiling of Potassium in Single Tubes at Saturation Temperatures of 1500 to 1750°F*, NASA-CR-842, G. E. Missile and Space Division (August 1967).
22. A. Kaiser et al., *Flow Pattern, Pressure Drop, and Critical Heat Flux of a Two Phase Sodium Flow*, EURFNR-1266, United States Euratom Fast Reactor Exchange Program (April 1975).
23. G. Samuels, "Coal-Fired Alkali Metal Power System Design Study," *Technical Progress Report for Period April 1, 1977-June 30, 1977*, ORNL/TM-6000, 1977.
24. G. Samuels et al., *Design Study of a 200 MW(e) Alkali Metal/Steam Binary Power Plant Using a Coal-Fired Fluidized Bed Furnace*, ORNL/TM-6041, to be published.

NOMENCLATURE

A_d	- flow area of downcomer
A_s	- heat transfer surface area
A_t	- flow area of boiler tube
C_p	- specific heat of boiling substance
C_{p_a}	- specific heat of combustion gas
c.v.	- refers to control volume
D_d	- ID of downcomer
D_o	- OD of boiler tube
D_t	- ID of boiler tube
f	- friction factor (Darcy)
f_d	- friction factor for downcomer
f_t	- friction factor for boiler tube

g	- gravitational acceleration
g_c	- gravitational conversion constant
h_{ex}	- exit enthalpy
h_f	- enthalpy of saturated liquid
h_{feed}	- enthalpy of make-up liquid
h_{fg}	- enthalpy of vaporization
h_i	- inlet enthalpy
K	- fitting loss constant $2\Delta P/\rho V^2$
L_b	- length of boiler tube immersed in bed
L_d	- length of downcomer
L_h	- heated length of horizontal tube
L_{sc}	- length of heated tube containing sub-cooled liquid
L_t	- length of boiler tube
L_{tt}	- total boiler tube length
L_v	- length of vertical tube section
$\dot{m}_a$	- mass flow rate in annulus
$\dot{m}_a$	- mass flow rate of combustion air
$\dot{m}_d$	- mass flow rate in downcomer
$\dot{m}_{ex}$	- exit mass flow rate
$\dot{m}_{feed}$	- mass flow rate of make-up liquid
$\dot{m}_i$	- inlet mass flow rate
$\dot{m}_t$	- mass flow rate in boiler tube
N	- number of boiler tubes per bundle
ΔP_d	- pressure change in downcomer
ΔP_{ex}	- driving head

ΔP_{fr}	- friction head loss
ΔP_t	- pressure change in boiler tubes
$\dot{Q}$	- heat transfer rate
R	- local two-phase friction multiplier
s	- dummy variable for tube length
T_b	- combustion temperature of fluidized bed
T_i	- temperature of liquid entering heated section of tube
T_g	- temperature of combustion gases
T_s	- saturation temperature
U_b	- overall heat transfer coefficient between fluidized bed and boiling alkali metal
U_g	- overall heat transfer coefficient between combustion gases and boiling alkali metal
V_d	- liquid velocity in downcomer
V_{cx}	- exit velocity
V_f	- liquid velocity in boiler tube
V_i	- inlet velocity
V_o	- velocity of sub-cooled liquid in boiler tube
x	- flow quality - fraction of mass flow rate which is vapor
x_{ex}	- exit flow quality

Greek Symbols

α	- fraction of tube cross section occupied by vapor, void fraction
α_{ex}	- exit void fraction
ρ	- density
ρ_f	- density of saturated liquid
ρ_g	- density of saturated vapor
τ_w	- wall shear stress from fluid flow
$(\tau_w)_{t.p.}$	- apparent wall shear for two-phase flow

Appendix A

LISTING OF COMPUTER PROGRAM FOR VERTICAL TUBE BOILER

The variables used in the program are defined in the program listing.

The output of the program includes the following:

1. Pressure drop values
2. Local quality and void in boiler tubes
3. Subcooling
4. Two-phase friction multiplier
5. Flow velocities and mass flow
6. Boiler power
7. Stability indicators

