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SIMPLIFIED COMPUTER PROGRAM FOR THE ANALYSIS OF PHASE CHANGE IN LIQUID FACE SEALS

Michael Birchak and William F. Hughes

Carnegie-Mellon University
Pittsburgh, Pennsylvania

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16. Abstract

A simplified computer program is presented which allows for the prediction of boiling (phase change) in liquid face seals. The program determines if and when boiling occurs and then calculates the location of the boiling interface, pressure and temperature profiles, and load. The main assumption which allows for a simplified analysis is the assumption of an isothermal gas phase. The results compare almost identically with the more exact analysis of Hughes and Kennedy and allow for a much simpler program which should be of immediate use to the design engineer. The conclusions are identical to those of the previous Hughes-Kennedy report, and this report serves as an extension of that report in terms of computational technique.

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INTRODUCTION

The purpose of this report is to present a simplified computer program capable of predicting boiling behavior in aligned liquid face seals. The mathematical model used is the same as that used by Hughes and Kennedy [1] with the exception that a further simplification is made that the vapor region is assumed isothermal. The previous results show this to be a reasonable assumption which greatly simplifies the analysis and calculations.

ANALYSIS

This analysis is based on the seal model shown in Figure 1. The following assumptions have been made throughout the modeling process:

1) The liquid flashes instantaneously to a vapor.
2) The vapor region is isothermal.
3) The flow is axisymmetric.
4) Inertia effects in the fluid are neglected.
5) Heat conduction in the radial direction within the fluid is neglected.
6) The seal plates can be treated as semi-infinite solids.
7) The fluid temperature does not vary across the film and is equal to the surface temperature of the seal plates.

General Equations--Steady State

The equations of motion which describe the fluid flow between the seal plates are

$$r: \quad \frac{\partial P}{\partial r} = \mu \frac{\partial^2 u}{\partial z^2} \tag{1}$$

$$\theta: \quad 0 = \frac{\partial^2 V}{\partial z^2} \tag{2}$$

for the radial and angular components. The mass flow rate is

$$m = 2\pi r \int_0^h \rho u dz = \text{constant} \tag{3}$$

from the continuity equation. The temperature in the film may be expressed as:

$$dT = \frac{q(r)}{4\pi k} [(R - r \cos\theta)^2 + r^2 \sin^2\theta]^{-1/2} \; RdRd\theta \tag{4}$$

which was derived in the previous report. k is the mean thermal conductivity of both face plate and nose piece.

Solving (1) with the boundary conditions that $u = 0$ at $z = 0$ and $z = h$ yields

$$u = \frac{1}{2\mu} \frac{dP}{dr} z \; (z - h) \tag{5}$$

Solving (2) with the boundary conditions that $V = 0$ at $z = 0$ and $V = r\omega$ at $z = h$ yields

$$V = r\omega \frac{z}{h} \tag{6}$$

Substitution of (5) into (3) yields the expression

$$m = \frac{-\pi\rho}{6\mu} rh^3 \frac{dP}{dr} \tag{7}$$

Equation (4) has been integrated for the configuration in Figure 2 by Hughes and Osterle [2] and discussed in general terms in the previous reports. The results are given below.

For $r_1' < r < r_2'$ (liquid region):

$$T(r) = \frac{\mu\omega^2 r^3}{2kh}\left\{\sum_{n=0}^{\infty} A_n\left[1 - \left(\frac{r_1'}{r}\right)^{2n+4}\right] + \sum_{n=0}^{\infty} B_n\left[1 - \left(\frac{r}{r_2'}\right)^{2n-3}\right]\right\} + T_\infty \tag{8a}$$

For $r < r_1'$ (inside the liquid region):

$$T(r) = \frac{\mu\omega^2 r^3}{2kh}\left\{\sum_{n=0}^{\infty} B_n\left[1 - \left(\frac{r}{r_2'}\right)^{2n-3}\right] - \sum_{n=0}^{\infty} B_n\left[1 - \left(\frac{r}{r_1'}\right)^{2n-3}\right]\right\} + T_\infty \tag{8b}$$

For $r > r_2'$ (outside the liquid region):

$$T(r) = \frac{\mu\omega^2 r^3}{2kh}\left\{\sum_{n=0}^{\infty} A_n\left[1 - \left(\frac{r_1'}{r}\right)^{2n+4}\right] + \sum_{n=0}^{\infty} A_n\left[1 - \left(\frac{r_2'}{r}\right)^{2n+4}\right]\right\} + T_\infty \tag{8c}$$

where

$$A_n = \frac{1}{2n+4}\,\frac{[(2n)!]^2}{(n!)^4 \cdot 2^{4n}}$$

$$B_n = \frac{1}{2n-3}\,\frac{[(2n)!]^2}{(n!)^4 \cdot 2^{4n}}$$

For this analysis only the first of these equations is needed. The necessary logical substitutions are presented in Figure 3.

Assuming the specific volume of a vapor to be much larger than that of a liquid and that the vapor acts like an ideal gas, the Clapeyron equation can be written

$$(\frac{dP}{P})_{sat} = \frac{h_{fg}}{R} (\frac{dT}{T^2})_{sat} \tag{9}$$

The ideal gas law states

$$\frac{P}{\rho_v} = RT \tag{10}$$

Particular Equations--Steady State

The above equations can now be manipulated to define the behavior of the liquid. In order to simplify the logic required for inside and outside seals two subscripts, i and o, will be used. X_i refers to a dimension or property, X, of the seal or fluid entering the seal space, and X_o refers to a dimension or property of the seal or fluid exiting the seal space. Thus for an inside seal $(P_1 > P_2)$ $P_i = P_1$, $r_i = r_1$, $P_o = P_2$, $r_o = r_2$, etc. For an outside seal $(P_1 < P_2)$ $P_i = P_2$, $r_i = r_2$, $P_o = P_1$, $r_o = r_1$, etc.

Equation (7) can be integrated for the pressure in the liquid region (ρ = constant)

$$P - P_i = \frac{-6m\mu}{\pi\rho_\ell h^3} \ln r/r_i \tag{11a}$$

or in dimensionless form

$$\frac{P - P_i}{P_b - P_i} = \frac{\ln r/r_i}{\ln r_b/r_i} \tag{11b}$$

For the vapor region, assuming isothermal flow at the flash temperature, the ideal gas equation is used to find ρ and the integration of (7) yields

$$P^2 - P_b{}^2 = -\frac{12\mu_g m\ RT_b}{\pi h^3} \ln r/r_b \tag{12a}$$

or in dimensionless form

$$\frac{P^2 - P_b{}^2}{P_o{}^2 - P_b{}^2} = \frac{\ln r/r_b}{\ln r_o/r_b} \tag{12b}$$

P_b can now be found by equating the leakage of the vapor in (12a) to the leakage of the liquid in (11a)

$$\frac{(P_b - P_i)\rho_\ell}{\mu \ln r_b/r_i} = \frac{(P_o{}^2 - P_b{}^2)}{2\mu_g\ RT_b \ln r_o/r_b}$$

Solving

$$P_b = [A^2 + 2AP_i + P_o{}^2]^{1/2} - A \tag{13}$$

where

$$A = \frac{\rho_\ell \mu_g\ RT_b \ln r_o/r_b}{\mu \ln r_b/r_i}$$

The Clapeyron equation (9), is used to test if the correct value of r_b has been chosen. Assuming h_{fg} constant, the integration of (9) yields

$$\frac{P_{bc}}{P_{sat}} = \exp[-\frac{h_{fg}}{R}(\frac{1}{T_b} - \frac{1}{T_{sat}})] \tag{14}$$

where T_{sat} and P_{sat} describe a reference saturation point sufficiently close to T_b and P_{bc} so that h_{fg} may be considered constant.

When P_{bc} is sufficiently close to P_b, the leakage and load characteristics of the seal may be found. The leakage is found by using either equations (11a) or (12a).

The absolute load, W, supported by the seal is found by

$$W = \int_a^b P \cdot 2\pi r \, dr = W_\ell + W_v \qquad (15)$$

The total load is simply the liquid load, W_ℓ, added to the load of the vapor region, W_v. P is given by (11b) for the liquid region and (12b) for the vapor region. The integration gives

$$W_\ell = \pi \left| P_b r_b^2 - P_i r_i^2 + \frac{(P_b - P_i)(r_i^2 - r_b^2)}{2 \ln r_b/r_i} \right| \qquad (16)$$

$$W_v = 2\pi \left| \int_{r_b}^{r_o} [P_b^2 + (P_o^2 - P_b^2) \frac{\ln r/r_b}{\ln r_o/r_b}]^{1/2} \; rdr \right| \qquad (17)$$

COMPUTER PROGRAM

Logic

Only the logic of the main program will be presented here. The logic of the subprograms is either trivial or stated clearly in the previous sections. The program is listed in Appendix A, and it defines variable names used. See Figure 4 for the flow chart.

Using the Program

The program is written in Fortran and contains four subprograms: (1) A factorial subprogram, (2) A temperature distribution subprogram, (3) A Clapeyron pressure subprogram, and (4) A gaseous load subprogram. Input is entered via a data deck which is described below.

The first card of the deck contains fluid information as well as plate conductivity. From left to right on this card appears:

XNAME	- the name of the fluid to be sealed (alphabetic)
MU, (μ)	- the liquid viscosity (lb-s/ft^2)
MUG, (μ_g)	- the gas viscosity (lb-s/ft^2)
RHO, (ρ)	- the liquid density (lbm/ft^3)
XK, (k)	- the mean plate thermal conductivity (Btu/hr-ft-^oR)
RVAP, (R)	- the ideal gas constant (ft-lbf/lbm-^oR)
NHFG	- the number of saturation states to be inputted.

Figure 5 shows a sample fluid information card.

The Clapeyron equation, (14), requires that saturation information be inputted for the particular liquid sealed. Because the Clapeyron equation assumes constant h_{fg}, the use of only one or two states may result in sizeable errors. To correct this, the program reads a saturation state matrix and uses the saturation data for the point closest to T_b, the temperature at boiling. There must be NHFG of these points supplied (in this case 25 saturation cards were used). The program also requires that these cards be placed in order of increasing saturation pressures. Each card contains the following three values:

PSAT(I), (P_{sat})	- any given saturation pressure (psia)
TSAT(I), (T_{sat})	- the saturation temperature at the above pressure (^oF)
HFG(I), (h_{fg})	- the heat of vaporization at the above temperature and pressure (Btu/lbm).

Figure 6 shows a sample saturation state deck.

The final type of data card required is the seal information card. From left to right on this card appears:

TINF, (T_∞) - the bulk temperature (^oF)
P1, (P_1) - the fluid pressure at r_1 (psia)
P2, (P_2) - the fluid pressure at r_2 (psia)
R1, (r_1) - the smaller seal radius (in)
R2, (r_2) - the larger seal radius (in)
H, (h) - the thickness of the lubricating film (μ in)
OM, (ω) - the angular velocity of the seal (rpm)

There is no limit to the number of seal information cards which can be entered at one time. The only requirement is that the final card must have TINF (T_∞) = 10,000. Figure 7 shows a sample seal information deck.

The program uses the data and outputs pressure and temperature distributions, leakage rates, and absolute load. The program is capable of handling liquid seals and gas seals in addition to mixed-phase seals. All output is given in both English and SI units. The computer program and sample output is found in Appendices A and B.

RESULTS AND CONCLUSIONS

The computer program (Appendix A) was used to analyze two seal configurations. The first configuration approximates that used by Orcutt [3] (r_1 = 2.025 inches (0.0514 m); r_2 = 2.225 inches (0.0565 m)). The second configuration approximates a commercial seal manufactured by the Crane Packing Company of Morton Grove, Illinois (r_1 = 1.693 inches (0.0430 m); r_2 = 1.849 inches (0.0470 m)). The thermal conductivity, k, is chosen to be the average of the thermal conductivities of the two seal plates. For example, in the case of the Orcutt seal k was taken to be 7.5 Btu/hr-ft^2-F (13.0 W/m-K), ($k_{quartz} \doteq 4.0$ Btu/hr-ft^2-F (6.9 W/m-K); $k_{carbon\text{-}graphite} \doteq 11.0$ Btu/hr-ft^2-F (19.0 W/m-K)). To find the effect of k on loading, other values were also used. The results of the computations are summarized in Figures 8 - 19.

The following conclusions have been made:

1) When phase change is included the pressure distribution is radically different from the simple linear pressure distribution commonly assumed in industry. The forces actually pushing the plates apart is greater due to phase change (Figures 8 and 9).

2) Leakage decreases when flashing occurs. The leakage from an inside seal is approximately the same as the leakage from an outside seal (Figure 10).

