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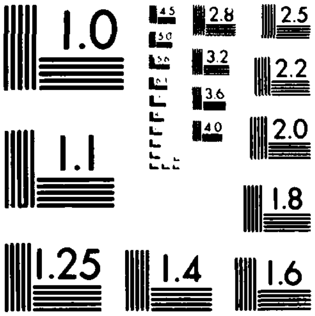
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CAVITATION DAMAGE MECHANISMS: REVIEW OF LITERATURE

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SECTION I

INTRODUCTION

This report is a companion volume to "Cavitation Damage Mechanisms: Experimental Study of Cavitation in a Spool Valve." The state-of-the-art available in the literature is reviewed relative to occurrence of cavitation, the effects of dissolved and free gas, and so-called secondary aspects of combustion/sono-luminescence and electrical/chemical effects. It should be noted that a paucity of literature exists with regard to cavitation in oil hydraulic systems; consequently much of the material discussed deals with water as the working fluid. Throughout the text clear distinctions are made as to the fluid under discussion. The small number of references which do relate to oils are covered as thoroughly as deemed necessary.

The last topic to be presented concerns cavitation in hydraulic actuators. This is a markedly different type of cavitation than is dealt with in the present experimental study; it is included for completeness and due to the fact that it can be a potential problem in control system performance, although most often it creates no permanent mechanical damage to actuator components.

Much of the subject matter can be attributed to three sources: the book Cavitation by Knapp, Daily and Hammitt(McGraw-Hill, 1970), the symposium proceedings Cavitation State of Knowledge, edited by Robertson and Wislicenus (ASME, 1969), and the book The Control of Fluid Power by McCloy and Martin (Longman, 1973).

SECTION II

OCCURRENCE OF CAVITATION

A. Initiating Mechanisms

Cavitation can be defined as the occurrence or formation of gas or vapor-filled pockets in flowing liquids by means of hydrodynamic generation of low pressure, on the order of vapor pressure (Robertson, 1969); the process takes place at essentially constant temperature conditions. The cavitation number, σ, is the parameter most commonly used to categorize cavitating flows; it is given by

$$\sigma = \frac{p_\infty - p_v}{\rho V_\infty^2/2} \qquad (1)$$

in which p_∞ and V_∞ are reference values of pressure and velocity, respectively, p_v = vapor pressure, and ρ = the liquid density. Cavitation appears when σ becomes sufficiently small; in a given flow system, this limited cavitation condition is of engineering significance, albeit difficult to obtain under experimental conditions.

According to Holl (1969) one can distinguish between three types of bubble growth as follows: consider a buble initially in equilibrium at a pressure p_1 followed by sudden reduction to pressure p_2. Vaporous cavitation takes place if the bubble grows explosively in an unbounded manner with rapid phase change of liquid into vapor; it is necessary for $p_2 < p_v$. Pseudo cavitation is when the initial bubble mass remains nearly constant and its volume grows to a larger equilibrium size at pressure p_2. Gaseous cavitation occurs if the pressure p_2 falls below the saturation pressure of a noncondensible gas in solution in the liquid which subsequently is transported across the bubble interface. Whereas vaporous cavitation is an extremely rapid process, and takes place in microseconds, gaseous cavitation is much slower, the time scale depending upon the degree of convection present.

In oil hydraulic control systems small scale vaporous cavitation may occur in spool valves because of significant pressure differences, and in rapid-moving actuators, large scale vaporous cavitation combined with gaseous cavitation can appear. Additional sources of vaporous cavitation in an aircraft control system are the improper filling of the pistons in an axial-flow pump and the large pressure drop across the orifice of a directional control valve, either in steady-state or transient operation.

It is well-accepted that the presence of submicroscopic nuclei is required to initiate cavitation (Knapp et al., 1970). These nuclei can be small gas-filled pockets in the crevices of the containment, or gas pockets either on contaminant particles or freely moving in the flow stream. All commercial liquids are considered to contain sufficient impurities to potentially produce cavitation, even though these may be quite small because of filtering of the working fluid. Holl (1969) elaborates more extensively on the form of cavitation nuclei.

The various factors which influence the initiation of cavitation can be qualitatively discussed by considering a simplified cavitation model (Holl, 1969). Assume a single cavitation bubble which is in a state of equilibrium, ignoring any dynamic effects. The equation of motion is

$$p_v - \Delta p_v + p_g = p_\ell + 2\sigma/R \qquad (2)$$

in which p_g = partial pressure due to non-condensible gases, Δp_v =

reduction in vapor pressure due to local cooling, p_ℓ = surrounding liquid pressure, s = surface tension, and R = bubble radius. The liquid pressure can be written in the form

$$p_\ell = \bar{p} - p_t - \Delta p_r \qquad (3)$$

in which $\bar{p}$ = mean value of liquid pressure, and Δp_t and Δp_r are reductions in liquid pressure due to turbulence and the presence of an isolated surface, respectively. Upon combination of the two equations to eliminate p_ℓ, and introducing p_∞ and $\rho V_\infty^2/2$, one obtains the relation

$$\sigma = -C_p + \frac{p_g}{\rho V_\infty^2/2} + \frac{\Delta p_t}{\rho V_\infty^2/2} + \frac{\Delta p_r}{\rho V_\infty^2/2} - \frac{2s/R}{\rho V_\infty^2/2} - \frac{\Delta p_v}{\rho V_\infty^2/2} \qquad (4)$$

in which the pressure coefficient C_p is given by

$$C_p = \frac{\bar{p} - p_\infty}{\rho V_\infty^2/2} \qquad (5)$$

One can observe from equation (4) that noncondensible gas, turbulence and surface roughness will increase σ while heat transfer and surface tension tend to decrease the parameter. These are all complex factors which are difficult to quantitatively isolate.

If cavitation occurs in the region of minimum pressure, $\bar{p} = \bar{p}_{min}$, and if one neglects the additional effects shown in equation (4) then

$$\sigma = -C_{p_{min}} = \frac{p_\infty - \bar{p}_{min}}{\rho V_\infty^2/2} \qquad (6)$$

Assuming further that cavitation occurs when normal stresses at a point in the liquid are zero, $\bar{p}_{min}$ becomes the vapor pressure p_v and equation (6) is equivalent to equation (1), the classical definition of the cavitation number. <u>Cavitation inception</u> can be qualitatively described as the appearance of small voids in the vicinity of the object or flow field where the minimum pressure is located. The value of σ at which incipient cavitation occurs is then designated as σ_i, and developed cavitation will take place when $\sigma<\sigma_i$.

B. Potential Damage as a Consequence of Cavitation

Hammitt(1969) has outlined the primary experimental observations which form the basis to consider the mechanisms of cavitation damage:

a) Rapid pitting and erosion often occurs in flows where cavitation is observed to exist. Its existence can be determined audibly, by acoustic instrumentation, visually if the containment system is transparent, by means of machine vibrations, or through decrease or other change in performance from the single-phase flow condition, as for example, a measurable decrease in head produced from a centrifugal pump for a given flow and rotating speed. If the cavitation region in a fluid machine is observed visually, it appears as a "frothy" region. If optical instrumentation of suitable time and space resolution is used, it is found that the "frothy" region is actually composed of a heterogeneous mixture of odd-shaped "voids", many of which are roughly spherical bubbles. In some cases a relatively clear cavity attached to the structure is found, but this is then often surrounded and followed by a "frothy" region of traveling "voids". In a cavitating flow the rate of attack can be many times that due to erosion and corrosion alone in the absence of cavitation.

b) Cavitation can damage, under certain conditions, even the strongest of materials such as stellites, tool steels, and any other known structural materials. This damage can occur rapidly even in cases where chemical corrosion in single-phase flow with the same liquid-material combination would not be significant, e.g. cavitation in petroleum products on metals or glass.

c) Cavitation pitting shows the characteristics of mechanical attack. Such well-known mechanical manifestations as e.g, slip lines in metals, have frequently been observed. The single craters which are formed in the early portion of the attack appear under a low-power microscope as "moon craters", i.e., more or less symmetrical craters often with a raised rim, as if formed by single impact rather than corrosion. In fact, damage to materials from liquid impact tests closely resembles cavitation damage both qualitatively and quantitatively.

d) Mechanical cavitation attack and corrosion can supplement each other through obvious mechanisms resulting in a damage rate increase, in cases where both are important, to many times the sum of damage rates from corrosion and cavitation acting separately and independently.

> e) An important theoretical contribution to the development of the concept of the mechanical cavitation damage mechanism was given by Rayleigh. He showed that a collapsing spherical vapor bubble has the potential for generating extremely high pressures and velocities in the fluid near the point of collapse. The original analysis, based entirely on ideal fluid concepts including that of spherical symmetry, shows that these quantities, i.e. pressure and velocity, become infinite. Thus, while more realistic assumptions are required to evaluate pressures and velocities quantitatively, it is apparent that the possibility exists for values large enough to be damaging even to very strong materials.

It is to be noted that a distinction is made between mechanical effects and corrosion effects; they are not mutually exclusive inasmuch as mechnical cavitation damage accelerates corrosion and vice versa (Knapp et al., 1970). Discussion herein is directed toward the hydrodynamic attack of cavitation rather than the chemical. The one common characteristic of cavitation that produces damage to a variety of materials is a mechanical one of high-intensity pressure or "blows." Hammitt(1969) draws two general conclusions from the observations noted above:

> 1) Since observed cavitation fields usually contain large numbers of essentially spherical bubbles of various diameters, and since as Rayleigh showed the collapse of such bubbles could create pressures and velocities large enough to be damaging, it is likely that the surface of a material exposed to cavitation will experience a multiplicity of impulse impositions of widely varying intensities and with locally random spatial distribution. The Rayleigh theory shows that the time of imposition of such impulses magnitudes and collapse times are greater for larger bubbles for a given collapsing pressure differential. Since individual symmetrical craters are observed, it is apparent that some of these impulses are sufficient to cause permanent material deformations. Since the spectrum of impulses varies widely, it is to be expected that individual craters with diameters covering a given range will be formed, . . . and that in fact many "blows" (i.e. impulses) may be of insufficient strength to cause permanent material deformation. A large number of these weaker blows, however, may be sufficient to also contribute to eventual fatigue failure. Thus it is to be expected that cavitation damage will often eventually take the form of fatigue failures, and this is in fact observed . . .

2) As the surface roughness increases due to accumulated cavitation (or corrosion) damage, the flow pattern near the surface will frequently be importantly altered. In addition the substantial cold-working of the material surface may affect its ability to resist further damage (increased strength and hardness will tend to increase its damage resistance while increased brittleness will have the opposite effect). Thus it is to be expected that the rate of cavitation damage in a given situation will not be constant with time. Often an "incubation period" is observed before substantial material loss occurs, presumably while fatiguing processes proceed to a point necessary to cause failure. The damage rate then often increases to a maximum after which it decreases. Later secondary and tertiary, etc. maxima may occur. This behavior probably depends primarily upon the interplay of flow pattern alteration by virtue of accumulated roughness and material surface property changes which are themselves due to the accumulated permanent deformations and stressings.

Further observations and conclusions of a more speculative nature are discussed by Hammitt(1969). Of significance is the concept of asymmetrical bubble collapse where a high velocity microjet is formed and impacts upon a surface; this may be an important damaging mechanism in addition to the pressure rise in the region of the collapsing bubble due to reduction of the bubble volume as proposed by the Rayleigh mechanism. Additional factors contributing to cavitation damage are electrochemical effects, thermal effects, and gas content in the cavitation bubbles (Knapp et al., 1970).

C. Mechanics of Collapsing Bubbles

Once initiated, bubble growth will continue and may stabilize in flow regions where low pressures exist. As the bubbles travel into high-pressure regions their collapse is imminent, and will result in the high intensity pressures mentioned in the previous section. Of particular concern is bubble growth and collapse taking place at high rates; here the motion is dominated by inertial forces, with effects of viscous, surface tension, and compressibility forces being of secondary importance. Modifications will appear if heat transfer or gaseous diffusion is present (Knapp et al., 1970).