IMPLICIT REAL (A-Z)
INTEGER I

C THE INPUT PARAMETERS NECESSARY TO RUN THE PROGRAM ARE
C DEFINED IN THE FOLLOWING COMMENT CARDS
C OTHER PARAMETERS ARE DEFINED IMPLICITLY
C HB IS THE HEAT TRANSFER COEFF BETWEEN THE BED AND ALKALI METAL BTU/HR-FT²-F
C DB IS THE OD OF THE HORIZONTAL BRANCH
C LD IS THE LENGTH OF THE DOWNCOMER FT
C BDEP IS THE DEPTH OF THE FLUIDIZED BED FT
C NN IS THE NUMBER OF TUBE BUNDLES
C TTL IS THE TOTAL LENGTH OF BOILER TUBES
C TB IS THE COMBUSTION TEMPERATURE OF THE BED
C TSAT IS THE ALKALI METAL SATURATION TEMP R
C N IS THE NUMBER OF TUBES PER BUNDLE
C HGAS IS THE HEAT TRAN COEFF BETWEEN THE COMBUSTION GAS AND THE ALK METAL
C TFLU IS THE TEMP OF THE FLUE GASES R
C DP IS THE ID OF THE BOILER TUBES IN
C DOT IS THE OD OF THE BOILER TUBES IN
C ODD IS THE OD OF THE DOWNCOMER IN
C DD IS THE ID OF THE DOWNCOMER IN
C ODA IS THE OD OF THE ANNULUS PIPE IN
C IDA IS THE ID OF THE ANNULUS PIPE IN
C LH IS THE LENGTH OF THE HORIZONTAL BRANCH FT
C AIRFLO IS THE MASS FLOW RATE OF FLUE GAS LBM/HR
C ACO,BCO,CCO,DCO ARE COEFFICIENTS OF THE POLYNOMIAL RELATING VOID
C FRACTION TO THE FLOW QUALITY
C MU IS THE LIQUID VISCOSITY LBM/FT-HR
C HFE IS THE ENTHALPY OF THE MAKE-UP LIQUID BTU/LBM
C HSAT IS THE ENTHALPY OF SAT LIQUID BTU/LBM
C HFG IS THE ENTHALPY OF VAPORIZATION BTU/LBM
C ROG IS THE VAPOR DENSITY LBM/FT³
C RO IS THE LIQUID DENSITY LBM/FT³
C CP IS THE SPECIFIC HEAT CAPACITY OF THE LIQUID BTU/LBM-R
C CPA IS THE SPECIFIC HEAT CAPACITY OF FLUE GAS BTU/LBM-R
C DHA IS A HYDRAULIC DIAMETER

HB=15.0
DO 5 I=1,20

C BASIC INPUT DATA FOR THIS CASE

DB=2.50
LD=25.0
VOLD=0.0
G=0.0
DV=100.0
BDEP=12.0
NN=37.0
TTL=25.0
TB=2210.0
TSAT=2000.0
N=324.
HGAS=2.64
TFLU=2210.0
DP=0.80
DOT=1.0
ODD=6.625
DD=6.357
ODA=8.625
IDA=8.125
VSAVE=20000.0
PSAVE=-1000.0
LH=2.0
PRINT 90

90 FORMAT (1H1,50X,'***** DATA FOR THIS CASE *****',////)
PRINT 771,TSAT,TB

```

771 FORMAT (1H , 'SATURATION TEMP-R=',F8.2,10X,'BED TEMP-R=',
#F8.2,/)
PRINT 93,BDEP
93 FORMAT (1H , 'THE DEPTH OF THE FLUID BED IS ',F12.4,/)
PRINT 920,HB
AIRFLO=1.2E04
PRINT 922,AIRFLO
PRINT 91,TTL
91 FORMAT (1H , 'THE BOILER TUBE LENGTH=',F8.3,/)
PRINT 94,N
94 FORMAT (1H , 'THE NUMBER OF BOILER TUBES PER BUNDLE=',F10.2,/)
TUBES=NN*N
PRINT 217,TUBES
217 FORMAT (1H , 'THE TOTAL NUMBER OF TUBES ',F12.2,/)
PRINT 921,DD
PRINT 772,DP,DDT
772 FORMAT (1H , 'BOILER TUBE ID IN.=',F8.2,10X,'BOILER TUBE OD IN.=',
#,F8.2,/)
PRINT 717,LD
717 FORMAT (1H , 'THE STATIC HEAD IN FT.=',F8.3,/)
DB=DB/12.0
DD=DD/12.
DDT=DDT/12.
DP=DP/12.
ODA=ODA/12.
IDA=IDA/12.
FK=2.0
ODD=ODD/12.
C PROPERTIES OF BOILING SUBSTANCE
ACO=0.99973
BCO=2.88343E-02
CCO=-1.15127E-02
DCO=-2.81755E-04
MU=0.31
HFE=329.67
HSAT=388.84
ROG=0.0599
RO=40.16
HFG=805.90
CP=.194
CPA=0.280
C PRELIMINARY CALCULATIONS *****
QDOT1=HB*3.14*DDT*(TB-TSAT)
QDOTA1=HB*3.14*ODA*(TB-TSAT)
AP=3.14*DP**2./4.
AA=3.14*(IDA**2.-ODD**2.)/4.
AD=3.14*DD**2./4.
L2=TTL-BDEP
Y2=L2
K1=QDOT1/(AP*HFG*RO)
Z1=QDOTA1/(AA*HFG*RO)
DHA=4.*AA/(3.14*(IDA+ODD))
DELH=HSAT+HFG-HFE
C START MAIN CALCULATION SCHEME *****
C VA IS THE NOMINAL LIQUID VELOCITY IN THE ANNULUS
C VO IS THE NOMINAL LIQUID VELOCITY IN THE TUBES FT/HR
C ASSUME VALUE FOR VA
C ASSUME VALUE OF VO IN BOILER TUBES
VA=2700.0
VO=3400.0
C TI IS THE TEMPERATURE AFTER MIXING THE RETURN LIQUID WITH THE MAKE-UP
C ASSUME VALUE OF TI
TI=1000.0
888 CONTINUE

