THE UNIVERSITY OF MICHIGAN
COLLEGE OF ENGINEERING
Department of Mechanical Engineering

Student Project Reports

INVESTIGATION OF DESIGN MEANS FOR HOME LAUNDRY APPLIANCES

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SIMULATION OF THE BALANCING MECHANISM ON THE COMBINATION WASHER-DRYER

Jack P. Smith

1. GOALS OF THE SIMULATION PROJECT

The first step in working out a computer simulation of the self-balancing washer was to formulate a model of the system. It was recognized that this model would involve those aspects of the machine pertinent to the high-speed spin condition when the balance control is in operation. From this an analytical model was to be derived including its equations of motion.

Second, it was desired to develop a computer simulation from this model which would, for a given set of input conditions, give the time response and other important data on the system operation.

Third, the computer program was to be used as a design tool. During this phase of the project the computer model would be run under different conditions and an attempt made to glean from the results possible design recommendations. Further it was desired to show by example how the program could be used as a design tool.

2. DEVELOPMENT OF A MODEL

A. DESCRIPTION OF FIRST MODEL

Figure 1 is a diagram representing the combination washer-dryer. As the figure indicates, the tank is supported from the bottom by the base plate attached to a channel frame. The position of the balance control device is also shown. The diagram is the mirror image of the actual configuration. This is so that the cylinder rotates in the counterclockwise direction, thus simplifying the trigonometry.

Figure 2 is a diagram of the first model. The suspension of the tank has been represented by the torsional spring on the bottom. The geometric center of the tank is allowed to move in a plane perpendicular to the tank's axis. Either rectilinear or cylindrical coordinates could be used. Here the cylindrical coordinates r and ψ locate the tank's moving geometric center relative to its static center.

The belt which drives the tank is elastic. This effect causes

$$\dot{\Omega} = \dot{\theta} + \dot{\gamma}$$

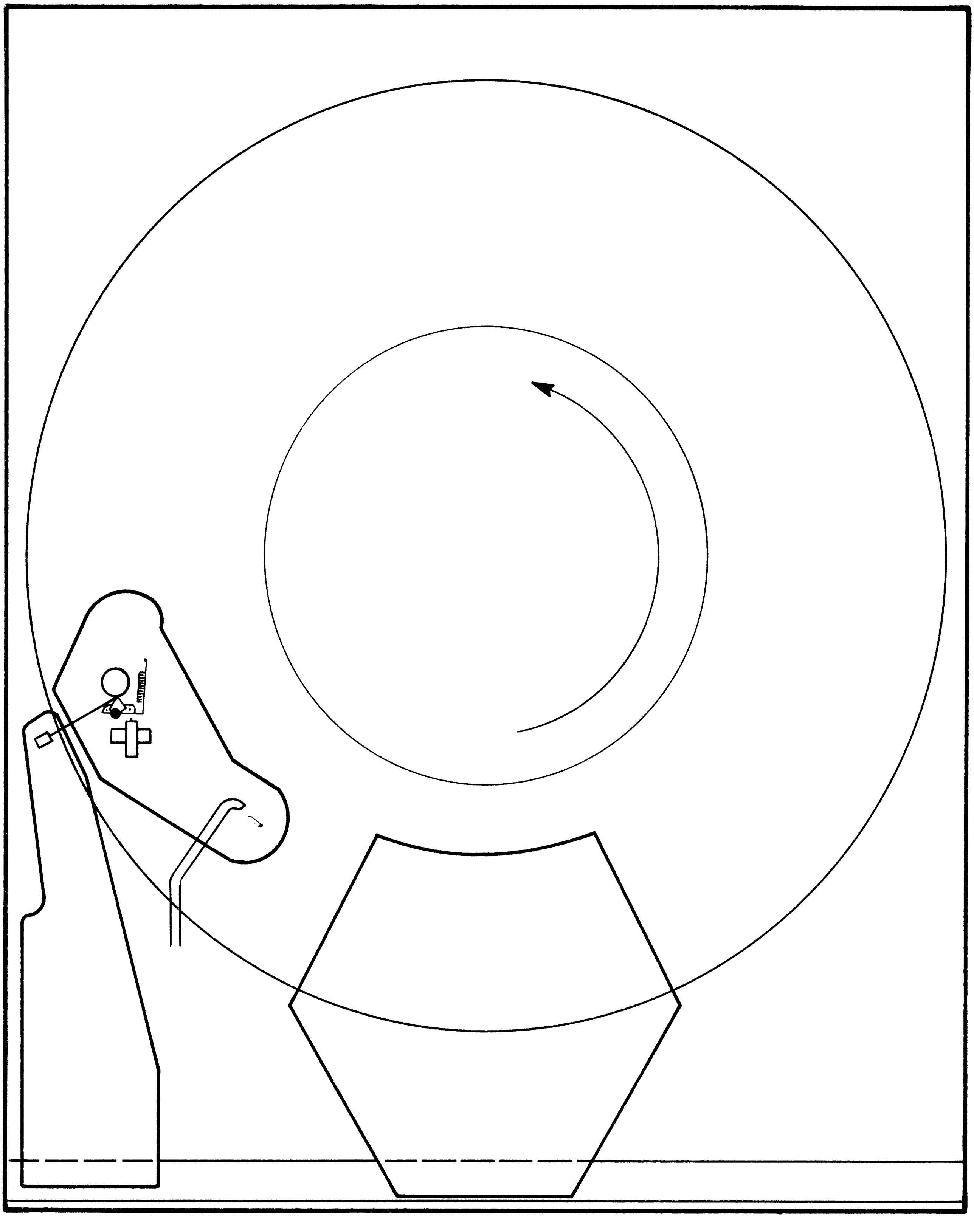


Figure 1. Pictorial diagram of machine.

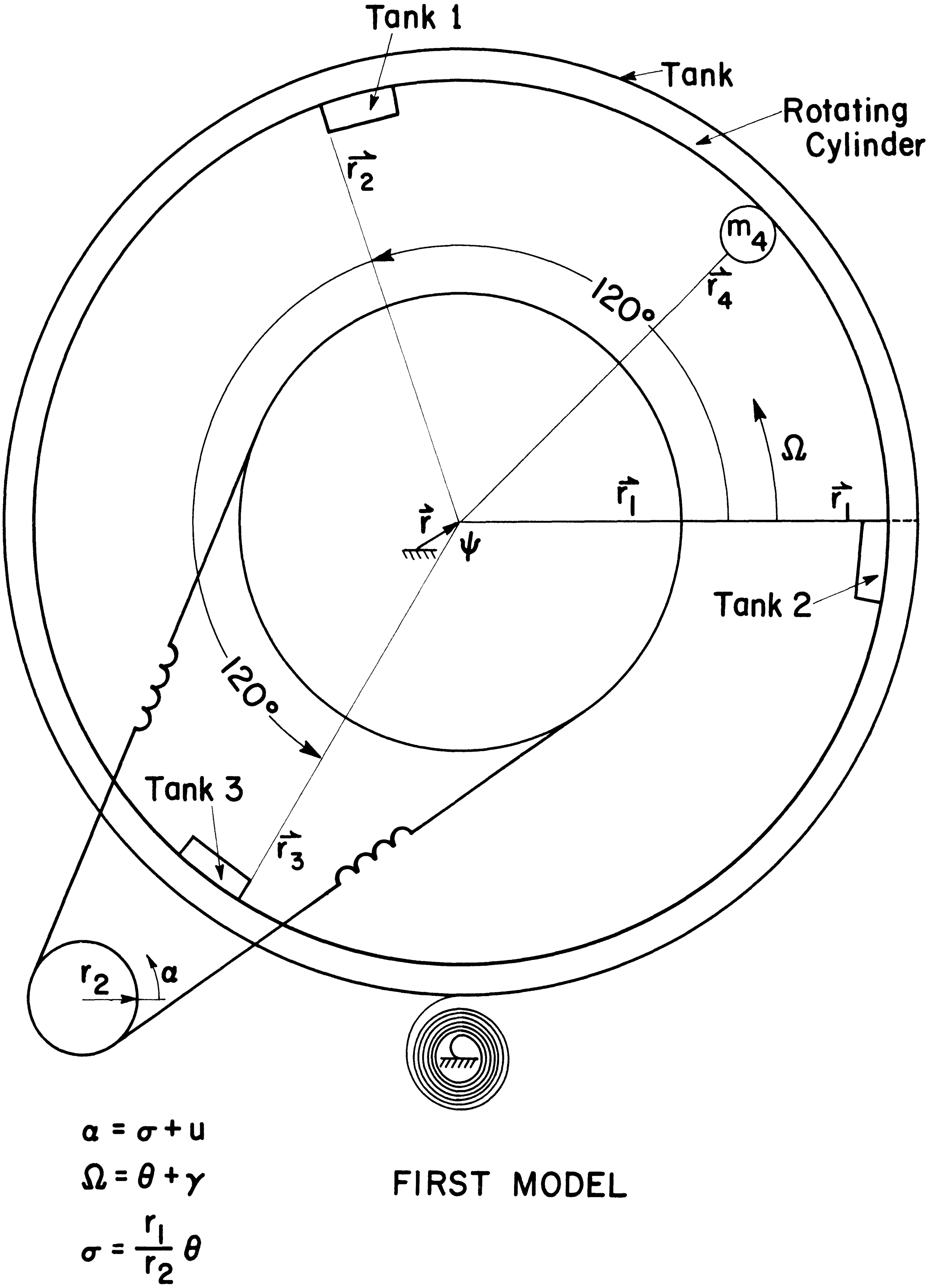


Figure 2. First model.

which says that $\dot{\Omega}$, the angular velocity of the tank, is equal to $\dot{\theta}$, the steady state velocity, plus $\dot{\gamma}$, a superimposed oscillatory velocity resulting from the belt's elasticity. Likewise for the drive take off,

$$\dot{\alpha} = \dot{\sigma} + \dot{\mu}$$

where $\dot{\alpha}$ is the velocity of the drive pulley. $\dot{\sigma}$ is the steady state velocity, and $\dot{\mu}$ is the oscillatory velocity. The two steady state coordinates will be related by the equation

$$\sigma = \frac{r_1}{r_2} \theta$$

where r_1/r_2 is the ratio of the two pulleys' radii. Thus this is a 5 degree of freedom system. θ, γ, μ, r, and ψ are independent coordinates. σ is related to θ by the above constraint.

B. EQUATIONS OF MOTION

It would be at best difficult to derive the equations of motion for a system such as this by a Newtonian or force-balance approach. Also a hazard of such an approach is that unexpected cross product terms are easily overlooked. A better method is to use the Lagrange energy formulation. The Lagrange equation is:

$$\frac{d}{dt}\left(\frac{\partial(T-V)}{\partial q_i}\right) - \frac{\partial(T-V)}{\partial q_i} = Q_i$$

In this equation

T	is an expression for the kinetic energy of the system
V	is the potential energy of the system
q_i	corresponds to a generalized coordinate
Q_i	corresponds to the associated nonconservative force, $i = 1,2,3,\ldots,n$.

First, T and V are expressed in terms of the five coordinates, and then the equation is applied once for each coordinate where the coordinate replaces q_i

$$T = 1/2[m_1\dot{\vec{\rho}}_1^2 + m_2\dot{\vec{\rho}}_2^2 + m_3\dot{\vec{\rho}}_3^2 + m_4\dot{\vec{\rho}}_4^2 + M\dot{\vec{r}}^2 + I(\dot{\theta}+\dot{\gamma})^2 + I_T(\dot{\sigma}+\dot{\mu})^2]$$

$$\vec{\rho}_i = \vec{r} + \vec{r}_i$$

$$\dot{\vec{\rho}}_i = \dot{r}\,\hat{r} + \psi(\hat{k} \times \vec{r}) + (\dot{\theta}+\dot{\gamma})(\hat{k} \times \vec{r}_i)$$

$$(\dot{\vec{\rho}}_i)^2 = \dot{r}^2 + (\dot{\psi}r)^2 + (\dot{\theta}+\dot{\gamma})^2\,r_i^2 - 2(\dot{\theta}+\dot{\gamma})\dot{r}\;r_i \sin\phi_i$$

$$+ 2\dot{\psi}(\dot{\theta}+\dot{\gamma})r\;r_i\cos\phi_i$$

where ϕ_i is the angle between $\vec{r}$ and $\vec{r}_i$ and $\phi_i = \theta + \gamma + a_i - \psi$,

$$\dot{\vec{r}} = \dot{r}\,\hat{r} + \dot{\psi}(\hat{k} \times \vec{r})$$

$$\dot{\vec{r}}^2 = \dot{r}^2 + (\dot{\psi}r)^2$$

So an expression for T can be written:

$$T = 1/2\left[\sum_{i=1}^{4} m_i(\dot{r}^2 + (\dot{\psi}r)^2 + (\dot{\theta}+\dot{\gamma})^2\,r_i^2 - 2(\dot{\theta}+\dot{\gamma})\dot{r}\;r_i\sin\phi_i\right.$$

$$\left. + 2\dot{\psi}(\dot{\theta}+\dot{\gamma})r\;r_i\cos\phi_i) + M(\dot{r}^2 + (\dot{\psi}r)^2 + I(\dot{\theta}+\dot{\gamma})^2 + I_T\left(\frac{r_1}{r_2}\,\dot{\theta}+\dot{\mu}\right)^2\right]$$

The potential energy of the system, V, is determined by superposition. To start the coordinates are all set to zero then the system is changed such that one coordinate at a time has some positive value. This can be seen vectorially by

$$V_i = \int_0^{q_i} (\Sigma\,\vec{F}_i)\cdot d\vec{q}_i$$

The total V then is $\sum_{i=1}^{n} V_i$. The resulting equation for V is

$$V = 1/2\, k_x r^2 + r M_T g \sin\psi + \left(\frac{k_x r^2 + k_y r^2}{2}\right)\sin^2\psi$$

$$+ \sum_{i=1}^{4} m_i gr(\sin(\theta + \gamma + \alpha_i) - \sin\alpha_i) + V_{belt}$$

where V_{belt} is the energy stored in the belt.

The nonlinear terms in the expressions for kinetic and potential energy show up in the equations of motion. It is very desirable to get equations which are linear since the system is basically linear. If this can be done the equations come within the scope of easier solution techniques. The replacement of r and ψ, the cylindrical coordinates, by x and y rectagonal coordinates reduces some of the nonlinearity but nonlinear terms still prevail in θ and γ.

By lumping the masses into an effective mass and eccentricity, it was hoped to simplify some of the complexity associated with terms involving the four separate masses. As shown in Figure 3, this effective mass would be

$$M_e = \sum_{i=1}^{4} m_i$$

Its eccentricity would be determined by the expression

$$M\cdot\vec{e} = \sum_{i=1}^{4} m_i \vec{r}_i$$

This equation would indicate that the M and $\vec{e}$ are the equivalent in a static situation. But since they are to be used in a dynamic expression, they should also be equivalent with respect to momentum. Thus

$$\frac{d}{dt}(M\cdot\dot{\vec{e}}) = \frac{d}{dt}\sum_{i=1}^{4} m_i \dot{\vec{r}}_i$$

$$\dot{M}\dot{\vec{e}} + M\ddot{\vec{e}} = \sum_{i=1}^{4} (\dot{m}_i \dot{\vec{r}}_i + m_i \ddot{\vec{r}}_i)$$

When it was attempted to prove the above relationships, it was found that there was no way to satisfy both constraint equations simultaneously.

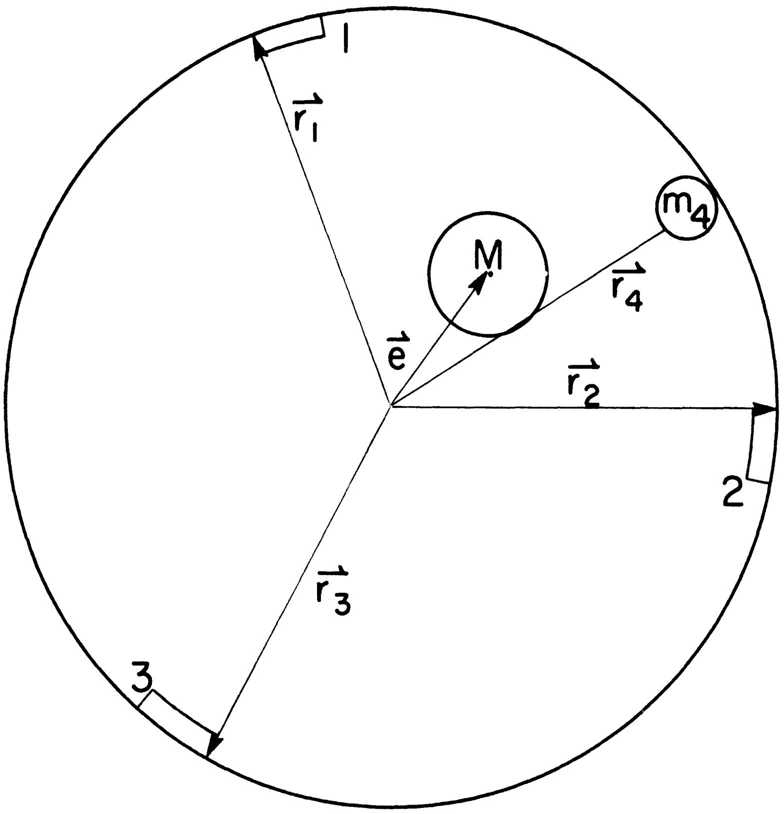


Figure 3. Three masses lumped into one effective mass and eccentricity.

C. REVISED MODEL

At this point some time was spent running the machine and determining its operating characteristics. The drive belt is so stiff that it was decided any superimposed oscillation would be small. The tank was found to oscillate about a point 20 in. below the tank center. Due to the stiffness of the system, this oscillation has an amplitude of only .016 in. when the clutch bleed valve is first touched. This is such a small arc that the motion is essentially horizontal and linear. Vertical motion is virtually nil due to the extreme stiffness in this direction. Thus it was possible to revise the model as shown in Figure 4. This is now a 2 degree of freedom system with x and θ as coordinates.

The equation for this system can be found, neglecting the inertia in the transmission:

$$T = 1/2\left[\sum_{i=1}^{4} m_i(\dot{\vec{\rho}}_i)^2 + M\dot{x}^2 + I\,\dot{\theta}^2\right]$$

$$\vec{\rho}_i = (x + r\cos(\theta+\alpha_i))\hat{i} + (r\sin(\theta+\alpha_i))\hat{j}$$

or

$$\vec{\rho}_i = x\hat{i} + \vec{r}_i$$

$$\dot{\vec{\rho}}_i = \dot{x}\hat{i} + \dot{\theta}\,\hat{k} \times \vec{r}_i$$

$$(\dot{\vec{\rho}}_i)^2 = \dot{x}^2 + \dot{\theta}^2\,r_i^2 - 2\dot{\theta}\,r_i\dot{x}\,\sin(\theta+\alpha_i)$$

so

$$T = 1/2\left[-\sum_{i=1} 2\dot{\theta}\,r\dot{x}\,\sin(\theta+\alpha_i) + \sum_{i=1}^{4} m_i\,\dot{\theta}^2\,r^2 + M_{TOT}\,\dot{x}^2 + I\,\dot{\theta}^2\right]$$

where

$$M_{TOT} = M + \sum_{i=1}^{4} m_i$$

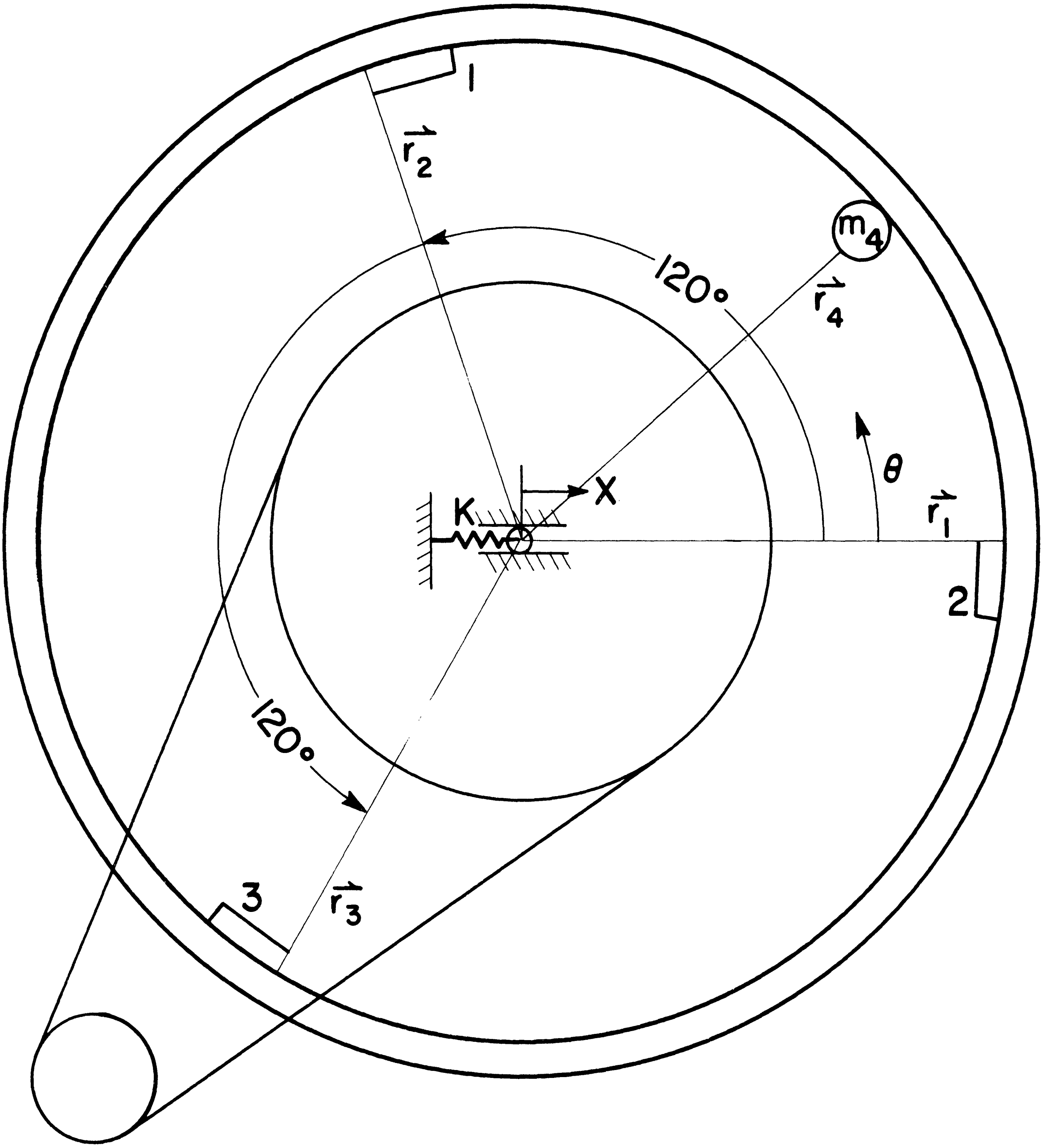


Figure 4. Final model.

The potential energy is

$$V = V_x + V_\theta$$

$$V_x = 1/2\ kx^2$$

$$V_\theta = \sum_{i=1}^{4} \int_{\alpha_i}^{\theta+\alpha_i} rmg \cos q_i(\hat{k}) \cdot dq_i(\hat{k})$$

$$V_\theta = \sum_{i=1}^{4} rm_i g(\sin(\theta+\alpha_i) - \sin \alpha_i)$$

$$V = 1/2\ kx^2 + \sum_{i=1}^{4} rm_i g(\sin(\theta+\alpha_i) - \sin \alpha_i)$$

For the x coordinate the equation of motion derived from the Lagrange formula using the above expressions for T and V is

$$\ddot{\theta} r \left[-\sum_{i=1}^{4} m_i \sin(\theta+\alpha_i) \right] + \dot{\theta} r \left[-\sum_{i=1}^{4} m_i \sin(\theta+\alpha_i) \right]$$

$$+ \dot{\theta}^2 r -\sum_{i=1}^{4} m_i \cos(\theta+\alpha_i) + \sum_{i=1}^{4} m_i x + M_{TOT}\ \ddot{x} + kx = 0$$

The second and fourth terms in this equation represent momentum transfer to the water being added to the ballast tanks. But since the water enters the ballast troughs tangentially and with a velocity not greatly different, the force on the tank due to this mass addition will be small and these terms can be neglected. Dropping these terms and rearranging

$$M_{TOT}\ \ddot{x} + kx = \dot{\theta}^2 r \sum_{i=1}^{4} m_i \cos(\theta+\alpha_i) + \ddot{\theta} r \sum_{i=1}^{4} m_i \sin(\theta+\alpha_i)$$

where the first summation represents the four centrifugal forcing functions and the second summation is the mass angular acceleration forces. This equation is a second-order differential equation, linear in x, with time varying forcing functions. The m_i are of course the three ballast tank masses and the off-balance load mass. The tank masses are going to be changing but in sequence. At any time, one tank will be changing, and the other two will have constant mass. M_{TOT} changes with time also, but not very substantially.

3. SOLUTION TECHNIQUE

An effort was made to apply the solution techniques available in control theory to the problem. CSAP (Control Systems Analysis Program) was considered but found to be too narrow to apply to this problem. The fact that the ballast tanks change in spurts or pulses necessitates the need for switches or pulsers in the control diagram to let the signal through the proper feed back loop at the proper time. Both Z and P transforms were investigated but lack of information on these techniques hindered a successful development.

A. STATE SPACE

State space was next investigated and this technique appeared to be applicable. In state space an nth order problem can be broken down into n first order systems. These are arranged in a matrix form and operated on by various matrix operations to yield a solution equation. This equation looks like a matrix form of the Duhamel superposition integral used in vibration study.

Figure 5 shows the relationship between x, the tank displacement, and the flow rate into the ballast tanks. This characteristic was found experimentally and it assumes a linear increase in flow as the displacement increases. In actuality the flow is probably increasing most rapidly when the flow of circular cross section is half uncovered than when it is only slightly uncovered. But in the interest of being able to find a solution this linearity was assumed.

Figure 6 is a diagram representing the state space system. In this system the feed forward transfer function is forced by the four centrifugal forces. The unbalance load force is of constant amplitude. The forces from the ballast tanks are of increasing amplitude where the amplitude of any one varies as the integral of x and increases only when its feed-back switch is closed. Figure 7 shows how mass accumulates in the tanks as a monotonically increasing function with time.

The state space problem is set up as follows. Let

$$x_1 = x$$

$$x_2 = \dot{x}_1 = \dot{x}$$

$$\dot{x}_2 = -\left(\frac{k}{M_T}\right)x_1 + \left(\frac{1}{M_T}\right)u$$

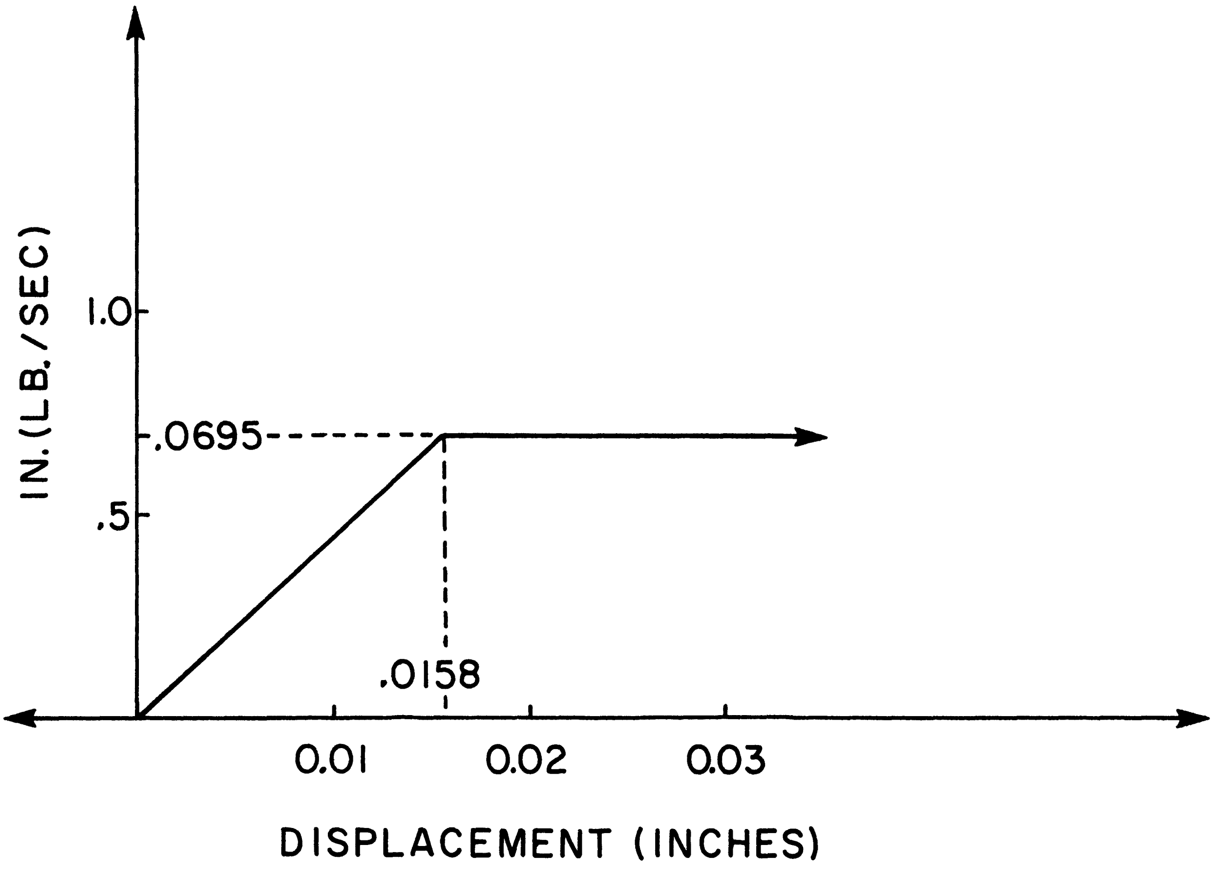


Figure 5. Ballast water flow rate vs. tank displacement.