3) The model breaks down when boiling occurs close to the entrance. This apparently happens because the model assumes instantaneous flashing, but when saturation conditions are reached very shortly after entrance into the seal, an extended region of mixed vapor-liquid flow probably exists. This is in agreement with Orcutt's observations (Figure 11).

4) For a given seal configuration there are two film thicknesses, h, which support the same load, W. When the spacing undergoes a small excursion about the larger equilibrium value (due to a vibration or some other external disturbance), the seal will return to its original position. However, an excursion about the lower space is not stable. An increase in spacing grows until the larger equilibrium spacing is reached, but a

decrease in spacing causes a catastrophic collapse of the seal faces. Metal-to-metal contact or rapid explosive boiling might occur as the spacing decreases. The consequent explosion then forces the plates apart. These phenomena have been observed under certain conditions (Figures 12, 13 and 14).

5) For a given seal configuration (and given spacing) there are two angular velocities, ω, which produce the same load, W. The seal is stable at the upper ω but unstable at the lower ω (Figures 15 and 16).

6) For a given seal configuration there are two bulk temperatures, T_∞, which produce the same load, W. The seal is stable at the upper T_∞, but unstable at the lower T_∞ (Figures 17 and 18).

7) Varying k changes the boiling radius and shifts the load curves either left or right. Plates with a high k will conduct more heat from the fluid and vaporization will occur closer to the exit. A low k has the opposite effect.

8) Equation (8) shows the seal load to be a function of the parameter h/ω^2. There are two ratios of h/ω^2 which support a given seal load. One is stable and the other is unstable. (Figure 19).

NOMENCLATURE

h - distance separating the seal plates

h_{fg} - heat of vaporization

k - thermal conductivity of the seal plates

m - mass flow rate

θ - circumferential coordinate

ρ - density

P - pressure

P_{bc} - pressure found by the Clapeyron equation, (14)

r - radial coordinate

R - ideal gas constant of the vapor

T - temperature

u - radial flow velocity component

μ - absolute viscosity of the liquid

μ_g - absolute viscosity of the vapor

V - circumferential flow velocity component

ω - angular velocity

W - the absolute load supported by the seal

z - axial coordinate

Subscripts

1 - a dimension or property of the seal or fluid at the inner radius

2 - a dimension or property of the seal or fluid at the outer radius

b - a dimension or property of the seal or fluid at the boiling radius (liquid-vapor interface)

i - a dimension or property of the seal or fluid at the point where fluid enters the seal space

ℓ - pertaining to the liquid region

o - a dimension or property of the seal or fluid at the point where fluid leaves the seal space

sat - defining a saturation state

v - pertaining to the vapor region

∞ - pertaining to the bulk properties

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2. Hughes, William F. and Osterle, J. Fletcher, "Heat Transfer Effects in Hydrostatic Thrust Bearing Lubrication," Trans. ASME, Vol. 79, 1957, pp. 1225-1228.

3. Orcutt, F. K., "An Investigation of the Operation and Failure of Mechanical Face Seals," Trans. ASME, Journal of Lubrication Technology, October 1969, pp. 713-725.

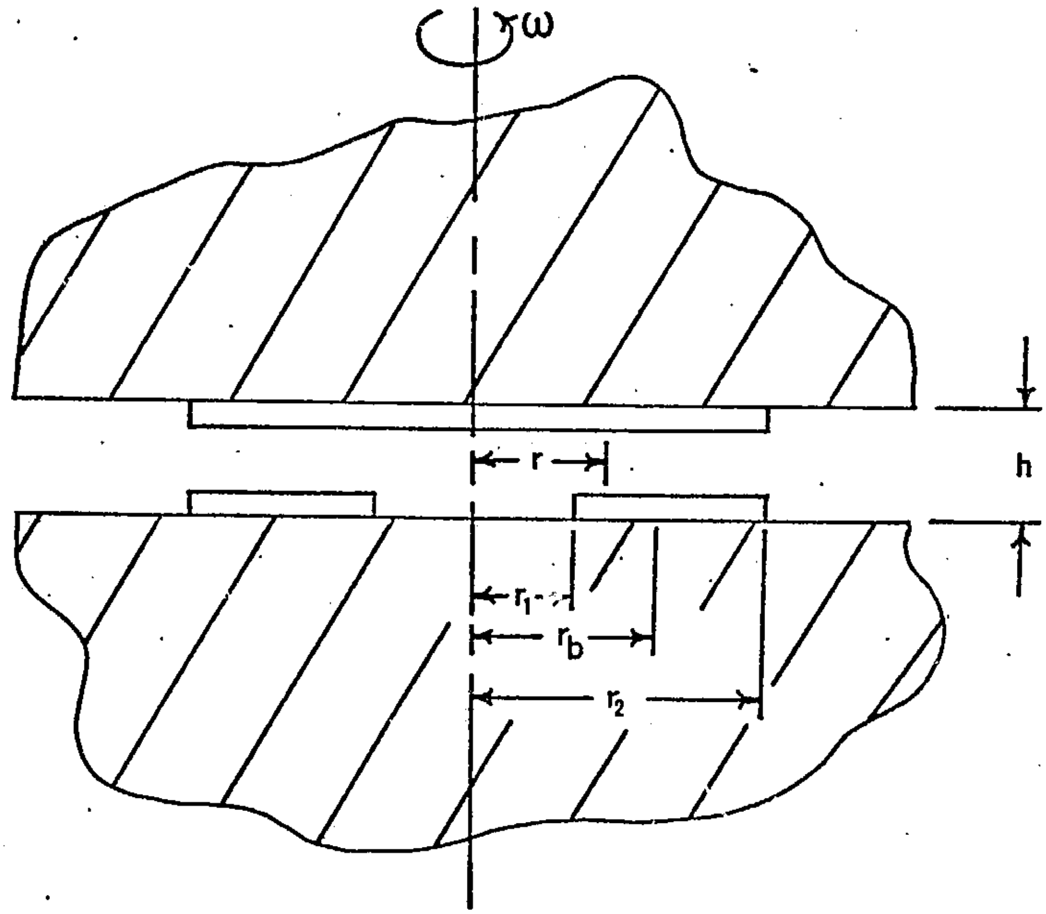

Figure 1. The Semi-Infinite Solid Seal Model.

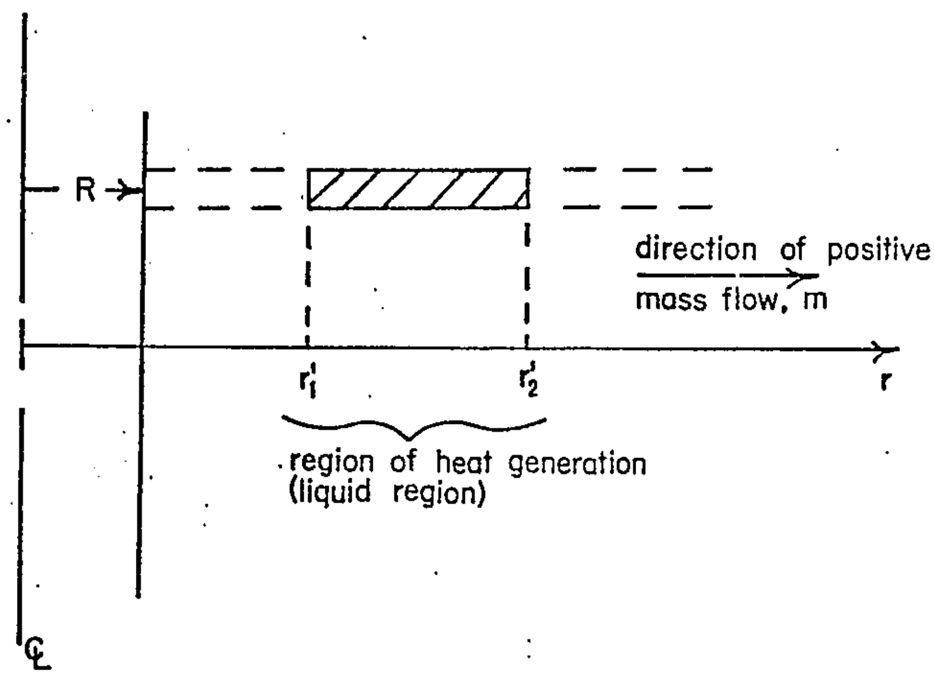

Figure 2. Hughes and Osterle Model for Temperature Distribution on the Surface of a Semi-Infinite Solid.

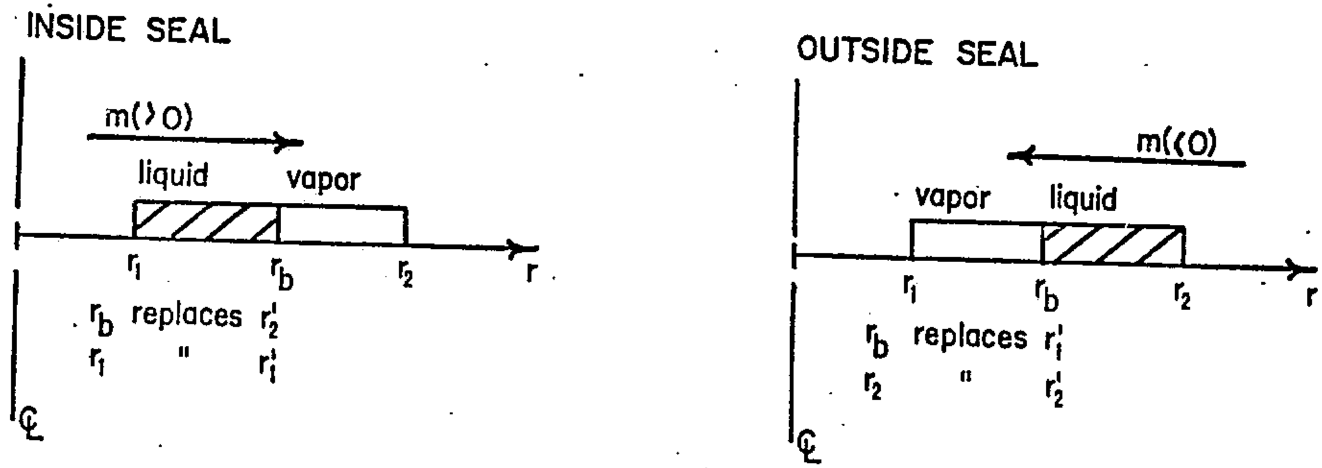

Figure 3. Logical Substitutions for the Temperature Distribution Equation, (8a).

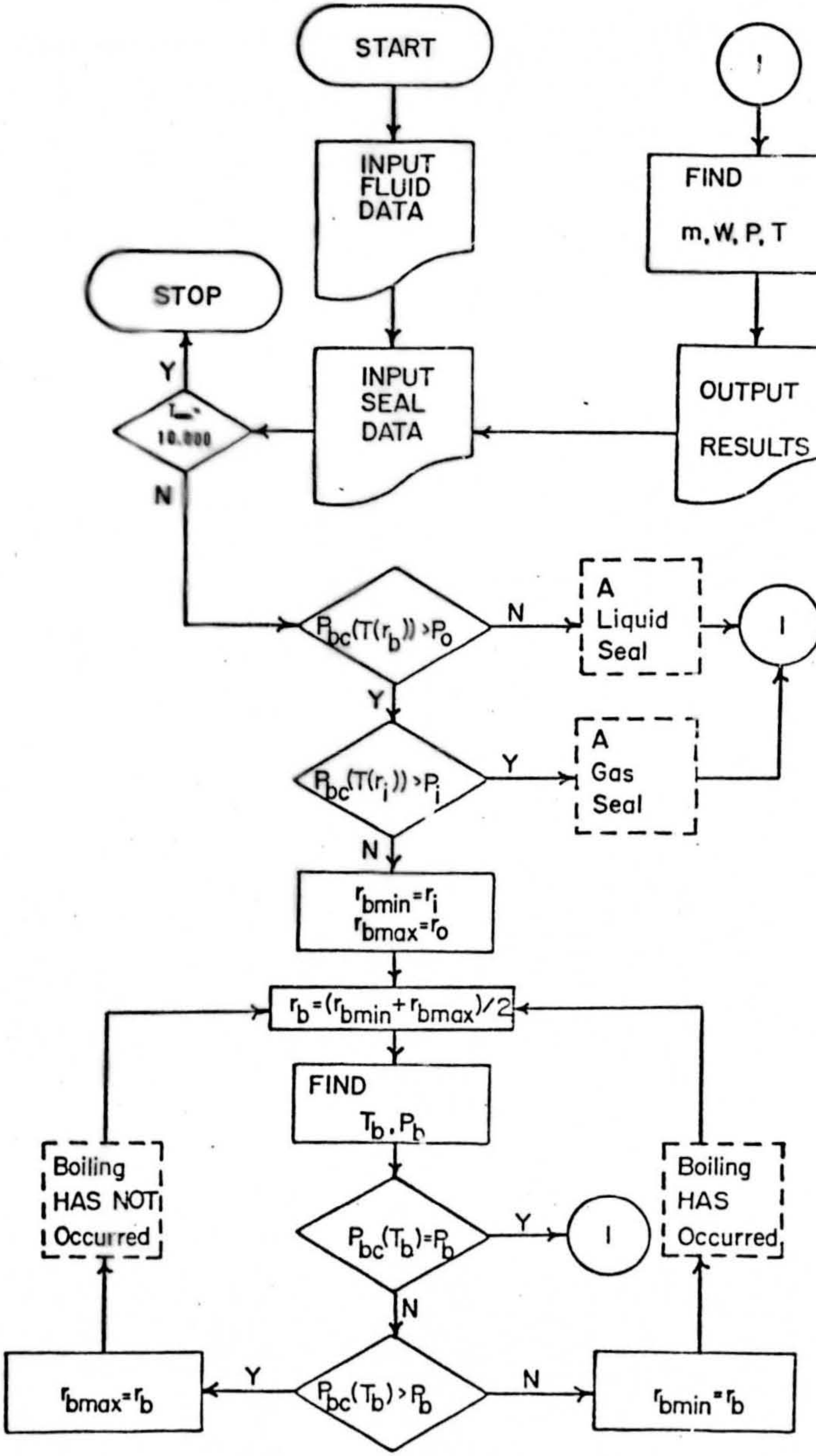

Figure 4. Program Flow Chart.

