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FORTRAN PROGRAMS FOR THE DESIGN OF LIQUID-TO-LIQUID JET PUMPS

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SUMMARY

The one-dimensional equations describing noncavitating and cavitating flow in liquid-to-liquid jet pumps were programmed for computer use. Each of five programs were written to incorporate a different set of design input conditions. The programs may be used for any liquid for which the physical properties are known. Calculations for noncavitating and cavitating performance were combined, permitting calculation of cavitation limits within the program. Design charts may therefore easily be developed without the manual iteration which is common to existing design methods.

The equations and method of calculation are presented for each program. And in each case, a sample design problem is solved which illustrates the procedures and the types of charts that can be developed.

The program inputs consist of pertinent pressure, flow, and geometric variables; estimated friction loss coefficients; and fluid properties. Outputs consist of the basic jet pump nondimensional parameters; other pertinent pressure, flow, and geometric variables; and an indication of whether the flow is cavitating or noncavitating.

Listings of the FORTRAN IV programs are included. Execution times for each program are less than 1 minute on IBM-7094 equipment.

INTRODUCTION

The liquid-to-liquid jet pump has found increasingly wide application in recent years. Some examples of its diverse usage include reactor coolant circulation pumps, aircraft fuel pumps, and condensate boost pumps for Rankine cycle space electric power systems.

To keep pace with the renewed interest in jet pumps, analytical and experimental research of their performance characteristics has also expanded. Attention has been directed toward optimization of geometry (refs. 1 and 2), cavitation performance (ref. 3), staged operation (ref. 4), and the operating characteristics of low-area-ratio jet pumps (ref. 5). Analytical and empirical relations have been developed which accurately predict both noncavitating and cavitating jet pump performance (refs. 3, and 6 to 10).

Yet, despite the greater amount of information, the designer of a jet pump for a specific application is still faced with a cumbersome task. Design charts of a general nature are available in some papers, but are restricted to noncavitating operation and to a relatively narrow range of area ratios. Separate calculations are necessary to check for cavitation limits. And, in most cases, several manual iterations are necessary.

To simplify and reduce the amount of work involved in the design procedure, the noncavitating and cavitating procedures have been combined and programmed for computer use. Five design routines are presented in this report. Each of them corresponds to a commonly encountered jet pump design problem. FORTRAN IV listings for each are included. The program can be used for any liquid for which the physical properties are known. Therefore, for a given set of input conditions, a designer can easily and quickly develop a complete set of predicted performance curves showing the cavitation limits as well as the required physical dimensions.

DESIGN EQUATIONS

A schematic representation of a jet pump is shown in figure 1, and all symbols used are defined in appendix A. The primary fluid (fig. 1) is pressurized by an independent source and leaves the nozzle as a core of high-velocity fluid. It is separated from the secondary stream by a region of high shear. Turbulent mixing between the two fluids occurs in this region, which grows in thickness with increasing axial distance from the

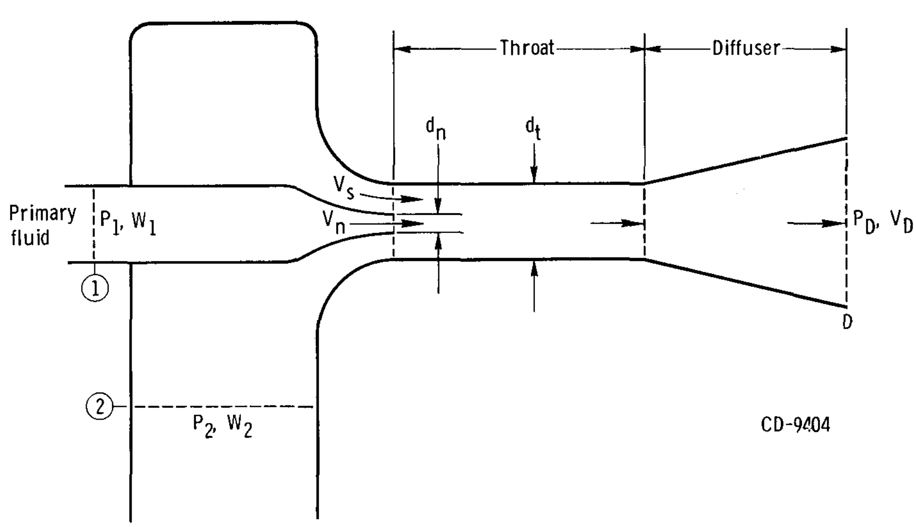


Figure 1. - Schematic representation of a jet pump.

nozzle exit. The lowest pressures in the flow field occur in the shear region, and therefore cavitation inception occurs there also.

Assumptions

The assumptions that are used in the analysis are

(1) Both the primary and secondary fluids are incompressible.

(2) The temperatures of the primary and secondary fluids are equal; therefore the specific weights are equal.

(3) Spacing of the nozzle exit from the throat entrance is zero.

(4) Nozzle wall thickness is zero.

(5) Mixing is complete at the throat exit.

Basic Parameters and Design Equations

Four basic jet pump parameters, all expressed in dimensionless form, are used. They are

(1) Nozzle-to-throat area ratio

$$R = \frac{A_n}{A_t} \tag{1}$$

(2) Secondary-to-primary flow ratio

$$M = \frac{W_2}{W_1} \tag{2}$$

(3) Head ratio

$$N = \frac{P_D - P_2}{P_1 - P_D} \tag{3}$$

(4) Efficiency

$$\eta = MN \tag{4}$$

The noncavitation analysis consists of an application of continuity, momentum, and energy equations across the jet pump (see ref. 8 for complete development). Because the analysis is one-dimensional and the mixing process is three-dimensional, the analysis must be supplemented by empirical information to determine optimum throat lengths, nozzle positions, diffuser geometry, and area ratios for specific applications (e.g., see "Design Considerations" section of ref. 5).

The formula for head ratio which results from the analysis is

$$N = \frac{2R + \dfrac{2R^2M^2}{1 - R} - (1 + K_t + K_d)R^2(1 + M)^2 - (1 + K_s)\dfrac{R^2M^2}{(1 - R)^2}}{1 + K_p - 2R - \dfrac{2R^2M^2}{1 - R} + (1 + K_t + K_d)R^2(1 + M)^2} \tag{5}$$

The theoretical expression for efficiency is obtained by multiplying equation (5) by M.

The formula for primary flow rate W_1 is

$$W_1 = \frac{\gamma A_n g_c}{144g} \frac{\sqrt{\dfrac{(P_1 - P_2)144}{\gamma/2g}}}{\sqrt{(1 + K_p) - (1 + K_s)\left(\dfrac{MR}{1 - R}\right)^2}} \tag{6}$$

and the formula for primary nozzle exit area A_n is derived from it:

$$A_n = \frac{144W_1 g}{g_c \gamma} \frac{\sqrt{(1 + K_p) - (1 + K_s)\left(\dfrac{MR}{1 - R}\right)^2}}{\sqrt{\dfrac{(P_1 - P_2)144}{\gamma/2g}}} \tag{7}$$

Friction losses are taken into account through the use of friction loss coefficients K, which are based on dimensionless total-pressure losses in individual components of the pump, such as the primary nozzle, throat, and diffuser. The friction loss coefficients may be determined either by estimating the values on the basis of information in the literature (refs. 6 to 8) or by calibrating the individual components.

Several cavitation prediction parameters have been proposed. One of them σ_L has been recommended for design use in a summary report on jet pump cavitation (ref. 3).

It was developed independently in 1968 by this author at NASA (referred to as the alternate cavitation parameter α in ref. 9), and also by Hansen and Na (referred to as σ in ref. 10). The parameter predicts conditions at the head-rise breakdown point, which is also the limiting flow point (not incipient cavitation) and is defined as

$$\sigma_L = \frac{P_2 - p_v}{\gamma V_s^2 / 2g} \tag{8}$$

where V_s is the secondary fluid velocity at the throat entrance (fig. 1),

$$V_s = \frac{144g}{\gamma g_c} \frac{W_2}{(A_t - A_n)} \tag{9}$$

A value for the minimum secondary inlet pressure required to prevent cavitation can be calculated from equation (8),

$$P_{2REQD} = \frac{\sigma_L}{144} \frac{\gamma}{2g} \left[\frac{144}{\gamma} \frac{g}{g_c} \frac{W_2 R}{A_n(1 - R)} \right]^2 + p_v \tag{10}$$

where A_n and R enter the relation from equation (1). The criterion used in the computer programs to determine cavitation-limited conditions is a comparison of P_{2REQD} and the available P_2.

The noncavitating theory predicts experimental performance quite well over a wide range of area ratios and flow conditions. Comparisons between theory and experimental performance are presented in references 6 to 8.

Cavitation-limited flow conditions have been investigated by various researchers, and empirical values for σ_L have been established. These values are summarized in reference 3. A conservative design value for σ_L is 1.35. Well-designed secondary inlet regions allow values of σ_L from 1.0 to 1.1 to be used; σ_L is an input to each program and may be specified by the user. In the numerical examples presented later in this report, $\sigma_L = 1.1$ is used.

DESIGN PROGRAMS AND PROCEDURES

Because of the diverse applications possible, there are several combinations of input conditions which a designer might encounter. Five combinations are presented in this section and the theoretical equations are developed into five design programs. The equations for each program are followed by a sample design problem illustrating use of the program. A FORTRAN IV listing of each program is given in appendix B. Execution time for each program is less than 1 minute on IBM-7094 equipment.

The choice of which program to use will depend on what input information is available, and what output is desired. Table I summarizes the input-output features of each program. Until the user is familiar with all the programs, table I should be used as a starting point.

Program I is one of the more versatile programs. It lends itself quite well to design chart development since P_1 and W_2 are the only inputs definitely required. The "varying input variables" (M, R, and P_2 for program I) may be selected at random to permit the effects of variation of each to be investigated. If specific values for each of

TABLE I. - INPUT AND OUTPUT VARIABLES FOR EACH DESIGN PROGRAM

[Input common to all programs: K_p, K_s, K_t, K_d, γ, p_v, σ_L.]

Program									
I	II	III	IV	V	I	II	III	IV	V
Fixed input variables					Output variables				
P_1	P_1	P_1		P_1	N	N	N	N	N
W_2	W_2	W_2	W_2		η	η	η	η	η
			P_2	P_2		M			
		P_{DREQD}	P_D		W_1	W_1	W_1	W_1	W_1
	d_t			d_t	P_{2REQD}	P_{2REQD}	P_{2REQD}		P_{2REQD}
				d_n	P_D	P_D	P_D		P_D
				R	d_n	d_n	d_n	d_n	
Varying input variables					d_t		d_t	d_t	
M		M	M	M					W_2
R	R	R	R					P_1	
P_2	P_2								

the varying independent variables are known (either initially or from the output of another program), program I may be run in a straightforward manner to produce only one set of output.

Program II is used when the throat diameter of a pump is known, either as a design constraint, or as part of an existing pump that is to be redesigned. Program III is the one program that will most often be used in conjunction with some other program. It is used when a pump must be designed to operate quite close to the cavitation limit. Program III identifies the cavitation-limited pump configurations. With this information the designer can apply a safety margin to the appropriate parameter and recalculate the final design using another program (e.g., program I).

Program IV is used when secondary flow rate W_2 and pump pressure rise $P_D - P_2$ are known, and when there is some flexibility in the choice of driving pressure P_1 or flow W_1. Finally, program V is used when the jet pump geometry is completely specified and it is desired to know the off-design performance.

Some design problems will probably occur which were not anticipated by these five computer programs. However, in most cases, it should be possible to create new programs by combining the appropriate design equations.

The sample design problems presented after each program do not represent the full range of applicability of each program. For some applications, enough information will be available to permit a straightforward once-through design procedure. In other cases, it will be necessary to create design charts before arriving at a final design.

Similarly, in the sample problems some programs are used in conjunction with others (programs III with I, I with II, and IV with V). How certain programs are used with each other, or if they are, will also depend on the specific application. The combinations used in the sample problems in this report are not suggested as the only possibilities open to a designer. As experience is gained using the programs, the potential relations between them will become clearer.

