MODELING PHILOSOPHY AND SELECTION OF CONF-730304--12

PUMPS FOR USE IN SMALL BLOWDOWN EXPERIMENTS

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ABSTRACT

In order to conduct small-scale experiments which attempt to duplicate the hydraulic phenomena occurring during a loss-of-coolant accident in a pressurized water reactor (PWR) plant, certain scaling philosophies must be employed to design the small system appropriately. Scaling considerations must be applied to all components of the small system and specifically to the primary circulation pump. Operating characteristics of small centrifugal pumps are generally quite different from those of PWR type pumps and the scaling of the small pump may involve various compromises. This paper describes a method by which the design of a small pump is specified such that the operating characteristics of the pump are expected to approach those of a large pump within the operating zones of primary interest.

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The operating characteristics of the primary loop circulation pumps of a pressurized water reactor (PWR) system are believed to play a significant role in determining the hydraulic behavior of the system following a loss-of-coolant accident (LOCA), particularly one due to an inlet pipe rupture.

The acquisition of information leading to the understanding of the hydraulic behavior of a PWR system during the course of an LOCA is the primary intent of the 1-1/2-loop Mod-1 semiscale project[1]. This project is being conducted to aid in developing an understanding of the phenomena involved in an LOCA, to aid in exploring the effects of component simulation as they relate to these phenomena, and to aid in the development of a suitable data base for assessment of system response analyses. The Mod-1 system is designed to represent, within known scaling limitations, a PWR system in terms of hydraulic resistance and system time response during an LOCA. Since the circulation pump is an important part of the small scale system, as it also is in the full size system, the scaling or sizing of the small pump, with respect to its large counterpart, is likewise important.

Two considerations must be included in scaling a small pump: (1) the pump must be capable of operating at steady state, single-phase (water) fluid flow conditions compatible with the requirements of the small scale system, and (2) because of the lack of two-phase fluid flow data, single-phase flow performance characteristics and single-phase flow theory must be used as an index for relating the large and small pumps. Since similar operation during the two-phase fluid conditions of an LOCA cannot be assured, the assumption is made that where the homologous curves are not applicable to the two-phase conditions appropriate correlations can be obtained between two-phase fluid conditions and pump performance.

This paper discusses two methods of modeling the characteristics of a PWR pump, with emphasis on the method chosen for the pump to be used in the 1-1/2 loop Mod-1 semiscale system.

SCALING CONSIDERATION AND METHODS

The scaling of a small experimental system to be used to investigate the hydraulic response of a large system involves several compromises because of practical or geometrical limitations. Requirements imposed on scaling the small system include the following: (1) the core fluid velocity for the small system must be consistent with the desired enthalpy rise for a given core power and core geometry, and (2) the hydraulic resistances must be specified such that the desired magnitude and distribution of pressure drops may be obtained for the given core fluid velocity. The design of the semiscale system is based on both of these requirements with the result that a small pump is required that satisfies a head requirement similar in order of magnitude to that of the large pump and at the same time satisfies a capacity requirement orders of magnitude less than that of the large pump.

Two procedures, both involving an index of performance and specific speed of the pump, may be considered for modeling a small pump within these requirements: (1) the specific speed of the small pump may be maintained similar to the specific speed of the large pump by linear scaling of all important pump dimensions; and (2) the important specific-speed-dependent flow characteristics of a large mixed-flow pump may be modeled, as nearly as possible, by implementing the proper constraints on the flow characteristics of the small centrifugal pump. In its basic form, the specific speed of a pump is a nondimensional index which is numerically equal to the rotative speed at which a geometrically similar model of that pump would operate in order to deliver one unit of capacity against one unit of head. Since pump rotative speed, capacity, and head all enter into the basic definition of specific speed, a specific speed can be calculated for any given operating condition of a centrifugal pump. However, the operating specific speed that gives maximum efficiency for a particular pump identifies the pump type and intimately relates the physical characteristics to the general impeller design. This specific speed, sometimes referred to as "type specific speed", is that specific speed which is used in basic pump design. Relationships between type specific speed and impeller design are shown in Figure 1. The method of scaling the specific speed of the