Knapp et al.(1970) plot the movement of a bubble during formation and collapse as it flows past a rigid body; of interest is that during its life cycle five to six collapse/rebound cycles were observed, with collapse taking place in high pressure regions and growth in low pressure zones, consistent with the pressure distribution along the body surface. A cavitation bubble formed in a free stream shear layer by jet action will most likely complete only one growth/collapse cycle, and upon collapse in the high pressure zone additional transient pressures will be generated. If a significant amount of noncondensible gas is present in the bubble subsequent rebounding, or oscillation could occur; in this regard Plesset and Prosperetti (1977) review in detail the aspect of small-amplitude bubble motion.

A significant amount of work has been conducted with regard to the mechanics of vapor bubble collapse and the accompanying transient pressure rises; herein it is briefly described, after Plesset and Prosperetti (1977). Attention is focussed upon a single spherical bubble whose mass is made up almost wholly by the surrounding fluid vapor. Furthermore the liquid is subcooled so that no heat transfer (latent heat flow) takes place between the vapor and liquid; consequently the motion becomes controlled by the liquid inertia. The liquid domain is assumed to be infinite in extent and incompressible.

The generalized Rayleigh equation for a single bubble in motion is

$$R\ddot{R} + \frac{3}{2}(\dot{R})^2 = \frac{1}{\rho}\left(p_i - p_\infty - \frac{2\sigma}{R} - \frac{4\mu}{R}\dot{R}\right) \qquad (7)$$

in which p_i = pressure in the bubble at the wall, p_∞ = liquid pressure a large distance from the bubble, and μ = liquid viscosity. The original solution to the problem was solved by Rayleigh (1917), who, assuming surface tension and viscous effects negligible and a constant p_∞, considered both an empty (i.e. vapor-filled) cavity and one filled with a non-condensible gas. In the former case his results showed that, as R decreases to 0, the bubble wall velocity $U = \dot{R}$ increases to infinity; and in the latter situation the bubble will not collapse entirely, but reaches a minimum size when U = 0. For the gas-filled bubble he also demonstrated that as R becomes small the pressure in the liquid surrounding the bubble can become very large.

Plesset (1949) extended the analysis by assuming p_∞ to vary with time and including surface tension and viscosity. From equation (7) an equilibrium radius R_0 can be defined for $p_i > P_\infty$:

$$R_0 = \frac{2\delta}{p_i - p_\infty} \qquad (8)$$

If p_∞ becomes less than p_i and remains constant, and with $p_i = p_v$ also constant, an asymptotic growth rate can be expressed as

$$U = \left(\frac{2}{3}\,\frac{p_v - p_\infty}{\rho}\right)^{\frac{1}{2}} \qquad (9)$$

Collapse can be considered by integrating equation (7) once with respect to time. With an initial radius of R_i and zero initial velocity of the bubble wall the result is

$$\left(\dot{R}\right)^2 = \frac{2}{3}\,\frac{p_\infty - p_v}{\rho}\left[\left(\frac{R_0}{R}\right)^3 - 1\right] + \frac{2\delta}{\rho R}\left[\left(\frac{R_i}{R}\right)^2 - 1\right] \qquad (10)$$

As R goes to zero U approaches an infinite value, consistent with the Rayleigh solution.

In the absence of surface tension effects the time of collapse is given by

$$t \doteq 0.915\left(\frac{\rho}{p_\infty - p_v}\right)^{\frac{1}{2}} R_i \qquad (11)$$

Even though liquid compressibility,bubble content behavior, and non-spherical bubble collapse is neglected, equation (10) has been experimentally confirmed, most likely because the final stage of collapse is very rapid (Plesset and Prosperetti, 1977).

In order to include liquid compressibility effects in the later collapse stages, use has been made of the Kirkwood-Bethe approximation in modifying the Rayleigh equation (Gilmore, 1952). Here the sum of the enthalpy plus the kinetic energy of the fluid multiplied by the radial distance r from the bubble is assumed to remain invariant as it propagates outward along the characteristic dr/dt = u + c, with u = liquid velocity and c = acoustic velocity in the liquid. The equation for the bubble wall motion becomes

$$\left(1 + \frac{1}{C}\dot{R}\right) R\ddot{R} + \frac{3}{2}\left(\dot{R}\right)^2\left(1 - \frac{1}{3C}\dot{R}\right) = H\left(1 + \frac{1}{C}\dot{R}\right) + \left(1 - \frac{1}{C}\dot{R}\right)\frac{R}{C}\dot{H} \qquad (12)$$

in which H and C refer to enthalpy and acoustic velocity at the bubble wall, respectively. This result again predicts an infinite U as R goes to 0 for a vapor-filled bubble. However, for cavities with a small gaseous component, Hickling and Plesset (1964) demonstrated that equation (12) is accurate up to Mach numbers (U/C) of 5 by comparisons with a numerically-obtained full solution. It was shown that the peak pressure during rebound radiates away from the bubble approximately as $^1/r$, and that pressures in the cavity attained magnitudes on the order of tens of kilobars. Additional refinements have been made to the model as noted by Plesset and Andretti (1977). However, it is now believed that in addition to the high pressures generated by the cavity collapse, the aspect of non-spherical bubble collapse (i.e., formation of microjets) may be the dominant contributor to cavitation damage. Plesset and Andretti (1977) review some of the work performed in this context; see also Mitchell and Hammitt(1970). Photographs of microjet formation are shown in Knapp <u>et al</u> (1970), page 136.

D. Scale Effects

Changes in velocity, size and fluid properties will influence the relative importance of the terms in equation (4), hence scale effects can become extremely complex and difficult to interpret (Holl, 1969). In the case of hydraulic control valves, since prototype systems are rather small, the trend has been to test models which are larger than prototype size (McCloy and Martin, 1973).

In practice the cavitation number σ is used for similarity. Arndt and Daily (1969) define a scale effect as ". . . any phenomenon which causes σ to have different values for the same event (e.g. for inception) . . . " They further classify the general scales effect into three-headings (assuming pressure measurement at a rigid boundary as a means of identifying cavitation): 1) the critical pressure at the location of inception unequal to vapor pressure; 2) the minimum pressure in the field of flow unrelated to $\rho V_{\infty}^2/2$ in a constant manner; 3) turbulence and vorticity present which locates the minimum pressure away from the boundary. The first category relates to the nature and source of nuclei and concomitant bubble dynamics, the second to the Reynolds number, and the third concerns interaction between boundary wall pressure, boundary layer turbulence, pressure minima in the boundary layer, and time scale effects between nuclei response time and pressure duration.

It is important to recognize that the cavitation number σ is based on the occurrence of cavitation at a minimum-pressure location on a solid boundary. Flow in a spool value is characterized by a high velocity submerged jet which may or may not be attached to a wall. In the case of a free jet, pressure minima may possibly be away from the wall. Cavitation can occur in the shear layer which separates the jet from the surrounding fluid; if the jet is turbulent, then it will be necessary to consider the time-average-mean pressure minimum. The σ_i values can become more scattered for free jet turbulence than for turbulent wall boundary layers (Knapp et al, 1970).

An investigation of cavitation in a circular submerged water jet was made by Rouse (1953, 1966). Using correlations of measurements in a turbulent air jet, it was demonstrated that the highest degree of turbulence, the peak shear stresses, and the peak pressure fluctuations occurred in the zone of flow establishment. Subsequently in a cavitating water jet, it was shown that the intensity of the cavitation bubble concentration was distributed similar to the turbulence intensity. The cavitation was occurring in the low-pressure regions of vortices generated in the shear zone and was spread over a wide region because of the random nature of the turbulence. It was concluded that negative pressure peaks of magnitude ten times greater than root-mean-square values induced cavitation. Based on sonic measurements, the greatest rate of bubble collapse coincided with the zone where turbulence reached the jet axis.

Arndt and Daily (1969) deal extensively with cavitation in the presence of a turbulent shear field. In particular they note ". . . A feature inherent to all turbulent flows is the nonsteady variation in pressure with peaks well below the static level. The intensity of these fluctuations appear to be directly related to the intensity of mean shear in the flow. Because of these turbulent fluctuations in pressure, cavitation is observed to occur at values of mean pressure at the boundary wall which are well above the vapor pressure . . . "

E. Brief Description of Cavitation in Spool Valve

The flow in a spool valve is characterized by a high velocity annular jet, likely turbulent in nature, issuing from an orifice of width b as shown in Figure 1.

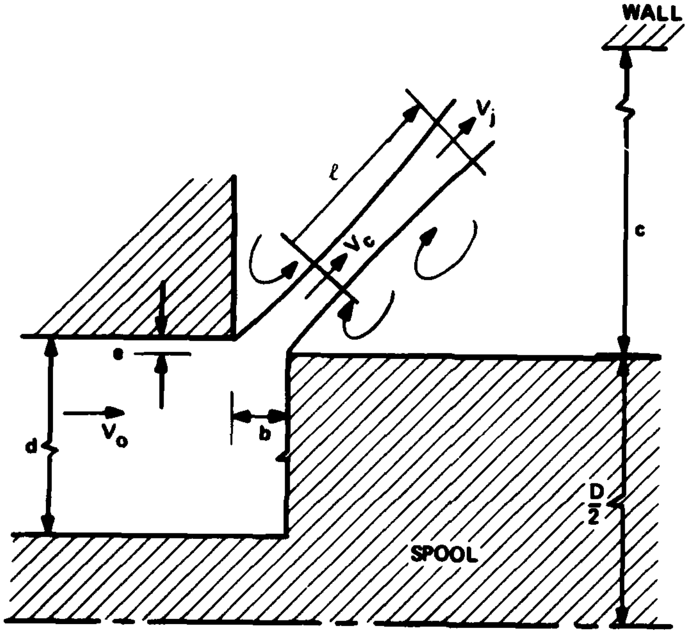

Fig. 1 Definition of valve and jet characteristics

If the jet is free as shown, for small opening b a two-dimensional von Mises' analysis would predict a contraction coefficient of 0.673 and a jet angle of 69° measured from the horizontal face (McCloy and Martin, 1973). The jet angle will be altered in an actual valve due to the necessary existence of the clearance e between the fixed and moving parts. Assuming inviscid flow from the approach region and opening b small relative to the annular dimension d, the velocity V_c in the vena contracta is given as

$$V_c = \sqrt{\frac{2\Delta p}{\rho}} \tag{13}$$

in which Δp is the load (upstream) pressure minus the return (downstream) pressure measured in the supply and return ports, respectively. The flow rate Q is given by the relation

$$Q = C_d \pi D b V_c \tag{14}$$

in which D is the spool diameter, and C_d is the discharge coefficient. Introducing the kinematic viscosity ν, the Reynolds number is defined as

$$R = \frac{Q}{\pi D \nu} \tag{15}$$

In defining the cavitation number for this system, it would be most appropriate to replace V_∞ by V_c in equation (1); however since V_c is not measured directly, but related to Δp, for the spool valve σ is defined in the manner

$$\sigma = \frac{p_c - p_v}{\Delta p} \tag{16}$$

in which p_c is the *time-average-mean pressure* in the downstream chamber, measured flush with the wall chamber.

McCloy and Martin (1973) discuss the possibility of jet attachment to either the vertical or horizontal wall of the spool chamber. Their observations were based on studies in a two-dimensional model; for a curved (reattached) jet, the flow coefficient showed a dependence upon the Reynolds number. In the present study C_d is nearly constant for the range of Reynolds numbers covered. McCloy and Martin remark further that a spool valve is not two-dimensional, and the possibility of reattachment will be dependent upon the particular geometry. For the case of a valve with a number of circular ports in the sleeve the likelihood of any reattachment was stated as doubtful. In addition, a study was reported of a two-dimensional model spool valve where the spool was oscillated; it was found that reattachment did not occur when the frequency of oscillation was above a limiting value, the frequency being dependent upon orifice opening and pressure drop (Foster et al, 1966).

