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BUBBLE GROWTH AND NUCLEATION

by

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A. GENERAL GROWTH AND NUCLEATION

1. General Background

The understanding and predictability of bubble nucleation is a major problem for both cavitation and boiling heat transfer. There is a very copious literature concerning both subjects. Much of that applying to cavitation is summarized in references 1 and 2, and that for boiling in references 3 and 4. The relatively standard and well-known part of that literature will not be covered in full detail here, but rather summarized fairly briefly. In addition, some relatively new and specialized information will be discussed more fully.

2. Models and Theories

a) General

There are two major nucleation models, both of which no doubt apply to some extent in all cases, but their significance differs substantially between boiling and cavitation applications. These are the stationary crevice model, pertinent primarily to boiling cases, and the entrained nuclei model, applied primarily to cavitation, but no doubt also operative for boiling, i.e., there is the possibility of both stationary and mobile inception "nuclei". "Nucleus" in this sense refers to agglomerations of gas or vapor molecules of sufficient size to allow later growth, upon the imposition of additional heat energy in the case of boiling or reduced liquid pressure in the case of cavitation, into conventional "bubbles". These then, by definition, constitute the presence of "boiling" or "cavitation".

Stationary nuclei are generally assumed to be harbored in micro-crevices of various shapes (3,4, eg.) in the adjacent wall, while travelling nuclei are assumed entrained with the main stream, primarily for cavitation. Of course, cavitation can also be initiated in some cases by stationary nuclei (3,5,eg.) in crevices guiding wall in the minimum pressure region, and boiling can of course be influenced in some cases by the presence of travelling nuclei. In either case, there is the fact that unless nuclei of appreciable size exist, boiling and cavitation, under the minimum superheat or under-pressure conditions under which they are commonly observed, could not exist. In most simple terms, this conclusion results from the static force balance at bubble wall between surface tension and pressure differential:

$$P_v - P_L = 2\,\sigma/R \qquad \text{--} \quad (3\text{-}1)$$

where the subscript v signifies vapor (and/or gas), and L liquid, P signifies pressure at bubble wall, and σ is surface tens Of course Eq. (3-1) is not pertinent when R approaches molecular dimensions.

From a slightly different viewpoint, all liquids possess a substantial tensile strength which greatly exceeds the observed under-pressures required to provoke bubble nucleation (1-4, eg.). Thus the generally observed existence of nucleation under many engineering conditions indicates the presence of "nuclei", i.e., small "micro-bubbles". Then generally small under-pressures of the magnitude predicted by Eq. (3-1) cause them to "nucleate" into the normally visible size range ($\sim$ 0.1 mm) associated with normal boil or cavitation.

A model which predicts stabilized nuclei, both stationary and entrained in the flow, is thus required. However, a simple, uncoated, static vapor micro-bubble is not possible, since its existence according to Eq. (3-1) requires an internal pressure greater than the vapor pressure of the surrounding liquid to overcome the effects of surface tension, which otherwise would cause its immediate collapse. The persistence of a simple gas micro-bubble is not possible either. According to Eq. (3-1) the internal gas pressure would be greater than the saturated gas pressure in the surrounding liquid, so that the gas would relatively quickly escape into the liquid by diffusion effects, if the bubble were in the "micro-bubble" size range. If it were larger, it would quickly escape by bouyancy effects, at least in a static liquid. This situation gives rise to the "micro-bubble paradox", the present resolution of which is described next.

b. Micro-Bubble Paradox

The "micro-bubble paradox" refers to the fact that experimental values of under-pressure or superheat necessary to provoke bubble nucleation generally are at least an order of magnitude less than the theoretically-predicted values of liquid tensile strength would indicate should be the case, even though extreme care is taken to de-gassify and purify the liquid. Thus the existence of stabilized gas or vapor micro-bubbles, or conceivably unwetted solid particles, must be postulated to explain the observed nucleation threshold values. Historically, from the viewpoint of cavitation, this situation was first documented in the papers of Harvey (6-9, eg.), who proposed (1944-45) the mechanism still generally believed to be pertinent in most cases. This model is discussed in detail in in Cavitation (1), but will also be covered here. The same mechan in stationary crevices is also believed generally predominent in boiling. While Harvey's work involved fluid-dynamic cavitation, many later and more precise experiments have utilized ultrasonic radiation of the test liquid.

For present illustrative purposes, consider a glass water-filled beaker, irradiated by an ultrasonic sound field of known and adjustable strength, so that the imposed pressure oscillation necessary to provoke visible bubble nucleation can be determined. This then provides a method for measuring bubble nucleation threshold for various liquid conditions. If the water is carefully filtered to remove solid particles down to an arbitrarily small size, and also well-deareated so that any entrained gas bubbles will either quickly go into solution or rise to the surface, there is then no apparent mechanism for the persistence of nucleation centers. Nevertheless, in such an experiment it is invariably found that the pressure oscillation magnitude is much less than would be expected if full pure liquid tensile strength values were realized. This is the case even if long settling times are provided to allow very small gas bubbles to dissolve, and larger bubbles to rise to the surface under easily calculable bouyancy effects. Also, as previously mentioned, pure vapor bubbles could not exist under such conditions due to surface tension effects. Hence the "micro-bubble paradox", and the necessity for the postulation of a "stabilized nucleus" mechanism exists.

Many explanations of this "paradox" have been suggested, including the continued generation of new "nuclei" by the action of cosmic ray bombardment (10,11,eg.), similar to the conventional "bubble chamber" mechanism used in high-energy physics for the study of nuclear radiations. While this and other specialized mechanisms may in fact sometimes contribute, it is generally assumed today that the mechanism originally proposed by Harvey and colleagues (6-9, eg.) is most probably most important.

c. Harvey Micro-Particle and Crevice Mechanism

Harvey, et al (6-9, eg.) proposed entrained micro-particles in the liquid, containing in themselves unwetted acute-angle micro-crevices. The proposed mechanism is illustratted in Fig. 3-1 (reproducedfrom ref. 1 for convenience). Essentially an "unwetted", i.e., "hydrophobic" acute-angle crevice in an entrained micro-particle is required. In this case, as shown in Fig. 3-1, the meniscus curvature is such that if the crevice walls are unwetted, the pressure in the gas pocket at the apex of the crevice is less than that in the adjacent liquid. According to Eq. (3-1), this liquid-gas pressure differential will increase as the radius of curvature decreases. This will occur if the interface advances more deeply into the acute-angle crevice. Thus the interface will advance into the crevice, with gas solution and diffusion across the interface continuing, until the gas pressure becomes sufficiently low, following Eq. (3-1), that it is equal to the partial pressure of the gas in the liquid. Further solution and diffusion of gas into the liquid will not occur, since no further solution concentration gradient will then exist.

Thus the gas cavity would become stabilized over indefinite time periods by this mechanism, whereas the same geometry with wetted crevice walls would lead to complete extinction of the cavity by gas solution effects.

The degree of gas saturation content in the liquid would not affect the eventual fate of the gas pocket, only the time required for it to be achieved, according to this model. Thus any degree of possible deaereation would not eliminate nucleation "nuclei" completely, since zero gas content is completely attainable. Also the type of gas and liquid involved would not affect the eventual outcome, assuming that less than infinite solubility for the gas in the liquid exists. Thus the mechanism appears pert to all liquid-gas combinations. Of course, increased gas pressure for fixed total gas content would result in reduction in nuclei size, as originally demonstrated by Harvey (6-9, eg.), and corresponding increase in nucleation threshold, i.e., increase in required "under-pressure", or reduction in actual liquid pressure. This was later demonstrated by Knapp (1,12,eg.) in experiments with cavitating venturis. The original Harvey work (1944-45) as a matter of interest, was motivated by the effects of bullet impact upon flesh, and the resultant cavitation induced in the wake of a bullet passing through a human body, eg. This cavity is presumably responsible in many cases for most of the resulting damage.

The effect of vapor within such an acute-angle crevice is the same as that of gas, since the vapor can exist in perpetuity at a pressure sufficiently less than that of the surrounding liqui Thus it would not be extinguished by any degree of "sub-cooling", or suppression pressure in the case of cavitation. The effects of gas and vapor together are obviously simply additive.

d. Alternative Nuclei Stabilization Mechanisms

1) Fox and Herzfeld Organic Skin Model (13, eg.)

The most prominent models for micro-nuclei stabilization, other than that of Harvey discussed above, are probably those assuming a bubble wall interface consisting of some impurity material capable of withstanding compressive strengths, and preventing or reducing gas diffusion between liquid and micro-bubble contents. If such a bubble wall were presumed, it would be capable of allowing an internal gas or vapor pressure less than that of the surrounding liquid in spite of the effects of surface tension or sub-cooling, so that a nucleus stabilizing mechanism would be provided. One of the earliest and best known proposals of this sort was that of Fox and Herzfeld (13, eg.) who postulated the existence of an organic skin formed of impurities in the liquid, particularly pertinent to cases of relatively impure natural water or sea water. This skin would be capable of withstanding some compressive stress and also prevent or reduce the outward diffusion of gas or vapor. This model is discussed in more detail in Cavitation (1). Later experiments by Bernd (14,eg.) seemed to confirm its existence at least in some cases, although the original authors later disclaimed its probable importance. In the opinion of the present author, it seems likely that the Fox-Herzfeld model may apply to some extent in some cases, but that it is in general probably less important than that of Harvey.

2) Unwetted Mote Model

It is apparent that small particles, or "motes", which are entirely or partially unwet by the liquid, can provide bubble nucleation "nuclei", even without the presence of gas, other than the inevitably present vapor of the liquid. The idea has been recently advanced by Plesset (15) that such unwetted motes would provide "weak spots" in the liquid, i.e., "stress raisers" from the viewpoint of solid mechanics, about which tensile failure of the liquid will occur at under-pressures much less than the theoretical strength of the pure liquid.

3) Regeneration Models

a) Cosmic and Nuclear Radiation

An alternative to a micro-bubble stabilization model is one assuming a constant balance between micro-bubble destruction and regeneration. Since some continuous elimination of nuclei must occur in almost all real situations, due to such effects as solution, disentrainment, entrappment in static regions, centrifugal disentrainment effects, etc., it must also be true that some countering mechanisms, which create nuclei must also exist in most real cases. A relatively exotic, but probably operative mechanism in some cases, was suggested by Sette, etal (10,11,eg.), i.e., the action of cosmic radiation. They verified the existence of this effect in a case involving ultrasonic cavitation by comparing nucleation sonic pressure threshold variation in their test beake with and without external lead shielding. Of course it is well-known (16, eg.) that high energy radiation of this sort can under some conditions, e.g., bubble chamber, cause bubble nucleation. While the cosmic ray effect is probably not significant in most engineering cavitation cases, it is certainly quite likely that nuclear radiation effects can importantly affect nucleation thresholds in liquid-cooled nuclear reactor situations (17-19, eg.). Of course the effect must always be in the direction of promoting nucleation and thus reducing required underpressures or superheats. This has especial practical importance in sodium-cooled reactors because of the sometimes appearance of large "sodium superheats".(20,eg

b) Gas Entrainment

A less exotic, and no doubt generally much more important mechanism for the generation of "nuclei" is that of gas entrainment, which may occur wherever a free surface is present. The high level of entrained micro-bubbles in normal tap water presumably results from the effect of such free surfaces as found in storage reservoirs, etc. Presumably there is also a high level of gas entrainment in most engineering equipment such as powerplant circuits and components, nuclear reactor flow circuits, the open ocean or other large bodies of water, and in most other important engineering applications. Thus a substantial lack of nuclei for bubble nucleation is to be expected only in very special cases where extraordinary degrees of gas removal and liquid purity are maintained.

Another practically important mechanism for the generation of entrained nuclei is that associated with "rectified diffusion" of gas or heat.

4. Gas and Heat Diffusion Effects

a) Conventional Diffusion

Many operative mechanisms pertinent to either generation or regeneration of nuclei involve conventional diffusion of both gas and heat. Such mechanisms are predominent particularly in the case of bubble nucleation from stationary crevices as in most boiling cases (3,4,eg.), and will be discussed later in further detail in that connection. However, they are obviously also of importance for stabilized entrained nuclei such as have been discussed in the foregoing sections, at least for cases where either the bubb motion carries it into regions where the partial pressure of the gas dissolved in the liquid is greater than that within the entrained nucleus, or the liquid temperature in some region of the circuit, through which the entrained nucleus passes before reaching the cavitation region, is greater than the saturation temperature corresponding to the vapor pressure existing within the bubble. However, the effects of such conventional diffusion are relatively slow, so that in many cases involving entrained nuclei, adequate time is not available to make such conventional diffusion important. This is obviously not generally a limitati for cases of nuclei in stationary crevices, for either boiling or cavitation.

b) Rectified Diffusion Effects

The effects of diffusion of either gas or heat can be greatly enhanced by the existence of "rectified diffusion". This is particularly important for cases of ultrasonic cavitatio involving thousands of cycles of pressure oscillation per second as perhaps originally investigated by Plesset (21, eg.). Under conditions of ultrasonic cavitation, gas nuclei are "inflated" rapidly and substantially by the effects of "rectified diffusion i.e., the gas diffusion effects upon a bubble in an oscillating pressure field are non-symmetrical, so that there is a net inwar flow of gas. In simplest terms, the bubble surface area is augmented during the low pressure part of the cycle, and diminis during the high pressure portion. Thus more inward gas diffusio occurs during the low pressure portion of the cycle, than outward diffusion during the high-pressure portion, when the surface area is relatively reduced. An analogous rectified diffusion effect can also be postulated for heat or any other quantity, the transfer of which depends essentially upon the linear diffusion law, i.e., "Fick's law".

Rectified diffusion effects, particularly for gas, were first noted and studied (21, eg.) for ultrasonic cavitation, where at least the gas effect is now generally accepted as of major importance. Since these rectified transfer effects depend upon large and rapid pressure oscillations, they are obviously not pertinent to ideally steady-state flowing systems. However, the existence of substantial turbulent pressure fluctuations in most engineering flowing systems provides the necessary pressure oscillations for at least the existence of such rectified bubble wall transfer mechanisms. Some computerized studies of such effects for flowing loops are reported, but no definitive results have yet been reported to my knowledge. Aside from the possibility of rectified turbulent diffusion mechanisms for potential nucleatio nuclei in flowing systems, there is also the possibility of relative velocities between nuclei and mean liquid velocity in such systems, i.e., "slip", particularly predominent for gas or vapor (rather than solid) particles, with or without turbulent effects. Such relative velocities would add to the apparent diffusion effects, since actual transport phenomena rather than simple static diffusion would then be involved. Obviously a quantitative solution of this overall problem would be highly complex.

5. Relative Velocity Effects

An important practical effect of relative (slip) velocity in cavitating systems is the "wind-shield" effect, i.e., gas or other low density nuclei entrained in a liquid flow will tend to avoid regions of increasing pressure and will be "attracted" in the directi of decreasing pressure by the action of slip velocity effects. This problem was investigated in some detail by Daily and Johnson (22) concerning cavitation inception effects. In general, it is thus then clear that a homogenous distribution of entrained gas or vapor nuclei in a liquid flow approaching a submerged object will become non-homog in the vicinity of the object. There will then develop a relative scarcity of nuclei in regions of rising pressure, such as near stagnation regions on the leading edge of an object, or on the outside of a pipe bend. On the other hand, there will be relatively increased nuclei population density in the low pressure region along a submerge body where cavitation inception would be expected to occur, or on the inside of a bend. Thus this "windshield effect" will in general increase the likelihood of cavitation inception for a given spectrum of upstream nuclei.

Of course, the nuclei trajectories relative to the mean liquid flow will depend upon nuclei size, shape and density relative to liquid density. Their trajectory will depend upon the balance between fluid-dynamic drag forces, and inertial and pressure forces. Thus very small nuclei, having a relatively very large ratio of surface area to volume, will exhibit less slip relative to the liqui than larger bubbles, the shape of which in their growth or collapse will also influence the problem.

Yeh and Yang (23) investigated these effects for larger bubbles, considering the effects of bubble profile asymmetries in a cavitatin venturi, showing that either negative or positive slip was possible, depending upon the relative velocity and other parameters as the bubbles entered the diffuser section of the venturi. These calculations were confirmed experimentally in this laboratory (24). A very recent study of this same venturi flow geometry but neglecting bubble asymmetries, is reported by Chincholle and Sevastianov (25), confirming the Yeh-Yang results with a somewhat simplified calculating mod

6. Special Shear Flow Effects

Separated flows, such as those downstream of an orifice, nozzle, or valve discharging into a submerged region, differ substantially in terms of cavitation inception sigma, from non-separated flows, such as, e.g., in a well-designed venturi or along a hydrofoil section of relatively gradual curvature. The inception sigmas for such separated flow geometries are in fact much greater than are normally encountered for "streamlined flows", as discussed in more detail in later sections of this book, and also in Cavitation (1), as well as elsewhere. The mechanism motivating this greatly increased cavitation sigma is presumably the presence of micro-vortices in the separated region, the center of which present very substantial and local underpressures. Such vortex cavitation is also common in the trailing vortices from propellor blades, unshrouded pump or turbine blades, or hydrofoils. In many cases, this type of cavitation does not lead to substantial damage effects, since the vortices in such cases as orifices and nozzles, propellor blades, etc., collapse far from material objects. This, however, may not be the case for unshrouded pump or turbine blades. The strength of the micro-vortices would of course depend strongly on viscosity and other fluid parameters, discussed later in the section on viscous effects.

Normal boundary layer flow of course also presents a shear flow region where micro-vortices and other turbulent manisfestations would no doubt influence cavitation sigma. This situation was investigated particularly by Daily and Johnson (22), and later Arndt and Ippen (26-27), with results discussed in Cavitation (1), where the probable effects of boundary layer turbulence upon inceptio sigma are discussed and tabulated. Holl in related studies (28-30, eg.) investigated the effects of finite and regular forms of wall roughness upon inception sigma.

Another very interesting effect of wall proximity is related to the fact that for potential flow (31, eg.) assumptions it can be shown that the pressures within the fluid cannot be less than a wall pressure, i.e., the locations of minimum and maximum pressure for a potential flow regime must be along a boundary, assuming other than simple one-dimensional translatory flow. Thus some streamline curvature must give actual minimum pressure along the wall, i.e., wall pressure must be somewhere less than mean stream pressure, thus indicating the probability of bubble inception within a boundary layer, where the above discussed effects of boundary layer turbulence and vortices would be operative.