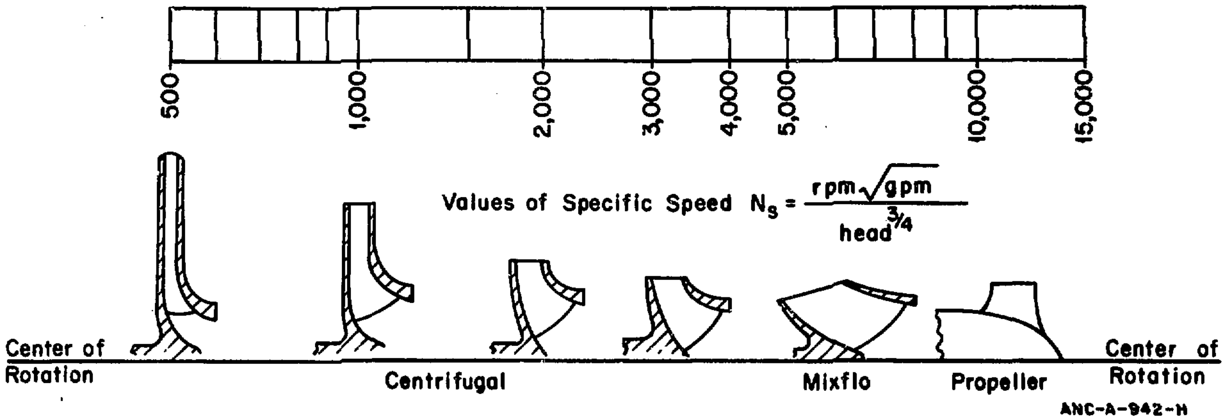

FIG. 1 VARIATIONS IN THE APPROXIMATE RELATIVE IMPELLER SHAPES WITH SPECIFIC SPEED.

small pump to that of the large pump (linear scaling) was considered unsatisfactory for use in sizing the semiscale pump because it results in extremely high rotative speeds; thus, this method is described only briefly in this paper. The method of modeling flow characteristics, which was used for the semiscale pump, is described in greater detail.

METHOD OF LINEAR SCALING

The method of scaling specific speeds (linear scaling), if strictly implemented, results in a pump dynamically similar to the large pump with similar performance characteristics. This similarity in characteristics between a small pump and a large pump is termed "homologous" and results from the two pumps having similar specific speeds.

Based on the homologous theory, a linearly scaled small pump having a head rating, which remains essentially the same as that of a large pump, but a flow rating several orders of magnitude less than that of the large pump, requires an impractical high rotative speed to achieve the necessary specific speed. For a small experimental system such as the 1-1/2-loop Mod-1 semiscale system, this method of scaling results in the specification of a model pump with extremely high rotative speeds (15,000 to 20,000 rpm). Primarily for this reason, this method was not chosen for modeling the pump to be used in the 1-1/2-loop Mod-1 semiscale system.

METHOD OF FLOW CHARACTERISTICS MODELING

The method of flow characteristics modeling used for specification of the semiscale pump is based on the premise that the homologous head-flow curves, which are generated from single-phase flow tests and theory, are applicable not only to the single-phase region of the model pump performance, but also to that portion of the two-phase region where the pump affinity laws are applicable. An example of the homologous head