Two types of cavitation in spool valves can be distinguished depending upon whether the jet is free or attached. In the latter case cavitation voids can be expected to form along a wall of the chamber, and in the former bubbles will appear in the high-intensity shear layer. Due to the expected high degree of turbulence for the free jet situation it is likely that cavitation will take place even when the chamber pressure is greater than vapor pressure. For the case of reattached flow McCloy and Martin (1973) reported the appearance of cavitation bubbles with back pressures as high as 0.7MPa (100 psi); here due to curvature in the jet the bubble pressure was less than the downstream chamber pressure.

In the present study, the primary flow mode is that of the free-jet type. High-frequency bubble collapse is monitored by placing a piezoelectric transducer flush in the chamber wall. In addition to cavitation noise, turbulent jet noise is also apparent, and it is necessary to differentiate between the two sources. Using energy spectra measurements as a means to determine incipient cavitation conditions, in the present study a dependence of σ_i on the Reynolds number is shown, Figure 2. McCloy and Martin (1973) show a similar trend for flows in a two-dimensional orifice, an axisymmetric spool valve orifice, and an axisymmetric 45° poppet orifice.

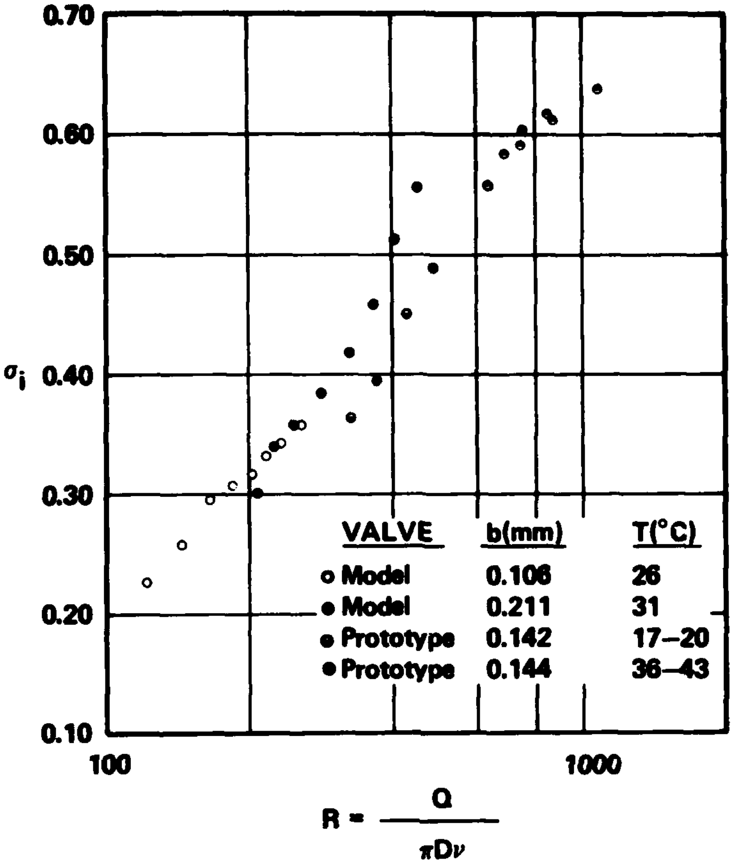

Fig. 2 Incipient cavitation index versus Reynolds number for model and prototype valves

The type of cavitation taking place is most probably vaporous, with small cavities appearing in the shear layer zone of reduced pressure in the jet. The number of cavitation events apparently are few. Even though dissolved air content can be as high as 10 percent in hydraulic oils, gaseous cavitation would have little effect since the bubble residence time in the jet is extremely short.

Thus for flow in a spool valve the observations given above suggest that cavitation can take place even if the chamber pressure is greater than vapor pressure. The cavitation voids can be expected to form along a wall of the chamber if the jet becomes attached, or in the high intensity shear layer if a turbulent free jet is present. Precise comparisons between a prototype and larger-than-prototype model are not possible since nuclei population distribution cannot be controlled, since Reynolds number effects may be significant, and since the interaction between nuclei and the turbulence field may differ.

SECTION III

DISSOLVED AND FREE GASES

A. Mechanics of Gas Release from Solution

If a gas remains completely dissolved in a liquid, it will have negligible influence on the effective tensile strength of the fluid. However, if the liquid pressure drops below the gas saturation pressure, in the presence of bubble nuclei mass diffusion will take place across the bubble-liquid interfaces. This process of gaseous cavitation can occur separately from, or along with, vaporous cavitation.

Henry's law provides the basis for understanding the gas release process; it states that at equilibrium -- that is, saturated -- conditions, the partial pressure p_g of a gas in contact with a liquid surface is proportional to the equilibrium mass concentration c_s of the gas in the liquid, or

$$c_s = \beta p_g \tag{17}$$

The coefficient β is termed Henry's constant and is primarily a function of temperature.

For a gas bubble surrounded by a liquid with an ambient pressure p_l, the bubble will be in a nonequilibrium state unless the dissolved gas concentration c at the liquid surface satisfies equation (17); it will grow if $c > c_s$ and diminish if $c < c_s$. Assuming slow bubble growth, equation (2) can be combined with the ideal gas relation to show the bubble growth rate dependence upon the molar flux of gas into the bubble:

$$\dot{R} = \frac{\tilde{R}T}{4\pi R[(p_l-p_v)R+4\sigma/3]} \quad \dot{N} \tag{18}$$

In equation (18) $\tilde{R}$ is the gas constant, T is the absolute temperature, and

$\dot{N}$ is the flux term. For fluid pressures close to vapor pressure, the denominator of equation (18) can become small for small values of R; this signifies the onset of vaporous cavitation. The mass balance at the bubble interface is given by

$$\dot{N} = D \int_S \frac{\partial c}{\partial n} \, dS \tag{19}$$

in which D = diffusion coefficient for gas in liquid, $\partial/\partial n$ = gradient normal to the surface, and dS = bubble surface elemental area. The convection diffusion equation for the liquid is

$$\frac{\partial c}{\partial t} + \vec{V} \cdot \vec{\nabla} c - D\nabla^2 c = 0 \tag{20}$$

where $\vec{V}$ is the fluid velocity vector. These equations have been utilized separately and in combination to effect approximate solutions for a variety of particular bubble growth problems.

Epstein and Plesset (1950) were one of the first to develop a solution for the rate of growth (and dissolution) of a bubble by diffusion. Neglecting surface tension, inertial effects associated with bubble motion, and assuming no translational motion of the bubble, the approximate solution from equation (20) takes the form

$$R\dot{R} = D \frac{c_\infty - c_s}{\rho_g} \left[1 + R(\pi D t)^{-1/2}\right] \tag{21}$$

in which c_α = concentration a large distance away from the bubble and ρ_g = gas density. Asymptotically the bubble growth rate $\dot{R}$ is proportional to $t^{-1/2}$, and for an air bubble in water, $\dot{R} \sim 10^{-4}$ cm/s (Plesset and Prosperetti, 1977), suggesting that bubble growth by diffusion is a much slower process than growth by inertially-controlled vaporization. Relatively few measurements of quiescent bubble growth are available; two of them are the binary systems carbon dioxide-water (Westwater, 1964) and n-pentane-ntetra-decane (Szekely and Martins, 1971). Additional theoretical studies related to mass-diffusion bubble growth in a non-convective field are summarized by Plesset and Prosperetti (1977).

Another significant non-translational type of bubble growth takes place if the bubble is situated in an oscillating pressure field, a situation encountered in cavitation experiments and in the propagation of sonic and ultrasonic waves in liquids (Hsieh and Plesset, 1961). Termed rectified diffusion the physical process is described in detail by Plesset and Prosperetti (1977). For a saturated solution they relate an approximate solution for bubble growth:

$$R\dot{R} = \frac{2}{3} D \frac{c_s}{\rho_g} \left(\frac{P_{max} - P_o}{P_o} \right) \tag{22}$$

Here P_o and P_{max} are the average and maximum mean pressures in the bubble, respectively. It is shown that equation (22) predicts bubble growth by rectified mass diffusion to be an extremely slow process. Nonlinear effects of the problem have been investigated by Eller and Flynn (1965).

Bubble growth by convective diffusion in a streaming fluid, in contrast to growth in a quiescent fluid, is a more complex process inasmuch as the relative motion between the bubble and the surrounding fluid is to be accounted for. Boussinesq (1905) solved the problem by neglecting the radial velocity of the bubble; this was subsequently examined further by Levich (1962). Using a large Peclet number approximation which implies that gas diffusion occurs in a narrow region surrounding the bubble, the mass flux into the bubble is

$$\dot{N} = 4\beta(p_s - p_l)\sqrt{2\pi UD}\; R^{3/2} \tag{23}$$

where p_s = saturation pressure and U = mean scalar relative velocity between the bubble and liquid. Combining equation (18) with equation (23) an expression for the bubble growth rate is obtained:

$$R\dot{R} = \frac{\tilde{R}T\beta(Ps - P_l)\ \sqrt{2\pi UD}\ \ R^{3/2}}{R(p_l - p_v) + 4\sigma/3} \qquad (24)$$

An asymptotic solution for relatively large times shows that $R \sim t^{2/3}$. Parkin and Kermeen (1962) have developed an approximate solution for convective air diffusion into bubbles in water at cavitation inception; they established that the growth time is several orders of magnitude greater when relative motion is included. Van Wijngaarden (1967) attempting to improve their analysis by including the effects of surface tension and vapor pressure, integrated equation (24) to obtain slightly better agreement with the data of Parkin and Kermeen. It is most probable that these growth rates still remain significantly below those for vaporous growth.

B. Capability of Hydraulic Fluid to Contain and Release Gas

In hydraulic fluids such as the MIL-H-5606 series, air will be the most probable gas to be either dissolved in solution or entrained in its free state. Other than recognizing its existence as nuclei present for subsequent cavitation to occur, the latter will not be dealt with further herein; McCloy and Martin (1973) discuss the various ramifications of having entrained air present in a hydraulic system and present ways in which aeration can be suppressed.

Figure 3 shows the solubility of air in various liquids where solubility is given as concentration by volume reduced to standard temperature. It can be seen that the MIL-H-5606 has the greatest capacity to contain dissolved air; at one atmosphere, approximately 10 percent by volume is potentially possible. In Figure 3 the slope of each line is effectively Henry's constant; referring to equation (23) one can conclude that once the

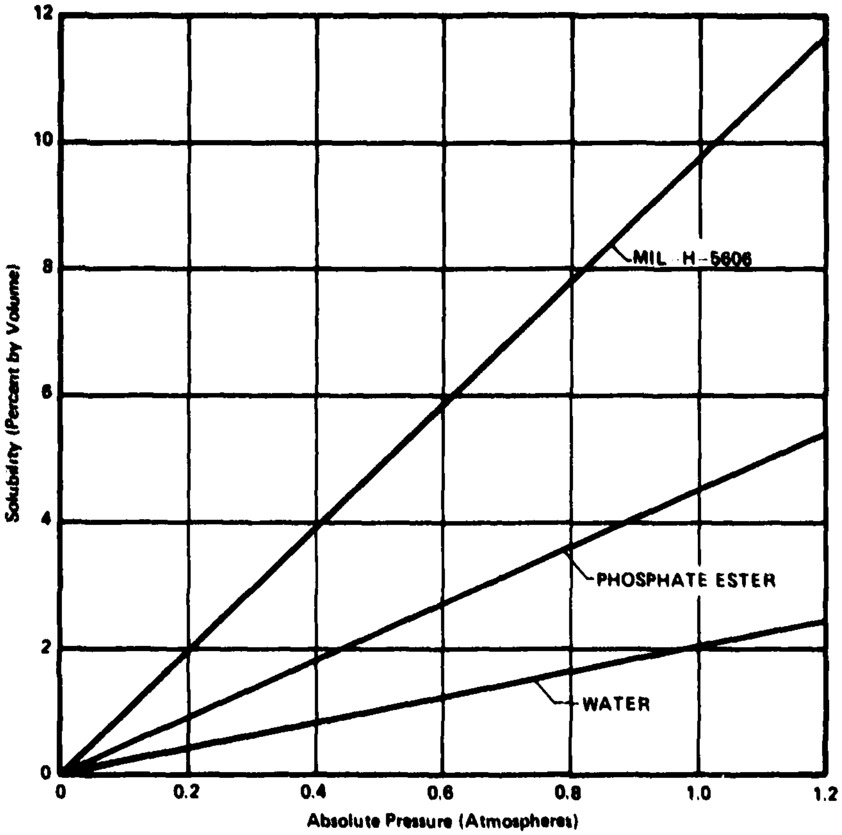

Fig. 3 Solubility of air in various liquids (after McCloy and Martin, 1973)

fluid becomes supersaturated ($p_l < p_s$), MIL-H-5606 will have the greatest amount of gas released, other parameters being constant. Indeed, the need to prevent excessive gaseous cavitation is a justification for incorporating deaeration devices in hydraulic control systems.