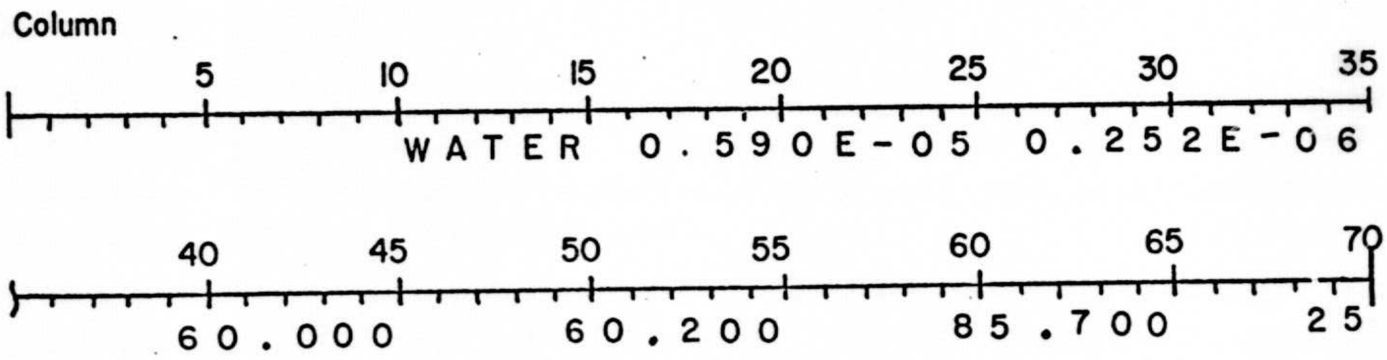

Figure 5. Fluid Information Card for Water.

Card	Column (1–10)	(11–20)	(21–30)
1	5.0	162.21	1000.9
2	10.0	193.19	982.1
3	15.0	213.03	969.7
4	25.0	240.08	952.2
NHFG	1600.0	605.06	538.9

Figure 6. Saturation State Deck for Water.

Card	Column 1–10	11–20	21–30	31–40	41–50	51–60	61–70
1	270.0	15.0	90.0	1.693	1.849	10.	7200.
2	230.0	45.0	15.0	2.025	2.225	50.	3000.
3	100.0	45.0	15.0	2.025	2.225	500.	20000.
⋮							
n	10000.						

Figure 7. Sample Seal Information Deck.

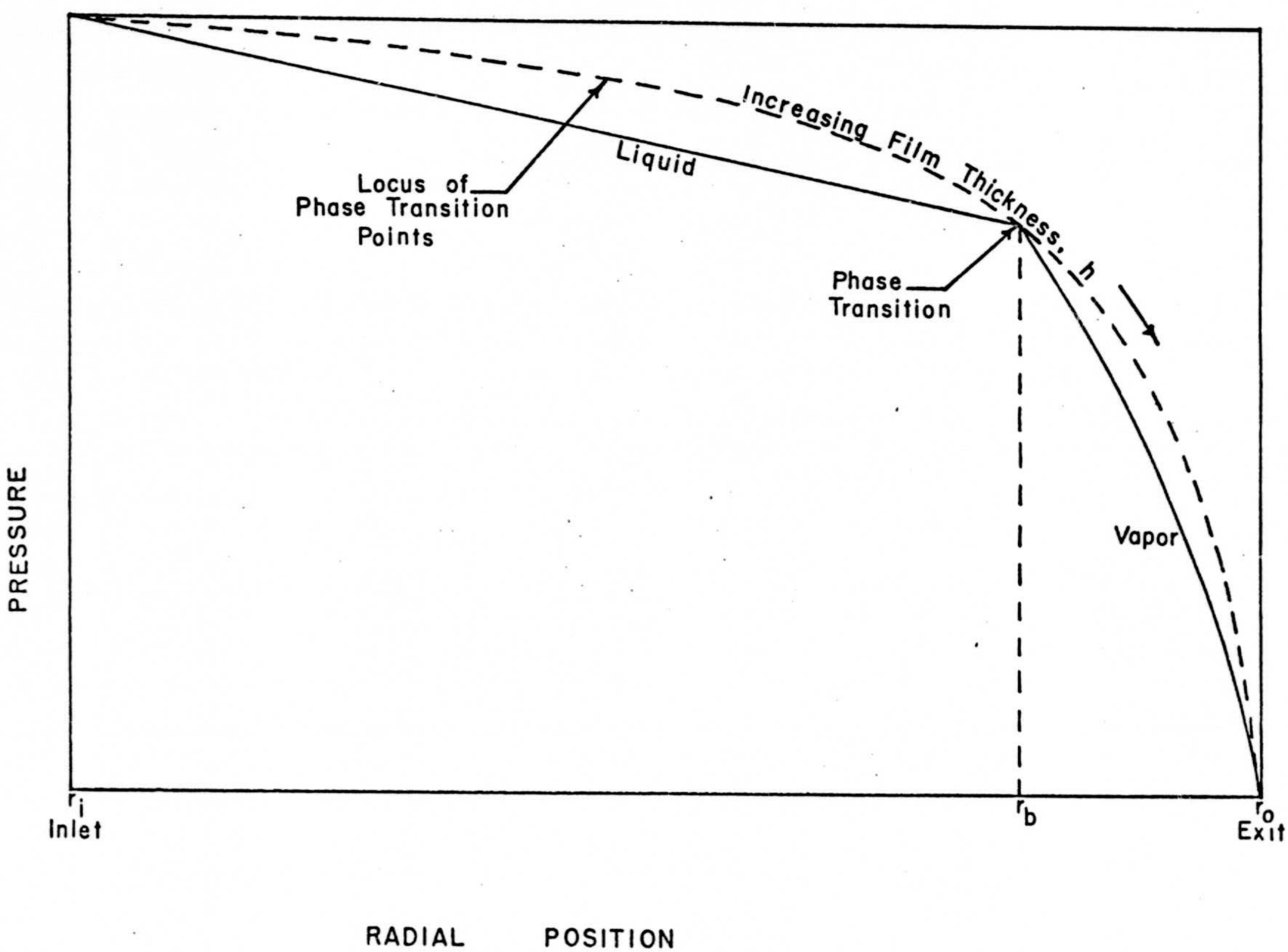

Figure 8. Effect of Phase Change on the Pressure Distribution.

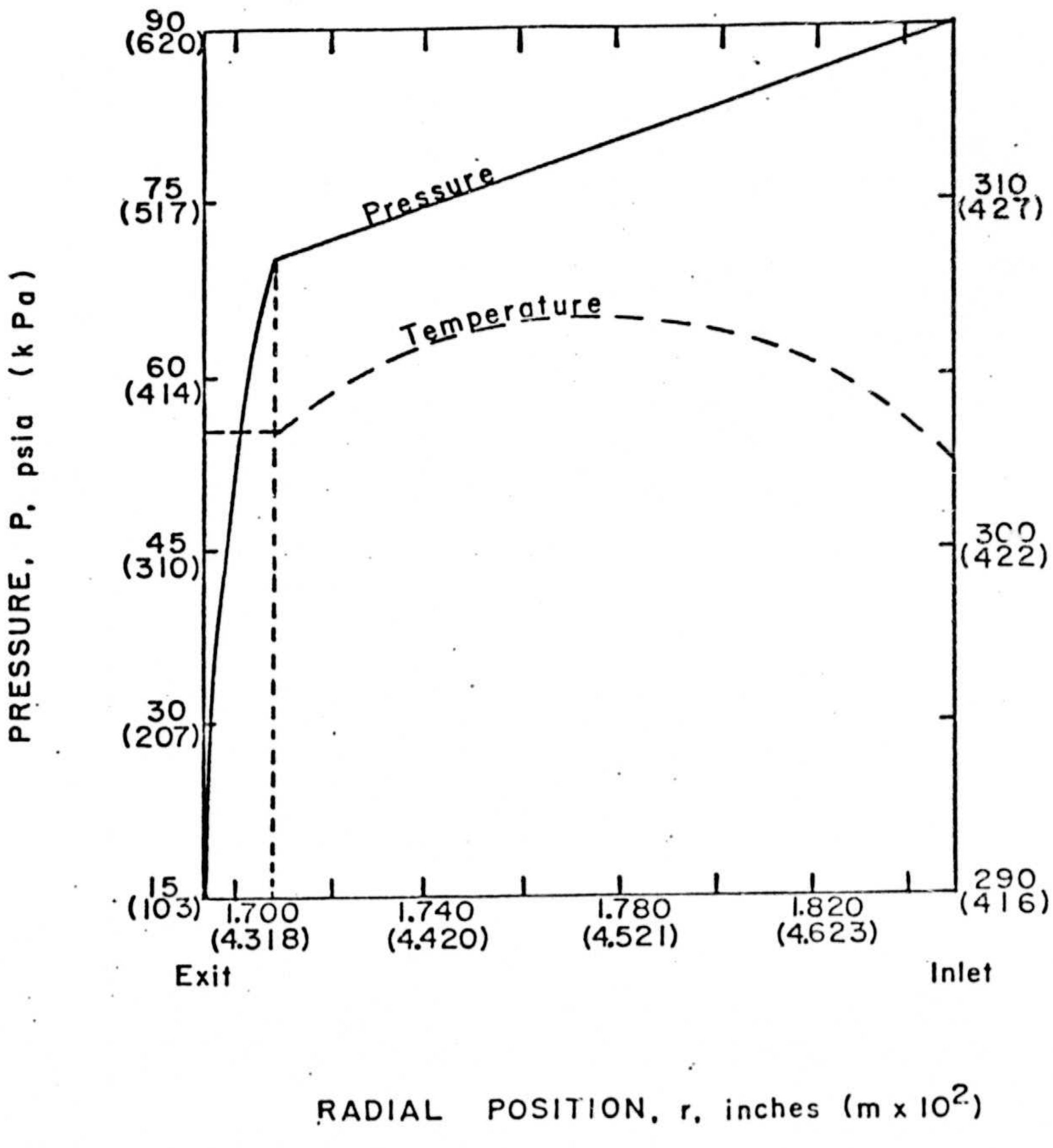

Figure 9. Temperature and Pressure Distribution in the Film Space. P_1 = 15.0 psia (103.4 kPa), P_2 = 90.0 psia (620.4 kPa), r_1 = 1.693 inches (0.04300 m), r_2 = 1.849 inches (0.04696 m), h = 50.0 x 10^{-6} inches (1.27 x 10^{-6} m), ω = 7200 rpm (754 rad/s), k = 26 Btu/hr-ft-°F (45 W/m-K).