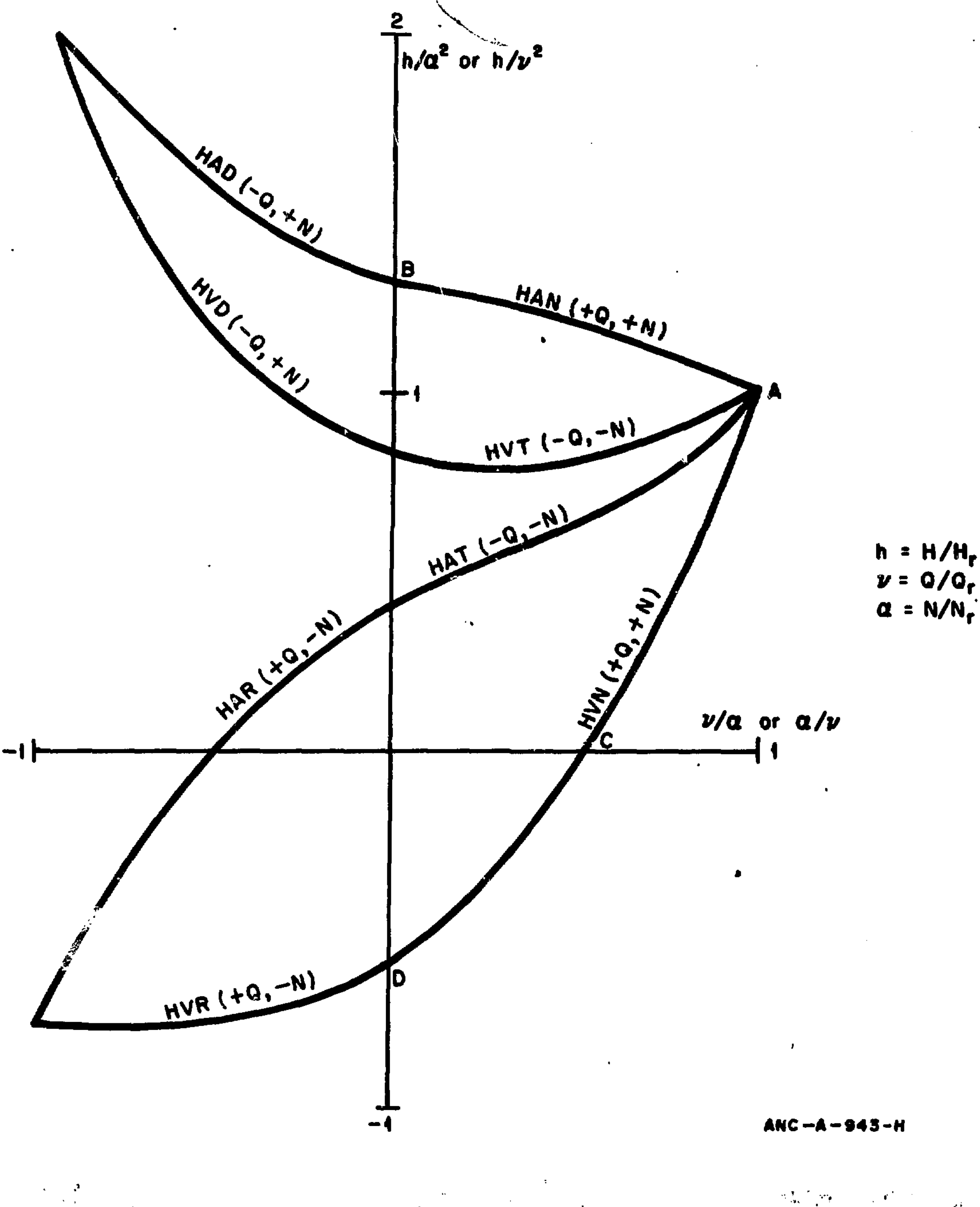

FIG. 2 TYPICAL HOMOLOGOUS HEAD CURVES.

curves is shown in Figure 2. The homologous head curves are dimensionless extensions of the more common four-quadrant pump characteristics curves in which the parameters H (head), Q (capacity), and N (impeller speed) are made dimensionless through division by the appropriate rated (point of maximum efficiency) parameter. The homologous curves are actually two sets of four dimensionless characteristic curves which are all plotted on the same set of coordinates. In one case the dimensionless head ratio ($h = H/H_r$) as a function of the dimensionless flow ($\nu = Q/Q_r$) is plotted versus the dimensionless speed ($\alpha = N/N_r$) which also is a function of dimensionless flow; that is, h/ν^2 is a function of α/ν. In the second case, the dimensionless head ratio as a function of dimensionless speed is plotted versus the dimensionless flow as a function of dimensionless speed; that is, h/α^2 is a function of ν/α. In this manner, the complete pump characteristics through all zones of operation can be represented by an intersecting set of eight curves. These eight curves are indicated in the example of Figure 2 in which a three letter acronym is used to designate the curve type. H refers to head ratio, A indicates division by α^2, N indicates the normal pump zone, V indicates division by ν^2, D is the zone of energy dissipation, R is the zone of reverse flow pump operation, and T is the zone of turbine operation.