It should also be noted that the residence time of supersaturation will also affect the amount of gas release. In the present study, a cavitation bubble will be formed and reside in a reduced-pressure jet region for a very brief time period, cf Figure 1; consequently a small--perhaps insignificant--amount of air may be released from the hydraulic fluid. Indirect evidence that this apparently did take place is that for dissolved air content at the two extremes observed in the investigation -- 4.5 and 9.0 percent -- there was no noticable difference between σ_i nor cavitation index. Furthermore in the model valve, cavitation bubbles disappeared as the flow left the downstream port, suggesting that only vaporous cavitation was present.

C. Effect of Dissolved and Free Gas on Cavitation

In the present study cavitation occurs in a flow field consisting of a steady, streaming turbulent motion, hence any nucleus present in the liquid must reach a critical size as it is swept through the low pressure field if it is to become unstable. For this imminent, i.e., incipient, cavitation condition, a small region exists where $p_l < p_v$; the flow velocity determines the magnitude of p_l and the time of traverse of the bubble. An additional parameter affecting whether cavitation takes place is the initial nucleus size. A detailed description of stability mechanics for entrained gas nuclei is given by Knapp et al. (1970).

Undissolved gas particles are the basic "impurity" which reduces the high theoretical tensile strength of liquids to the values encountered in practice. For water flow in a venturi meter, Knapp et al. (1970) give evidence that as the free air content is increased, the pressure at inception likewise increases. As the air content varied from 0.60 to 1.20 (absolute air content divided by saturation air content), the pressure at cavitation inception $(p_i - p_v)/\sigma$ varied from approximately -2.0 m (-7.0 ft) to 1.0 m (3.0 ft) of water. They also note experiments in which water samples containing undissolved air exhibited no tensile strength unless prior to testing, the liquid was subjected to high static pressure, apparently driving free gas into solution. The conditions necessary for a gas nuclei or vapor pocket to remain stabilized in a liquid is most plausibly explained by use of the mechanism suggested by Harvey et al. (1944). It is shown that undissolved gas nuclei can exist under pressure when located in extremely small openings in container walls or in solid contaminant particles.

Dissolved gas will have negligible effect on the tensile strength of fluid, although it may have an effect analogous to increasing the vapor pressure (Knapp et al., 1970). As discussed previously, with inertia-dominated cavitation the formation and collapse of a moving cavity is on a time scale which is too small to allow significant gas diffusion from the surrounding liquid. Hence the air content will most likely have only a small effect on the bubble dynamics, except at initial growth and final collapse stages. However, since not all the free gas will redissolve upon collapse, sufficient nuclei will remain for subsequent cavitation to occur. Knapp et al. (1970) mention the concept of "hysteresis", observed in water-tunnel experiments, where due to repeated cycles of gaseous diffusion, it is necessary to drop tunnel pressures below previous inception values in order to form a cavity.

Apparently little work has been performed in liquids with high dissolved gas content. It is likely that with sufficient nuclei present the critical pressure p_i for cavitation inception could be substantially increased. Figure 4 shows the vapor pressure of hydraulic oils versus temperature. With

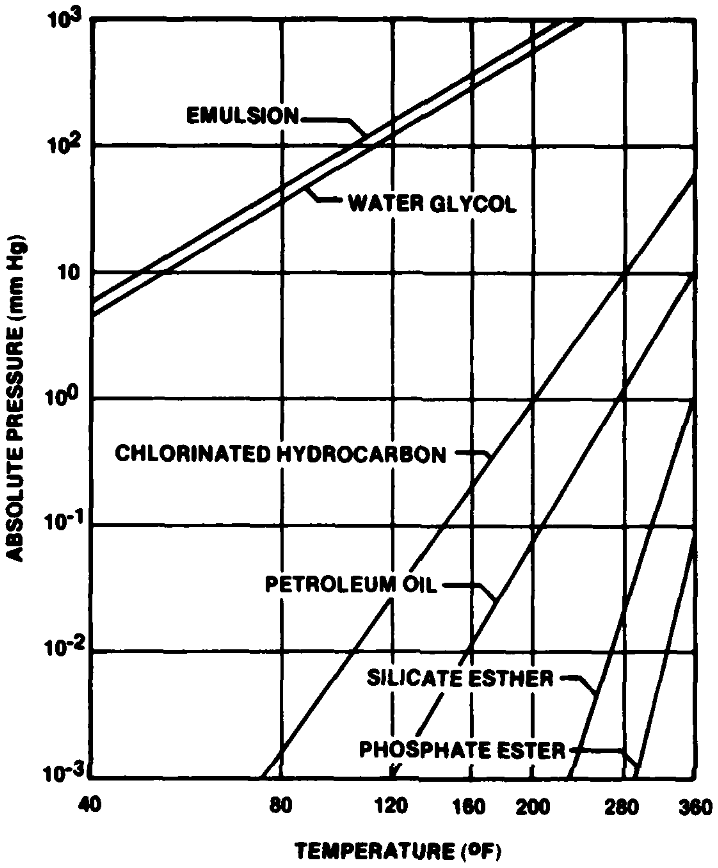

Fig. 4 Vapor pressure of hydraulic fluids (after McCloy and Martin, 1973)

significant amounts of dissolved gas present (cf Figure 3), coupled with the presence of nuclei for inception which reduces the liquid tensile strength, it is probable that cavitation would occur in hydraulic fluids above these vapor pressure limits. In the present study, p_v is utilized as a lower bound for cavitation whereas saturation pressure p_s could be considered an upper limit.

Knapp et al. (1970) qualitatively discuss the effect of gas content upon cavitation collapse pressures, and subsequently, the effect upon mechanical attack of the vessel wall material. Neglecting any dissipative effects, they argue that the maximum collapse pressure will be reached when the potential energy generated by collapse is stored in compressing the surrounding liquid. However, if some of the energy is stored in compressing the gaseous or vaporous contents of the voids, the pressure rise on collapse would be less severe. Thus an explanation is suggested for the practice of injecting gas into a cavitating flow to reduce damage. In a similar manner, if significant gaseous cavitation were present, one might expect that cavitation damage would be lessened when compared to the situation for pure vaporous cavitation.

One study more directly related to hydraulic control valves deals with vaporous and gaseous cavitation in long orifices (Lichtarowitz and Pearce, 1974). Here, a jet issues into a short tube (long orifice), with reattached flow occurring downstream, and cavitation taking place in the free shear mixing layer. In addition to water, tests were conducted using kerosine and Tellus 15 oil. The total air content was varied by conventional gassing or degassing procedures; for kerosine it ranged from 5 to 200 percent of saturation at atmospheric conditions, and for the oil, two values of 30 and 100 percent were reported. Most of the data obtained were for kerosine as the test fluid. Visual observations of cavitation "tails" were made with the qualitative conclusion--supported by hydrophone detection -- that vaporous cavitation inception and desinence were unaffected by air content, but gaseous cavitation (termed aeration by the authors) was significantly delayed. Analysis of the pressure data for kerosine revealed the following: the performance characteristic (i.e., drop in discharge coefficient) was not affected by air content; gaseous cavitation (aeration) occurred before vaporous cavitation; as the air content was reduced, the desinent cavitation number decreased with the lower bound approaching the value for vaporous cavitation. Unfortunately no significant results with Tellus 15 oil were reported.

D. Summary

The influence of gas content and nuclei on cavitation is well summarized by Holl (1969). Even though the primary concern of his paper deals with limited cavitation on streamlined bodies in water flow, it remains relevant to the present study.

> The total gas content of the liquid is equal to the dissolved gas plus the free gas. Generally speaking the amount and distribution of free gas at a given point in time will depend upon the past history of the flow as influenced by the total gas content, pressure, velocity and the flow characteristics of the particular facility in question.
>
> The dissolved gas content is of importance for gaseous cavitation since the rate of transport of noncondensable gas is directly dependent upon the amount of dissolved gas. Furthermore, the dissolved gas will influence the size and distribution of free gas bubbles. Thus, if the liquid is undersaturated the free gas bubbles will tend to decrease in size with time whereas the opposite is true if the liquid is oversaturated.
>
> In most practical cases the dissolved gas content will have little or no influence on pseudo or vaporous cavitation. If however, the time during which a bubble is in the region of cavitation is of the same order or magnitude as significant diffusion times then the dissolved gas content may be important. This may be the case for very large scale bodies.
>
> The free gas content should be an important factor for pseudo cavitation and vaporous cavitation which depend on stream nuclei. This may be the reason why separated flows seem to depend strongly on the amount of entrained gas since many such flows may depend almost exclusively on stream nuclei.
>
> Vaporous cavitation which occurs in the boundary layer may depend for the most part on surface nuclei and thus for these flows the free gas content should not be an important factor.

For tests conducted at rather large values of free gas content, it may be that pseudo cavitation is one of the most dominating flow regimes because of the availability of stream nuclei. Furthermore, for these flows, the same reasoning implies that the most dominant form of vaporous cavitation which occurs on streamlined bodies may be that which occurs outside of the boundary layer.

The delay in cavitation inception which is sometimes observed may be due to a deficiency of stream nuclei. On the other hand, even with a deficiency of stream nuclei it may be that cavitation delay will not occur if there is an abundance of surface nuclei.

SECTION IV
SUBSIDIARY FACTORS

The phenomena described in this section -- a) combustion, b) sonoluminescence, c) electrical and chemical effects -- have not been observed in the present experimental investigation. They are more likely to occur in liquids other than hydrocarbon-based oils, e.g., water (b, c), synthetic-based oils (c), and fuels (a). The cited literature is not exhaustive but serves to provide a basic understanding of the processes involved, as well as relate some of the outward manifestations of the various factors.

A. Combustion

One of the least understood and least documented subsidiary effects is that of combustion, or "dieseling" of a hydrocarbon fluid. Apparently the phenomenon is of more concern in aircraft fuels than in hydraulic oils. With regard to the latter, one study has been reported in the German literature (Lohrenz, 1974) which provides a qualitative view of dieseling. The author argues for the necessary presence of free air, which upon being transported into high pressure (collapsing) regions will compress adiabatically, giving rise to an increase of temperature and subsequent combustion. The event could occur without cavitation (macro-diesel effect) or in a cavitation trail (micro-diesel effect). The necessary conditions for combustion are uncertain; apparently what is needed is the correct combination of free oxygen, hydrocarbon constituents and temperature. Deleterious effects are aged oil products, damaged seals and increased pressure peaking.

B. Sonoluminescence

Sonoluminescence is defined by Jarman (1960) as "weak emission of light occurring in engassed liquids when cavitated by sound fields." Most observations have been made in a water medium with cavitation induced by intense ultrasonic fields; other liquids as well as various gases which give rise to varying intensities of luminescence are given by Knapp et al. (1970).