Finally, a word about design compromises. In general, the ideal jet pump design would possess several desirable but mutually unattainable qualities. Large amounts of secondary flow W_2 would be pumped by a minimum of primary flow W_1. This corresponds to a high flow ratio, $M = W_2/W_1$. The pressure supplied by an outside source P_1 would be kept low while jet pump pressure rise was maximized $(P_D - P_2)$. This corresponds to a high head ratio, $N = (P_D - P_2)/(P_1 - P_D)$. Efficiency would be high ($\eta = MN$), and operation would be cavitation free.

In practice, of course, compromises must be made. Achieving all these idealized goals concurrently would violate the laws of conservation of energy and momentum. Some of the compromises encountered in practice are illustrated in the sample problems.

Program I

Variables. - The known and unknown variables incorporated in program I are as follows: The known variables are

(1) Primary fluid inlet pressure P_1

(2) Secondary flow rate W_2

(3) Fluid properties γ and p_v

(4) Friction loss coefficients K_p, K_s, K_t, and K_d

(5) Cavitation parameter σ_L

(6) Secondary inlet pressure P_2, flow ratio M, and area ratio R (to be selected and their ranges varied)

The variables to be calculated are

(1) Outlet pressure P_D

(2) Required secondary inlet pressure P_{2REQD}

(3) Area ratio R

(4) Nozzle diameter d_n

(5) Throat diameter d_t

(6) Primary flow rate W_1

(7) Head ratio N

(8) Efficiency η

Equations. - The program uses the design equations in the order presented. From the input information and the definition of flow ratio (eq. (2)), the primary flow rate is calculated

$$W_1 = \frac{W_2}{M} \tag{2}$$

and from it and other input information, the primary nozzle area and diameter are calculated:

$$A_n = \frac{144 W_1 g}{g_c \gamma} \frac{\sqrt{(1 + K_p) - (1 + K_s)\left(\frac{MR}{1 - R}\right)^2}}{\sqrt{\frac{(P_1 - P_2)144}{\gamma/2g}}} \tag{7}$$

$$d_n = \sqrt{\frac{A_n}{0.7854}}$$

Throat area is computed from the definition of area ratio (eq. (1))

$$A_t = \frac{A_n}{R} \tag{1}$$

and throat diameter is calculated from

$$d_t = \sqrt{\frac{A_t}{0.7854}}$$

Head ratio N is computed from equation (5) and is multiplied by flow ratio M to obtain efficiency:

$$N = f(M, R, K_p, K_s, K_t, K_d) \tag{5}$$

$$\eta = MN \tag{4}$$

Outlet pressure is calculated from the definition of head ratio (eq. (3)) and input values for P_1 and P_2,

$$P_D = \frac{NP_1 + P_2}{1 + N} \tag{3}$$

Total flow rate is calculated by summing primary and secondary flow rates,

$$W_T = W_1 + W_2$$

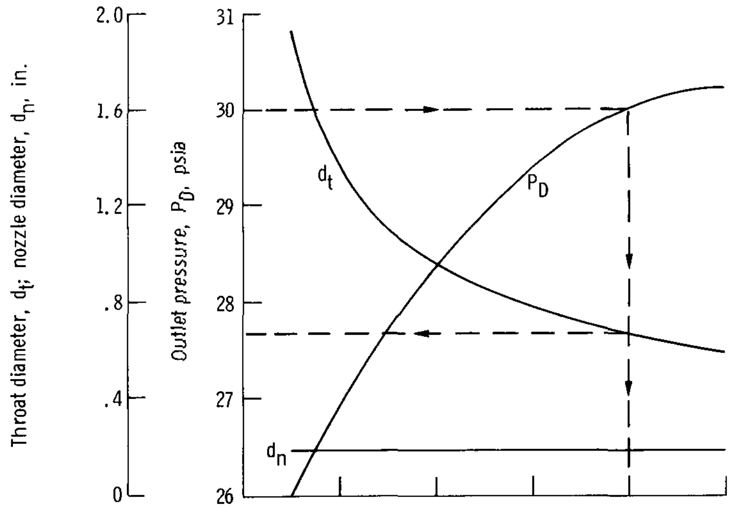
The minimum secondary inlet pressure required for cavitation-free operation is computed and compared to the input P_2:

$$P_{2REQD} = \frac{\sigma_L}{144} \frac{\gamma}{2g} \left[\frac{144}{\gamma} \frac{g}{g_c} \frac{W_2 R}{A_n(1 - R)}\right]^2 + p_v \tag{10}$$

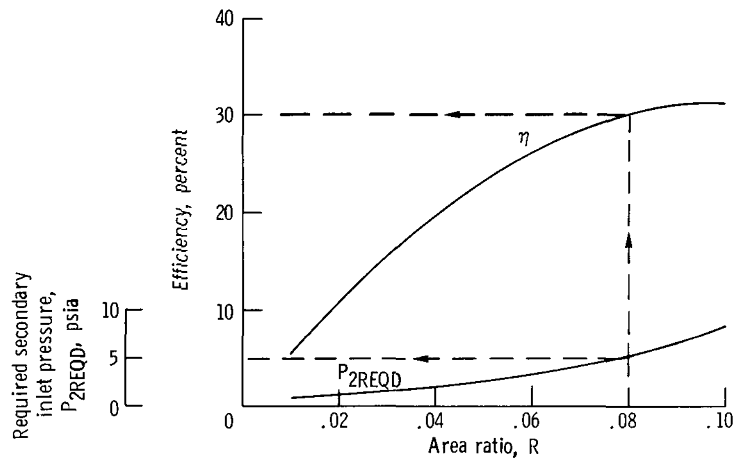
If P_2 is greater than P_{2REQD}, the flow is noncavitating and a message indicating this is printed out.

Sample design problem. - A jet pump is used to circulate 1200° F liquid sodium through the core of a nuclear reactor. It has a throat diameter d_t of 0.930 inch and an area ratio R of 0.0425. An auxiliary pump supplies a weight flow W_1 of 1 pound per second of drive fluid at a pressure P_1 of 80 psia to the jet pump, which pumps a weight flow W_2 of 3 pounds mass per second from an inlet pressure P_2 of 25 psia. A redesign of the reactor core requires that the jet pump produce a pressure P_D of 30 psia instead of the present 28.5 psia. This will require a new jet pump design.

For this sample problem the known variables are P_1 = 80 psia; P_2 = 25 psia; P_D = 30 psia; W_2 = 3 lbm/sec; W_1 = 1 lbm/sec; γ = 49.33 lbf/ft^3; p_v = 0.96 psia; K_p = 0.03, K_s = 0.1, K_t = 0.1, and K_d = 0.1 (estimated); and σ_L = 1.1. The variables to be calculated are R, d_n, and d_t.



(a) Outlet pressure, throat diameter, and nozzle diameter as function of area ratio.



(b) Efficiency and required secondary inlet pressure as function of area ratio.

Figure 2. - Program I sample problem.

Since pressure and flow requirements are completely prescribed, the design procedure is straightforward. The results are shown in figure 2 as functions of area ratio. To achieve an outlet pressure of 30 psia requires a pump having an area ratio of 0.08, a throat diameter of 0.668 inch, and a nozzle diameter of 0.189 inch. Such a pump will have an efficiency of 30.2 percent. The secondary inlet pressure required to prevent cavitation is 5.3 psia, well under the 25 psia available.

Program II

Variables. - Program II uses the following information to calculate the unknown variables:

(1) Primary fluid inlet pressure P_1
(2) Secondary flow rate W_2
(3) Throat diameter d_t
(4) Fluid properties γ and p_v
(5) Friction loss coefficients K_p, K_s, K_t, and K_d
(6) Cavitation parameter σ_L
(7) Secondary inlet pressure P_2 and area ratio R (to be selected and their ranges varied)

The variables to be calculated are

(1) Outlet pressure P_D
(2) Required secondary inlet pressure P_{2REQD}
(3) Flow ratio M
(4) Primary flow rate W_1
(5) Nozzle diameter d_n
(6) Head ratio N
(7) Efficiency η

Equations. - The program calculations are performed using the following equations and procedure in the order listed.

Knowing the throat diameter, the throat area is calculated, and from the definition of area ratio (eq. (1)), the nozzle area is computed:

$$A_t = 0.7854\, d_t^2$$

$$A_n = A_t R \tag{1}$$

$$d_n = \sqrt{\frac{A_n}{0.7854}}$$

The only flow parameter known is the secondary flow rate W_2. If either W_1 or M were known, the other could be calculated from the definition of flow ratio, $M = W_2/W_1$ (eq. (2)). This equation is used in an iterative procedure in this program to determine both W_1 and M. A first approximation for W_1 is made by dropping the term in equation (6) which contains M.

$$W_1(1) = \frac{\gamma A_n g_c}{144g} \frac{\sqrt{\frac{(P_1 - P_2)144}{\gamma/2g}}}{\sqrt{1 + K_p}} \qquad \text{(first approximation for } W_1\text{)}$$

Having this value for W_1, a corresponding first approximation for flow ratio can be calculated:

$$M(1) = \frac{W_2}{W_1(1)} \tag{2}$$

An iteration loop is then begun using the complete equation (6). Each succeeding W_1 is computed using the flow ratio M calculated in the preceding iteration. The resulting value of M calculated is compared to the value calculated in the preceding iteration. When the percentage deviation between the two is less than 0.05, the loop is completed and a final value for W_1 is completed:

$$W_1(j) = \frac{\gamma A_n g_c}{144g} \frac{\sqrt{\frac{(P_1 - P_2)144}{\gamma/2g}}}{\sqrt{(1 + K_p) - (1 + K_s)\left[\frac{M(j - 1)R}{1 - R}\right]^2}} \tag{6}$$

$$M(j) = \frac{W_2}{W_1(j)} \tag{2}$$

$$\Delta M = M(j) - M(j - 1)$$

$$\text{Percent deviation} = \frac{\Delta M}{M(j)} \times 100$$

If the percent deviation is greater than 0.05, recalculate the loop.

If the percent deviation is less than 0.05, set $M = M(j)$.

$$W_1 = \frac{\gamma A_n g_c}{144g} \frac{\sqrt{\frac{(P_1 - P_2)144}{\gamma/2g}}}{\sqrt{(1 + K_p) - (1 + K_s)\left(\frac{MR}{1 - R}\right)^2}} \tag{6}$$

Head ratio, efficiency, and outlet pressure are then calculated:

$$N = f(M, R, K_p, K_s, K_t, K_d) \tag{5}$$

$$\eta = MN \tag{4}$$

$$P_D = (NP_1 + P_2)/(1 + N) \tag{3}$$

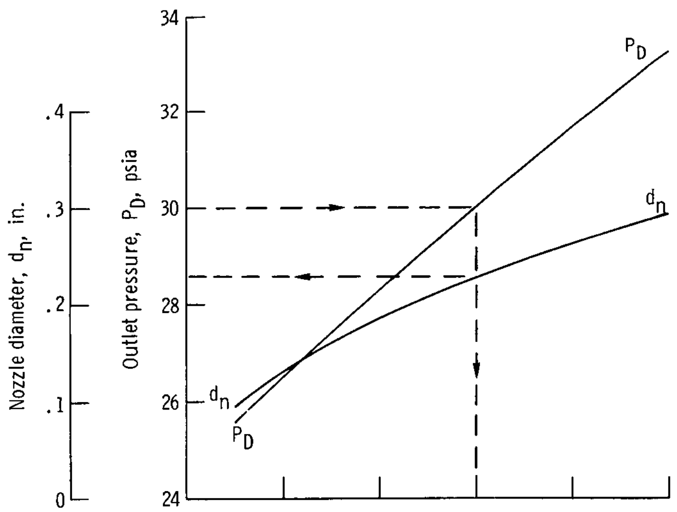
And finally, a cavitation check is made:

$$P_{2REQD} = \frac{\sigma_L}{144}\frac{\gamma}{2g}\left[\frac{144}{\gamma}\frac{g}{g_c}\frac{W_2 R}{A_n(1 - R)}\right]^2 + p_v \tag{10}$$

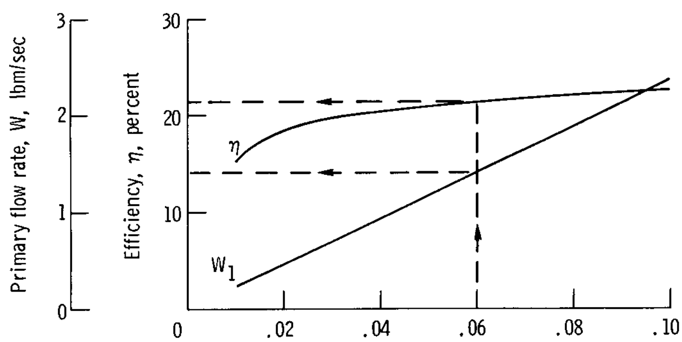
If P_2 is greater than P_{2REQD}, flow is noncavitating, and a message indicating this is printed.