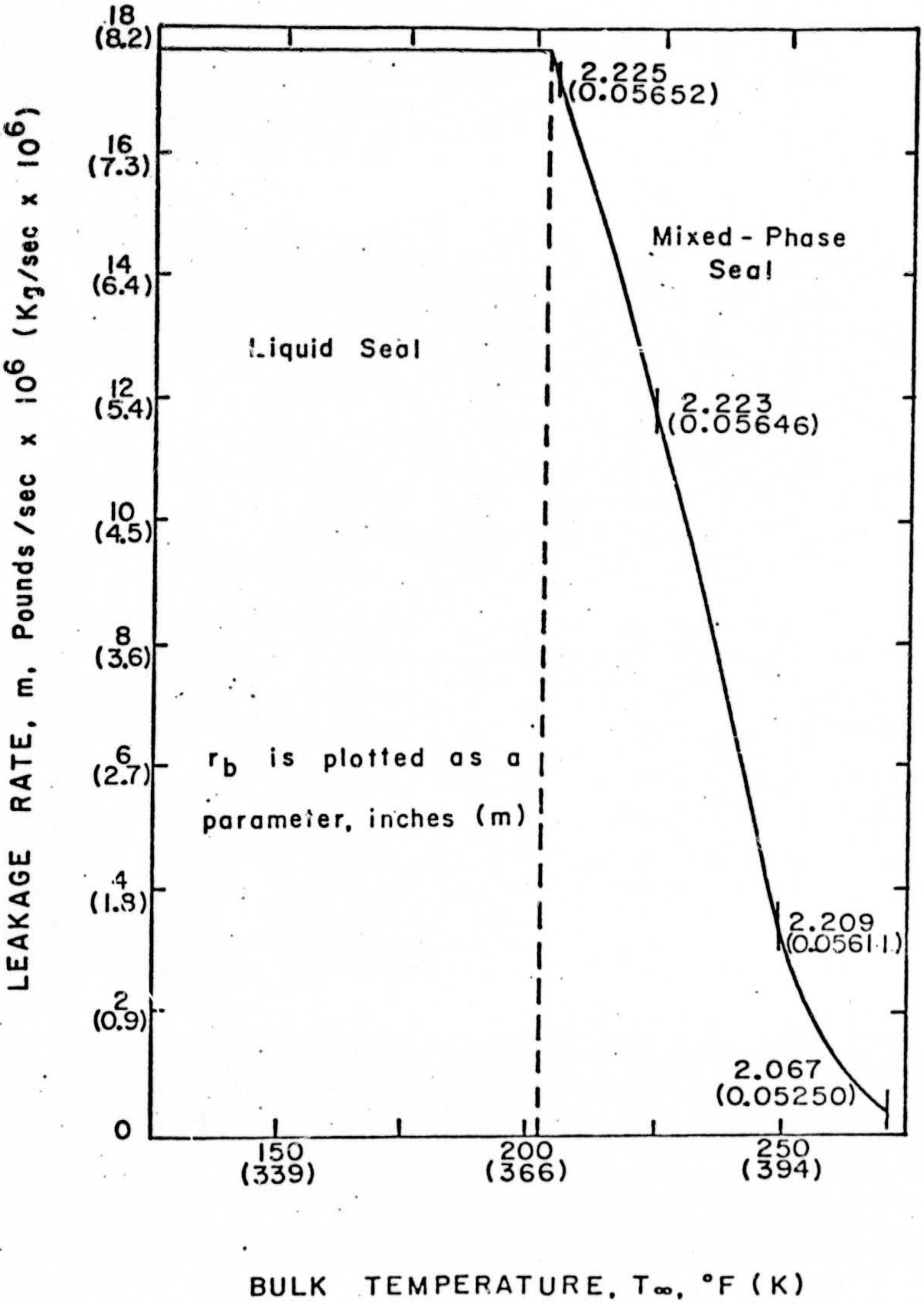

Figure 10. Effect of Bulk Temperature on Leakage. P_1 = 45.0 psia (310.2 kPa), P_2 = 15.0 psia (103.4 kPa), r_1 = 2.025 inches (0.05144 m), r_2 = 2.225 inches (0.05652 m), h = 50.0 x 10^{-6} inches (1.27 x 10^{-6} m), ω = 3600 rpm (377 rad/s), k = 26 Btu/hr-ft-°F (45 W/m-K).

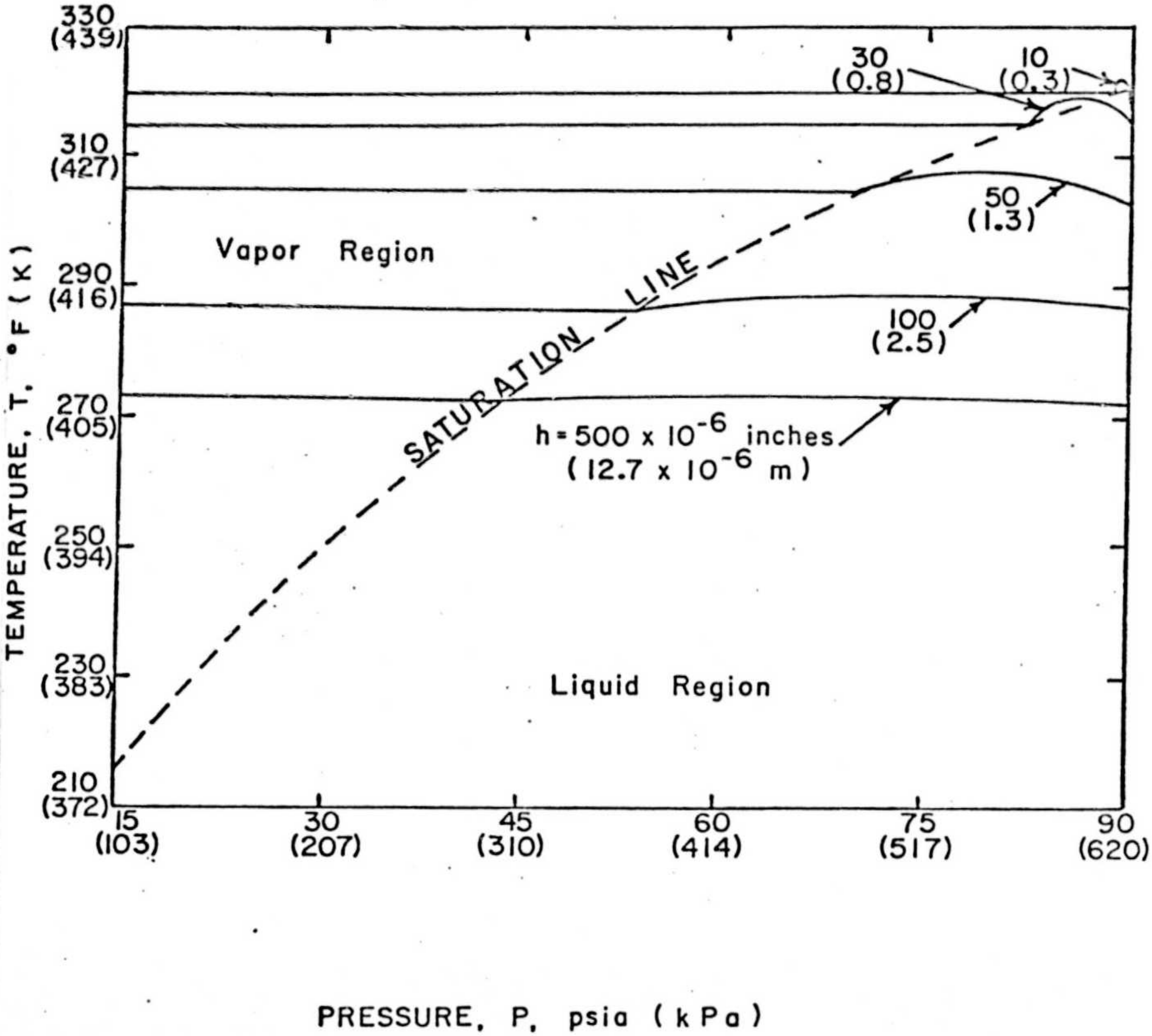

Figure 11. Fluid Temperature and Pressure at Various Seal Spacings. P_1 = 15.0 psia (103.4 kPa), P_2 = 90.0 psia (620.4 kPa), r_1 = 1.693 inches (0.04300 m), r_2 = 1.849 inches (0.04696 m), T_∞ = 270°F (405 K), ω = 7200 rpm (754 rad/s), k = 26 Btu/hr-ft-°F (45 W/m-K).

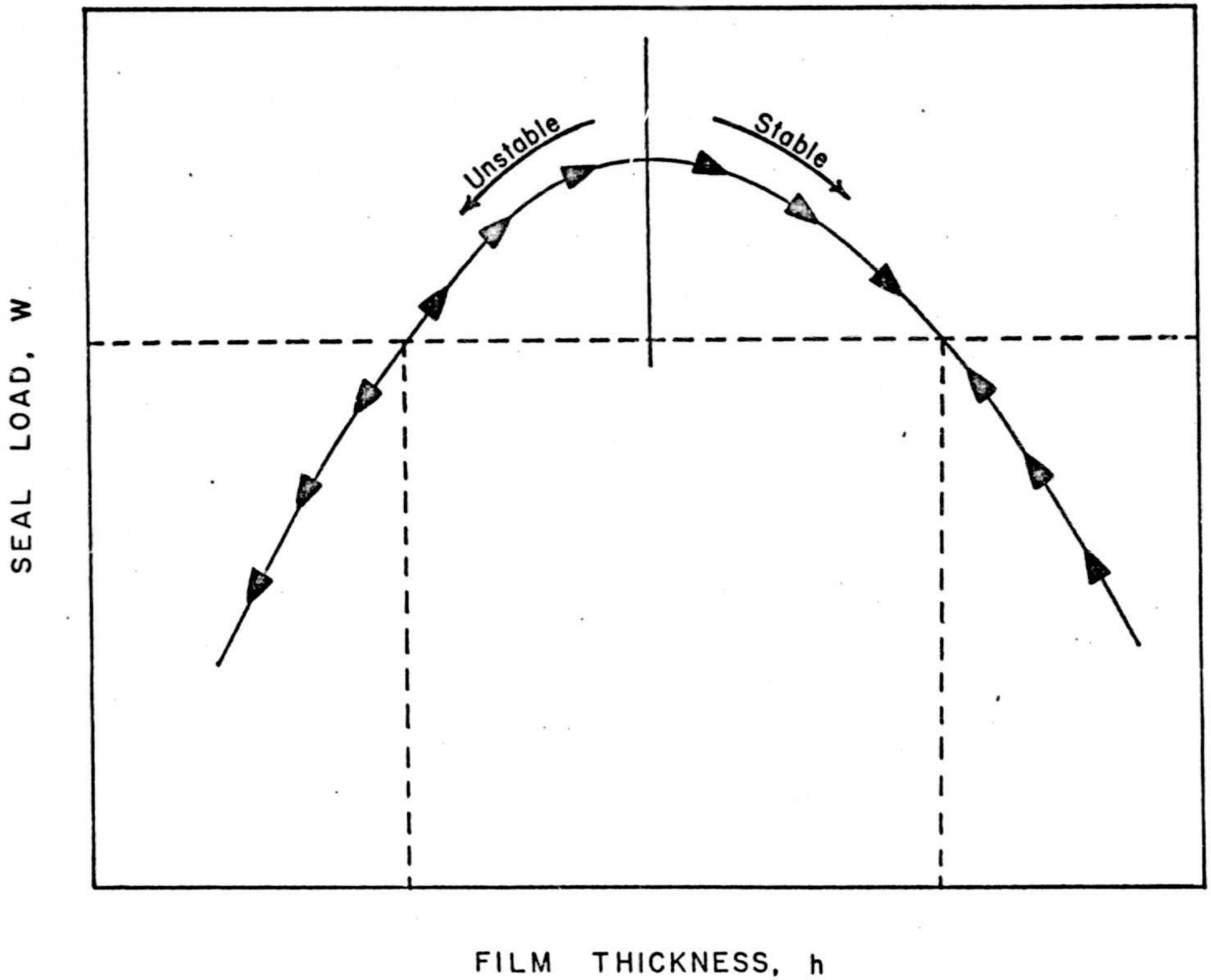

Figure 12. Effect of Film Thickness on Seal Instability.