Jarman (1959) listed four existing theories for the origin of luminescence:

a) Electrical microdischarge theory in which lens-shaped cavities are produced in the liquid by the sound field and electrical double layers surrounding the cavities are torn apart with occurring discharges.

b) Mechanical-chemical theory, where the formation of free ions accompany the mechanical dissociation of molecules at nascent surfaces created by the sound field, with light emitted when the ions recombine.

c) Hot-spot theory, which is black body radiation from incadescent gas inside collapsing cavitation bubbles.

d) Chemiluminescence theory, the photo-chemical recombination of dissociated molecules, presuming thermal dissociation of the molecules when bubbles collapse.

Current understanding of the phenomenon concludes that it is primarily thermal in origin, in support of the hot-spot theory. Hickling (1963) observed a strong dependence of the luminous intensity upon the nature of the gas dissolved in the liquid, explained in terms of thermal conduction between the bubble and surrounding liquid. Jarman (1960) also concluded that sonoluminescence is basically thermal in origin, possible arising from the microshocks associated with collapsing cavities. Hickling (1969) reaffirms the idea that temperature -- that is, thermal effect -- plays an important role in luminescence, as well as in chemical reactions and initiation of explosions.

C. Electrical and Chemical Effects

In hydraulic control systems nearly all of the problems encountered in this category are with synthetic-based oils; at present there is no known difficulty with respect to hydrocarbon oils such as the 5606 series. It is important to note in relation to the material discussed below, that the mechanical aspects of cavitation attack and chemical corrosion cannot be easily separated. For example, the mechanical removal of corrosion products deposited on valve surfaces would permit further corrosion to take place at a high, or possible maximum, rate (Knapp et al., 1970).

Beck et al. (1969) studied the corrosion of servo valves by an electrokinetic streaming current with phosphate ester (synthetic) fluids. The corrosion was driven by a flow-induced electric current; both cavitation and particle erosion played a secondary role. The authors concluded that this type of damage appears in the absence of cavitation. They further found that the amount of corrosion produced depended upon the fluid composition and that the addition of water would reduce corrosion but could increase film formation. It is worthwhile to reproduce their report summary:

> A laboratory system was developed which simulated the flow conditions in hydraulic valves. The flow rate and geometry of the system was accurately reproducible. Damage identical in appearance to that in the valves was produced. Increasing the back pressure while maintaining constant flow eliminated cavitation but not damage. This proved that cavitation was not the primary damage mechanism. Experiments using a one-micron membrane filter to remove foreign particles indicated that particle erosion was not the primary process as the presence of this filter did not stop the damage. Optical observations and measurements with a small electrode inserted in the wall at the orifice failed to show the presence of sparks. However, a small steady current was observed flowing from the electrode. This current normal to the wall, herein termed the wall current, is produced by the generation of an electrical streaming current in an accelerating fluid flow, and causes electrochemical corrosion damage of the metal. The wall current was quantitatively accounted for from measured values of the electrical properties of the fluid and a calculation involving hydrodynamic and electrokinetic theory.
>
> Supporting evidence for this corrosion mechanism includes the following observations: The current measured from an electrode in the wear area is more than sufficient to account for the amount of metal removed by electro-chemical corrosion; damage could be eliminated on the specimen through the application of an electrical current from an external source to cancel that produced by the flow;

> an insulating aluminum oxide specimen, which should not be subject to electrochemical pitting corrosion, was not damaged even under cavitating conditions; the damage observed with various hydraulic fluids was related to their electrical properties; corrosion damage similar to that in valves was obtained electrochemically without fluid flow.
>
> During the course of the investigation a considerable body of supplemental information pertinent to the problem was obtained. A white insulating film was observed on both the anode and cathode of an electrochemical cell and near the orifice in the flow experiments. The thickness of the film increased with increasing water content. This may be an important factor in the reduction of damage when water is added to the fluid because the film formation affects the flow rate of the fluid and may affect the flow of electrical current from the metal. The electrical conductivity of the hydraulic fluid affects the amount of damage observed. It is believed that either a substantial increase or a substantial decrease in conductivity would significantly decrease the amount of damage. Experiments and analysis suggest that the conductivity of the fluid is due to hydrolysis products. These products may contribute to the generation of the streaming current. Filtration through fuller's earth is believed to remove these hydrolysis products. Some experiments were performed to determine the effect of changes in fluid composition on streaming current and electrochemical properties. The results of these experiments were consistent with the proposed damage mechanism.

In a more recent study Burrous (1977) measured electrolytic corrosive erosion by monitoring leakage rates in a spool valve bench test. Concern was with phosphate-ester based hydraulic fluids (Hyjet III, IV; Skydrol 500B, LD, 500B-4; AeroSafe 2300W). Correlations were made with respect to leakage rates, electrical conductivity and wall current, with the conclusion that a simple measurement of electrical properties of the fluid can determine if it is essentially noneroding.

Chincholle et al. (1978) describe a series of experimental studies which measure the electrical effects accompanying cavitation events. Both vibratory horn and cavitating tunnel facilities were employed, and the fluid mediums included tap water, distilled water and oil (which type was not stated). The authors report the presence of two electrical effects: a pulsating type (1mV, 5μs duration) corresponding to the generation of electrical charges by cavitation bubbles, and an electrochemical potential (150 to 230 mV) dependent upon the cavitation intensity as well as additional parameters. They suggest that the latter is due to the mechanical action of the collapsing cavitation bubble microjet on the probe surface. Figure 5 shows the ultrasonic (18 kHz) apparatus used for the oil experiment, and Figure 6 gives the variation of electric potential as a function of time for three different probe positions in the vicinity of the cavitation zone.

Another effect is produced by inducing an electric or magnetic field in a liquid which is cavitating. Hammitt et al. (1975) provide a summary of Russian literature from 1967-1974 and in addition report recent tests conducted in the United States. The Russian tests showed that a magnetic field (1-10kG) in a flowing cavitating water regime can produce damaging effects and can significantly alter the growth and collapse rates of single bubbles in tap water. An electrical field in tap water produced damage, but the results were inconclusive. In addition, with conducting liquids (possibly liquid sodium) at high temperatures, damage was significantly reduced when a magnetic field was applied, although secondary effects may have been responsible. In the United States tests were made on the effect of a 6 kG magnetic field upon nucleation threshold in a vibratory cavitation system using tap water, salted water and mercury. No significant effects beyond an experimental accuracy of ± 1 percent were observed.

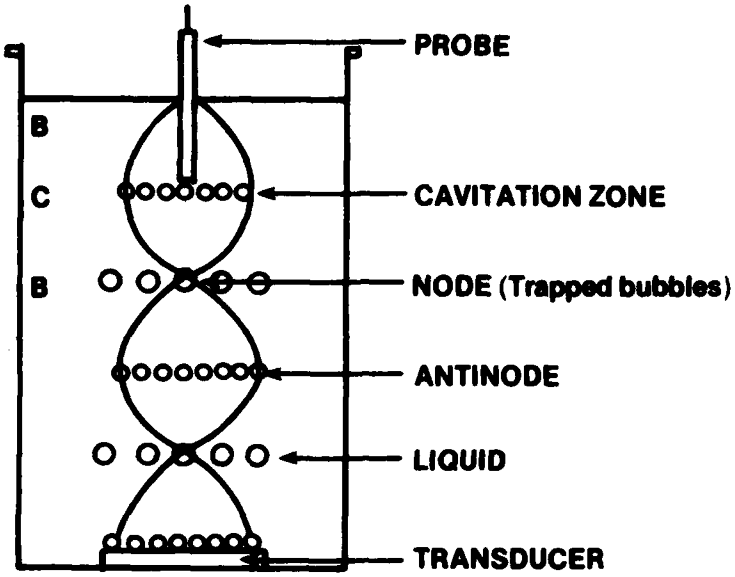

Figure 5. Ultrasonic apparatus for oil experiment (after Chincholle et al., 1978)

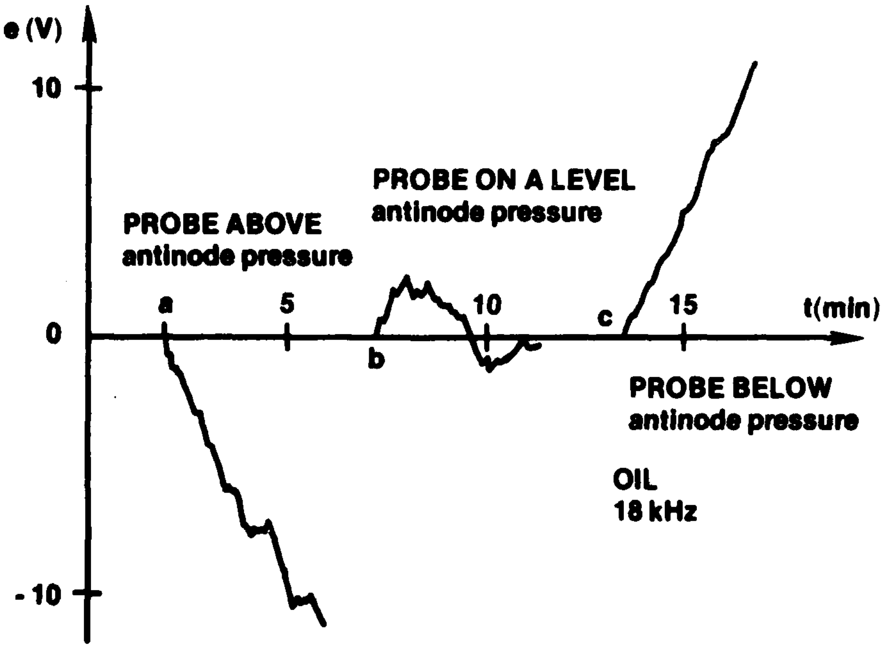

Figure 6. Electric potential versus time in regions of cavitation in oil (after Chincholle et al., 1978)

SECTION V

CAVITATION IN OIL HYDRAULIC ACTUATORS

A. Description of Phenomenon

The experimental phase of this study has dealt with a localized cavitation which occurs in regions near a valve port; cavitation on a larger scale takes place in oil hydraulic actuators. For such systems, Wang and Ma (1963) have classified two distinct modes of cavitation, namely the rapid formation and collapse of air or vapor bubbles in low-pressure regions, and large cavity formation behind the moving actuator piston. The former type is termed incipient cavitation by the authors, who note that this mode was observed to be dominant under nearly all cavitated motions. The second mode is one which has undergone extensive investigation, from both experimental and analytical approaches. The process is succintly stated by Wang and Ma (1963):

> The second mode of cavitation is the cavity formation behind the moving piston. Its development can be explained by considering the case where the valve ports are fully open so that the actuator piston moves from left to right at a uniform velocity. If the valve ports are reduced instantaneously to a smaller size in such a way that there is insufficient incoming fluid to fill the volume displaced by piston motion, the fluid on the left side of the piston will expand and cause the pressure to drop rapidly. However, the fluid expansion rate is not uniform everywhere inside the cylinder. Cavities will first develop at regions where the fluid velocity gradient or shear stress is the greatest, provided that the local shear stress is sufficiently large to cause liquid rupture. Clearly, such a region can exist within the clearance space between the cylinder wall and the moving piston. The shear-stress magnitude depends upon both the fluid viscosity and the piston velocity. When the shear stress near the surface of the moving piston is sufficiently large to overcome the adhesive force between the fluid and the solid boundary, the fluid will begin to separate from the piston surface causing liquid rupture. The adherence of a fluid to a solid surface can also be weakened by a monolayer of some active surface-contaminating substance. If the contaminations are not distributed uniformly over the whole surface, but concentrated over certain isolated regions, ruptures usually initiate within these regions. Once a cavity is initiated, it tends to grow along the direction of maximum shear stress.