```

K
K
K
K
K
K
K
K
K

```

500 CONTINUE
C  FAA AND FA ARE FRICTION FACTORS
   FAA=0.680*(ALOG10(RO*VA*DHA/MU))**(-2.2)
   FA=0.680*(ALOG10(RO*VO*DP/MU))**(-2.2)
   FFA=-RO*FAA*VA**2./(DHA*64.4)/1.296E07
   FF=-RO*VO**2.*FA/DP/64.4/1.296E07
   MDOA=RO*VA*AA
   MDOT=RO*VO*AP
   MDOTB=N*MDOT/6.0
   BETA=3.14*DOT*HGAS*(TFLU-TSAT)/(AP*VO*RO*HFG)
   ZETA=HGAS*3.14*N*DOT/(AIRFLO*CPA)*(-1.)
   BETAA=3.14*ODA*HGAS*(TFLU-TSAT)/(MDOA*HFG)
C  CALCULATE VALUE OF TI FROM ENERGY EQUATION *****
   IF (G.GT.1.0) GO TO 111
101 CONTINUE
C  TE IS THE TEMPERATURE ENTERING THE VERTICAL BOILER TUBES
   TE=(TI-TB)*EXP((-HB*DB*LB*3.14)/(MDUIB*CP))+TB
   IF (TE.GT.TSAT) PRINT 19
   IF (TE.GT.TSAT) GO TO 89
   L1=BDEP-(RO*DP*CP*VO/4./HB)*ALOG((TE-TB)/(TSAT-TB))* (DP/DOT)
   XO=K1*L1/VO
   XEX=BETA/ZETA*EXP(ZETA*(TTL-BDEP))+XO-BETA/ZETA
   XOA=Z1*BDEP/VA
   XEXA=BETAA/ZETA*EXP(ZETA*(TTL-BDEP))+XOA-BETAA/ZETA
   TEST1=((1.-XEX)*N*MDOT-XEXA*MDOA)*HSAT+XEX*N*MDOT*HFE
   #XEXA*MDOA*HFE
   TINEW=TEST1/(N*MDOT*CP)
   ACC=0.10
   CHK1=TI+ACC
   CHK2=TI-ACC
   IF (TINEW.GE.CHK2.AND.TINEW.LE.CHK1) GO TO 111
   TI=(TI+TINEW)/2.
   GO TO 101
111 CONTINUE
C  CALCULATION OF VFLOCITY THROUGH ANNULAR PIPE
   DL=0.20
   TERM12=0.0
   TERM4=0.0
   TERM6=0.0
   TERM11=0.0
   Y=0.01
C  DY IS THE INTEGRATION STEP SIZE
C  *****
C  *****THE INTEGRATION IS DONE BY EULER METHOD*****
C  *****
   DY=0.20
C  INTEGRATION OF THE TWO PHASE MULTIPLIER
950 CONTINUE
   XA=Z1*Y/VA
   IF (Y.GE.BDEP) XA=BETAA/ZETA*EXP(ZETA*(Y-BDEP))+XOA-BETAA/ZETA
C  A AND ANA ARE VALUES OF VOID FRACTION
   ANA=ACC+BCO*ALOG(XA)+CCO*ALOG(XA)**2+DCO*ALOG(XA)**3
   DP11=((1.-XA)**2./(1.-ANA)**2.)*DY
   TERM11=TERM11+DP11
C  INTEGRATION OF THE GRAVITY HEAD TERM
   DP12=(-(1.-ANA)*RO-ANA*ROG)*DY
   TERM12=TERM12+DP12
   IF (Y.GE.TTL) GO TO 802
   Y=Y+DY
   GO TO 950
802 CONTINUE
   TERM14=-(MDOA**2.*(1.-XA)**2./RO/(1.-ANA)+
#MDOA**2.*XA**2./ROG/ANA)/32.2/AA**2./1.296E07
   TERM11=TERM11+FFA