Sample design problem. - The original jet pump in design problem I had a diameter d_t of 0.930 inch and an area ratio R of 0.0425. Rather than build an entirely new jet pump, a designer may wish to remove the nozzle from the pump body and replace it with one having a different diameter.

For this sample problem the known variables are P_1 = 80 psia; P_2 = 25 psia; P_D = 30 psia; W_2 = 3 lbm/sec; γ = 49.33 lbf/ft^3; p_v = 0.96 psia; K_p = 0.03, K_s = 0.1,



(a) Outlet pressure and nozzle diameter as function of area ratio.



(b) Efficiency and primary flow rate as function of area ratio.

Figure 3. - Program II sample problem.

$K_t = 0.1$, and $K_d = 0.1$ (estimated); and $\sigma_L = 1.1$. The variables to be calculated are R, d_n, and W_1.

The design curves corresponding to this set of conditions are presented in figure 3. Once again the design procedure is straightforward, but a compromise is involved. To achieve a higher outlet pressure than the original 28.5 psia (see problem I), using the same primary inlet pressure and same throat diameter, requires a greater amount of primary fluid and therefore a larger nozzle diameter (0.228 in. compared to 0.192 in.).

The results show that a jet pump having an area ratio R of 0.06 provides an outlet pressure of 30.0 psia. But it requires 1.41 pounds mass per second of primary flow rate to do it. The design decision (comparing problems I and II) is whether the reduced cost and simpler replacement features are worth the required extra flow rate of 0.41 pound mass per second and the lower efficiency (21.3 against 30.2 percent).

Program III

Variables. - Program III takes the following information and calculates the corresponding flow and geometric variables:

(1) Primary fluid inlet pressure P_1

(2) Secondary flow rate W_2

(3) Required outlet pressure P_{DREQD}, the lower limit for outlet pressure

(4) Fluid properties γ and p_v

(5) Friction loss coefficients K_p, K_s, K_t, and K_d

(6) Cavitation parameter σ_L

(7) Flow ratio M and area ratio R (to be selected and their ranges varied)

The variables to be calculated are

(1) Primary flow rate W_1

(2) Outlet pressure P_D

(3) Required secondary inlet pressure P_{2REQD}

(4) Nozzle diameter d_n

(5) Throat diameter d_t

(6) Head ratio N

(7) Efficiency η

Equations. - The calculations are performed using the following equations in the order listed. From the input information, values are calculated for primary flow rate W_1, head ratio N, and efficiency η:

$$W_1 = \frac{W_2}{M} \tag{2}$$

$$N = f(M, R, K_p, K_s, K_t, K_d) \tag{5}$$

$$\eta = MN \tag{4}$$

An iteration loop is then begun. A first estimate for the secondary inlet pressure P_2 is calculated from the definition of head ratio (eq. (3)) using the lower limit for outlet pressure (P_{DREQD}) for P_D. Nozzle area A_n is computed from equation (7) and P_{2REQD} from equation (10). The value thus obtained for P_{2REQD} is set equal to P_2 and used to recalculate A_n and P_{2REQD} until the difference between successive iterative calculations for P_{2REQD} is within specified limits.

The first estimate for P_2 is

$$P_2 = P_{DREQD} - N(P_1 - P_{DREQD})$$

$$A_n = \frac{144W_1 g}{g_c \gamma} \frac{\sqrt{(1 + K_p) - (1 + K_s)\left(\frac{MR}{1 - R}\right)^2}}{\sqrt{\frac{(P_1 - P_2)144}{\gamma/2g}}} \tag{7}$$

$$P_{2REQD} = \frac{\sigma}{144} \frac{\gamma}{2g} \left[\frac{144g}{\gamma g_c} \frac{W_2 R}{A_n(1 - R)}\right]^2 + p_v \tag{10}$$

$$\text{Percent deviation} = \left|\frac{P_{2REQD} - P_2}{P_{2REQD}}\right| \times 100$$

If percent deviation is greater than 0.05, set $P_2 = P_{2REQD}$ in equation (7) for A_n, and recalculate the values for A_n and P_{2REQD}. If percent deviation is less than 0.05, continue to the next step.

After the loop is satisfied, the outlet pressure and geometry are calculated from equations (3) and (1) and the formulas for d_t and d_n:

$$P_D = \frac{NP_1 + P_{2REQD}}{1 + N} \tag{3}$$

$$A_t = \frac{A_n}{R} \tag{1}$$

$$d_t = \sqrt{\frac{A_t}{0.7854}}$$

$$d_n = \sqrt{\frac{A_n}{0.7854}}$$

Thus, beginning with a small amount of specified information, this program computes a jet pump configuration designed to operate at the minimum possible secondary inlet pressure, $P_2 = P_{2REQD}$. Having arrived at a geometric configuration and an operating point, the designer may then apply a safety margin to any of several variables (e.g., P_2, d_n, d_t, R, or W_2) and enter any of the other programs to compute the final pump design.

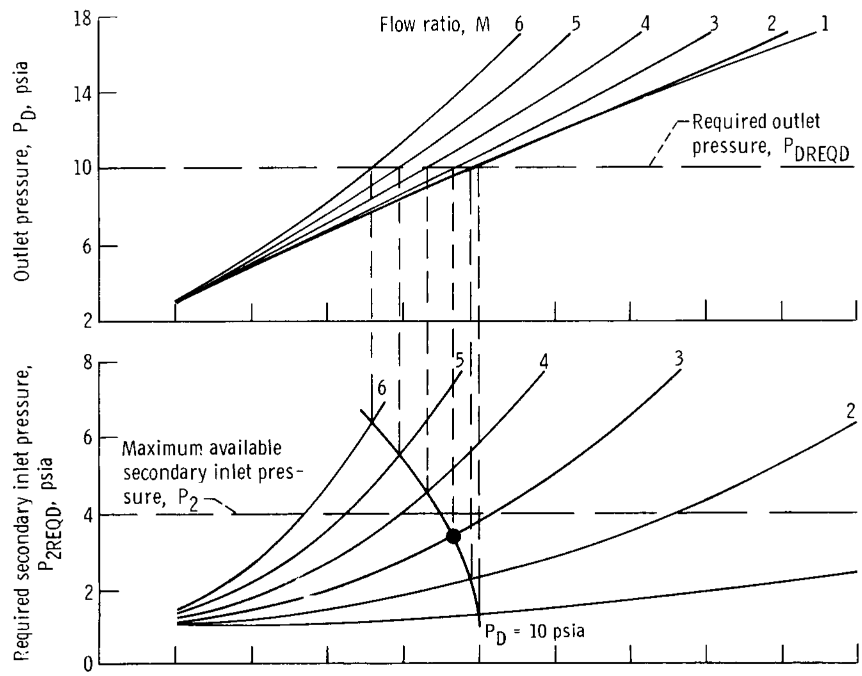
Sample design problem. - A Rankine cycle system is to be used for generating on-board electric power for a spacecraft. Working fluid is liquid potassium. A condensate pump is to be designed, and a jet pump will be needed to act as a booster pump to increase the inlet pressure to the condensate pump to 10 psia. A pressure of up to 300 psia will be available from the system to drive the jet pump (P_1), and 2.5 pounds mass per second of fluid (W_2) must be supplied by the pump to the system. Fluid at the inlet of the jet pump will be at a temperature of 1000° F. System size requirements place a constraint on throat diameter, limiting it to less than 1 inch. And radiator weight limitations specify that available secondary inlet pressure P_2 will be less than 4 psia. The designer must determine the amount and pressure of the recirculated fluid necessary to drive the jet pump (W_1 and P_1), the size of the jet pump (d_t, d_n, and R), and the inlet pressure of the condensate fluid required to prevent cavitation (P_{2REQD}).

For this sample problem the known variables are P_1 = up to 300 psia; $W_2 = 2.5$ lbm/sec; P_{DREQD} = 10 psia; $\gamma = 44.38$ lbf/ft^3; $p_v = 1.1$ psia; $K_p = 0.03$, $K_s = 0.1$, $K_t = 0.1$, and $K_d = 0.1$ (estimate based on literature); and $\sigma_L = 1.1$. The variables to be calculated are P_{2REQD}, W_1, P_1, R, d_n, d_t, and actual P_D.

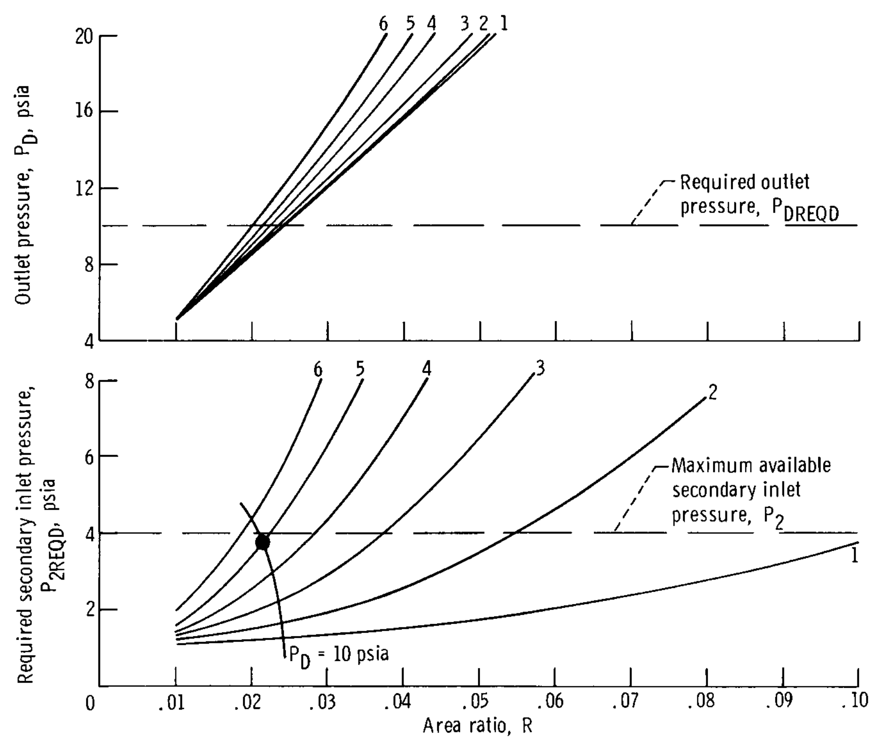
Program III was run for values of P_1 of 100, 200, and 300 psia and over a range of flow ratios M from 1 to 6 and area ratios R from 0.01 to 0.10. Results are plotted in figure 4.

Figures 4(a-1) to (a-3) are plots of outlet pressure and required secondary inlet pressure as a function of area ratio for six values of flow ratio.