While the inflow side of the actuator experiences vapor conditions which may result in implosion damage, the outflow side will experience a large peak pressure which can give rise to fatigue failure. McCloy and Martin (1973) note that pressure peaks as high as five times the supply pressure have been experimentally observed. They further note that valve overlap can markedly increase the pressure peaks, and that the worst condition occurs when the valve is within the lap region and the load is decelerating, since the fluid trapped in the cylinder must absorb the kinetic energy of the moving mass.

A second effect of cavitation on the valve-actuator is to alter the system dynamic response. The formation of cavities gives rise to discontinuous motions which complicate the mathematical model description of the actuator motion and increase the complexity of the analytical design process.

B. Analytical and Experimental Studies

A major contributor to the advancement of fluid power control is D. McCloy, who along with several coinvestigators, studied numerous aspects of cavitation in oil hydraulic systems. The major treatise is a book (McCloy and Martin, 1973) which includes a description of the underlying cause of cavitation in the hydraulic actuator. Analytical developments include theoretical estimates of conditions giving rise to cavitation for zero lap and underlap when the actuator is oscillating sinusoidally. In addition an analog computer model is presented which shows the effect of viscous friction on the cavitation limits. A series of publications prior to the printing of the book give more detail related to the cavitating actuator problem; these are outlined in the following paragraphs.

McCloy and Martin (1963-64) in an early paper demonstrate the application of computers to the modeling of a control system. In a discussion of cavitation they demonstrate that even for zero-lapped conditions, vapor pressure can occur under large acceleration demands, and cylinder pressures in excess of system pressure will be present. The pressure peaks can be worsened by the presence of valve overlap, but are attenuated by the effect of oil compressibility (McCloy, 1965).

Attention is drawn to the relation between aeration and cavitation by McCloy (1966); both phenomena have adverse effects on system performance and reliability. Entrained air can substantially reduce the system stiffness, but the effect can be suppressed by maintaining high system pressures. In addition the author gives evidence of the presence of cavitation in orifices and of the accompanying erosion damage. It is argued that dangers of valve erosion by cavitation are more important than small changes in the valve discharge coefficient.

Martin and Lichtarowicz (1966-67) effect an analog simulation of an open-loop hydraulic system with the inclusions of cavitation and oil compressibility. A parametric study is made of the effects of viscous damping, seal friction, leakage across the piston and pressure feedback in an attempt to reduce cavitation and pressure peaking. The authors conclude that leakage is the most effective means, but unfortunately the system loses static stiffness. It is also noted that the suggested methods for reducing cavitation are not effective in the low frequency range.

An analysis of a valve-driven actuator assuming incompressible oil is made by McCloy (1969). The occurrence of cavitation on one or both sides of the cylinder is noted, although compressibility and leakage effects would render the latter condition unlikely in practice. The author suggests that hydraulic servo-systems can be operated in the cavitating mode with little effect on the dynamic response and unlikely cavitation damage. A simple analytic model which neglects cavitation is claimed to be adequate for the cavitating mode of operation.

McCloy (1972) produced an analytical study of the response of a loaded hydraulic cylinder to step inputs. The theory assumes incompressibility and no cavitation, and is in agreement with a more exact theory which accounts for cavitation. It is remarked that the occurrence of cavitation minimizes the variation of the natural frequency with load position.

Two additional papers are mentioned herein by authors other than McCloy and coworkers. The first is a comprehensive analytical and experimental treatment of cavitation in actuators (Wang and Ma, 1963). Equations are derived which approximate cavitation conditions for actuators subjected to sinusoidal or step inputs. Confirmation of the theory is made by experimental tests on a physical model. Additional experimentation consists of highspeed photographs showing the two cavitation modes: incipient cavitation and large cavity formation behind the moving piston. Harmful effects to the system that can be attributed indirectly to cavitation are oil oxidation intensified by temperature increase at the cavity surfaces, accompanied by gums, resins and slags formed in the fluid, causing further deterioration and mechanical wear. Because of cavitation damage and complications arising in analytical design procedures, it is suggested that cavitation in operating systems be avoided.

The second investigation is concerned with the response of a time-optimized hydraulic servomechanism (Nikiforuk, et al., 1970-71). In addition to possible cavitation the analysis accounts for the effects of valve dynamics, valve hysteresis, oil compressibility, actuator leakage and nonlinear load friction. The main conclusions are: during acceleration mode, compressibility of the oil can be neglected; during deceleration compressibility must be accounted for; actuator cavitation increases the effective damping of lightly damped systems and cannot be omitted from the analysis without substantial differences between predicted and experimental response patterns of load oscillations.

REFERENCES

Arndt, R.E.A., and Daily, J.W., "Cavitation in Turbulent Boundary Layers," Cavitation State of Knowledge, ASME, 1969, pp. 64-86.

Backé, W., and Riedel, H.P., "Kavitation in Ölhydraulischen Systemen," (Cavitation in Oil Hydraulic Systems), Industrie-Anzeiger, Vol. 94, January, 1972, pp. 153-158.

Beck, T.R., Mahaffey, D.W., and Olsen, J.H., "Corrosion of Servovalves by an Electrokinetic Streaming Current," Boeing Scientific Research Laboratories Document D1-82-0839, September, 1969.

Boussinesq, J., "Calcul du Pouvoir Refroidissant des Courants Fluides," Journal de Mathématiques Pures et Appliquées,Paris, Vol. 6, No. 1, 1905, pp. 285-332.

Burrous, M., "Recent Developments in Aviation Hydraulic Fluids," 25th Aerospace Fluid Power Conference, Oct. 31-Nov. 1, 1977, Jackson, Mississippi.

Chincholle, L., Gimenez, G., and Goby, F., "Electrical Effects Accompanying Cavitation Events and Detection of Erosive Cavitation," ASME Polyphase Flow and Turbomachinery Symposium, San Francisco, December, 1978, pp. 309-326.

Eller, A., and Flynn, H.G., "Rectified Diffusion During Nonlinear Pulsations and Cavitation Bubbles," Journal of the Acoustical Society of America, Vol. 37, March, 1965, pp. 493-503.

Epstein, P.S., and Plesset, M.S., "On the Stability of Gas Bubbles in Liquid-Gas Solutions," Jour. Chem. Phys., Vol. 18, 1950, pp. 1505-1509.

Foster, K., and Kulkarni, M.M., "The Free Oscillations of an Inertia Loaded Hydraulic Spool Valve," Univ. of Birmingham Mech. Eng. Dept. Research Rept. 50, May, 1966.

Gilmore, F.R., "The Growth and Collapse of a Spherical Bubble in a Viscous Compressible Liquid," Calif. Inst. of Techn. Hydrodyn. Lab. Report 26-4, 1952.

Hammitt, F.G., "Collapsing Bubble Damage to Solids," Cavitation State of Knowledge, ASME, 1969, pp. 87-102.

Hammitt, F.G., Yilmaz, E., Ahmed, O., Bhatt, N.R., and Mikielewicz, J., "Effects of Magnetic and Electric Fields upon Cavitation in Conducting and Non-Conducting Fluids," ASME Cavitation and Polyphase Flow Forum, Minneapolis, 1975, pp. 26-28.

Harvey, E.N., Barnes, D.K., McElroy, W.D., Whiteley, A.H., Peace, D.C., and Cooper, K.W., "Bubble Formation in Animals. I, Physical Factors," Jour. Cellular and Comp. Physiol., Vol. 24, No. 1, August, 1944, pp. 1-22.

Hickling, R., "Effects of Thermal Conduction in Sonoluminescence," Jour. Acoustical Soc. America, Vol. 35, No. 7, July, 1963, pp 967-974.

Hickling, R., and Plesset, M.S., "Collapse and Rebound of a Spherical Bubble in Water," Physics of Fluids, Vol. 7, 1964, pp. 7-14.

Hickling, R., "Compressive Effects in Cavity Collapse," Cavitation State of Knowledge, ASME Fluids Eng. and Applied Mech. Conf., Evanston, Ill, 1969, pp. 103-105.

Holl, J.W., "Limited Cavitation," Cavitation State of Knowledge, ASME, 1969, pp. 26-63.

Hsieh, D-Y., and Plesset, M.S., "Theory of Rectified Diffusion of Mass into Gas Bubbles," Jour. Acoustical Soc. America, Vol. 33, No. 2, February, 1961, pp. 206-215.

Jarman, P., "Measurements of Sonoluminescence from Pure Liquids and Some Aqueous Solutions," Proc. Phys. Soc. (London), Vol. 73, 1959, pp. 628-640.

Jarman, P., "Sonoluminescence: A Discussion," Jour. Acoustical Soc. America, Vol. 32, No. 11, November, 1960, pp. 1459-1462.

Knapp, R.T., Daily, J.W., and Hammitt, F.G., Cavitation, McGraw-Hill, New York, 1970.

Levich, V.G., Physicochemical Hydrodynamics, Prentice-Hall, Inc., Englewood Cliffs, N.J., 1962.

Lichtarowicz, A., and Pearce, I.D., "Cavitation and Aeration Effects in Long Orifices," Cavitation Conference, Institution Mechanical Engineers, Sept. 3-5, 1974, Edinburgh, pp. 129-144.

Lohrenz, H.-J., "Mikro-Dieseleffect als Folge der Kavitation in Hydrauliksystemen," (Micro-Diesel Effect as a Result of Cavitation in Hydraulic Systems), Ölhydraulic und Pneumatic, Vol. 18, No. 3, 1974, pp. 175-180.

Martin, H.R., and Lichtarowicz, A., "Theoretical Investigation into the Prevention of Cavitation in Hydraulic Actuators," Proceedings, Institution Mechanical Engineers, Vol. 181, Part 1, 1966-67, pp. 423-436.

McCloy, D., and Martin, H.R., "Some Effects of Cavitation and Flow Forces in the Electro-Hydraulic Servomechanism," Proceedings Institution Mechanical Engineers, Vol. 178, Part 1, 1963-64, pp. 539-558.

McCloy, D., "Pressure Peaks in the Hydraulic Actuator," Journal of Basic Engineering, TRANSACTIONS, ASME, Vol. 87, December, 1965, pp. 953-959.

McCloy, D., "Cavitation and Aeration - The Effect on Valves and Systems - Part II," Hydraulic and Pneumatic Power, Vol. 12, February, 1966, pp. 100-105.

McCloy, D., "Cavity Formation in Valve Controlled Hydraulic Cylinders," Proceedings, Institution Mechanical Engineers, Vol. 184, Part 1, 1969-1970, pp. 969-982.

McCloy, D., "Cavitation Effects in On-Off Controlled Hydraulic Servos," Journal of Dynamic Systems, Measurement and Control, TRANSACTIONS, ASME, Vol. 94, March, 1972, pp. 50-56.

McCloy, D., and Martin, J.R., The Control of Fluid Power, Longman, London, 1973.

Mitchell, T.M., and Hammitt, F.G.,"Collapse of a Spherical Bubble in a Pressure Gradient," ASME 1970 Cavitation Forum.

Nikiforuk, P.N., Wilson, J.N., and Lepp, R.M., "Transient Response of a Time Optimized Hydraulic Servomechanism Operating under Cavitation Conditions," Proceedings, Institution Mechanical Engineers, Vol. 185, 1970-71, pp. 837-846.

Parkin, B.R., and Kermeen, R.W., "The Role of Convective Air Diffusion and Liquid Tensile Stresses during Cavitation Inception," Proc. IAHR Symp. on Cavitation and Hydraulic Machinery, Sendai, Japan, 1962.

Plesset, M.S., "The Dynamics of Cavitation Bubbles," Jour. Appl. Mech., TRANSACTIONS, ASME, Vol. 16, 1949, pp. 228-231.

Plesset, M.S., and Prosperetti, A., "Bubble Dynamics and Cavitation," Ann. Review Fluid Mech., Vol. 9, 1977, pp. 145-185.

Rayleigh, Lord, "On the Pressure Developed in a Liquid During the Collapse of a Spherical Cavity," Phil. Mag. Vol. 34, August, 1917, pp. 94-98.