7. Liquid Cavitatability

In principle, it should be possible to compute cavitation thresholds, or boiling superheat requirement, from essentially "basic principles", i.e., if the detailed characteristics of the operative entrained or stationary "nuclei" were known, as well as the details of the flow regime, then it should be possible with modern-day computer techniques, to accurately compute nucleation thresholds for any given case. While attainment of this capability is no doubt the desired objective of research in this field, it has not yet been attained to a useful degree, because of the very large complexities of the problem, as discussed in the foregoing sections. Hence, another alternative, at least from the viewpoint of nuclei content, would be the use of a "standard cavitator" to measure the cavitatability of the liquid in use, as it exists under the particular application. For example, such a device could be used to measure the "nucleation resistence" of molten sodium in a nuclear reactor circuit under the particular conditions pertinent to that circuit. A simple small-scale venturi in a by-pass loop might be used for this purpose. The use of such a venturi for water tests was suggested recently by Oldenziel (32). Work toward the development of an ultrasonic device for testing the cavitatability of sodium has also been reported (33). In principle, the adoption of this techique would avoid the detailed measuement of nucleation "nuclei" spectra, and the subsequent calculation of their effect upon bubble nucleation. They would be replaced by a simple measurement of cavitation sigma (or superheat) under a simple standard condition, and then its calculation from this measured point in the realistic geometry.

e. Pertinence of Entrained Nuclei Models to Stationary Crevice Nucleation

Many of the previous sections obviously apply particularly to "travelling nuclei", which it is generally believed are of primary importance in cavitation, but less so in boiling where stationary crevices in the heated walls are supposedly of predominent importance. Of course, if in a particular case these are absent, the possibility of the attainment of large superheats would then be obviated by the presence of entrained nuclei. This factor could be of considerable importance in such applications as the sodium-cooled nuclear reactor, where the possibility of substantial "sodium-superheat" has been an important problem related to reactor safety. In many cases of conventional cavitation, there is also the possibility of an important contribution from nuclei entrapped in stationary crevices in the region of minimum pressure.

While some of the mechanisms discussed in the foregoing obviously do not apply to stationary crevices, or to boiling applications in general in some cases, some obviously do apply almost directly, particularly those having do with liquid tensile strength, and the necessity for stabilization mechanisms for nuclei. The role of gas diffusion effects in this case differs somewhat between stationary and travelling nuclei. For example, in many cases involving travelli nuclei, sufficient time is not afforded to allow gas diffusion effects to become important. The growth (or collapse) of a small bubble passing through a region of strong pressure gradients in a flowing system does not react primarily to gas-diffusion effects, but rather to the effects of surface tension, pressure, and inertia. As previously indicated, these effects may become important in cases of very rapid and repeated pressure variation through "rectified diffusion" effects, such as encountered in "ultrasonic cavitation", or conceivably in flowing cavitation through the effects of turbulent pressure and velocity variations. However, the situation is very different for nuclei entrapped in a stationary crevice in a flow field. In this case, since the nucleus is stationary, it cannot be assumed that sufficient time for substantial conventional diffusion effects will not be available. Thus there is no difficulty imposed upon the continued growth of a gas or vapor nucleus entrapped in the low pressure region of a cavitating body, provided the dissolved gas content of the liquid is sufficient. Of course in this case also there is the possibility of added rectified diffusion effects, due to pressure variations from turbulence or pressure pulsations in the main flow, as, e.g., from the action of a centrifugal pump, trailing vortices from a submerged object, or similar cause.

3. Bubble Growth Dynamics

a. General

From a relatively general viewpoint, the subject of bubble dynamics is discussed in detail in Chapter IV, primarily from the viewpoint of cavitation (Section IV-A), but boiling bubble dynamics are also included, and the differences between boiling and cavitation analyses are discussed. Both growth and collapse are considered, but again the emphasis is upon collapse, since that is of more pressing interest for the cavitation case. In general the emphasis is on the intermediate portion and termination of collapse, rather than initial growth, i.e., "nucleation", which is the subject of the present chapter. It is the purpose of the present section to consider the differences between bubble dynamics analyses pertinent especially to the nucleation phase as opposed to more general bubble dynamics, including the collapse portion.

b. Nucleation vs. General Bubble Dynamics

As discussed in detail in Chapter IV, the problem of single bubble dynamics in the general case, is controlled by the interaction of the effects of pressure differential between bubble contents and external liquid, inertial effects, viscous effects, and heat transfer restraints. The latter are primarily important in boiling cases, but also in the final phases of symmetrical collapse. Surface tension effects are not important during these phases of bubble dynamics, but asymmetrical effects induced by external asymmetries are of major importance in collapse, controlling the type of collapse which occurs. For nucleation, on the other hand, surface tension is of major importance (Eq. 3-1) in controlling the size of "nucleus" which will be available for future growth into actual bubbles, generally of visible size. Initial growth is then most closely controlled by the balance between internal and external pressure and surface tension. The initial rate of growth may also depend upon either inertial or thermal restraints, or in some cases upon gaseous diffusion effects, as already discusse The latter are usually not of importance for cases of cavitation bubble collapse, since insufficient time is afforded. Gaseous diffusion, however, is of major importance in nucleation, since this depends upon the stabilization and gradual growth of small gaseous or vaporous "nuclei". Whether these are located in stationary wall crevices or in entrained micro-particles, adequate time for gaseous, or heat, diffusion effects is often available. For entrained nuclei, sufficient time for important diffusion effects during the passage through the minimum pressure region where cavitation occurs may not exist. However, prior to their arrival at the minimum pressure point, relatively long exposure to the surrounding liquid may exist. This is especially the case for closed loop geometries. To prevent the gradual accumulation of nuclei of this type, some large cavitation research tunnels include special "resorbers" for entrained nuclei (1). The behavior of entrained nuclei in such circuits is complicated, from the viewpoint of analysis, by the effects of turbulent pressure and velocity oscillations to which they are exposed, providing the possibility of "rectified diffusion" effects, as discussed elsewhere.

1) Stability and Asymmetrical Effects

As previously indicated, asymmetrical effects are very important in bubble collapse and cavitation damage, since both photographic and theoretical evidence shows that the basic form of the collapse is entirely controlled by these effects, so that the basic Rayleigh (1, eg.) spherical collapse model becomes essentially inapplicable in many cases. However, analogous asymmetrical fects are not of comparable importance in bubble nucleation. Of course spherical symmetry would not normally be assumed in any case for nucleation, except for "homogeneous nucleation" from the main stream where it is in fact applicable, since nucleation originates otherwise from acute angle crevices which obviously control the bubble geometry.

On both theoretical and experimental grounds, spherical bubble growth is inherently much more stable than collapse. As initially shown by Plesset (34,35), bubble collapse from an initially spherical shape is inherently unstable , while growth from an initially spherical shape is stable, i.e., a small asymmetric perturbation imposed upon a spherically collapsing bubble will grow in many cases, while the same is not true to the same extent for a growing bubble. This situation is somewhat analogous to the well-known

Taylor instability (36,37) involving the acceleration of a low density fluid torward one of relatively higher density in a planar geometry, as in a gravity or centrifugal field. The situation however is reversed for the spherical geometry, where the acceleration of the heavier fluid toward the lighter fluid, as in the bubble collapse, is the more unstable.

The question of these bubble collapse and growth instabilities is discussed in considerable detail in Cavitation (1), along with the related work of Plesset concerning particularly the relation between the Taylor instability for a planar case and the instabiliti applicable to the spherical geometry. These instabilities originate presumably from miscellaneous small perturbations of an initially spherical shape. However, in most cases much more substan asymmetries result from virtual mass effects related to such asymmet cal factors as wall proximity, external liquid translatory velocity, external pressure or velocity gradients, or imposed accelerations such as gravity or centrifugal effects in many common flow cases. These questions are discussed in further detail in Chapter IV.

4. Magnetic and Electrostatic Field Effects

Various recent experiments from both the USSR and Japan indicate the existence of significant effects of magnetic fields and electrostatic fields on cavitation damage (38,39,eg.) and bubble growth (40 or nucleation sigma (41,42, eg.). While some of these tests were in liquid metals (38,41,42), others were in ordinary tap water (39,4 and most involved magnetic rather than electrostatic fields. If these effects do in fact exist in water they may indicate a strong ionized layer along the liquid vapor interface. At the moment this seems the only credible mechanism. The effects in liquid metals (41) may also operative through rearrangement of upstream velocity profiles.

These effects are of interest not only from the viewpoint of basic science, but also in connection with various fusion power reactor concepts involving the pumping of liquid metal coolants through strong magnetic fields. Another less exotic application involving water is that of the cooling of certain computer components.

Recent experiments in this laboratory have been conducted for both tap water and mercury using "ultrasonic cavitation" with a magnetic field strength in the cavitating region of ~ 6 kG (19). This is only about 1/10 the magnetic field strength pertinent to the fusion reactor concepts. Our tests (19) indicated no measurable effect on either nucleation thresholds or nuclei spectra (for water, measured using laser light scattering as discussed in Section B of this chapter). From these results, any such effect must have been less than $\sim 3\%$ for cavitation threshold and $\lesssim 1\%$ for nucleus spectrum. These negative results are not, however, in accord with those of the other previous investigators (38-42, eg.). However, our experiment was the only one involving nucleation thresholds with ultrasonic rather than flowing cavitation. Hence it may be assumed perhaps that this type of cavitation is less sensitive to magnetic field nucleation effects than are flowing cavitation regimes. Intuitively, this does not seem unreasonable, since much greater under-pressure values are involves with the ultrasonic cavitation experiment.

B. Effects of Air and Gas Content

1. General Background

The major past and on-going studies of the effects of gas content upon cavitation are reviewed in this section. Those studies are considered first which provide information directly applicable to the estimation of air content effects upon cavitation inception sigma or other performance parameters. Next, studies are considered which are of more basic nature. Finally, those studies pertinent to a prediction of the effects of gas content upon cavitation damage are discussed. Conclusions where possible,and recommendations for future directions of research are included.

Nucleation thresholds of liquids, whether in cavitation or boiling, depend very strongly on the population and size spectrum of microbubbles (gas "nuclei") in the liquid. In addition, the violence of collapse of cavitation bubbles appears also to be strongly influenced by the quantity of gas (free or dissolved) in the liquid. Cavitation damage is thus usually found to be reduced for "gassy" liquids. While the existence of substantial effects of gas (or air) content upon both the inception of cavitation (or boiling) and cavitation damage has long been recognized, no full understanding of these effects, or any simple and reliable method for their prediction is available. A large quantity of pertinent, sometimes conflicting, technical literature exists. Reasonably complete survey reports have been published (43, eg.)

a. Air Content Effects

The effects of air content (or gas content in general) upon cavitation can be considered under three main headings, of which the first is probably the most important, i.e.,

1) Cavitation inception sigma
2) Flow regime, torque, power, head, efficiency, noise, vibration, etc. for well-developed cavitation.
3) Cavitation erosion

There is evidence of important air content effects under each of these three headings, and these will be considered elsewhere. However, a major portion of the research has been concentrated under the first category for which theoretical treatments are more possible. This category is also the subject of the present section.

The available information can also be divided as follows:

1) That which is directly applicable to the prediction of field and laboratory performance.
2) That which is primarily of the nature of basic research which can then be used to clarify the observed trends or make meaningful predictions from observed trends.

2. Data Directly Applicable to Sigma and Performance Effects of Air Content

There have been numerous fairly systematic and comprehensive studies of the effects of air content upon cavitation inception sigma (or boiling nucleation), and also upon its effects, after initiation, upon head, efficiency, power, etc. However, it is difficult to apply this information in general because of the large number of independent parameters having an apparently very important influence upon the results. The importance of some of these has not been recognized until recently, and it seems probable that insufficient understanding of the overall phenomena exists to define and construct a basic test which would provide data entirely applicable to the various prototype or model devices at this time. There are two primary reasons for this:

i) Experimental Difficulty

No readily practical and usable method exists as yet for the measurement of the number, size and location distribution of the very small entrained gas "nuclei" in the flow from which audible and visible cavitation develop, the effects of which can be measurable upon machine performance, etc. These "microbubbles" probably cover the diameter range of 10^{-5}-10^{-3} cm, thus being invisible to the unaided eye. Knowledge of the total gas content is insufficient in itself.

ii) Theoretical Difficulty

It is not possible to describe in sufficient detail actual flow patterns in order to delineate the pressure and velocity history, or the trajectory, of a given gaseous "nucleus", assuming that its position and condition at a given instant of time were known by such a measurement as that discussed above. The realistic problem is 2-or 3-dimensional (depending upon the type of device), essentially biphasic in nature (even if only a question of cavitation inception), since the trajectory of the low-density entrained nuclei may not even be approximately that of the liquid, if important pressure or velocity gradients exist. Finally, turbulence must be considered, since turbulent fluctuations importantly influence gas diffusion effects into and from the nuclei, as well as affecting the liklihood of cavitation inception through the application to the gas nucleus of instantaneous pressures, which may be considerably below the time-mean pressure. These questions were discussed in the last section.

Thus a complete solution of the air effects problem seems unlikely at this time. However, an improving theoretical understanding of the phenomena involved, the increasing availability of large computers, and the on-going development of instrumentation techniques continually reduces the gap between the possibilities of basic investigations and their direct application to model and prototype devices. Pertinent studies date from the 1930's. These are considered under the continuing efforts of various institutions, universities, companies, etc., rather than as isolated papers by individuals. More complete detail is provided elsewhere (1).

a. F. Numachi and T. Kurokawa, Institute of High Speed Mechanics, Tohoku University, Sendai, Japan(44-49). This group working in the late 1930(s) apparently conducted the earliest comprehensive investigations of the effects of total air content upon cavitation sigma. Both a venturi test section and an isolated profile were used. Tests were in distilled water, tap water, and salt water(44-49). Water temperature covered the range 10-40°C, and air content 0.3-1.3 saturation at STP, measured by Van Slyke.

In general, a fairly linear rise of inception sigma with air content was observed with greater effect at lower temperature. The change in sigma was considerable, ranging from up to tenfold in the venturi to 20-50% for profile tests. Figure 1 is typical of their results.

b. H. Edstrand, H. Lindgren and C. A. Johnson, Swedish State Shipbuilding Tank, Goteborg, Sweden(50-52). This group has reported a very comprehensive series of experiments on the effects of air content on inception sigma and other performance parameters for marine propellers in both tap water and sea water (1946-1950, Ref.(50,51). More recent data is found in Ref. (43). A substantial effect of relative air content ranging between

0.23 and 0.73, i.e. relative to saturation at STP,was noted with efficiency,as relative air content dropped from 0.62 to 0.48 for a given advance coefficient and sigma. Figure 2 is typical. Their results differ considerably from those of Numachi, et al(44-49), and the geometries tested are very different. Some difference between tap and sea water was found, though not so great as that found by Numachi. This comparison is shown in Fig. 3. They also noted a considerable effect upon inception sigma of the rate of lowering of pressure to obtain cavitation (52). They thus confirmed that inception sigma is not determined solely by the flow parameters and total air content. They found also that the type of cavitation influenced the magnitude of the air content effect. For inception, they found large effects for "laminar cavitation" steady-state cavities. The variation in performance parameters such as torque, thrust, and efficiency was little affected however by large differences in total air.

c. Escher-Wyss and I. Vuskovic (53). A relatively comprehensive series of tests on air content effects upon both performance and erosion in a Kaplan turbine was reported by Vuskovic working at Escher-Wyss (53) in 1940. The damage will be discussed in a later chapter.

Vuskovic observed a tip-vortex cavitation (which he considered to be simply "gaseous" rather than true "vaporous" cavitation, to use present-day termininology), the inception of which was sensitive to air content. However, this type of cavitation in his tests had little effect upon turbine performance parameters such as torque, etc. Vuskovic observed "true" cavitation, which comprised a heavier and whiter cloud, which does affect turbine performance, but which is not sensitive to air content.

d.Miscellaneous Venturi Tests - Crump(54,55), Williams and McNulty (56), Ziegler (57). In the 1940(s) and 50(s), various relatively isolated tests of the effects of total air content upon cavitation inception sigma are reported e.g., Ref. (54-57) The tests are rather similar to the earlier tests of Numuchi(44-49) However, the results of the various investigators do not agree quantitatively, and there is scatter in the individual data sets. In general, inception sigma is reduced for reduced air content, and for the lowest air contents, liquid tensions sometimes appear. A "hysteresis effect" is noted in one of these studies (56). showing again the impossibility of representing air content effects in terms of total air content only, i.e., presumably the hysteresis effect is due to changes in nuclei content between inception and desinence, though total air content remains constant.

e. Large Water Tunnel Investigations in USA - Pennsylvania State University (Penn State), University of Minnesota (U-Minn), California Institute of Technology (CIT) (16-23 , 58-65). Work in the USA on gas content effects upon inception sigma for submerged objects has been largely conducted since World War II, and in the large water tunnels of Penn State, CIT, and U-Minn. While the work at CIT has not involved air content effects specifically, it has served as a good basis for comparison with other investigators.

The work of these various institutions (pertinent to the present discussion) has centered upon the observed difference in sigma between incidence and "desinence", so named by Holl (5,60). It was generally found that desinent sigma exceeds inception sigma, so that a "hysteresis" exists. This difference appears to decrease with increased velocity or size, so that it is actually a "scale effect". It was further found that desinent sigma data exhibits much less scatter than incident. Inception sigma depends upon rate of lowering of pressure, as also reported by Lindgren and Johnsson (52).

All the above effects appear closely connected with the details of the nucleation process from entrained or stationary "nuclei". Hence, knowledge of the distribution and size spectra of these nuclei is needed. Recent work at U-Minn has been aimed in this direction. Ripken and Killen (61) found an equilibrium of entrained gas nuclei to be attained in a closed tunnel for given tunnel conditions. They also found no hysteresis if the free gas conditions were maintained the same, so that hysteresis ceases to be a scale effect under these conditions. The U-Minn investigators also developed a method for the continuous monitoring of the free gas distribution, using its effects upon velocity of propagation of a pressure pulse and the attention of pressure pulses with resonant bubbles. (1,61-64).

f. Bassin d'Essais des Carènes, Paris (65-67). A comprehensive series of tests has been conducted by Bindel et al. on the effects of the variation of total air content upon inception sigma for various ogives, hydrofoils, and propellers (65-67). In agreement with Vuskovic at Escher-Wyss (53) and Edstrand, et al. (50-52) in Sweden, they found that the effects of velocity and total air content upon sigma depend strongly on the type of cavitation. They observed bubble (or "burbling") cavitation, cavitation by lamina (steady-cavity), and vortex cavitation, although all types did not appear in all tests. Figure 4 is typical. In general, an increase of air or velocity reduces sigma. Their results are qualitatively similar to those of both Edstrand and Vuskovic, in that they found large effects of air for vortex cavitation, and little effect with laminar cavitation. The data for "burbling cavitation" are less consistent between Bindel, et al.

and the others.