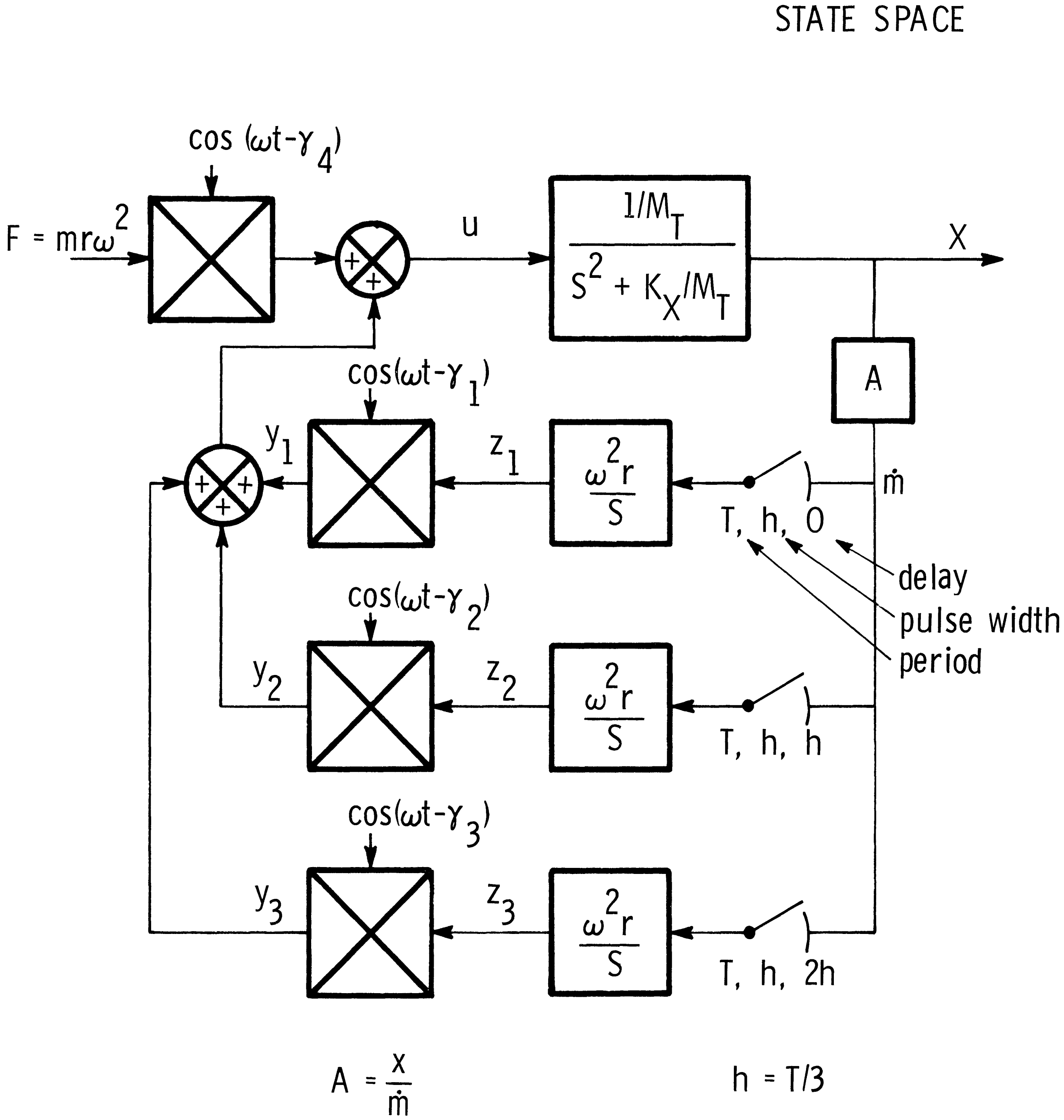


Figure 6. Flow diagram for state space solution.

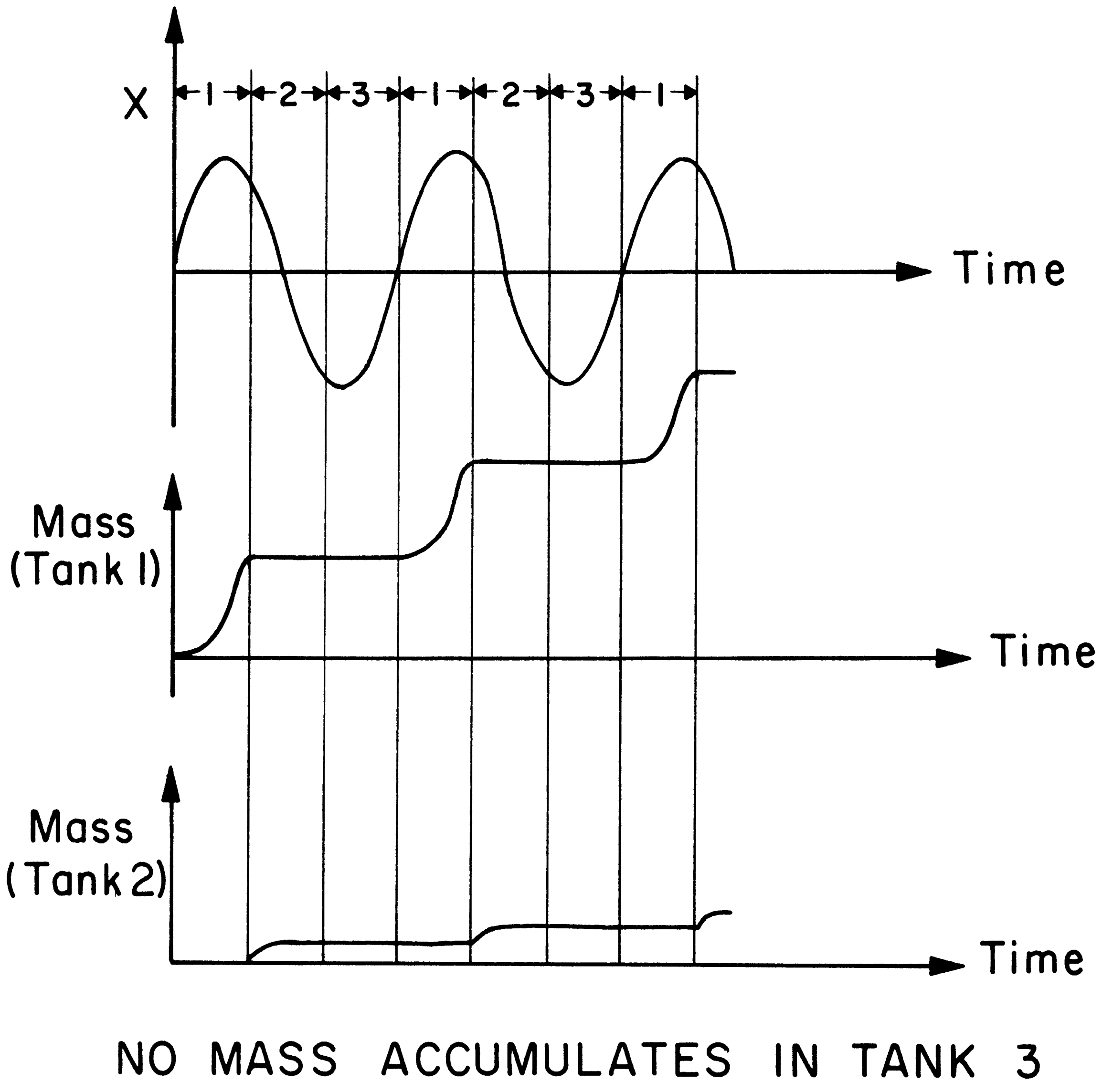


Figure 7. Manner in which mass accumulates in ballast tank #2.

where M_T is the total mass of the system. The above equation can be rewritten in matrix form as

$$\{\dot{x}\} = \begin{bmatrix} 0 & 1 \\ -\frac{k}{M_T} & 0 \end{bmatrix} \{x\} + \begin{bmatrix} 0 \\ \frac{1}{M_T} \end{bmatrix} u$$

where

$$\{x\} = \begin{Bmatrix} x_1 \\ x_2 \end{Bmatrix}$$

and

$$u = m_4\, r\omega^2 \cos(\omega t - \gamma_4) + y_1 + y_2 + y_3$$

$$y_1 = \cos(\omega t - \gamma_1) z_1$$

$$y_2 = \cos(\omega t - \gamma_2) z_2$$

$$y_3 = \cos(\omega t - \gamma_3) z_3$$

$$\dot{z}_1 = \left\{\begin{matrix} \omega^2 r\ Ax \\ 0 \end{matrix}\right\} \text{when} \left\{\begin{matrix} kT < t \leq kT + T/3 \\ \text{otherwise} \end{matrix}\right. \qquad k = 0,1,2,\ldots.$$

$$\dot{z}_2 = \left\{\begin{matrix} \omega^2 r\ Ax \\ 0 \end{matrix}\right\} \text{when} \left\{\begin{matrix} kT + T/3 < t \leq kT + 2T/3 \\ \text{otherwise} \end{matrix}\right. \qquad k = 0,1,2,\ldots.$$

$$\dot{z}_3 = \left\{\begin{matrix} \omega^2 r\ Ax \\ 0 \end{matrix}\right\} \text{when} \left\{\begin{matrix} kT + 2T/3 < t \leq (k+1)T \\ \text{otherwise} \end{matrix}\right. \qquad k = 0,1,2,\ldots.$$

where A is the linear relationship between displacement and flow rate

$$A = \frac{X}{\dot{m}}$$

For the first time period $kT < t \leq kT + T/3$, the equations for $\dot{x}$ and $\dot{z}_1$ can be combined.

$$\{\dot{r}\} = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 \\ \dfrac{-k}{M_T} & 0 & \dfrac{\cos(\omega t-\gamma_1)}{M_T} & \dfrac{\cos(\omega t-\gamma_2)}{M_T} & \dfrac{\cos(\omega t-\gamma_3)}{M_T} \\ A\omega^2 r & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix} \{r\} + \begin{Bmatrix} 0 \\ \dfrac{m_4 r\omega^2\cos(\omega t-\gamma_4)}{M_T} \\ 0 \\ 0 \\ 0 \end{Bmatrix}$$

where

$$\{r\} = \begin{Bmatrix} X_1 \\ X_2 \\ z_1 \\ z_2 \\ z_3 \end{Bmatrix}$$

The equation for the second time period, when the second ballast tank is being filled or when $kT + T/3 < t \leq kT + 2T/3$, will be the same except the $A\omega^2 r$ will occupy the 4,1 position. In the equation for the third period when the third tank is filled, the $A\omega^2 r$ term will occupy the 5,1 position. Letting [B] represent the square matrix and {C} the force vector

$$\{\dot{r}\} = [B]\{r\} + \{C\}$$

The transition matrix $[\Phi(t,t_o)]$ required in the solution equation is now found

$$[\Phi(t,t_o)] = [I] + \int_{t_o}^{t} [B(\tau)]d\tau + \int_{t_o}^{t} [B(\tau_1)]\left(\int_{t_o}^{\tau_1} [B(\tau_2)]d\tau_2\right) d\tau_1 + \ldots$$

Because the problem has time varying coefficients this series form for the transition matrix Φ is necessary. In a problem with constant coefficients it is possible to obtain the transition matrix in closed form. Once the transition matrix is determined the solution equation is

$$\{r(t)\} = [\Phi(t,t_o)]\{r(t_o)\} + \int_{t_o}^{t} [\Phi(t,\tau)]\{C(t)\}d\tau$$

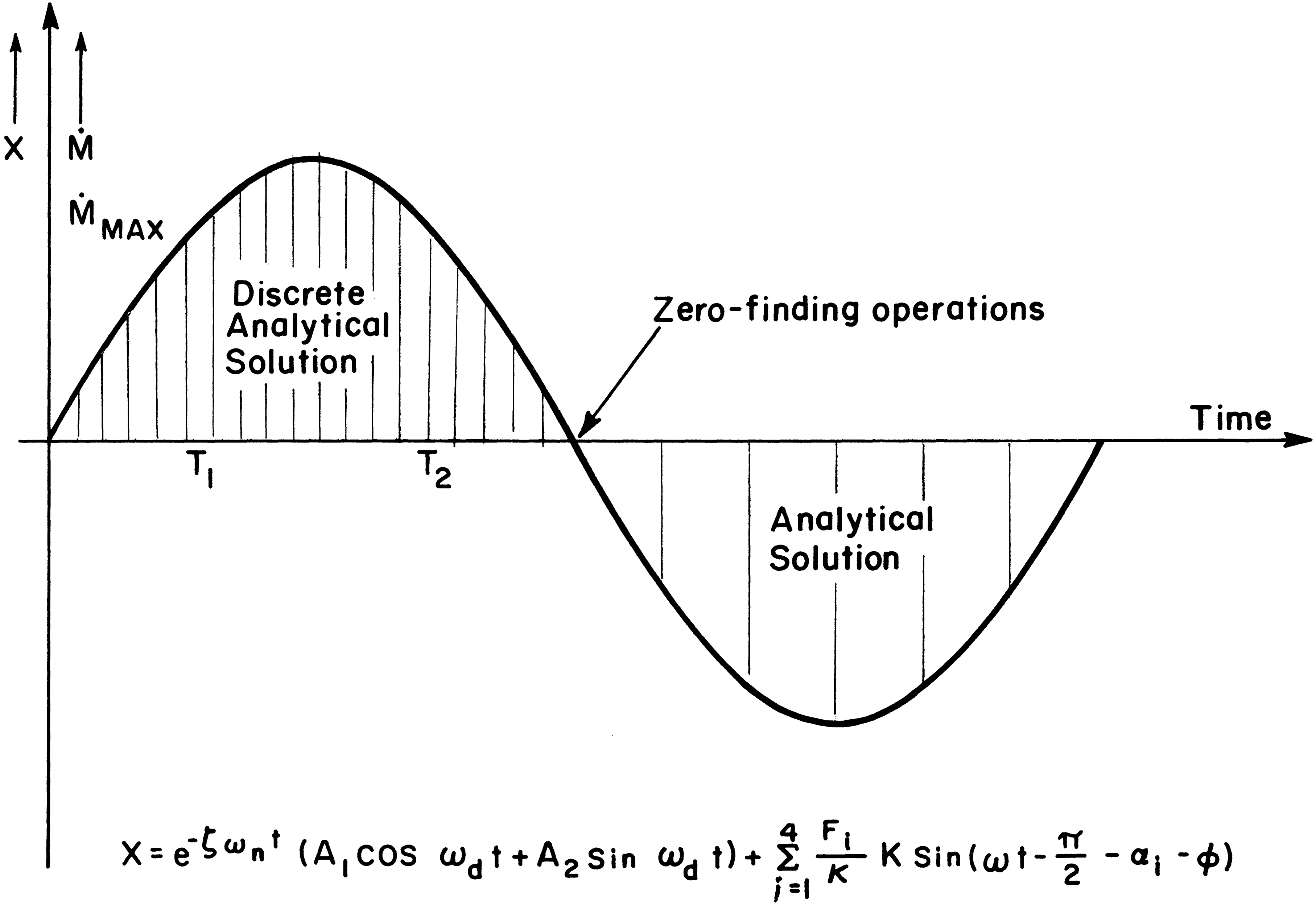
This equation looks a lot like the Duhamel superposition integral used in vibration study. It contains a transient term dependent upon the initial conditions and a steady state portion, the second term.

The clear advantage of using state space is that once the transition matrix $[\Phi]$ and $\int[\Phi]\{C\}d\tau$ are determined, the response of the system is easily obtained at any time t given the initial conditions at time t_o. In this particular problem there will be three different solution equations, one of which will correspond to each tank. And that equation will be valid while its corresponding tank is adjacent to the flow nozzle. So a time increment of 1/3 of a revolution or 120° is possible.

In attempting to obtain the solution equation, the first five terms of the transition matrix were determined. As each successive term is the integral of the product of the [B] matrix times the preceding term, and these matrices are 5 by 5, the elements of the fourth and fifth terms' matrix become very involved expressions. It was hoped that five terms would be sufficient to assure convergence, but due to the complexity of the terms it was very difficult to evaluate by hand. As a result, a computer program was developed based on this solution method. The results obtained after the program was running indicated a basic error in formulation. It turned out that in the second term of the solution equation the integral was taken over t rather than t_o. This change makes a big difference in the steady state term. Also there was question as to whether five terms assured convergence of the transition matrix.

B. ANALYTICAL METHOD

At this point it was decided to take smaller time increments, assume coefficients are constant over that increment and solve the problem analytically. This scheme is shown in Figure 8. As indicated in Figure 5, there is a maximum flow rate point past which an increase in X does not increase $\dot{m}$. Also for negative X the flow is zero. Thus in Figure 8 there are two solution schemes. When X is positive, small time increments are taken and the mass change is determined by integrating the flow rate over the time increment. This change is added to the appropriate ballast tank, the initial conditions are reset and another time increment is taken. As the displacement may increase past the point at which $\dot{m}_{max}$ has been attained, it is necessary to determine the time at which this occurs, marked T_1 on Figure 8. Likewise T_2 must be determined. When X becomes negative there is no flow rate so no mass changes, and the time increments can be increased. In Figure 8, 30° time increments are shown. It is necessary to determine the time at which X = 0 so the appropriate solution technique can be applied.



$$X = e^{-\zeta\omega_n t}\,(A_1 \cos \omega_d t + A_2 \sin \omega_d t) + \sum_{i=1}^{4} \frac{F_i}{K} K \sin\left(\omega t - \frac{\pi}{2} - \alpha_i - \phi\right)$$

Figure 8. Analytical approach towards the solution.

Originally the system was considered to be undamped. When the program based on the undamped solution was run, a time response as shown in Figure 9(a) was obtained. The high frequency superimposed signal is due to the transient portion of the solution and in an undamped system this does not attenuate. The real system has a certain amount of damping and does not behave this way. Although the damping in the real system is structural or hysteretic it was found that the addition of a small amount of viscous damping into the model attenuated the transient, "filtering" it out of the steady state signal. This response is shown in Figure 9(b).

The equation of motion with damping added becomes

$$M_{TOT}\ddot{X} + c\dot{x} + kx = \dot{\theta}^2 r \sum_{i=1}^{4} m_i \cos(\theta + \alpha_i) + \ddot{\theta} r \sum_{i=1} m_i \sin(\theta + \alpha_i)$$

The analytical solution to this equation is

$$X = e^{-\zeta\omega_n t}(A_1 \cos \omega_d t + A_2 \sin \omega_d t) + \sum_{i=1}^{4} \frac{m_i r\omega^2}{k} K \sin(\omega t + \frac{\Pi}{2} + \alpha_i - \Phi)$$
$$+ \sum_{i=1}^{4} \frac{m_i r\dot{\omega}}{k} K \sin(\omega t + \alpha_i - \Phi)$$

where $\omega = \dot{\theta}$ the angular speed and $\dot{\omega} = \ddot{\theta}$ the angular acceleration.

From Figure 4 it can be seen that:

α_1, the position of ballast tank 1 = -240°

α_2, the position of ballast tank 2 = 0°

α_3, the position of ballast tank 3 = -120°

α_4, the position of the off balance load is equal to $-\gamma_4$ in other notation, and is variable.

A_1 and A_2 are constants of integration which depend upon the initial conditions.

$$A_1 = X(0) - \sum_{i=1}^{4} \frac{m_i r\omega^2}{k} K \sin(\frac{\Pi}{2} + \alpha_i - \Phi) - \sum_{i=1}^{4} \frac{m_i r\dot{\omega}}{k} K \sin(\alpha_i - \Phi)$$

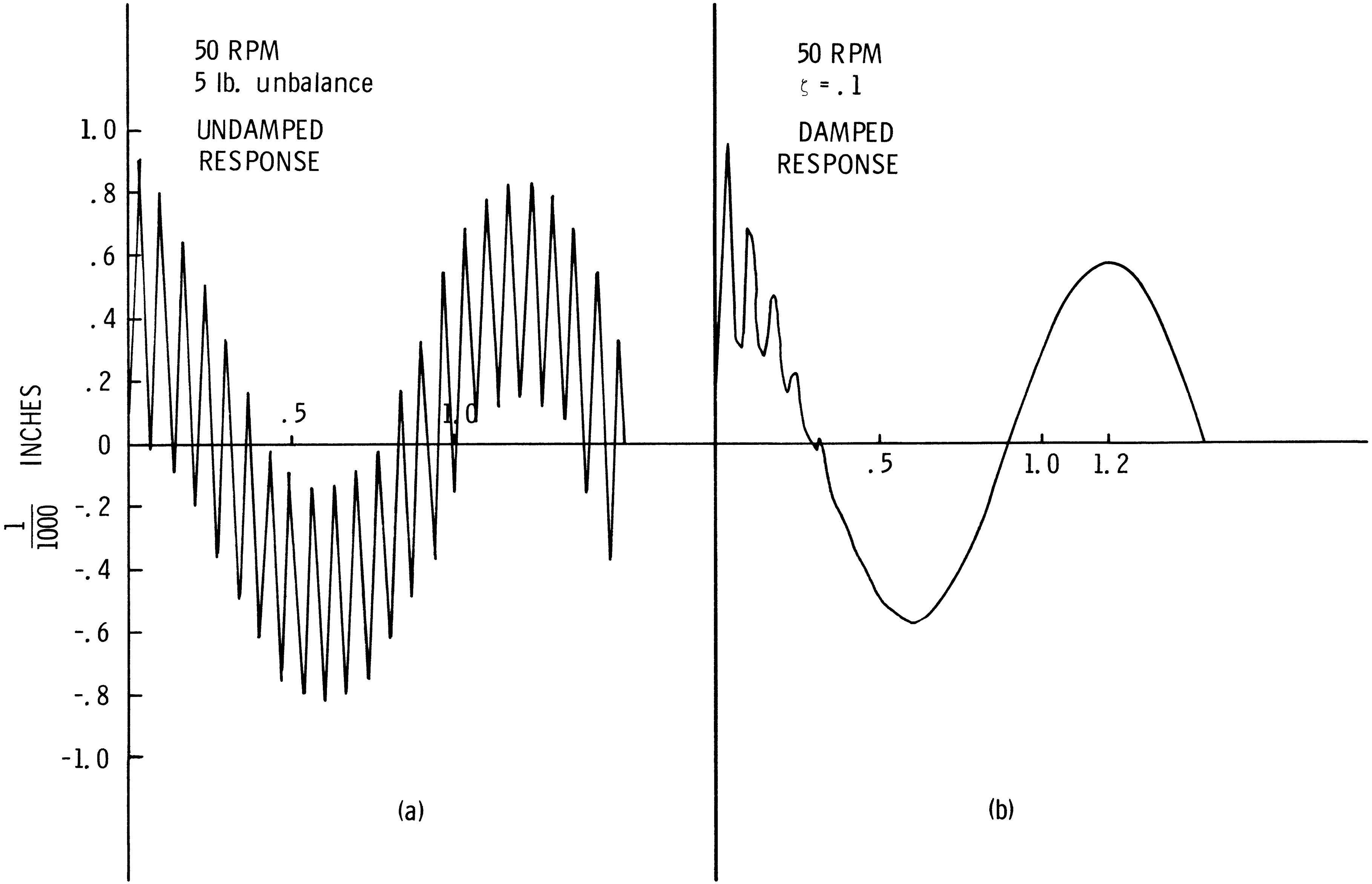


Figure 9. Effect of damping on time response.

$$A_2 = \frac{1}{\omega_d}\left[\dot{X}(0) + A_1\zeta\omega_n - \sum_{i=1}^{4}\frac{m_i r\omega^3}{k} K\cos\left(\frac{\Pi}{2}+\alpha_i - \Phi\right) - \sum_{i=1}^{4}\frac{m_i r\omega\dot{\omega}}{k} K\cos(\alpha_i - \Phi)\right]$$

Φ is the phase angle between force and displacement which is present in a damped system.

$$\Phi = \tan^{-1}\frac{2\zeta r}{1-r^2}$$

where r here is the frequency ratio ω/ω_n, not to be confused with the r in previous equations representing the tank radius. Figure 10 shows how Φ varies with ζ and the frequency ratio. Also shown in Figure 10 is plot of K, the magnification factor. This factor enters into the solution equation and is evaluated as follows

$$K = \frac{1}{\sqrt{(1-r^2)^2 + (2\zeta r)^2}}$$

where r is the frequency ratio.

To apply the solution equation the constants K and Φ are first evaluated, then the constants of integration A_1 and A_2 are determined based on the initial conditions. Then these values are used in the solution equation itself.

4. COMPUTER SIMULATION

Now follows a discussion of the computer program developed to simulate the machine's operation. Figures 11(a) and (b) show a simplified flow diagram for the main program, a listing of which begins on page 36. Note the diagrams shown in Figure 11(b) are connected through points ⑩ and (106). The program begins by making the necessary declarations and reading the user's input. Certain initializations are made and ISTART is set to 1. Additional input can be read if either INOUT or ITANK of the first input are set equal to anything but 1. Briefly, INOUT allows the user to control the program's output. It is possible to blank out certain portions of the output with this control. ITANK can be used if it is desired to start the run with a certain amount of mass in

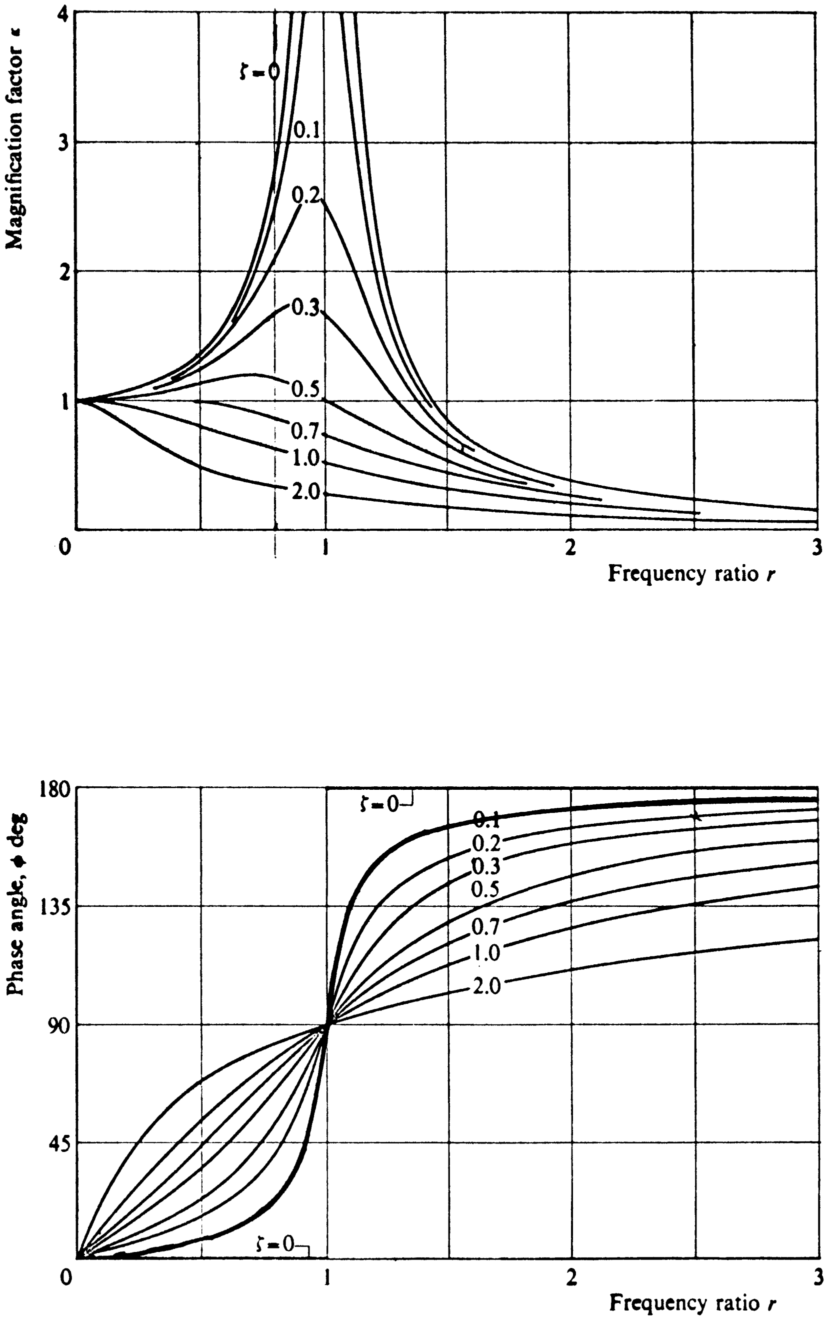
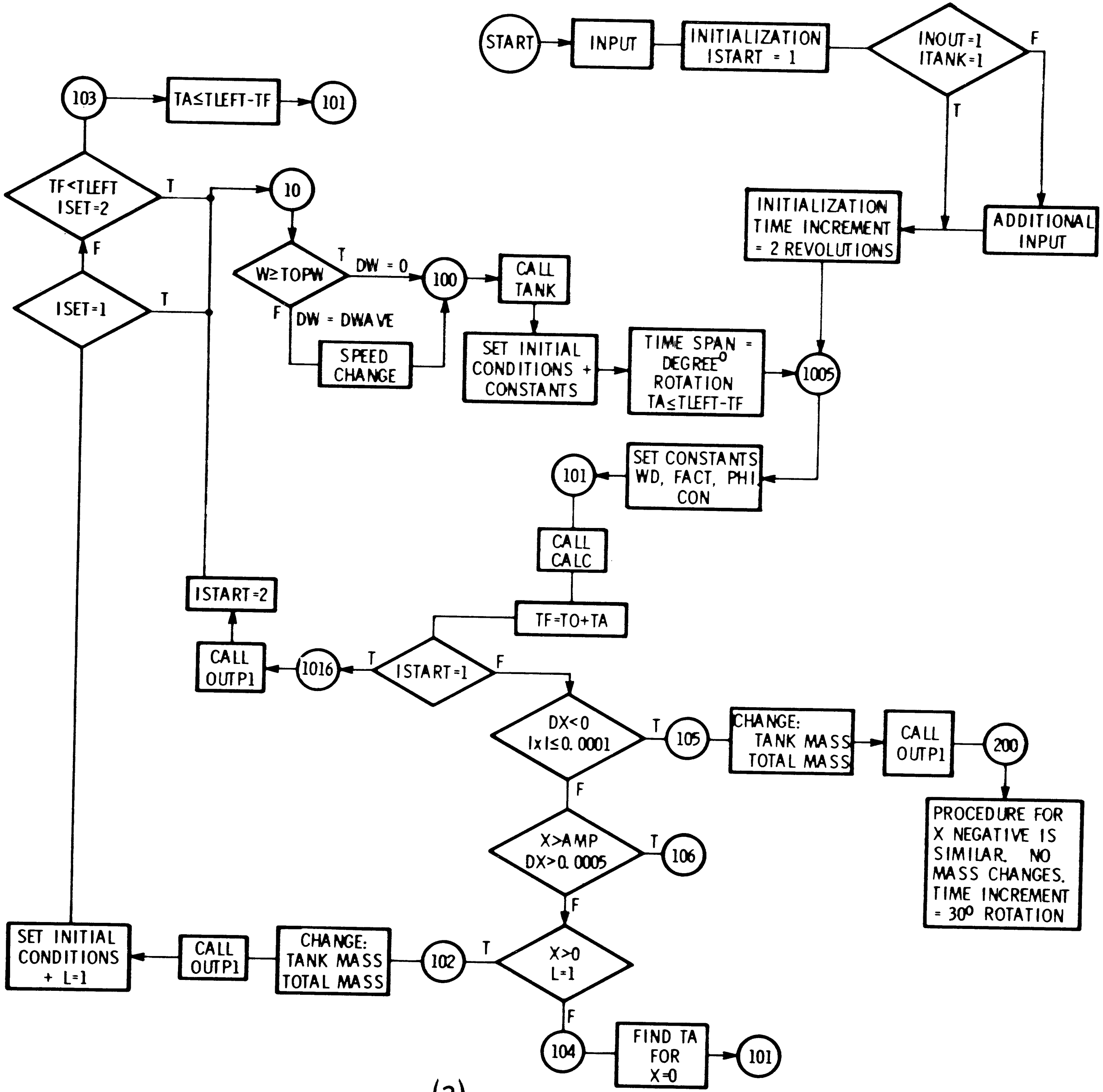
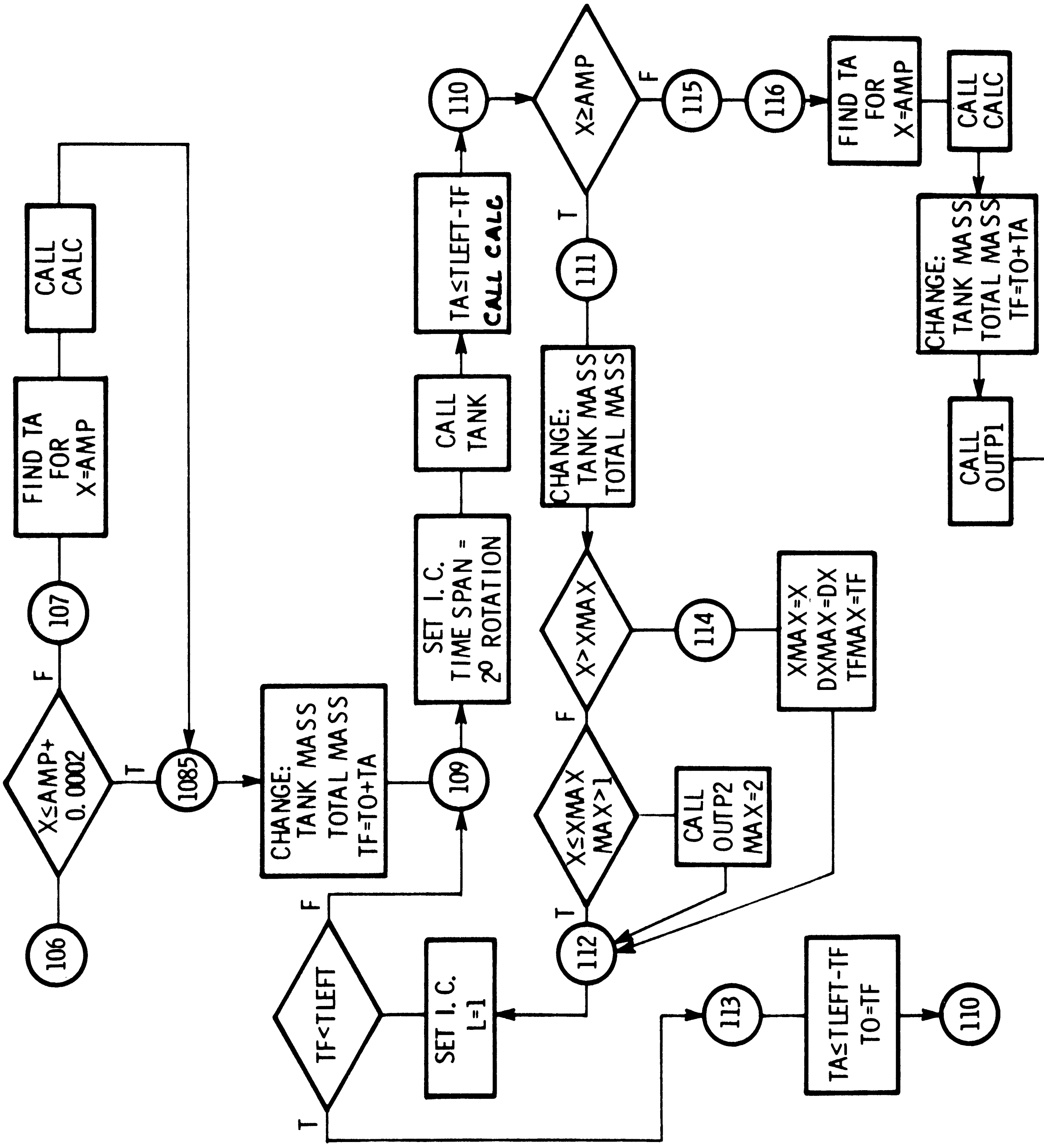


Figure 10. Effect of damping on phase angle and magnification factor.