Figures 4(a-1), (a-2), and (a-3) are for primary inlet pressures of 100, 200, and 300 psia, respectively. In figure 4(a-1) a horizontal line has been drawn, corresponding to



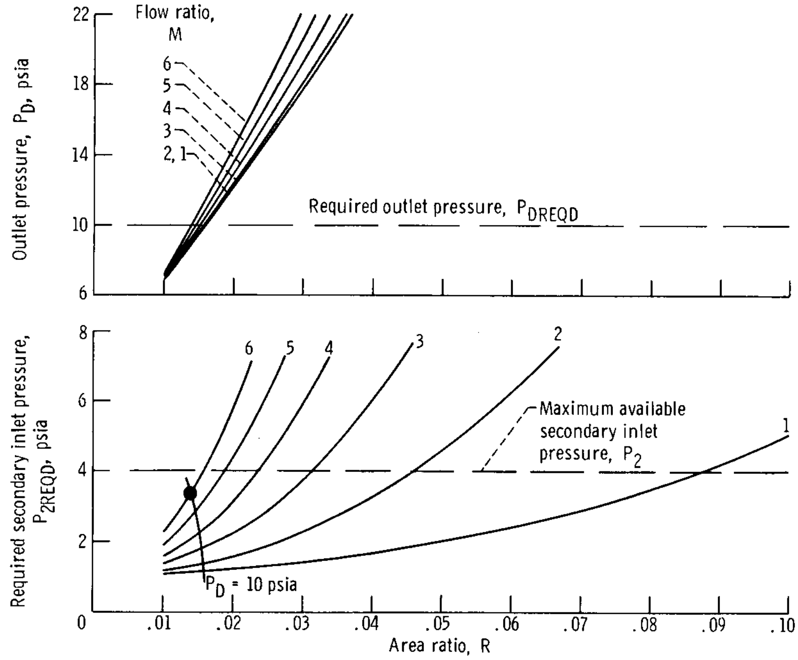
(a-1) Primary inlet pressure, P_1 = 100 psia.



(a-2) P_1 = 200 psia.

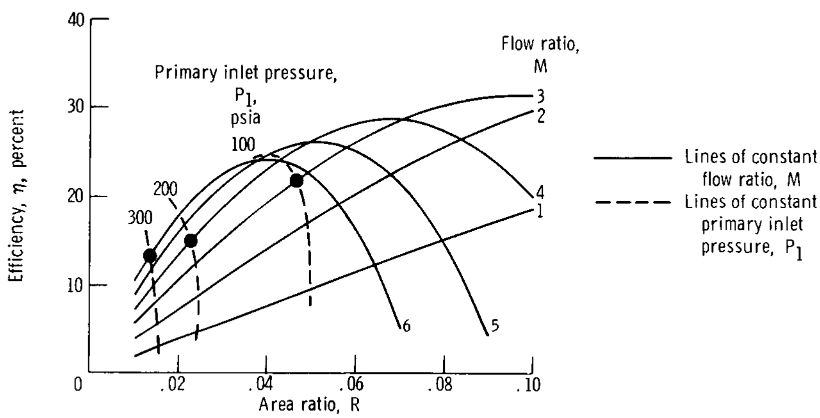
(a) Outlet pressure and required secondary inlet pressure as function of area ratio and flow ratio.

Figure 4. - Program III sample problem.

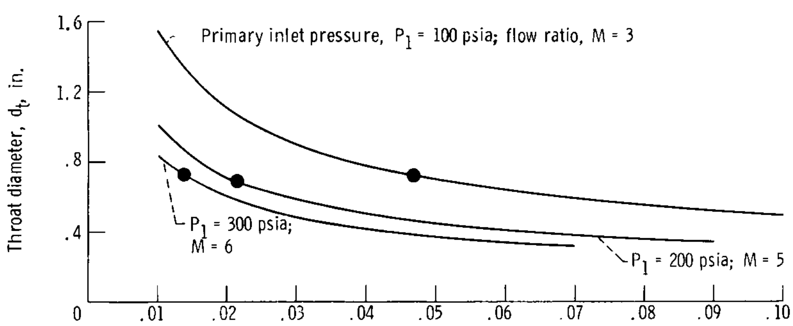


(a-3) P_1 = 300 psia.

(a) Concluded.



(b) Efficiency as function of area ratio, flow ratio, and primary inlet pressures for jet pump outlet pressure of 10 psia.



(c) Throat diameter as function of area ratio, primary inlet pressure, and flow ratio.

Figure 4. - Concluded.

the P_{DREQD} of 10 psia. It intersects each of the six flow ratio curves at a specific area ratio. This area ratio and the flow ratio corresponding to it are then used to locate points on the P_{2REQD}-against-R curves so as to construct a characteristic curve for $P_D = 10$ psia.

Figure 4(b) is a plot of efficiency as a function of area ratio for each of the six flow ratios. Superposed on this figure are characteristic curves for P_1 of 100, 200, and 300 psia, constructed from the intersections of the curves for $P_{DREQD} = 10$ psia of figure 4(a). Therefore, figure 4(b) is restricted to a P_D of 10 psia.

A study of figures 4(a) and (b) will reveal the design compromises that must be made. Figure 4(a) shows that as P_1 increases, the characteristic curves for $P_D = 10$ psia shift to lower required secondary inlet pressures, a favorable trend. But figure 4(b) shows that increasing P_1 corresponds to decreasing efficiency, an unfavorable trend. Figure 4(a) also shows that to achieve the desirable goal of high-flow-ratio operation (low W_1) means accepting a high required secondary inlet pressure, an undesirable trend. So, as observed earlier, it is impossible to achieve all the desirable goals concurrently (in this case, high flow ratio, low required secondary inlet pressure, and high efficiency).

In selecting an operating point, it should first be recognized that the required secondary inlet pressure produced by the program is the minimum possible operating pressure and the resulting jet pump geometry is calculated based on this minimum pressure. It is unlikely that this set of conditions (P_2 and geometry) will ever constitute the final design point because of the lack of operating margin with respect to cavitation. But, having established the minimum possible secondary inlet pressure and an acceptable throat and nozzle diameter, the designer can then easily determine the final design by making one pass through program I, for example. The input to program I is the same as for program III except that a value for secondary inlet pressure must also be given. When the minimum secondary inlet pressure from program III is known, it can be increased by an appropriate margin of safety and used as input for program I.

Figures 4(a) and (b) may be reviewed to clearly illustrate the procedure. The object is to keep P_2 less than 4 psia and concurrently to maximize flow ratio M. Many operating points could be chosen. Three are indicated in figures 4(a) and (b), and are listed below. The throat diameters corresponding to these points are noted in figure 4(c), a plot of throat diameter against area ratio.

(1) $P_1 = 100$ psia; $M = 3$; $\eta = 21.7$ percent; $P_{2REQD} = 3.4$ psia; $R = 0.0466$; $W_2 = 2.5$ lbm/sec; $W_1 = 0.83$ lbm/sec (fig. 4(a-1)), (b), and (c)).

(2) $P_1 = 200$ psia; $M = 5$; $\eta = 17.0$ percent; $P_{2REQD} = 3.75$ psia; $R = 0.0215$; $W_2 = 2.5$ lbm/sec; $W_1 = 0.50$ lbm/sec (fig. 4(a-2), (b), and (c)).

(3) $P_1 = 300$ psia; $M = 6$; $\eta = 13.3$ percent; $P_{2REQD} = 3.4$ psia; $R = 0.0139$; $W_2 = 2.5$ lbm/sec; $W_1 = 0.42$ lbm/sec (fig. 4(a-3), (b), and (c)).

For all cases, P_2 is less than 4 psia (fig. 4(a)) and d_t is less than 1 inch (fig. 4(c)).

A compromise must be made between high flow ratio and high efficiency. At $M = 6$ the specified W_2 can be pumped with one-half as much primary flow as at $M = 3$, thereby reducing the size and weight of the main stage pump. Since 300 psia is available for use, the choice made by the author for this set of conditions is the configuration corresponding to operating point (3). In making the choice, some efficiency was conceded.

To arrive at the final design, program I was used. No figures are presented herein, but the final results are given below. The secondary inlet pressure P_2 was set at the maximum allowable 4 psia, which provides a safety margin of greater than 15 percent over P_{2REQD} of 3.4 psia. This and the other conditions cited earlier for operating point (3) were used as input to program I and the results were

(1) Area ratio, $R = 0.0125$
(2) Throat diameter, $d_t = 0.749$ in.
(3) Nozzle diameter, $d_n = 0.084$ in.
(4) Primary inlet pressure, $P_1 = 300$ psia
(5) Secondary inlet pressure, $P_2 = 4$ psia
(6) Minimum operating secondary inlet pressure, $P_{2REQD} = 2.9$ psia
(7) Outlet pressure, $P_D = 10$ psia
(8) Efficiency, $\eta = 12.5$ percent
(9) Primary flow rate, $W_1 = 0.42$ lbm/sec

Program IV

Variables. - The input variables for program IV are

(1) Secondary fluid inlet pressure P_2
(2) Outlet pressure P_D
(3) Secondary flow rate W_2
(4) Fluid properties γ and p_v
(5) Friction loss coefficients K_p, K_s, K_t, and K_d
(6) Cavitation parameter σ_L
(7) Area ratio R and flow ratio M (to be selected and their ranges varied)

The output of the program is

(1) Primary fluid inlet pressure P_1
(2) Primary flow rate W_1
(3) Nozzle diameter d_n
(4) Throat diameter d_t
(5) Head ratio N
(6) Efficiency η
(7) Indication of cavitating or noncavitating flow

Equations. - The calculations are performed in the order that the following equations are listed.

The secondary flow rate W_2 is known and values for flow ratio M are selected and varied. Primary flow rate is then calculated from equation (2)

$$W_1 = \frac{W_2}{M} \tag{2}$$

Head ratio and efficiency are then calculated,

$$N = f(M, R, K_p, K_s, K_t, K_d) \tag{5}$$

$$\eta = MN \tag{4}$$

The definition of head ratio is used to compute primary inlet pressure,

$$P_1 = P_D + \frac{P_D - P_2}{N} \tag{3}$$

and equation (7) is applied to calculate primary nozzle area,

$$A_n = \frac{144W_1g}{g_c\gamma} \frac{\sqrt{(1 + K_p) - (1 + K_s)\left(\frac{MR}{1 - R}\right)^2}}{\sqrt{\frac{(P_1 - P_2)144}{\gamma/2g}}} \tag{7}$$

Throat area is calculated from the definition for area ratio

$$A_t = \frac{A_n}{R} \tag{1}$$

and throat and nozzle diameters are calculated from the simple area relations

$$d_t = \sqrt{\frac{A_t}{0.7854}}$$

$$d_n = \sqrt{\frac{A_n}{0.7854}}$$

Finally, a cavitation check is made by computing P_{2REQD} and comparing it with the available secondary inlet pressure P_2,

$$P_{2REQD} = \frac{\sigma_L}{144} \frac{\gamma}{2g} \left[\frac{144}{\gamma} \frac{g}{g_c} \frac{W_2 R}{A_n(1 - R)}\right]^2 + p_v \tag{10}$$

If P_2 is greater than P_{2REQD}, flow is noncavitating and a message indicating this is printed out.

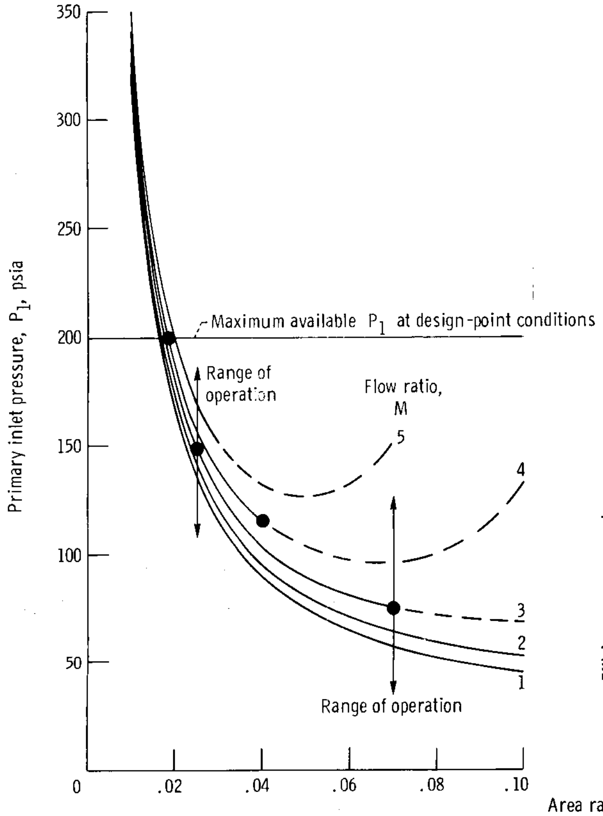
Sample design problem. - A jet pump is to be designed to pump 1.25 pounds mass per second of JP-4 aircraft fuel at a temperature of 100° F from a pressure of 6 to 12 psia. No more than 200 psia will be available from the system for primary fluid pressure P_1 at design-point operating conditions. It is desired to use as little primary fluid as is consistent with high efficiency and cavitation-free operation. The designer must determine the size of the jet pump and the primary inlet pressure required.