```

```

      L=0.01
806  CONTINUE
C    THE FOLLOWING TERMS APPLY TO THE MAIN BOILER TUBES
C    INTEGRATION OF THE TWO PHASE MULTIPLIER
      LACT =BDEP-L1+L
      X=K1*L/VD
      IF (X.GT.1.0) PRINT 214
      IF (X.GT.1.0) GO TO 5
      IF (LACT.GE.BDEP) X=BETA/ZETA*EXP(ZETA*(L-BDEP))+XO-BETA/ZETA
      A=ACO+BCO*ALOG(X)+CCO*ALOG(X)**2+DCO*ALOG(X)**3
      DP4=((1.-X)**2./(1.-A)**2.)*DL
      TERM4=TERM4+DP4
C    INTEGRATION OF THE GRAVITY HEAD TERM
      DP6=-((1.-A)*RO+A*ROG)*DL
      TERM6=TERM6+DP6
      IF (LACT.GE.TTL) GO TO 805
      L=L+DL
      GO TO 806
805  CONTINUE
      TERM4=TERM4+FF
      TERM8=-((MDOTT**2.)*((1.-X)**2./RO/(1.-A)+X**2./ROG/A)/32.2/AP
      ***2./1.296E07
C    TERM5 IS A MOMENTUM TERM
      TERM5=RO*VO**2./32.2 /1.296E07
C    TERM3 IS FLUID FRICTION AND GRAVITY IN THE SUBCOOLED REGION
      IF (G.GT.1.0) XNEW=X
      TERM3=-((RO*FA*(VO/3600.))**2./(2.*DP*32.2)+RO)*(BDEP-L1)
      TUBDP=TERM4+TERM5+TERM6+TERM8 +TERM3
      ANNDP=TERM11+TERM12+TERM14
      AK=1000.0
      ANNDP=ANNDP-AK*RO*VA**2./8.35E08
      DIFF=ANNDP-TUBDP
      ZIG=5.0
      IF (DIFF.LE.-ZIG ) VA=VA-ZIG
      IF (DIFF.GE.ZIG ) VA=VA+ZIG
      IF (DIFF.LE.ZIG .AND.DIFF.GE.-ZIG ) GO TO 11
      GO TO 500
11  CONTINUE
C    DOWNCOMER PRESSURE CHANGE TERMS
C    A VALUE FOR VD IS CALCULATED HERE FROM CONTINUITY
      VD=((1.-XEX)*N*MDOTT+(1.-XEXA)*MDOTA)/(RO*AD)
      FD=0.680*(ALOG10(RO*VD*DD/MU))**(-2.2)
C    TERM1 IS FOR FLUID FRICTION
      TERM1=-RO*FD*LD*VD**2./(DD*64.4)/1.296E07
C    TERM2 IS A GRAVITY HEAD TERM
      TERM2=RO*LD
C    TERM10 IS A FITTING LOSS FACTOR
      N1=1.2
      LOSS1=-N1*RO*VD**2./8.35E08
      N2=1.4
      N2=N2+2.88
      LOSS2=-N2*RO*VD**2./8.35E08
      N3=1.0
      LOSS3=-N3*RO*VO**2./8.35E08
      VF=VO*(1.-X)/(1.-A)
      N4=0.20
      LOSS4=-N4*RO*VF**2./8.35E08
      SEPL0S=-72.0
      TERM10=LOSS1+LOSS2+LOSS3+LOSS4 +SEPL0S
C    SATISFY MOMENTUM BALANCE AROUND LOOP
      ZERO=TERM1+TERM2+TERM3+TERM4+TERM5+TERM6+TERM8+TERM10
      IF (G.GT.1.0) GO TO 600
      NIT=5.0
      PIK=-5.0

```



```

IF (VO.GT.VSAVE.AND.ZERO.GT.PSAVE) PRINT 711 ,VO,ZERO
IF (VO.GT.VSAVE.AND.ZERO.GT.PSAVE) VO=VO+100.0
IF (VO.LT.VSAVE.AND.ZERO.LT.PSAVE) PRINT 712 ,VO,ZERO
IF (VO.LT.VSAVE.AND.ZERO.LT.PSAVE) VO=VO-100.0
PSAVE=ZERO
VSAVE=VO
IF (ZERO.GE.NIT) VO=VO+NIT
IF (ZERO.LE.PIK) VO=VO+PIK
IF (ZERO.LE.NIT .AND.ZERO.GE.PIK ) GO TO 600
GO TO 888
600 CONTINUE
IF (G.GT.1.0) PRINT 605
PRINT 577,VA,VO
577 FORMAT (1H ,2F14.3)
C CALCULATE BOILER PERFORMANCE DATA
MFLOW=N*MDOTT
FEED=XEXA*MDOTA+XEX*MFLOW
PRINT 700
700 FORMAT (1H1,40X,'PRESSURE CHANGE TERMS',///)
214 FORMAT (1H ,///,5X,'**** BAILED OUT OF PROGRAM AT SATURATED VAPOR
# POINT ****')
PRINT 200
200 FORMAT (1H ,//,4X,'VISCOUS',3X,'GRAVITY',3X,'FITTINGS',3X,
#'SUBCOOL',3X,'TWO-PHASE',2X,'MOMENTUM',3X,'GRAVITY',2X,
#'MOMENTUM',//)
PRINT 701,TERM1,TERM2,TERM10,TERM3,TERM4,TERM8,TERM6,TERM5,FF
701 FORMAT (1H ,9F10.2,/////////)
C DPDV IS THE STABILITY CHECK DERIVATIVE
DPDV=(ZERO-POLD)/DV
IF (G.GT.1.0) PRINT 606,DPDV
IF (G.GT.1.0) PRINT 639,XNEW
IF (G.GT.1.0) GO TO 89
PRINT 900
900 FORMAT (1H ,38X,'BOILER PERFORMANCE DATA',///)
PRINT 201
201 FORMAT (1H ,//,2X,'CIRC LBM/HR',9X,'TUBE-X',6X,'FEED LBM/HR',
#7X,'ANN-X',5X,'TUBE FT/HR',5X,'DOWN FT/HR ',//)
PRINT 901,MFLOW,XEX,FEED,XEXA,VO,VD
901 FORMAT (1H ,6F14.5)
VVAP=RO*VO*XEX/ROG/A/3600.0
TFLO=NN*FEED
PRINT 959,TFLO
POWER=TFLO*DELH*0.2931E-03
PRINT 441,POWER
PRINT 29,VVAP
TGAS=(TB-TSAT)*EXP(-HGAS*3.14*L2*N*DOT/AIRFLO/CPA)+TSAT
VF=VF/3600.0
PRINT 560,VF
PRINT 550,TCAS
MULT=TERM4/FF/(L1+L2)
PRINT 588,MULT
SUBCL=TSAT-TI
PRINT 661,SUBCL
PRINT 18,LH
PRINT 17,TI,TE
PRINT 775,QDOT1
PRINT 33
L=1.0
99 CONTINUE
LACT =BDEP-L1+L
X=K1*L/VO
IF (LACT.GE.BDEP) X=BETA/ZETA*EXP(ZETA*(L-BDEP))+XO-BETA/ZETA
A=ACO+BCQ*ALOG(X)+CCO*ALOG(X)**2+DCO*ALOG(X)**3
RLOCL=(1.-X)**2./(1.-A)**2.