(a)

Figure 11. Main program flow diagram.



(b)

Figure 11. (Concluded)

the ballast tanks. Normally, however, INOUT and ITANK will be equal to 1 and this additional input will be skipped. The first time increment is taken as two rotations of the tank. This is to get past that portion of the time response where the transient is significant and into the smooth steady state response (see Figure 9(b)). Next the constants required by the solution equation are calculated. FACT and PHI are K and Φ described above. CALC is the subroutine called which takes the initial conditions and the constants just evaluated and determines the system response at the end of the given time increments and returns this information to the main program. The final time, TF, is set equal to the initial time, TO, plus the time increment, TA. If the program has just started and ISTART = 1, it outputs the information through subroutine OUTP1. ISTART is now set to 2 indicating the initial large time increment has been taken. At ⑩ it is determined whether or not to increment the angular speed of the tank. If the speed, W, is already greater than the top speed desired, TOPW, the speed change routine is skipped. Also ISET must be equal to 1 for the speed to increase. ISET will be 1 only if the displacement of the tank on the previous half cycle was less than the desired amplitude, AMP. TANK is a subroutine which determines which ballast tank is adjacent to the flow nozzle and how much longer it will be there. The program sets the initial conditions and constants, and takes a time increment equal to the number of degrees of rotation as specified by input variable DEGREE. It makes sure, however, that this increment will not overlap two of the tanks. It does this by making sure $TA < TLEFT - TF$ where TLEFT is the time at which the end of the current ballast tank will be reached, and is determined in the subroutine TANK. It then returns to (1008) and the same course traveled before. This time, however, $ISTART \neq 1$ so it goes through the three conditionals. Normally it will pass through all three, update the mass in the ballast tanks, output the information, reset the initial conditions, and arrive back at ⑩. This process continues until the tank displacement becomes negative at which point the third conditional is not satisfied, and at (104) it finds the time at which $X = 0$ and returns to (101) for a final iteration. When $X = 0$ it switches out of the main loop and at (105) updates the masses in the ballast tanks, outputs the information, and proceeds to (200) where the procedure for negative displacement begins. As indicated on the diagram, this procedure is similar except the ballast tank masses do not change. The other condition, where it switches out of the main loop, is if $X > AMP$. AMP is the desired displacement amplitude. (106) connects to Figure 11(b). This portion of the program first accurately establishes the time at which $X = AMP$. It updates the masses in the ballast tanks and proceeds taking a 2° of rotation time increment. The following steps are similar to those described above. This continues until $X < AMP$ at which point it locates the $X = AMP$ time, calls on CALC, updates the masses, and outputs the information prior to returning to ⑩. This portion of the program is also set up to find the point at which X is the maximum (XMAX) and output this information.

A. SUBROUTINE CALC

The flow diagram for this subroutine is shown in Figure 12(a). The calling variables for CALC are TA, X, DX, AREA. DX is the velocity $\dot{X}$ and AREA is the area under the displacement curve over the time increment TA. The necessary initial conditions and constants are obtained through the COMMON/VAR statement. The angular position of the tank is determined at T_O. The transient trig terms are evaluated along with the constants of integration A1 and A2. Then after the steady state trig terms and EXP the exponential decay term are evaluated the solution equation is applied to find X, DX. AREA is determined by trapezoidal integration. This information is then returned to the main program.

B. SUBROUTINE TANK

Figure 12(b) shows a flow diagram for TANK whose calling variables are TF, TSAVE, W, ADJ, MTANK, TLEFT. These variables are defined as follows:

TF - current time in the simulation run

TSAVE - time at which present speed was reached

W - present angular speed

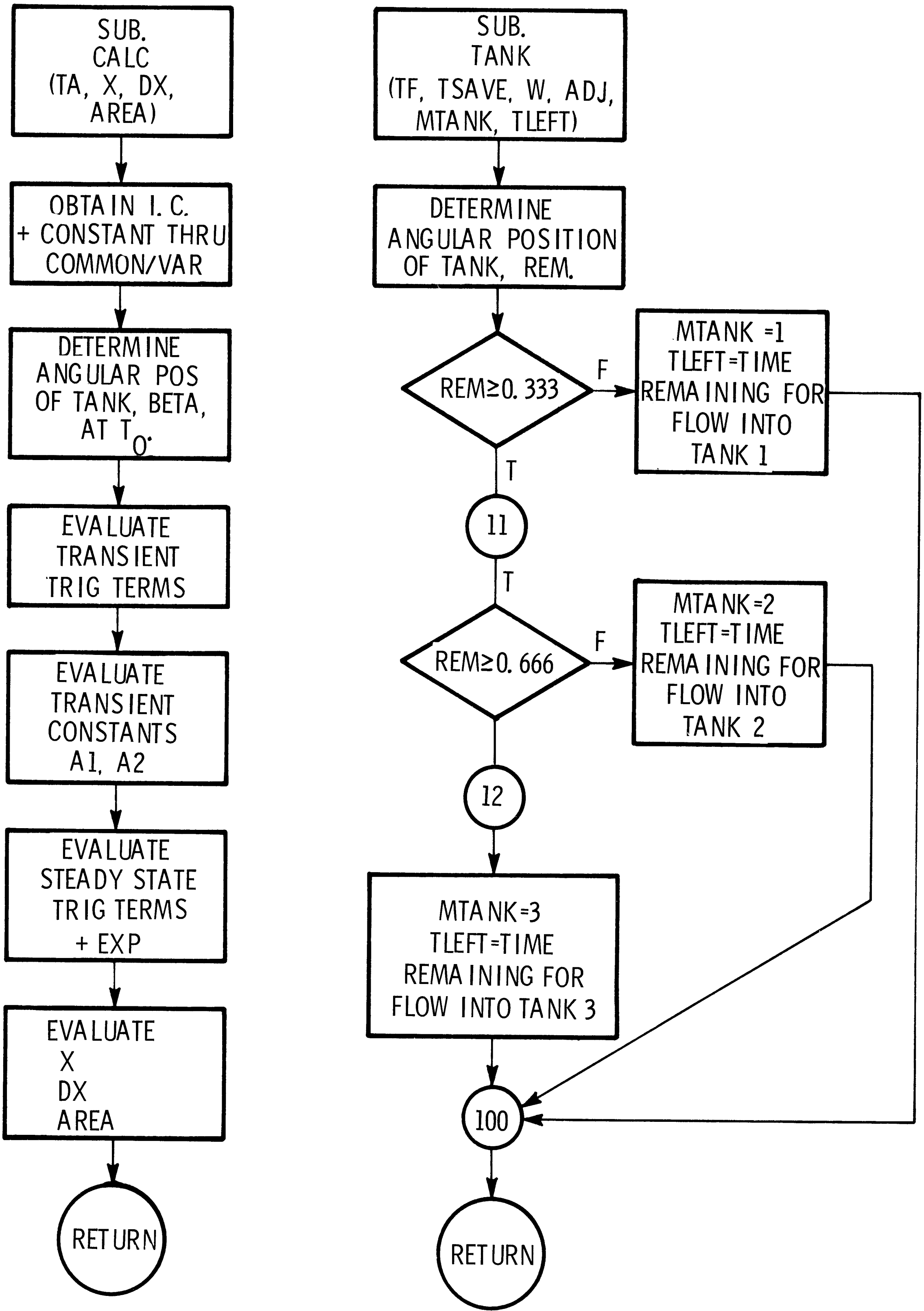
MTANK - a return variable indicating the current ballast tank

TLEFT - time at which flow stream will start filling the next ballast tank

First the position of the tank in fractions of a revolution from the normal position (see Figure 4) is determined as REM. Then according to whether REM $< 1/3$ or $1/3 \leq$ REM $< 2/3$ or REM $> 2/3$ the ballast tank is determined as #1, #2, or #3. MTANK is set to this integer value, TLEFT is determined and the information is returned to the main program.

C. SUBROUTINE FIND

Figure 13 shows the flow diagram for FIND. This subroutine is called to interpolate a given table of values for X and TF to locate the time at which X has a certain value. The calling variables are:



(a) (b)

Figure 12. Subroutine flow diagrams.

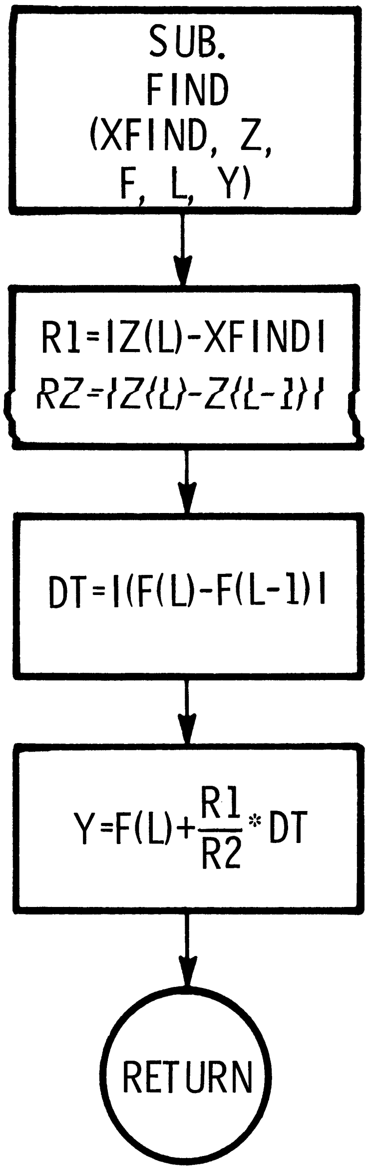


Figure 13. Subroutine flow diagram.

XFIND - the value of displacement desired

Z - table of displacement values

F - corresponding table of times

L - subscript of the last element of the above tables. The desired point is between elements L and L-1.

Y - the returned value of time corresponding to XFIND

The subroutine does a linear interpolation to find Y according to

$$Y = F(L) + \left(\frac{|Z(L) - XFIND|}{|Z(L) - Z(L-1)|}\right) |F(L) - F(L-1)|$$

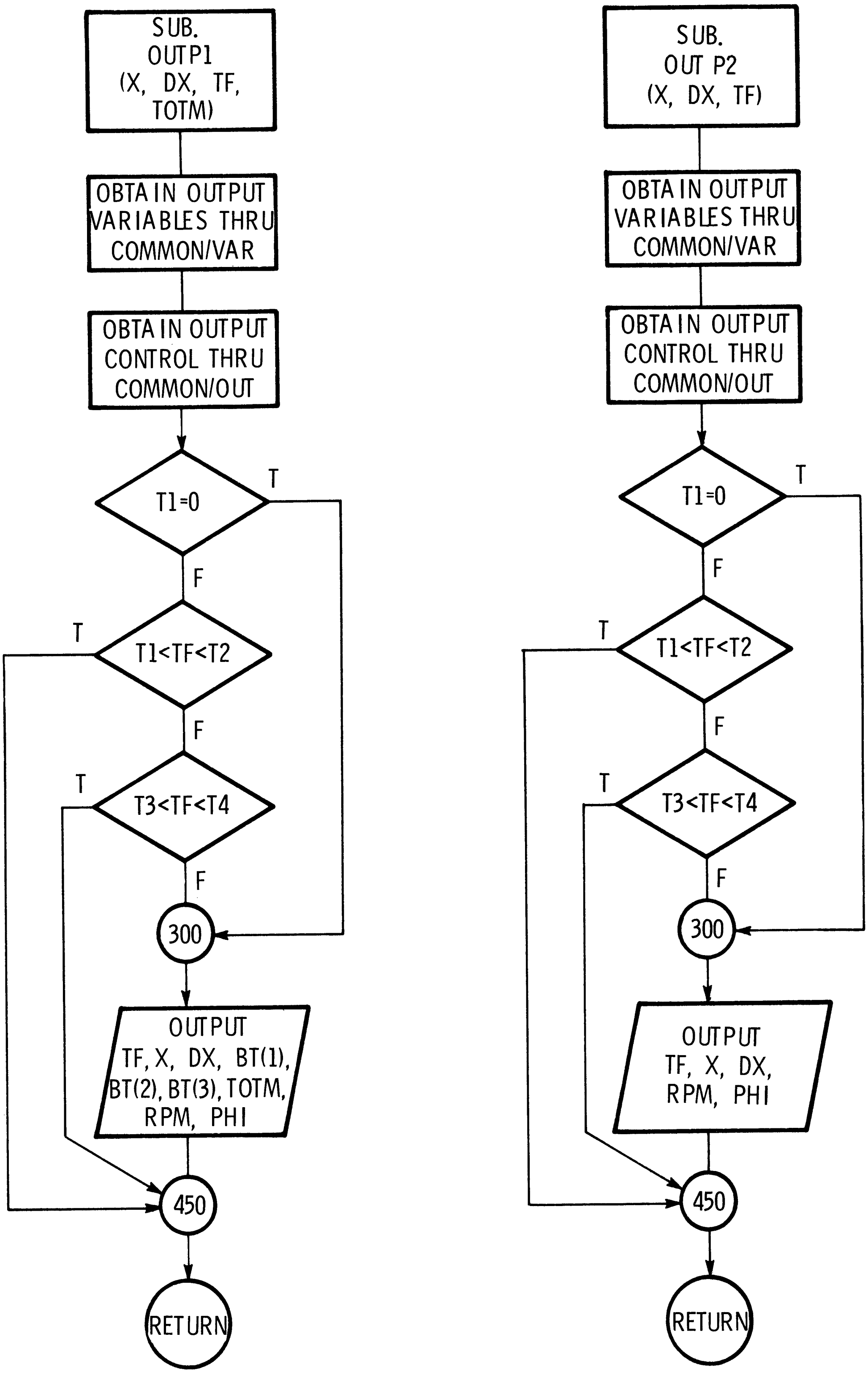
Y is then returned to the main program.

D. SUBROUTINE OUTP1

This subroutine has a flow diagram as shown in Figure 14(a). It is called with the variables X, DX, TF, and TOTM where the latter is the total system weight. Output variables are obtained through the COMMON/VAR statement. Output control variables are obtained through the COMMON/OUT statement. As mentioned before these variables allow the user to blank out certain portions of the OUTPUT. If T1 = 0 as preset in the main program, this output control is by-passed to (300). If T1 $\neq$ 0, the next two conditionals let pass only times which are not between T1 and T2 or T3 and T4. Output between these times is not printed out as the program skips to (450). When it is desired to print the output, however, the output variables are TF, X, DX, BT(1), BT(2), BT(3), the masses in the three ballast tanks, TOTM, the total system mass, RPM, machine speed, and PHI, the phase angle between force and displacement.

E. SUBROUTINE OUTP2

This subroutine shown by the flow diagram in Figure 14(b) is identical to OUTP1 except only TF, X, DX, RPM, and PHI, are output variables. This output subroutine is called during negative displacement when no mass changes occur, and during positive displacement when displacement is at a maximum and is above the AMP level. This helps to identify this point in the output listing.



(a) (b)

Figure 14. Subroutine flow diagram.

The following is a list of input and output variables with a description of their meaning.

F. INPUT VARIABLES

RPM - starting speed in rpm

OFFBAL - weight of off-balance load in lb

G4 - position of OFFBAL load measured counterclockwise in radians from ballast tank 2

TFIN - final time of run in sec

DEGREE - amount of rotation in one time increment during the positive X half cycle. Should be less than 15°

ZETA - damping factor of the system

INOUT - output control variable. If INOUT = 1, entire time response is output. If INOUT = any other integer, portions of output can be skipped using NAMELIST/OUTPUT

FLOW - maximum flow rate in lb/sec

TOTWT - total system weight in lb

SPRING - spring constant in lb/in.

RPMPS - acceleration in rpm/sec

TOPRPM - top speed in rpm

AMP - max amplitude of X in in. when $|X|$ is greater than AMP, $\dot{m}$ = FLOW and/or acceleration = 0

ITANK - input control variable. If ITANK is set equal to any integer but 1, starting mass in the ballast tanks can be input through "TANKIN"

G. OUTPUT CONTROL

If INOUT is set not equal to 1, T1 and T2, and T3 and T4 may be read in "OUTPUT." Output between T1 and T2 sec, and T3 and T4 sec will not be printed.

H. OUTPUT COLUMNS

TIME - in sec (TF)

X - displacement of the tank center in in.

DX - velocity of the tank center in in./sec

TANK 1 - mass in tank 1, lb-sec^2/in. (BT(1))

TANK 2 - mass in tank 2, lb-sec^2/in. (BT(2))

TANK 3 - mass in tank 3, lb-sec^2/in. (BT(3))

TOT MASS - total mass of the system, lb-sec^2/in. (TOTM)

RPM - speed in rpm

PHI - phase angle between force and displacement, in radians

The following is a list of other important variables in the program listing beginning on page 36, taken in order of first occurrence.

RIN - input variable DEGREE in radians

TSAVE - reset to the current time whenever the speed is changed

ADJ - the angular position of the tank reset whenever the speed is changed

UNBAL - OFFBAL converted to mass (lb-sec^2/in.)

R - tank radius (in.)

DWSAVE - acceleration (rad/sec^2)

TOPW - TOPRPM converted to (rad/sec)

ISET - memory interger controlling acceleration. Normally ISET = 1 and acceleration can take place. ISET = 2 if AMP was reached on prior half cycle and acceleration is not permitted. (Physically air clutch has been bled)

ISTART - if set equal to 1 indicates run is beginning

DW - angular acceleration (rad/sec^2)

W - angular speed (rad/sec)

TIN - time increment (sec)

WN - natural frequency of system (rad/sec)

RATIO - frequency ratio

MTANK - number of current ballast tank

TA - time increment to be taken (sec)

TO - initial time at beginning of increment (sec)

DXO - initial velocity (in./sec)

XO - initial displacement (in.)

WIN - speed increment (rad/sec)

WD - damped natural frequency (rad/sec)

FACT - magnification factor, K

PHI - phase angle between force and displacement, Φ

AREA - integral of the displacement curve over the time increment

BT(MTANK) - mass in the ballast tank indicated by MTANK

XFIND - argument of the value to be found by subroutine FIND

RIN2 - angular increment taken during negative displacement (rad)

I. OUTPUT

An example of the output obtained is on page 44. The two types of format help to distinguish the positive and negative portions of the time response cycle. Note that there are many more interations taken during the positive displacement portion than there are during the negative.

PROGRAM LISTING

```
$SIG 50X3     T=60  P=50
**LAST SIGNON WAS: 08:19.12   04-16-71
 USER "50X3" SIGNED ON AT  12:27.14 ON 04-17-71
$LIST SPIN
                NAMELIST/DATA/RPM,OFFBAL,G4,TFIN,DEGREE,ZETA,INOUT,FLOW,
              1 TOTWT,SPRING,RPMPS,TOPRPM,AMP,ITANK
                READ(5,DATA)
                DIMENSION Z(50),F(50),BT(3),BBT(3)
                COMMON/VAR/TO,TSAVE,W,PHI,G4,XO,CON,BT,UNBAL,ZETA,WN,DXO,
              1 WD,ADJ,DW
                COMMON/OUT/T1,T2,T3,T4

                EQUIVALENCE(BBT(1),BT(1)),(BBT(2),BT(2)),(BBT(3),BT(3))
                RIN=DEGREE*6.28319/360.0
                WRITE(6,2)
          2     FORMAT('     TIME',6X,' X',8X,' DX',3X,' TANK 1',3X,' TANK 2',3X,
              1 ' TANK 3',3X,' TOT MASS  RPM',5X,' PHI')
                TSAVE=0.0
                DATA BBT,X,DX,TF/0.,0.,0.,0.,0.,0./
                T1=0.0
                FL=FLOW/(AMP*386.)
                ADJ=0.0
                UNBAL=OFFBAL/386.
                TOTM=TOTWT/386.
                R=12.
                DWSAVE=RPMPS*6.28319/60.0
                TOPW=TOPRPM*6.28319/60.0
                L=1
                ISET=2
                ITEST1=1
                ITEST2=1
                ISTART=1
                DW=0.0
                IF(INOUT.EQ.1) GO TO 5
                NAMELIST/OUTPUT/ T1,T2,T3,T4
                READ(5,OUTPUT)
          5     CONTINUE
                IF(ITANK.EQ.1) GO TO 6
                NAMELIST/TANKIN/BT
                READ(5,TANKIN)
          6     CONTINUE
                W = (RPM/60.0)*6.28319
                TIN=RIN/W
                WN=SQRT(SPRING/TOTM)
                RATIO=W/WN
                MTANK=1
                TA=(2.0*60.0)/RPM
                TO=TF
                DXO=DX
                XO=X
                GO TO 1005
           10   IF(TF.GE.TFIN) GO TO 300
                IF(W.GE.TOPW) GO TO 11
                IF(ISET.EQ.1) GO TO 12
          11    DW=0.0
                GO TO 100
          12    DW=DWSAVE
                WIN=DW*TA
                WNEW=W+WIN
                REV=(TF-TSAVE)*W/6.28319
```

```
      IREV=REV+ADJ
      REM=REV+ADJ-IREV
      ADJNEW=REM
      TIN=RIN/WNEW
      L=1
      TSAVE=TF
      W=WNEW
      ADJ=ADJNEW
  100 WN=SQRT(SPRING/TOTM)
      CALL TANK(TF,TSAVE,W,ADJ,MTANK,TLEFT)
      RATIO=W/WN
      TO=TF
      DXO=DX
      XO=X
      TA=TIN
      TILEFT=TLEFT-TF
      IF(TA.GT.TILEFT) TA=TILEFT
 1005 WD=(SQRT(1.0-ZETA**2))*WN
      FACT=1.0/(SQRT((1.0-RATIO**2)**2+(2*ZETA*RATIO)**2))
      PHI=ATAN((2.0*ZETA*RATIO)/(1.0-RATIO**2))
      CON=(R*W*W*FACT)/SPRING
  101 CONTINUE
      CALL CALC(TA,X,DX,AREA)
      TF=TO+TA
      IF(ISTART.EQ.1) GO TO 1016
      IF(DX.LT.0.0 .AND.ABS(X).LE.0.0001) GO TO 105
      IF(X.GT.AMP   .AND.DX.GT.0.0005) GO TO 106
      IF(X.GT.0.00.AND.L.EQ.1) GO TO 102
      GO TO 104
 1016 CALL OUTP1(X,DX,TF,TOTM)
      ISTART=2
      GO TO 10
  102 BT(MTANK)=BT(MTANK)+FL*AREA
      TOTM=TOTM+FL*AREA
      CALL OUTP1(X,DX,TF,TOTM)
      L=1
      XO=X
      DXO=DX
      IF(ISET.EQ.1) GO TO 10
      IF( TF.LT.TLEFT .AND. ISET.EQ.2) GO TO 103
      GO TO 10
  103 TILEFT=TLEFT-TF
      IF( TA.GT.TILEFT) TA=TILEFT
      TO = TF
      GO TO 101
  104 Z(L)=X
      F(L) = TF
      TA= TA-0.01745/W
      IF(X.GE.0.0) GO TO 1045
      L=L+1
      CALL CALC(TA,X,DX,AREA)
      TF=TO+TA
      GO TO 104
 1045 XFIND=0.0
      CALL FIND(XFIND,Z,F,L,Y)
      TA=Y-TO
      L=1
      GO TO 101
  105 BT(MTANK)=BT(MTANK)+FL*AREA
      TOTM=TOTM+FL*AREA
```

```
      CALL OUTP1(X,DX,TF,TOTM)
      IF(ITEST1.EQ.1) ISET=1
      ITEST2=1
      GO TO 200
  106 MAX=1
      XMAX=0.0
      IF(X.LE.(AMP+0.0002)) GO TO 1085
  107 Z(L)=X
      F(L)=TF
      TA=TA-0.01745/W
      IF(X.LE.AMP) GO TO 108
      CALL CALC(TA,X,DX,AREA)
      TF=TO+TA
      L=L+1
      GO TO 107
  108 XFIND=AMP
      CALL FIND(XFIND,Z,F,L,Y)
      TA=Y-TO
      L=1
      CALL CALC(TA,X,DX,AREA)
 1085 BT(MTANK)=BT(MTANK)+FL*AREA
      TOTM=TOTM+FL*AREA
      TF=TO+TA
  109 TA=0.0349/W
      XO=X
      DXO=DX
      TO=TF
      L=1
      CALL TANK(TF,TSAVE,W,ADJ,MTANK,TLEFT)
      TILEFT=TLEFT-TF
      IF(TA.GT.TILEFT) TA=TILEFT
  110 CALL CALC(TA,X,DX,AREA)
      TF=TO+TA
      AREA=AMP*TA
      IF(X.GE.AMP) GO TO 111
      GO TO 115
  111 BT(MTANK)=BT(MTANK)+FL*AREA
      TOTM=TOTM+FL*AREA
      IF(X.GT.XMAX) GO TO 114
      IF(X.LE.XMAX .AND. MAX.GT.1) GO TO 112
      CALL OUTP2(XMAX,DXMAX,TFMAX)
      MAX=2
  112 L=1
      XO=X
      DXO=DX
      IF(TF.LT.TLEFT) GO TO 113
      GO TO 109
  113 TILEFT=TLEFT-TF
      IF(TA.GT.TILEFT) TA=TILEFT
      TO =TF
      GO TO 110
  114 XMAX=X
      DXMAX=DX
      TFMAX=TF
      GO TO 112
  115 CONTINUE
  116 Z(L)=X
      F(L)=TF
      TA=TA-0.01745/W
      IF(X.GE.AMP) GO TO 117
```

```
      CALL CALC(TA,X,DX,AREA)
      TF=TO+TA
      L=L+1
      GO TO 116
 117  XFIND=AMP
      CALL FIND(XFIND,Z,F,L,Y)
      TA=Y-TO
      ISET=2
      ITEST1=2
      L=1
      CALL CALC(TA,X,DX,AREA)
      TF=TO+TA
      AREA=AMP*TA
      BT(MTANK)=BT(MTANK)+FL*AREA
      TOTM=TOTM+FL*AREA
      CALL OUTP1(X,DX,TF,TOTM)
      GO TO 10
 200  RIN2=0.5236
      TLEFT=  TF+(3.14159/W)
 210  IF(TF.GT.TFIN) GO TO 300
      TA=RIN2/W
      IF(W.GE.TOPW) GO TO 211
      IF(ISET.EQ.1) GO TO 212
 211  DW=0.0
      GO TO 220
 212  DW=DWSAVE
      WIN=DW*TA
      REV=(TF-TSAVE)*W/6.28319
      IREV=REV+ADJ
      REM=REV+ADJ-IREV
      ADJ=REM
      W=W+WIN
      TA=RIN2/W
      L=1
      TSAVE=TF
 220  WN=SQRT(SPRING/TOTM)
      RATIO=W/WN
      DXO=DX
      XO=X
      TO=TF
 221  WD=(SQRT(1.0-ZETA**2))*WN
      FACT=1.0/(SQRT((1.0-RATIO**2)**2+(2*ZETA*RATIO)**2))
      PHI=ATAN((2.0*ZETA*RATIO)/(1.0-RATIO**2))
      CON=(R*W*W*FACT)/SPRING
 222  CALL CALC(TA,X,DX,AREA)
      TF=TO+TA
      IF(DX.GT.0.0.AND. ABS(X).LE.0.0001) GO TO 236
      IF(X.LT.-AMP   .AND. DX.GT.0.0005) GO TO 227
      IF(X.LT.0.0 .AND.L.EQ.1) GO TO 223
      GO TO 225
 223  CALL OUTP2(X,DX,TF)
      TO=TF
      XO=X
      DXO=DX
      IF((TF+.5236/W).GT.TLEFT) GO TO 224
      IF(ISET.EQ.1) GO TO 210
      GO TO 222
 224  TA=0.08727/W
      GO TO 222
 225  Z(L)=X
```

```
      F(L)=TF
      TA=TA-0.01745/W
      IF(X.LE.0.0) GO TO 226
      L=L+1
      CALL CALC(TA,X,DX,AREA)
      TF=TO+TA
      GO TO 225
  226 XFIND=0.0
      CALL FIND(XFIND,Z,F,L,Y)
      TA=Y-TO
      L=1
      GO TO 222
  227 MIN=1
      XMIN=0.0
      IF(X.GE.-(AMP+0.0002)) GO TO 230
  228 Z(L)=X
      F(L)=TF
      TA=TA-0.01745/W
      IF(X.GE.-AMP) GO TO 229
      CALL CALC(TA,X,DX,AREA)
      TF=TO+TA
      L=L+1
      GO TO 228
  229 XFIND=-AMP
      CALL FIND(XFIND,Z,F,L,Y)
      TA=Y-TO
      L=1
      CALL CALC(TA,X,DX,AREA)
      TF=TO+TA
  230 TA=0.0349/W
      XO=X
      DXO=DX
      TO=TF
  231 CALL CALC(TA,X,DX,AREA)
      TF=TO+TA
      IF(X.GT.-AMP) GO TO 234
  232 CONTINUE
      IF(X.LT.XMIN) GO TO 233
      IF(X.GE.XMIN .AND. MIN.GT.1) GO TO 230
      CALL OUTP2(XMIN,DXMIN,TFMIN)
      MIN=2
      GO TO 230
  233 XMIN=X
      DXMIN=DX
      TFMIN=TF
      GO TO 230
  234 Z(L)=X
      F(L)=TF
      TA=TA-0.01745/W
      IF(X.LE.-AMP) GO TO 235
      CALL CALC(TA,X,DX,AREA)
      L=L+1
      GO TO 234
  235 XFIND=-AMP
      CALL FIND(XFIND,Z,F,L,Y)
      TA=Y-TO
      ISET=2
      ITEST2=2
      L=1
      CALL CALC(TA,X,DX,AREA)
```

```
             CALL OUTP2(X,DX,TF)
             GO TO 210
      236    CALL OUTP2(X,DX,TF)
             IF(ITEST2.EQ.1) ISET=1
             ITEST1=1
             L=1
             GO TO 10
      300    CONTINUE
             END
END OF FILE
```

```
$LIST SUB
      SUBROUTINE CALC(TA,X,DX,AREA)
      DIMENSION BT(3)
      COMMON/VAR/TO,TSAVE,W,PHI,G4,XO,CON,BT,UNBAL,ZETA,WN,DXO,
     1 WD,ADJ,DW
      RAD=(TO-TSAVE)*W
      REV=RAD/6.28319
      IREV=REV+ADJ
      REM=REV+ADJ-IREV
      BETA=REM*6.28319
      THETA1=BETA-2.618-PHI
      THETA2=BETA+1.5708-PHI
      THETA3=BETA-0.5236-PHI
      THETA4=BETA+1.5708-G4-PHI
      S1=SIN(THETA1)
      S2=SIN(THETA2)
      S3=SIN(THETA3)
      S4=SIN(THETA4)
      CON2=(CON*DW)/(W**2)
      C1=COS(THETA1)
      C2=COS(THETA2)
      C3=COS(THETA3)
      C4=COS(THETA4)
      A1=XO-CON*(BT(1)*S1+BT(2)*S2+BT(3)*S3+UNBAL*S4)+CON2*
     1 (BT(1)*C1+BT(2)*C2+BT(3)*C3+UNBAL*C4)
      A2=(A1*ZETA*WN+DXO-CON*W*(BT(1)*C1+BT(2)*C2+BT(3)*C3+UNBAL*C4))
     1 /WD-(CON2*W*(BT(1)*S1+BT(2)*S2+BT(3)*S3+UNBAL*S4))/WD
      WT=W*TA
      SW1=SIN(WT+THETA1)
      SW2=SIN(WT+THETA2)
      SW3=SIN(WT+THETA3)
      SW4=SIN(WT+THETA4)
      CW1=COS(WT+THETA1)
      CW2=COS(WT+THETA2)
      CW3=COS(WT+THETA3)
      CW4=COS(WT+THETA4)
      SWD=SIN(WD*TA)
      CWD=COS(WD*TA)
      EXP=2.71828**(ZETA*WN*TA)
      STERM=BT(1)*SW1+BT(2)*SW2+BT(3)*SW3+UNBAL*SW4
      CTERM=BT(1)*CW1+BT(2)*CW2+BT(3)*CW3+UNBAL*CW4
      X=(A1*CWD+A2*SWD)/EXP+CON*STERM-CON2*CTERM
      DX=(-ZETA*WN*(A1*CWD+A2*SWD)+WD*(-A1*SWD+A2*CWD))/EXP+CON*W*
     1 CTERM+CON2*W*STERM
      AREA=0.5*(XO+X)*TA
      RETURN
      END
      SUBROUTINE TANK(TF,TSAVE,W,ADJ,MTANK,TLEFT)

      REV = ((TF-TSAVE)*W)/6.28319
      IREV=REV+ADJ
      REM=REV+ADJ-IREV
      IF(REM.GE.0.999) REM=0.0
      IF(REM.GE.0.333) GO TO 11
      MTANK = 1
      TLEFT=TF+(0.3333-REM)*6.28319/W
      GO TO 100
   11 IF(REM.GE.0.666) GO TO 12
      MTANK = 2
```

```
      TLEFT=TF+(0.6667-REM)*6.28319/W
      GO TO 100
   12 MTANK = 3
      TLEFT=TF+(1.0    -REM)*6.28319/W
  100 CONTINUE
      RETURN
      END
      SUBROUTINE OUTP1(X,DX,TF,TOTM)
      DIMENSION BT(3)
      COMMON/VAR/TO,TSAVE,W,PHI,G4,XO,CON,BT,UNBAL,ZETA,WN,DXO,
     1 WD,ADJ,DW
      COMMON/OUT/T1,T2,T3,T4
      IF(T1.EQ.0.0) GO TO 300
      IF(TF.GT.T1 .AND. TF.LT.T2) GO TO 450
      IF(TF.GT.T3 .AND. TF.LT.T4) GO TO 450
  300 CONTINUE
      RPM=W*60.0/6.28319
      WRITE(6,400) TF,X,DX,BT(1),BT(2),BT(3),TOTM,RPM,PHI
  400 FORMAT(F10.4,2F10.5,4F10.7,F8.3,F8.4)
  450 CONTINUE
      RETURN
      END
      SUBROUTINE OUTP2(X,DX,TF)
      DIMENSION BT(3)
      COMMON/VAR/TO,TSAVE,W,PHI,G4,XO,CON,BT,UNBAL,ZETA,WN,DXO,
     1 WD,ADJ,DW
      COMMON/OUT/T1,T2,T3,T4
      IF(T1.EQ.0.0) GO TO 300
      IF(TF.GT.T1 .AND. TF.LT.T2) GO TO 450
      IF(TF.GT.T3 .AND. TF.LT.T4) GO TO 450
  300 CONTINUE
      RPM=W*60.0/6.28319
      WRITE(6,410) TF,X,DX,RPM,PHI
  410 FORMAT(F10.4,2F10.5,40X,F8.3,F8.4)
  450 CONTINUE
      RETURN
      END
      SUBROUTINE FIND(XFIND,Z,F,L,Y)
      DIMENSION Z(50),F(50)
      R1=ABS(Z(L)-XFIND)
      LL=L-1
      R2=ABS(Z(L)-Z(LL))
      DT=ABS(F(L)-F(LL))
      Y=F(L)+(R1/R2)*DT
      RETURN
      END
END OF FILE
```