For this sample problem the known variables are P_2 = 6 psia; P_D = 12 psia; P_1 = up to 200 psia; W_2 = 1.25 lbm/sec; γ = 47.6 lbf/ft^3; p_v = 2.0 psia; K_p = 0.03, K_s = 0.1, K_t = 0.1, and K_d = 0.1 (estimated); and σ_L = 1.1. The variables to be calculated are P_1, R, d_n, and d_t.

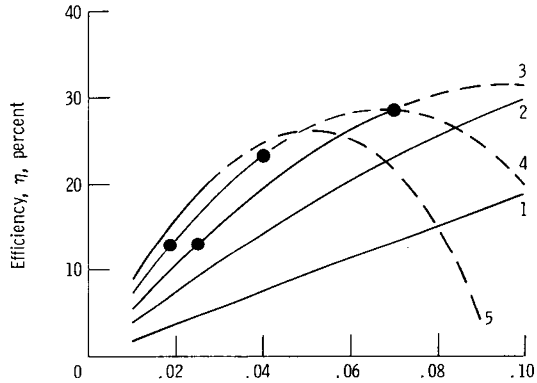
Program IV was run for values of flow ratio M ranging from 1 to 5 and for area ratios R from 0.01 to 0.10. The results are plotted in figures 5(a) to (c) as a function of area ratio. Before selecting an operating point, and thereby a geometric configuration, the specific application must be considered. There are two general classes of applications or operating conditions. First, if no off-design operation is expected (i.e., fixed point operation), the configurations which operate very close to the cavitation limit and have high efficiency can be selected. For the curves shown, this would correspond, for example, to R = 0.04, M = 4 and R = 0.07, M = 3 (figs. 5(a) and (b)).

The second class of operation would correspond to the sample problem cited; that is, off-design operation over a range of flow is expected. In such a case the operating point must be chosen to allow a margin for increase in flow W_2 without causing cavitation.

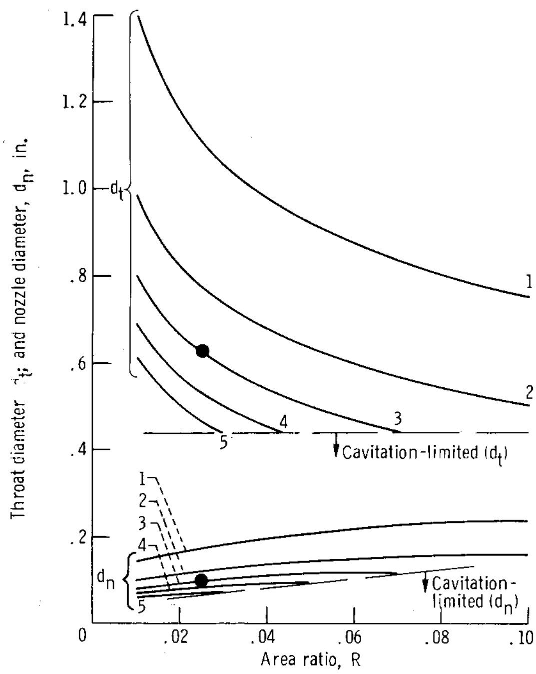
Let us take R = 0.07, M = 3 (fig. 5(a)) for an example. If such a configuration were to be operated over a range of flows, it would follow the vertical operating line shown in figure 5(a) (constant area ratio R). Following such a path, it is found that the intersection with the M = 4 curve is in the cavitating region. The operating range of this configuration is obviously restricted. Therefore, another point should be chosen on the noncavitating portion of the same flow ratio curve. It should be located at a greater distance



(a) Primary inlet pressure as function of area ratio and flow ratio. Outlet pressure, P_D = 12 psia.



(b) Efficiency as function of area ratio and flow ratio.



(c) Throat and nozzle diameter as function of area ratio and flow ratio. Outlet pressure, P_D = 12 psia.

Figure 5. - Program IV sample problem.

from the cavitation-limit point and such that operation at a fixed area ratio (vertical line) would indicate cavitation-free operation at higher flow ratios M. The point $M = 3$, $R = 0.025$, $P_1 = 148$ (figs. 5(a) to (c)) would be a good example. Once such a point is determined, the predicted operating range and cavitation capabilities can be checked by using program V (results from program IV used as input to program V). Should the operating range appear unsatisfactory, the designer can then return to figure 5(a), select another point and repeat the process.

That procedure was used to determine the design point ($R = 0.025$) indicated in figures 5(a) and (b). A further explanation of the procedure will be given in the sample design problem for program V. The design point conditions and geometry corresponding to the point indicated in figures 5(a) to (c) are

(1) Primary inlet pressure, $P_1 = 148$ psia
(2) Flow ratio, $M = 3$
(3) Area ratio, $R = 0.025$
(4) Efficiency, $\eta = 13.2$ percent
(5) Nozzle diameter, $d_n = 0.099$ in.
(6) Throat diameter, $d_t = 0.624$ in.

Program V

Variables. - Program V is used when the jet pump geometry is known and it is desired to predict off-design performance. The known variables are

(1) Primary inlet pressure P_1
(2) Secondary inlet pressure P_2
(3) Area ratio R
(4) Nozzle diameter d_n
(5) Throat diameter d_t
(6) Fluid properties γ and p_v
(7) Friction loss coefficients K_p, K_s, K_t, and K_d
(8) Cavitation parameter σ_L
(9) Flow ratio M (to be selected and the range varied)

The variables to be calculated by the program are

(1) Outlet pressure P_D
(2) Required secondary inlet pressure P_{2REQD}
(3) Primary flow rate W_1
(4) Secondary flow rate W_2
(5) Head ratio N
(6) Efficiency η

Equations. - The equations and calculation procedure are as follows: All the information necessary to calculate head ratio is available as input,

$$N = f(M, R, K_p, K_s, K_t, K_d) \tag{5}$$

Outlet pressure can be calculated from the previously calculated N and from input values for primary and secondary inlet pressures P_1 and P_2.

$$P_D = \frac{NP_1 + P_2}{1 + N} \tag{3}$$

Nozzle area is calculated from the area formula $A_n = 0.7854d_n^2$ and is used in equation (6) with input information to compute primary flow rate

$$W_1 = \frac{\gamma A_n g_c}{144g} \frac{\sqrt{\frac{(P_1 - P_2)144}{\gamma/2g}}}{\sqrt{(1 + K_p) - (1 + K_s)\left(\frac{MR}{1 - R}\right)^2}} \tag{6}$$

Secondary flow rate is calculated from the definition of flow ratio,

$$W_2 = W_1 M \tag{2}$$

and the cavitation limit is checked,

$$P_{2REQD} = \frac{\sigma_L}{144} \frac{\gamma}{2g}\left[\frac{144}{\gamma} \frac{g}{g_c} \frac{W_2 R}{A_n(1 - R)}\right]^2 + p_v \tag{10}$$

If P_2 is greater than P_{2REQD}, flow is noncavitating and a message indicating this is printed out.

Sample design problem. - The jet fuel pump designed in the program IV sample problem must be able to operate over a range of flows and pressures to meet varying engine requirements. The designer is therefore interested in developing a series of predicted performance curves for the jet pump for the conditions and flow rate range specified as follows:

The known variables are P_1 = up to 400 psia (to meet the flow range requirement); $P_2 = 6$ psia; $R = 0.025$; $d_n = 0.099$ in.; $d_t = 0.624$ in.; $W_2 = 0.75$ to 2.5 lbm/sec; $M = 3.0$; $\gamma = 47.6\ \mathrm{lbf/ft^3}$; $p_v = 2.0$ psia; $K_p = 0.03$, $K_s = 0.1$, $K_t = 0.1$, and $K_d = 0.1$ (estimated); and $\sigma_L = 1.1$. The variables to be calculated are P, P_{2REQD}, W_1, N, and η for any point in the operating range.

At design conditions, the primary inlet pressure required by the jet pump will be 148 psia; the geometric configuration was sized according to this requirement. As the engine operating conditions vary for off-design operation, the primary inlet pressure available to drive the jet pump will change and the maximum available P_1 will be 400 psia. Therefore, input values to program V for P_1 were arbitrarily selected at 50, 100, 200, 300, and 400 psia.

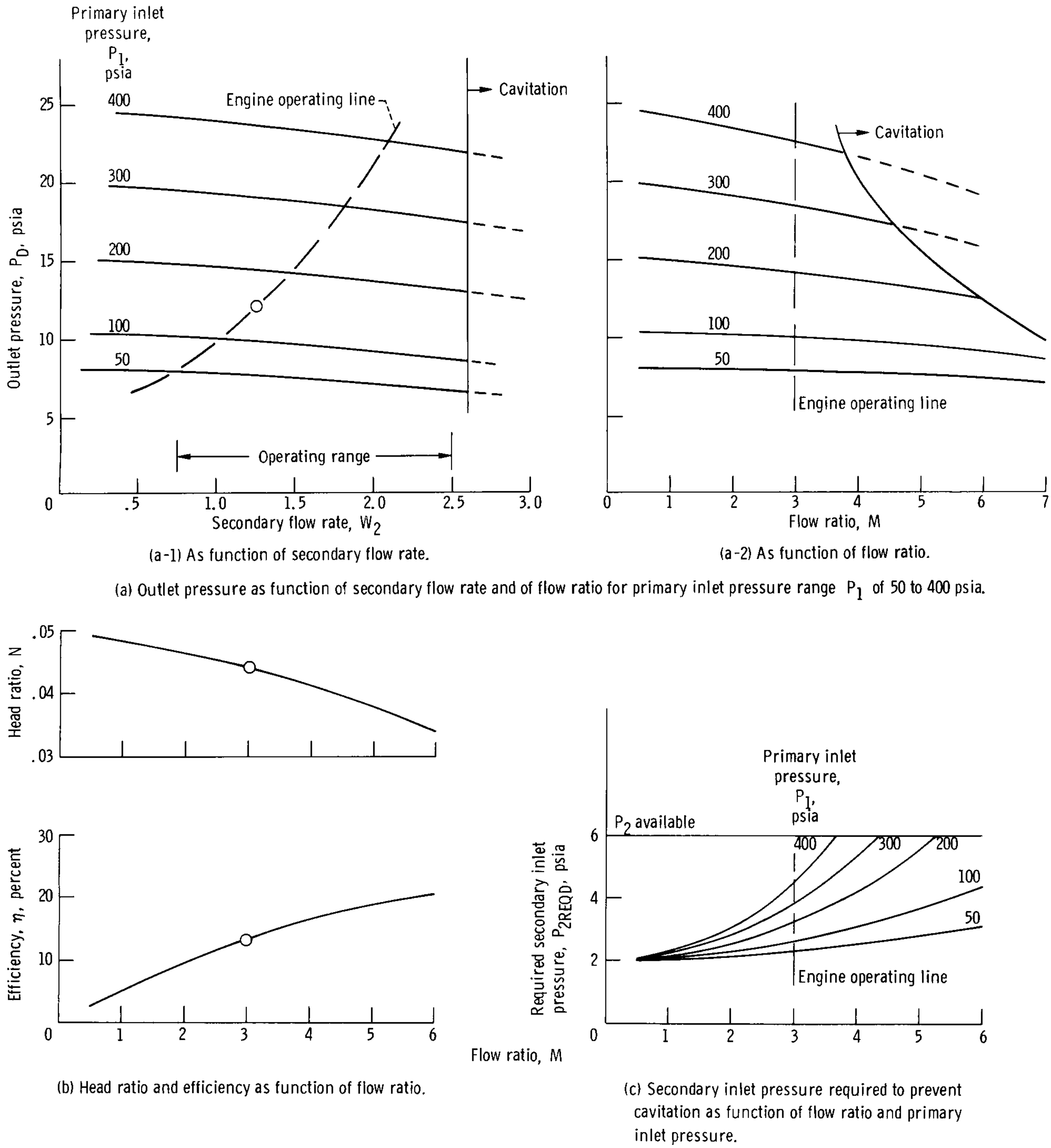
The performance curves are presented in figure 6. Of most direct use to the designer is figure 6(a-1) which gives developed outlet pressure P_D and the corresponding flow rate W_2 to the system. Outlet pressure is also plotted in figure 6(a-2) as a function of flow ratio. In both figures an engine operating line was constructed assuming jet pump operation at constant flow ratio. The indicated cavitation-limiting secondary flow rate W_2 for all operating conditions is 2.6 pounds per second (fig. 6(a-1)) because secondary inlet area and pressure are fixed. However, the cavitation-limiting flow ratio, $M = W_2/W_1$, varies (fig. 6(a-2)) because changes in primary inlet pressure cause changes in primary flow rate W_1.