```

```

      IF (LACT.GT.TTL) GO TO 79
      L=L+0.5
      GO TO 99
79 CONTINUE
33 FORMAT (1H1,'LOCATION IN TUBE',8X,'FLOW QUALITY',4X,'VOID FRACTION
   #',6X,'LOCAL TWO-PHASE MULT',//)
560 FORMAT (1H ,//,2X,'THE EXIT LIQUID VELOCITY FT/SEC=',F10.2)
550 FORMAT (1H ,//,2X,'THE EXIT FLUE GAS TEMP-R=',F10.2)
17 FORMAT (1H , 'BRANCH INLET TEMP-R=',F10.3,3X,'BRANCH EXIT TEMP-R=',
   #F10.3,//)
18 FORMAT (1H , 'BRANCH LENGTH IN FT.=',F8.3,//)
639 FORMAT (1H , 'NEW EXIT X AFTER VELOCITY PERTURB=',F10.5)
441 FORMAT (1H , 'THE TOTAL BOILER POWER IN KW =',F12.2,//)
29 FORMAT (1H , 'EXIT VAPOR VELOCITY FT/SEC =',F12.4)
661 FORMAT (1H ,//,2X,'SUBCOOLING-R=',F14.5,//)
588 FORMAT (1H ,//,2X,'THE AVERAGE TWO-PHASE MULTIPLIER=',F14.5)
959 FORMAT (1H ,//,2X,'THE TOTAL BOILER THRU FLOW IN LBM/HR =',E10.3,
   #//)
605 FORMAT (1H ,///// ,40X,'STABILITY INDICATOR DERIVATIVES',//)
606 FORMAT (1H , 'PRESSURE DROP DERIVATIVE,PSF/FT/SEC =',E12.5)
920 FORMAT (1H ,/,2X,'BED H =',F10.4,//)
921 FORMAT (1H , 'DOWNCOMER ID-INCHES=',F10.4,//)
922 FORMAT (1H , 'THE COMBUSTION AIR FLOW LBM/HR=',E12.4,//)
775 FORMAT(1H ,//,2X,'THE HEAT FLUX PER UNIT LENGTH IN THE BED=',
   #F14.3,'BTU/HR-FT')
19 FORMAT (1H ,//,2X,'***** PROGRAM WILL TERMINATE DUE TO BOILING IN
   #HORIZONTAL BRANCH *****')
711 FORMAT (1H ,////,5X,'***** PROGRAM MAY TERMINATE DUE TO ATTEMPTED
   #OPERATION IN UNSTABLE ZONE **** CODE-1',2F12.2)
712 FORMAT (1H ,////,5X,'***** PROGRAM MAY TERMINATE DUE TO ATTEMPTED
   #OPERATION IN UNSTABLE ZONE **** CODE-2',2F12.2)
      IF (G.GT.1.0) GO TO 89
C ***** CALCULATION OF STABILITY INDICATOR DERIVATIVES *****
      G=1.5
      POLD=ZERO
      VO=VO+DV
      GO TO 888
89 CONTINUE
      HB=HB+0.10
5 CONTINUE
      STOP
      END

```

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

Appendix B

LISTING OF COMPUTER PROGRAM FOR HORIZONTAL TUBE BOILER

The variables used in the program are defined in the program listing.
The output of the program includes the following:

1. Pressure drop values
2. Exit quality
3. Flow velocities
4. Boiler power
5. Pumping power
6. Alkali metal inventory in boiling loop
7. Subcooling