A further result of Bindel, et al. is that velocity and air content effects are not independent. In all cases where there is an effect of air content, an increase therein favoring the appearance of cavitation. However, the effect of velocity increase upon sigma is not consistent in direction, and depends upon other conditions.

g. National Physical Laboratory Water Tunnel Tests, Teddington, U.K., (68). Propeller performance tests are reported by Silverleaf and Berry (68) in which total air content was varied. An ultrasonic transmission method was tried unsuccessfully to distinguish entrained from dissolved gas. Again it was found that the development of cavitation is favored by an increase of air content.

h. Colorado State University Water Tunnel(29, eg.) Tests upon cavitating valves and orifices ranging in diameter from 1 to 40 in. are reported by Tullis, etal.(69,70) for a once-through pipe system in which air content was not measured. Size scale effects were found as expected, but there was little evidence of effect upon inception sigma of probable large variations in total air and entrained air content in these tests.

i. SOGREAH, Grenoble, France(71-77,eg). A series of tests have been reported(71-75) from SOGREAH upon cavitation in regions of strong shear such as the wake region downstream of an orifice wherein air content, velocity, and temperature were varied (to increase Reynolds Number variation). A substantial effect upon sigma of total air content was found (Fig. 5), particularly in the range of moderate air contents (30-60% saturation at STP). Also a strong effect of the previous pressure history of the water was found, again indicating the necessity of a more detailed specification of entrained air content than that provided by total air content. A "bubble microscope"(76,77) for the direct observation and photography of the entrained gas nuclei has been studied in this laboratory. A difficulty with this approach is that only a very small field can be sampled, and counting and classification of particles is very tedious.

j. University of Michigan Venturi Studies (78-82, e.g.). A relatively long and comprehensive study of both damage and performance effects in venturi test sections has been made in the writer's laboratory at the University of Michigan (78-82, e.g.). Considerable work on gas effects on cavitation sigma for both water and mercury has been done. The inclusion of liquid metals is of basic as well as practical interest because gas solubility is usually much reduced for such fluids. The cavitation sigma studies have been in two parts:

i) Cavitation venturi tests for geometrically similar venturis over a range of throat diameter from 3-18 mm. with 6° included angle (Fig. 6-a) for water and mercury with considerable variation of temperature and velocity (78-82,e.g.).

ii) Development of modified Coulter-counter (78,82) system, and light scattering , e.g., for measurement of gas nuclei size and population distribution, and correlation with sigma. Typically for this small high-speed tunnel (to 70 m/s) the entrained gas volume is only about 10^{-6} of the total. The effects of gas content and velocity are substantial (Fig. 7). For high gas contents, sigma decreases strongly with velocity, passes through a minimum, and then increases. This behavior is similar to that found by Jekat (43) in an axial-flow "hub-less" inducer for air-saturated water.

For low gas content in these venturi tests (Fig. 7) sigma increases monotonically with velocity. The separation between sigma curves is much greater at low than at high velocity, consistent with work by Holl (60) and Bindel (65-67). Since this separation is approximately inversely proportional to kinetic head, it appears that the gas pressure in the bubbles is constant over the range tested. Following the approach suggested by Holl (5,60).

$$\sigma = \sigma_o + \sigma_{gas}; \quad \sigma_{gas} = \frac{k\, P_{gas\ sat}}{\rho V_t^2/2}; \quad P_{gas\ sat} = \text{gas pressure to which water is exposed.} \qquad --- (1)$$

k = proportion of saturation pressure actually in bubble.

It can be computed from the data, but with considerable scatter, which is presumably largely due to the differing pressure histories of the water. Fig. 8 shows this effect. For water, k averages 0.009, and for mercury 0.058, in the present tests.

k. Swedish State Power Administration (84). Figure 9 shows data by Fallstrom (84) from tests upon a Kaplan turbine. The results are consistent with those of Vuskovic (53), also upon a Kaplan turbine. It is Fallstrom's opinion (84) that air content within the range tested affects only the initial appearance of bubbles in this type of machine.

l. Technischen Hochschule, Darmstadt, West Germany. A recent doctoral dissertation by P. Gast (85) from Darmstadt reports on experiments involving cavitation upon a submerged object in a water tunnel, in which the effects of air content upon inception sigma were studied. Consistent with other work, it was found that sigma increased for higher air contents. Some theoretical justification based on the dynamics of individual bubbles is included.

m. National Engineering Laboratory, East Kilbride, Scotland (86-90,eg) and University of Durham. While no air content work from the water tunnels at NEL have been reported to the writer's knowledge, some relatively basic work relating air content and nucleation under non-flowing conditions has been supported by NEL at King's College, University of Durham. Nucleation thresholds in static samples (water and organic liquids) under ultrasonic irradiation as a function of total air content, pressurization history (and other forms of pre-treatment such as centrifuging) were reported by Richardson, et al. (86-89). For fixed total air content it was found that nucleation thresholds were strongly influenced by the distribution between entrained and dissolved portions, and nuclei diameters. Generally only the entrained portion was of importance. They developed a technique to measure the entrained gas spectra (86-89) based upon the attenuation of an ultrasonic beam caused by bubbles of a size resonant with the imposed frequency. This approach is similar to that used at the University of Minnesota (61-64,eg.) , previously discussed. Iyengar and Richardson also experimented with a light-scattering instrument for the same purpose (89).

n. Miscellaneous Nucleation Studies for Non-Flowing Systems (93-98).

1) Galloway (91) · Figure 10 shows the strong increase in cavitation threshold (comparable to decrease in sigma in flowing test) observed by Galloway (91) for water and also benzine from a static test in an ultrasonic field, as air content is reduced. For this case of high-frequency excitation, substantial liquid tensions are found.

2) Hayward (90) Hayward (90) at NEL investigated the effects upon cavitation threshold of prepressurization with various liquids of various purities included water in a small flowing system. He deduced

from this result that, of the common liquids, water alone contained nuclei of the type postulated by Harvey (6-9,eg). Thus he felt that the conventional Harvey model was not the major cavitation nucleation mechanism.

3) Ward, Balakrishan and Cooper (92). These authors theorize a much greater importance for dissolved (vs. entrained) gas than is usually supposed. However, their viewpoint is disputed by others in a discussion of their paper (93). The above paper, and others pertinent to the subject, appear in an ASME Symposium Booklet, "The Role of Nucleation in Boiling and Cavitation" (2,4,93), and the accompanying Discussion Booklet (92). Reference (2) by Holl in this Symposium Booklet is a particularly good survey of the nucleation state of art pertaining to cavitation.

4) Nystrom and Hammitt, University of Michigan (94,95, eg.). Ultrasonic cavitation threshold tests in molten sodium by these authors (94,95, eg) show the existence of large liquid tensions to nucleate cavitation under high-frequency irradiation (tension increasing with frequency), consistent with the previously discussed results of Galloway (91) for water and organic liquids.

3. "Nuclei" Measurement Techniques and Inception Sigma

a. General Background

Entrained "nuclei", which are generally too small to be visible to the unaided eye, can be measured and counted only through the use of sophisticated instrumentation. For transparent liquids, the first and most obvious technique is that of high-speed photography combined with a high resolution microscope. Such an instrument this purpose has in fact been developed at SOGREAH (76,77). Practical difficulties for its routine use lie in the very restricted field of view and the tedious nature of data reduction. A related and improved technique is the use of holographic photography. Many focal planes can be recorded with one holograph. Automatized data reduction techniques have been developed (96,97), but the equipment is costly and complex. The last report compares the results of sev optical methods.

A very useful optical technique which has recently been developed for this purpose is that of light scattering (96-101,eg). Instruments of this type using laser light have been developed at the University of Munich by A. Keller (98), and by Landa, etal at Hydronautics, Inc. (96,97). Figure 11 is a schematic of this system. In practice laser light was used in these cases because of its well-controlled and collimated nature. Scattered light is measured at any convenient scattering angle by a photomultiplier. Light is scattered to the photo-multiplier only when a particle is present in the field of view, the volume of which is defined by the optics of the system. The energy of the scattered light pulse is theoretically proportional to the volume of the particle. However, calibration with particles of known volume is necessary. The particle size to be measured in the usual case ($\sim$10-1000 μm) is in the range convenient for the scattering of visible light. Such an instrument could thus not measure individual particle size if this were, e.g., in the range 0.01-1 μm which is in fact the case for the primary droplet content of wet steam flows (discussed in another chapter). A somewhat similar system was also studied at NEL (89 ,eg)

One of the earliest tools used for the detection and measurement of entrained cavitation nuclei is that of imposed ultrasonic irradiation (61-64, 86-89, 103-107). Microbubble resonances in the range (1-10 MHz) can be exploited for this purpose. An input signal of a narrow frequency band will be attenuated by microbubbles of the resonant size for that particular frequency,and thus the number of such bubbles within the beam volume can be estimated. Use of other frequency bands can then produce a microbubble spectrum, similar to that from the light scattering method already discussed. Figure 12 (ref. 104) shows the relation between bubble diameter and resonant frequency (inversely proportional).

Other acoustic systems which have been used for the purpose of microbubble spectra measurement involve sound scattering as well as the effect of a very small "void fraction" on the speed of sound in the liquid. The latter approach can determine a total entrained gas volume, but the distribution into particle size can only be inferred(105,106,eg.). This approach may not be useful for very small relatively gas volume, which may range from 10^{-6} to 10^{-9} in different cases. The acoustic techniques have the inherent advantage that they can be applied to non-transparent liquids, where they represent perhaps the only feasible approach, such as sodium, e.g.

Still another effect which has been utilized to produce this type of measurement is that of gas "nuclei" upon the electrical conductivity of the liquid. If a sample of the test liquid (water, etc.) is considered as an electrolyte, and is drawn through a micro-orifice in the wall of a glass test tube, eg, the passage of a gas microbubble through the orifice will provide a measurable pulse in the electronic circuitry measuring the resistance between points in the test liquid inside and outside the glass test tube. The strength of this pulse is proportional to the volume of the gas particle. This system, known as a "Coulter counter", is shown schematically in Fig. 13. It has been developed (78,82, 108-111,eg,) for use at the University of Michigan, along with the laser light scattering system (69,99,111) for use in both venturi and vibratory cavitation systems. A comparison between the results obtained (99,111) shows agreement within a factor of $<$ 2 (Coulter system provides the lower count), only if about 0.1% NaCl is added to the water. The necessity of such an additive, plus that of obtaining a correct water sample in the instrument which is outside the tunnel, tend to limit the utility of the Coulter counter system for this purpose. However, it is a relatively simple and low cost instrument, which can be easily adapted to some opaque liquids. The application to molten sodium, however, involves difficult material problems which may not be solvable.

b. International Towing Tank Conference (ITTC) Studies (112,113,e.g.)

A recent "round-robin" test program to measure cavitation inception sigma for various selected "head forms" in various cavitation tunnels was sponsored by ITTC (112,113,e.g.). The large resultant scatter in inception sigma between different installations for the same head-forms and otherwise identical nominal tunnel conditions has motivated ITTC to encourage the development of readily usable and practical instruments for the measurement of entrained gas nuclei spectra in cavitating water tunnels, and to organize a comparison between the results of some of the presently available techniques. For this purpose a comparative test between microscopic photography, holographic photography, and laser light scattering was conducted at the SOGREAH cavitation tunnel in Grenoble (114). The Coulter counter was not included, but the comparison between that instrument and the laser scattering system was made at the University of Michigan (19,19-a,99,100,111,e.g.) as already discussed. The results of the SOGREAH experiment (113) were that the holographic and light scattering systems agreed quite closely, but not the microscopic photography system. No similar direct comparison between the ultrasonic and other systems has yet been made. Hence, it appears that much remains to be done before a standardized system for gas nuclei spectrum measurement will be available, but that reasonable agreement has already been demonstrate between the laser scattering, holographic, and Coulter counter systems. However, of these only the latter can be conceivably applied to non-transpare liquids.

c. University of Michigan Nuclei Spectra and Sigma Tests (78-82,115,e.g.). A series of studies over the past several years at the University of Michigan to measure microbubble spectra in water and correlate with cavitation thresholds in both venturi and vibratory cavitation facilities has been conducted involving 5 separate Ph.D. theses (80,82,109,111,116). Nuclei spectra have been measured with both Coulter counter and laser light scattering systems, and cavitation thresholds have been measured in both vibratory and venturi systems. Water, distilled and with various additives, has been used. Cavitation thresholds have also been measured in mercury and sodium (79,94,95,116) but no nuclei measurement was possible. Nuclei sizes can, however, be inferred from cavitation threshold measurements for all the liquids tested (115).

The results of this work as they pertain to threshold correlations in general will be discussed in an appropriate later section. Here, the particular features pertaining to the entrained nuclei spectra measurements will be considered.

The earliest particle spectrum studies at the University of Michigan involved the application of the Coulter counter to a closed cavitating venturi loop with water[78,82,108,115]. These tests showed that the entrained portion of the total gas, measured by "Van Slyke" (78,82,eg), has relative volume only of the order 10^{-6} in our facility, but that the entrained volume decreased constantly for long periods of tunnel operation (1-2 weeks) after start-up. Thus the possibility of constantly changing entrained portion even over very long periods in a closed loop facility where the total gas content ($\sim 1-2\%$ by volume at STP) is maintained constant is demonstrated.

The above described venturi program with Coulter counter was followed by two in-series Ph.D. investigations (109,111) in a vibratory cavitation facility shown schematically in Fig. 13. This is again essentially a closed-loop sealed facility where total gas content can be measured (Van Slyke), varied, or maintained constant. However, as opposed to the venturi tests conducted in our "high-speed water-tunnel" (117), the vibratory test loop is of small bore glass tubing with a small plastic circulating pump, so that high degrees of water purity can be maintained. The rate of circulation is sufficient only to allow measurement of entrained nuclei content, so that velocity effects are nil. This loo and the vibratory cavitation facility may be considered as providing an essentially static test. Nevertheless,glass stilling tanks were included in the second investigation (109) to allow more complete detrainment of larger microbubbles.

Typical micro-particle spectra from the two investigations are shown in Fig. 15 and 16. Considering the anticipated differences between the Coulter counter results of Pyun (109) with unsalted water, and the later primarily laser-scattering results of Yilmaz (111) in the facility with stilling tanks added, the overall microbubble spectra are reasonably similar, at least over the mid-portion of the range where the majority of the particles exist. For the very small particles, Pyun shows a decrease in number with diameter, so that his results show a "most probable size", whereas the results of Yilmaz show a continually increasing number as size is decreased to the limits of the instrumentation (∼5 μm). This discrepancy is not explained, but previous results from the water tunnel at University of Munich by Keller (98) agree with Yilmaz in this respect.

While the particle spectra of Pyun and Yilmaz agreed reasonably well over the main part of the diameter range, no valid comparison can be made for the few larger particles, which no doubt exist in either case, but may well escape measurement entirely. However, it is reasonable to assume that these would be reduced in number by perhaps orders of magnitude by stilling tanks incorporated by Yilmaz but not used by Pyun (Fig. 14). This hypothesis is confirmed by the fact that the thresholds measured by Pyun were of the order 1-2 psi, whereas those of Yilmaz were the order 4-5 bar as shown by Fig. 15 and 16. This discrepancy is of major importance, because it shows that reasonably detailed microbubble spectra, such as obtained in the case under present discussion, may not be sufficient to predict cavitation threshold. It is reasonably only the few very large microparticles which control, rather than the distribution in general and the "most probable size". These few large particles may be much more difficult to detect in practice than measuring the overall spectrum.

Another possible cause, aside from the possible existence of a few larger bubbles, of the low thresholds measured by Pyun (as compared to Yilmaz in almost the identical facility) may be the effect of "rectified diffusion"(118-120,eg) in inflating originally small microbubbles to those of sufficient diameter to explain the low measured thresholds. However, this effect should have existed in the Yilmaz experiment to the same degree as in that of Pyun, since the dissolved gas contents were similar.

The first relatively comprehensive cavitation nucleation experiments at Michigan, conducted before the availability there of particle spectra-measuring techniques, were the Ph.D. theses of Ericson (80) and Nystrom (116). Ericson's work was conducted in venturi systems (and has already been mentioned) and that of Nystrom in a vibratory facility. Ericson studied effects upon cavitation sigma, including overall gas content as measured by Van Slyke, in water and mercury, while Nystrom studied effects in high temperature sodium in a sealed vibratory facility. The effects of imposed frequency (14.5 to 24.5 kHz) as well as temperature (500-1500°F) were investigated. While it was not possible to measure entrained particles in either of these investigations, their "effective" diameter can be inferred from the cavitation threshold measurements. As a first approximation, the well-known static balance equation between surface tension and pressure differential of bubble contents to the surrounding liquid can be used, i.e.,

$$\Delta p = 2\sigma/R, \quad \text{so that} \quad R = 2\sigma/\Delta p \quad . \qquad \text{---} \qquad (2)$$

From this calculation it was found that, for the sodium tested, the "effective" nucleus radius ranged from ~ 10 to $\sim 600\ \mu m$. The radius increased with increased temperature, and decreased with imposed frequency (94,95). However, over most of the test range, the effective radius varied from 9 to 30 μm, which is about the same range found in our vibratory cavitation water tests (68,111). The apparent much larger size nucleus, i.e., smaller threshold, found in the maximum temperature, minimum frequency tests may stem from the increased importance of rectified gas diffusion (discussed earlier) at the high temperature condition (94,95,115, 120). As opposed to most liquids, the solubility for inert gas in sodium increases rapidly with temperature. These results are summarized in Table 1 from ref. 95. The increased radius with reduced frequency is no doubt due to the reduced importance of inertial resistance to bubble growth at lower frequency. Conditions thus approach those predicted by the static balance, eq. (2).