Nondimensional jet pump parameters N and η are plotted as a function of flow ratio in figure 6(b). And for convenience, the secondary inlet pressure required to prevent cavitation is plotted in figure 6(c) for a range of flow ratios and primary inlet pressures.

In selecting a jet pump to meet program IV sample problem requirements, the information presented in figure 6 would be used directly. The configuration finally chosen (the performance of which is shown in figs. 6(a) to (c)) had the following characteristics: $R = 0.025$; $M = 3$; $P_1 = 148$ psia; $d_n = 0.099$ inch; $d_t = 0.624$ inch; and $\eta = 13.2$ percent.

The specified secondary flow rate range W_2 was 0.75 to 2.5 pounds mass per second. Figure 6(a-1) shows that the cavitation-limiting flow rate is 2.6 pounds mass per second, and this configuration is therefore acceptable.

On the other hand, a configuration which was not acceptable corresponded to the point on figure 5(a) where $R = 0.0185$, $P_1 = 200$ psia, and $M = 4.0$. This was initially attractive because of its higher flow ratio of $M = 4.0$. However, when data corresponding to this configuration were entered into program V, the results (not shown here) gave a W_2 of 2.3 pounds mass per second as the limiting secondary flow rate, less than the upper limit of the specified flow range.



(a-1) As function of secondary flow rate.

(a-2) As function of flow ratio.

(a) Outlet pressure as function of secondary flow rate and of flow ratio for primary inlet pressure range P_1 of 50 to 400 psia.

(b) Head ratio and efficiency as function of flow ratio.

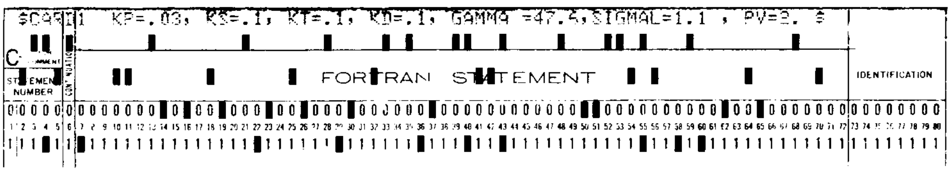
(c) Secondary inlet pressure required to prevent cavitation as function of flow ratio and primary inlet pressure.

Figure 6. - Program V sample problem. Area ratio, R = 0.025 inch; throat diameter, d_t = 0.624 inch.

Input and Output

This section describes the procedures for entering input data into the program and the form in which output is printed.

Input. - All input variables for each program are entered with NAMELIST declarations. The first set of data entered is the same for each program. It consists of the friction loss coefficients K_p, K_s, K_t, and K_d; the specific weight of the fluid γ; the vapor pressure of the secondary fluid p_v; and the limiting cavitation parameter σ_L. This group of data is identified as CARD1, and a sample is shown below



On IBM-7094 equipment the set of data in a NAMELIST declaration must begin with a \$ in card column 2, followed by the group identification name (i.e., CARD1 in columns 3 to 8); and a \$ must appear at the end of the data on the last card.

The second group of data entered in each program is identified as CARD2 and differs for each program. A list of CARD2 input variables for each program follows:

(1) Program I: P1, W2, NORS, R, NOMS, M, NOP2, P2

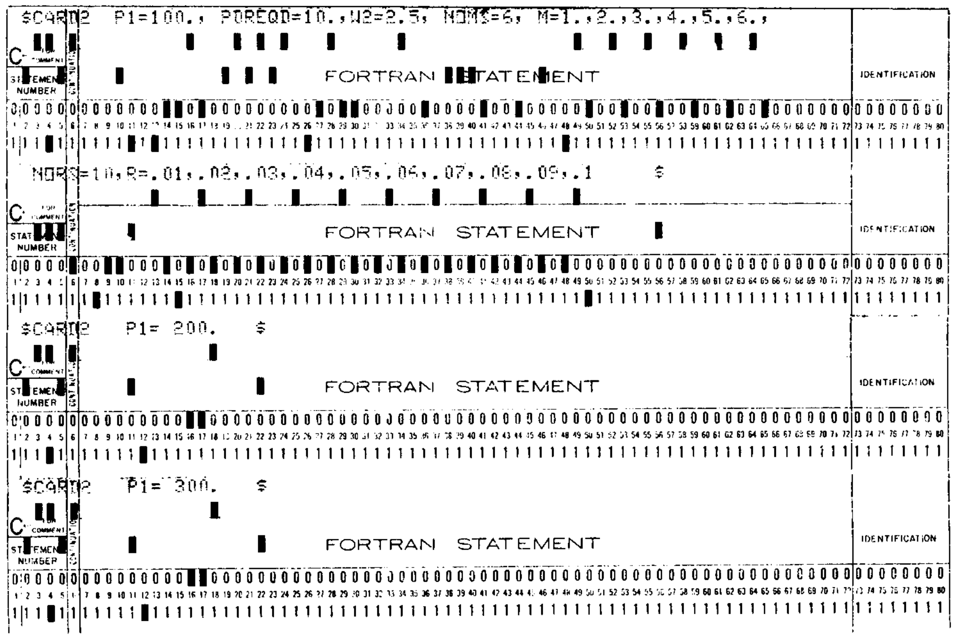
(2) Program II: P1, W2, DT, NOP2, P2, NORS, R

(3) Program III: P1, PDREQD, W2, NOMS, M, NORS, R

(4) Program IV: NORS, R, NOMS, M, P2, PD, W2

(5) Program V: P1, P2, DN, DT, R, NOMS, M

The variables in a specific group may be entered in any order. An example of input for the program III sample problem is given here:



The NAMELIST declaration permits a simple variation of parameters (e.g., P1 above) with a minimum of card punching and with no concern for format fields.

Output. - Output variables are printed according to FORMAT declarations. Pertinent input information is printed first. Then program-calculated information and special messages are printed. A sample output sheet from the program III sample problem is given here.

P1	PDREQD	W2	KP	KS	KT	KD	GAMMA	SIGMAL	PV
1C0.C	10.C	2.5	C.C3C	C.1C0	0.100	0.100	44.4	1.1	1.1

M = 1.C00

R	N	ETA	P2 REQD	PD	DT	CN	W1	
C.C1C	0.C19	C.019	1.1	3.C	2.700	0.270	2.50	PD IS LESS THAN PDREQD
C.C20	0.C39	0.039	1.1	4.8	1.909	C.270	2.50	PD IS LESS THAN PDREQD
C.C3C	0.C58	C.C58	1.2	6.6	1.559	0.270	2.50	PD IS LESS THAN PDREQD
C.C4C	0.C77	C.077	1.3	8.4	1.350	0.270	2.50	PD IS LESS THAN PDREQD
C.C50	0.C96	C.C96	1.4	1C.1	1.208	0.270	2.50	
C.C60	0.115	0.115	1.5	11.7	1.102	0.270	2.50	
C.C70	0.134	C.134	1.7	13.3	1.021	0.270	2.50	
C.C80	0.152	0.152	1.9	14.8	0.955	0.270	2.50	
C.C9C	0.170	0.17C	2.1	16.4	0.90C	C.270	2.50	
C.1C0	0.188	0.188	2.4	17.8	0.854	0.270	2.50	

M = 2.000

R	N	ETA	P2 REQD	PD	DT	DN	W1	
0.010	0.019	0.038	1.1	3.0	1.909	0.191	1.25	PD IS LESS THAN PDREQD
0.020	0.037	0.075	1.3	4.8	1.350	0.191	1.25	PD IS LESS THAN PDREQD
0.030	0.055	0.110	1.5	6.6	1.102	0.191	1.25	PD IS LESS THAN PDREQD
0.040	0.072	0.143	1.8	8.4	0.955	0.191	1.25	PD IS LESS THAN PDREQD
0.050	0.087	0.175	2.3	10.1	0.854	0.191	1.25	
0.060	0.102	0.204	2.8	11.8	0.780	0.191	1.25	
0.070	0.116	0.232	3.5	13.5	0.722	0.191	1.25	
0.080	0.128	0.256	4.3	15.2	0.675	0.191	1.25	
0.090	0.139	0.279	5.2	16.8	0.636	0.191	1.25	
0.100	0.149	0.298	6.3	18.5	0.604	0.191	1.25	

M = 3.000

R	N	ETA	P2 REQD	PD	DT	DN	W1	
0.010	0.019	0.056	1.2	3.0	1.559	0.156	0.83	PD IS LESS THAN PDREQD
0.020	0.036	0.108	1.5	4.9	1.102	0.156	0.83	PD IS LESS THAN PDREQD
0.030	0.051	0.154	2.0	6.8	0.900	0.156	0.83	PD IS LESS THAN PDREQD
0.040	0.065	0.196	2.8	8.7	0.780	0.156	0.83	PD IS LESS THAN PDREQD
0.050	0.077	0.232	3.7	10.6	0.697	0.156	0.83	
0.060	0.087	0.262	5.0	12.6	0.636	0.156	0.83	
0.070	0.095	0.286	6.5	14.6	0.589	0.156	0.83	
0.080	0.101	0.302	8.3	16.7	0.551	0.156	0.83	
0.090	0.104	0.312	10.4	18.8	0.520	0.156	0.83	
0.100	0.104	0.313	12.8	21.1	0.493	0.156	0.83	

CONCLUDING REMARKS

The one-dimensional equations describing noncavitating and cavitating flow in liquid-to-liquid jet pumps were programmed for computer use. Each of the five programs was written to incorporate a different set of design input conditions. The programs may be used for any liquid for which the physical properties are known. Calculations for non-cavitating and cavitating conditions were combined, permitting calculation of cavitation limits within the program. Design charts may therefore easily be developed without the manual iteration which is common to existing design procedures.

Three types of input data are required for each program. One is composed of fluid properties, friction factors, and other constants. Another type is made up of certain fluid dynamic and geometric parameters which are specified invariant by design requirements. And the third type of input is composed of parameters which may be varied to allow flexibility in choice of the design point.

The programs are adaptable in use. Single-pass design-point calculations may be made if the design requirements are fully specified. Or, if some of the parameters are variable, one or more programs may be used to construct elaborate design charts.

Program I is a versatile program which requires only two invariant input parameters: primary inlet pressure P_1; and secondary flow ratio W_2. Through variation of flow ratio M, area ratio R, and secondary inlet pressure P_2 design charts may be constructed which specify the other geometric and fluid dynamic parameters. Program II is used when the designer knows the throat diameter of the jet pump d_t, the primary inlet pressure P_1, and the secondary flow rate W_2.

Program III is used when the primary inlet pressure P_1, the secondary flow rate W_2, and the minimum allowable outlet pressure P_D are specified. It calculates a configuration which is sized for operation just at the cavitation-limiting condition. This program may be used to establish a first-approximation design for jet pumps which must operate close to the cavitation limit. In such cases, a cavitation safety margin is applied to output parameters from program III, and those data are used as input to one of the other programs to determine the final design.

Program IV is used when the secondary flow ratio W_2, the secondary inlet pressure P_2, and outlet pressure P_D are known (i.e., W_2 and jet pump pressure rise). Program V is used when the jet pump geometry has been specified (area ratio R, nozzle diameter d_n, and throat diameter d_t) and the primary and secondary inlet pressures P_1 and P_2 are known. The off-design performance of an existing jet pump is calculated by this program.