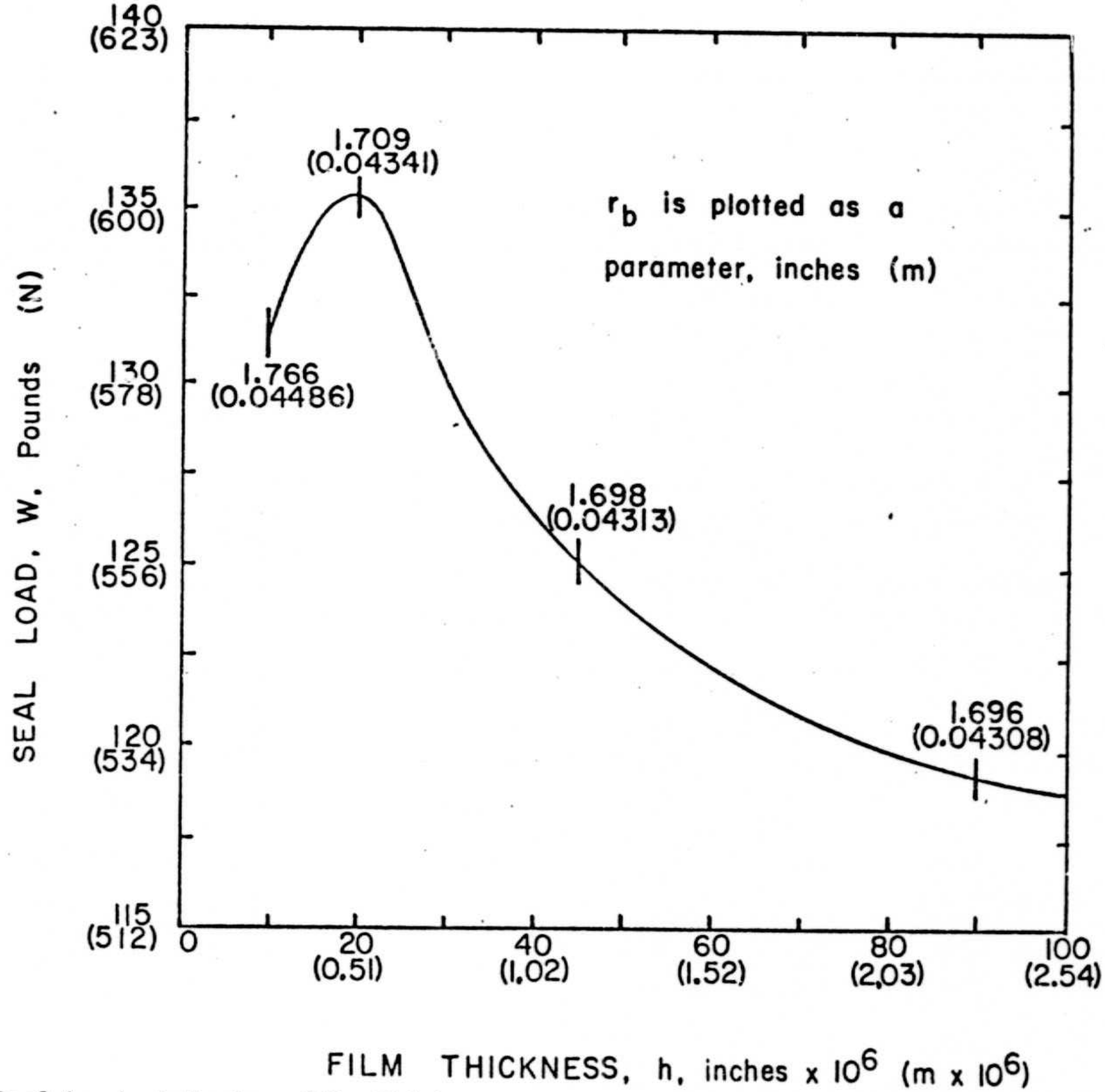

Figure 13. Seal Load at Various Film Thicknesses for an Outside Seal. P_1 = 15.0 psia (103.4 kPa), P_2 = 90.0 psia (620.4 kPa), r_1 = 1.693 inches (0.04300 m), r_2 = 1.849 inches (0.04696 m), T_∞ = 270°F (405 K), ω = 7200 rpm (754 rad/s), k = 60.2 Btu/hr-ft-°F (104 W/m-K).

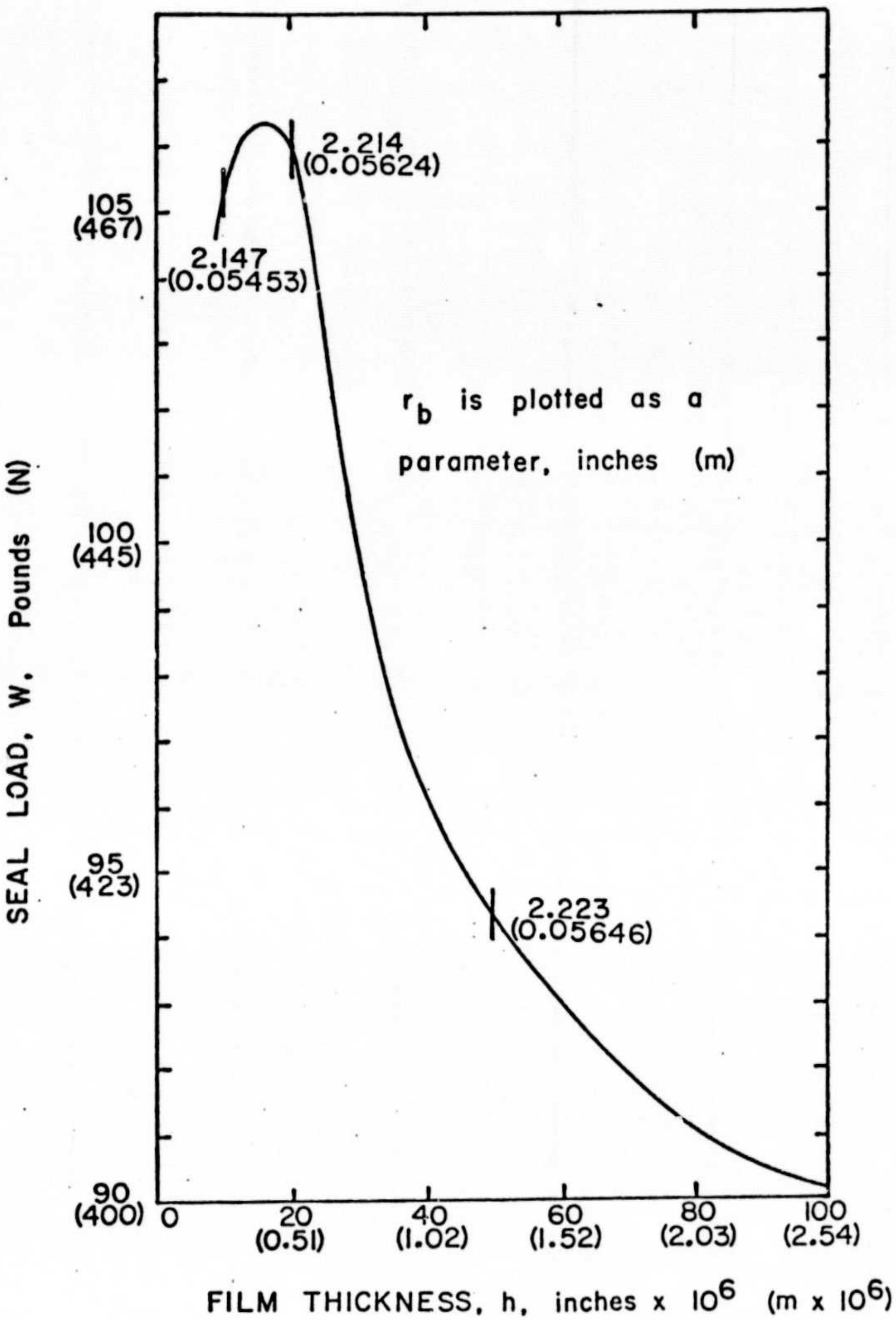

Figure 14. Seal Load at Various Film Thicknesses for an Inside Seal. P_1 = 45.0 psia (310.2 kPa), P_2 = 15.0 psia (103.4 kPa), r_1 = 2.025 inches (0.05144 m), r_2 = 2.225 inches (0.05652 m), T_∞ = 230°F (383 K), ω = 5000 rpm (524 rad/s), k = 60.2 Btu/hr-ft-°F (104 W/m-K).

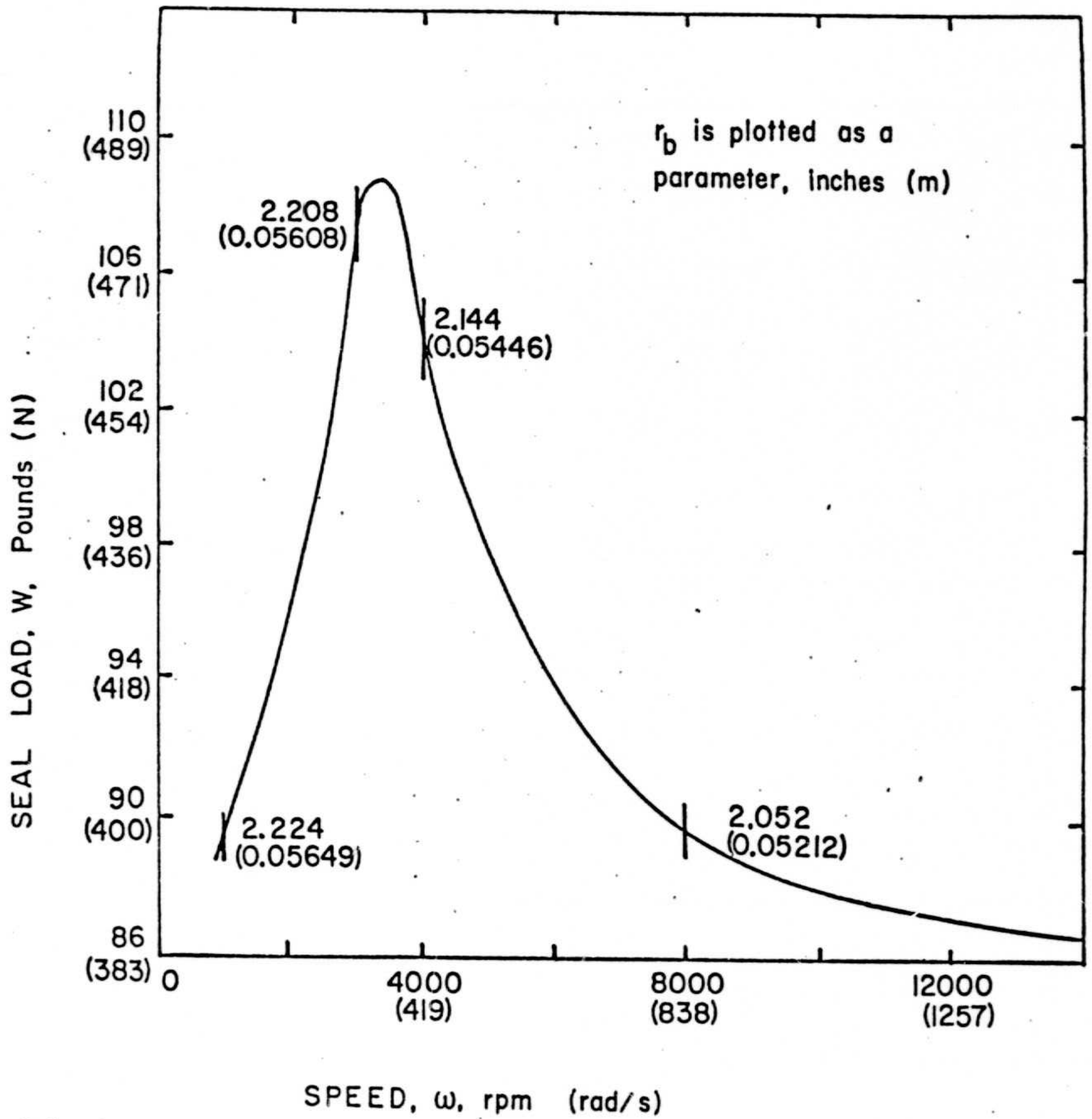

Figure 15. Seal Load at Various Speeds for an Inside Seal. P_1 = 45.0 psia (310.2 kPa), P_2 = 15.0 psia (103.4 kPa), r_1 = 2.025 inches (0.05144 m), r_2 = 2.225 inches (0.05652 m), T_∞ = 230°F (383 K), h = 50 x 10^{-6} inches (1.27 x 10^{-6} m), k = 7.5 Btu/hr-ft-°F (13 W/m-K).