IMPLICIT REAL (A-Z)
INTEGER I

```

C      *****THE INPUT PARAMETERS NECESSARY TO USE THE PROGRAM ARE
C      DEFINED IN THE FOLLOWING COMMENT CARDS.  OTHER PARAMETERS
C      ARE EITHER DEFINED IMPLICITLY OR IN COMMENTS IN THE BODY
C      OF THE PROGRAM TEXT.
C  MDOTT--MASS FLOW RATE IN BOILER TUBES  LBM/HR
C  NN--FEET OF BOILER UNDER CONSIDERATION
C  N--NUMBER OF TUBES PER FOOT OF BOILER
C  DP--ID OF BOILER TUBE IN
C  DOT-- OD OF BOILER TUBE IN
C  ENTL--ENTRANCE LENGTH OF BOILER UNHEATED FT
C  LHEAT--HORIZONTAL LENGTH OF HEATED TUBE FT
C  LVERT--VERTICAL LENGTH OF BOILER TUBE HEATED  FT
C  LINSUL--INSULATED SECTION OF BOILER TUBE-OPTIONAL-
C  SV--VERTICAL SPACING OF BOILER TUBES IN
C  SH--HORIZONTAL SPACING OF BOILER TUBES IN
C  LD--LENGTH OF DOWNCOMER FT
C  PEFF--EFFICIENCY OF PUMP
C  DE--EQUIVALENT DIAMETER OF FLUIDIZED PARTICLES
C  AIRP-- AIR PRESSURE PSI
C  RHOBED--APPARENT DENSITY OF BED MATERIAL LBM/FT3
C  AIRMU-- VISCOSITY OF AIR LBM/FT-HR
C  TB--TEMP OF FLUIDIZED BED R
C  AIRK-- THERMAL CONDUCTIVITY OF AIR  BTU/HR-FT-R
C  AIRT--TEMPERATURE OF AIR IN COMBUSTION ZONE
C  ACO,BCO,CCO,DCO,--COEFFICIENTS OF POLYNOMIAL RELATING THE ALKALI METAL
C      VOID FRACTION TO THE LOCAL FLOW QUALITY
C  MU--VISCOSITY OF ALKALI METAL LIQUID  LBM/FT-HR
C  HFE--ENTHALPY OF MAKE-UP LIQUID  BTU/LBM
C  H$AT--ENTHALPY OF SAT LIQUID  BTU/LBM
C  RHO--DENSITY OF VAPOR  FT3/LBM
C  RO--DENSITY OF SAT LIQUID  FT3/LBM
C  HFG--ENTHALPY OF VAPORIZATION  BTU/LBM
C  CP--SPECIFIC HEAT CAPACITY OF SAT LIQUID  BTU/LBM-R
C  TSAT--SATURATION TEMPERATURE R
      MDOTT=2000.0
      DO 5 I=1,25
      P=50.0
      MDOTT=MDOTT+P
C  ***** INPUT DATA FOR GEOMETRY *****
      NN=1.0
      N=149.06
      DP=0.80
      DOT=1.0
      ENTL=2.0
      LHEAT=17.5
      LVERT=36.0
      LINSUL=2.0
      SV=1.0
      SH=3.46
      LD=36.0
      PEFF=0.80
C  ***** INPUT DATA FOR FLUIDIZED BED, COAL-AIR *****
      DE=0.04
      AIRP=1.4*14.7
      RHOBED=130.0
      AIRMU=0.12
      TB=2210.0
      AIRK=C.044
      AIRT=2210.0
      AIRRHO=AIRP*144./53.3/AIRT
C  ***** PROPERTIES OF CESIUM OR POTASSIUM *****
      Q=1.0
      RO=85.47

```

FEET

INCH

FEET

INCH

INCH

INCH

PUMP

INCH

CS

CS

```

ROG=0.4077
HSAT=112.26
HFG=197.24
HFE=93.83
MU=0.339
CP=0.0568
ACQ=0.999373
BCQ=5.53601E-02
CCQ=-9.93718E-03
DCQ=-3.0889E-04
TSAT=2000.0
IF (Q.LT.1.5) PRINT 345
IF (Q.GT.1.5) PRINT 355
PRINT 90
PRINT 91
PRINT 92,N,DOT,SV,SH
PRINT 93,ENTL,LHEAT,LINSUL,LVERT
PRINT 94
C ***** PRELIMINARY CALCULATIONS *****
  DE=DE/12.
  DOT=DOT/12.
  LVERT=LVERT/12.
  DP=DP/12.0
  SH=SH/12.
  SV=SV/12.
  LD=LD/12.
  LHEAT=2.*LHEAT+LVERT
C***THE HEAT TRANSFER COEFF IN THE BED IS CALCULATED HERE***
  AR=32.17*DE**3*AIRRHO*(RHOBED-AIRRHO)/AIRMU**2*1.296E07
  NUS=0.74*AR**.22*(1.-DOT*(1.+(DOT/(DOT+SV)))/SH)**.25
C  HB--OVERALL HEAT TRANSFER COEFF BETWEEN BED AND ALKALI METAL
  HB=NUS*AIK*0.94/DE
  QDOT1=HB*3.14*DOT*(TB-TSAT)
  AP=3.14*DP**2./4.
  K1=QDOT1/(AP*HFG*RO)
  DELH=HSAT+HFG-HFE
  DE=DE*12.
  N=N/2.0
  PRINT 61,HB,AIRP,TB
  PRINT 62,RHOBED,DE
C          START MAIN CALCULATION SCHEME *****
C          FOR THE HORIZONTAL TUBE BOILER THE MAIN
C          SCHEME INVOLVES CALCULATION OF BOILER
C          PERFORMANCE AND PUMPING REQUIREMENTS FOR
C          VARIOUS MASS FLOW RATES
C *** CALCULATION OF SUBCOOLING ***
C   ASSUME VALUE OF TI
  TI=1000.0
C  TI--TEMPERATURE RESULTING FROM MIXING RETURN LIQUID WITH MAKE-UP LIQUID
888 CONTINUE
C   CALCULATE VALUE OF TI FROM ENERGY EQUATION *****
C  LSC--LENGTH OF HEATED TUBE CONTAINING SUBCOOLED LIQUID
  LSC=(MDOTT*CP/3.14/HB/DOT)*ALOG((TB-TI)/(TB-TSAT))
  XE=QDOT1*( LHEAT-LSC)/MDOTT/HFG
  TINEW=((1.-XE)*HSAT+XE*HFE)/CP
  ACC=0.10
  CHK1=TI+ACC
  CHK2=TI-ACC
  IF (TINEW.GE.CHK2.AND.TINEW.LE.CHK1) GO TO 111
  TI=(TI+TINEW)/2.
  GO TO 888
111 CONTINUE
  VO=MDOTT/RO/AP
C  FA--FRICTION FACTOR
  FA=0.680*(ALOG10(RO*VO*DP/MU))**(-2.2)