4. Major Basic Research Trends

Since the overall objective of predicting in advance air content effects upon the cavitating behavior of various apparata has not yet been attained, many studies of empirical nature such as those already reviewed have been necessary. To attain a predicting capability, more basic work is required. Three major issues are outstanding:

i) Measure (or compute) the upstream nuclei spectrum.

ii) Compute nuclei trajectory and growth or collapse rates during their passage between the region where the spectrum is known and the region of cavitation. Since the flow is likely to be turbulent, 3-dimensional, and biphasic, this is probably infeasible at present even for large computers. The applicability of adequately simplified flow models is then the question.

iii) Compute the effect of the cavitating flow on the machine.

At present it is not feasible to fully implement any of these above. However many studies, as already discussed, have sought to improve these capabilities. Such miscellaneous studies are discussed below.

a. Bubble and Fluid Flow Calculations.

1) Pennsylvania State University (Penn State) and California Institute of Technology (CIT). Theoretical and experimental studies in these laboratories have considered both the behavior of bubble nuclei attached to a wall (58,59,121,eg.)at CIT) and those growing in the flowing stream (Holl, et al., Penn State,(5,60,e.g.). This latter theoretical work has been applied successfully to the venturi sigma measurements at the University of Michigan(79-81), previously discussed. However, important features such as turbulent effects upon gas diffusion have been largely neglected.

b. Individual Bubble Studies

Many individual bubble studies exist in the literature, but are too numerous to list here; and many are not pertinent to nucleation. One of the more comprehensive and applicable early studies, however, is that of Gallant (122). Another of special interest, in that it involves overall bubble trajectories, is that by Johnson and Hsieh (123). This is one of the few studies which considers the effects of pressure and velocity gradients upon bubble trajectories.

5. Air or Gas Content Effects Upon Cavitation Damage

Studies of the effects of air content upon cavitation damage are far more limited than those upon cavitation inception and performance effects. However, air content should have a substantial effect, at least in some cases, through the action of the following opposing mechanisms:

i) Higher air contents favor cavitation, providing an increased number of bubbles, the collapse of which may be damaging.

ii) Higher air contents within individual bubbles reduces collapsing wall velocities and hence pressure radiation into the surrounding liquid (81,82, e.g.). Field observations show that large quantities of free air in damage-prone regions reduces damage rates (1 ,e.g.).

More detailed consideration of these mechanisms indicates the strong probability that for very high gas contents (saturation and above), an increase in air will reduce damage through the "cushioning" effect on individual bubble collapse, and perhaps through more rapid attenuation of shock waves in the surrounding liquid. On the other hand, for very low gas contents, sigma is substantially increased if gas content is further reduced (80-82,91, e.g.), so that the reduction in number of bubbles is more important than the increased collapse violence for individual bubbles. Thus cavitation damage is reduced if gas content is further reduced, and, in fact, in some cases cavitation may disappear entirely.

Beyond the individual bubble collapse studies already discussed, there are very few theoretical studies of the effects of gas content upon cavitation damage. One recent such study is that by Smith and Mesler (126).

The known experimental results will be discussed next.

a. Venturi Tests at Holtwood Laboratory, Safe Harbor Water Power Corporation, USA, Mousson (127). The earliest report of tests of air content effects upon cavitation damage is that by Mousson (127) in 1937 (Fig. 17), for runs made in a special damage venturi. For substantial rates of air injection (range of 1-2%) damage was substantially reduced (air content itself was not measured). The proportionate air flow to reduce damage markedly increased with water velocity, so that injection power loss may become substantial at high water velocity.

b. Venturi Tests at Escher-Wyss, Vuskovic (11). Vuskovic's air content damage tests (1940, Ref. (11) were made in a venturi similar to that of Mousson (127) at a velocity of 60 m/s (lowest velocity of Mousson). No actual weight loss measurements were made, but air content was measured. Consistent generally with Mousson's results, there was a steady reduction of damage as air content was increased from 0.3 to 1.7% of saturation at STP.

c. Rotating Disc and Venturi Test, Rasmussen (128,129). Rasmussen (1955) used both a rotating disc apparatus and a special damage venturi

(Shal'nev-type). Air contents were measured. Figure 18 and 19 show typical results for the rotating disc and the venturi, respectively. Again, damage decreased continuously and substantially as air content was increased from near zero to about 10% by volume (i.e. about 5x saturation at STP), thus covering a range similar to that of Mousson (127) and Vuskovic (53). The proportionate decrease depends both on material and the type of test, being much greater for aluminum than for cast iron, and greater for the venturi than for the rotating disc.

d. Non-Flowing, Vibratory Damage Tests-Hobbs (130,131) and Sirotyuk (132). Air content effects upon damage in a static vibratory-type test were measured by Hobbs (130,131) in 1969 and Sirotyuk (132) in 1966. It is well known that damage rates maximize in a test of this sort for an intermediate temperature (1,130-134,e.g.). It has been suggested that the reduction at the low temperature end is due to increased gas solubility at low temperature (and hence increased gas content, since tests are normally conducted in an open beaker with free surface). Hobbs' results show little effect on damage over the gas content range 0.1-1.0 x saturation at STP, tending to disapprove this hypothesis. Hobbs does show a reduction in damage near the upper end of his gas content range (which is much lower than that used in the flowing tests), so that his results are not inconsistent with these tests. He also shows a reduction in damage at low gas content (which the flowing tests did not), presumably due to the lack of "nuclei" under this condition. The results of Sirotyuk (132) are relatively similar.

e. Cathodic Protection and Gas Content (135,136). Cathodic protection to suppress electro-chemical effects in cavitation was apparently first suggested by Petracchi (135) in 1944. Later work by Plesset (136) suggested that the damage reduction might be partially due to the gas cushioning effects of the electrolytic hydrogen released at the wall. Thus, the success of cathodic protection may be partially a gas content effect.

6. Conclusion and Recommendations

Much remains to be done in achieving an understanding of gas content effects upon cavitation and bubble nucleation in general. However, at this point it is possible to formulate certain important recommendations and conclusions, as e.g.:

i) In general, variation of gas content has little observable effect upon the overall performance of machines operating well into the cavitating regime. It does, however, often have an important effect upon inception sigma, in that an increase in air causes an increase in sigma. It can thus importantly affect the prediction of inception sigma for prototype machines from tests on models, if there are differences in water quality with respect to gas nuclei between model and prototype conditions.

ii) Air content can importantly affect cavitation damage rates if, as in same cases, it establishes the existence and quantity of cavitation itself. Also large amounts of air, usually well in excess of saturation, will often substantially reduce cavitation damage, probably because of the reduced violence of bubble collapse in a gassy liquid.

iii) The importance of air content upon inception sigma depends upon the type of cavitation, i.e. bubble, laminar (steady cavity), vortex cavitation, etc.; bubble cavitation is most sensitive. The type of cavitation found depends on geometry and other flow parameters.

iv) Predictions of gas content effects upon cavitation are not possible if only total gas content is known. It is necessary to assure water of similar population and size spectra of "nuclei",as well as total gas content, if gas content "scale effects" are to be avoided.

v) A general capability for a fully theoretical prediction of gas content effects upon cavitation is not within the present state of the art, since the flow is biphasic, multi-dimensional and turbulent. None of these three factors can be feasibly handled in general even alone. However, mathematical models of limited appliability are helpful to indicate at least the trends to be expected. Much has been done in this direction and much remains.

vi) Another essential capability for the prediction of gas content effects is the easy and practical measurement of the gas nuclei spectra in a flowing system. An alternative and complementary capability is the "calibration" of the liquid for "cavitability" using a standard cavitating device.

Finally, it appears from all the foregoing that only rather vague guidelines can be drawn for the quantitative effects of gas content either upon inception sigma or damage rate for an untested condition. However, fairly firm qualitative results can be utilized, which are consistent both with the experimental and theoretical studies discussed, and with the pertinent physical laws. Figure 20 and 21 show such hypothetical curves for both inception sigma and damage rate. The curve for inception sigma (Fig.20 -a) is based upon the fact that for very small gas contents the tensile strength of the liquid is appreciable, and for very large gas contents, a large liquid pressure is required to prevent rapid growth of gas bubbles, ie. "gaseous cavitation". The same concept leads to the damage curve (Fig. 21). No cavitation should occur for extremely low gas content due to insufficient nuclei. For somewhat higher gas content, the nuclei population would approach sufficiency, so that a further increase in gas content would not significantly increase the number of cavitation bubbles and hence damage. For very large gas contents, the cushioning effect upon bubble collapse would become predominant, and damage would decrease. The typical values shown in both curves (Fig.20,21) are estimates from experimental results already discussed.

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C. Scale Effects in Machines and Components

1. General Background

Following the accepted terminology in the literature, cavitation "scale effects" cover any important deviations from the expectations of classical cavitation laws. These "classical laws" are based upon the assumption that cavitation will occur whenever the static pressure in the region of minimum pressure falls to the vapor pressure of the liquid at the existing temperature. This general statement of course also applies to cases of boiling, except that it is usually then stated that boiling will occur whenever the fluid temperature reaches the saturation temperature at the existing pressure. In either case it is further presumed that the pressure in the non-cavitating (or non-boiling) portions of the liquid, i.e., the entire flow regime for pre-inception conditions, will follow conventional scaling laws for single-phase flow of an incompressible liquid, i.e., for conditions of geometric and dynamic "similarity", pressure (or "head", if elevation differences are involved) differen are proportional to differentials of velocity squared.

Important deviations from such classical scaling conditions have commonly been found to exist for cavitating flows under conditions involving differences of size, i.e., "scale", and hence the name "scale effects". However, it is found that substantial deviations also exist in most cases also for differentials in velocity and pressure. Of course, velocity and pressure effects are related to their interdependence in most cases. However, if geometric and dynamic similarity are maintained between model and prototype, the origin of important size scale effects is not obvious. However, there are secondary effects which also must be involved, such as changes in turbulence level, Reynolds number, etc. Unfortunately, it has not yet been possible to correlate such size or velocity effects in terms of simple parameters such as Reynolds number. These factors are discussed in more detail in the following sections.

In addition, to size, velocity and pressure scale effects, there are most importantly, "thermodynamic" and gas content effects. The former is primarily due to the increased vapor density and pressure within cavitation bubbles (or other cavities) for some liquids, or at higher temperature for any. This leads to an increased restraint upon either bubble collapse or growth, due to the necessary condensation or evaporization of the vapor and the concomittant requirement for transport of the resultant latent heat to or from the bubble wall. Otherwise the vapor pressure within the bubble will either rise or decrease, thus retarding collapse or growth. "Thermodynamic" effects upon collapse and damage are discussed in detail in Chapter IV, and the parallel effects upon nucleation and growth will be further discussed in this section.

Effects related to gas content within the liquid, while not being perhaps truly "scale effects", produce results very similar to those of the more conventional scale effects. Hence, these cannot in general be understood without first "sorting out" the effects due to difference in gas content. As explained in considerable detail in Section B of this chapter, these effects are primarily related to the population spectra of "microbubbles" from which the macro-bubbles comprising a normal cavitation or boiling regime originate. In addition, there are also effects of gas content upon damage as explained in Chapter IV, i.e., increased gas within the bubbles restrains collapse due to strongly increasing internal pressure as this gas is compressed. Also, the presence of even a very small quantity of gas within bubbles (see Chapter IV for more quantitative information) promotes bubble "rebound" which itself appears to contribute importantly to the resultant damage. Hence gas content can create important variations from classical expectations for both inception and damage, and can thus be legitimately considered as a "scale effect".

As explained in the foregoing, cavitation scale effects apply to all important aspects of cavitation, i.e., inception and damage, but also performance. Inception and damage effects are probably in general of greater, but not exclusive, importance. By "performan effects" here is meant such items as changes in efficiency, power, head, thrust (from a propellor), and shape of characteristic curves such as "head" vs. "NPSH", e.g. For example, the "sharpness" of fall-off of head with reducing NPSH often differs between model and prototype as a typical "scale effect". This could be important in the determination of "inception", since inception is usually defined in terms of a certain percent fall-off of head or power from a pump or turbine (or thrust or power for a propellor) from the non-cavitating head at the same pump (or turbine, or propellor) speed and flow, rather than in terms of the first acoustic (or visible) manifestation of cavitation. These latter indications would perhaps be less sensitive to possible scale effects as compare to the overall externally-measured performance curves such as the he NPSH curve, since no measurable change in head will often occur until quite considerable cavitation exists, and often the first externally observable change is in the reverse direction, i.e., a small amount of cavitation may slightly improve performance. However, insufficient information is as yet available to determine the validity of the foregoing supposition concerning scale effects and "first" inception.

The scale effect due to the"thermodynamic effect" mechanism may be more dependent upon performance scale effects than those due to changes in velocity, pressure, or size, since it could be argued that no thermodynamic effect changes will exist until cavitation has become relatively well-developed beyond the "minimum" (acoustic or visible) inception condition. This is especially true for thermodynamic damage effects, since damage occurs only when cavitation is relatively extensive. The characteristics of the entire cavitation field are certainly strongly affected by thermodynamic effects, i.e., the size and number of bubbles existing, since their development from the nucleation state is relatively restrained when thermodynamic effects are important. Thus the cavitation performance effects upon the machine are also reduced in these cases, as is well known in the commercial pump field. Of course, in addition the damage is further drastically reduced in such cases by the reduced collapse violence of individual bubbles, if initial size and number of bubbles were the same as in the absence of the thermodynamic effect mechanism. This strong damage fall-off with increased temperature for a given liquid at given suppression pressure is well documented and discussed in Chapters IV and V.

In addition to the various "scale effects" discussed in the foregoing, there are also the effects upon inception, performance, and damage which are incurred through the change of liquids or of liquid temperature for the same liquid. Assuming that classical cavitation scaling laws are met, i.e., cavitation "sigma", suction specific speed*, Thoma sigma, or other similar scaling parameters, are held constant, and the performance of different liquids, or alternatively the same liquid at different temperatures, are compare significant differences in all phases of cavitation performance are often observed. Presumably these differences are due to differences in the many liquid properties which influence cavitatio behavior beyond those considered in the classical scaling laws already discussed. All these questions are discussed in some detail with respect to specific machines in the next section.

2. General Machinery Effects

a. Pumps and Turbines - General

Of the fluid-flow components of major importance and perha least subject to exact analyses because of the rotating and complex nature of the flow are turbomachinery units such as pumps and turbi It is conceivable that meaningful progress could be made at this ti in the analyses necessary for cavitation prediction by highly sophi ticated computer studies of the flow in the rotor to determine locations and magnitudes of minimum pressure. However, this does n seem yet to have been accomplished to the necessary degree. If this were accomplished to the necessary extent, presumably "scale effects" would become predictable, qualitatively and quantitatively Since it is not possible at present, however, to predict these scale effects, it is necessary to draw upon all experience availabl where cavitation performance data exist comparing geometrically

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$*S = (RPM)(GPM)^{1/2}/NPSH^{3/4}$ in English units, for pumps. A dimensionless form is also possible.

similar units or the same unit at different speeds, or with different liquids.

b. Effects of Size, Velocity and Pressure

There is much experimental information at present proving the existence of large cavitation scale effects due to size, velocity, and pressure changes for geometrically similar turbomachines. However, the causative mechanisms are at present only slightly if at all understood, and detailed numerical studies are not as yet sufficiently reliable to provide trustworthy predictions. It is thus in general impossible to predict either the magnitude or direction of these scale effects in the absence of specific model-to-prototype tests for specific designs.

Indicative of the above, sophisticated cavitation pump work is being continued at National Engineering Laboratory (NEL). The group at NEL, Glasgow have long experience with, and are world leaders in, cavitation pump research and design (43-45 eg.). To quot their Dr. Pearsall(139) concerning pump cavitation inception scale effects, i.e., variation of inception sigma with model size, speed, etc., in a recent article (1974): "On cavitation inception there is so little information that no reliable conclusions can be drawn. There is some evidence that air content alters the trends of scale effects. Most of the tests on pump performance breakdown have shown an improvement with higher speeds and larger sizes (---- i.e., higher suction specific speed). Some tests, however, show the reverse effects.". The present author fully agrees.

It thus appears that very careful model tests are necessary to achieve a given objective regarding cavitation performance, and that the possible differences between model and prototype due to speed and size changes, etc., are much greater than the uncertainties between different liquids. In any case, acoustically instrumented prototype tests are clearly necessary to verify the full detailed cavitation performance of a new pump.

1) Typical Specific Results

a) University of Michigan Pump Tests (140, 141)

Typical specific data results from tests at the University of Michigan (U-M) using a low specific speed centrifugal pump tested over a range of speed, flow, and temperature in both water and mercury (140,141,eg.). This unit is a small single-stage sump-type centrifugal pump used to power the U-M mercury cavitation loop. Specific speed is 740 in GPM, RPM and ft units, and design flow at 1800 RPM is ~40 GPM, for $\Delta H = 40$ ft.

In this loop, pump cavitation can only be obtained by reducing the sump pressure to near vacuum, balancing vacuum pump capacity against stuffing-box leakage. The rather large scatter of the data is probably a result of this test procedure.

A long-radius elbow immediately upstream of the pump suction is partially responsible for the low suction specific speed values. In addition, the pump was designed for high-temperature liquid metal operation rather than good cavitation performance.

The data points (Fig. 21) with one exception, are the result of several repetitive runs (varying from 2 to 6). In each case a standard deviation was calculated, and from these an average value computed which is shown in the figure. Data of sufficient precision to be statistically meaningful has been obtained (Figs. 21-23). The onset of cavitation is defined as sufficient cavitation to cause a decrease of 5% in the pump head at a fixed speed and system resistance.

i) Water Results (140,141)

Pump speed was varied over a range of about 1.7; flow (i.e., ratio of actual to design flow) over a range of 1.3; and water temperature over the range from about 80°F to 160°F. Tests were run at three distinct speeds, denoted in the figures as ratios of actual to design speed, two flow ratios, and three temperatures (including the extremes of the range above).