In order to design and specify a pump by modeling flow characteristics, three major design requirements must be considered to ensure, as nearly as possible, that the performance of the small-scale pump will be representative of that of the PWR pump during an LOCA initiated by an inlet pipe break. These requirements are related to the general shape of the homologous head flow curves and are as follows:

(1) The nondimensional flow characteristics of the small pump during steady state design operation as well as during blowdown and reflood should be similar to that of the large pump.

(2) The ratio of rated head to shutoff head and the ratio of rated flow to flow at zero head for the small pump should be similar to those of the large pump.

(3) The maximum value of stopped rotor forward flow resistance relative to the small system should be the same as that relative to the large system.

The following paragraphs explain in more detail the significance of these requirements.

Nondimensional Flow Characteristics

During the course of an LOCA, the capability of a pump to remain functioning as a pump is a complex function of the speed and flow ratios (N/N_r and Q/Q_r) of the pump. Flow ratios for a small pump, such as that employed in the semiscale system, representative of those in a PWR, are considered to result from the design criteria of the experimental system. Since PWR pumps are designed and rated, not for blowdown or abnormal conditions, but for normal operating conditions, the ratio of operating to rated conditions is approximately equal to one. Likewise, for a small model pump the requirement is, therefore, that the steady state operating flow and the rated flow relationships be equal to one. This requirement is represented by Point A in Figure 2.

Ratio of Rated to Maximum Conditions

The ratio of rated head to shutoff head (H_r/H_{max}) has been determined to be approximately equal to 0.6 for a reference PWR. Similarly, the ratio of rated flow to flow at zero head (Q_r/Q_{max}) has been determined to be approximately equal to 0.67 for the reference PWR. In Figure 2, the curves designated HAN and HVN represent the normal forward flow characteristics of a pump, and Point B represents the point of maximum head for zero flow (shutoff head). Point C represents the point of maximum forward flow for zero head.

As previously implied, pumps of different specific speeds have differently shaped homologous curves; however, specification of the same rated to maximum characteristics ratios in the normal operating quadrant (represented for example, by Points B and C in Figure 2) will ensure that those operating limits will, at least, be approached in the model pump in a manner representative of the way in which they are approached in a PWR.

Maximum Forward Flow Resistance

The point during a pump transient at which the volumetric flow through a pump becomes sufficiently great, because of external pressure gradients, such that the pump loses the capability of generating head and becomes a hydraulic resistance is represented by Point C in Figure 2. The maximum value of stopped rotor forward flow resistance is represented by Point D in Figure 2 where pump rotation changes from positive to negative. The representation of this value is indirect and results from the following derivation:

Darcy's equation for head loss is

$$H = f \frac{\ell}{D} \frac{V^2}{2g} \tag{1}$$

where

H = static head, ft

f = Darcy friction factor, dimensionless

$\frac{\ell}{D}$ = length-to-diameter ratio, dimensionless

V = fluid velocity, ft/sec

g = gravitational constant.

By substituting an assumed overall dimensionless resistance coefficient,

$$K^* = f \frac{\ell}{D}, \tag{2}$$

which incorporates all of the complex hydraulic losses within the pump volute together with entrance and exit losses, into Equation (1) the following expression is obtained relating head loss to resistance coefficient:

$$H = K^* \frac{V^2}{2g}. \tag{3}$$

Since the volumetric flow, Q (ft^3/sec), is the product of the fluid velocity, V (ft/sec), and the flow area, A (ft^2), substitution Q^2/A^2 into Equation (3) for V^2 results in

$$H = K^* \frac{Q^2}{2gA^2} \tag{4}$$

or

$$K^* = \frac{2gA^2H}{Q^2}. \tag{5}$$

Substitution of the homologous definitions, $h = H/H_r$ and $\upsilon = Q/Q_r$, into Equation (5) produces

$$K^* = \frac{h}{\nu^2} \left[\frac{2gA^2 H_r}{Q_r^2}\right]. \tag{6}$$

A resistance coefficient, R', in common usage by experimentalists, which relates measurable variables is defined as

$$R' = \frac{\Delta P \rho}{w^2} \tag{7}$$

where

R' = resistance coefficient, $lb_f.sec^2/lb_m$-in.^{2}-ft^3

ΔP = pressure drop, $lb_f/in.^2$

ρ = fluid fluid density, lb_m/ft^3

w = flow rate, lb_m/sec.