```

CS
CS
CS
CS
CS
CS
CS
CS
CS
CS

```

      FF=-RO*VO**2.*FA/DP/64.4/1.296E07
C ***** CALCULATION OF PRESSURE DROP IN LOOP *****
      S=LSC+0.01
C DS AND DL ARE INTEGRATION STEP SIZES ****
      DS=0.05
      DL=0.05
      MASS=0.0
      TERM4=0.0
      TERM6=0.0
C ***** INTEGRATION OF THE TWO-PHASE MULTIPLIER *****
C *****
C *****THE INTEGRATION IS DONE BY EULER METHOD*****
C *****
806 CONTINUE
C X--FLOW QUALITY
      X=K1*(S-LSC)/VO
      IF (X.GT.1.0) PRINT 214,MDOTT
      IF (X.GT.1.0) GO TO 5
C A--VOID FRACTION
      A=ACO+BCO*ALOG(X)+CCO*ALOG(X)**2+DCO*ALOG(X)**3
      DP4=((1.-X)**2./(1.-A)**2.)*DS
      TERM4=TERM4+DP4
      DM=((1.-A)*RO+A*ROG)*DS
      MASS=MASS+DM
      IF (S.GE.LHEAT) GO TO 805
      S=S+DS
      L=S-(LHEAT-LVERT)/2.
      IF (L.LE.0.0) GO TO 800
      IF (L.GE.LVERT) GO TO 800
      DP6=-((1.-A)*RO+A*ROG)*DL
      TERM6=TERM6+DP6
800 GO TO 806
005 CONTINUE
      XSAVE=X
905 CONTINUE
C *** TWO-PHASE MULTIPLIER IN LAST UNHEATED LENGTH, X= CONSTANT ***
      UNDP4=((1.-X)**2./(1.-A)**2.)*ENTL
      TERM4=TERM4+UNDP4
      UNDM=((1.-A)*RO+A*ROG)*ENTL
      MASS=MASS+UNDM
C *** APPLICATION OF TOTAL MULTIPLIER ***
      TERM4=TERM4*FF
C *** MOMENTUM CHANGE ***
      TERM8=-(MDOTT**2.)*((1.-X)**2./RO/(1.-A)+X**2./ROG/A)/32.2/AP
      #**2./1.296E07
      TERM5=RO*VO**2./32.2 /1.296E07
C ***** SINGLE PHASE FRICTION LOSS REGIONS *****
C *** INITIAL UNHEATED LENGTH (ENTRANCE) ***
      SPDP=-FF*(ENTL+LSC)
C *** SINGLE PHASE GRAVITY HEAD ***
      TERM2=RO*LD
C **** FITTING LOSSES ****
      N1=1.0
      LOSS1=RO*N1*VO**2/8.35E08
      SEPLOS =72.0
      TERM10=LOSS1+SEPLOS
      TERM10=-1.*TERM10
C ***** SUM OF PRESSURE LOSSES AROUND LOOP *****
C *** SINGLE PHASE FRICTION IN DOWNCOMER HAS BEEN NEGLECTED ***
      SUMDP= TERM4+TERM6+TERM5+TERM8+TERM2+TERM10 +SPDP
      PRINT 700
      PRINT 200,TERM4,TERM8,TERM10,SUMDP,TERM6
C ***** CALCULATION OF MAJOR PARAMETERS *****
      PRINT 205
      PRINT 206,MM