The resulting Thoma* cavitation parameters are presented in Figs. 21 and 22 plotted against normalized Reynolds number and normalized pump speed, respectively. The figures disclose:

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*$NPSH/\Delta H_{pump}$

1) The data can be correlated reasonably well either in terms of Reynolds' number or pump speed, i.e., velocity.
2) The data divides naturally according to the flow ratios, i.e., the Thoma parameter for the higher flow ratio (somewhat above design flow) is higher than for the lower (close to design flow), for the same N/N_o or Re/Re_o.
3) There is no significant separation within the precision of the data as plotted against either velocity or Reynolds number. In the case of velocity curves there is no substantial separation according to Reynolds number, as Fig. 21 shows. However, it is not in the direction anticipated from a consideration of the thermodynamic parameters (1, 146). The indicated separation of the curves is small as expected from previous venturi results since the pump cavitation condition correspond only to initiation. Thus, only a single curve is warranted within the precision of the data.
4) There is a substantial decrease in Thoma cavitation parameter as the Reynolds number or velocity is increased (30-50% for a speed increase of 75%).

The data from Fig. 22 are replotted in Fig. 23 in terms of suction specific speed which varies over almost a 2:1 range, from about 2500 to 4500. The direction of variation and the relation between high and low flow curves of course follows from the previous curves.

ii) Mercury and Water Results

It was found for water and mercury, considered together, that Thoma's cavitation parameter decreased virtually on a single smooth curve as normalized pump speed, N/N_o increased, for fixed flow coefficient. Although the pump speeds with mercury and water did not overlap due to equipment limitations, it appears from these data that the Thoma cavitation parameter for a given flow coefficient is a function solely of pump speed, regardless of fluid (Fig. 24).

The Thoma cavitation parameter also decreased for increasing normalized Reynolds number for both water and mercury, when considered separately (Fig. 25), although the curves for the two fluids did not coincide. For a given flow coefficient and Reynolds number, the Thoma cavitation parameter is about twice as large for mercury as for water. This variation is in the direction predicted by the thermodynamic parameters (1,142,eg.), although the magnitude of the thermodynamic effect cannot be predicted. It may be that the apparent correlation in terms of velocity is actually a result of opposing separate effects due to Reynolds number and thermodynamic parameters.

As mentioned previously, little difference was noted between "hot" and "cold" water (~160°F and 80°F). However, the thermodynamic parameter (1,142,eg.) equilibrium ratio of vapor volume to liquid volume formed per unit head depression, differs by a factor of about 5 from "hot" to "cold" water, but by a factor of about 10^7 from "cold" water to mercury. However, mercury is a fluid for which very little thermodynamic effect would be expected, ie, it is "a very cold water" in this respect.

Figure 26 is a plot of suction specific speed versus normalized pump speed. It, of course, shows simply the inverse trend from the Thoma parameter plots, ranging from about 2500 in GPM units for low speed with mercury to about 4000 for high speed with water.

A hysteresis effect in the Δ H vs. NPSH curves was noted for both water and mercury. The pump head tends to be higher for a given NPSH while NPSH is being increased, rather than decreased, through the pump cavitation region. A typical curve from the mercury data (Fig. 27) illustrates the effect. Since the average passage time for fluid around the loop is about 10 seconds (and the time between readings and reversal of pressure variation for the runs much longer), no explanation is readily apparent. However, cavitation inception hysteresis is a common observation in large water tunnels giving rise to Holl's suggested terminology of "incidence" and "desinence"(143 ,eg. Obviously, only a detailed study and visualization of the flow in the impeller could shed light on this and other phenomena, which complicate at present the evaluation of pump scale effects.

iii) General Trends

The specific results discussed in the foregoing indicated that an incre in speed (or Reynolds number) caused a substantial reduction in cavitation sigma (increase in suction specific speed) over the range tested. They also indicated that pump speed alone was a more successful correlating parameter than Reynolds number, at least for the comparison between mercury and water. Somewhat similar tests for venturis, to be discussed later, indicate the same in this regard. However, the trend of improved cavitation inception performance for increased speed or Reynolds number is not always found, and in fact the opposite trend has been observed in other cases. In general, the direction and magnitude of this scale effect cannot be predicted in the present state of the art(137, eg.) for cases where specific test results are not available. No doubt they depend upon various parameters such as specific speed, detailed pump design, etc. There are numerous fragmentary results published in the literature, but since no definable trends yet emerge, these are not cited in detail here. For many flow components, including both venturis and pumps, cavitation performance can be expected to improve for increase in velocity or Reynold's number for relatively low velocity and Reynold's number, but a reverse trend may occur for higher velocity or perhaps Reynold's number. This favorable trend has sometimes been accepted as valid, eg., for some designs of rocket turbopumps. However, the unfavorable trend also certainly exists in some cases.

Test results including both a favorable trend at relatively low velocity and an unfavorable trend at increased velocity were reported, eg., by Jekat (144) for tests on an axial-flow inducer-pump, and were also observed in our venturi tests (140).

b) Turbine Scale Effects

Much of what has already been said applies to water turbines (1, 137, 145-147, eg.) as well as pumps, but there are essential differences, as discussed by Pearsall (137). Since water turbines are very large machines, efficiency is more important than for most pumps. Secondly, a water turbine differs hydraulically from a pump in that the cascade of blades is an accelerating cascade, rather than a diffusing set as in a pump. Thus minimum pressure occurs near cascade exit rather than near the inlet as for pumps.

Analysis of test results on many turbines allows an empirical correlation of the critical Thoma coefficient* against specific speed (147) as shown in Fig. 29. An empirical correlation has been fitted to this data by Karelin (146) and is reported and discussed by Pearsall (137).

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* $\sigma_{Thoma} = H_{sv}/H_{turbine}$, where H_{sv} is suppression head, i.e., head above vapor head.

c. Venturi Geometry

1) General Background

As illustrated by Fig. 28, eg., important and substantial cavitation scale effects due to changes in size, velocity, pressure, thermodynamic parameters, gas content, etc. for geometrically similar venturi flow paths may be expected. Even though the geometry is much simpler than that of centrifugal pumps, it is still true that the theory is unfortunately lacking to allow the prediction of either the magnitude or direction of these effects except with relatively rare exceptic as eg., the gas content effect discussed in section B, where some predicting ability appears to exist. Venturi flows differ basically from orifice flows, which will be discussed separately, since a non-cavitating venturi flow is a non-separated flow, while that from an orifice definitely involves separation even in the absense of cavitation. Hence, vortices downstream of an orifice are presumably the most important cavitation inception mechanism for such "separated flows", while they are often of minor importance in venturi flows. They may, however, be of primary importance in some instances of pump cavitation, especially those involving unshrouded impelle

One of the most comprehensive sets of cavitation tests involving venturis is that conducted over the past 10-15 years at the University of Michigan. Hence these results will be here reviewed. Other venturi cavitation investigations have also been reported, but to the author's knowledge, there is no conflict reported with the U-M data.

2) University of Michigan (U-M) and Electricite de France (EdF) Tests

The Michigan tests included both water and mercury. The basic venturi geometry (Fig. 29 for a nominal 1/2 in. throat diameter) involves a 6 degree included angle nozzle and diffuser section separated by a cylindrical throat (2.25 L/D). Geometrically similar units were tested for various throat diameters ranging from 1/8 to 1 in. ([illegible] Throat velocities ranged from ~40 to 220 ft/sec. Cavitation condition ranged from inception to fully-developed, i.e., extending well into the diffuser section. Gas content in many cases was controlled and measured. Both water and mercury were used as test fluids, and a relatively broad temperature range was investigated. For low temperature tests the venturis were of plexiglas, and cavitation inception was detected both acoustically and visually. In some cases high-speed motion pictures of the cavitating regimes were made.

The investigations were extended also to sodium by tests at Electricité de France (EdF), where stainless steel venturis of identical flow-path geometry were used. EdF also performed water tests in the same venturi with results consistent with those from U-M. The sodium tests were at a single temperature and throat diameter, but velocity was varied to the extent possible, so that a sodium velocity scale effect was also measured for this geometry. These sodium results will be reviewed in a later section. Thus water, sodium, and mercury have been tested in identical geometry, involving tests in two different laboratories and over differing parameter ranges.

a) U-M Water Tests

i) Inception Sigma

Figure 14 shows the basic flow-path dimensions and indicates the various cavitation conditions ("degrees of cavitation") used. Figure 15 shows a typical normalized wall axial static pressure profile for "sonic initiation", i.e., first detectable sound by stethescope or hydrophone due to cavitation. "Visible initiation" differed from "sonic" in that it involved a continuous ring of cavitation at the exit to the cylindrical throat, the position at which cavitation first appeared.

Figure 32 shows typical cavitation sigma* vs. throat Reynolds number for "sonic initiation", for both 1/4 and 1/2 inch throat venturis with varying conditions of temperature and gas content. It is noted that there is very substantial decrease in sigma with increased Reynolds number (or velocity) from ~ 0.2 to ~ 0.0. The data from all these tests for differing degrees of cavitation is combined in Fig. 33. It is noted that the velocity or Reynolds number effect upon sigma decreases strongly for increased degree of cavitation but is less pronounced for more fully developed cavitation. However, sigma always decreases for these tests to some extent for increased Reynolds number. However, later tests showed that a minimum sigma was obtained, after which further increase in Reynolds number corresponded to an increasing sigma, i.e., an "optimum" Reynolds number was observed. This is of course consistent with the Jekat pump results (50) previously mentioned.

Figure 34 illustrates the U-M water and mercury sigma results in the same venturi geometry for various "degrees of cavitation" as a function of throat Reynolds number. While the trends are in all cases the same for water and mercury, the water and mercury data do not collapse to single curves when plotted against Reynolds number. Rather they are separated by a factor of ~ 10. This is consistent with the previously discussed U-M pump results between water and mercury, where it was found that pump speed was a much better correlating parameter than Reynolds number. However, Reynolds number did reasonabl well correlate separately the water (or mercury) sigma results (Fig. 32 eg.). It thus appears that the best correlating parameter at present would be the product V x D alone, rather than the complete Reynolds number. In any case Reynolds number does not appear to be a successful correlating parameter betwee water and mercury, where a very large factor in kinematic viscosity (or density) is involved. As explained later, Reynolds number does seem reasonably successful as a correlating parameter between water and sodium

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* $\sigma = (p_{min} - p_v)/\rho V^2$, where p_{min} is minimum throat pressure.

ii) Loss Coefficient*

As previously indicated, cavitation scale effects include "performance effects" as well as inception. The U-M tests included the measurement of "loss coefficient" as well as sigma. The venturi loss coefficient for non-cavitating flow is of course a relatively insensitive function of Reynolds number, and that for cavitation inception is approximately the same. However, there is a large effect for more developed cavitation conditions (Fig. 35-37). Figure 35 shows the inception loss coefficient as a function of throat Reynolds number, indicating that it is ~0.2. Presumably it is essentially a function of the friction losses for the basic venturi geometry used. The friction losses for this venturi design are relatively large because of the small nozzle and diffuser angles, and the relatively long cylindrical throat. Our later tests with much shorter and more abrupt venturi geometries (148) showed that then loss coefficients were less than 0.1, depending upon details of the geometry.

Figures 36 and 37 show loss coefficient as a function of throat Reynolds number for relatively well-developed cavitation conditions. In these cases it increases with Reynolds number for fixed degree of cavitation, reaching values as large as ~0.9. Two points from sodium results achieved in recent Westinghouse venturi tests (149) are included in Fig. 36. These agree closely with the U-M water results. Loss coefficient also depends strongly on the "thermodynamic effects", as expected (142,150) , eg) i.e., the losses are less for "hot" than for "cold" water. Presumably this would also be the case for sodium, although no comprehensive sodium test results are yet available to the author's knowledge.

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*Loss Coefficient = $(p_{in} - p_{out})/ \rho V^2/2 = 0$ for ideal flow.

iii) Gas Content Effects

Some discussion of gas content effects, though they are beyond the basic scope of this report, is necessary for an understanding of the U-M and EdF venturi results. As shown in Fig. 28 the optimum Reynolds number freature of the sigma curves mentioned above appears to be true only for relatively high gas contents. The differential between these curves can be computed quite closely (151-153) following a model suggested by Holl. A permanent gas content within the bubbles is then assumed proportional to the total liquid gas content (entrained and dissolved).

The generally expected effect of gas content is carefully reviewed in Section B of this chapter. In general it is expected that gas content will have little effect over the moderate gas content range, causing only a gradually increasing sigma. For very low gas contents, so that there are insufficient "nuclei" for inception, sigma should increase strongly, i.e., the "sodium superheat" problem may be encountered. For very high gas content, sigma should increase strongly so that the cavitation would become essentially "gaseous cavitation", as opposed to conventional vaporous cavitation.

b) Electricité de France (EdF) and University of Michigan (U-M) Sodium Comparisons

As already mentioned, cavitation inception sigma tests in water and sodium were conducted by Electricité de France at their Chatou Laboratory in a stainless steel venturi of flow-path identical to the venturis previously tested at U-M. Gas content was neither measured nor controlled, but was probably typical for reactor loops. Both helium and argon were used as cover gas, but no difference was attributed thereto. Two test temperatures and velocities were used, and the results plotted as a function of Reynolds number (Figs. 38 and 39). The water portion of the data is obviously very closely similar to the U-M water data (Fig. 28). The comparison between the EdF and U-M data sets is shown directly in Fig. 40 as a function of throat Reynolds number. It is noted that the EdF data falls within the envelope of the U-M curves, which differ because of differing gas contents. No more exact direct comparison is possible, since the gas content of the EdF tests is not known. However, the major result from these tests is that inception sigma for water and sodium lay within the same scatter data band, which, even considering the substantial effects of velocity or Reynolds number, is still small enough to be considered negligible from an engineering viewpoint.

c) Cadarache Tests (French Atomic Energy Commission)

In later tests conducted by the French Atomic Energy Laboratory at Cadarache (56) in sodium for various orifices and nozzles, it was found that inception sigma depended significantly upon the cover gas used, i.e., helium or argon. This may be due to differing solubilities for these gases, and hence differing quantities of entrained gas. The differences in NPSH were about 2 psi, and hence generally negligible from the engineering viewpoint.

d) Westinghouse Sodium Tests

It is possible to obtain two experimental points on cavitating venturi loss coefficient in sodium from recent tests conducted by Westinghouse-Advanced Reactor Division (W-ARD). These agree closely with the U-M water venturi results (Fig. 36). This is probably partially fortuitous since the venturi geometries used differed considerably.

. Orifices

1. General Background

There is an important basic difference between venturi geometry on the one hand and orifices or nozzles on the other from the viewpoint of cavitation inception, performance, and damage. Venturis are essentially a streamlined or non-separated flow, at least for only slight cavitation (or inception), while orifices and nozzles lack the diffuser geometry necessary to prevent such separation, with or without cavitation. Orifices and nozzles are in fact often called "free-shear" or "free-jet" flows for that reason, and the micro-vortices formed in the free-shear layer around the downstream jet are usually considered to be instrumental in the inception of cavitation, because of the strong under-pressures generated at the center of such vortices. Such vortices are not of major importance for cavitation inception in venturis, at least for those with moderate diffuser angles. Of course the venturi becomes a "free-jet" flow once developed cavitation is formed, but that does not influence the inception problem. Performance effects in terms of loss coefficient of course also differ between venturi and nozzle or orifice flows because of differing effects of cavitation upon downstream pressure recovery. Damage effects are also entirely different because much of the bubble collapse activity is usually not adjacent to the pipe wall in orifices or nozzles, as opposed to venturis, unless the cavitation regime is very extensive, which is not usually the case for engineering applications of nozzles or orifices.

The published scale effects data for orifices and nozzles (156-161, eg.) is apparently much less extensive than that for venturis, which is also not sufficient, as previously indicated to allow prediction of inception sigma for cases for which actual experimental data is not available. However, the orifice or nozzle geometry is perhaps the simplest possible for the theoretical prediction of inception sigma. Obviously it depends strongly on entrained gas micro-bubble spectra, which unfortunately are not usually measured for most test results. It also depends upon upstream turbulence levels which control instantaneous under-pressures, flow distribution approaching the restriction, and thermodynamic effects as well as the usual flow parameters.

2. Typical Specific Results

a) Arndt and Keller (157)

Figures 41 and 42 show typical inception vs. velocity and Reynolds number results from Arndt and Keller (157) These show differing trends in that Fig. 41 indicates an increasing sigma for increasing Reynolds number, while Fig. 42 indicates a strongly decreasing sigma for increasing velocity. As for the U-M and EdF venturi tests (Fig. 34,39,e.g.), there is an optimum Reynolds number or velocity for high gas content (Fig. 41) with a more strongly decreasing sigma with increasing velocity for high gas content. In any case the results are not sufficiently consistent to allow a confident prediction of inception sigma as a function of conventional flow parameters unless entrain gas contents are known. In this particular case these were in fact measured.

b) Tullis (158)

The most comprehensive cavitation scale effects data available for both orifices (158,eg.) and valves (162-165)* have been published by Tullis, et al. Again these are primarily experimental studies presenting empirical results and possible curve-fitting relations. Nevertheless insufficient results from this and other sources are yet available to allow confident prediction of results

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*Discussed later.

for as yet untested situations. In the case of orifices there are two questions of interest, i.e., cavitation inception sigma, and loss coefficient, for cavitating orifices. Since cavitating venturis, nozzles, and orifices are "choked flow" devices, the changes in loss coefficient ("discharge coefficient") can be dramatic. However, presumably heavily cavitating orifices (or nozzles) are not likely to be useful components for LMFBR because of eventual damage considerations. Nevertheless, typical results from Tullis (158) will be here reviewed.

Figure 43 shows orifice discharge flow as a function of pressure differential, indicating the "choked flow" nature of this type of flow component. Figure 44 shows inception sigma as a function of orifice to pipe diameter ratio, β. Sigma is here defined with respect to upstream pipe pressure rather than throat pressure as used here for venturi results. A very strong effect of β is indicated for the various size pipes tested. It is possible that at least the shape of these curves could be predicted by Bernoulli-type calculations, assuming some friction loss although no such calculations have as yet been made. Such results would be useful in achieving predicting capability.

Figure 45 for the onset of "choking cavitation", again shows a strong scale effect with β, and also the effect of different pipe sizes. Again, it appears probable that a relatively simple theoretical analysis could predict at least a significant portion of these trends, but such an analysis is not yet available. Figure 45 summarizes the Tullis results for various "degrees of cavitation" including inception and choking as extremes, and also various intermediate conditions.

Gas contents were not measured for any of these tests, though they were probably approximately constant and relatively low because of the nature of the experimental facility.

c) SOGREAH

A considerable test program to evaluate cavitating behavior of orifices and nozzles in water was conducted during the 60's at SOGREAH Grenoble, France (159,160,eg.). Typical curves from ref. 159 are included here for convenience (Fig. 47). Figure 47-a shows the effect of total oxygen content (measured in lieu of total air), for various nozzle and orifice forms, upon cavitation inception sigma,(. referred to upstream pressure and jet velocity. A substantial effect upon inception sigma was noted for this relatively small variation of air content well within the saturated air content at STP (~5 mg/l).