OUTPUT LISTING

```
$RUN SPINOBJ+SUBOBJ 5=*SOURCE* 6=*SINK*
EXECUTION BEGINS
    TIME        X          DX      TANK 1     TANK 2     TANK 3      TOT MASS   RPM
   0.8000    0.00033    0.15379 0.0        0.0        0.0        0.5181347 150.000
   0.8133    0.00236    0.14945 0.0000031  0.0        0.0        0.5181378 150.000
   0.8267    0.00429    0.13833 0.0000106  0.0        0.0        0.5181453 150.000
   0.8400    0.00602    0.12086 0.0000224  0.0        0.0        0.5181571 150.000
   0.8533    0.00748    0.09807 0.0000378  0.0        0.0        0.5181724 150.000
   0.8667    0.00862    0.07121 0.0000561  0.0        0.0        0.5181907 150.000
   0.8800    0.00937    0.04153 0.0000766  0.0        0.0        0.5182112 150.000
   0.8933    0.00971    0.01019 0.0000983  0.0        0.0        0.5182329 150.000
   0.9067    0.00963   -0.02155 0.0001204  0.0        0.0        0.5182549 150.000
   0.9200    0.00914   -0.05229 0.0001418  0.0        0.0        0.5182762 150.000
   0.9333    0.00825   -0.08057 0.0001616  0.0        0.0        0.5182960 150.000
   0.9467    0.00701   -0.10524 0.0001616  0.0000174  0.0        0.5183133 150.000
   0.9600    0.00546   -0.12584 0.0001616  0.0000316  0.0        0.5183275 150.000
   0.9733    0.00367   -0.14148 0.0001616  0.0000420  0.0        0.5183379 150.000
   0.9867    0.00171   -0.15070 0.0001616  0.0000481  0.0        0.5183440 150.000
   0.9979   -0.00000   -0.15284 0.0001616  0.0000498  0.0        0.5183456 150.000
   1.0311   -0.00475   -0.13396                                             150.637
   1.0642   -0.00857   -0.08237                                             151.271
   1.0971   -0.00995    0.00008                                             151.902
   1.1298   -0.00878    0.07639                                             152.530
   1.1625   -0.00516    0.14192                                             153.156
   1.1950   -0.00011    0.16360                                             153.780
   1.1957   -0.00000    0.16368                                             153.780
   1.1971    0.00023    0.16379 0.0001616  0.0000498  0.0000000  0.5183456 153.792
   1.2101    0.00235    0.16082 0.0001644  0.0000498  0.0000000  0.5183484 153.819
   1.2230    0.00438    0.15057 0.0001719  0.0000498  0.0000000  0.5183558 154.067
   1.2360    0.00622    0.13329 0.0001836  0.0000498  0.0000000  0.5183675 154.315
   1.2489    0.00781    0.10984 0.0001991  0.0000498  0.0000000  0.5183830 154.562
   1.2619    0.00905    0.08150 0.0002177  0.0000498  0.0000000  0.5184016 154.809
   1.2747    0.00990    0.04961 0.0002386  0.0000498  0.0000000  0.5184225 155.056
   1.2876    0.01032    0.01548 0.0002609  0.0000498  0.0000000  0.5184447 155.302
   1.3005    0.01030   -0.01953 0.0002835  0.0000498  0.0000000  0.5184674 155.548
   1.3133    0.00982   -0.05398 0.0003056  0.0000498  0.0000000  0.5184894 155.794
   1.3261    0.00893   -0.08627 0.0003261  0.0000498  0.0000000  0.5185099 156.039
   1.3389    0.00763   -0.11500 0.0003261  0.0000679  0.0000000  0.5185280 156.283
   1.3517    0.00601   -0.13947 0.0003261  0.0000828  0.0000000  0.5185428 156.528
   1.3645    0.00410   -0.15861 0.0003261  0.0000938  0.0000000  0.5185538 156.772
   1.3772    0.00199   -0.17084 0.0003261  0.0001004  0.0000000  0.5185604 157.015
   1.3887    0.00000   -0.17494 0.0003261  0.0001024  0.0000000  0.5185623 157.258
   1.4204   -0.00534   -0.15342                                             157.866
   1.4519   -0.00932   -0.09045                                             158.470
   1.4833   -0.01085   -0.00079                                             159.073
   1.5146   -0.00948    0.09060                                             159.673
   1.5458   -0.00552    0.15999                                             160.271
   1.5769   -0.00001    0.18734                                             160.867
   1.5781    0.00022    0.18746 0.0003261  0.0001024  0.0000000  0.5185623 161.460
   1.5905    0.00253    0.18435 0.0003290  0.0001024  0.0000000  0.5185652 161.484
   1.6029    0.00475    0.17314 0.0003367  0.0001024  0.0000000  0.5185729 161.720
   1.6152    0.00678    0.15352 0.0003489  0.0001024  0.0000000  0.5185850 161.956
   1.6276    0.00851    0.12632 0.0003650  0.0001024  0.0000000  0.5186011 162.192
   1.6399    0.00987    0.09336 0.0003843  0.0001024  0.0000000  0.5186204 162.427
   1.6522    0.01079    0.05666 0.0004060  0.0001024  0.0000000  0.5186421 162.662
   1.6645    0.01125    0.01783 0.0004292  0.0001024  0.0000000  0.5186653 162.897
   1.6767    0.01123   -0.02189 0.0004527  0.0001024  0.0000000  0.5186888 163.132
   1.6890    0.01072   -0.06113 0.0004757  0.0001024  0.0000000  0.5187117 163.366
   1.7012    0.00975   -0.09819 0.0004971  0.0001024  0.0000000  0.5187331 163.599
```

J. HOW TO USE THE PROGRAM

The following are the commands required to do a typical run. It is assumed the program has been compiled and is in object file OBJ. For completeness the run will start with masses in the ballast tanks, and it will be desired to blank out some of the object.

```
$RUN OBJ 5 = *SOURCE* 6 = *SINK*
 &DATA RPM = 150., OFFBAL = 5., G4 = 0., TFIN = 40., DEGREE = 10.,
 ZETA = 0.1., INOUT = 3, FLOW = 0.695, TOTWT = 200., SPRING = 500.,
 RPMPS = 2., TOPRPM = 450., AMP = 0.7, ITANK = 2 &END
 &OUTPUT T1 = 15., T2 = 30., &END
 &TANKIN BT = 0.002, 0., 0.004 &END
$ENDFILE
```

Note the input is name listed and starts in column 2 on the card. If INOUT = 1, this would mean no &OUTPUT card. If ITANK = 1, no &TANKIN card would be read.

K. RESULTS AND CONCLUSIONS

The results of two runs have been reduced to amplitude and speed vs. time. These are shown in Figures 15 and 16. The two runs are identical except for the flow rate. Figure 15 has a flow rate comparable to the present washer-dryer and in Figure 16 this has been increased by 50%. As might be expected, the higher flow rate allows the machine to attain maximum spin speed faster. In interpreting the results of various simulation runs, the differences between the actual machine and the computer model must be kept in mind. The model does not incorporate the air clutch speed control system. A direct simulation of this system was considered outside the scope of this project. Therefore, it was replaced by an ON-OFF constant acceleration system whereby the tank is either accelerating at the specified input rate or is not accelerating at all. The criterion being whether or not the displacement on the prior half cycle was greater than AMP. As a result it would not be expected that the simulation would yield the same time-speed characteristic as the actual machine, but comparison of two simulations as in Figures 15 and 16 might be expected to parallel changes in machine hardware.

As described above it is possible to vary certain parameters and investigate the effects of hardware changes on the machine. It is also possible to investigate other possible spinning schemes. One such scheme which was tried was to balance the load at low speed and then spin it at a speed above critical. This involves two separate runs. First the off-balance load was balanced at 150 rpm for 40 sec with 5 gal/min flow rate. The suspension in

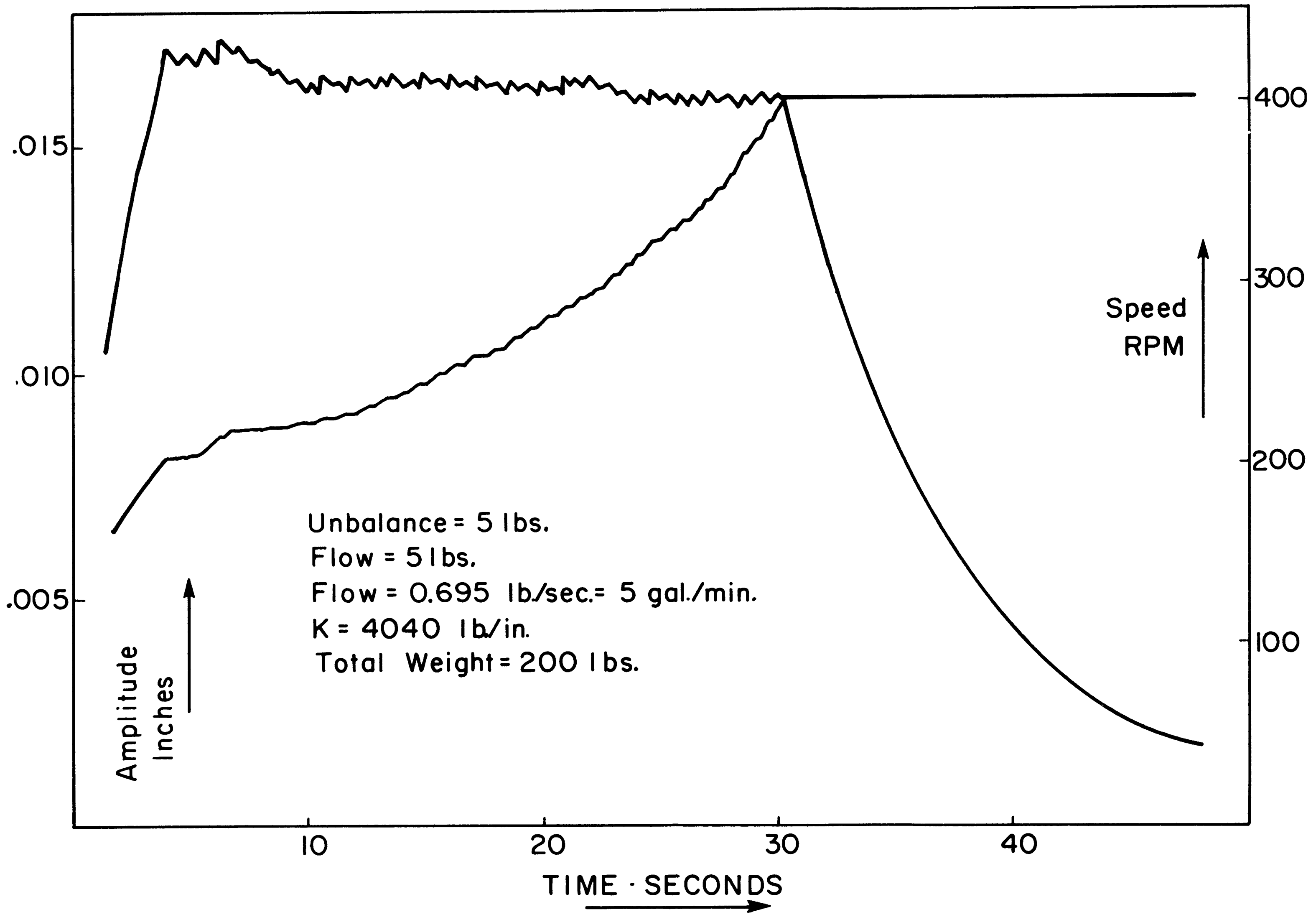


Figure 15. Time to attain balanced spin—data from program output.

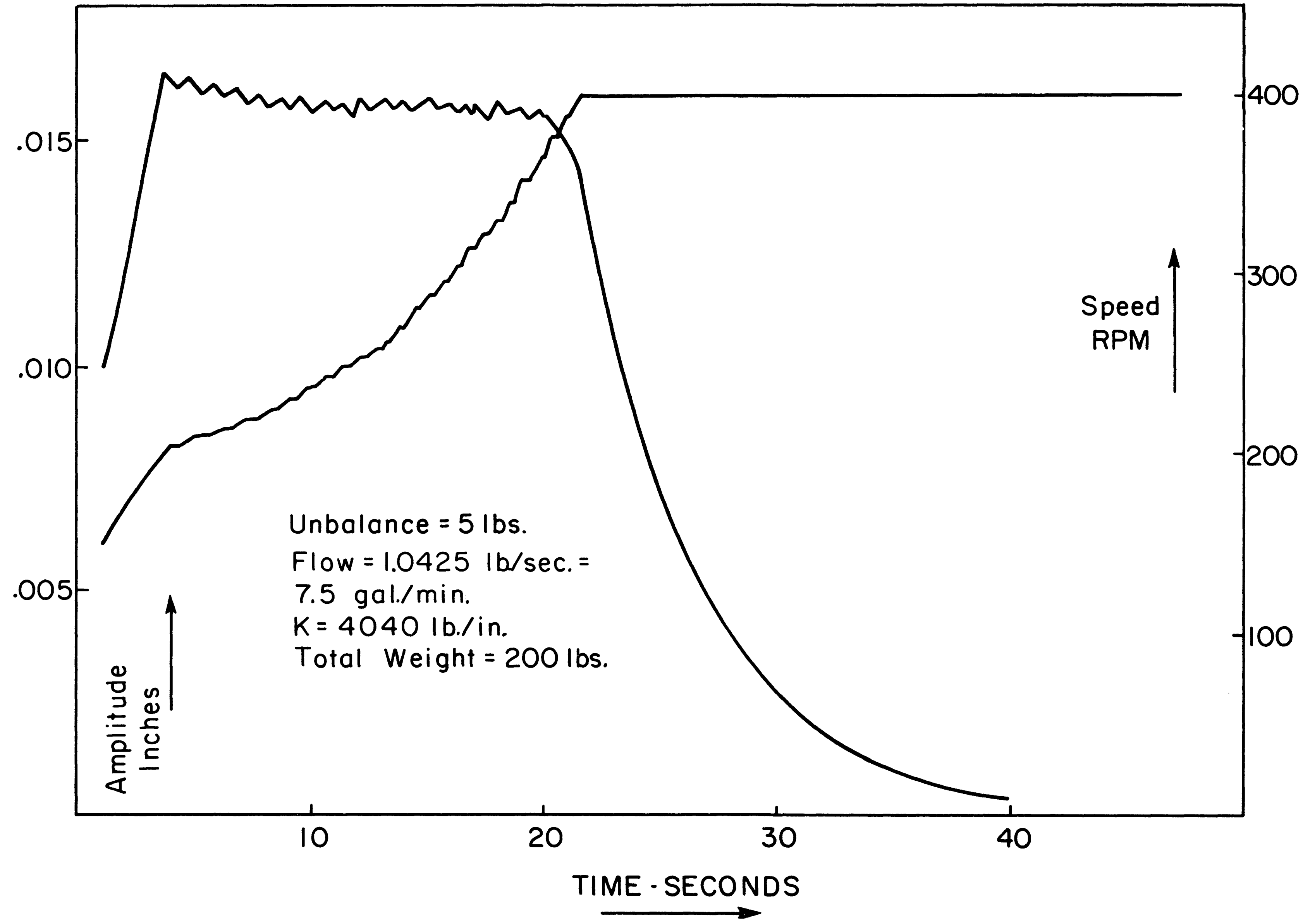


Figure 16. Time to attain balanced spin—at a different flow rate. Data from program output.

this scheme was softened to 500 lb/in. which gave a critical speed of 300 rpm assuming the same machine weight. Then with the final masses in the ballast tanks given as input, a run was made starting at 150 rpm accelerating at 50 rpm/sec to 600 rpm with no flow rate. The value for ζ was .1 in this run and at critical an amplitude of .5 in. was reached. The limitation of the program in simulating a soft suspension such as this is, of course, the fact that the simulation has 1 degree of freedom. In a soft suspension system the tank will be allowed vertical as well as horizontal deflection. But it would be possible to make changes in the program to take into account the effects of coupling between the coordinates. Instead of calling on the subroutine CALC, a vibration program such as VIB which handles multi-freedom systems could be called. It would return the horizontal deflection which would then be fed back into the balance control as is presently done. Thus it would be possible to incorporate into the present ballast tank simulation a multi-freedom model.

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A COMPUTER SIMULATION OF A VENTLESS CLOTHES DRYER USING A REFRIGERATION CYCLE

Kenneth J. Timmer

1. OBJECTIVES

The purpose of this project was to develop a digital computer program to simulate the behavior of a closed-loop or ventless clothes dryer. This system passes the dryer exhaust air over the evaporator and condenser coils of a refrigeration cycle to change the properties of the air in the feedback portion of the closed-loop system (Figure 1).

The principal reasons for developing this computer simulation were to determine the feasibility and capability of such a clothes dryer system and to aid in the actual design of such a system.

2. RESULTS

The computer simulation program consists of a main program which performs the principle calculations, a psychrometric subroutine which calculates the thermodynamic properties of the air-vapor mixture, a plotting subroutine, and a somewhat modified version of the dryer simulation subroutine package developed by Whirlpool.

The general results of the simulation indicate that such a clothes dryer system is feasible. The system performs the primary objective of drying clothes and does so in a reasonable amount of time. The system has the advantages of not requiring any vent and operating on normal 110-volt household current. The simulation results show that although the drying time required is about 36% greater than with the conventional electric dryer which requires a 220-volt source and uses a 5600-watt heater, the amount of power required is only 1/3 of that required with the conventional system. Figure 2 compares the power and drying time required of a 5600-watt heater system with the simulated close-loop refrigeration system. The figure also includes a 1200-watt heater system which is approximately the wattage required by the refrigeration system, and a system using a refrigeration system but in an open-loop configuration. A schematic diagram of an open-loop system is given in the Appendix.

3. BACKGROUND

The drying of clothes in an electric clothes dryer is accomplished by passing warm dry air over the clothes. The water in the clothes is evaporated and carried out of the dryer by the air stream. In a conventional dryer this

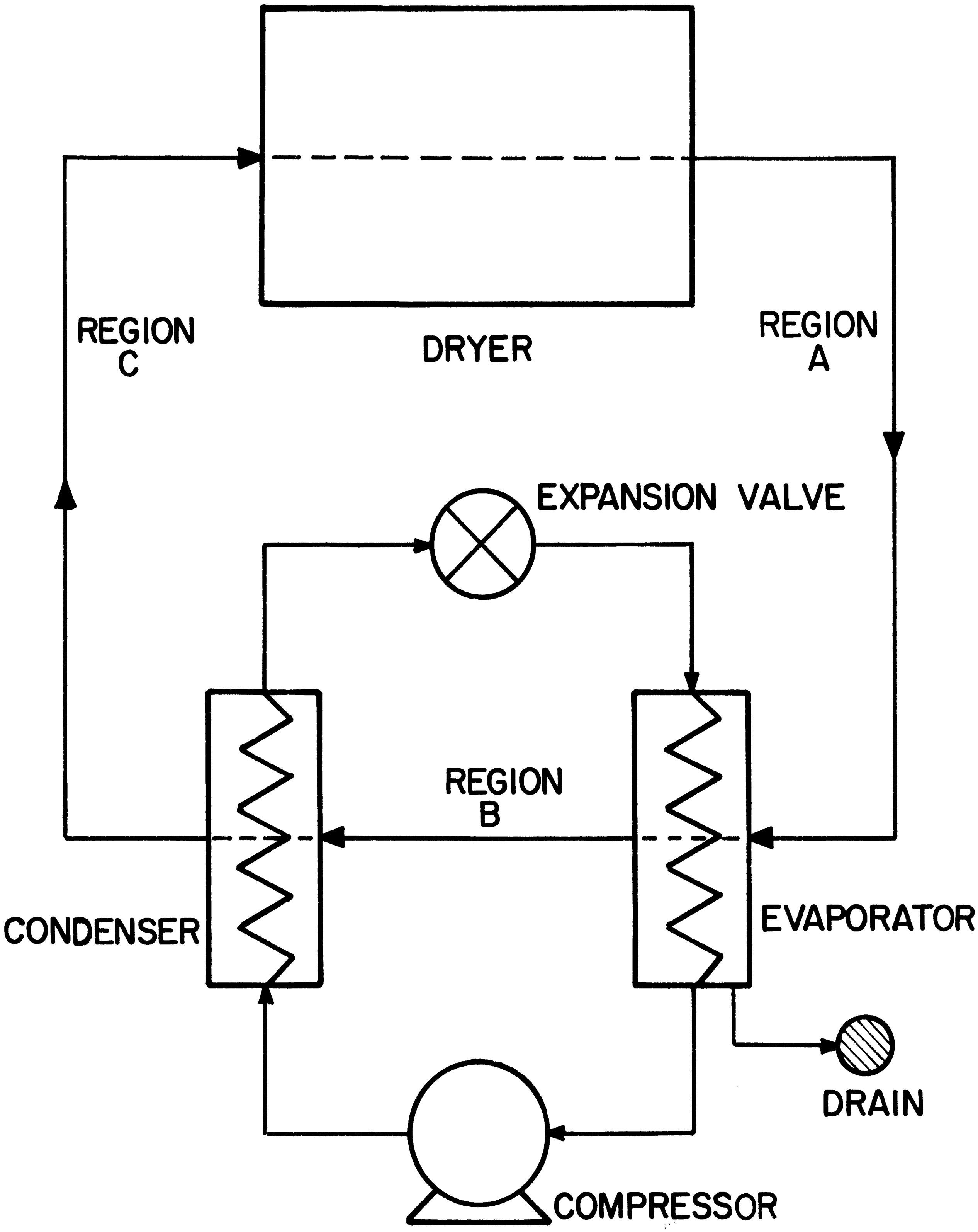


Figure 1. Schematic diagram of ventless dryer system.

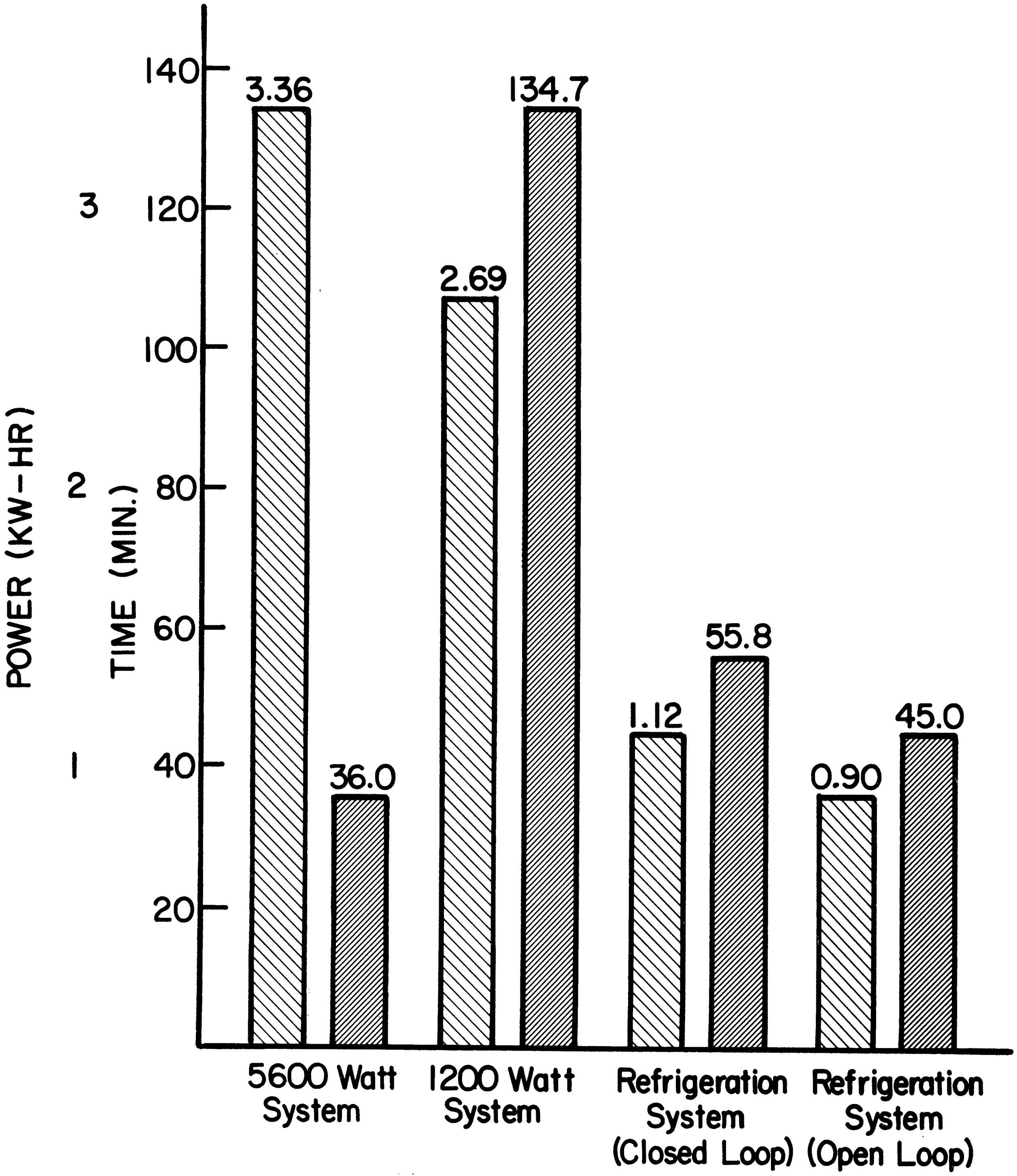


Figure 2. Comparison chart of power and time required to dry a normal clothes load (9 lb dry weight, 85% initial moisture content).

air is exhausted to the outside and a fresh quantity of dry air is constantly being drawn into the dryer. In order to operate a clothes dryer using a ventless system, some method is needed to remove water from the air stream to keep the air going over the clothes dry enough to pick up moisture from the clothes. To condense water the air-vapor mixture must be cooled below the dew point of the mixture. This can be accomplished with a variety of types of heat exchangers. However, once the air-vapor mixture has been cooled below its dew point and water has been condensed out to reduce its specific humidity (lbm H_2O/lbm air), it must then be reheated to reduce its relative humidity and enable it to continue to absorb moisture from the clothes. This requires another heat exchanger or electrical heating element.