Robertson, J.M., "Cavitation Today--An Introduction," Cavitation State of Knowledge, ASME, 1969, pp. 1-9.

Szekely, J., and Martins, G.P., "Non-Equilibrium Effects in the Growth of Spherical Gas Bubbles due to Solute Diffusion-II," Chem. Eng. Sci,, Vol. 28, 1973, pp. 2127-2140.

VanWinjngaarden, L., "On the Growth of Small Cavitation Bubbles by Convective Diffusion," Int. Jour. Heat Mass Transfer, Vol. 10, 1967, pp. 127-134.

Wang, P.K.C., and Ma, J.T.S., "Cavitation in Valve-Controlled Hydraulic Actuators," Journal of Applied Mechanics, TRANSACTIONS, ASME, Vol. 85, December, 1963, pp. 537-546.

Westwater, J.W., "Measurements of Bubble Growth During Mass Transfer," Cavitation in Real Liquids, Elsevier Pub. Co., New York, 1964, pp. 34-54.

BIBLIOGRAPHY ON CAVITATION IN OIL HYDRAULIC SYSTEMS

I. CAVITATION IN VALVES AND ORIFICES

I.1 McCloy, D., and Beck, A., "Some Cavitation Effects in Spool Valve Orifices," Proceedings, Institution Mechanical Engineers, Vol. 182, Part, 1, 1967-68, pp. 163-174.

I.2 McCloy, D., and Beck, A., "Flow Hysteresis in Spool Valves," Proceedings, First Fluid Power Symposium, BHRA, January, 1969, Paper SP989.

I.3 Lichtarowicz, A., and Pearce, I.D., "Cavitation and Aeration Effects in Long Orifices," Cavitation Conference, Institution Mechanical Engineers, Sept. 3-5, 1974, Edinburgh, pp. 129-144.

I.4 Pearce, I.D., and Lichtarowicz, A., "Dishcarge Performance of Long Orifices with Cavitating Flow," Second Fluid Power Symposium, BHRA, January 4-7, 1971, Guilford, Paper D2.

I.5 Stiles, G. F., "Cavitation in Control Valves," Instruments and Control Systems, Vol. 34, November, 1961, pp. 2086-2093.

I.6 Tullis, J. P., "Cavitation Scale Effects for Valves," Journal of the Hydraulics Division, ASCE, Vol. 99, HY7, July, 1973, pp. 1109-1128.

I.7 Tullis, J.P., and Govindarajan, R., "Cavitation and Size Scale Effects for Orifices," Journal of the Hydraulics Division, ASCE, Vol 99, HY3, March, 1973, pp. 417-430.

I.8 Backé, W., and Benning, P., "Über Kavitationserscheinungen in Querschnittsverengungen von Ölhydraulischen Systemen, (Cavitation Phenomena in Narrow Passages of Oil Hydraulic Systems), Industrie Anzeiger, Vol. 63, August, 1962, pp. 35-42.

I.9 Dahm, B., "Kavitationsercheinungen an hydraulischen Schiebern und Reglern," (Cavitation Phenomena in Hydraulic Valves and Control Devices), Industrie Anzeiger, Vol. 98, December, 1976, pp. 1864-1869.

I.10 Backé, W., and Riedel, H.P., "Kavitation in Ölhydraulischen Systemen," (Cavitation in Oil Hydraulic Systems), Industrie-Anzeiger, Vol. 94, January, 1972, pp. 153-158.

I.11 Hoffman, D., "Die Dampfung von Flüssigkeitsschwingungen in Ölhydralikleitungen," (The Damping of Oscillations in Oil Hydraulic Lines), VDI-Forschungsheft 575, 1976, 48 pages.

I.12 Kobayashi, R., "Effect of Cavitation on the Discharge Coefficient of Standard Flow Nozzles," Journal of Basic Engineering, TRANSACTIONS, ASME, Vol. 89, September, 1967, pp 677-685.

I. CAVITATION IN VALVES AND ORIFICES (continued)

I.13 MacLellan, G.D.S., Mitchell, A.E., and Turnbull, E.E., "Flow Characteristics of Piston-Type Control Valves,"

I.14 Turnbull, E.E., and Whiteman, K.J.," Oscillations of Hydraulic Valves," Fifth Conference on Hydromechanics, Cranfield, England, September, 1957.

I.15 Numachi, F., Yamabe, M., and Oba, R., "Cavitation Effect on the Discharge Coefficient of the Sharp-Edged Orifice Plate," Journal of Basic Engineering, TRANSACTIONS, ASME, Vol. 82, March, 1960, pp. 1-11.

I.16 Shalven, K.K., and Chernyavskii, B.A., "Investigation of Slide-Type Electrohydraulic Control Valve Without and With Cavitation,"

II. CAVITATION IN ACTUATORS AND SERVOVALVES

II.1 Wang, P.K.C., and Ma, J.T.S., "Cavitation in Valve-Controlled Hydraulic Actuators," Journal of Applied Mechanics, TRANSACTIONS, ASME, Vol. 85, December, 1963, pp. 537-546.

II.2 McCloy, D., and Martin, H.R., "Some Effects of Cavitation and Flow Forces in the Electro-Hydraulic Servomechanism," Proceedings, Institution Mechanical Engineers, Vol. 178, Part 1, 1963-64, pp. 539-558.

II.3 McCloy, D., "Pressure Peaks in the Hydraulic Actuator," Journal of Basic Engineering, TRANSACTIONS, ASME, Vol. 87, December, 1965, pp. 953-959.

II.4 McCloy, D., "Cavitation and Aeration - The Effect on Valves and Systems - Part II," Hydraulic and Pneumatic Power, Vol. 12, February, 1966, pp. 100-105.

II.5 McCloy, D., "Cavity Formation in Valve Controlled Hydraulic Cylinders," Proceedings, Institution Mechanical Engineers, Vol. 184, Part 1, 1969-1970, pp. 969-982.

II.6 Nikiforuk, P.N., Wilson, J.N., and Lepp, R.M., "Transient Response of a Time Optimized Hydraulic Servomechanism Operating under Cavitation Conditions," Proceedings, Institution Mechanical Engineers, Vol. 185, 1970-71, pp. 837-846.

II.7 McCloy, D., "Cavitation Effects in On-Off Controlled Hydraulic Servos," Journal of Dynamic Systems, Measurement and Control, TRANSACTIONS, ASME, Vol. 94, March, 1972, pp. 50-56.

II.8 Martin, H.R., and Lichtarowicz, A., "Theoretical Investigation into the Prevention of Cavitation in Hydraulic Actuators," Proceedings, Institution Mechanical Engineers, Vol. 181, Part 1, 1966-67, pp. 423-436.

II.9 Shalnev, K.K., and Chernyavskii, B.A., "Investigation of Slide-Type Electrohydraulic Control Valve Without and With Cavitation," Proc. Fourth Conf. Fluid Machinery, Budapest, 1972, pp. 1229-1245.

II.10 McCloy, D., and Beck, A., "Flow Hysteresis in Spool Valves," First Fluid Power Symposium, Cranfield, England, January, 1969.

II.11 McCloy, D., and Martin, J.R., The Control of Fluid Power, Longman, London, 1973.

III. CAVITATION DAMAGE AND EROSION

III.1 Thiruvengadam, A., "A Unified Theory of Cavitation Damage," Journal of Basic Engineering, TRANSACTIONS, ASME, Vol. 85, September, 1963, pp. 365-376.

III.2 Martin, J.A., "Cavitation dans un Milieu Corrosif," (Cavitation in a Corrosive Medium), Die Schweizerische Bauzeitung, Vol. 89, June, 1971, pp. 587-590.

III.3 Hobbs, J. M., and McCloy, D., "Cavitation Erosion in Oil Hydraulic Equipment," Metals and Materials, Vol. 1, January, 1972, pp. 27-35.

III.4 Hirth, F.W., and Speckhardt, H., "Zur Kavitation von Kupferlegierungen in Hydraulikflüssigkeiten," (Cavitation of Copper Alloys in Hydraulic Liquids), Metall, Vol. 29, November, 1975, pp. 1106-1110.

III.5 Kleinbreuer, W., "Werkstoffzerstörung durch Kavitation in Ölhydraulischen Systemen," (Material Damage by Cavitation in Oil Hydraulic Systems), Industrie-Anzeiger, Vol. 98, 1976, pp. 1096-1100.

III.6 Endo, K., Okada, T., and Baba, Y., "Fundamental Studies on Cavitation Erosion," Bulletin, Japan Society of Mechanical Engineers, Vol. 12, 1969, page 729.

III.7 Shives, T.R., and Willard, W.A., eds., "The Role of Cavitation in Mechanical Failures," Proc. 19th Mtg. Mechanical Failures Prevention Group, National Bureau of Standards, Oct. 31-Nov. 2, 1973, Boulder, Colorado, NBS Special Publication 394, 175 pages.

III.8 Lazarenko, B. R., Bologa, M.K., Derendovsky, A.F., and Paukov, Yu N., "The Development of Cavitation Erosion and the Action of Electric Protection," Proc. Fourth Conf. Fluid Machinery, Budapest, 1972, pp. 743-754.

III.9 Rachman, D., and Connell, R., "Cavitation Erosion of White Metal on Steel Backing in Lubricating Oils," Proc. Fourth Conf. Fluid Machinery, Budapest, 1972, pp. 1091-1108.

III.10 Varga, J.J., Sebestyen, Gy., and Bata, T., "Investigation of Erosion and Acoustic Characteristics of Cavitation in Rotary Disc Equipment," Proc. Fourth Conf. Fluid Machinery, Budapest, 1972, pp. 1431-1443.

III.11 "Handbook of Cavitation Damage," Techn. Rpt. No. 233-8, Hydronautics, Inc., Laurel, Md., March, 1965, 186 pages.

III.12 Kelly, E.S., "Erosive Wear of Hydraulic Valves Operating with Fire-Resistant Emulsions," Proc. Second Fluid Power Symposium, BHRA, Cranfield, England, 1971.

III. CAVITATION DAMAGE AND EROSION (continued)

III.13 Ellis, A.T., "Production of Accelerated Cavitation Damage by an Acoustic Field in a Cylindrical Cavity," *Jour. Acoustical Society of America*, Vol. 27, No. 5, September, 1955, pp. 913-921.

III.14 Plesset, M.S., and Ellis, A. T., "On the Mechanism of Cavitation Damage," TRANSACTIONS, ASME, Vol. 77, 1955, pp. 1055-1064.

IV. MEASUREMENT TECHNIQUES AND DIAGNOSTICS

IV.1 Srinivasan, D., and Padmanabhan, V., "Investigations on the Noise Due to Acoustically Induced Cavitation in Water," Journal Scientific and Industrial Research, Vol. 21B, April, 1962, pp. 161-166.

IV.2 Rata, M., "Recensement et Examen Critique des Méthodes d' Observation de la Cavitation par Voie Acoustique," (A Review and Critical Examination of Acoustic Methods of Observing Cavitation), La Houille Blanche, No. 6, October, 1963, pp. 671-677.

IV.3 Varga, J., and Sebestyén, G., "Experimental Investigation of Cavitation Noise," La Houille Blanche, No. 8, 1966, pp. 905-910.

IV.4 Varga, J., and Sebestyén, G., "Experimental Investigations of Cavitation Erosion in the Incubation Period," La Houille Blanche, No. 8, 1966, pp. 911-916.

IV.5 Sebestyén, G., Fáy, Á., and Csemniczky, J., "Measurements of Cavitation Characteristics of a Pump Connected With Measurement of Noise," Acta Technica Academiae Scientarum Hungaricae, Vol. 66, No. 4, 1969, pp. 305-323.

IV.6 Sebestyén, G., Stvrteczky, F., and Szabó, Á., "Correlation Between the Acoustical and Erosion Properties of Cavitation in a Pump," IAHR Symp. on Current Problems Associated with Hydraulic Machinery for Pumped Storage Power Plants, Rome, 1972.