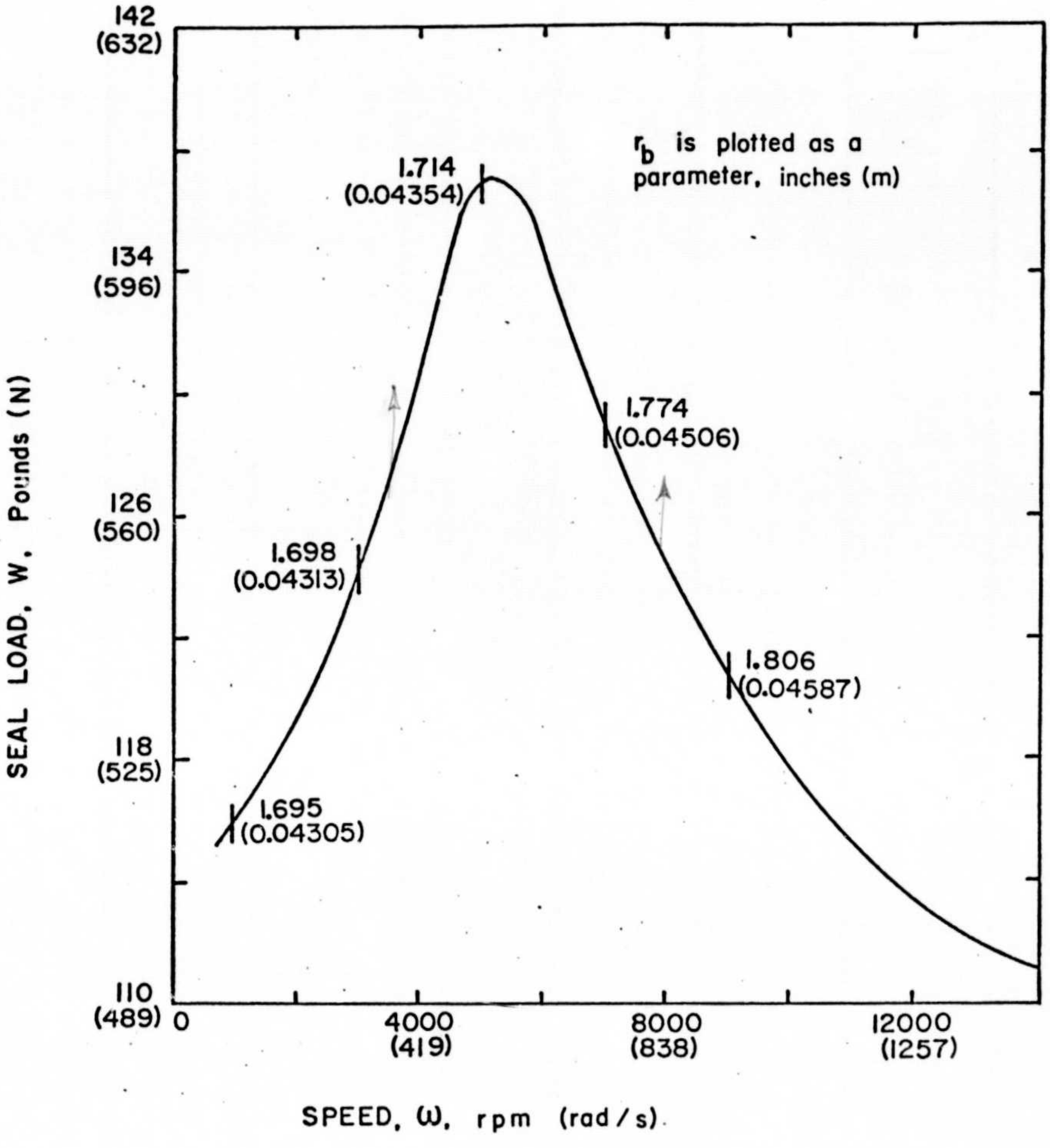

Figure 16. Seal Load at Various Speeds for an Outside Seal. P_1 = 15.0 psia (103.4 kPa), P_2 = 90.0 psia (620.4 kPa), r_1 = 1.693 inches (0.04300 m), r_2 = 1.849 inches (0.04696 m), T_∞ = 270°F (405 K), h = 20.0 x 10^{-6} inches (0.508 x 10^{-6} m), k = 26 Btu/hr-ft-°F (45 W/m-K).

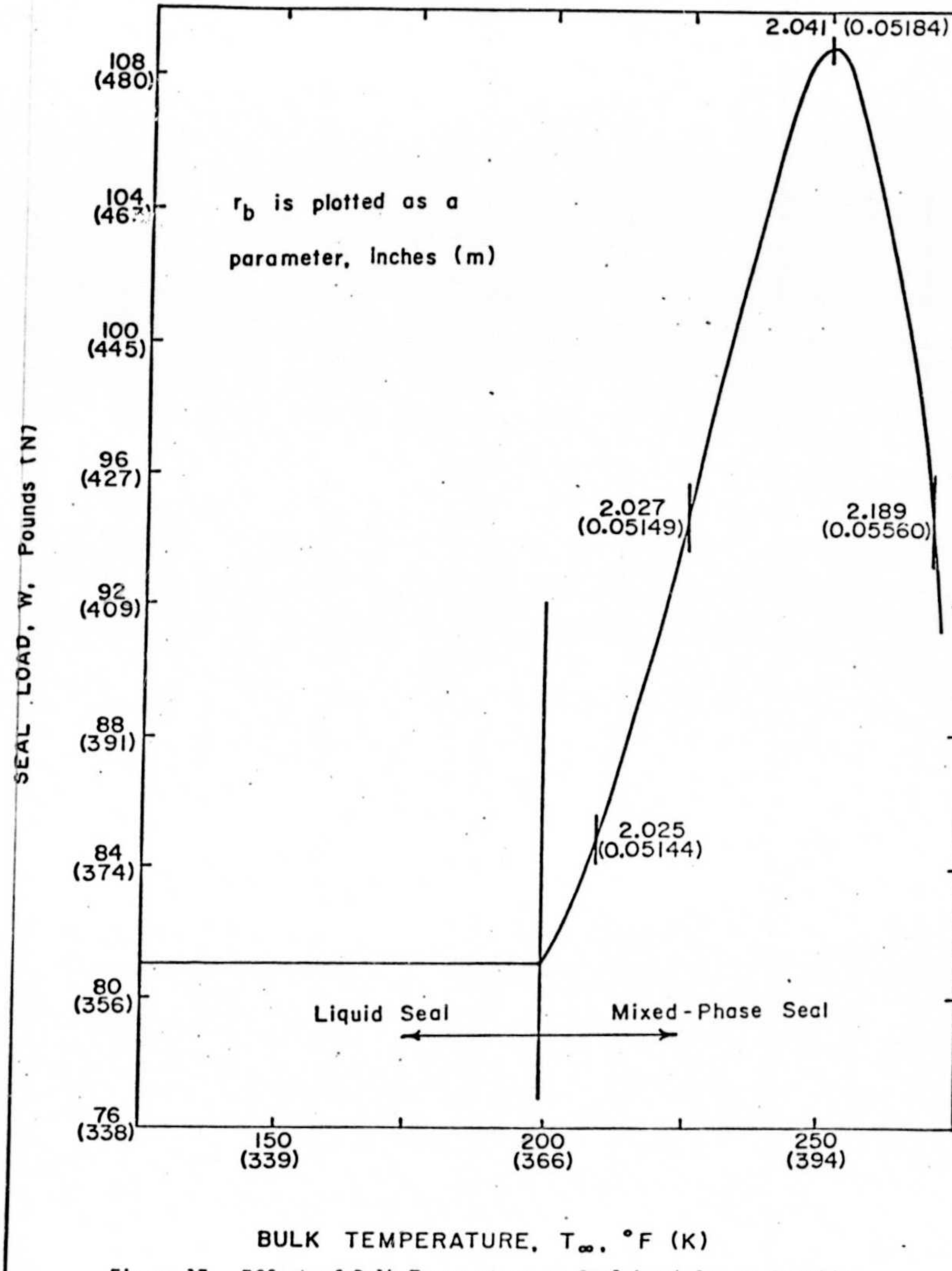

Figure 17. Effect of Bulk Temperature on Seal Load for an Outside Seal. P_1 = 15.0 psia (103.4 kPa), P_2 = 45.0 psia (310.2 kPa), r_1 = 2.025 inches (0.05144 m), r_2 = 2.225 inches (0 05652 m), h = 50.0 x 10^{-6} inches (1.27 x 10^{-6} m), ω = 3600 rpm (377 rad/s), k = 26 Btu/hr-ft-°F (45 W/m-K).

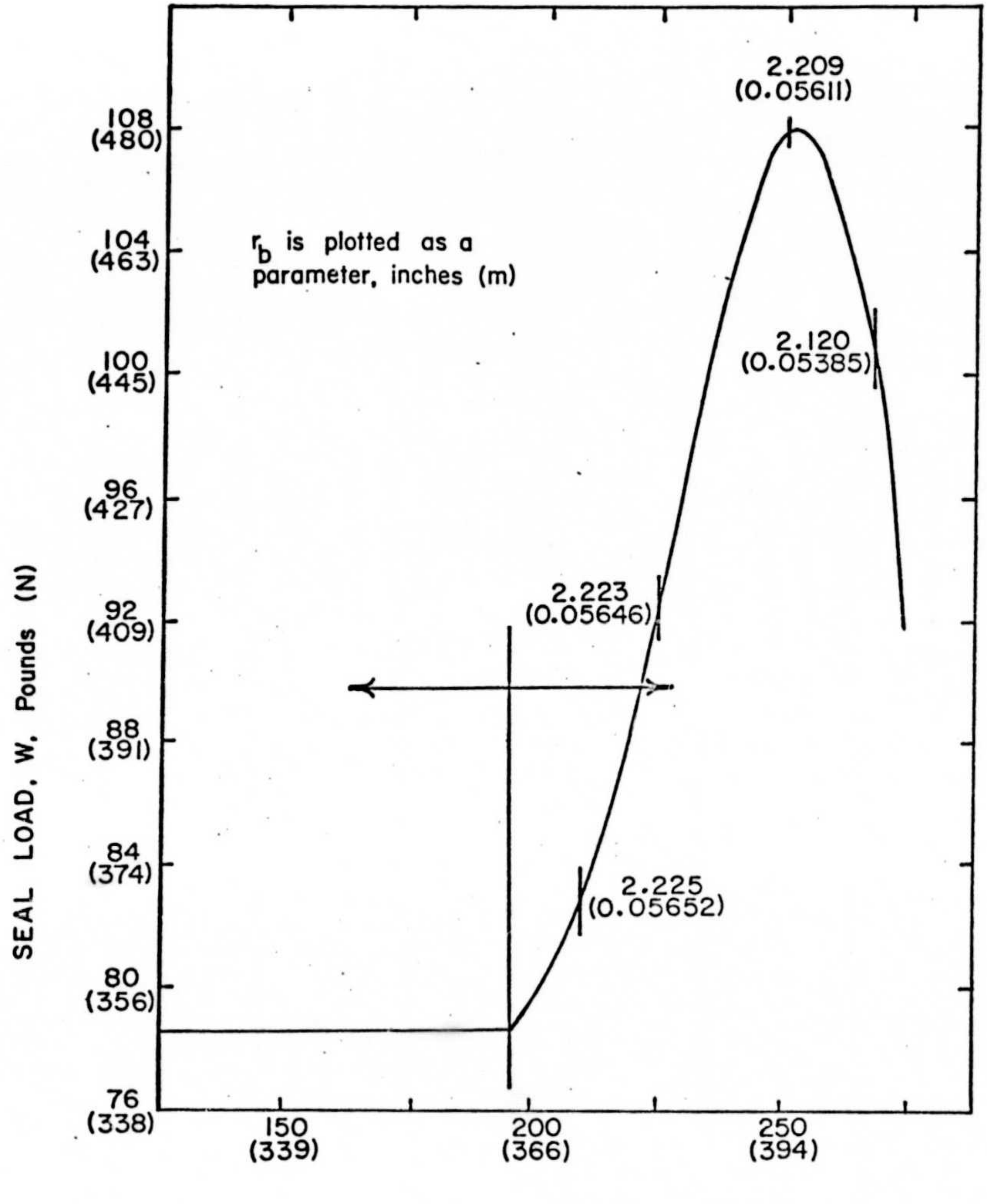

Figure 18. Effect of Bulk Temperature on Seal Load for an Inside Seal. P_1 = 45.0 psia (310.2 kPa), P_2 = 15.0 psia (103.4 kPa), r_1 = 2.025 inches (0.05144 m), r_2 = 2.225 inches (0.05652 m), h = 50.0 x 10^{-6} inches (1.27 x 10^{-6} m), ω = 3600 rpm (377 rad/s), k = 26 Btu/hr-ft-°F (45 W/m-K).