If these two heat exchangers are operated separately, the energy obtained when the air-vapor mixture is cooled is merely dissipated and a significant amount of additional energy is required to heat the air. This brings us to the investigation of using a refrigeration cycle in a ventless clothes dryer. Not only does a refrigeration cycle have the necessary heat exchangers—the evaporator for cooling and condensing water and the condenser for heating—but it absorbs the energy obtained in cooling the air at the evaporator and turns it to energy used in heating the air at the condenser. Therefore, it is possible to operate such a system with only a fraction of the power required with separate heat exchangers.

4. BASIC EQUATIONS

It is possible to analytically represent the changes in the air-vapor mixture as it passes over the evaporator and condenser coils of the refregeration cycle with energy balance equations once the amount of heat transfer at each coil is known.

The terms which are necessary for these equations are:

Q_E - heat transfer at the evaporator (Btu/hr)

Q_C - heat transfer at the condenser (Btu/hr)

$\mathring{m}$ - mass flow of air (lbm/hr)

h - enthalpy of air (Btu/lbm)

ω - specific humidity of air (lbm H_2O/lbm air)

h_v - enthalpy of vapor (Btu/lbm)

h_l - enthalpy of liquid (Btu/lbm)

If we denote regions A, B, and C as in Figure 1, the basic equations of the simulation are:

At the evaporator

$$\underbrace{h_A + \omega_A h_{v_A}} + \underbrace{Q_E/\mathring{m}_A} = \underbrace{h_B + \omega_B h_{v_A}} + \underbrace{(\omega_A - \omega_B)h_l} \qquad (1)$$

$$\text{ENTHA} + \text{-QEVAP} = \text{ENTHB} + \Delta\text{E}$$

$$\text{ENTHB} = \text{ENTHA} - \text{QEVAP} - \Delta\text{E} \qquad (2)$$

At the condenser

$$\underbrace{h_B + \omega_B h_{v_B}} + \underbrace{Q_C/\mathring{m}_B} = \underbrace{h_C + \omega_C h_{v_C}} \qquad (3)$$

$$\text{ENTHB} + \text{QCOND} = \text{ENTHC}$$

$$\text{ENTHC} = \text{ENTHB} + \text{QCOND} \qquad (4)$$

In these two equations the energy quantity of the air and vapor in any particular region can be lumped together to form an ENTH quantity which refers to the energy of the air-vapor mixture. These energy terms can be found directly using a psychrometric chart. The ΔE term is very small relative to the other terms in equation (2) and is assumed to be a constant fraction of ENTHB (see Appendix). The mass flow of the air can be calculated from the given volumetric air flow in ft^3/min and the density of the air vapor mixture which is also found from the psychrometric chart. This leaves Q_E and Q_C as the only terms to be determined.

During much of the initial work on the program these two terms were given constant values based on what heat transfer quantities could reasonably be expected with a compressor which operates on 110 volts. The values used during this work were 11,000 Btu/hr heat transfer at the evaporator (Q_E), and 15,000 Btu/hr heat transfer at the condenser (Q_C) using Freon-22 as the refrigerant.

5. ANALYSIS OF THE REFRIGERATION CYCLE

The type of refrigeration cycle used in the simulation was a vapor-compression cycle using a refrigerant such as Freon-22 as the working fluid. In such a system, heat is transferred to the refrigerant in the evaporator, work is done on the refrigerant in the compressor, and heat is transferred from the refrigerant in the condenser. The temperature-entropy diagram for this system is shown in Figure 3.

The amount of heat transferred from the refrigerant to the air in the condenser is the sum of the heat transferred to the refrigerant from the air in the evaporator and the work done on the refrigerant in the compressor. In the closed-loop dryer the same air stream passes over the evaporator and condenser. Therefore, since the heat transferred to the air is always greater than the heat transferred from the air, the temperature of the air stream will be constantly increasing.

Because of this constant temperature buildup it is erroneous to assume constant heat transfer quantities. Increasing air temperatures cause increasing refrigerant temperatures and these in turn cause changes in the heat transfer quantities and amount of compressor work required. Published compressor curves prepared by pump manufacturers show the effect of evaporator temperature and high side, or condenser, pressure on the capacity or heat transfer of the evaporator and on the power required in the compressor (see Appendix for example). The high side pressure in turn is directly related to the temperature of the refrigerant in the condenser. These compressor curves can be reduced to equation form to be used in the computer simulation.

To determine the effect of rising air temperatures on the properties of the refrigerant and thus be able to calculate heat transfer quantities, a series of constraints were used in the computer program. With the use of this part of the program the properties of the air and refrigerant are constantly checked and as the air temperatures increase the refrigerant temperatures are incrementally increased and new heat transfer quantities are calculated and used in the basic system equations.

The constraints used are:

1. The temperature of the refrigerant in the evaporator increases as the enthalpy of the air passing over the evaporator increases. This relationship is found from McQuay refrigeration coil data. A designed air enthalpy value is chosen by the user of the simulation. When the enthalpy of the air increases above this chosen value, the evaporator temperature increases at a rate determined from the McQuay data.

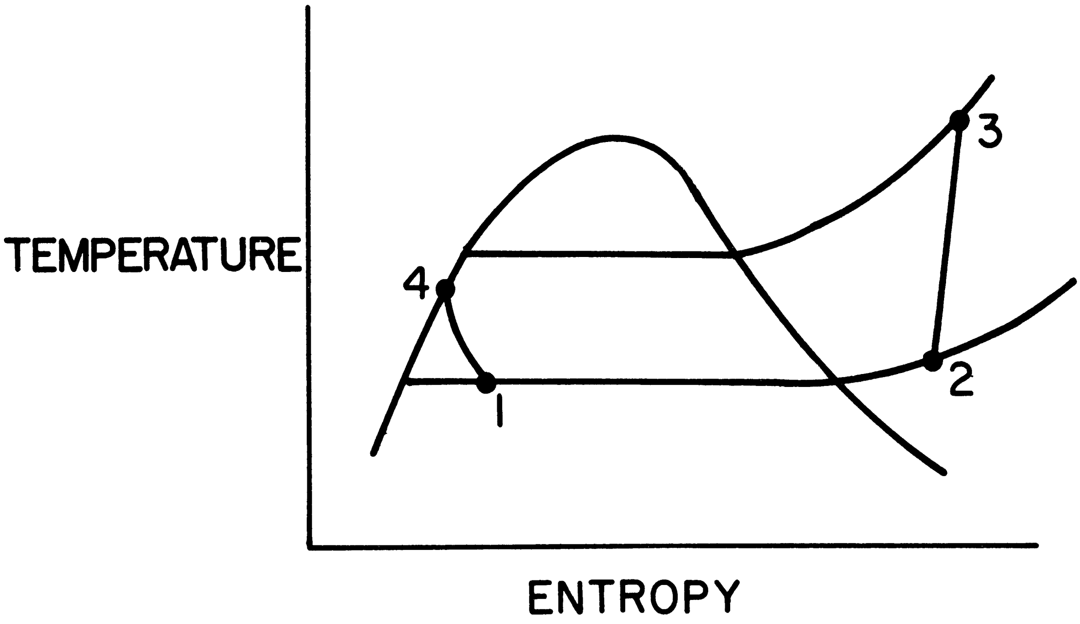


Figure 3. Temperature-entropy diagram of refrigeration system.

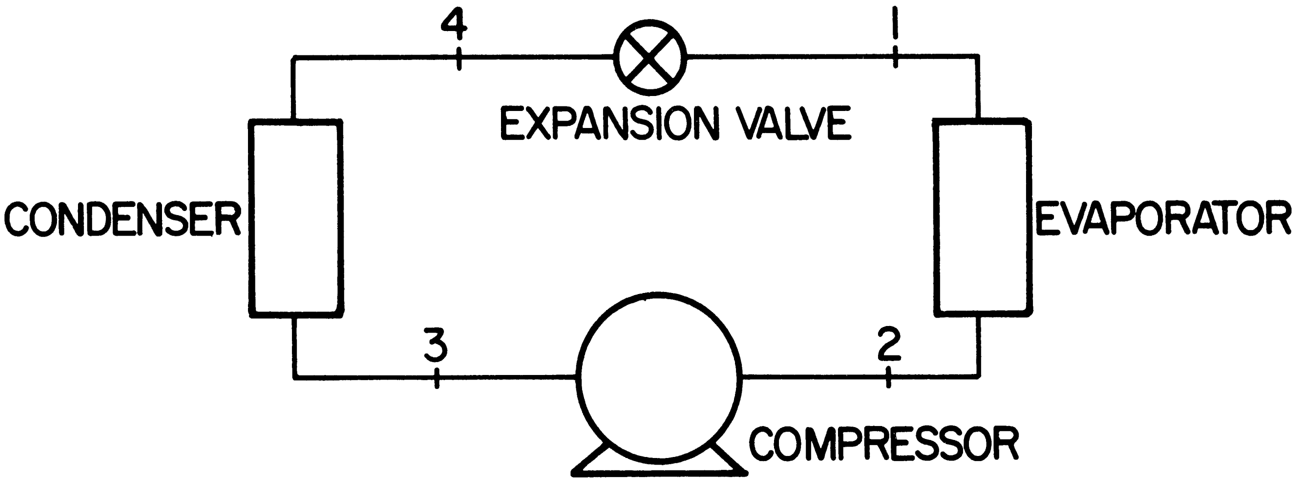


Figure 4. Schematic diagram of refrigeration system.

2. The temperature of the refrigerant in the condenser increases as the temperature of the air over the condenser increases. A designed temperature for air going into the condenser is chosen by the user. When the air temperature increases above this value, the condenser temperature also increases at a rate determined from the McQuay data.

3. The amount of heat transferred in the condenser is limited by the temperature of the refrigerant in the condenser. A maximum temperature of 5° less than the condenser temperature is defined. The maximum amount of heat transferred is then that amount which raises the air temperature to the maximum just defined. Since this has the effect of increasing the amount of energy remaining in the refrigeration cycle, an incremental temperature difference chosen by the user is added to the refrigerant temperatures of both the condenser and evaporator.

4. As indicated above, the condenser temperature and high side pressure are directly related. The high side pressure is limited by the capability of the compressor to pump the refrigerant above a certain maximum value without burning out. This maximum pressure is chosen by the user based on knowledge of the refrigerant and compressor being used. When the pressure in the condenser reaches this maximum value the capacity or heat transfer quantities that the evaporator and condenser have at that time are assumed to remain constant for the remainder of the drying time. Possible suggestions to accomplish this steady state period include bleeding enough air from the dryer exhaust and replacing it with room air to reduce the energy content of the air the same amount as it is increased as it passes over the evaporator and condenser (see Appendix for this calculation).

This series of constraints was based on the best information I could find in the time available. It is quite possible, however, that as a prototype such a system is tested better relationships between air and refrigerant properties will be found. These relationships can then be put into the simulation without destroying the basic logic of the program.

6. DISCUSSION OF MAIN PROGRAM

The simulation of this ventless clothes dryer is a combination of the basic equations discussed and the four constraints necessary in determining the capacities of the evaporator and condenser of the refrigeration cycle.

The input data which must be read into the program are:

(1) TDB = Ambient dry bulb temperature [°F]

(2) TWB = Ambient wet bulb temperature [°F]

(3) CLOAD = Dry weight of the clothes load [lb]

(4) CMOIST = Initial moisture content of the clothes as a percentage of the dry weight [%]

(5) CTEMP = Initial clothes load temperature [°F]

(6) CFM = Volumetric flow of the air-vapor mixture in the closed-loop [ft^3/min]

(7) HSP = Initial high side pressure of the refrigerant [psig]

(8) EVTP = Initial temperature of the refrigerant in the evaporator [°F]

(9) HSPMAX = Maximum high side pressure of the refrigerant [psig]

(10) HMAX = Value of the enthalpy of the air-vapor mixture going into the evaporator used in the refrigeration cycle constraints [Btu/lbm]

(11) TBMAX = Value of the temperature of the air-vapor mixture going into the condenser used in the refrigeration cycle constraints [°F]

(12) CONADD = Temperature added to the temperature of the refrigerant in the condenser as part of the constraints [°F]

(13) EVADD = Temperature added to the temperature of the refrigerant in the evaporator as part of the constraints [°F]

(14) IPLOT = Control integer governing the number of plots printed out:
0 = no plots
1 = one plot
2 = two plots

The meaning of symbols of other properties used in the program are:

(1) MMOIST = Moisture content of the clothes [lbm water]

(2) WATTS = Wattage of the heating element [watts]

(3) TDBA, TDBB, TDBC = Dry bulb temperature of the air-vapor mixture in region A, B, and C, respectively [°F]

(4) TWBA, TWBB, TWBC = Wet bulb temperature of the air-vapor mixture in region A, B, and C, respectively [°F]

(5) HUSA, HUSB, HUSC = Specific humidity of the air-vapor mixture in region A, B, and C, respectively [lbm H_2O/lbm dry air]

(6) DENSA, DENSB, DENSC = Density of the air-vapor mixture in region A, B, and C, respectively, [lbm dry air/ft^3]

(7) ENTHA, ENTHB, ENTHC = Enthalpy of the air-vapor mixture in region A, B, and C, respectively [Btu/lbm dry air]

(8) MDAA, MDAB, MDAC = Mass flow of the air-vapor mixture in region A, B, and C, respectively [lbm dry air/hr]

(9) DENSEV, DENSCO = Average density of the air-vapor mixture in the evaporator and condenser, respectively [lbm dry air/ft^3]

(10) MDAEVA, MDACON = Average mass flow of the air-vapor mixture in the evaporator and condenser, respectively [lbm dry air/hr]

(11) CONTP = Temperature of the refrigerant in the condenser [°F]

(12) QOUT = Heat transferred in the evaporator [Btu/hr]

(13) POWW = Power required in the compressor [watts]

(14) POWB = Energy required in the compressor [Btu/hr]

(15) QADD = Heat transferred in the condenser [Btu/hr]

(16) QEVAP = Energy transferred in the evaporator [Btu/lbm dry air]

(17) QCOND = Energy transferred in the condenser [Btu/lbm dry air]

(18) TMAX = Maximum temperature of the air out of the condenser [°F]

(19) HDIFF = Enthalpy difference [Btu/lbm dry air]

(20) TADDE = Temperature to be added to the refrigerant in the evaporator [°F]

(21) TADDC = Temperature to be added to the refrigerant in the condenser [°F]

(22) CONMIN = Minimum temperature of the refrigerant in the condenser [°F]

(23) EVTPIN, CONIN = Initial temperature of the refrigerant in the evaporator and condenser, respectively [°F]

(24) TIME = Actual time the dryer has been operating [hr]

(25) DRATE = Rate at which water is being removed from the clothes [lbm H_2O/hr]

(26) HOR = Variable on the horizontal axis of the printed plots

(27) FUNC1, FUNC2 = Variables on the vertical axis of the first and second plots, respectively

PROGRAM DISCUSSION

Numbers correspond to numbers on the flow diagram which follows.

(1) To begin the program the input data are read in. These values can be put on cards or kept in the memory file.

(2) The initial moisture content of the clothes is calculated from the input data.

(3) The DRYER subroutine requires a value for WATTS, but since this simulation does not include a heating element the variable is set equal to zero. The air going into the evaporator is set equal to the ambient dry and wat bulb temperatures.

(4) The PSYCKT subroutine is called to calculate the other properties of the air in region A and the mass flow of air is calculated.

(5) Enough information has been calculated to call the DRYER subroutine to initialize the time and give initial values to the properties of the clothes. The DRYER subroutine does not perform any calculations to simulate drying of the clothes at this time.

(6) Initial values of zero are given to all the control integers and initial values of the temperature of the refrigerant in the evaporator and condenser are calculated. The relationship of condenser temperature to high side pressure would differ with a different compressor or refrigerant.

(7) The amount of heat transferred from the air-vapor mixture to the refrigerant in the evaporator is calculated:

$$\text{QOUT} = 30(300 - \text{HSP}) + .281(800)(\text{EVTP} - 35) + 9200$$

This equation is one of a series of equations derived by the Air Conditioner Division of Whirlpool in Evansville, Indiana from actual compressor curves. This particular equation is for a Tecumseh B1613 compressor using Freon-22.

(8) Based on the evaporator temperature and high side pressure, the power required at the compressor is calculated, using a relationship derived from this particular compressor curve.

$$\text{POWW} = [4.35 + .06(\text{HSP} - 260)](\text{EVTP} - 43.5) + 1.75(\text{HSP} - 260) + 1030$$

This equation is accurate when:

$$\text{EVTP} \geq 43.5\ ^\circ\text{F, and}$$

$$\text{HSP} \geq 260 \text{ psig}$$

(9) The power at the compressor is limited to a maximum of 1200 watts and is changed from [watts] to [Btu/hr] with the conversion constant of 3.413.

(10) The amount of heat transferred from the refrigerant to the air-vapor mixture in the condenser is calculated as the sum of the heat transferred at the evaporator and the power added at the compressor. This assumes no heat losses in the refrigeration cycle.

(11) This block of equations calculates the properties of the air-vapor mixture as it passes the evaporator, corresponding to equations (1) and (2) of the Basic Equations section. The amount of heat transfer in [Btu/lbm] is calculated using QOUT and the density of the air in region A. A value for the enthalpy of the mixture coming out of the evaporator is then found by subtracting this amount of heat transfer from the enthalpy of the mixture going into the evaporator.

ENTHB = ENTHA - QEVAP [Btu/lbm]

The mixture coming out of the evaporator is assumed to be at saturation. The PSYCKT subroutine is called to get the density of the mixture in region B and an average density and mass air flow in the evaporator is calculated:

DENSEV = (DENSA + DENSB)/2

MDAEVA = CFM x DENSEV x 60 [lbm/hr]

Using this average mass air flow, the heat transfer and resulting enthalpy is recalculated. To compensate for the amount of energy lost due to the condensed liquid which is drained away, a constant fraction of the enthalpy is subtracted.

ENTHB = ENTHB - .0085 ENTHB

The enthalpy of the condensed liquid is assumed to be the enthalpy of the saturated liquid at the same temperature. Since this value is very small relative to ENTHB this is an adequate approximation. The PSYCKT subroutine is called to calculate the remaining properties of the air-vapor mixture in region B.

(12) This block of equations calculates the properties of the air-vapor mixture as it passes the condenser, corresponding to equations (3) and (4) of the Basic Equations section. The logic is identical to that of the evaporator

block except that here heat is added to the mixture and there is no condensed water to deal with. Also, the specific humidity of the mixture is assumed to remain constant over the condenser. With this value of specific humidity and the calculated value of enthalpy the PSYCKT subroutine is called to get the remaining properties of the air-vapor mixture in region C.

The next section of the program constitutes the application of the four constraints discussed in the previous section of this report. As these constraints necessitate the change of the refrigerant temperatures or pressure, new values for the heat transfer quantities are calculated and used in blocks (11) and (12) above.

(13) The control integer ISS remains zero until the high side pressure reaches the maximum value permitted, it is then set equal to 1. When this occurs, the only constraint checked for the remainder of the drying time is that the temperature of the air-vapor mixture going into the dryer is no higher than 5° less than the condenser temperature.

(14) If either the enthalpy of region A or the temperature of region B is higher than the stipulated design values, the properties of the refrigerant are changed. When the enthalpy in region A becomes higher than the designed value the evaporator temperature is increased by an amount proportional to the enthalpy difference.

HDIFF = ENTHA - HMAX

TADDE = 1.7 x HDIFF

The constant of proportionality of 1.7 is determined from the McQuay data curves, samples of which are in the Appendix. When the temperature in region B becomes higher than the designed value, a check is made on the condenser temperature to ensure that it has correspondingly increased. When either or both of these changes in refrigerant temperatures is made, the heat transfer values are recalculated. The constraints and subsequent alterations of this section are checked three times before the program proceeds.

(15) The temperature of the air-vapor mixture as it leaves the condenser can never be greater than 5° less than the temperature of the refrigerant in the condenser. If an intermediate value violates this constraint the heat transfer in the condenser is reduced to the point where the constraint is met.

QADD = QADD - QDIF

Since this reduction in heat transfer will increase the temperature of the refrigerant in the cycle, an incremental temperature difference chosen by the user is added to the temperature of the condenser and evaporator.

```
CONDTP  =  CONDTP + CONADD

EVTP    =  EVTP + EVADD
```

Using these new temperatures the heat transfer in the evaporator is also recalculated.

(16) The final constraint is to limit the high side pressure of the refrigeration cycle to a maximum value chosen by the user in conjunction with the capabilities of the compressor and refrigerant being used. When the pressure reaches this maximum, the control integer ISS is set equal to 1 and the heat transfer values and refrigerant properties that exist at that time remain constant for the remainder of the drying time.

(17) Now that all the air-vapor mixture properties and refrigeration cycle properties have been made compatible with each other, these values are printed out in a temporary file which can be listed out when the execution of the program has terminated. These values are printed out every .3 min of real time until the maximum high side pressure has been reached.

(18) The DRYER subroutine is called to perform calculations representing the drying of the clothes based on the inlet conditions and returns to the main program the enthalpy and specific humidity of the air-vapor mixture coming out of the dryer in addition to the new properties of the clothes load.

(19) The PSYCKT subroutine is called to calculate the remaining properties of the air-vapor mixture. The mass flow of the dryer exhaust and drying rate of the clothes are also determined.

(20) Every ten times the DRYER subroutine is called (or every 3 min), the properties of the clothes, the air-vapor mixture in the three regions, and the refrigeration cycle are printed out.

(21) A maximum of two arrays are filled with the values of two properties of the system to be plotted against time. The properties to be plotted are set equal to FUNC1 and FUNC2. In the flow diagram these properties are arbitrarily chosen to be TDBA and CTEMP. A value is put into each array every time the values of the system are printed out, or every 3 min.

(22) The moisture content of the clothes is checked and the simulated drying system keeps operating until the water content of the clothes is less than or equal to 3% of the dry weight.

(23) When the clothes are determined to be "dry" the final values of the system are printed out and the GRAPH subroutine is called to plot the graphs that the user has chosen.

7. DISCUSSION OF PSYCKT SUBROUTINE

The subroutine performs psychrometric calculations to determine the properties of the air-vapor mixture. The properties used in the subroutine are:

TDB = Dry bulb temperature [°F]

TWB = Wet bulb temperature [°F]

HUS = Specific humidity [lbm H_2O/ lbm dry air]

DENS = Density of the mixture [lbm dry air/ ft^3]

ENTH = Enthalpy of the mixture [Btu/lbm dry air]

Other properties used in the calculations but not input or output are:

PW = Water vapor pressure at wet bulb temperature [in Hg]

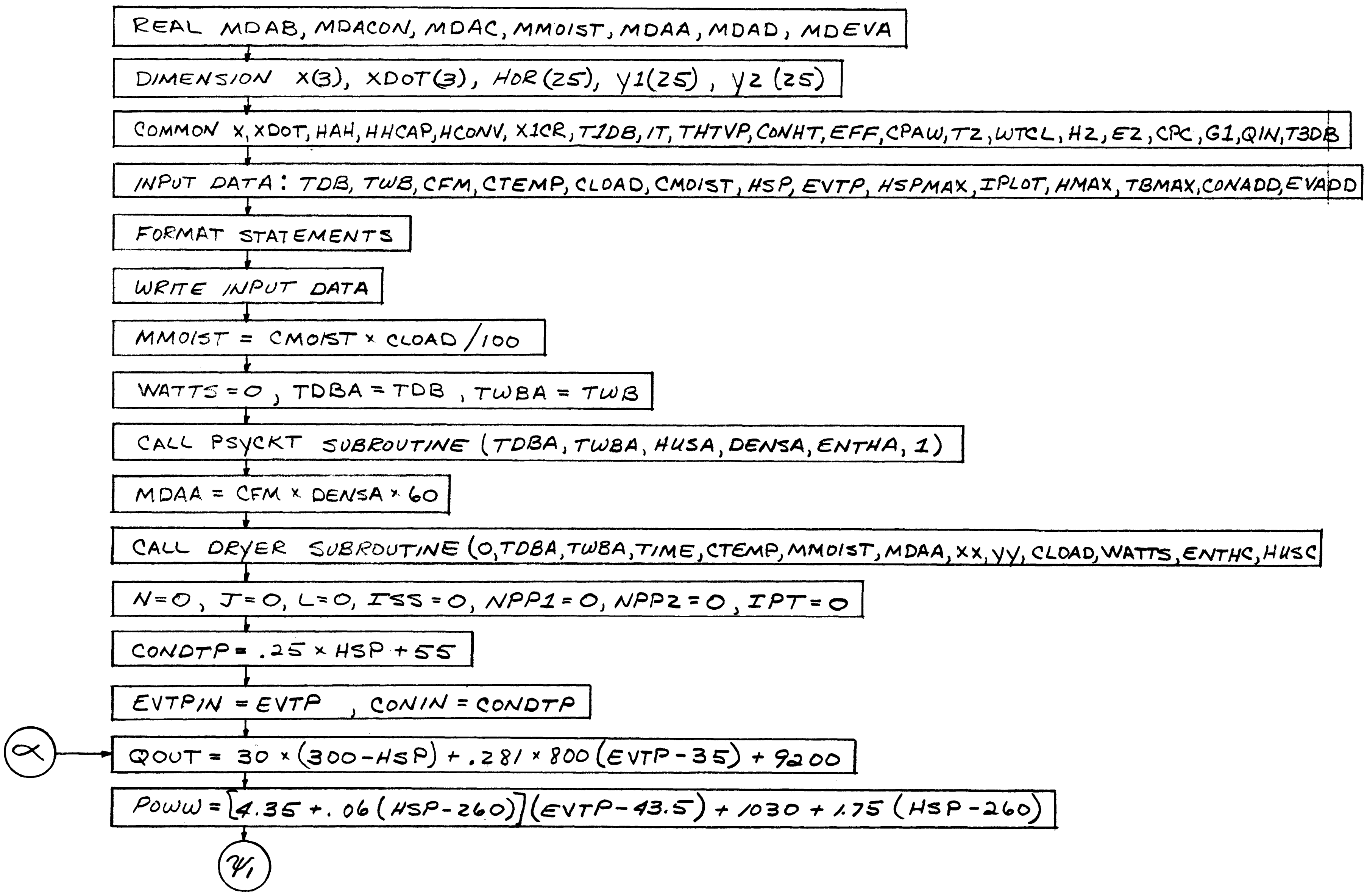
BARO = Total pressure of air-vapor mixture [in Hg]

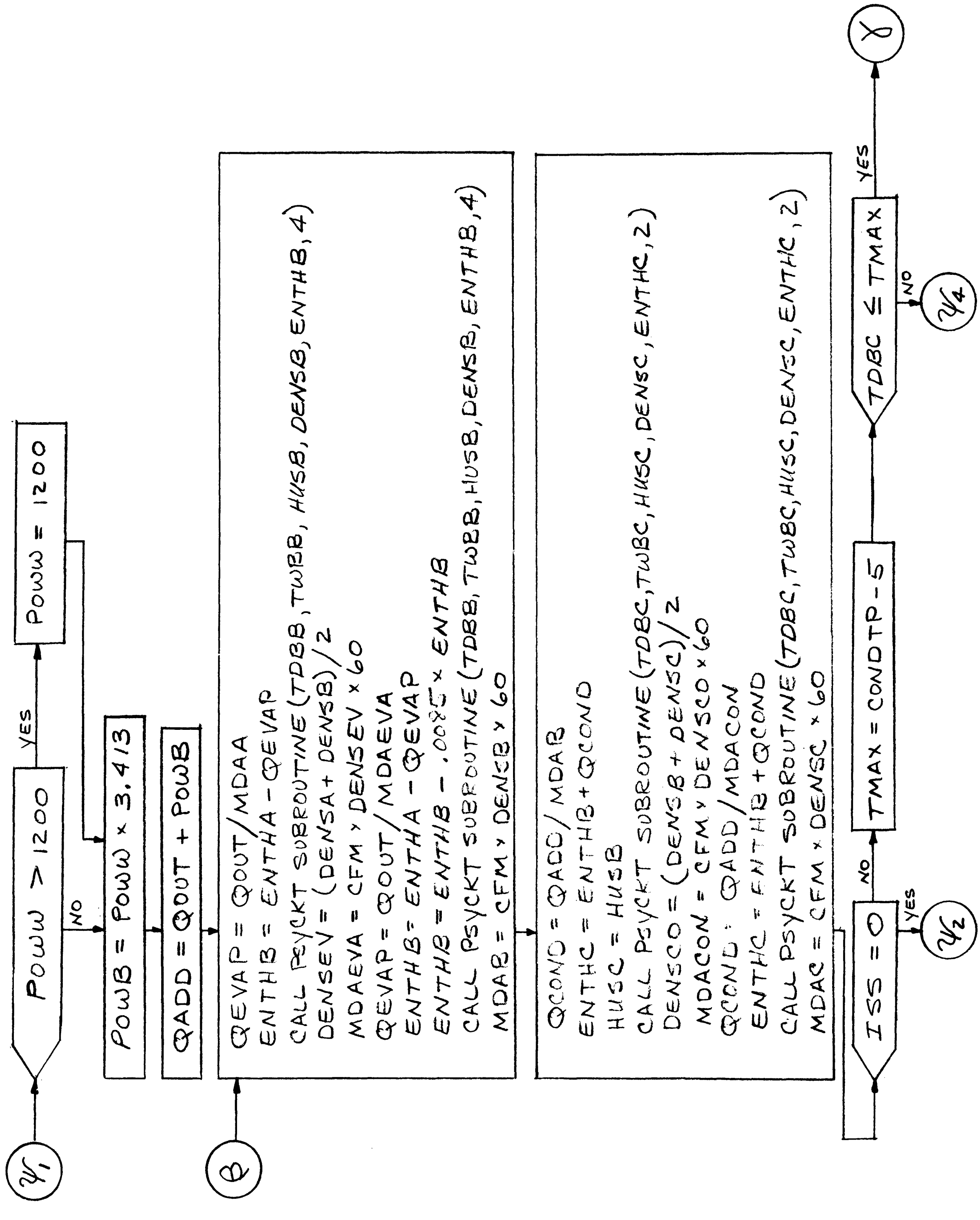
PVA = Partial pressure of water vapor in air [in Hg]

The equations used in this subroutine were obtained from Richard Fanson of the Laundry Group of Whirlpool. These equations were used in the form in which they were obtained except for modification of the value used for the enthalpy of evaporation due to temperature variations.