IV.7 Wolde, T. Ten, Moelker, W. H., and Mendte, K.W., "Experience with Acoustical Methods for the Detection of Cavitation in Pumps," Cavitation Conference, Institution Mechanical Engineers, Sept. 3-5, 1974, Edinburgh, pp. 363-372.

IV.8 Deeprose, W.M., King, N.W., McNulty, P.J., and Pearsall, J.S., "Cavitation Noise, Flow Noise and Erosion," Cavitation Conference Institution Mechanical Engineers, Sept. 3-5, 1974, Edinburgh, pp. 373-381.

IV.9 Tullis, J.P., "Testing Valves for Cavitation, "Cavitation Conference Institution Mechanical Engineers, Sept. 3-5, 1974, Edinburgh, pp. 47-55.

IV.10 Eich, O., "Massnahmen zur Minderung von Kavitationsgeräuschen in Geräten der Ölhydraulik," (Measures towards the Reduction of Cavitation Noise in Oil-Hydraulic Equipment), Industrie-Anzeiger, Vol. 98, May, 1976, pp. 739-743.

IV.11 Federici, G., Raiteri, E., and Siccardi, F., "Cavitation Detection and Control in Pumps," Proc. Fifth Conf. Fluid Machinery, Vol. 1, Budapest, 1975, pp. 273-284.

IV. MEASUREMENT TECHNIQUES AND DIAGNOSTICS (continued)

IV.12 Lush, P.A., "Noise From Cavitation in Venturi-Type Sections," *Proc. Fifth Conf. Fluid Machinery*, Vol. 1, Budapest, 1975, pp. 627-638.

IV.13 Rebernik, B., "Investigation on Cavitation Noise in Pumps," *Proc. Fifth Conf. Fluid Machinery*, Vol. 2, Budapest, 1975, pp. 889-899.

IV.14 Shalnev, K.K., Shalobasov, I.A., Kozirev, S.P., and Haldeev, E.V., "Cavitation Bubble in Magnetic Field," *Proc. Fifth Conf. Fluid Machinery*, Vol. 2, Budapest, 1975, pp. 1021-1028.

IV.15 Deeprose, W.M., and McNulty, P.J., "Cavitation Noise in Pumps," *Proc. Fourth Conf. Fluid Machinery*, Budapest, 1972, pp. 321-341.

IV.16 Tullis, J.P., and Govindarajan, R., "Cavitation and Size Scale Effects for Orifices," *Jour. Hyd. Div. ASCE*, Vol 99, No. HY3, March, 1973, pp. 417-430.

IV.17 Tullis, J.P., "Cavitation Scale Effects for Valves," *Jour. Hyd, Div. ASCE*, Vol. 99, No. HY7, July, 1973, pp. 1109-1128.

V. DISSOLVED GASES AND LIQUID PROPERTIES

V.1 Hayward, A.T.J., "Aeration in Hydraulic Systems--Its Assessment and Control," Institution Mechanical Engineers, Oil Hydraulics Conference, 1961, Paper 17, pp. 216-224.

V.2 Hayward, A.T.J., "Two New Instruments for Measuring the Air Content of Oil," Journal of the Institute of Petroleum, Vol. 47, March, 1961, pp. 99-106.

V.3 Buchanan, R.H., Oedjoe, D., and Wong, C.L., "Cavitation in Low-Frequency Vertically Vibrating Liquid Columns and Its Use in Liquid Degassing," Australian Chemical Engineering, Vol. 5, February, 1964, pp. 9-14.

V.4 Stepanoff, A.J., "Cavitation Properties of Liquids," Journal of Engineering for Power, Vol. 86, April, 1964, pp. 195-200.

V.5 Eller, A., and Flynn, H.G., "Rectified Diffusion During Nonlinear Pulsations and Cavitation Bubbles," Journal of the Acoustical Society of America, Vol. 37, March, 1965, pp. 493-503.

V.6 McCloy, D., "Cavitation and Aeration-The Effect on Valves and Systems," Hydraulic and Pneumatic Power, Vol. 12, January, 1966, pp. 32-37.

V.7 Magorien, V.G., "Effects of Air on Hydraulic Systems," Hydraulics and Pneumatics, October, 1967, pp. 128-131.

V.8 Neidhardt, von Ch., "Verhinderung von Kavitation in Drosselblenden von Ölsystemen," (Hinderance of Cavitation in Orifices of Oil Systems), Brennstoffe-Wärme-Kraft, Vol. 21, July, 1969, pp. 360-365.

V.9 Hatton, R.E., "Status Report on Skydrol Hydraulic Fluids," 25th Aerospace Fluid Power Conference, Oct. 31-Nov. 1, 1977, Jackson, Mississippi, 16 pages.

V.10 Riedel, H.P., "Kavitationsverhalten von verschiedenen Druckflüssigkeiten," (Cavitation Behavior of Various Liquids), Industrie-Anzeiger, Vol. 94 August, 1972, pp. 1724-1727.

V.11 Plesset, M.S., and Prosperetti, A., "Bubble Dynamics and Cavitation," Ann. Review Fluid Mech., Vol. 9, 1977, pp. 145-185.

V.12 Holl, J.W., "An Effect of Air Content on the Occurrence of Cavitation," Jour. of Basic Eng., TRANSACTIONS ASME, December, 1960, pp. 941-946.

V.13 Hsieh, D-Y., and Plesset, M.S., "Theory of Rectified Diffusion of Mass into Gas Bubbles," Jour. Acoustical Soc. America, Vol. 33, No. 2, February, 1961, pp. 206-215.

V.14 VanWijngaarden, L., "On the Growth of Small Cavitation Bubbles by Convective Diffusion," Int. Jour. Heat Mass Transfer, Vol. 10, 1967, pp. 127-134.

V.15 Tsuji, S., and Katakura, H., "A Fundamental Study of Aeration in Oil: Effect of Air Diffusion on the Change in Bubble Diameter," Bull, JSME, Vol. 19, No. 138, December, 1976, pp. 1497-1503.

V.16 Blume, K., "Luft im Hydrauliksystem," (Air in Hydraulic Systems), Ölhydraulic und Pneumatic,

VI. ELECTRICAL, THERMAL AND CHEMICAL EFFECTS

VI.1 Frenzel, H., and Schultes, H., "Luminescence in Ultrasonically Irradiated Water," Journal Physical Chemistry, Vol. 27, 1934, pp. 421-424.

VI.2 Jarman, P.D., and Taylor, K.J., "Light Emission from Cavitating Water," British Journal of Applied Physics, Vol. 15, 1964, pp. 321-322.

VI.3 Larazenko, B.R., Bologa, M.K., Derendovsky, A.F., and Paukov, Y.N., "The Development of Cavitation Erosion and the Action of Electric Protection," Elektronnaya Mat., 1965.

VI.4 Iribarne, J.V., and Mason, B.J., "Electrification Accompanying the Bursting of Bubbles in Water and Dilute Aqueous Solutions," Transactions, Faraday Society, Vol. 63, 1967.

VI.5 Shalobasov, I.A., and Shalnev, K.K., "The Effect of the External Magnetic Field on the Intensity of Cavitation Erosion," Soviet Physics, Doklady, Vol. 15, 1971.

VI.6 Medrow, R.A., and Chao, B.T., "Charges on Jet Drops Produced by Bursting Bubbles," Journal, Colloid Interface Science, Vol. 35, 1971.

VI.7 Pantony, D.A., and Stagg, D.C., "Electrification of Gas Bubbles as an Analytical Tool," Talanta, Vol. 19, 1972.

VI.8 Degrois, M., and Baldo, P., "Hypothèse de la Décharge Électrique de Bulles de la Cavitation de Gaz," (Hypotheses of the Electrical Discharge from Cavitation Bubbles), Revue d'Acoustique, Vol. 19, 1972.

VI.9 Chincholle, von L., and Goby, F., "Studie über die elektrischen Aspekte der Kavitation," (Investigations on the Electrical Aspects of Cavitation), Öesterrische Ingenieur Zeitschrift, Vol. 17, 1964, pp. 364-371.

VI.10 Burrous, M., "Recent Developments in Aviation Hydraulic Fluids," 25th Aerospace Fluid Power Conference, Oct. 31-Nov. 1, 1977, Jackson, Mississippi.

VI.11 Brennen, C., "The Dynamic Behavior and Compliance of a Stream of Cavitating Bubbles," Journal of Fluids Engineering, TRANSACTIONS, ASME, Vol. 95, December, 1973, pp. 533-541.

VI.12 Shalnev, K.K., "Influence of Magnetic Field on Cavitation and Erosion," Trans. I.A.H.R. Symposium, Section for Hydraulic Machinery. Equipment and Cavitation, Part 1, Paper H1, Stockholm, 1970.

VI.13 Bologa, M.K., Lazarenko, B.R., Paukov, Ju.N., and Derendovsky, A.F., "Cavitation and Erosion Development Under Electric Action on Zone," Trans, I.A.H.R. Symposium, Section for Hydraulic Machinery, Equipment and Cavitation, Part 1, Paper H2, Stockholm, 1970.

VI. ELECTRICAL, THERMAL AND CHEMICAL EFFECTS (continued)

VI.14 Bologa, M.K., Lazarenko, B.R., Paukov, Ju.N., and Ttjan, S.A., "The Development of Separated Cavitation Flows Under Direct Electric Current Influence," *Proc. Fifth Conf. Fluid Machinery*, Vol. 1, Budapest, 1975, pp. 113-120.

VI.15 Hammitt, F.G., Yilmaz, E., Ahmed, O., Bhatt, N.R., and Mikielewicz, J., "Effects of Magnetic and Electric Fields upon Cavitation in Conducting and Non-Conducting Fluids," *ASME Cavitation and Polyphase Flow Forum*, Minneapolis, 1975, pp. 26-28.

VI.16 Beck, T.R., Mahaffey, D.W., and Olsen, J.H., "Corrosion of Servovalves by an Electrokinetic Streaming Current," Boeing Scientific Research Laboratories Document D1-82-0839, September, 1969.

VI.17 Chincholle, L., Gimenez, G., and Goby, F., "Electrical Effects Accompanying Cavitation Events and Detection of Erosive Cavitation," *ASME Polyphase Flow and Turbomachinery Symposium*, San Francisco, December, 1968, pp. 309-326.

VI.18 Shalnev, K.K., Shalobasov, I.A., Kozirev, S.P., and Haldeev, E.V., "Cavitation Bubble in Magnetic Field," *Proc. Fifth Conf. Fluid Machinery*, Vol. 2, Budapest, 1975, pp 1021-1028.

VI.19 Lohrenz, H.-J., "Mikro-Dieseleffect als Folge der Kavitation in Hydrauliksystemen," (Micro-Diesel Effect as a Result of Cavitation in Hydraulic Systems), *Ölhydraulic und Pneumatic*, Vol. 18, No. 3, 1974, pp. 175-180.

VI.20 Hickling, R., "Compressive Effects in Cavity Collapse," *Cavitation State of Knowledge*, ASME Fluids Eng. and Applied Mech. Conf., Evanston, Ill, 1969, pp. 103-105.

VI.21 Harvey, N.E., "Sonoluminescence and Sonic Chemiluminescence," Jour. Am. Chem. Soc., Vol. 61, 1939, pp. 2392-2398.

VI.22 Jarman, P., "Measurements of Sonoluminescence from Pure Liquids and some Aqueous Solutions," *Proc. Phys. Soc. (London)*, Vol. 73, 1959, pp. 628-640.

VI.23 Jarman, P., "Sonoluminescence: A Discussion," *Jour. Acoustical Soc. America*, Vol. 32, No. 11, November, 1960, pp. 1459-1462.

VI.24 Hickling, R., "Effects of Thermal Conduction in Sonoluminescence," *Jour. Acoustical Soc. America*, Vol. 35, No. 7, July, 1963, pp 967-974.

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