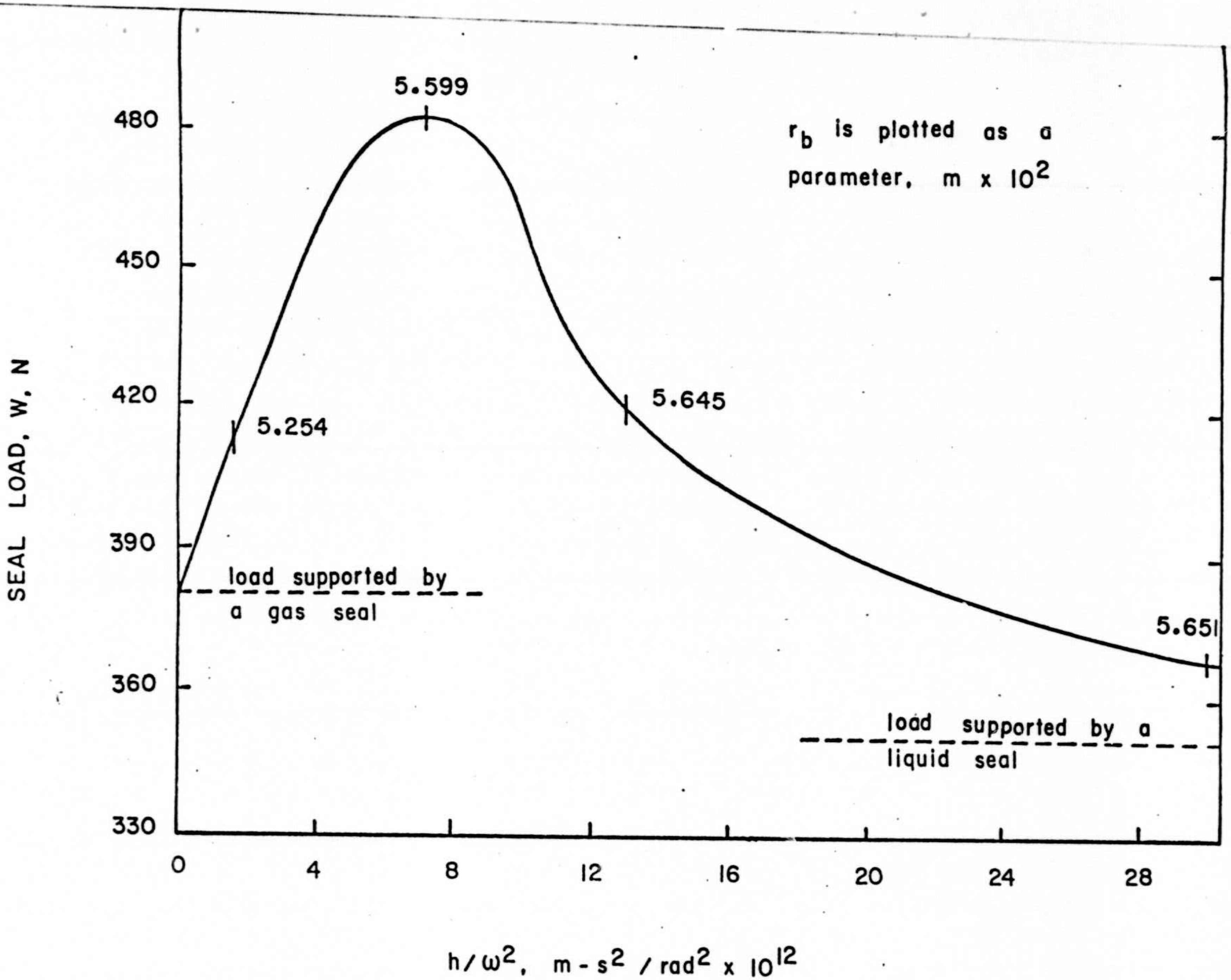

Figure 19. Effect of h/ω^2 on the Seal Load. P_1 = 45.0 psia (310.2 kPa), P_2 = 15.0 psia (103.4 kPa), r_1 = 2.025 inches (0.05144 m), r_2 = 2.225 inches (0.05652 m), k = 7.5 Btu/hr-ft-^{0}F (13 W/m-K), T_∞ = 205^{0}F (369 K).

Appendix A

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COMPUTER PROGRAM

```
C
C        THE MAIN PROGRAM STARTS HERE
C
C        THIS PROGRAM SOLVES THE ALIGNED RADIAL FACE SEAL PROBLEM ASSU-
C     MING THE VAPOR REGION(IF ANY)IS ISOTHERMAL.
C     THROUGHOUT THIS PROGRAM VARIABLES STARTING WITH THE LETTER R,P, OR
C        T REFER TO RADII, PRESSURES, OR TEMPERATURES AT VARIOUS POINTS
C        ALONG THE SEAL PLATES.
C     THE POINTS ARE DEFINED BY THE FOLLOWING FIVE SUBSCRIPTS:
C        1 - A VALUE AT THE INNER RADIUS
C        2 - A VALUE AT THE OUTER RADIUS
C        B - A VALUE AT THE BOILING RADIUS
C        I - A VALUE AT THE POINT WHERE FLUID ENTERS THE SEAL PLATES
C        O - A VALUE AT THE POINT WHERE FLUID LEAVES THE SEAL PLATES.
      DIMENSION P(21),TD(21),RM(21),TDM(21),PM(21)
      COMMON/AREA1/RI,RO,RB,R2,R1,NMAX,AN(100),BN(100),XMU,OM,XK,H,TINF/
     1AREA2/PSAT(50),TSAT(50),HFG(50),RVAP,NHFG/AREA3/R(21),DRG,C1,C2
C        FAHRENHEIT TO KELVIN
      FTOC(A)=(A-32.)/1.8+273.
C        PSI TO KPASCALS
      PTOPA(A)=A*6.893
C        INCHES TO METERS
      XITOCM(A)=A*2.54/100.
C        LIQUID PRESSURE DISTRIBUTION
      PL(A)=PI+(PB-PI)*(ALOG(A/RI)/ALOG(RB/RI))
C        BOILING PRESSURE AT INTERFACE
      PIF(A)=SQRT((EZ*TB*ALOG(RO/A)/ALOG(A/RI))**2.+2.*EZ*TB*PI*ALOG(RO/
     1A)/ALOG(A/RI)+PO*PO)-(EZ*TB*ALOG(RO/A)/ALOG(A/RI))
C        GASEOUS PRESSURE DISTRIBUTION
      PG(A)=SQRT(PB*PB+(PO*PO-PB*PB)*(ALOG(A/RB)/ALOG(RO/RB)))
C        MASS FLOW IN THE LIQUID REGION
      XML(A,B)=((-PIE*RHO*H**3.)/(6.*XMU*ALOG(B/RI)))*(A-PI)/1000000.**3
C        MASS FLOW IN THE VAPOR REGION
      XMV(A,B)=-((PO*PO-A*A)*PIE*H**3.)/(12.*XMUG*RVAP*TB*ALOG(RO/B))/10
     100000.**3
C        LOAD OF THE LIQUID REGION
      WL(A,B)=ABS(PIE*(A*B*B-PI*RI*RI+((A-PI)*(RI*RI-B*B))/(2.*ALOG(B/RI
     1))))
C     INPUT:
C        XNAME - THE NAME OF THE FLUID TO BE SEALED
C        XMU - THE VISCOSITY OF THE LIQUID(LBF-SEC/FT**2)
C        XMUG - THE VISCOSITY OF THE VAPOR(LBF-SEC/FT**2)
C        RHO - THE FLUID DENSITY(LBM/FT**3)
C        CXK - THE THERMAL CONDUCTIVITY OF THE SEAL PLATES(BTU/HR-FT-F)
C        RVAP - THE IDEAL GAS CONSTANT OF THE FLUID(FT-LBF/LBM-R)
C        NHFG - THE NUMBER OF SATURATION STATES TO BE ENTERED
      READ(5,800)XNAME,XMU,XMUG,RHO,CXK,RVAP,NHFG
C        INPUT - NHFG SATURATION STATES
      DO 10 I=1,NHFG
   10    READ(5,810)PSAT(I),TSAT(I),HFG(I)
C        MAKE INPUT DATA DIMENSIONALLY CORRECT AND SUPPLY CONSTANTS
      XK=CXK*778./3600.
      PIE=3.14159
      NMAX=100.
      EPMAX=.25
```

```
      C       WHERE:
      C            PIE IS THE MATHEMATICAL CONSTANT
      C            NMAX IS THE NUMBER OF TERMS TO BE TAKEN IN THE TEMPERATURE SERIE
      C            EPMAX IS THE MAXIMUM ERROR BETWEEN THE CLAPEYRON AND ITERATED
      C                 PRESSURES(LBF/FT**2)
            XMUM=XMU*47.883
            XMUGM=XMUG*47.883
            RHOM=RHO*16.018
            RVAPM=RVAP*5.38
            CXKM=CXK*1.7303
               WRITE(6,900)XNAME,XMU,XMUM,XMUG,XMUGM,RHO,RHOM
               WRITE(6,905)RVAP,RVAPM,CXK,CXKM
      C        SOLVE FOR TEMP. CONSTANTS(AN(I) AND BN(I))
            DO 20 J=1,NMAX
             XJ=J-1
             IF(J .GE. 12)GO TO 12
             F=(FACT(2.*XJ)**2./FACT(XJ)**4.)/2.**(4.*XJ)
             GO TO 16
       12    F=((8./(PIE*(2.*XJ+1.)))*((XJ+1.)*EXP(1.)/(2.*XJ+1.))**2.*((2.*X
           1J+1.)/(2.*XJ+2.))**(4.*(XJ+1.))*(1.+1./(12.*(2.*XJ+1.)))**2.)/(1.+
           21./(12.*(XJ+1.)))
       16    AN(J)=F/(2*XJ+4.)
       20    BN(J)=F/(2*XJ-3.)
      C        INPUT VARIABLE INPUT DATA(VID):
      C        CTINF - THE BULK TEMPERATURE(F)
      C        CP1 - THE FLUID PRESSURE AT THE INNER RADIUS(PSIA)
      C        CP2 - THE FLUID PRESSURE AT THE OUTER RADIUS(PSIA)
      C        CR1 - THE INNER RADIUS(IN)
      C        CR2 - THE OUTER RADIUS(IN)
      C        CH - THE FLUID THICKNESS(MICROINCHES)
      C        COM - THE SEAL ANGULAR VELOCITY(RPM)
       30   READ(5,820)CTINF,CP1,CP2,CR1,CR2,CH,COM
            IF(ABS(CTINF-10000.) .LT. .001)STOP
            EZ=RHO*XMUG*RVAP/XMU
      C        CONVERT VID TO PROPER UNITS
            TINF=CTINF+460.
            P1=CP1*144.
            P2=CP2*144.
            R1=CR1/12.
            R2=CR2/12.
            H=CH/12.
            OM=COM*2.*PIE/60.
      C        SET UP SEAL AS INFLOW OR OUTFLOW
            IF(P2 .GT. P1)GO TO 35
             RI=R1
             PI=P1
             RO=R2
             PO=P2
             GO TO 40
       35    RI=R2
             PI=P2
             RO=R1
             PO=P1
      C        TEST FOR A COMPLETE LIQUID SEAL(ITYPE=1)
       40   RB=RO
            TO=T(RO)
            IF(PBC(TO)-PO)60,60,45
```

```
      C          TEST FOR A COMPLETE GAS SEAL(ITYPE=2)
       45   RB=RI
            ITYPE=3
            TI=T(RI)
            IF(PBC(TI)-PI)50,65,65
      C          THIS SEAL IS A MIXED-PHASE SEAL(ITYPE=3).  ITERATE FOR RB.
       50   RBMAX=RO
            RBMIN=RI
            PBCCLT=0.
       55   RB=(RBMAX+RBMIN)/2.
            TB=T(RB)
            PB=PIF(RB)
            PBCC=PBC(TB)
            IF(ABS(PBCCLT-PBCC) .LT. .0001)GO TO 100
            PBCCLT=PBCC
            IF(ABS(PBCC-PB) .LT. EPMAX)GO TO 100
            IF(PBCC-PB)56,56,57
       56   RBMIN=RB
            GO TO 55
       57   RBMAX=RB
            GO TO 55
       60   PB=PO
            TB=T(RO)
            ITYPE=1
            GO TO 100
       65   TB=TINF
            PB=PI
            XM=XMV(PB,RB)
      C          WHERE XM IS THE SEAL LEAKAGE RATE
            ITYPE=2
            GO TO 110
      C          THE ITERATION HAS BEEN COMPLETED. CALCULATE THE MASS FLOW AND
      C                              OTHER VALUES.
      100   XM=XML(PB,RB)
      C          CALCULATE THE PRESSURE DIST IN THE LIQUID REGION
      110   R(1)=RI
            DRL=(RB-RI)/10.
            DO 120 I=1,10
              P(I)=PL(R(I))
      120     R(I+1)=R(I)+DRL
      C          CALCULATE THE PRESSURE DIST IN THE VAPOR REGION
            P(11)=PB
            R(11)=RB
            DRG=(RO-RB)/10.
            DO 130 I=12,21
              XI=I-11
              R(I)=R(11)+DRG*XI
      130     P(I)=PG(R(I))
      C          CALCULATE THE TEMP DIST ACROSS THE SEAL
            DO 140 I=1,10
              TD(I)=T(R(I))-460.
      140     TDM(I)=FTOC(TD(I))
            TD(11)=TB-460.
            TDM(11)=FTOC(TD(11))
      C          CALCULATE CONSTANTS IN GASEOUS LOAD EQUATION
            C1=PB*PB
            C2=(PO*PO-PB*PB)/ALOG(RO/RB)
      C          CALCULATE THE ABSOLUTE LOAD SUPPORTED BY THIS SEAL
```

```
      W=WL(PB,RB)+WG(PB,RB)
C         CONVERT TO PROPER OUTPUT UNITS
      CTINFM=FTOC(CTINF)
      CP1M=PTOPA(CP1)
      CP2M=PTOPA(CP2)
      CR1M=XITOCM(CR1)
      CR2M=XITOCM(CR2)
      CHM=XITOCM(CH)
      COMM=COM*2.*PIE/60.
      RB=RB*12.
      TB=TB-460.
      PB=PB/144.
      DO 150 I=1,21
        R(I)=R(I)*12.
        P(I)=P(I)/144.
        RM(I)=XITOCM(R(I))
  150   PM(I)=PTOPA(P(I))
      XMM=XM*.454
      WM=W*4.448
C         WRITE THE PERTINENT INFORMATION
          WRITE(6,910)CTINF,CTINFM,CP1,CP1M,CP2,CP2M,CR1,CR1M,CR2,CR2M
          WRITE(6,915)CH,CHM,COM,COMM
      IF(ITYPE .EQ. 1)WRITE(6,920)
      IF(ITYPE .EQ. 2)WRITE(6,925)
      IF(ITYPE .EQ. 3)WRITE(6,930)
      IF(ITYPE .EQ. 2)GO TO 170
          WRITE(6,935)
          WRITE(6,941)
      DO 160 I=1,10
  160     WRITE(6,946)R(I),RM(I),TD(I),TDM(I),P(I),PM(I)
      IF(ITYPE .EQ. 1)WRITE(6,946)R(11),RM(11),TD(11),TDM(11),P(11),PM(1
     11)
      IF(ITYPE .EQ. 3)WRITE(6,950)R(11),RM(11),TD(11),TDM(11),P(11),PM(1
     11)
      IF(ITYPE .EQ. 1)GO TO 190
  170     WRITE(6,955)
          WRITE(6,940)
      DO 180 I=12,21
  180     WRITE(6,945)R(I),RM(I),P(I),PM(I)
  190     WRITE(6,960)XM,XMM,W,WM
      GO TO 30
C
C         FORMAT STATEMENTS
C
  800 FORMAT(A15,2E10.3,3F10.3,I5)
  810 FORMAT(3F10.4)
  820 FORMAT(7F10.3)
  900 FORMAT(/' THE FLUID TO BE SEALED IS: ',A10///,' MU, THE LIQUID VIS
     1COSITY = ',E10.3,' LB-S/FT**2 =',E10.3,' PA-S     '//' MUG, THE GAS
     2 VISCOSITY = ',E10.3,' LB-S/FT**2 =',E10.3,' PA-S     '//' RHO, THE
     3 LIQUID DENSITY = ',F10.3,' LBM/FT**3 = ',F10.3,' KG/M**3'/)
  905 FORMAT(' RVAP, THE IDEAL GAS CONSTANT = ',F7.2,' FT-LBF/LBM-R = ',
     1F7.2,' J/KG-K'//' THE THERMAL CONDUCTIVITY OF THE SEAL PLATE = ',F
     27.2,' BTU/HR-FT-F = ',F7.2,'W/M-K')
  910 FORMAT('1   TINF = ',F6.1,' DEG F = ',F6.1,' DEG K'/' P1 = ',F6.1,
     1' PSIA = ',F7.1,' KPA     P2 = ',F6.1,' PSIA = ',F7.1,' KPA'/' R1
     2= ',F6.3,' IN = ',F7.5,'  M         R2 = ',F6.3,' IN = ',F7.5,'  M
     3')
```

```
C           FACTORIAL SUBPROGRAM
      FUNCTION FACT(A)
      N=A
      FACT=1.0
      IF(N .LT. 2)GO TO 1010
      DO 1000 K=1,N
        FN=K
 1000   FACT=FACT*FN
 1010 RETURN
      END
```

```
C           LIQUID TEMPERATURE DISTRIBUTION SUBPROGRAM
      FUNCTION T(A)
      COMMON/AREA1/RI,RO,RB,R2,R1,NMAX,AN(100),BN(100),XMU,OM,XK,H,TINF
      IF(RI .LT. RO)GO TO 1100
       QR1=RB
       QR2=R2
      GO TO 1110
 1100  QR1=RI
       QR2=RB
 1110 SUMA=0.
      SUMB=0.
      IF(ABS(A-QR1) .LT. .00001)GO TO 1130
      DO 1120 L=1,NMAX
        XL=L-1
        AA=AN(L)*(1.-(QR1/A)**(2.*XL+4.))
 1120   SUMA=SUMA+AA
      IF(ABS(A-QR2) .LT. .00001)GO TO 1140
 1130 DO 1150 L=1,NMAX
        XL=L-1
        BB=BN(L)*(1.-(A/QR2)**(2.*XL-3.))
 1150   SUMB=SUMB+BB
 1140 T=((1000000.*XMU*OM*OM*A**3)/(2.*XK*H))*(SUMA+SUMB)+TINF
      RETURN
      END
```