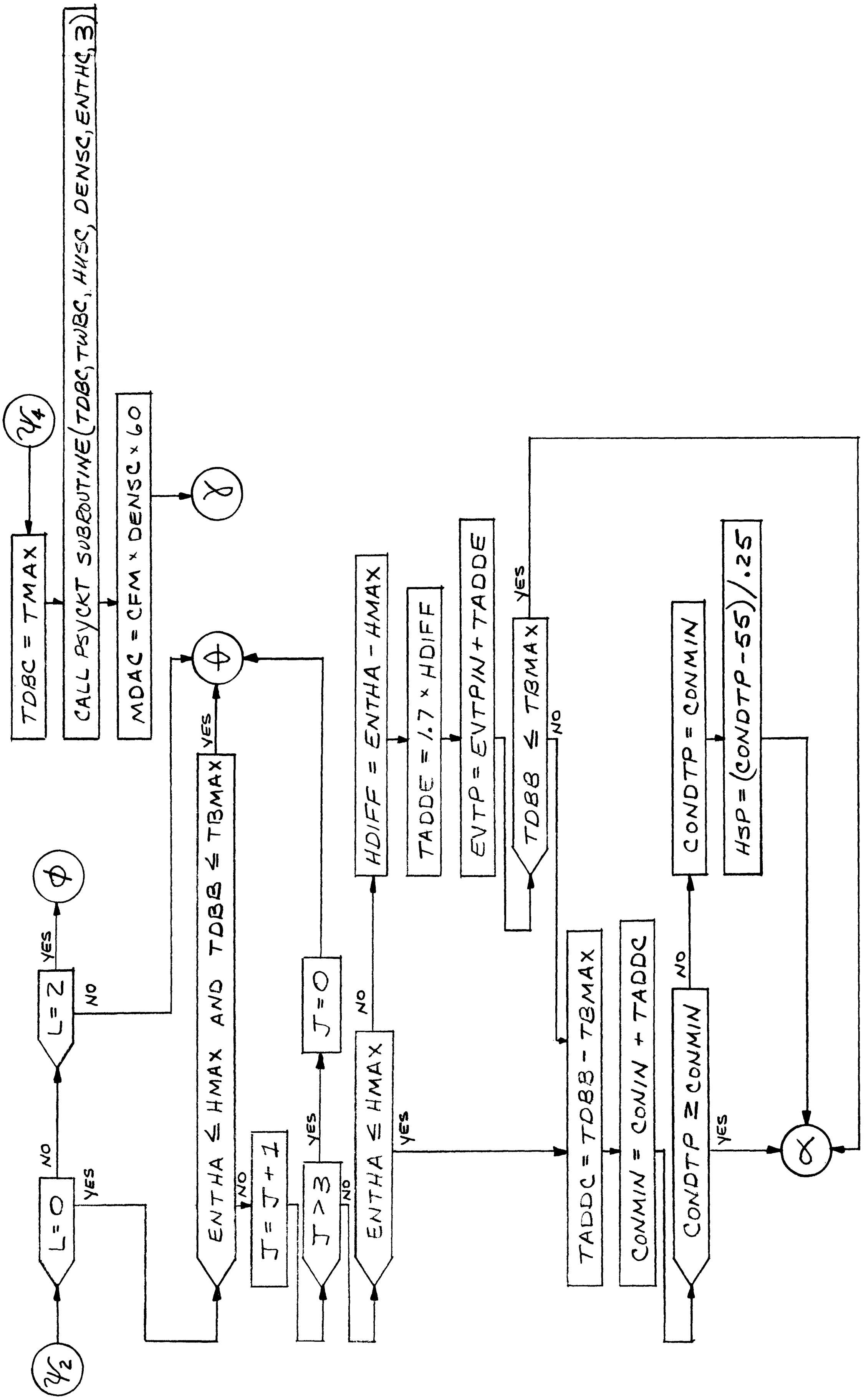
The subroutine includes four cases in which one or two of the properties are known and the others are calculated. These cases correspond to the value of the control integer NJT.

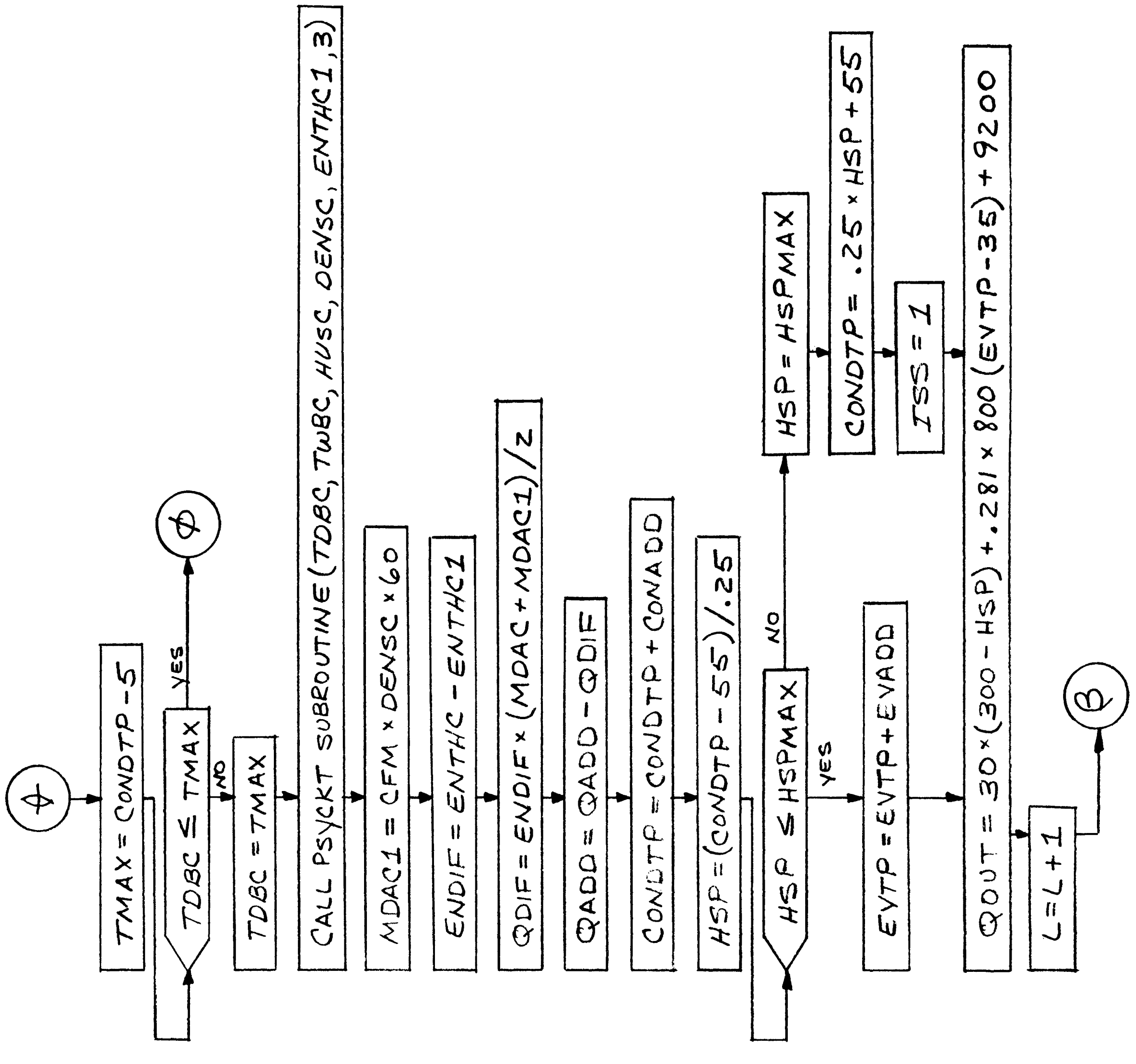
MAIN PROGRAM

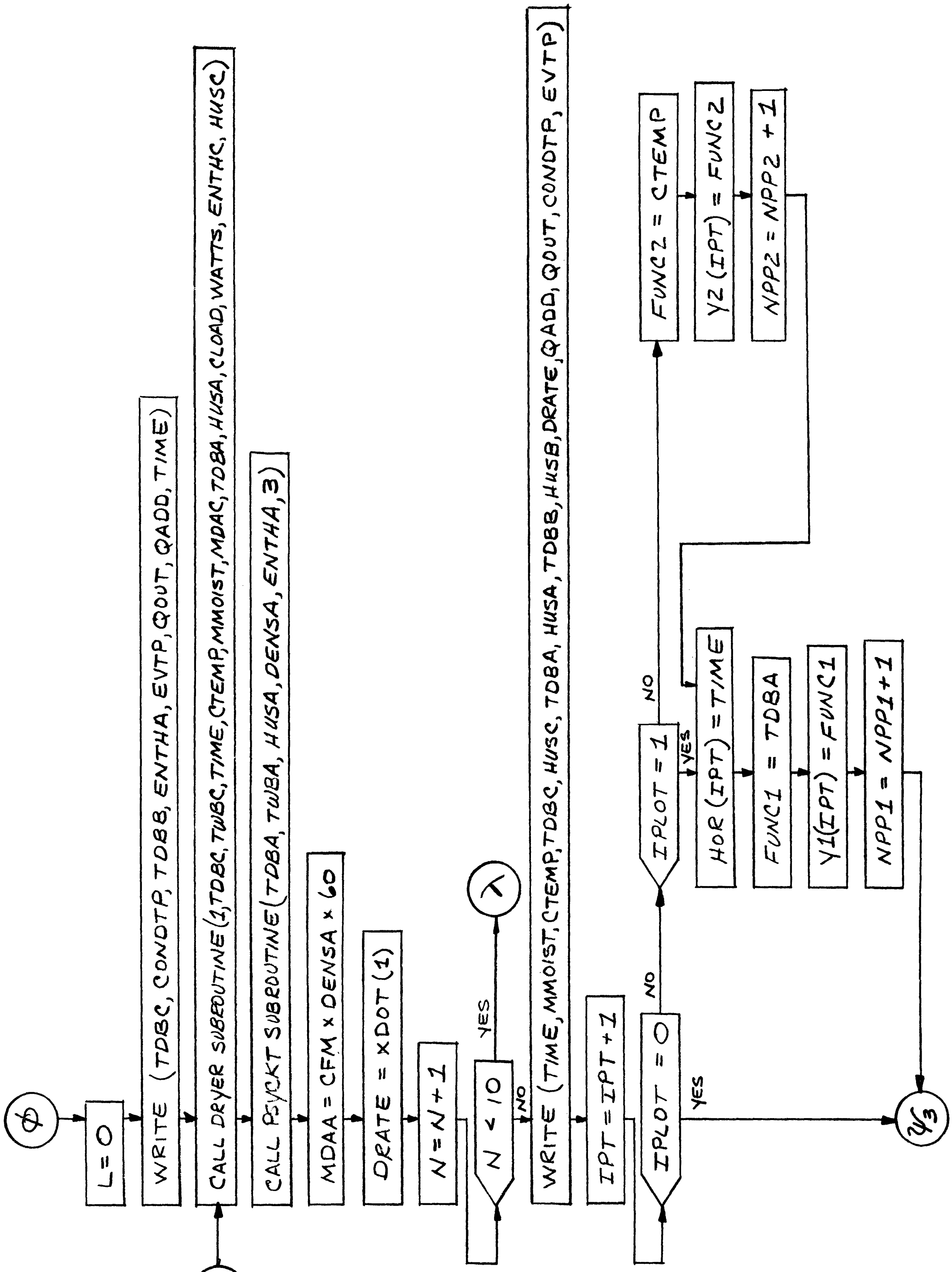


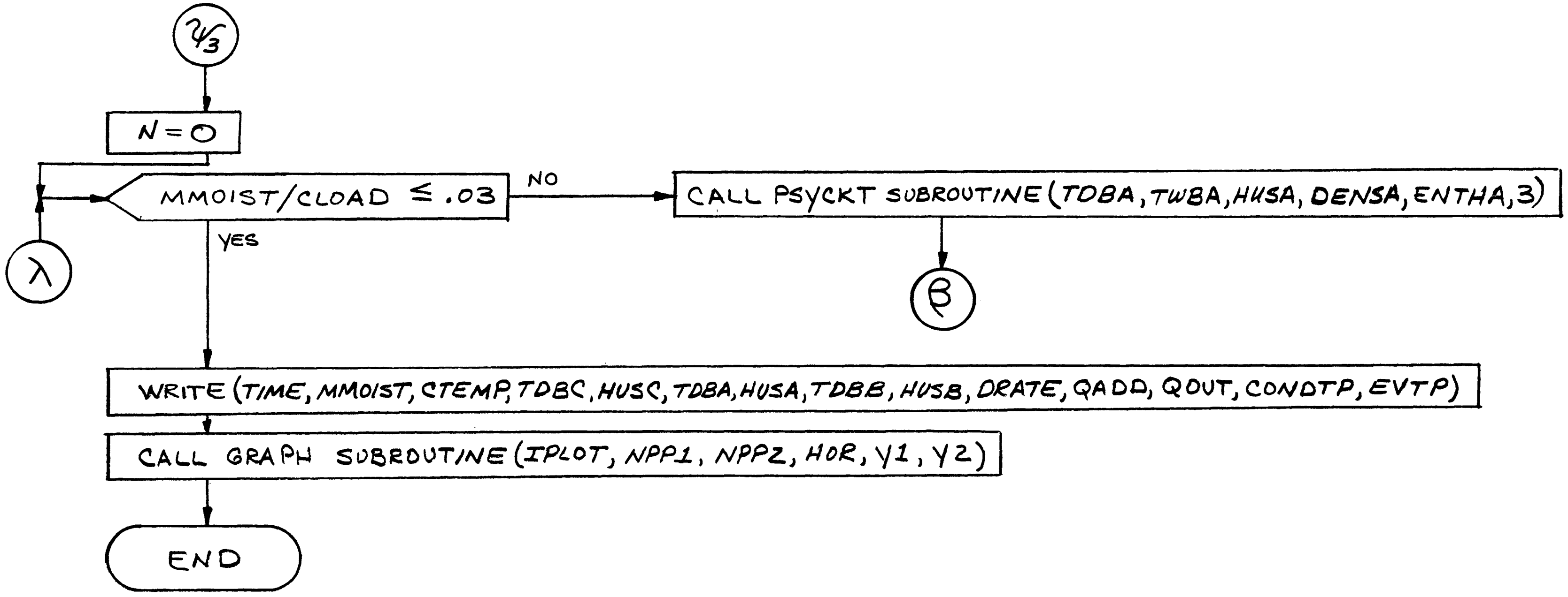


ψ1
POWW > 1200
YES
NO
POWW = 1200
POWB = POWW × 3.413
QADD = QOUT + POWB
B
QEVAP = QOUT/MDAA
ENTHB = ENTHA - QEVAP
CALL PSYCKT SUBROUTINE (TDBB, TWBB, HUSB, DENSB, ENTHB, 4)
DENSEV = (DENSA + DENSB)/2
MDAEVA = CFM × DENSEV × 60
QEVAP = QOUT/MDAEVA
ENTHB = ENTHA - QEVAP
ENTHB = ENTHB - .0085 × ENTHB
CALL PSYCKT SUBROUTINE (TDBB, TWBB, HUSB, DENSB, ENTHB, 4)
MDAB = CFM × DENSB × 60
QCOND = QADD/MDAB
ENTHC = ENTHB + QCOND
HUSC = HUSB
CALL PSYCKT SUBROUTINE (TDBC, TWBC, HUSC, DENSC, ENTHC, 2)
DENSCO = (DENSB + DENSC)/2
MDACON = CFM × DENSCO × 60
QCOND = QADD/MDACON
ENTHC = ENTHB + QCOND
CALL PSYCKT SUBROUTINE (TDBC, TWBC, HUSC, DENSC, ENTHC, 2)
MDAC = CFM × DENSC × 60
ISS = 0
YES
NO
ψ2
TMAX = CONDTP - 5
TDBC ≤ TMAX
NO
YES
ψ4
γ


Ψ2
L = 0
NO
YES
L = 2
YES
NO
Φ
ENTHA ≤ HMAX AND TDBB ≤ TBMAX
YES
NO
J = J + 1
J > 3
YES
NO
J = 0
ENTHA ≤ HMAX
YES
NO
HDIFF = ENTHA - HMAX
TADDE = 1.7 × HDIFF
EVTP = EVTPIN + TADDE
TDBB ≤ TBMAX
YES
NO
TADDC = TDBB - TBMAX
CONMIN = CONIN + TADDC
CONDTP ≥ CONMIN
YES
NO
CONDTP = CONMIN
HSP = (CONDTP - 55)/.25
γ
Ψ4
TDBC = TMAX
CALL PSYCKT SUBROUTINE (TDBC, TWBC, HUSC, DENSC, ENTHC, 3)
MDAC = CFM × DENSC × 60
γ


Φ
TMAX = CONDTP - 5
TDBC ≤ TMAX
YES
Φ
NO
TDBC = TMAX
CALL PSYCKT SUBROUTINE (TDBC, TWBC, HUSC, DENSC, ENTHC1, 3)
MDAC1 = CFM × DENSC × 60
ENDIF = ENTHC - ENTHC1
QDIF = ENDIF × (MDAC + MDAC1)/2
QADD = QADD - QDIF
CONDTP = CONDTP + CONADD
HSP = (CONDTP - 55)/.25
HSP ≤ HSPMAX
NO
HSP = HSPMAX
CONDTP = .25 × HSP + 55
ISS = 1
YES
EVTP = EVTP + EVADD
QOUT = 30 × (300 - HSP) + .281 × 800 (EVTP - 35) + 9200
L = L + 1
B


φ
L = 0
WRITE (TDBC, CONDTP, TDBB, ENTHA, EVTP, QOUT, QADD, TIME)
CALL DRYER SUBROUTINE (1, TDBC, TWBC, TIME, CTEMP, MMOIST, MDAC, TDBA, HUSA, CLOAD, WATTS, ENTHC, HUSC)
γ
CALL PSYCKT SUBROUTINE (TDBA, TWBA, HUSA, DENSA, ENTHA, 3)
MDAA = CFM × DENSA × 60
DRATE = XDOT (1)
N = N + 1
N < 10
YES
NO
λ
WRITE (TIME, MMOIST, CTEMP, TDBC, HUSC, TDBA, HUSA, TDBB, HUSB, DRATE, QADD, QOUT, CONDTP, EVTP)
IPT = IPT + 1
IPLOT = 0
YES
NO
IPLOT = 1
YES
NO
HOR (IPT) = TIME
FUNC1 = TDBA
Y1(IPT) = FUNC1
NPP1 = NPP1 + 1
FUNC2 = CTEMP
Y2 (IPT) = FUNC2
NPP2 = NPP2 + 1
ψ3


ψ3
N = O
MMOIST/CLOAD ≤ .03
NO
YES
λ
CALL PSYCKT SUBROUTINE (TDBA, TWBA, HUSA, DENSA, ENTHA, 3)
β
WRITE (TIME, MMOIST, CTEMP, TDBC, HUSC, TDBA, HUSA, TDBB, HUSB, DRATE, QADD, QOUT, CONDTP, EVTP)
CALL GRAPH SUBROUTINE (IPLOT, NPP1, NPP2, HOR, Y1, Y2)
END

Case 1. The dry bulb and wet bulb temperatures are known. Since this case is used in the program with only ambient conditions, 1050 Btu/lbm is used for the enthalpy of evaporation which corresponds to 76°F.

Case 2. The enthalpy and specific humidity of the air-vapor mixture are known. This case is used with the mixture as it enters the dryer. Therefore, the value used for enthalpy of evaporation is 1035 Btu/lbm which corresponds to 103°F.

Case 3. The dry bulb temperature and specific humidity of the mixture are known. Since this case is used with the dryer exhaust the enthalpy of evaporation used is again 1035 Btu/lbm.

Case 4. The enthalpy of the mixture and the fact that the mixture is at saturation are known.

8. DISCUSSION OF GRAPH SUBROUTINE

This subroutine prepares the information necessary for calling on a subroutine stored in the MTS Library which prints out plotted graphs. Y1MAX and Y1MIN are the maximum and minimum values of the variable to be plotted on the y-axis of the first graph. Likewise, Y2MAX and Y2MIN are the maximum and minimum values for the second graph.

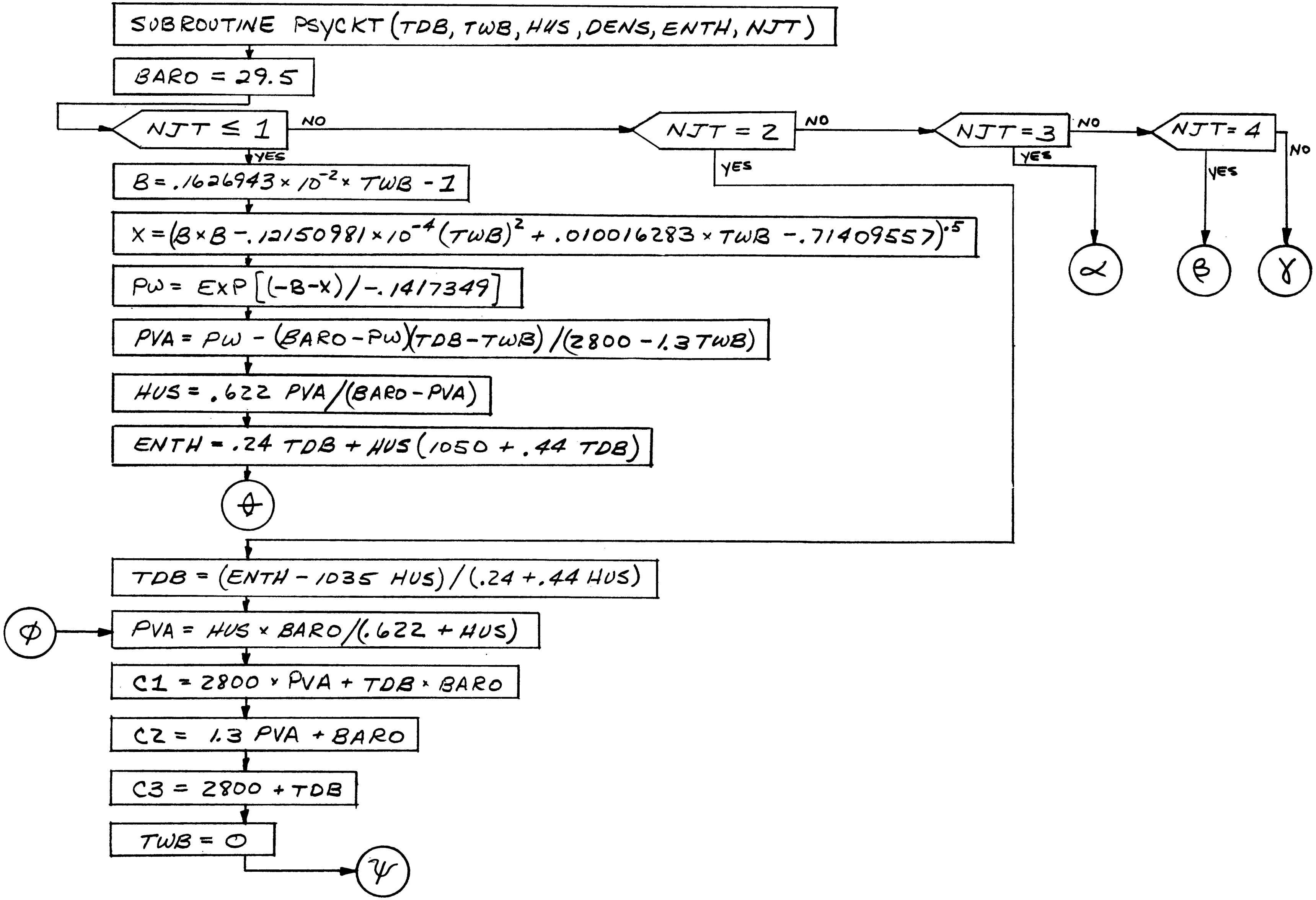
If this program is run on a system other than that of The University of Michigan, IPLOT must be set equal to zero and no plots will be produced.

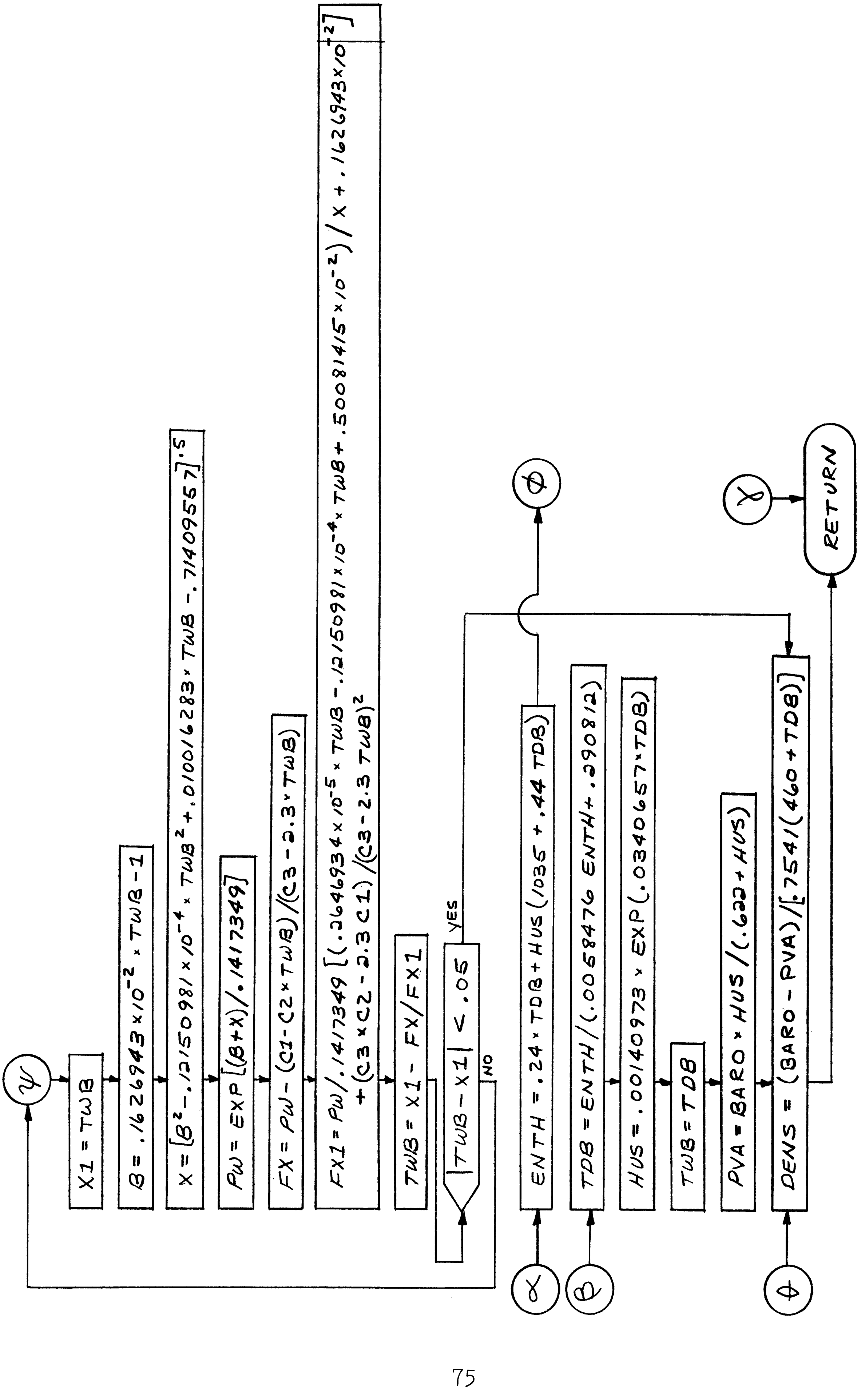
9. DISCUSSION OF DRYER SUBROUTINE

The DRYER subroutine package which includes four subroutines was used to simulate the actual clothes dryer portion of the system. This package was previously developed by Whirlpool. The meanings of the symbols used as arguments of the subroutine are given in the main program discussion. The control parameter must be set equal to zero to initialize a new run and is thereafter set equal to 1. The DRYER package controls and increments the time parameter.

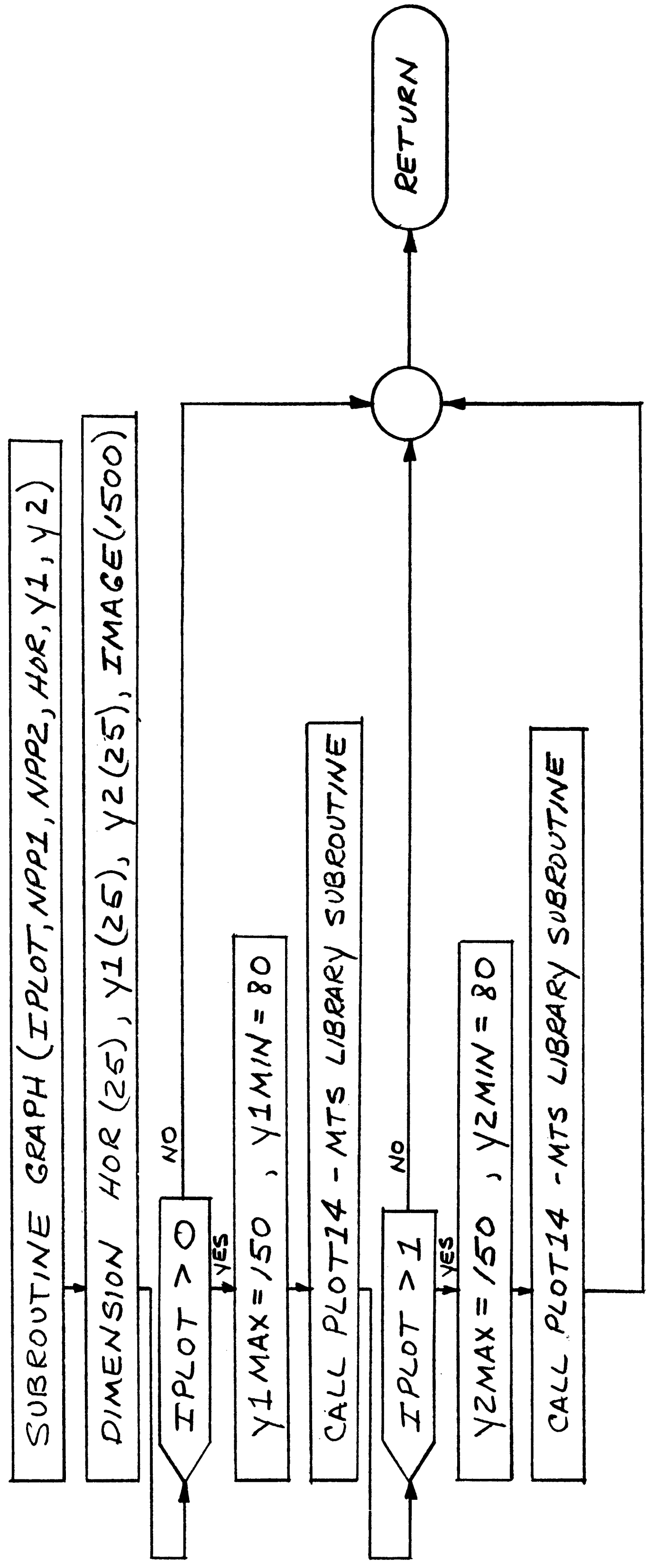
One alteration of the subroutine was necessary to use it in a ventless dryer system. An additional call to the package's own psychrometric subroutine was needed to calculate new properties of the air-vapor mixture entering the dryer every time the DRYER subroutine is called. In a conventional dryer the inlet air properties remain constant but in a closed-loop system these properties constantly change.

PSYCHROMETRIC SUBROUTINE




ψ
X1 = TWB
B = .1626943×10^-2 × TWB - 1
X = [B^2 - .12150981×10^-4 × TWB^2 + .010016283 × TWB - .71409557]^.5
PW = EXP[(B+X)/.1417349]
FX = PW - (C1 - C2×TWB)/(C3 - 2.3×TWB)
FX1 = PW/.1417349 [(.2646934×10^-5 × TWB - .12150981×10^-4 × TWB + .50081415×10^-2)/X + .1626943×10^-2] + (C3×C2 - 2.3 C1)/(C3 - 2.3 TWB)^2
TWB = X1 - FX/FX1
|TWB - X1| < .05
YES
NO
Φ
γ
ENTH = .24×TDB + HUS(1035 + .44 TDB)
β
TDB = ENTH/(.0058476 ENTH + .290812)
HUS = .00140973 × EXP(.0340657×TDB)
TWB = TDB
PVA = BARO × HUS/(.622 + HUS)
Φ
DENS = (BARO - PVA)/[.7541(460 + TDB)]
γ
RETURN

GRAPH SUBROUTINE



10. EXPERIMENTAL RESULTS

To evaluate the possible capabilities of a clothes dryer system of this type and to obtain some initial design parameters the effect of several parameters on the operation of the system was investigated.