A sample design problem was solved for each program. In some cases, it was shown how two programs may be used in series. FORTRAN IV listings of the programs, sample input data cards, and an output data listing sheet are also included.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, May 18, 1971,
128-31.

APPENDIX A

SYMBOLS

FORTRAN variable	Mathematical symbol	Definition
AN	A_n	area of primary nozzle at nozzle exit plane, $in.^2$
AT	A_t	area of throat, $in.^2$
DN	d_n	diameter of primary nozzle exit plane, in.
DT	d_t	diameter of throat, in.
ETA	η	efficiency, 100MN, percent
	g	acceleration due to gravity, 32.163 ft/sec^2
GAMMA	γ	specific weight of fluid, $\rho(g/g_c)$, lbf/ft^3
	g_c	dimensional constant, 32.174 (ft-lbm)/(sec^2)(lbf)
KD	K_d	friction loss coefficient for diffuser
KP	K_p	friction loss coefficient for primary nozzle
KS	K_s	friction loss coefficient for secondary inlet
KT	K_t	friction loss coefficient for throat
M	M	flow ratio, W_2/W_1
N	N	head ratio, $(P_D - P_2)/(P_1 - P_D)$
NOMS		number of values of M to be read as input
NOP2		number of values of P_2 to be read as input
NORS		number of values of R to be read as input
P1	P_1	primary total inlet pressure, psia
P2	P_2	secondary total inlet pressure, psia
P2REQD	P_{2REQD}	secondary inlet pressure required to avoid cavitation, psia
PD	P_D	outlet total pressure, psia
PDREQD	P_{DREQD}	total pressure to which jet pump is required to discharge, psia
PV	p_v	vapor pressure of secondary fluid, psia

FORTRAN variable	Mathematical symbol	Definition
R	R	area ratio, A_n/A_t
	ρ	fluid density, lbm/ft^3
SIGMAL	σ_L	jet pump cavitation prediction parameter at headrise drop-off, $(P_2 - p_v)\Big/\left(\gamma V_s^2/2g\right)$
	V	fluid velocity, ft/sec
W1	W_1	primary fluid weight flow, lbm/sec
W2	W_2	secondary fluid weight flow, lbm/sec
WT	W_t	total weight flow, $W_1 + W_2$, lbm/sec

Subscripts:

D	discharge
d	diffuser
n	primary nozzle exit plane, jet pump
p	primary nozzle
s	secondary fluid inlet
T	total
t	throat
1	primary fluid
2	secondary fluid