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```
C           CLAPEYRON PRESSURE SUBPROGRAM
      FUNCTION PBC(A)
      COMMON/AREA2/PSAT(50),TSAT(50),HFG(50),RVAP,NHFG
      IF(A .LT. (TSAT(1)+460.))PBC=PSAT(1)*EXP((-HFG(1)*778./RVAP)*(1./A
     1-1./(TSAT(1)+460.)))*144.
      IF(A .GT. (TSAT(NHFG)+460.))PBC=PSAT(NHFG)*EXP((-HFG(NHFG)*778./RV
     1AP)*(1./A-1./(TSAT(NHFG)+460.)))*144.
      IF((A .LT. (TSAT(1)+460.)) .OR. (A .GT. (TSAT(NHFG)+460.)))RETURN
      L=2
 1200 IF((A .GE. (TSAT(L)+460.)) .AND. (A .LT. (TSAT(L+1)+460.)))GO TO 1
     1210
        L=L+1
        GO TO 1200
 1210 L1=L
      IF((A-460.-TSAT(L)) .GT. (TSAT(L+1)-(A-460.)))L1=L+1
      PBC=PSAT(L1)*EXP((-HFG(L1)*778./RVAP)*(1./A-1./(TSAT(L1)+460.)))*1
     144.
      RETURN
      END
```

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```
C          GASEOUS LOAD SUBPROGRAM
      FUNCTION WG(A,B)
      COMMON/AREA3/R(21),DRG,C1,C2
C          DIFFERENTIAL LOAD OF THE GASEOUS REGION
      FWG(A)=SQRT(C1+C2*ALOG(A/RB))*A
      RB=B
      Z=FWG(R(11))+FWG(R(21))
      DO 1300 L=12,20,2
 1300 Z=Z+4.*FWG(R(L))
      DO 1310 L=13,20,2
 1310 Z=Z+2.*FWG(R(L))
      WG=ABS(2.*3.14159*DRG*Z/3.)
      RETURN
      END
```

Appendix B

SAMPLE OUTPUT

```
'E FLUID TO BE SEALED IS:      WATER

, THE LIQUID VISCOSITY =     .590-05 LB-S/FT**2 =    .283-03 PA-S
G, THE GAS VISCOSITY =    .252-06 LB-S/FT**2 =    .121-04 PA-S
), THE LIQUID DENSITY =     60.000 LBM/FT**3 =     961.080 KG/M**3
AP, THE IDEAL GAS CONSTANT =   85.70 FT-LBF/LBM-R =  461.07 J/KG-K
: THERMAL CONDUCTIVITY OF THE SEAL PLATE =    7.50 BTU/HR-FT-F =   12.98W/M-K
```

TINF = 205.0 DEG F = 369.1 DEG K
P1 = 45.0 PSIA = 310.2 KPA   P2 = 15.0 PSIA = 103.4 KPA
R1 = 2.025 IN = .05143 M   R2 = 2.225 IN = .05651 M

H = 50.0 MICROINCHES = 1.27 MICRONS
OM = 1000.0 RPM = 104.72 RAD/SEC

THIS SEAL ACTS AS A LIQUID SEAL

THE LIQUID DISTRIBUTION IS:

R,IN(M)	T,F(K)	P,PSIA(KPA)
2.025(.05143)	209.35(371.53)	45.00(310.18)
2.045(.05194)	209.55(371.64)	41.87(288.61)
2.065(.05245)	209.68(371.71)	38.77(267.24)
2.085(.05296)	209.76(371.76)	35.70(246.08)
2.105(.05347)	209.80(371.78)	32.66(225.12)
2.125(.05397)	209.82(371.79)	29.65(204.36)
2.145(.05448)	209.80(371.78)	26.66(183.79)
2.165(.05499)	209.75(371.75)	23.71(163.41)
2.185(.05550)	209.65(371.69)	20.78(143.22)
2.205(.05601)	209.50(371.61)	17.88(123.22)
2.225(.05651)	209.26(371.48)	15.00(103.39)

THE LEAKAGE RATE = .177-04 LBM/SEC = .802-05 KG/SEC
THE ABSOLUTE LOAD SUPPORTED BY THIS SEAL = 79. LBF = 351. N

TINF = 205.0 DEG F = 369.1 DEG K
P1 = 45.0 PSIA = 310.2 KPA P2 = 15.0 PSIA = 103.4 KPA
R1 = 2.025 IN = .05143 M R2 = 2.225 IN = .05651 M

H = 50.0 MICROINCHES = 1.27 MICRONS
OM = 5000.0 RPM = 523.60 RAD/SEC

THIS SEAL ACTS AS A MIXED-PHASE SEAL

THE LIQUID DISTRIBUTION IS:

R,IN(M)	T,F(K)	P,PSIA(KPA)
2.025(.05143)	273.42(407.12)	45.00(310.18)
2.037(.05174)	276.16(408.64)	44.88(309.32)
2.049(.05205)	277.99(409.66)	44.75(308.47)
2.061(.05236)	279.18(410.32)	44.63(307.62)
2.073(.05266)	279.83(410.68)	44.51(306.77)
2.085(.05297)	280.01(410.78)	44.38(305.93)
2.098(.05328)	279.72(410.62)	44.26(305.10)
2.110(.05359)	278.93(410.18)	44.14(304.27)
2.122(.05389)	277.58(409.43)	44.02(303.44)
2.134(.05420)	275.51(408.28)	43.90(302.62)

RB = 2.146 IN = .05451 M TB = 272.44 F = 406.58 K
PB = 43.78 PSIA = 301.81 KPA

THE VAPOR DISTRIBUTION IS:

R,IN(M)	P,PSIA(KPA)
2.154(.05471)	41.77(287.95)
2.162(.05491)	39.67(273.45)
2.170(.05511)	37.46(258.19)
2.178(.05531)	35.11(242.03)
2.185(.05551)	32.61(224.78)
2.193(.05571)	29.91(206.16)
2.201(.05591)	26.95(185.76)
2.209(.05611)	23.63(162.91)
2.217(.05631)	19.79(136.38)
2.225(.05651)	15.00(103.39)

THE LEAKAGE RATE = .116-05 LBM/SEC = .528-06 KG/SEC
THE ABSOLUTE LOAD SUPPORTED BY THIS SEAL = 105. LBF = 465. N

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TINF = 280.0 DEG F = 410.8 DEG K

P1 = 45.0 PSIA = 310.2 KPA   P2 = 15.0 PSIA = 103.4 KPA

R1 = 2.025 IN = .05143 M   R2 = 2.225 IN = .05651 M

H = 50.0 MICROINCHES = 1.27 MICRONS

OM = 5000.0 RPM = 523.60 RAD/SEC

THIS SEAL ACTS AS A GAS SEAL

THE VAPOR DISTRIBUTION IS:

R,IN(M)	P,PSIA(KPA)
2.045(.05194)	42.86(295.45)
2.065(.05245)	40.63(280.10)
2.085(.05296)	38.30(264.01)
2.105(.05347)	35.84(247.05)
2.125(.05397)	33.22(229.01)
2.145(.05448)	30.41(209.62)
2.165(.05499)	27.34(188.45)
2.185(.05550)	23.91(164.81)
2.205(.05601)	19.94(137.44)
2.225(.05651)	15.00(103.39)

THE LEAKAGE RATE = .470-06 LBM/SEC = .213-06 KG/SEC

THE ABSOLUTE LOAD SUPPORTED BY THIS SEAL = 86. LBF = 381. N

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