The input data which were kept constant throughout these runs were:

Ambient dry bulb temperature	TDB	=	72°F
Ambient wet bulb temperature	TWB	=	60°F
Initial clothes load temperature	CTEMP	=	72°F
Initial high side pressure of refrigeration cycle	HSP	=	290 psig
Initial evaporator temperature	EVTP	=	45°F
Maximum high side pressure	HSPMAX	=	400 psig
Designed air temperature over the condenser	TBMAX	=	60°F
Temperature added to condensor in constraints	CONADD	=	3.0°F
Temperature added to evaporator in constraints	EVADD	=	0.38°F

(1) In Figure 5 the effect of moisture content and load size on drying time is shown. The remaining input data were:

Volumetric air flow	CFM	=	220 CFM
Designed air enthalpy over the evaporator	HMAX	=	40 Btu/lbm

while varying the moisture content:

Dry weight of clothes load	CLOAD	=	9 lb

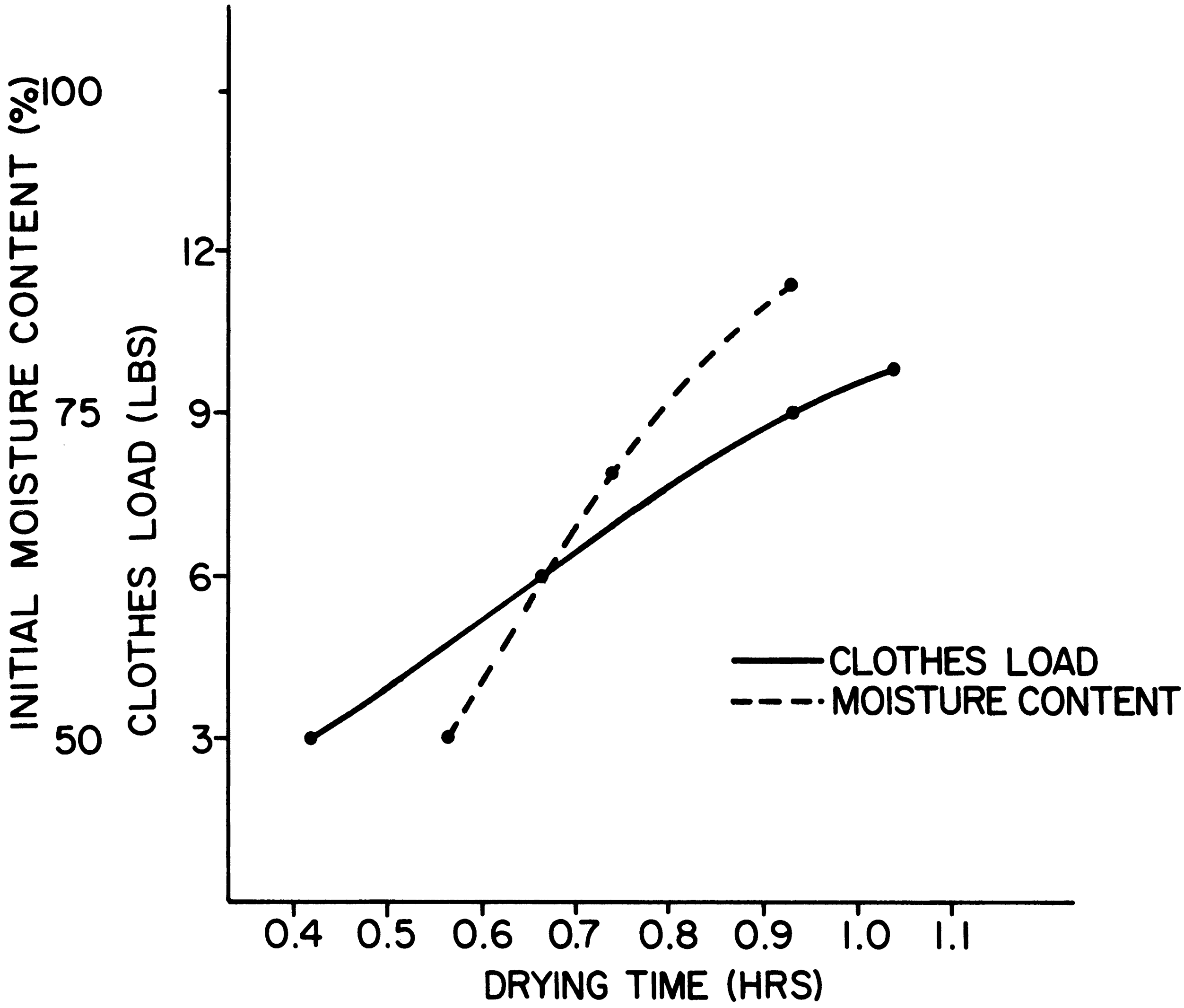


Figure 5. Clothes load and moisture content vs. drying time.

while varying the clothes load:

Initial moisture content of clothes CMOIST = 85%

(2) The effect of the volumetric air flow in the closed-loop on the drying time required is shown in Figure 6. The remaining input data were:

Designed air enthalpy over the evaporator HMAX = 40 Btu/lbm

Dry weight of clothes load CLOAD = 9 lb

Initial moisture content of clothes CMOIST = 85%

(3) The effect of increasing the designed air enthalpy over the evaporator is an increase in the amount of time into the drying period before the constraint which increases the evaporator temperature begins to operate. Since an increase in the evaporator temperature causes an increase in the capacities of the system, the longer the time before this increase begins the longer the drying time required. This effect is shown in Figure 7 where the remaining input data were:

Volumetric air flow CFM = 220 CFM

Dry weight of clothes load CLOAD = 9 lb

Initial moisture content of clothes CMOIST = 85%

The following is an example of the computer simulation output. The input data are given in the printed output. The results given here are those used to compare the simulated system to the other systems in Figure 2. Following the program output is a listing of a temporary file containing the values of properties in the system before the maximum high side pressure was reached.

It is evident that with the refrigerant, compressor, and resulting maximum pressure used here, the fluctuations in heat transfer at the evaporator and condenser occur during only the first few minutes of the drying time. The capacity of the condenser during this time is shown in Figure 8. The capacity drops as the condenser temperature increases and then increases as the evaporator temperature starts increasing until the maximum pressure is reached and the capacity remains constant thereafter. The capacity of the evaporator follows a similar pattern.

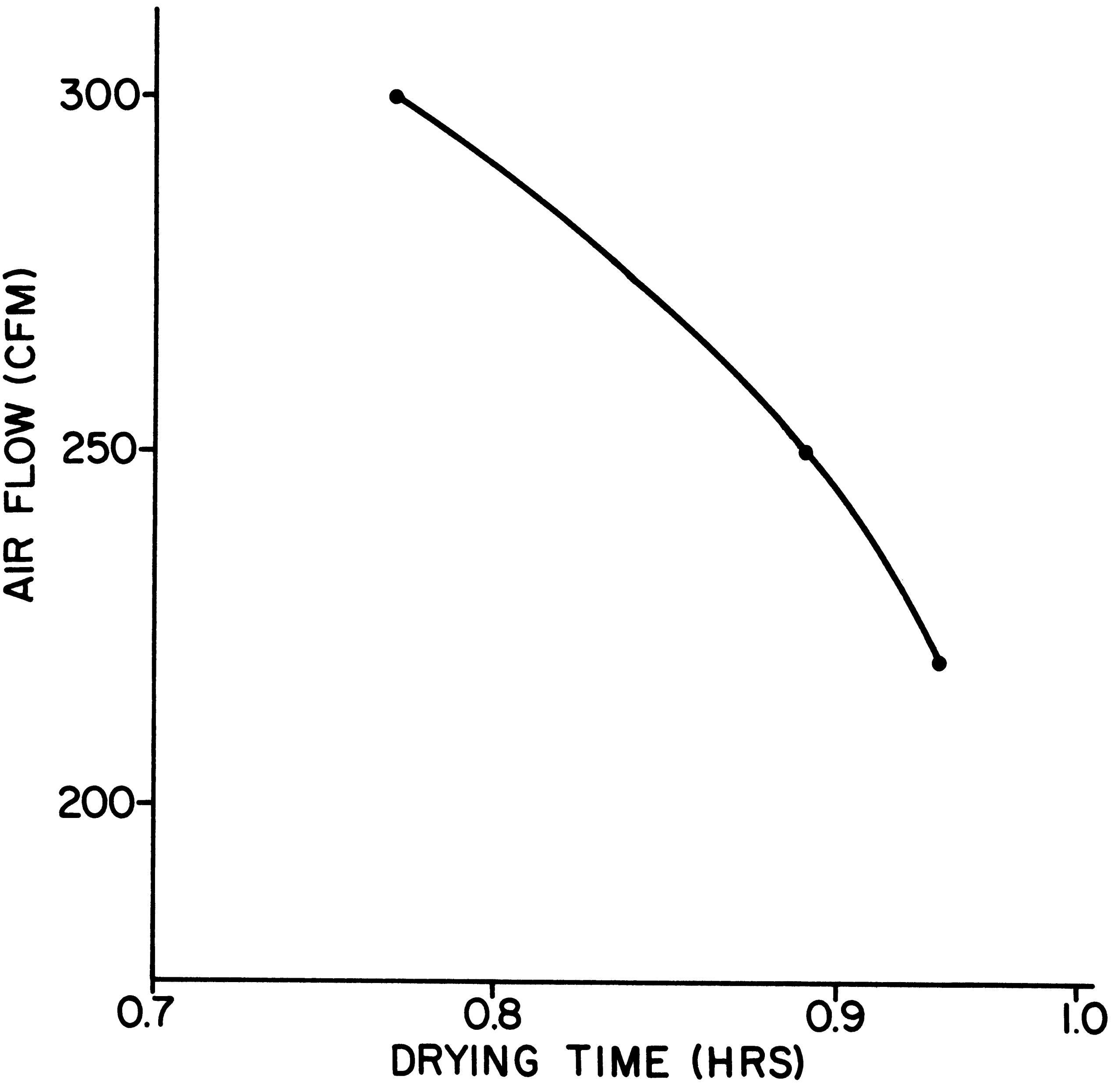


Figure 6. Air flow vs. drying time.

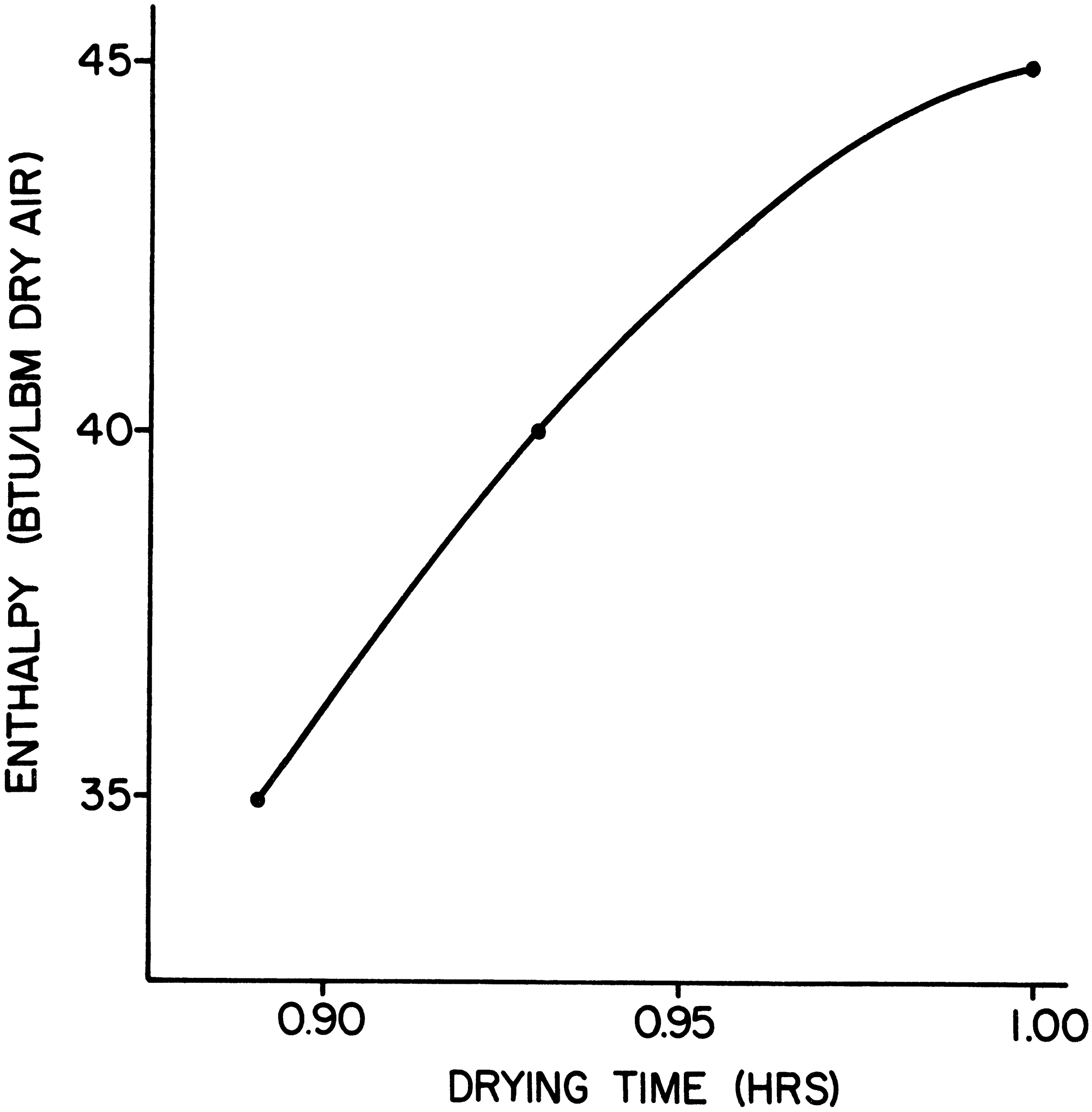


Figure 7. Enthalpy vs. drying time.

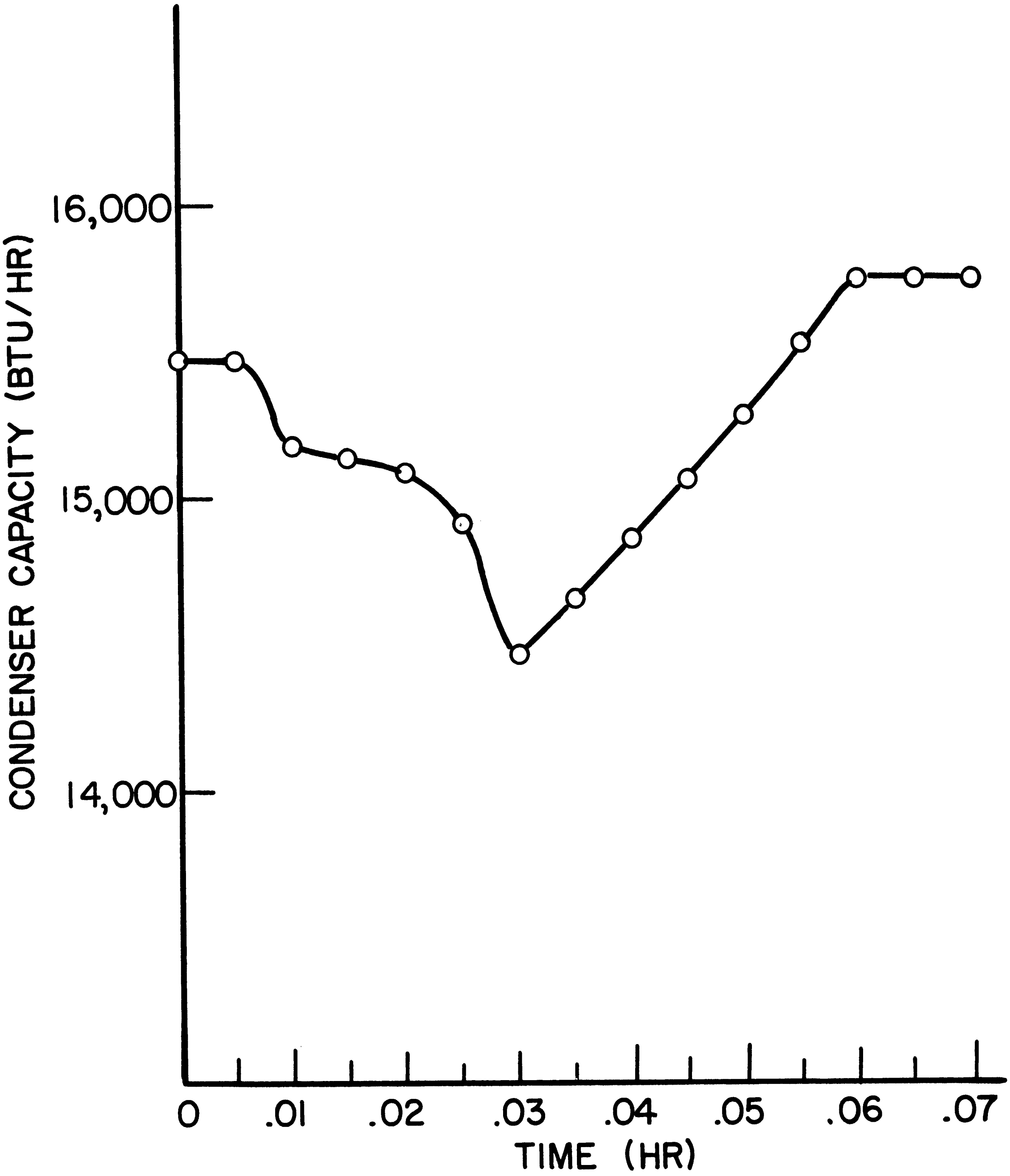


Figure 8. Condenser capacity vs. time.

```
                    ***** DRYER SIMULATION *****


               DRYER INPUT DATA

AMB. DRY BULB TEMP. =   72.0 F       AMB. WET BULB TEMP. =   60.0 F
AIR FLOW = 220.0 CFM                 INITIAL CLOTHES TEMP. =   72.0 F
INITIAL CLOTHES LOAD =    9.0 LBS    INITIAL MOISTURE CONTENT =   85.0 %


               REFRIGERATION CYCLE INPUT DATA

CONDENSER                            EVAPORATOR

INITIAL PRESSURE = 290.0 PSI         INITIAL TEMP. =   45.0 F
MAXIMUM PRESSURE = 400.0 PSI
DESIGNED AIR TEMP. =   60.0 F        DESIGNED AIR ENTHALPY =   40.0 BTU/LBM
DELTA TEMP. =    3.0 F               DELTA TEMP. =    0.4 F


THE RESULTS FOLLOW


TIME   MMOIST   CTEMP    TDBC    HUSC     TDBA    HUSA    TDBB    HUSB     DRATE    QADD      QOUT     CONDTP    EVTP
0.05   7.288    82.5    141.0   0.0142    87.6   0.0238   67.9   0.0142    -8.1   15074.2   11240.0    148.5    54.0
0.10   6.852    92.5    150.0   0.0221    97.5   0.0333   80.8   0.0221    -9.2   15758.1   12228.7    155.0    61.8
0.15   6.400    96.0    150.0   0.0261   100.7   0.0374   85.7   0.0261    -9.1   15758.1   12228.7    155.0    61.8
0.20   5.948    97.2    150.0   0.0278   101.9   0.0390   87.5   0.0278    -9.1   15758.1   12228.7    155.0    61.8
0.25   5.496    97.7    150.0   0.0285   102.3   0.0396   88.2   0.0285    -9.0   15758.1   12228.7    155.0    61.8
0.30   5.045    97.9    150.0   0.0288   102.5   0.0399   88.5   0.0288    -9.0   15758.1   12228.7    155.0    61.8
0.35   4.593    98.0    150.0   0.0288   102.6   0.0400   88.6   0.0288    -9.0   15758.1   12228.7    155.0    61.8
0.40   4.142    98.0    150.0   0.0289   102.6   0.0400   88.6   0.0289    -9.0   15758.1   12228.7    155.0    61.8
0.45   3.691    98.1    150.0   0.0289   102.6   0.0401   88.7   0.0289    -9.0   15758.1   12228.7    155.0    61.8
0.50   3.240    98.1    150.0   0.0289   102.6   0.0401   88.7   0.0289    -9.0   15758.1   12228.7    155.0    61.8
0.55   2.789    98.1    150.0   0.0289   102.7   0.0401   88.7   0.0289    -9.0   15758.1   12228.7    155.0    61.8
0.60   2.338    98.1    150.0   0.0289   102.7   0.0401   88.7   0.0289    -9.0   15758.1   12228.7    155.0    61.8
0.65   1.887    98.1    150.0   0.0289   102.7   0.0401   88.7   0.0289    -9.0   15758.1   12228.7    155.0    61.8
0.70   1.454   100.5    150.0   0.0275   104.9   0.0377   87.2   0.0275    -8.2   15758.1   12228.7    155.0    61.8
0.75   1.069   106.2    150.0   0.0263   110.1   0.0350   85.9   0.0263    -7.1   15758.1   12228.7    155.0    61.8
0.80   0.752   114.2    150.0   0.0255   117.4   0.0324   85.0   0.0255    -5.6   15758.1   12228.7    155.0    61.8
0.85   0.513   123.4    150.0   0.0250   125.8   0.0300   84.4   0.0250    -4.0   15758.1   12228.7    155.0    61.8
0.90   0.348   132.0    150.0   0.0250   133.6   0.0283   84.5   0.0250    -2.6   15758.1   12228.7    155.0    61.8
0.93   0.269   136.8    150.0   0.0253   138.0   0.0277   84.8   0.0253    -1.9   15758.1   12228.7    155.0    61.8
```

```
$LIST -A
     1         TDBC   CONDTP     TDBB    ENTHA     EVTP    QOUT     QADD       TIME
     2        103.1    127.5     38.6     26.4     45.0 11748.0  15474.1     0.0
     3        120.9    127.5     51.5     33.7     45.0 11748.0  15474.1     0.005
     4        123.1    130.5     54.1     35.1     45.4 11473.4  15182.6     0.010
     5        126.1    133.5     56.3     36.3     45.8 11198.8  15144.1     0.015
     6        129.1    136.5     58.7     37.7     46.1 10924.3  15091.8     0.020
     7        131.0    136.5     60.8     39.1     46.1 10924.3  14908.7     0.025
     8        132.1    139.5     63.1     40.6     46.4 10616.6  14470.8     0.030
     9        135.1    142.5     64.7     42.0     48.8 10806.9  14665.6     0.035
    10        138.0    145.5     66.3     43.5     51.3 11014.8  14865.5     0.040
    11        141.0    148.5     67.9     45.0     54.0 11240.0  15074.2     0.045
    12        144.0    151.5     69.4     46.6     56.6 11482.0  15292.0     0.050
    13        147.0    154.5     70.9     48.2     59.4 11740.1  15519.8     0.055
END OF FILE
```

APPENDIX

(1) Figure A-1 is a schmatic diagram of a system where the refrigeration system is used in an open-loop configuration. Such a system operates more effectively than a closed-loop system because the air entering the condenser is ambient air at approximately 50% relative humidity rather than saturated air. The air into the dryer is also at a "dryer" state and more able to absorb the moisture of the clothes.

An additional feature of such a system would be the possibility of using either the cool air from the evaporator or the warm humid air from the dryer to cool or humidify the room.

(2) Calculation of the energy lost in draining the condensed water.

This calculation is made using the data from sample output of the simulation program.

General equation:

$$h_A + \omega_A h_{v_A} + Q/\overset{\circ}{m} = h_B + \omega_{v_B} + (\omega_A - \omega_B)h_\ell$$

Mass flow of air:

$$\overset{\circ}{m} = \overset{\circ}{V}/v \times 60 = \frac{200 \text{ ft}^3/\text{min}}{14.8 \text{ ft}^3/\text{lbm}} \times 60 = 810 \text{ lbm/hr}$$

Heat transfer:

$$Q/\overset{\circ}{m} = \frac{12228 \text{ Btu/hr}}{810 \text{ lbm/hr}} = 15.1 \text{ Btu/lbm}$$

ENTHA = 69 Btu/lbm, HUSA = .0400 lbm H_2O/lbm air

Ignoring the drained water we get:

ENTHB = 69 Btu/lbm - 15.1 Btu/lbm = 54 Btu/lbm

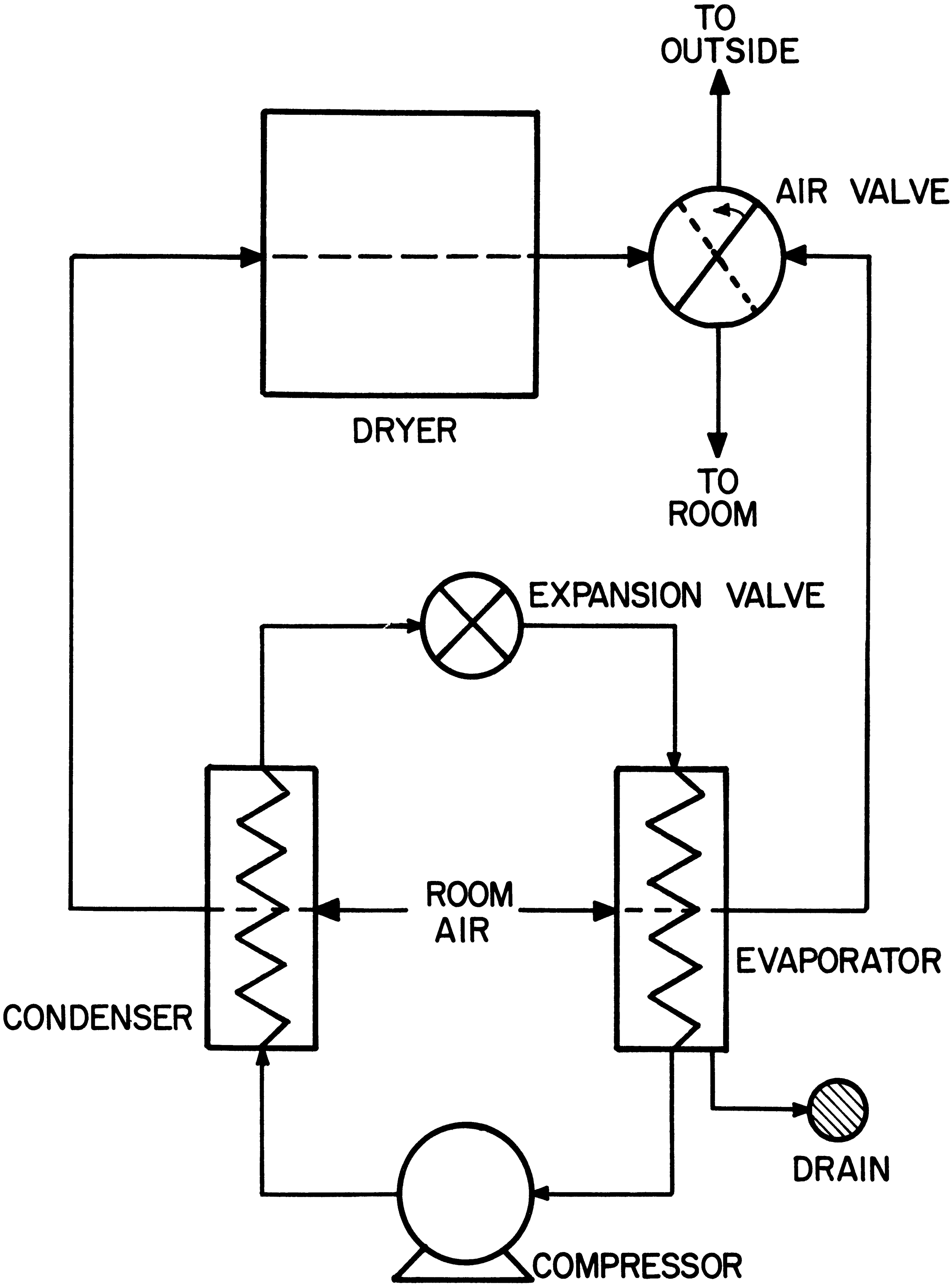


Figure A-1. Schematic diagram of open-loop system.

Since this is at saturation:

$$\text{HUSB} = .0295 \text{ lbm } H_2O/\text{lbm air}$$

Assume the enthalpy of the condensed liquid is the enthalpy of the saturated liquid at 88°F. An approximate value for the energy of the liquid is:

$$(\omega_A - \omega_B)h_\ell = (.0400 - .0295)\ 56 = 1.1480 \text{ Btu/lbm}$$

In the computer program, this is assumed to be a constant fraction of ENTHB:

$$1.1480/54 = .0212$$

The simplified approximation is then:

$$\text{ENTHB} = \text{ENTHB} - .0212 \text{ ENTHB}$$

The value in the program listing is lower than this since it was calculated using lower temperatures. This higher value will be useful in lengthening the energy build-up time.

(3) Calculation of the amount of air bleed at the dryer exhaust necessary for the system to remain at a steady state operating condition after the maximum high pressure has been reached. The values used are taken from the sample simulation output.

Dryer exhaust conditions:

$\text{TDBA} = 102.6°\text{F}$, $\text{HUSA} = .040 \text{ lbm } H_2O/\text{lbm air}$

$\text{ENTHA} = 69 \text{ Btu/lbm}$, $v = 15 \text{ ft}^3/\text{lbm}$

relative humidity = 87%

Ambient air conditions:

$$TDB = 72°F \qquad TWB = 60°F$$

$$ENTH = 26.5 \text{ Btu/lbm}, \qquad v = 13.6 \text{ ft}^3\text{/lbm}$$

relative humidity = 50%

Amount of energy that must be dissipated:

$$QADD - QOUT = 15758 - 12228 = 3{,}530 \text{ Btu/hr}$$

Necessary air bleed:

$$\overset{o}{m}_{bleed} = \frac{3{,}530 \text{ Btu/hr}}{(69-26.5)\text{Btu/lbm}} = 83 \text{ lbm/hr}$$

$$\overset{o}{V}_{bleed} = 83 \text{ lbm/m} \times \frac{15 \text{ ft}^3\text{/lbm}}{60} = 20.8 \text{ CFM}$$

Approximate amount of moisture this would add to the room:

$$(HUSA - HUS)\,\overset{o}{m} = .032 \text{ lbm } H_2O\text{/lbm air} \times 83 \text{ lbm air/m}$$

$$= 2.65 \text{ lbm } H_2O\text{/m.}$$

(4) Figure A-2 is a copy of the compressor curves used in the simulation. Another compressor could be used in the simulation as long as curves such as these were available from which to derive the necessary equations.

(5) Figure A-3 shows the McQuay data curves relating evaporator temperature to the enthalpy of the air over the evaporator.

(6) Figure A-4 shows the McQuay data curves relating condenser temperature to air temperature over the condenser.

(7) The following is a compiled listing of the main program and subroutines PSYCKT and GRAPH. A sample of a computer output plot and data file are also included.