Since $w = \rho Q$ and $H = (144) \Delta P/\rho$, Equation (7) can be rewritten as

$$H = 144Q^2R'. \tag{8}$$

Equating Equations (4) and (6) results in

$$R' = \frac{K^*}{2(144)g\ A^2} \ . \tag{9}$$

Substitution of Equation (6) into Equation (9) gives

$$R' = \frac{h}{\nu^2} \left(\frac{H_r}{144\ Q_r^2}\right) \ . \tag{10}$$

The quantity in parentheses is constant for a given pump. The maximum value of R', therefore, depends on the maximum absolute value of h/ν^2 (the intersection Point D in the example of Figure 2). The value of h/ν^2 has been determined to be a function of specific speed, with the maximum absolute value decreasing with decreasing specific speed. Thus, a mutually dependent relationship exists between the maximum possible stopped rotor forward flow resistance and the rated head-flow characteristics of a given pump. Figure 3 depicts the relationship for several values of specific speed within the range of consideration. This relationship must be considered when a pump is specified and may result in a compromise between the desired rated conditions and the desired pump resistance.

APPLICATION OF FLOW CHARACTERISTICS SCALING TO SEMISCALE PUMP

Within the requirements of the semiscale system design, attempts to simultaneously satisfy the three requirements listed by an appropriate modification of an existing semiscale pump resulted in these requirements being ranked in relative importance. Because the main emphasis of the semiscale program is on the inlet break situation, the majority of the tests will result in forward flow through the pump. The pump transient path for forward flow will, therefore, be from Point A to Point C to Point D along the HVN curve as shown in Figure 2. Since the magnitude and distribution of system resistances influences the flow split in the operating loop and ultimately the core flow during an LOCA, the point at which the pump becomes a resistance (Point C) and the maximum value of that resistance (Point D) were considered most important in specifying the characteristics of the small pump. The initial operating point (Point A) of the small pump was considered next in importance because of the requirement on the small pump during the transient to traverse the path from the operating point to the point of maximum flow for positive head (Point C) in relatively the same time as for the large pump. The point of rated to shutoff head (Point B) is of least importance to current semiscale requirements, because operation on the HAN curve is not anticipated. Table I gives the ex-