APPENDIX B

FORTRAN IV LISTINGS

```
C
C     JET PUMP DESIGN - I -
C
      DIMENSION R(30), M(30), P2(20)
      REAL M,NTH,KP,KS,KT,KD,NN
      NAMELIST/CARD1/KP,KS,KT,KD,GAMMA,SIGMAL ,PV
      NAMELIST/CARD2/P1,W2,NORS,R,NOMS,M,NOP2,P2
      READ (5,CARD1)                                                      1
   10 READ (5,CARD2)                                                      3
      WRITE(6,100) P1,W2,PV,GAMMA ,SIGMAL,KP,KS,KT,KD                     4
      GAO2G = GAMMA/64.326
      DO 1000  L=1,NOP2
      WRITE (6,200) P2(L)                                                 7
      DO 1000  J=1,NOMS
C
C     CALCULATE FLOW RATES
C
      W1 = W2/M(J)
      WT = W1 + W2
      DO 1000 I=1,NORS
C
C     CALCULATE GEOMETRY, AN, DN, AT, DN.
C
      AN2T =  1.+KP - (1.+KS)*((M(J)*R(I)/(1.-R(I)))**2)
      IF (AN2T.LT.0.) GO TO 1000
      AN = (144.*W1/64.348/GAO2G)* SQRT(AN2T/(144.*(P1-P2)/GAO2G))       20
      DN = SQRT(AN/.7854)                                                21
      AT = AN/R(I)
      DT = SQRT(AT/.7854)
C
C     CALCULATE HEAD RATIO, EFFICIENCY, AND OUTLET PRESSURE
C                                                                        23
      NTH = NN(R(I),M(J),KP,KS,KT,KD)                                    25
      IF (NTH.GE.0.) GO TO 999
      WRITE (6,300) M(J),W1,WT,R(I),NTH                                  29
      GO TO 1000
  999 ETA = M(J)* NTH
      PD = (NTH*P1 + P2(L))/(1. +NTH)
C
C     CHECK FOR CAVITATION
C
      P2REQD = (SIGMAL* GAO2G /144.)* (( 144./(2.*GAO2G *32.174))**2)*
     X(((W2 * R(I))/ (AN *(1. - R(I))))**2)  + PV
      IF (P2(L).GT.P2REQD) GO TO 600
      WRITE (6,400)M(J),W1,WT,R(I),DN,DT,NTH,ETA,PD,P2REQD               41
      GO TO 1000
  600 WRITE (6,500)M(J),W1,WT,R(I),DN,DT,NTH,ETA,PD,P2REQD               45
 1000 CONTINUE
      GO TO 10
C
C     FORMAT STATEMENTS
C
  100 FORMAT(1H1,49X,21HJET PUMP DESIGN - I -////10X,2HP1,7X,2HW2,7X,
     A2HPV,5X,7HGAMMA   ,3X,7HSIGMAL  ,5X,2HKP,8X,2HKS,8X,2HKT,8X,2HKD//
     BF13.1,F9.2,F9.1,2F10.1,4F10.3)
  200 FORMAT(///9X,5HP2 = ,F5.2,//10X,1HM,8X,2HW1,8X,2HWT,8X,1HR,8X,
     A2HDN,8X,2HDT,8X,3H N ,5X,3HETA,7X,2HPD,5X,6HP2REQD,4X,7HNC OR C)
  300 FORMAT (F13.1,2F10.2,F9.3,20X,F9.3)
  400 FORMAT (F13.1,2F10.2,F9.3,F10.3,F9.3,F10.3,F9.3,2F9.1,7X,1HC)
  500 FORMAT (F13.1,2F10.2,F9.3,F10.3,F9.3,F10.3,F9.3,2F9.1,7X,2HNC)
      END
```

```
C
C     FUNCTION SUBPROGRAM FOR HEAD RATIO CALCULATION
C
      REAL FUNCTION NN(R,M,KP,KS,KT,KD)
      REAL M, KP, KS, KT, KD
      TERM1 = 2.*R + ((2.*R**2*M**2)/(1.-R))- (1. + KT + KD)*R**2*(1.+M)
     A**2
      TERM2 = ((1. + KS)*R**2*M**2)/(1.-R)**2
      NN = (TERM1 - TERM2 ) /((1. + KP) - TERM1)
      RETURN
      END
```

```
C
C     JET PUMP DESIGN - II -
C
      DIMENSION R(30), P2(20), EM(30)
      REAL M,NTH,KP,KS,KT,KD,NN
      NAMELIST/CARD1/KP,KS,KT,KD,GAMMA ,SIGMAL,PV
      NAMELIST/CARD2/P1,W2,DT,NOP2,P2,NORS,R
      READ (5,CARD1)                                                    1
   10 READ (5,CARD2)                                                    3
      WRITE(6,100) P1,W2,DT,PV,GAMMA ,SIGMAL,KP,KS,KT,KD               4
      GAO2G = GAMMA/64.326
      DO 1000  L=1,NOP2
      WRITE(6,200) P2(L)                                                7
      DO 1000 I=1,NORS
C
C     CALCULATE GEOMETRY, AT, AN, DN.
C
      AT= 0.7854*DT**2
      AN=AT*R(I)
      DN=SQRT(AN/0.7854)
C
C     BEGIN APPROXIMATION PROCEDURE FOR PRIMARY FLOW RATE, W1, AND FLOW RATIO, M
C                                                                       12
      ANUM = SQRT( 144. *(P1-P2(L) )/ GAO2G )                           14
      FAC = (AN*64.348 * GAO2G ) / 144.
      BNUM=ANUM*FAC
      DEN1= SQRT(1.+KP)                                                 15
      FW1 = BNUM/DEN1
      EM(1)= W2/FW1
C
C     ENTER LOOP FOR CALULATION OF FLOW RATIO.
C
      DO 2000  J=1,15
      BDEN=(1.+KP)-(1.+KS)*(EM(J)*R(I)/(1.-R(I)))**2
      IF (BDEN.LT.0.) GO TO 800
      CDEN=SQRT(BDEN)                                                   24
      WW1= BNUM/CDEN
      EM(J+1)=W2/WW1
      DELM= ABS(EM(J+1)-EM(J))
      PERDEV = DELM/EM(J+1)
      IF(PERDEV.LE.0.0005) M=EM(J+1)
      IF(PERDEV.LE.0.0005) GO TO 250
 2000 CONTINUE
  249 GO TO 750
C
C     CALCULATE PRIMARY FLOW RATE, HEAD RATIO, EFFICIENCY, AND OUTLET PRESSURE.
C
  250 EDEN= 1.+KP -(1.+KS)*(M*R(I)/(1.-R(I)))**2
      IF (EDEN.LT.0.) GO TO 850
      FDEN= SQRT (EDEN)                                                 44
      W1= BNUM/FDEN
```

```
      NTH = NN(R(I),M,KP,KS,KT,KD)                                      45
      IF(NTH.GE.0.) GO TO 999
      WRITE (6,300) R(I),DN,W1,NTH                                      49
      GO TO 1000
  999 ETA = M*NTH
      PO=(NTH*P1+P2(L))/(1.+NTH)
C
C     CHECK FOR CAVITATION
C
      P2REQD = (SIGMAL* GAO2G /144.)* (( 144./(2.*GAO2G *32.174))**2)*
     X(((W2 * R(I))/ (AN *(1. - R(I))))**2)  + PV
      IF (P2REQD.LT.P2) GO TO 450
      WRITE (6,410) R(I),DN,W1,NTH,M,ETA,PO,P2REQD                      53
      GO TO 1000
  450 WRITE (6,400) R(I),DN,W1,NTH,M,ETA,PO,P2REQD                      61
      GO TO 1000
  750 WRITE(6,751) R(I)                                                 64
      GO TO 1000
  800 WRITE (6,801) R(I)                                                67
      GO TO 1000
  850 WRITE (6,851) R(I)                                                70
 1000 CONTINUE
      GO TO 10
C
C     FORMAT STATEMENTS
C
  100 FORMAT(1H1,49X,21HJET PUMP DESIGN- II -////10X,2HP1,7X,2HW2,7X,
     A2HDT,7X,2HPV,5X,7HGAMMA  ,3X,7HSIGMAL ,5X,2HKP,8X,2HKS,8X,2HKT,8X,
     B2HKD//F13.1,F9.2,F9.3,F9.1,2F10.1,4F10.3)
  200 FORMAT(///9X,5HP2 = ,F5.2//12X,1HR,6X,2HDN,8X,2HW1,8X,3HN ,6X,
     A1HM,6X,3HETA,6X,2HPO,5X,6HP2REQD,4X,7HNC OR C//)
  300 FORMAT (F15.3,F8.3,F9.2,F11.3)
  400 FORMAT (F15.3,F8.3,F9.2,F11.3,F8.2,F8.3,F7.1,F9.1,9X,2HNC)
  410 FORMAT (F15.3,F8.3,F9.2,F11.3,F8.2,F8.3,F7.1,F9.1,9X,1HC)
  751 FORMAT(F15.3,10X, 30HPROGRAM UNABLE TO CALCULATE W1)
  801 FORMAT(F15.3,10X,15HNEG SQRT IN WW1 )
  851 FORMAT(F15.3,10X,14HNEG SQRT IN W1 )
      END
```

```
C
C     FUNCTION SUBPROGRAM FOR HEAD RATIO CALCULATION
C
      REAL FUNCTION NN(R,M,KP,KS,KT,KD)
      REAL M, KP, KS, KT, KD
      TERM1 = 2.*R + ((2.*R**2*M**2)/(1.-R))-(1.+KT+KD)*R**2*(1.+M)**2
      TERM2 = ((1.+KS)*R**2*M**2)/(1.-R)**2
      NN = (TERM1 - TERM2) /((1. + KP) - TERM1 )
      RETURN
      END
```

```
C
C     JET PUMP DESIGN - III -
C
      DIMENSION M(30), R(30),P2(30)
      REAL M,NTH,KP,KS,KT,KD,NN
      NAMELIST/CARD1/KP,KS,KT,KD,GAMMA ,SIGMAL,PV
      NAMELIST/CARD2/P1,PDREQD,W2,NOMS,M,NORS,R
      READ(5,CARD1)                                                     1
      GAD2G = GAMMA/64.326
```

```
   10 READ(5,CARD2)                                                           3
      WRITE(6,100) P1,PDREQD,W2,KP,KS,KT,KD,GAMMA ,SIGMAL,PV                  4
      DO 1000 I=1,NOMS
      WRITE(6,150) M(I)                                                       7
      W1= W2/ M(I)
      DO 1000  J=1,NORS
      TEM = ((M(I)*R(J)/(1.-R(J)))**2) * (1.+KS)
C
C     CALCULATE HEAD RATIO AND EFFICIENCY
C
      NTH= NN( R(J), M(I), KP,KS,KT,KD)                                      16
      IF(NTH.GE.0.)   GO TO 200
      GO TO 1000
  200 ETA  = NTH * M(I)
C
C     BEGIN ITERATION LOOP ON P2. FIRST ESTIMATE OF P2 CALCULATED FROM
C     DEFINITION OF HEAD RATIO.
C
      P2(1)= PDREQD - NTH * (P1-PDREQD)
      DO 250  L=1,15
      C = (144.*W1) / (32.174*GAO2G * 2.)
      C1 = 1. + KP - TEM
      IF (C1.LE.0.) GO TO 750
      C2= (P1 - P2(L)) * 144./GAO2G
      AN1= C*SQRT(C1/C2)                                                     30
      P2REQD = (SIGMAL* GAO2G /144.)* (( 144./(2.* GAO2G*32.174))**2)*
     X((W2 * R(J))/ (AN1*(1. - R(J))))**2)  + PV
      DELP= P2REQD - P2(L)
      PERDEV = ABS(100.*DELP/P2REQD)
      IF(PERDEV .GT. .05) GO TO 240
C
C     WHEN PERCENT DEVIATION IS LESS THAN OR EQUAL TO .05, END THE LOOP
C
      P2F = P2REQD
      AN = AN1
      GO TO 300
  240 P2(L+1)= P2REQD
  250 CONTINUE
      GO TO 800
C
C     CALCULATE OUTLET PRESSURE AND GEOMETRY, AT, DT, AND DN.
C
  300 PD= (NTH * P1 + P2F)/(1.+NTH)
      AT = AN/R(J)
      DT = SQRT(AT/.7854)                                                    45
      DN= SQRT(AN/.7854)                                                     46
      WRITE (6,110) R(J), NTH, ETA, P2F, PD, DT, DN, W1                      47
      IF(PD.LT.PDREQD)  GO TO 700
      GO TO 1000
  700 WRITE(6,120)                                                           53
      GO TO 1000
  750 WRITE (6,135)                                                          55
      GO TO 1000
  800 WRITE(6,130)  PERDEV                                                   57
 1000 CONTINUE
      GO TO 10
C
C     FORMAT STATEMENTS
C
  100 FORMAT (1H1 47X,22HJET PUMP DESIGN- III -////13X,2HP1,5X,6HPDREQD,
     A5X,2HW2,7X,2HKP,8X,2HKS,8X,2HKT,8X,2HKD,6X,7HGAMMA  ,3X,7HSIGMAL ,
     B5X, 2HPV// F16.1, 2F9.1, 4F10.3,2F10.1, F9.1 )
  110 FORMAT (F17.3,F10.3,F9.3,F10.1,F11.1,2F11.3,F10.2)
  120 FORMAT (1H+ 92X, 22HPD IS LESS THAN PDREQD  )
  130 FORMAT (1H+ 24X, 12HPERDEV(15) =, F10.8,6X,31HCONVERGENCE ON P2 DI
     AD NOT OCCUR    )
  135 FORMAT (1H+ 30X, 31HCONVERGENCE ON P2 DID NOT OCCUR     )
  150 FORMAT (/// 12X,4HM = ,F6.3//14X,1HR,9X, 1HN,7X, 3HETA,5X,7HP2 REQ
     AD,6X, 2HPD, 8X,2HDT,9X, 2HDN, 9X,2HW1 //)
      END
```

```
C
C     FUNCTION SUBPROGRAM FOR HEAD RATIO CALCULATION
C
      REAL FUNCTION NN(R,M,KP,KS,KT,KD)
      REAL M, KP, KS, KT, KD
      TERM1 = 2.*R + ((2.*R**2*M**2)/(1.-R))-(1.+KT+KD)*R**2*(1.+M)**2
      TERM2 = ((1.+KS)*R**2*M**2)/(1.-R)**2
      NN = (TERM1 - TERM2) /((1. + KP) - TERM1 )
      RETURN
      END
```

```
C
C     JET PUMP DESIGN - IV -
C
      DIMENSION R(30), M(30)
      REAL M,NTH,KP,KS,KT,KD,NN
      NAMELIST/CARD1/KP,KS,KT,KD,GAMMA ,SIGMAL,PV
      NAMELIST/CARD2/NORS,R,NOMS,M,P2,PD,W2
      READ (5,CARD1)                                                      1
   10 READ (5,CARD2)                                                      3
      WRITE (6,100) P2,PD,W2,PV,GAMMA ,SIGMAL,KP,KS,KT,KD                 4
      GAO2G = GAMMA/64.326
      DO 1000 J=1,NORS
      WRITE (6,200) R(J)                                                  7
      DO 1000 I=1,NOMS
      W1= W2/M(I)
      NTH= NN(R(J),M(I),KP,KS,KT,KD)                                      13
      IF (NTH.GE.0.) GO TO 999
      WRITE (6,300) M(I),W1,NTH                                           17
      GO TO 1000
  999 ETA= M(I)*NTH
      P1= (PD-P2) / NTH + PD
C
C     CALCULATE GEOMETRY, AN, AT, DN, DT.
C
      AN2T = 1. + KP - (1.+KS)*((M(I)*R(J) / (1.-R(J)))**2)
      IF  (AN2T.LT.0.)  GO TO 1000
      AN=(144.*W1/64.348/GAO2G)*SQRT(AN2T/(144.*(P1-P2)/GAO2G))           28
      AT= AN / R(J)
      DT= SQRT( AT/.7854)                                                 30
      DN= SQRT(AN/.7854)
C
C     CHECK FOR CAVITATION.
C                                                                         31
      P2REQD = (SIGMAL* GA2O2G/144.)* (( 144./(2.* GAO2G*32.174))**2)*
     X(((W2 * R(J))/ (AN *(1. - R(J))))**2)  + PV
      IF(P2 .GT. P2REQD) GO TO 550
      WRITE (6,399) M(I), W1, NTH, ETA, P1, AN, AT, DT, DN                35
      GO TO 1000
  550 WRITE (6,400) M(I), W1, NTH, ETA, P1, AN, AT, DT, DN                39
 1000 CONTINUE
      GO TO 10
C
C     FORMAT STATEMENTS
C
  100 FORMAT  (1H1 49X,21HJET PUMP DESIGN- IV -////10X,2HP2,7X,2HPD,
     A7X,2HW2,7X,2HPV,5X,7HGAMMA   ,3X,7HSIGMAL  ,5X,2HKP,8X,2HKS,8X,
     B2HKT,8X,2HKD//F13.2,3F9.2,2F10.2,4F10.3)
  200 FORMAT (///9X,4HR = ,F5.3,//10X,1HM,8X,2HW1,7X,3H N ,7X,3HETA,7X,
     A2HP1,8X,2HAN,10X,7HNC OR C,5X,2HAT,9X,2HDT,9X,2HDN//)
  300 FORMAT (F13.2,F9.2,F10.3)
  399 FORMAT (F13.2,F9.2,2F10.3,F10.1,F10.3,10X,1HC,7X,F5.3,2F11.3 )
  400 FORMAT (F13.2,F9.2,2F10.3,F10.1,F10.3,10X,2HNC,6X,F6.3,2F11.3   )
      END
```

```
C
C     FUNCTION SUBPROGRAM FOR HEAD RATIO CALCULATION
C
      REAL FUNCTION NN(R,M,KP,KS,KT,KD)
      REAL M, KP, KS, KT, KD
      TERM1 = 2.*R + ((2.*R**2*M**2)/(1.-R))-(1.+KT+KD)*R**2*(1.+M)**2
      TERM2 = ((1.+KS)*R**2*M**2)/(1.-R)**2
      NN = (TERM1 - TERM2) /((1. + KP) - TERM1 )
      RETURN
      END
```

```
C
C     JET PUMP DESIGN - V -
C
      DIMENSION   M(30)
      REAL   M,N,KP,KS,KT,KD,NN
      NAMELIST/CARD1/ KP,KS,KT,KD,GAMMA ,SIGMAL,PV
      NAMELIST/CARD2/ P1,P2,DN,DT,R,NOMS,M
      READ (5,CARD1)                                                        1
   10 READ (5,CARD2)                                                        3
      WRITE (6,500) P1,P2,R,DN,DT,KP,KS,KT,KD,GAMMA ,SIGMAL, PV             4
      GA02G = GAMMA/64.326
      AN = .7854 * DN **2
      DO 1000  I=1,NOMS
      N = NN (R,M(I), KP,KS,KT,KD)                                          9
      ETA = N * M(I)
      PD = (N*P1 + P2) / (1. + N)
C
C     CALCULATE PRIMARY FLOW RATE, W1
C
      TEM = 1. + KP - (1. + KS) * (R*M(I)/(1. - R))**2
      IF(TEM .LE. 0.) GO TO 600
      W1 = (GA02G*2.*32.174*AN/144.) * SQRT(((P1-P2)*144./GA02G)/TEM)      15
      W2 = W1 * M(I)
C
C     CHECK FOR CAVITATION
C
      P2REQD = (SIGMAL* GA02G /144.)* (( 144./(2.*GA02G *32.174))**2)*
     X(((W2 * R    )/ (AN *(1. - R    )))**2)   + PV
      IF (P2REQD.LT.P2) GO TO 700
      WRITE (6,520) M(I),N,ETA,PD,W1,W2,P2REQD                             19
      GO TO 1000
  600 WRITE (6,530)                                                        22
      GO TO 1000
  700 WRITE (6,510) M(I),N,ETA,PD,W1,W2,P2REQD                             24
 1000 CONTINUE
      GO TO 10
C
C     FORMAT STATEMENTS
C
  500 FORMAT (1H1 47X, 21HJET PUMP DESIGN - V - ////4X,2HP1,5X,2HP2,6X,
     A1HR, 6X,2HDN,5X, 2HDT, 6X,2HKP,6X,2HKS,6X,2HKT,6X,2HKD,4X,7HGAMMA
     B ,3X, 7HSIGMAL ,5X, 2HPV// F8.1,F6.1,F7.3,F8.3,F7.3,4F8.3,F8.1,
     C2F10.1 ///13X,1HM,9X, 1HN,8X,3HETA,8X,2HPD,9X,2HW1,9X,2HW2,9X,5HP2
     DREQD    //)
  510 FORMAT (   10X,F6.2,2F10.3, F10.2, 2F11.2 ,F12.1)
  520 FORMAT (   10X,F6.2,2F10.3, F10.2, 2F11.2 ,F12.1,2H C)
  530 FORMAT (10X,20HNEGATIVE SQUARE ROOT    )
      END
```

FUNCTION SUBPROGRAM FOR HEAD RATIO CALCULATION

```
REAL FUNCTION NN(R,M,KP,KS,KT,KD)
REAL M, KP, KS, KT, KD
TERM1 = 2.*R + ((2.*R**2*M**2)/(1.-R))-(1.+KT+KD)*R**2*(1.+M)**2
TERM2 = ((1.+KS)*R**2*M**2)/(1.-R)**2
NN = (TERM1 - TERM2) /((1. + KP) - TERM1 )
RETURN
END
```

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