Figure 47-b shows the effect of dissolved air upon cavitation inception sigma for air contents ranging up to ~1.6 x saturated content at STP. Sigma approximately doubles over this range. This is roughly consistent with Fig.20-a showing general expectations of air content effects upon cavitation sigma. Figure 47-c shows analogous results for an orifice, with approximately the same proportional increase of inception sigma for a total gas content increase over the same range.

Figure 47-d shows the increase of inception sigma for an orifice for two gas contents (within the saturated range at STP) as a function of Reynolds number referred to jet velocity and diameter. These results are at least approximately consistent with the U-M - EdF results previously discussed for the higher Reynolds number range (Figs. 28 and 38-40).

From the SOGREAH tests it can be concluded that inception sigma for both orifices and venturis is a strong function of Reynolds number as well as total gas content even for moderate variation within the saturated range, but that Reynolds number alone is not a sufficient correlating parameter, in that considerable data scatter remains.

d) French Atomic Energy Commission - Cadarache Tests (56,161)

Sodium cavitation tests in nozzles and orifices is reported from the French Atomic Commission laboratory at Cadarache (156,161). This work, as previously mentioned indicated a substantial difference in inception sigma depending upon whether the cover gas were argon or helium. Also as previously mentioned, no difference according to cover gas was found in the EdF venturi tests. The Cadarache results (156) also indicate a substantial (~20%) drop of inception sigma for increasing Reynolds number, over a Reynolds number variation range of only ~1.5. This trend was found for either argon or helium cover gas. Over the relatively very limited Reynolds number range tested, the difference in suppression pressure ($\rho \cdot$ NPSH)is only ~ 2 psi, so that it could be argued that this difference is negligible for most engineering considerations. However, the differential in NPSH could become substantial over larger ranges of Reynolds number which would be encountered in most model to prototype tests. Thus these Cadarache results are consistent with the other scale effect data reported, but again allow little predicting ability without further understanding of the basic mechanisms than is presently available.

be reproduced here.

Figure 48 from a published Cadarache report (161) does indicate substantial change in inception sigma for sodium reactor components as a function of pressure drop, i.e. velocity.

e. Valves

1. General Background

It is generally accepted from whatever evidence is presently available, that very large cavitation inception and performance scale effects exist for flow-control valves of all types.

Since the basic flow patterns for valves are considerably more complex than those for nozzles, orifices, or venturis, even less basic understanding exists than for these components, so that little "a priori" predicting capability exists, as is also the case for the other components. Also there is considerably less data available so far for valves. Furthermore, it is generally reported in a format quite different from that used for the other components, so that making of direction comparisons is difficult at present. Typical results will be discussed below.

2) Colorado State University (CSU) Results (162-165, eg.)

Cavitation scale effects for valves are important from the viewpoint of inception of course, but also for performance effects including "choking" characteristics.

In addition, the problem is complicated by the fact that a given valve must be investigated for various valve openings, so that the problem is an order of magnitude more complex than that for orifices, nozzles, and venturis. The CSU results include all these factors for various types of valves.

There was no control or measurement of air content for these tests, though it was probably relatively low and constant, considering the nature of the experimental facility. The test fluid was in all cases cold water so that vapor pressure was very low, and essentially neglible in the calculation of sigma.

Figure 49 shows sigma for "moderate cavitation", i.e. about midway between inception and "critical" cavitation, beyond which major flow instabilities and vibrations occur, so that valve operation from an engineering viewpoint no longer appears feasible, for "ball valves" ranging between 2 and 12 in. pipe sizes. A very strong scale effect in sigma, referred to upstream pressure*, is noted in terms of Reynolds number, which varies for a given valve size by a factor of ~3. Sigma over this increasing Reynolds number range increases by a factor of ~3 also. Thus the effect upon sigma is proportionately much greater than previously discussed for any of the other flow components considered. Reynolds number does not at all correlate the different valve sizes (Fig. 49).

Figure 50 shows inception sigma for "butterfly" valves for different valve openings, as a function of C_p, i.e., inlet static pressure divided by inlet kinetic pressure. This parameter is closely ~~similar~~ to inception sigma in this case, since the vapor pressure is here essentially negligible. Again strong scale effects are noted for each valve opening.

Figure 51 shows upstream velocity as a function of suppression pressure for "critical cavitation", i.e., maximum limiting cavitation, for different valve openings. While the curves differ for the different openings, their slope is relatively constant on such a log-log plot.

Figure 52 shows the size effect for ball valves as corresponding to critical cavitation, V_c vs C_d, which is defined as inlet pressure divided by pressure drop across, the valve. Figure 52 is a similar plot for orifices, showing that in these terms, orifices and valves are indeed quite similar. The conversion of these curves into terms of cavitation sigma vs. Reynolds number or velocity would obviously be highly useful, and is perhaps the logical next step.

Recommended curve-fitting relations from the CSU data to allow prediction of prototype performance from model tests are presented by Tullis (165).

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* $\sigma = (P_{out}-P_v)/(P_{in}-P_{out})$, which differs considerably from the usual definition in the cavitation literature for other components.

3. Miscellaneous Fluid Property Effects

Various possible effects of liquid viscosity upon cavitation inception "sigma"* exist. These will be discussed in the following in the order of their greatest probable importance, in the author's opinion. The extent of actual quantitative knowledge existing in each area is considered also.

1) Shear Flow-Field and Cavitation Inception

It is probable that the influence of viscosity upon cavitation inception sigma for shear flows such as those downstream of an orifice, or other sharp-edged aperture producing separated flow, would be much more substantial than for non-separated flows, such as in a cavitating venturi. This hypothesis is based upon the following reasoning. It is generally supposed (1,158-160, that cavitation in such separated flows is a result of the local underpressures existing in small turbulent vortices created by the high-shear region around the submerged jet, discharging from a sharp-edged aperture, e.g. The controlling importance of this mechanism is verified by the fact that inception sigma for orifices, etc. is of the order 0.4 (1,158-16-, eg.), whereas that for a venturi is of the order 0.0 to 0.1(43,140,/154,159,160,166,eg.). This difference can only be justified if the vortices in the separated region are quite powerful, so that their center pressure is indeed well below that of the mean flow in that region. However, the local pressure difference generated by such vortices depends strongly upon liquid viscosity. However, few quantitative analyses of such vortex flows, where losses are considered, exist. However, experiments for the purpose of investigating the hypothesized different magnitudes of sigma

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*Inception Sigma = $(p_{ref}-p_v)/\rho V^2/2$. p_{ref} is usually jet or throat pressure.

dependence upon liquid viscosity appear to be quite simple. Different mixtures of glycerine and water, eg, could be used to vary viscosity as desired in any small water tunnel facility.

In conclusion, it might be supposed that inception sigma for separated flows would be somewhat decreased for liquids of increased viscosity, because the under-pressures produced by the turbulent vortices would be reduced.*

2) Development of Vortices

The effect of viscosity upon the development of turbulent vortices, and the effect thereon on cavitation inception sigma, is to a large extent, discussed in the foregoing. However, the effect of increased liquid viscosity upon the strength and number of such vortices generated in the shear-flow layer must also be considered. This appears to be a somewhat more complex analytical problem than that of the effect of viscosity on individual vortices, once they are in fact produced.

The effect of increased viscosity in producing more and stronger turbulent vortices by virtue of increased shear in the liquid layer surrounding the jet would obviously produce a trend opposite to that previously discussed, ie., a decreased pressure differental between centers of vortices and the surrounding liquid due to increased viscosity. It is at this point impossible to predict which of these trends is the more important.

From one viewpoint, the importance of increased shear around the jet due to increased viscosity may not be of major importance, since the contribution of conventional viscosity to shear in highly turbulent flows is usually small or negligible. It is rather a question of "eddy viscosity", which depends upon velocity gradients, etc., rather than viscosity itself. The effect of increased viscosity in decreasing the pressure differential across small travelling vortices may, on the other hand, be of major importance, since the local Reynolds number

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*Recent simplified numerical calculations by the writer, do in fact, show that losses due to viscous effects are substantial.

pertaining to the vortex flow itself is probably small, and perhaps not even in the turbulent range. Hence, the effect of conventional (not "eddy") viscosity may be appreciable for this case.

3. Fluid Dynamic Parameters

The conventional fluid-dynamic parameter involving viscosity and having the most obvious pertinence to cavitation inception sigma is certainly Reynolds number. In fact, inception sigma has very often been correlated against Reynolds number (1,43,140,154,158-160,166,eg.). However, other parameters of possible importance are Prandtl number, Weber number (based on presumed diameter of "nuclei"), Jacob number, Strouhal number, and some perhaps as yet undefined parameter involving velocity and distance (related to time of exposure of "nuclei" to under pressure). Reynolds number is discussed first, and then those others which seem to be of possible pertinence. These latter will only be discussed very briefly, since they do not in fact involve viscosity which is the subject of this section.

a) Boundary Layer Thickness and Reynolds Number

Reynolds number can be expected to be of importance, since it affects both boundary layer thickness and level of turbulence. The boundary layer thickness is probably of more importance for nominally non-separated flows such as in a venturi, where it will directly affect the possibility of flow separation leading perhaps directly to the existence of a region of cavitation. A heavily-cavitating venturi is, in fact, a separated flow (140,eg). However, this is presumably not the case, at least for a well-designed venturi, for inception, where the quantity of cavitation is too limited to affect the overall flow. The boundary layer thickness will have an influence on inception, since it will affect the entrainment of stationary "nuclei" growing from wall crevices. Presumably reduced boundary layer thickness, ie, increased Reynolds number and reduced viscosity, will thus add to the population of travelling "nuclei", and increase inception sigma.

b) Turbulence and Reynolds Number

The other apparent possibly major influence of Reynolds number on cavitation inception sigma is through its effect upon the level of turbulence, and the resultant instantaneous under-pressures resulting therefrom. The turbulence level of course depends upon both Reynolds number and the possible effect of upstream obstacles, elbows, roughnesses, etc., ie, in the absence of such upstream obstacles, a fully-developed turbulence level will exist which depends upon Reynolds number alone. The turbulent pressure coefficient for well-developed turbulence is generally in the range 0.01-0.05, and hence would not greatly affect inception sigma for flow regimes involving separated flow where the sigma values are of the order 0.4. However, for streamlined non-separated flows such as in a well-designed venturi, the under-pressure effect of turbulence originating upstream would be of greater relative importance, since the measured sigma values (43, 140,154, eg.) are of the same order as the pressure coefficient for turbulent eddies. Nevertheless, it is likely that these effects would be overwhelmed by the effects of upstream obstacles as elbows, wall obstruction etc., if these in fact exist in the case under consideration.

In brief summary, it then appears that the effect of local under-pressures due to well-developed turbulence, as characteristic of a particular Reynolds number, are likely to be relatively unimportant for separated flows (as orifices, or the flow downstream of blunt obstacles), but could be of significance for inception sigma for well-streamlined non-separated flows.

c) Size and Velocity Scale Effects

Many experiments, attempting to show the effect of Reynolds number may rather show direct velocity or size effects, which are in addition to the normal Reynolds number effects discussed above. Velocity and size are the parameters usually varied in tunnel tests from which most of this are produced. These possibilities are discussed next.

The growth of "nuclei" into bubbles large enough to create a cavitating flow regime requires the existence of a positive pressure differential between the vapor or gas within the nucleus and the liquid pressure at a distance, for a time long enough for the growth to take place. Hence both magnitude of under-pressure and time of exposure are involved. Since the basic bubble growth (and collapse) mechanisms are highly complex and non-linear (1, eg) no tractable mathematical model (other than large computerized studies) exists to allow the estimation of the required inter-relations between bubble under-pressure and time of exposure. Due to the complex nature of these relationships in general, it seems highly probable that there are large influences of liquid velocity and model size upon cavitation inception sigma beyond those included within the obvious Reynolds number effects already discussed. These presently unexplained effects are usually considered as "cavitation scale effects" (43,140,154,158,159,166). Present information shows that the direction of the velocity effect upon inception sigma can be either positive or negative It is often negative for high entrained gas contents and streamlined objects, as venturis (43,166,eg.) but positive for the same devices with low gas contents. It also appears to be usually positive for blunt bodies, including orifices (1,158,eg.).

d. Other Non-Viscous Flow Parameter Effects

Numerous other liquid and flow parameters, which do not involve viscosity, can affect inception sigma. Experiments to determine the effects of viscosity may also inadvertently involve changes in some of these. Those which seem most likely to affect bubble nucleation, and hence cavitation inception sigma, are listed below.

i) Prandtl and Jacob Numbers. Cavitation bubble growth (after the initial stage) as well as collapse is usually assumed to be primarily governed by the interrelation of pressure and inertial effects. However, in the case of conventional boiling, "thermodynamic" restraints (discussed in detail elsewhere) become more important than the effects of inertia. However, for cases of highly subcooled boiling, or cavitation in "hot" liquids (where vapor density is substantial), both inertial and thermal restraints become significant, as recently described by Bonnin (154,eg.) and others. Damage tests in any liquid in a vibratory facility, including sodium (167,eg.).

show that "thermodynamic effects" strongly reduce damage rates at high temperatures, as discussed in detail elsewhere in this book. It is thus probable that these same effects influence nucleation in the same temperature range, though apparently no pertinent experimental data nor precise analyses are available for the nucleation case. These effects involve both heat conductivity of the liquid (Prandtl number), and heat capacity, including latent heat effects of the vapor contents of the bubble (Jacob number), or as expressed by various forms of thermodynamics parameter, (142,154,eg.).

ii) Weber number. Initial bubble growth from a "nucleus" is presumably controlled by the balance between surface tension which restrains growth, and under-pressure which provides the motivating force. A "Weber number" based on nucleus diameter is thus the conventional non-dimensional flow parameter involved.

iii) Strouhal number. For certain types of flow regimes, such as for orifices or the flow behind blunt obstacles in general, the travelling vortice presumably giving rise to the under-pressures necessary to provoke cavitation are shed from the obstacle in "Karman vortex streets", whose spacing and shedding frequency is governed by a "non-dimensional frequency", ie; Strouhal number. For flows where cavitation inception depends upon these vortices, presumably the Strouhal number may be important.

4) Viscosity Effects: -- Individual Bubble Dynamic Relations

There is no doubt that increased viscosity reduces rates of bubble collapse or growth, assuming the other governing parameters of the problem to remain constant. However, pertinent experimental measurements are virtually non-existent, and theoretical studies also , particularly concerning bubble growth rather than collapse. Numerical studies of spherical bubble collapse, wherein the effects of viscosity were consider were made here Chap. 4, by Ivany (124, eg.). Figure 5, summarizes t the effects for various values of viscosity for water. Cananvelis (168) also investigated the effects of viscosity, among numerous other parameters, upon spherical bubble collapse. His results generally agree with those of Ivany, discussed below. While bubble collapse is discussed in much more detail in Chapt. 4, it is introduced here only to indicate the possible effects of viscosity on cavitation inception.

Figure 5 of Chapter 4 shows bubble wall velocities and Mach numbers existing at various stages of bubble collapse plotted against radius ratio based upon initial bubble radius. The classical Rayleigh solution, assuming neither liquid viscosity nor compressibility, is shown as an upper limit. Bubble wall velocity and Mach number tend to infinity as radius tends to zero for this solution. The introduction of liquid compressibility brings both to large but finite limits. If spherical symmetry could be maintained through a large enough radius ratio. These results (124,168, eg.) would be quite precise for bubble collapse in cold water. However, high-speed photographs show that such symmetry generally cannot be maintained as discussed in detail in Chapter 4. The effect of internal gas in restraining collapse (and producing eventual rebound) is also included in Fig. 4. Chapter 4.

The addition of terms to consider viscosity at a level similar to that of cold water does not significantly affect the collapse rates (Fig. 5, Chap. 4). A "critical viscosity" for which collapse would be virtually stopped was first computed by Poritsky (169) His theoretical value (derived under certain simplifying assumptions, since the study was conducted before the advent of large computers), indicated a value ~1470 x that of cold (70°F) water to produce this result. Thus the liquid viscosity necessary to significantly affect bubble collapse is that of liquids such as heavy oil. The Poritsky "critical viscosity" was confirmed by Ivany (Fig. 5, Chap. 4) These results (and those of Canavelis, which is apparently the only other pertinent study) indicate that viscosity has little effect upon bubble collapse unless very large changes in viscosity for quite viscous liquids are involved.

It seems even less likely that there would be a significant influence of viscosity upon bubble growth, since the wall velocities for growth are typically much less than for collapse, and the term involving viscosity is proportional to velocity gradient, whereas those involving other terms as surface tension and pressure differential are not velocity dependent.

discussed in detail in Chapter 4

The term involving viscosity, as derived originally by Poritsky, and/ appears in the force balance at the bubble wall, along with terms representing pressure differential and surface tension, as shown by Eq. 3-2 below:

$$p_{liq.} = p_i - 2\sigma/R + 2\mu_{liq.} (\partial u/\partial r)_R \quad \text{------------} \quad (3\text{-}2)$$

where $p_{liq.}$ is liquid pressure near bubble, and p_i the pressure within bubble, $\mu_{liq.}$ is liquid viscosity, σ is surface tension, u the velocity, r the radial velocity, and R is bubble wall radius.

5) Asymmetric Bubble Effects and Viscosity

Photographic data as well as numerical studies discussed in detail in Chapter 4 show that bubble collapse in flowing systems such as venturis, eg., is in fact highly asymmetric, resulting in the eventual formation of a liquid micro-jet to which the damage is partially attributed, rather than to shock waves,as in the classical Rayleigh model of spherical collapse, on which earlier calculations such as thos by Ivany and Canavelis (124,168) previously discussed were based. Although viscosity was included in these numerical studies of asymmetric collapse no comprehensive studies have yet been made of the effects of viscosity upon the micro-jet type of collapse as compared to the Rayleigh model. However, since, as previously discussed, viscosity for most ordinary liquids such as water does not appear to have a major effect, it seems equally unlikely that it will strongly influence the micro-jet model.