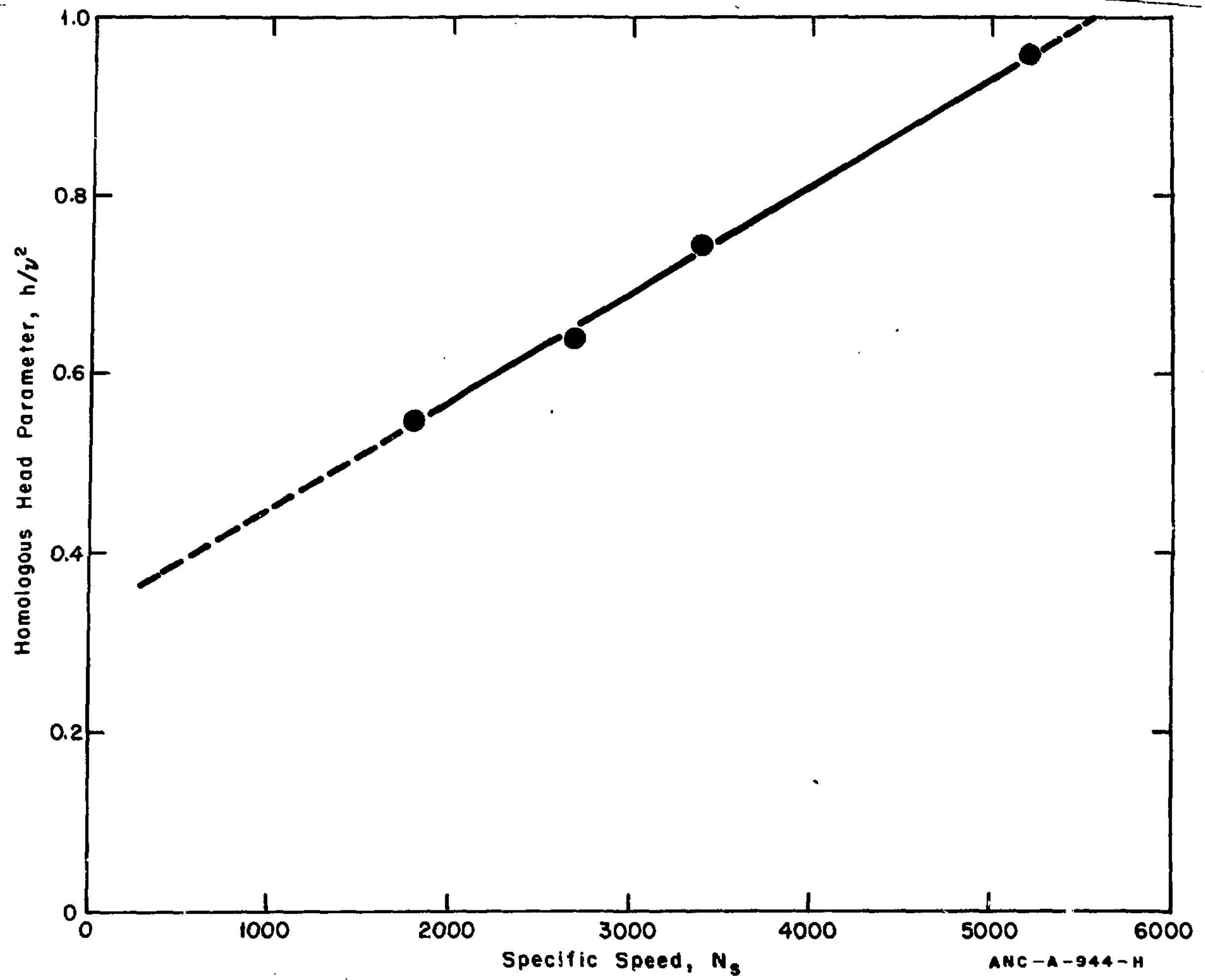

FIG. 3 RELATIONSHIP BETWEEN HOMOLOGOUS HEAD PARAMETER AND SPECIFIC SPEED.

TABLE I

COMPARISON OF SIGNIFICANT PUMP PARAMETERS

	Semiscale	Typical PWR
Ratio of rated to maximum conditions		
H_r/H_{max}	0.78	0.60
Q_r/Q_{max}	0.60	0.67
Ratio of operating to rated flow	1.1	1.0
Maximum forward flow resistance (R')[a] $(lb_f\text{-}sec^2/lb_m\text{-}in.^2\text{-}ft^3)$	3.3	4.6
Specific speed	1000	5200
Rotative speed (rpm)	2600	1200

[a] R'_{PWR} = (scaling factor relating semiscale to PWR) $R'_{semiscale}$.

pected values of the parameters for the semiscale pump and, for comparison, those of a reference PWR. Figure 4 presents the estimated homologous head curves for the semiscale pump based on the modeling philosophies outlined in this paper.