```

```

C ***** PUMPING POWER $$$
POWER=-MDOIT*SUMDP*N/RO/PEFF*NN/778.*0.293E-03
C ***** MAKE-UP LIQUID *****
FEED=N*MDOIT*X*NN
MDOIT=MDOIT*NN*N
C ***** BOILER OUTPUT *****
OUTPUT=FEED*DELH*0.293E-03
VVAP=RO*VO*X/ROG/A/3600.
VF=VO*(1.-X)/(1.-A)
VF=VF/3600.0
SUBCL=TSAT-TI
RHOEX=A*ROG+(1.-A)*RO
TMASS=MASS*AP+(ENTL+LSC)*AP*RO
PRINT 401,MDOIT,FEED,POWER
PRINT 402,OUTPUT,SUBCL,X,LSC
PRINT 303,XSAVE
VO=VO/3600.
PRINT 403,RHOEX,VVAP,VF,VO
PRINT 707,TMASS
MDOIT=MDOIT/N/NN
707 FORMAT (1H,'INVENTORY OF ALKALI METAL PER TUBE-LBM=',F10.4,/)
345 FORMAT (1H1,50X,'*** CESIUM * CESIUM * CESIUM ***',///)
355 FORMAT (1H1,40X,'*** POTASSIUM * POTASSIUM * POTASSIUM ***',///)
700 FORMAT (1H1,40X,'PRESSURE CHANGE TERMS',///)
214 FORMAT (1H,///,5X,'***** BAILED OUT OF PROGRAM AT SATURATED VAPOR
# POINT ***** -----MASS FLOW RATE WAS',F10.4)
90 FORMAT (1H,50X,'***** DATA FOR THIS CASE *****',///)
91 FORMAT (1H,50X,'** GEOMETRY **',///)
92 FORMAT (1H,5X,'TUBES/FT=',F8.2,5X,'TUBE OD-IN=',F5.1,3X,
# 'VERT SPACE-IN=',F5.2,3X,'HORIZ SPACE-IN=',F5.2,/)
93 FORMAT (1H,5X,'ENTR LENGTH-FT=',F5.2,3X,'HEATED LENGTH-FT=',F5.2,
# 3X,'INSUL LENGTH-FT=',F5.2,3X,'VERTICAL LENGTH-IN=',F5.1,///)
94 FORMAT (1H,40X,'** ATMOSPHERIC PRESSURE FLUIDIZED BED **',///)
61 FORMAT (1H,5X,'BED H BTU/HR-FT**2-F=',F5.2,3X,'BED PRESSURE-PSIA=
# ',F6.1,3X,'BED TEMP-R=',F7.1,/)
62 FORMAT (1H,5X,'BED DENSITY-LBM/FT**3=',F7.1,3X,'EQUIV PARTICLE DI
# A-IN=',F6.5,/)
200 FORMAT (1H,3X,'TWO-PHASE-',F8.2,3X,'MOMENTUM-',F8.2,3X,'FITTING'
# ,F7.2,3X,'TOTAL-',F8.2,20X,F8.2,///)
205 FORMAT (1H,/,45X,'*** BOILER CHARACTERISTICS ***',///)
206 FORMAT (1H,10X,'*** VALUES ARE FOR BOILER-BED LENGTH OF',F6.2,
# 'FT *****',///)
401 FORMAT (1H,5X,'CIRCULATION-LBM/HR=',F10.2,3X,'FEED-LBM/HR=',
# F10.2,3X,'PUMP POWER-KW=',E10.3,/)
402 FORMAT (1H,5X,'BOILER OUTPUT-KW=',F10.2,3X,'SUBCOOL-F=',F8.1,2X,
# 'EXIT QUALITY=',2F8.4,/)
303 FORMAT (1H,5X,'THE QUALITY AFTER THE FIRST HEATED SECTION WAS',
# F8.4,/)
403 FORMAT (1H,5X,'EXIT DENSITY-LBM/FT**3=',F8.2,3X,'VAPOR-FT/S=',
# F8.2,3X,'LIQUID FT/S=',F8.2,3X,'NOMINAL FT/S=',F8.2,/)
5 CONTINUE
STOP
END

```


THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

Internal Distribution

1. S. I. Auerbach	35. J. R. McWherter
2. Seymour Baron	36-38. W. R. Mixon
3. M. Bender	39-43. J. P. Nichols
4. R. E. Brooksbank	44. J. C. Oakes
5. D. A. Canonico	45-46. T. W. Pickel
6. F. L. Culler	47. H. Postma
7. G. G. Fee	48. M. W. Rosenthal
8. D. E. Ferguson	49. T. H. Row
9. L. M. Ferris	50. Royes Salmon
10. M. H. Fontana	51-60. G. Samuels
11. A. P. Fraas (consultant)	61. C. D. Scott
12. W. Fulkerson	62. M. R. Sheldon
13-22. R. L. Graves	63. I. Spiewak
23. W. L. Greenstreet	64. H. E. Trammell
24. R. H. Guymon	65. D. B. Trauger
25. R. S. Holcomb	66. G. D. Whitman
26. G. R. Jasny, Y-12	67. M. K. Wilkinson
27. J. E. Jones	68. L. V. Wilson
28. M. A. Karnitz	69. R. G. Wymer
29. M. E. Lackey	70. G. P. Zimmerman
30. Milton Levenson	71. ORNL Patent Office
31. D. B. Lloyd	72-73. Central Research Library
32. R. E. MacPherson	74. Document Reference Section
33. A. P. Malinauskas	75-77. Laboratory Records Department
34. L. E. McNeese	78. Laboratory Records (RC)

External Distribution

79. R. Beck, Coal Conversion and Utilization, Division of Fossil Energy Research, ERDA, Washington, D.C. 20545
80. W. M. Crim, Coal Conversion and Utilization, Division of Fossil Energy Research, ERDA, Washington, D.C. 20545
- 81-82. Steven Freedman, Coal Conversion and Utilization, Division of Fossil Energy Research, ERDA, Washington, D.C. 20545
- 83-92. Carey Kinney, Coal Conversion and Utilization, Division of Fossil Energy Research, ERDA, Washington, D.C. 20545
93. M. B. Neuworth, Coal Conversion and Utilization, Division of Fossil Energy Research, ERDA, Washington, D.C. 20545
94. Director, Research and Technical Support Division, ERDA, ORO
- 95-334. Given distribution as shown in TID-4500 under category UC-90f