While bubble collapse has been shown to be strongly asymmetrical (17-21, eg), the growth process is much more stable, as discussed in Chap. 4, so that spherical symmetry is a much better model. Hence , it appears most unlikely that the inter-relation between viscous effect and possible lack of spheroidicity represents an important effect in the determination of cavitation inception sigma.

6) Velocity of Bubble Relative to Flow ("Slip Velocity")

The possible "slip velocity" of micro-bubbles, i.e., "nuclei"[*], with respect to the main flow could certainly be affected significantly by changes of viscosity. Even in highly turbulent flows the relative motion of very small bubbles, motivated primarily by pressure differentials, would presumably be restrained primarily by viscous drag. For larger bubbles, such as might be characteristic of fully-developed cavitation rather than inception, the effects of changes in viscosity would presumably be less than for "nuclei", since inertial rather than viscous restraints would be controlling. However, even though "slip velocity" of nuclei might be significantly affected by changes in viscosity, it does not follow necessa that this would represent an important influence on cavitation inception sigma. While there appears to be no experimental confirmation of such an effect, the probable importance of an accelerating "slip" on bubble collapse in pump impellers and flowing ~~devices~~ has been investigated in France by Chinchol (170-172, e.g.).

The generally recognized mechanism of bubble "slip velocity" in a liqui flow results in a positive slip in regions of decreasing pressure, and negative slip in positive pressure gradients. Thus, differences in resisten to motion between the vapor and liquid phases result in a relative motion between these. The slip phenomenon would thus reduce the penetration of "nuclei" into high pressure regions because of negative slip, and increase their rate of penetration into low pressure regions. Thus conceivably some reduction of "superheat", or increase in cavitation inception sigma, due to increased slip might result. Increased slip would correspond to reduced viscosity, so that a mechanism relating viscosity to cavitation inception through changes in slip velocity is possible. However, there is

[*] vapor and/or gas filled.

generally no difficulty involved in the penetration into low pressure regions of gas or vapor nuclei. Hence, it seems unlikely author that this effect would be of more than relatively minor significance for cavitation (or boiling) inception. It seems more likely that it would be of importance for cavitation damage, where the convection of larger bubbles to higher pressure regions adjacent to submerged bodies, etc. would be reduced. However, the trajectory of larger bubbles is less affected by viscous effects. These trajectories were investigated by Chincholle (170-172, eg.) and also Johnson (123). However, "ideal fluid" assumptions were made so that viscous effects were neglected.

The overall effects of slip velocity over the entire flow loop may, of course, be important in determining the number and size of "nuclei", in that it may affect their solution or dissolution in different parts of the overall loop, since it affects "dwell time" in the different pressure regimes. However, only a very complex computer study, none of which has yet been reported, could shed light on this problem.

7) Growth of Bubbles Trapped in Wall Crevices

This subject has already been mentioned under the subject of Reynolds number effects, where the effects of Reynolds number on boundary layer thickness, and hence the entrainment into the main flow of such "trapped" bubbles was considered. Briefly, increased Reynolds number (reduced viscosity) would lead to higher shear stresses along the wall and hence earlier entrainment, i.e. entrainment of smaller bubbles. On the other hand, increased viscosity would increase viscous shear in the "sub-boundary-layer", assuming a fixed Reynolds number and hence velocity profile. Thus if viscosity of the liquid were increased, but Reynolds number maintained constant either by increased velocity or diameter, then an increased liquid velocity would result in increased entrainment capability for bubbles trapped in wall crevices. On the other hand, if viscosity were increased with constant VD so that Reynolds number were reduced proportionately confl mechanisms would exist so that the direction of any trend on wall bubble entrainment could only be determined by more detailed study of the particu situation. Apparently, no such detailed studies have yet been made.

8) Viscosity Experiments Using Water Soluble Polymers (176-179, eg.)

In recent years there has been some experimentation upon the effects of the addition of small quantities of high molecular weight, water-solubl polymers to water upon its cavitation performance (176-179). The special high resis to cross-velocity flow created by the visco-elasticity of such aqueous polymer solutions was expected to affect their cavitation performance to a much greater extent than would the concommittent increase in ordinary viscosity achieved otherwise. The results obtained so far have been somewhat inconsistent sc application to cavitation inception sigma differences attributed to viscos changes for ordinary liquids is not clear.

Much of the cavitation work with high-polymer aqueous solutions has so far been applied to cavitation (or jet impact) applications. It has been hoped that the jet-stabilizing effect of the polymer, in tending suppress cross-flow turbulence, would increase the damaging capability of given jet impact. For devices designed for liquid jet cutting of materia this would be advantageous, assuming that the special effect of the poly was greater than the general damage-reducing effect of increased viscosit The ratio of viscosity increase caused by addition of 100 ppm of polymer solutions of various types to distilled water is $\sim$ 4. This is about the same increase of viscosity as compared to cold water as would be obtained by substitution $\sim$ 40% aqueous solution by volume of glycerol (174). The effects upon erosion rates from liquid jet impact might be assumed to be similar to those to be expected with cavitation. Hence, cavitation damage tests of this kind would be useful in helping to verify the importance of the micro-jet impact mechanism in cavitation damage (damaged in Chap. 5). In fact, recent cavitation damage tests in a conventional* vibratory facility did show an increase in damage rate of up to $\sim$ 10 x (as compared with distilled water) with 100 ppm aqueous polymer solutions of this sort (174) in spite of the increase in ordinary viscosity of $\sim$ 4x. This is then taken to be strong evidence for the importance of the micro-jet damage mechanism in these tests. However, pertinent to the present discussion, it also shows that the major effect of the polymer addition is not its effect upon ordinary viscosity, since vibratory cavitation damage tests with liquids of varying viscosity, such as glycerol-water solutions, show a strong decrease of damage rates with increased viscosity (175).

Only limited tests have so far been reported for the effects of polymer solution additions to water upon cavitation inception sigma. The effect in one case (1000 ppm polymer addition) was a suppression of cavitation inception, i.e., a decrease in inception sigma/ (176,177). Assuming that the main effect of the polymer addition is the suppression of cross-flow velocities this suppression of bubble growth is to be expected. Of course this trend would also be expected considering only the corresponding increase in ordinary viscosity.

In summary, information concerning the effects of polymer addition is thus too sketchy at present to draw any conclusions pertinent to the effects of viscosity change upon the cavitation behaviour of ordinary liquid such as water.

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*See ASTM Standard Method No. 32-72

9) Summary of Viscosity-Sigma Effects

Various preliminary conclusions can be drawn from this consideration of the possible effects of liquid viscosity upon cavitation inception. These are listed below: according to their probable order of importance.

i. It is likely that one of the more important effects relating liquid viscosity and cavitation inception sigma will be found in the different sensitivities of sigma to viscosity changes to be found for separated flows (such as orifices, blunt obstacles, etc.) as compared with nominally non-separated flows (venturis, streamlined objects, etc.). Such a difference should exist because of the much greater dependence of separated flow cavitation inception sigma upon the travelling orifices generated in the high-shear layer around the central jet Increased viscosity may substantially increase inception sigma for separated flows by suppressing the strong and local under-pressures generated by such vortices.

ii. Reynolds number is probably the most important of the conventional non-dimensional flow parameters which should be considered for the correlation of inception sigma changes which might be attributed to viscosity changes. However, past experience shows that it is not a complete sufficient correlating parameter for sigma. Probably the most important effect which prevents the complete correlation of sigma with Reynolds number is the effect of time of exposure of bubbles to under-pressure. Thus a pur velocity and size effect appears to exist above and beyond the conventional effect of Reynolds number changes, brought about only by changes in viscosity. Conventional Reynolds number effects include both effects upon turbulence level (and hence local turbulent under-pressures) and those upon boundary layer thickness, which influences the entrainment of micro-bubbles trapped in wall crevices. For both of these effects, increase in Reynolds number would increase cavitation inception sigma.

iii. A viscosity increase for constant Reynolds number would increase shear stresses both in the shear layer of separated flows thus increasing the number and intensity of individual travelling vortices, as well as in the vicinity of micro-bubbles trapped in upstream wall crevices, which is probably more important for non-separated flows. Both these effects would tend to increase cavitation probability, and thus increase inception sigma.

iv. Bubble "slip velocities" (relative to the main flow) would be reduced in general by increase of viscosity. This effect would reduce micro-bubble penetration into high pressure regions, thus perhaps reducing damage, but it probably would not substantially affect inception. However, more complex effects due to changed "slip velocities" (due to viscosity changes) for the entire loop may affect both the dissolving propensity and the entrainment capability for micro-bubbles by changes of "dwell time" in different pressure regimes around the circuit.

v. The probable effect of changes in viscosity, as seen through the analysis of individual bubble dynamics, is such that both bubble growth (inception) and collapse (damage) will be somewhat inhibited for more viscous liquids. However, existing numerical analyses, indicate that these effects are probably small for liquids with viscosity similar to water.

b. Thermodynamic Effects

"Thermodynamic effects" upon cavitation have been discussed in several portions of this book including 3 (d-i) of the present chapter. In general, these "effects" exist with reltion to cavitation damage as well as to performance and inception, and hence must be mentioned in various portions of this book. Since the present chapter concerns "Nucleation and Growth", thermodynamic effects must be considered from those viewpoints here. This has been done briefly in Section 3 (d-i) above in discussing the effect of Prandtly and Jacob Numbers in either cavitation or boiling bubble dynamics. As indicated, the two phenomena become essentially identical for sub-cooled boiling applications, where from the cavitation viewpoint, "thermodynamic effects" become important. From the same viewpoint, these are entirely controlling for saturated boiling applications, where inertial restraints to growth or collapse become negligible and only heat transfer mechanisms control bubble behavior.

In general, since thermodynamic effects from the cavitation viewpoint add an additional restraint to growth or collapse, they must act in the direction or restraining either bubble growth or collapse. Thus they very substantially reduce damage in some cases, and little doubt on this scoe appears to exist. Similarly, they must also inhibit nucleation to some extent so that an increase in inception sigma should be expected. However, the extent of this effect is difficult to predict in a given case. This aspect of the problem is discussed in detail in Chaper 4 on bubble dynamics, and will not be further considered here. No precise data relating the increase of sigma as referred to acoustic or first visible initiation is known to the author at this point. Unless "nuclei" content were also measured precisely, any observed effect due to increased temperature might well be partially due also to changes in this very important nucleation parameter.

The thermodynamic effects relating to cavitating component performance can be substantial, and were discussed already in this chapter concerning other machinery scale effects. Since thermodynamic effects can only be expected to restrict the growth of a cavitation region, their effect upon cavitating machinery components must be assumed to be favorable, in the sense that the existence of any cavitation is a disadvantage. This is certainly a "truism" from the viewpoint of erosion, but may not always be true for "performance effects". It has sometimes been observed, particularly with centrifugal pumps, that a very small quantity of cavitation actually improves slightly the performance, i.e., there is sometimes a small rise in the head-NPSH curve before the overall fall-off of head with subtantial cavitation occurs. The only plausible mechanism to explain this type of behavior in the author's opinion is that the streamline pattern allowed when a small cavity exists along the blading surface is more favorable than that formed by the blade itself.

D. General Conclusions

Bubble growth and nucleation in general have been covered in this chapter. While cavitation applications have been emphasized herein, some consideration has also been given to boiling situations, particularly in those regimes where boiling and cavitation overlap, such as highly sub-cooled boiling or cavitation cases where "thermodynamic effects" predominate. In these cases, cavitation and boiling are nearly identical phenomena.

Bubble growth and nucleation in general has been covered in Section A, while Sections B and C concern special features of special interest. Section B concerns particularly the effects of entrained gas "micro-nuclei" in generating the inception of conventional "macro-bubbles" of which cavitation and boiling regimes are presumed to consist, as well as methods for the measurement and detection. Such micro-nuclei are presumably of primary importance for cavitation inception, but are also at least contributory to boiling inception in most cases. Inception mechanisms of primary importance only to boiling, such as stationary wall crevices, are not discussed in full detail, as being beyond the scope of this book. The measurement and detection of travelling "nuclei", is believed by the writer to be the present necessary direction of research for further improvement of understanding and predictability of cavitation inception sigma and related scale effects.

Section C covers actual cavitation inception scale effects as they are observed in various machinery components. The state-of-art of understanding and predicting ability in this highly complex field is reviewed in detail, with relation to all pertinent fluid and flow parameters. A brief summary of the state of the art is there provided as well. In general, it can be stated that predicting ability with regard to cavitation inception and performance scale effects (as well as damage) is extremely limited at this time, so that only highly empirical and highly uncertain approaches are as yet available.

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Multiphase Fluid Flow - Theory and Practice

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TABLE 1

Rectified Diffusion Parameters for Sodium and Water (58)

Temp. °F	Fluid	C Concentration gr/gr	D Diffusion Coefficient cm²/sec	CD cm²/sec
68	Water-Air	2.4×10^{-5}	2.0×10^{-5}	5.0×10^{-10}
500	Sodium-Argon	6.9×10^{-11}	7.0×10^{-5}	4.8×10^{-15}
800	" "	4.4×10^{-8}	13.0×10^{-5}	5.7×10^{-13}
1000	" "	3.5×10^{-8}	18.0×10^{-5}	6.3×10^{-12}
1500	" "	1.10×10^{-6}	31.0×10^{-5}	3.4×10^{-11}
500	Sodium-Helium	1.1×10^{-8}	11.5×10^{-5}	1.3×10^{-12}
800	"	1.1×10^{-7}	21.5×10^{-5}	2.4×10^{-11}
1000	"	3.5×10^{-7}	30.0×10^{-5}	1.0×10^{-10}
1500	"	2.2×10^{-6}	52.0×10^{-5}	1.1×10^{-9}

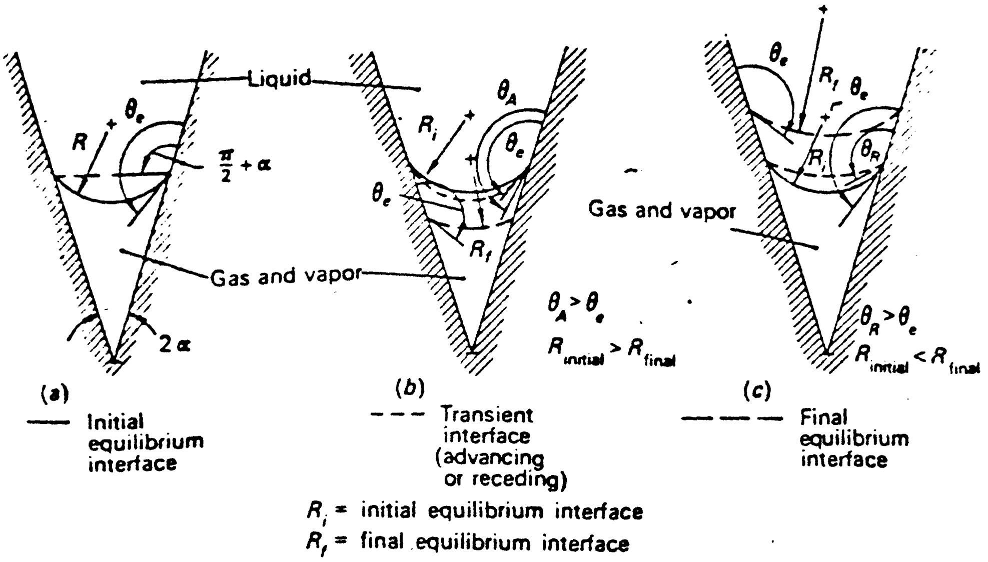
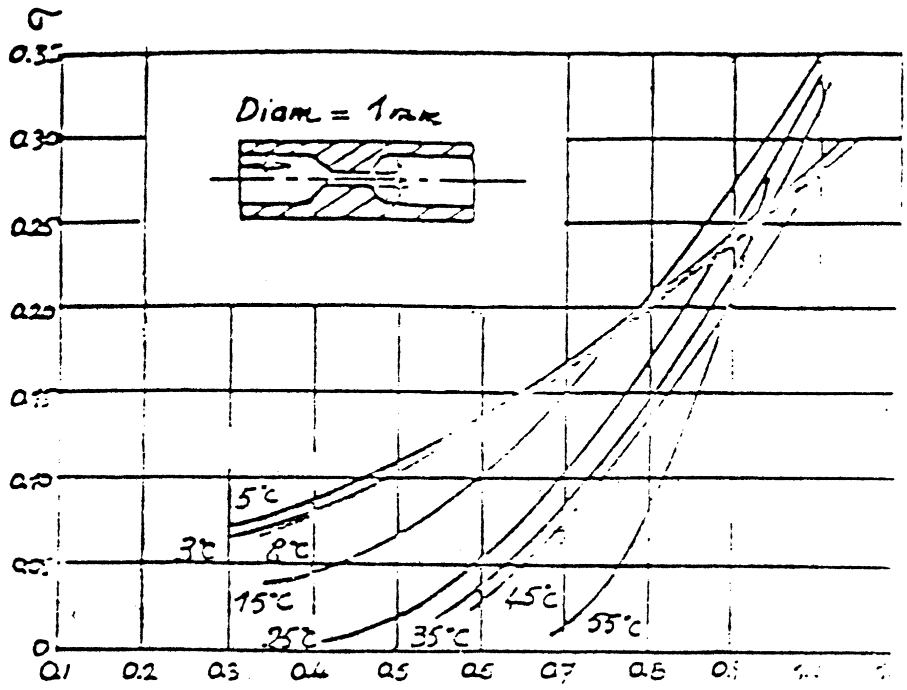


FIG. 1 Stabilization of a gas-vapor pocket in a hydrophobic crevice.

(*a*) Liquid saturated with gas. Interface in an equilibrium position with radius R and contact angle $\theta_e > \pi/2 + \alpha$.

(*b*) Liquid undersaturated with gas. Liquid advances with reduced R and $\theta_A > \theta_e$. As the gas solution proceeds, θ_A decreases until at equilibrium the contact angle is again θ_e.