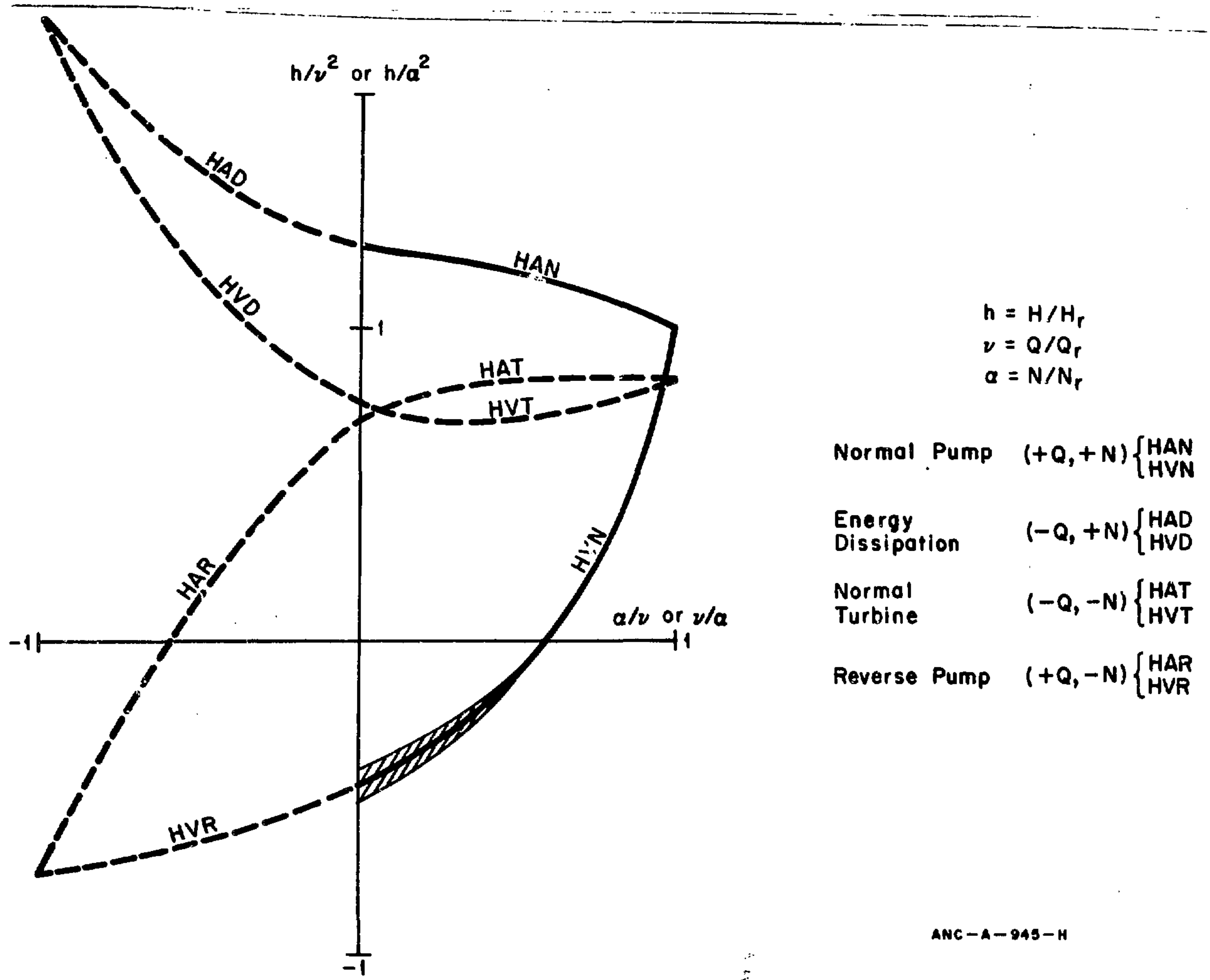

FIG. 4 ESTIMATED HOMOLOGOUS HEAD CURVES FOR THE 1−1/2−LOOP MOD−1 SEMISCALE SYSTEM.

SUMMARY

A method for modeling small pumps based on the single-phase homologous characteristics of large pumps has been chosen for use in specifying the design of the 1-1/2-loop Mod-1 semiscale pump. The success of this method of specifying a small pump depends on several factors, the most important being the applicability of the single-phase homologous theory to a pump within a system undergoing a rapid two-phase fluid transient. Currently many two-phase pump test programs are underway or being planned in which pumps of various specific speeds are to be tested through all zones of pump operation. Results of these test programs are expected to provide, if not a direct indication of the applicability of the single-phase homologous theory, at least a data base on which to develop an empirical or analytical correlation between the two-phase fluid conditions and pump performance.

REFERENCE

1. J. O. Zane, "Separate Effects Testing," Annual Report of the Nuclear Safety Development Branch, January 1 - December 31, 1970, K. A. Dietz (ed.), ANCR-1089 (November 1972) p 155.