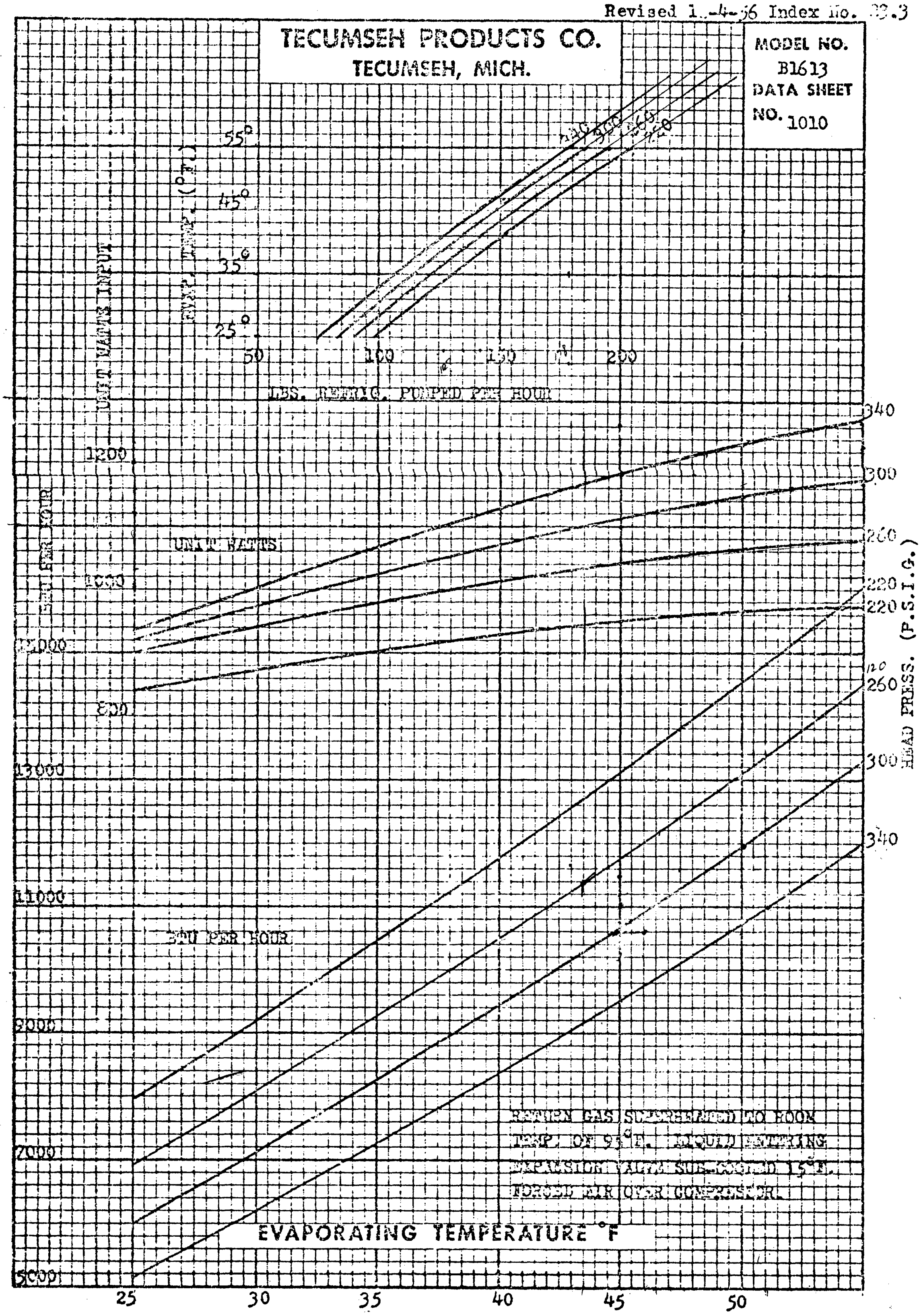


Figure A-2. Compressor curves.

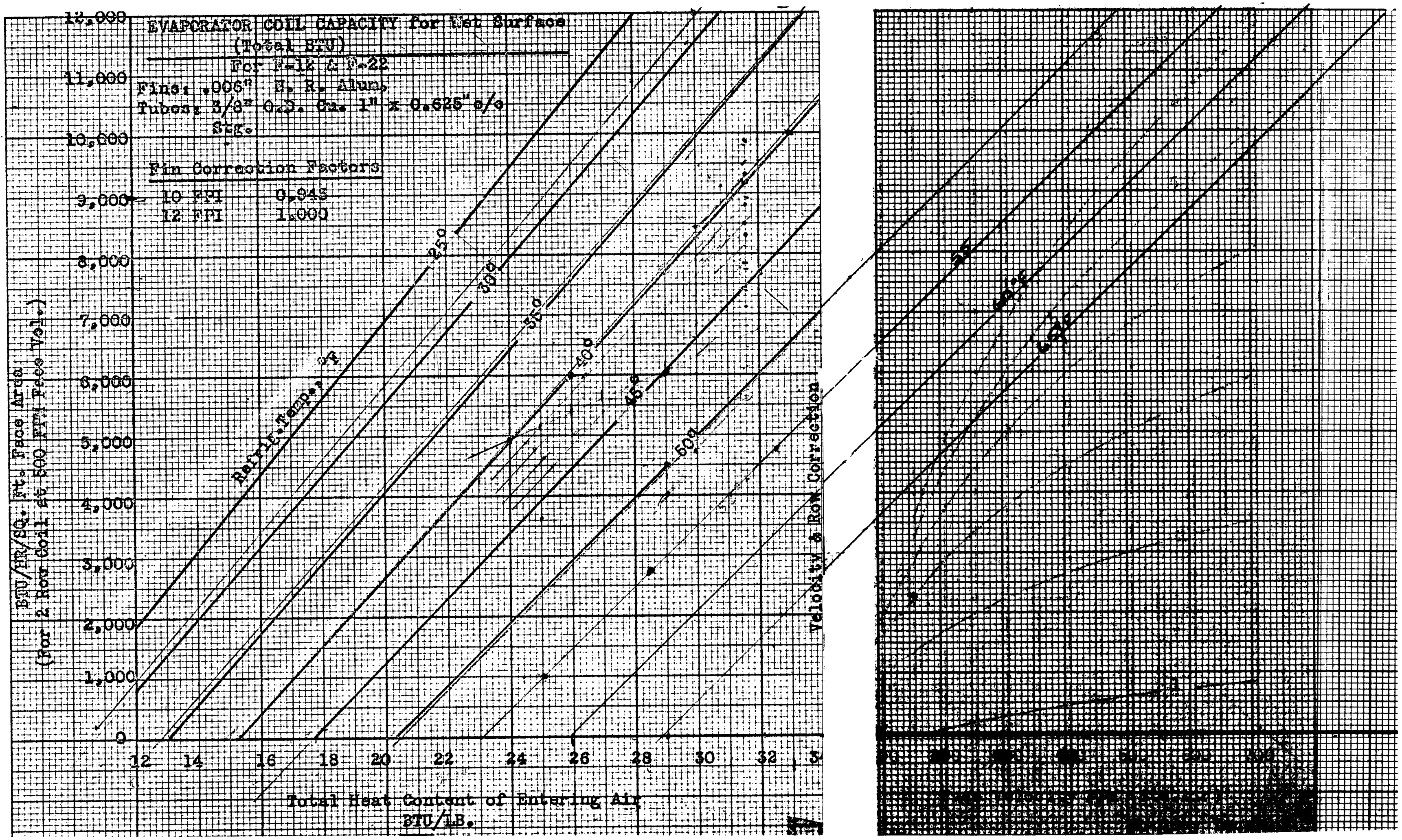
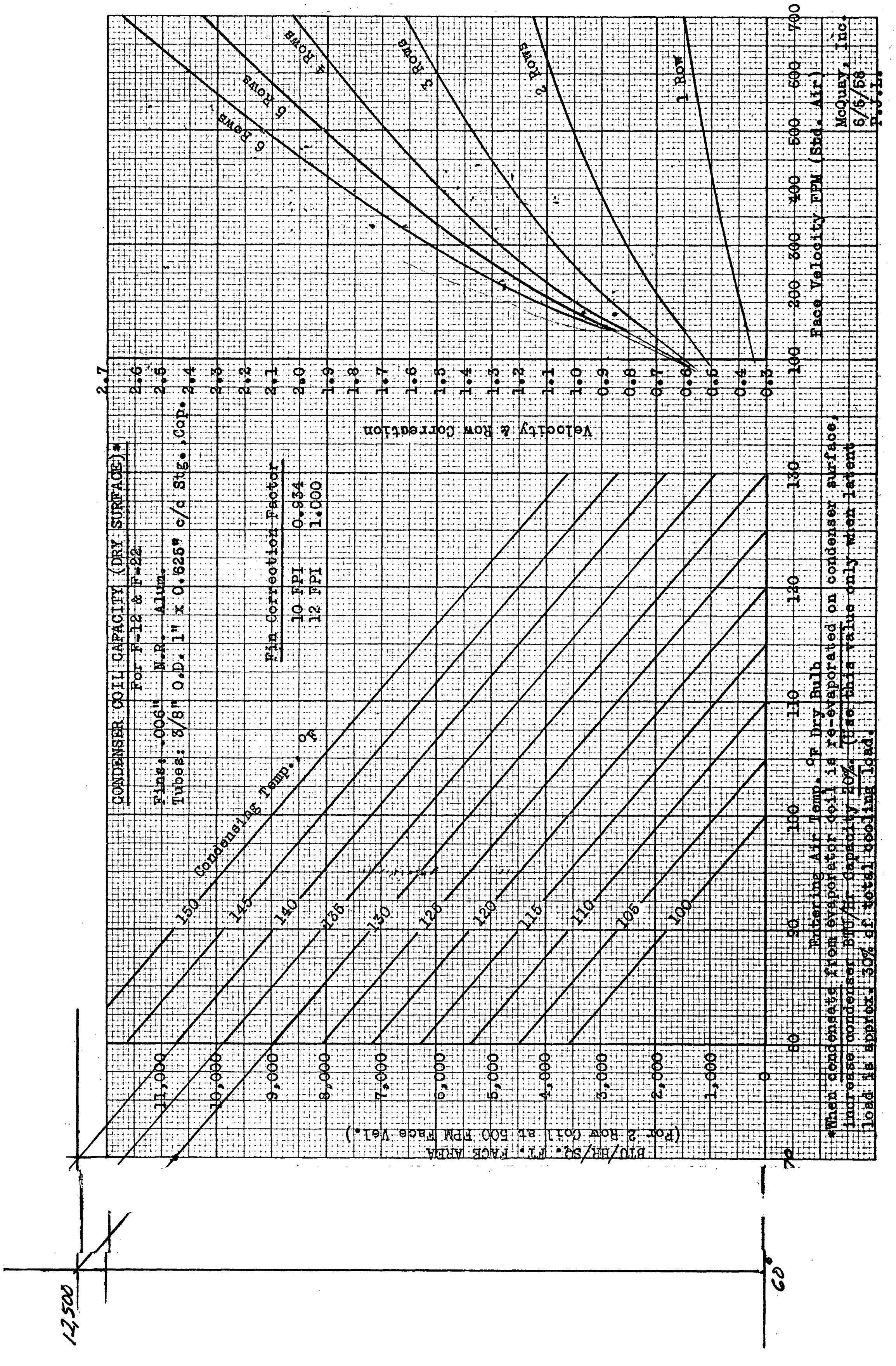


Figure A-3. Compressor curves.

EPS # 2401



*When condensate from evaporator coil is re-evaporated on condenser surface, increase condenser BTU/Hr capacity 20%. (Use this value only when latent load is approx. 30% of total cooling load.

Figure A-4. Compressor curves.

```
C************************ DRYER SIMULATION ************************
C**                                                              **
C**   THIS IS A SIMULATION OF A CLOSED-LOOP CLOTHES DRYER WHICH  **
C**   PASSES THE DRYER EXHAUST AIR OVER THE EVAPORATOR AND       **
C**   CONDENSER COILS OF A REFRIGERATION CYCLE IN THE FEEDBACK   **
C**   LOOP.                                                      **
C**                                                              **
C**   THE PURPOSE OF THIS SIMULATION IS TO AID IN THE DESIGN OF  **
C**   SUCH A CLOTHES DRYER SYSTEM.                               **
C**                                                              **
C**   THE FOLLOWING IS A LIST OF THE INPUT AND OUTPUT PARAMETERS:**
C**       INPUT:                                                 **
C**                 TDB - AMBIENT DRY BULB TEMP. (F)             **
C**                 TWB - AMBIENT WET BULB TEMP. (F)             **
C**                 CLOAD - DRY WEIGHT OF CLOTHES LOAD (LBS)     **
C**                 CMOIST - MOISTURE CONTENT AS PERCENT OF DRY  **
C**                          WEIGHT (%)                          **
C**                 CTEMP - INITIAL CLOTHES LOAD TEMP. (F)       **
C**                 CFM - VOLUMETRIC AIR FLOW (CFM)              **
C**                 HSP - INITIAL HIGH SIDE PRESSURE (PSI)       **
C**                 EVTP - INITIAL EVAPORATOR TEMP. (F)          **
C**                 HSPMAX - MAXIMUM HIGH SIDE PRESSURE (PSI)    **
C**                 HMAX - DESIGNED AIR ENTHALPY OVER EVAPORATOR **
C**                        (BTU/LBM)                             **
C**                 TBMAX - DESIGNED AIR TEMP. OVER CONDENSER (F)**
C**                 CONADD - TEMP. ADDED TO CONDENSER WHEN AIR   **
C**                          TEMP. GETS TOO HIGH                 **
C**                 EVADD - TEMP. ADDED TO EVAPORATOR WHEN CONADD**
C**                         IS ADDED TO CONDENSER                **
C**                 IPLOT - CONTROL INTEGER PLOTTING:            **
C**                            0 - NO PLOTS                      **
C**                            1 - ONE PLOT                      **
C**                            2 - TWO PLOTS                     **
C**                                                              **
C**       OUTPUT:                                                **
C**                 TIME - TIME IN HRS                           **
C**                 MMOIST - MOISTURE CONTENT OF CLOTHES (LBS)   **
C**                 CTEMP - CLOTHES TEMP. (F)                    **
C**                 TDBA,TDBB,TDBC - DRY BULB TEMP. OF AIR       **
C**                          LEAVING THE DRYER, LEAVING THE      **
C**                          EVAPORATOR, AND ENTERING THE DRYER, **
C**                          RESPECTIVELY (F)                    **
C**                 HUSA,HUSB,HUSC - SPECIFIC HUMIDITY OF THE    **
C**                          AIR LEAVING THE DRYER, LEAVING THE  **
C**                          EVAPORATOR, AND ENTERING THE DRYER, **
C**                          RESPECTIVELY (LBS WATER/LBS AIR)    **
C**                 DRATE - DRYING RATE (LBS/HR)                 **
C**                 QADD - CONDENSER CAPACITY (BTU/HR)           **
C**                 QOUT - EVAPORATOR CAPACITY (BTU/HR)          **
C**                 CONDTP - REFRIGERANT TEMP. AT CONDENSER      **
C**                 EVTP - REFRIGERANT TEMP. AT EVAPORATOR       **
C**                                                              **
C******************************************************************
C
C
```

```
      REAL MDAB,MDACON,MDAC,MMOIST,MDAA,MDAD,MDEVA
      DIMENSION X(3),XDOT(3),HOR(25),Y1(25),Y2(25)
      COMMON X,XDOT,HAH,HHCAP,HCONV,X1CR,T1DB,IT,THTVP,CONHT,EFF,CPAW,T2
     1,WTCL,H2,E2,CPC,G1,QIN,T3DB
      NAMELIST/DATA/TDB,TWB,CFM,CTEMP,CLOAD,CMOIST,HSP,EVTP,HSPMAX,
     1IPLOT,HMAX,TBMAX,CONADD,EVADD
   24 FORMAT('-THE RESULTS FOLLOW')
   25 FORMAT('-TIME   MMOIST   CTEMP   TDBC    HUSC    TDBA    HUSA    TD
     1BB    HUSB    DRATE    QADD     QOUT     CONDTP      EVTP')
   30 FORMAT(F5.2,F8.3,2F8.1,F8.4,F8.1,F8.4,F7.1,F8.4,F8.1,4F10.1)
    3 FORMAT ('-',15X,'DRYER INPUT DATA')
    4 FORMAT('0','AMB. DRY BULB TEMP. = ',F5.1,' F',5X,
     1'AMB. WET BULB TEMP. = ',F5.1,' F'/1X,'AIR FLOW = ',
     2F5.1,' CFM',14X,'INITIAL CLOTHES TEMP. = ',F5.1,' F'/1X,
     3'INITIAL CLOTHES LOAD = ',F5.1,' LBS',2X,
     4'INITIAL MOISTURE CONTENT = ',F5.1,' %')
   80 READ (5,DATA)
      WRITE (6,8)
    8 FORMAT ('1',20X,'***** DRYER SIMULATION *****')
      WRITE (6,3)
      WRITE (6,4)TDB,TWB,CFM,CTEMP,CLOAD,CMOIST
    5 FORMAT('-',15X,'REFRIGERATION CYCLE INPUT DATA')
      WRITE (6,5)
      WRITE (6,6)
    6 FORMAT ('0','CONDENSER',25X,'EVAPORATOR')
      WRITE (6,7) HSP,EVTP,HSPMAX,TBMAX,HMAX,CONADD,EVADD
    7 FORMAT('0','INITIAL PRESSURE = ',F5.1,' PSI',6X,
     1'INITIAL TEMP. = ',F5.1,' F'/1X,'MAXIMUM PRESSURE = ',
     2F5.1,' PSI'/1X,'DESIGNED AIR TEMP. = ',F5.1,' F',6X,
     3'DESIGNED AIR ENTHALPY = ',F5.1,' BTU/LBM'/1X,
     4'DELTA TEMP. = ',F5.1,' F',13X,'DELTA TEMP. = ',F5.1,
     5' F')
      MMOIST=CMOIST*CLOAD/100.
      WRITE (6,24)
      WRITE (6,25)
    9 FORMAT (5X,'QADD       QOUT       CONDTP       EVTP')
      WATTS=0.
      EVTPIN=EVTP
      TDBA=TDB
      TWBA=TWB
      WRITE (7,2000)
 2000 FORMAT (4X,'TDBC   CONDTP    TDBB    ENTHA     EVTP    QOUT',
     14X,'QADD      TIME')
      WRITE (8,2000)
C INITIALIZE DRYER SUBROUTINE
      CALL PSYCKT(TDBA,TWBA,HUSA,DENSA,ENTHA,1)
      MDAA=CFM*DENSA*60.
      N=0
      CALL DRYER(0,TDBA,TWBA,TIME,CTEMP,MMOIST,MDAA,XX,YY,CLOAD,WATTS,EN
     1THC,HUSC)
      J=0
      L=0
      ISS=0
      NPP1=0
      NPP2=0
```

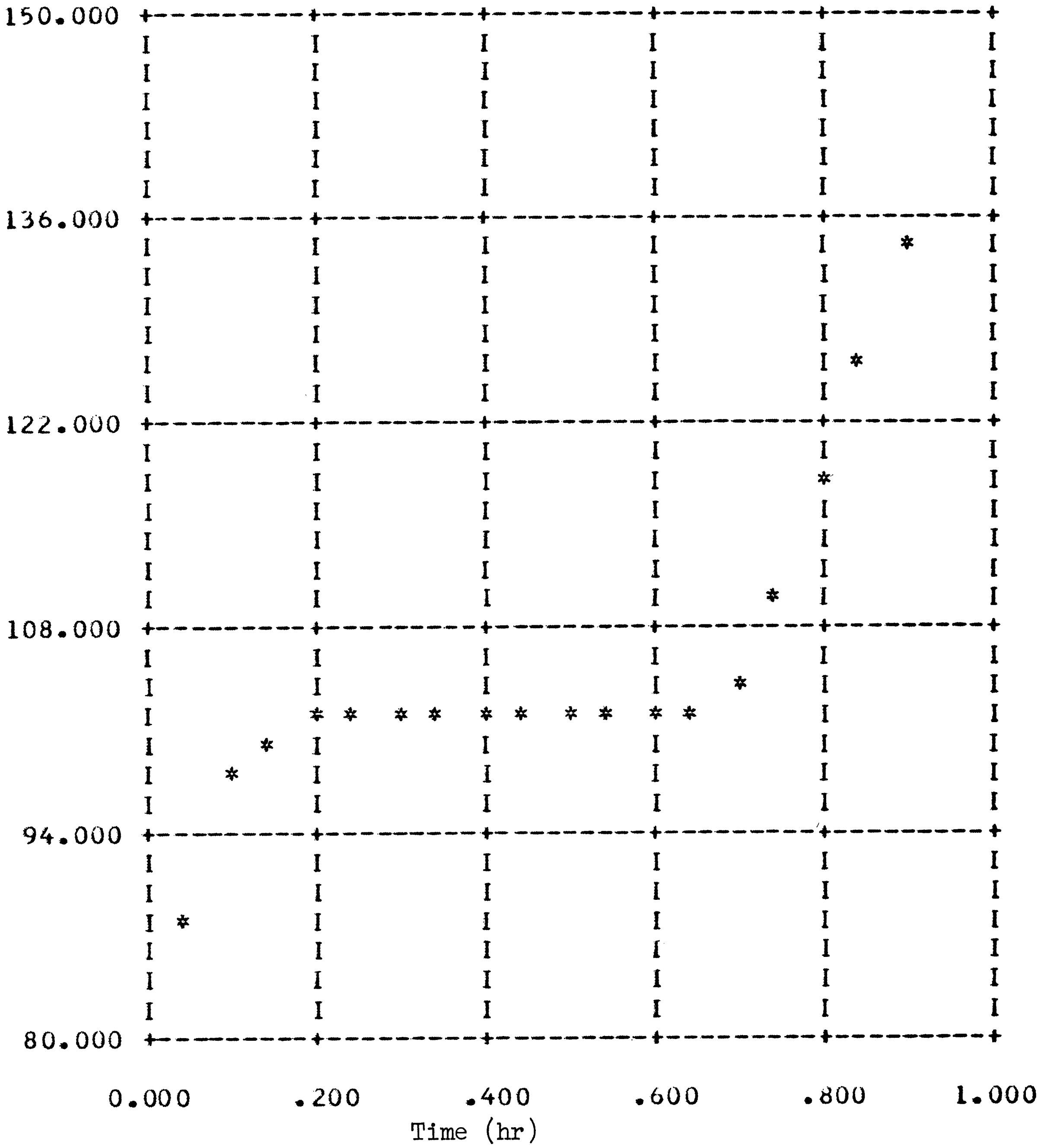
```
      IPT=0
      CONDTP=.25*HSP+55.
      CONIN=CONDTP
  500 BTUEV=30.*(300.-HSP)+.281*800.*(EVTP-35.)+9200.
      POWW=(4.35+.06*(HSP-260.))*(EVTP-43.5)+1030.+1.75*(HSP-260.)
      IF (POWW-1200.) 520,520,510
  510 POWW=1200.
  520 POWB=POWW*3.413
      BTUCON=BTUEV+POWB
      QOUT=BTUEV
      QADD=BTUCON
C AIR IS NOW ENTERING EVAPORATOR.
  600 QEVAP=QOUT/MDAA
      ENTHB=ENTHA-QEVAP
      CALL PSYCKT(TDBB,TWBB,HUSB,DENSB,ENTHB,4)
      DENSEV=(DENSA+DENSB)/2.
      MDAEVA=CFM*DENSEV*60.
      QEVAP=QOUT/MDAEVA
      ENTHB=ENTHA-QEVAP
      ENTHB=ENTHB-.0085*ENTHB
      CALL PSYCKT(TDBB,TWBB,HUSB,DENSB,ENTHB,4)
      MDAB=CFM*DENSB*60.
C AIR IS NOW ENTERING CONDENSER.
      QCOND=QADD/MDAB
      ENTHC=ENTHB+QCOND
      HUSC=HUSB
      CALL PSYCKT(TDBC,TWBC,HUSC,DENSC,ENTHC,2)
      DENSCO=(DENSB+DENSC)/2.
      MDACON=CFM*DENSCO*60.
      QCOND=QADD/MDACON
      ENTHC=ENTHB+QCOND
      CALL PSYCKT(TDBC,TWBC,HUSC,DENSC,ENTHC,2)
      MDAC=CFM*DENSC*60.
      IF (ISS-1) 602,601,601
  601 TMAX=CONDTP-5.
      IF (TDBC-TMAX) 660,660,900
  900 TDBC=TMAX
      CALL PSYCKT (TDBC,TWBC,HUSC,DENSC,ENTHC,3)
      MDAC=CFM*DENSC*60.
      GO TO 660
  602 IF (L-1) 603,640,658
  603 IF (ENTHA.LE.HMAX .AND. TDBB.LE.TBMAX) GO TO 640
      J=J+1
      IF (J-3) 605,605,604
  604 J=0
      GO TO 640
  605 IF (ENTHA.LE.HMAX) GO TO 606
      HDIFF=ENTHA-HMAX
      TADDE=1.7*HDIFF
      EVTP=EVTPIN+TADDE
      IF (TDBB.LE.TBMAX) GO TO 620
  606 TADDC=TDBB-TBMAX
      CONMIN=CONIN+TADDC
      IF (CONDTP-CONMIN) 610,620,620
  610 CONDTP=CONMIN
```

```
      HSP=(CONDTP-55.)/.25
  620 GO TO 500
  640 TMAX=CONDTP-5.
      WRITE (8,642) TDBC,CONDTP,TDBB,ENTHA,EVTP,QOUT,QADD,TIME
  642 FORMAT (7F8.1,F8.3)
      IF (TDBC-TMAX) 658,658,650
  650 TDBC=TMAX
      CALL PSYCKT(TDBC,TWBC,HUSC,DENSC,ENTHC1,3)
      MDAC1=CFM*DENSC*60.
      ENDIF=ENTHC-ENTHC1
      QDIF=ENDIF*(MDAC1+MDAC)/2.
      QADD=QADD-QDIF
      CONDTP=CONDTP+CONADD
      HSP=(CONDTP-55.)/.25
      IF (HSP-HSPMAX) 654,654,652
  652 HSP=HSPMAX
      ISS=1
      CONDTP=.25*HSP+55.
      GO TO 655
  654 EVTP=EVTP+EVADD
  655 QOUT=30.*(300.-HSP)+.281*800.*(EVTP-35.)+9200.
      L=L+1
      GO TO 600
  658 L=0
      WRITE(7,642)TDBC,CONDTP,TDBB,ENTHA,EVTP,QOUT,QADD,TIME
C AIR IS NOW ENTERING DRYER.
  660 CALL DRYER(1,TDBC,TWBC,TIME,CTEMP,MMOIST,MDAC,TDBA,HUSA,CLOAD,WATT
     1S,ENTHC,HUSC)
      CALL PSYCKT(TDBA,TWBA,HUSA,DENSA,ENTHA,3)
      MDAA=CFM*DENSA*60.
      DRATE=XDOT(1)
      N=N+1
      IF (N-10) 680,670,670
  670 WRITE(6,30)TIME,MMOIST,CTEMP,TDBC,HUSC,TDBA,HUSA,TDBB,HUSB,
     1DRATE,QADD,QOUT,CONDTP,EVTP
      IPT=IPT+1
      IF (IPLOT-1) 676,674,672
  672 CONTINUE
      FUNC2=CTEMP
      Y2(IPT)=FUNC2
      NPP2=NPP2+1
  674 HOR(IPT)=TIME
      FUNC1=TDBA
      Y1(IPT)=FUNC1
      NPP1=NPP1+1
  676 CONTINUE
 1000 FORMAT(4F10.1)
      N=0
  680 IF (MMOIST/CLOAD-.03) 700,700,690
  690 CALL PSYCKT(TDBA,TWBA,HUSA,DENSA,ENTHA,3)
      GO TO 600
  700 WRITE(6,30)TIME,MMOIST,CTEMP,TDBC,HUSC,TDBA,HUSA,TDBB,HUSB,
     1DRATE,QADD,QOUT,CONDTP,EVTP
      CALL GRAPH(IPLOT,NPP1,NPP2,HOR,Y1,Y2)
      GO TO 80
```

```
FORTRAN IV G COMPILER        MAIN            05 10-71          16:28.00        PAGE 0005

 0145               END

  TOTAL MEMORY REQUIREMENTS 001330 BYTES
```

```
FORTRAN IV G COMPILER        GRAPH            05-10-71         16:28.06         PAGE 0001

                  SUBROUTINE GRAPH(IPLOT,NPP1,NPP2,HOR,Y1,Y2)
                  DIMENSION HOR(25),Y1(25),Y2(25),IMAGE(1500)
                  WRITE (6,5)
                5 FORMAT ('1')
                  IF (IPLOT-1) 30,10,10
               10 Y1MAX=150.
                  Y1MIN=80.
                  CALL PLOT14(0,6,6,6,9,IMAGE,1.,0.,Y1MAX,Y1MIN,'*',HOR,Y1,NPP1,4,0,
                 10)
                  WRITE (6,5)
                  IF (IPLOT-1) 30,30,20
               20 Y2MAX=150.
                  Y2MIN=80.
                  CALL PLOT14(0,6,6,6,9,IMAGE,1.,0.,Y2MAX,Y2MIN,'*',HOR,Y2,NPP2,4,0,
                 10)
               30 CONTINUE
                  RETURN
                  END

  TOTAL MEMORY REQUIREMENTS 001A76 BYTES
```

```
FORTRAN IV G COMPILER        PSYCKT          05-10-71         16:28.07        PAGE 0001

            SUBROUTINE PSYCKT(TDB,TWB,HUS,DENS,ENTH,NJT)
            BARO=29.5
            IF(NJT-2) 100,200,10
   10       IF(NJT-4) 300,400,1000
  100       B=.1626943E-2*TWB-1.
            X=(B*B-.12150981E-04*TWB*TWB+.010016283*TWB-.71409557)**.5
            PW=EXP((-B-X)/(-.1417349))
            PVA=PW-(BARO-PW)*(TDB-TWB)/(2800.-1.3*TWB)
            HUS=.622*PVA/(BARO-PVA)
            ENTH=.24*TDB+HUS*(1050.+.44*TDB)
            GO TO 600
  200       TDB=(ENTH-1035.*HUS)/(.24+.44*HUS)
  210       PVA=HUS*BARO/(.622+HUS)
            C1=2800.*PVA+TDB*BARO
            C2=1.3*PVA+BARO
            C3=2800.+TDB
            TWB=0
          4 X1=TWB
            B=.1626943E-2*TWB-1.
   80       X=(B*B-.12150981E-4*TWB*TWB+.010016283*TWB-.71409557)**.5
            PW=EXP((B+X)/.1417349)
            FX=PW-(C1-C2*TWB)/(C3-2.3*TWB)
            FX1=PW/.1417349*((.2646934E-5*TWB-.12150981E-4*TWB+.50081415E-2)/X
          1+.1626943E-2)+(C3*C2-2.3*C1)/(C3-2.3*TWB)**2
            TWB=X1-FX/FX1
            IF (ABS(TWB-X1)-.05) 600,4,4
  300       ENTH=.24*TDB+HUS*(1035.+.44*TDB)
            GO TO 210
  400       TDB=ENTH/(.0058476*ENTH+.290812)
            HUS=.00140973*EXP(.0340657*TDB)
            TWB=TDB
  500       PVA=BARO*HUS/(.622+HUS)
  600       DENS=(BARO-PVA)/(.7541*(460.+TDB))
 1000       RETURN
            END

 TOTAL MEMORY REQUIREMENTS 0005FE BYTES
```



Sample Computer Plot

```
$LIST DRYDATA
     1        &DATA TDB=72., TWB=60.,
     2         CLOAD=9., CMOIST=85.,
     3         CTEMP=72., CFM=220.,
     4         HSP=290., EVTP=45.,
     5         HSPMAX=400.,
     6         IPLOT=2,
     7         HMAX=40., TBMAX=60.,
     8         CONADD=3., EVADD=.38   &END
     9        &DATA CTEMP=72.,
    10         HSP=290.,
    11         EVTP=45.,
    12         CLOAD=10.   &END
    13        &DATA CTEMP=72.,
    14         HSP=290., EVTP=45.,
    15         CLOAD=6.   &END
    16        &DATA CTEMP=72.,
    17         HSP=290., EVTP=45.,
    18         CLOAD=3.   &END
    20        &DATA CTEMP=72.,
    21         HSP=290., EVTP=45.,
    22         CLOAD=9., CMOIST=70.   &END
    23        &DATA CTEMP=72.,
    24         HSP=290., EVTP=45.,
    25         CMOIST=50.   &END
    26        &DATA CTEMP=72.,
    27         HSP=290., EVTP=45.,
    28         CMOIST=85.,
    29         CFM=250.   &END
    30        &DATA CTEMP=72.,
    31         HSP=290., EVTP=45.,
    32         CFM=300.   &END
    40        &DATA TDB=72., TWB=60.,
    41         CLOAD=9., CMOIST=85.,
    42         CTEMP=72., CFM=220.,
    43         HSP=290., EVTP=45.,
    44         HSPMAX=400.,
    45         IPLOT=0,
    46         HMAX=45., TBMAX=60.,
    47         CONADD=3., EVADD=.38   &END
    48        &DATA CTEMP=72.,
    49         HSP=290., EVTP=45.,
    50         HMAX=35.   &END
    51        &DATA CTEMP=72.,
    52         HSP=250., EVTP=45.,
    53         HMAX=40.   &END
END OF FILE
```

Sample Data File