(*c*) Liquid supersaturated with gas. Liquid recedes with increased R and $\theta_R < \theta_e$. As the gas release proceeds, θ_R increases. For equilibrium within the crevice, the contact angle is again θ_e.



g. 2 Cavitation Inception Sigma in Venturi as Function of Relative Air Content Compared to Saturation at STP, Numachi Data (44-49)

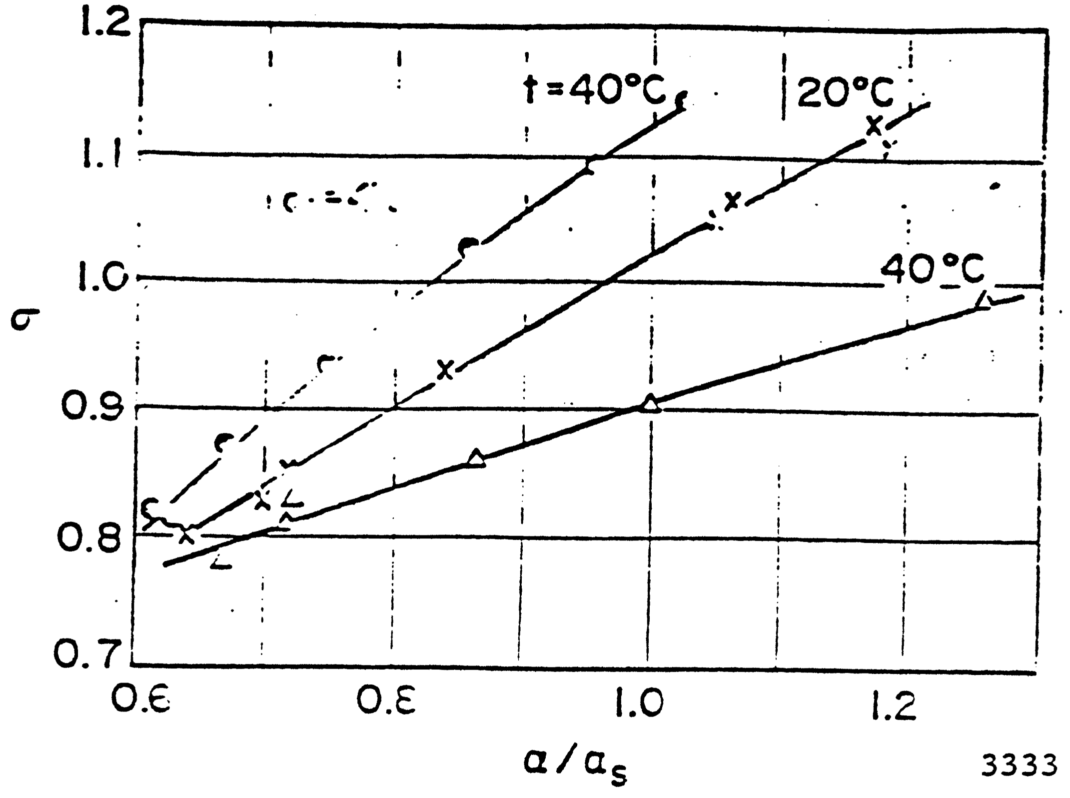
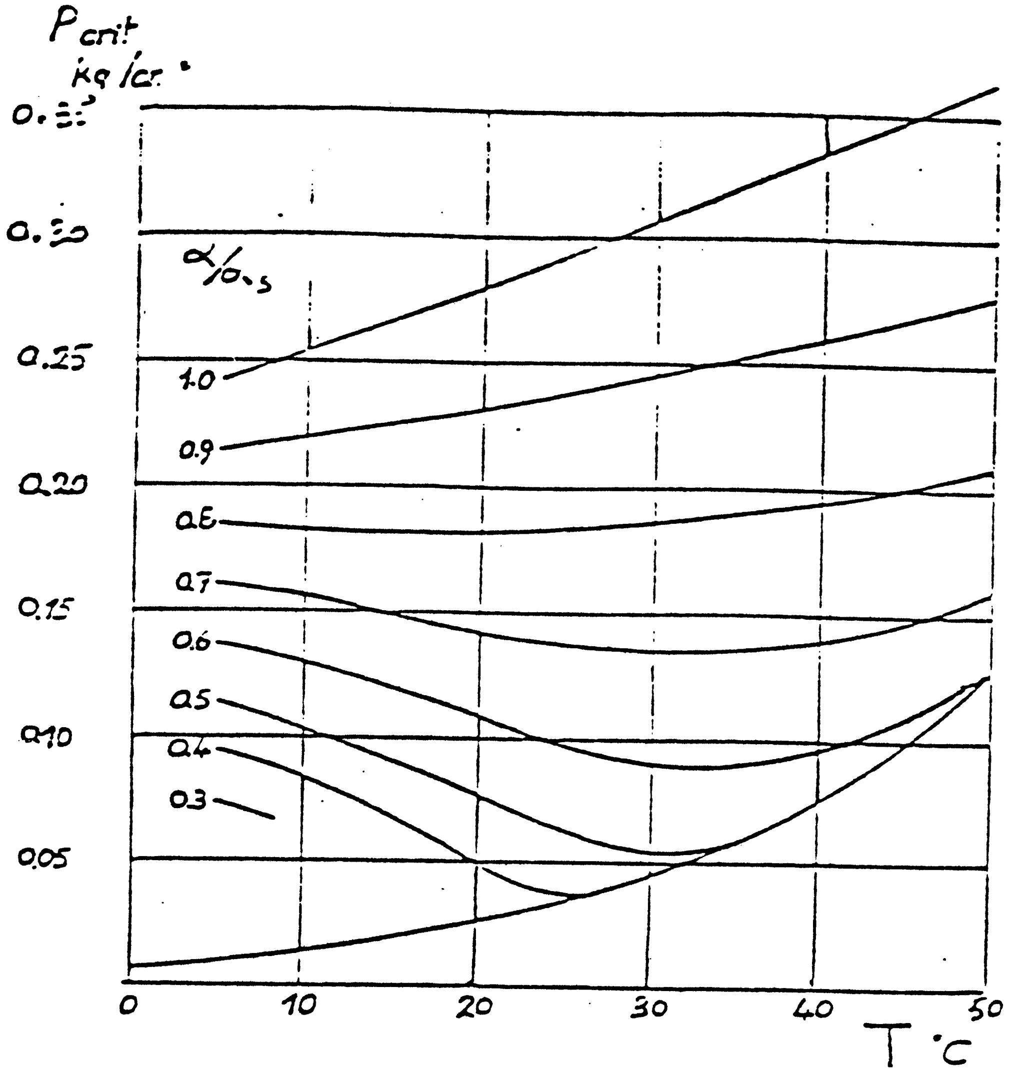
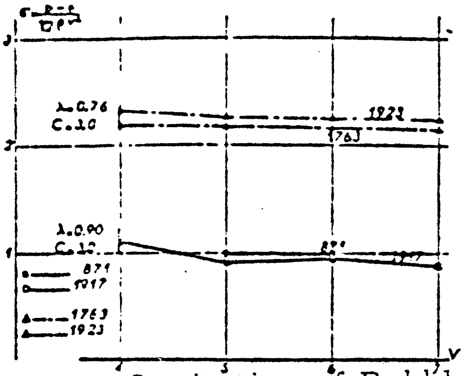


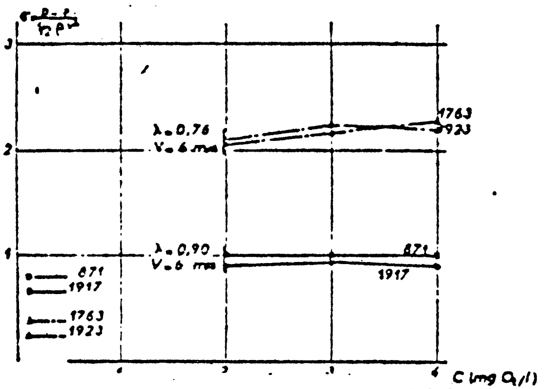
Fig. 3 Cavitation Inception Sigma for Flow Past Circular Section as Function of Relative Air Content Compared to Saturation at ST Edstrand (50).



g. 4 Critical Pressure as Function of Water Temperature in Numachi Venturi for Different Relative Air Contents (Compared to STP). Gutsche (49) via Edstrand (50)

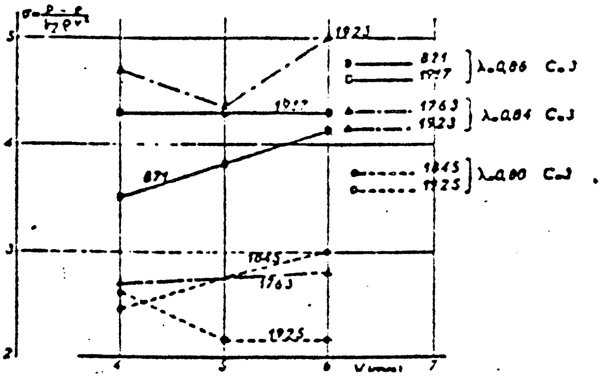


(a) Cavitation of Bubbles
Influence of Velocity

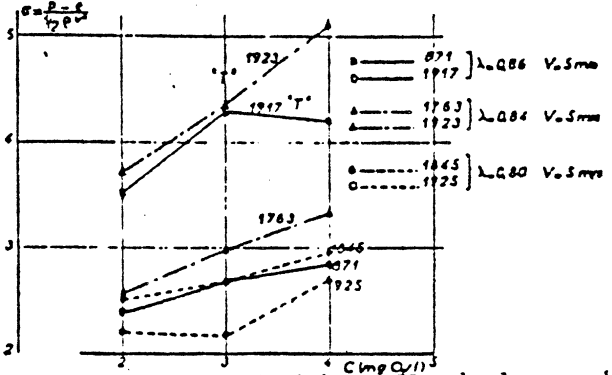


(b) Cavitation by Bubbles
Influence of Gas Content

Fig. (a and b) Propellors - Scale Effects



(c) Cavitation 'edt' Turbulence 'T'
Influence of Velocity



(d) Cavitation 'edt' or Turbulence 'T'
Influence of Gas Content

Fig. (c and d) Propellors - Scale Effect

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Types of Cavitation Observed

Fig. 5 Types of Cavitation Observed on Propellors and Effects of Oxygen Content and Velocity on Inception Sigma, Bindel and Riou (67)

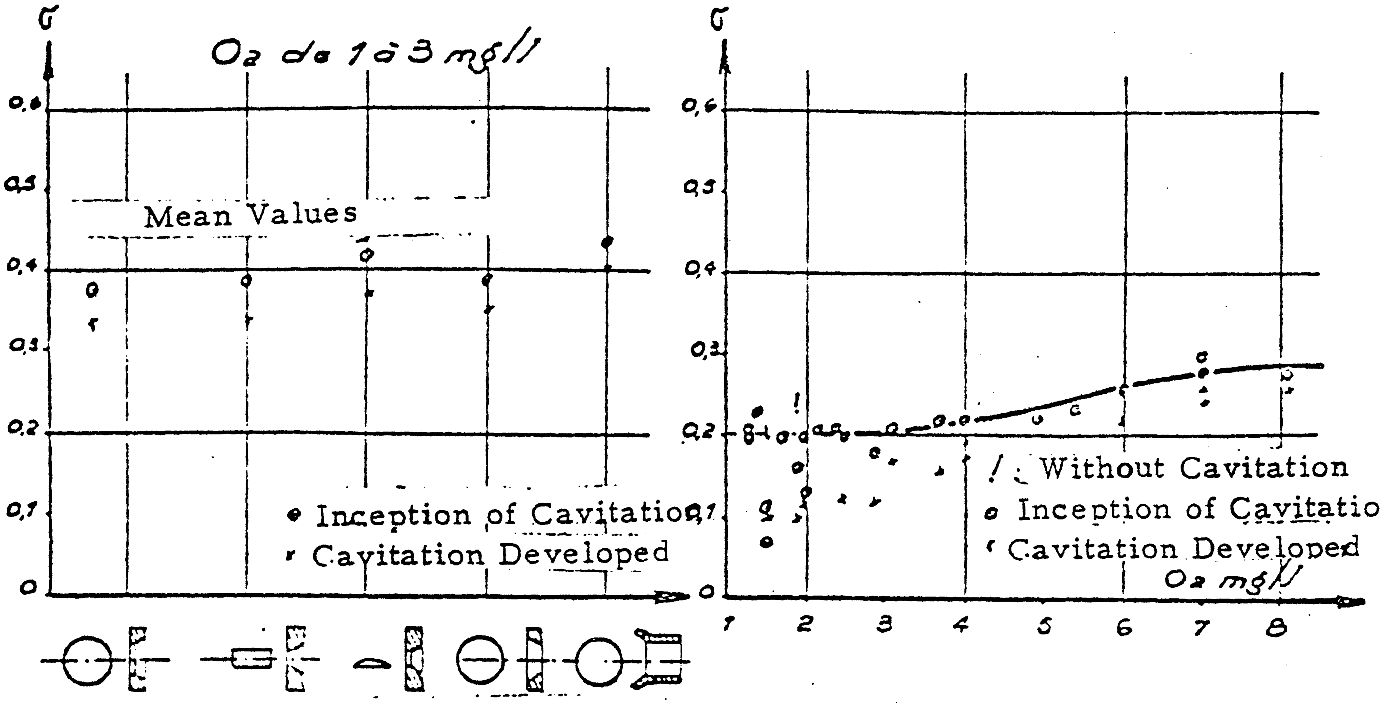

Fig. a — Influence of Form of Jet and Nozzle

Fig. c — Influence of O_1

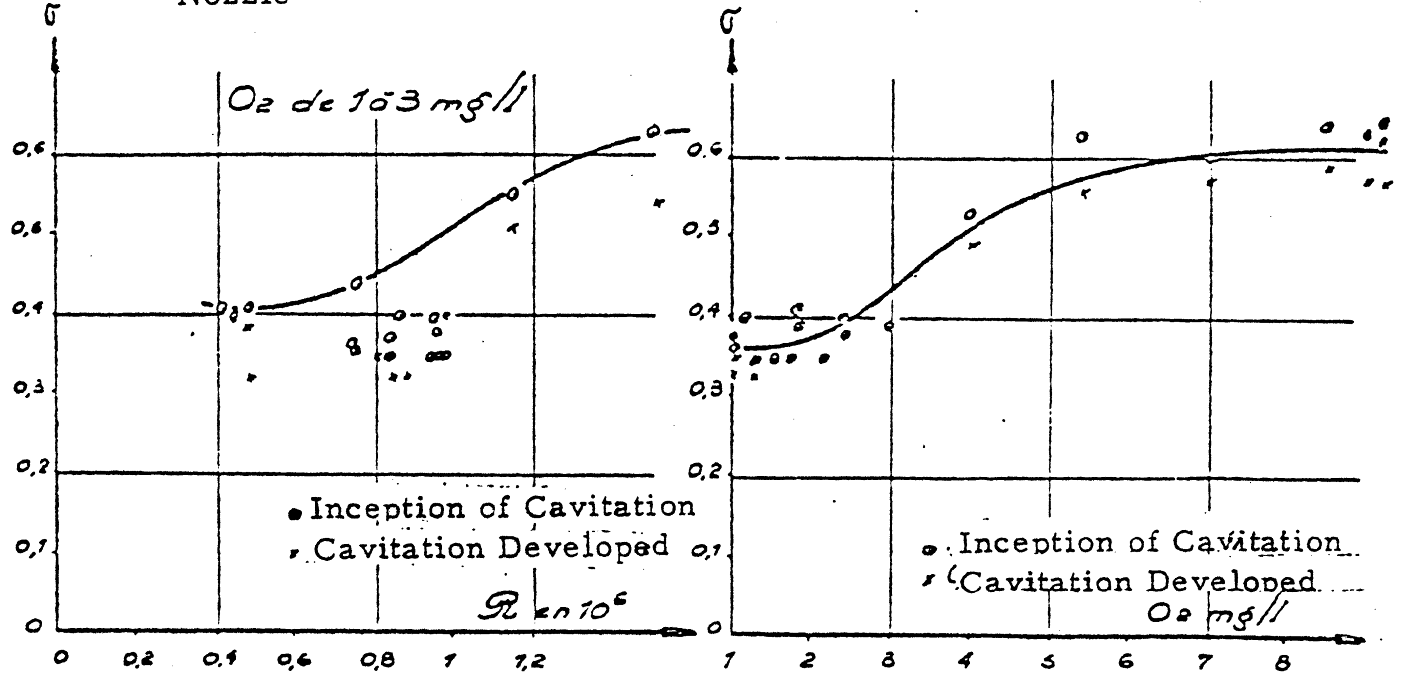

Fig. b — Influence of Reynolds Number (Circular Orifice)

Fig. d — Influence of O_1 (Circular Orifi

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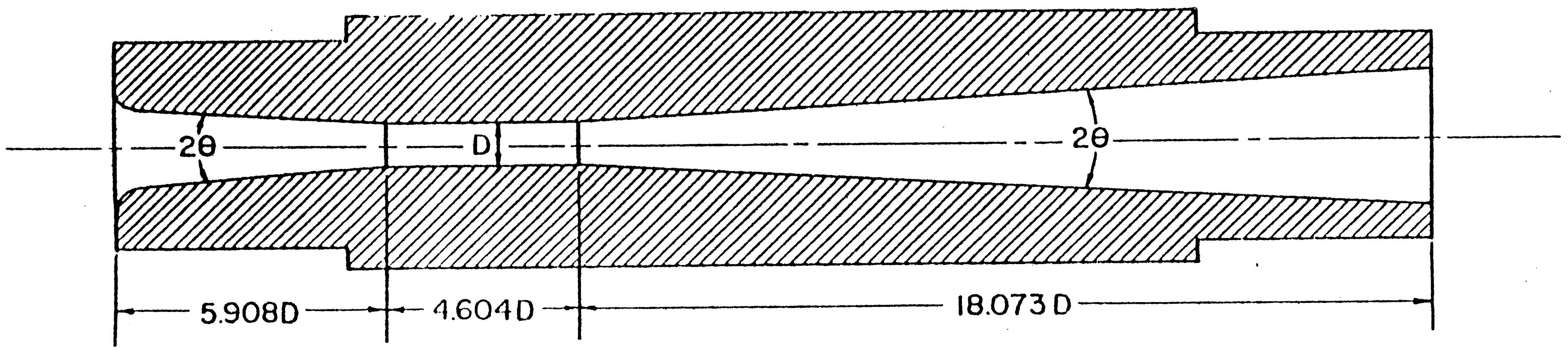
Fig. 6 Influence of Oxygen Content and Reynolds Number for Various Orifice Shapes on Inception Sigma, Duport (75)



$$2\theta = \frac{5^\circ 54'}{6^\circ 04'}$$

D = 1/2 - INCH

1849

Fig. 17.a. University of Michigan Venturi Flow Path (1/2 inch throat), Hammitt, etal. (80-82)

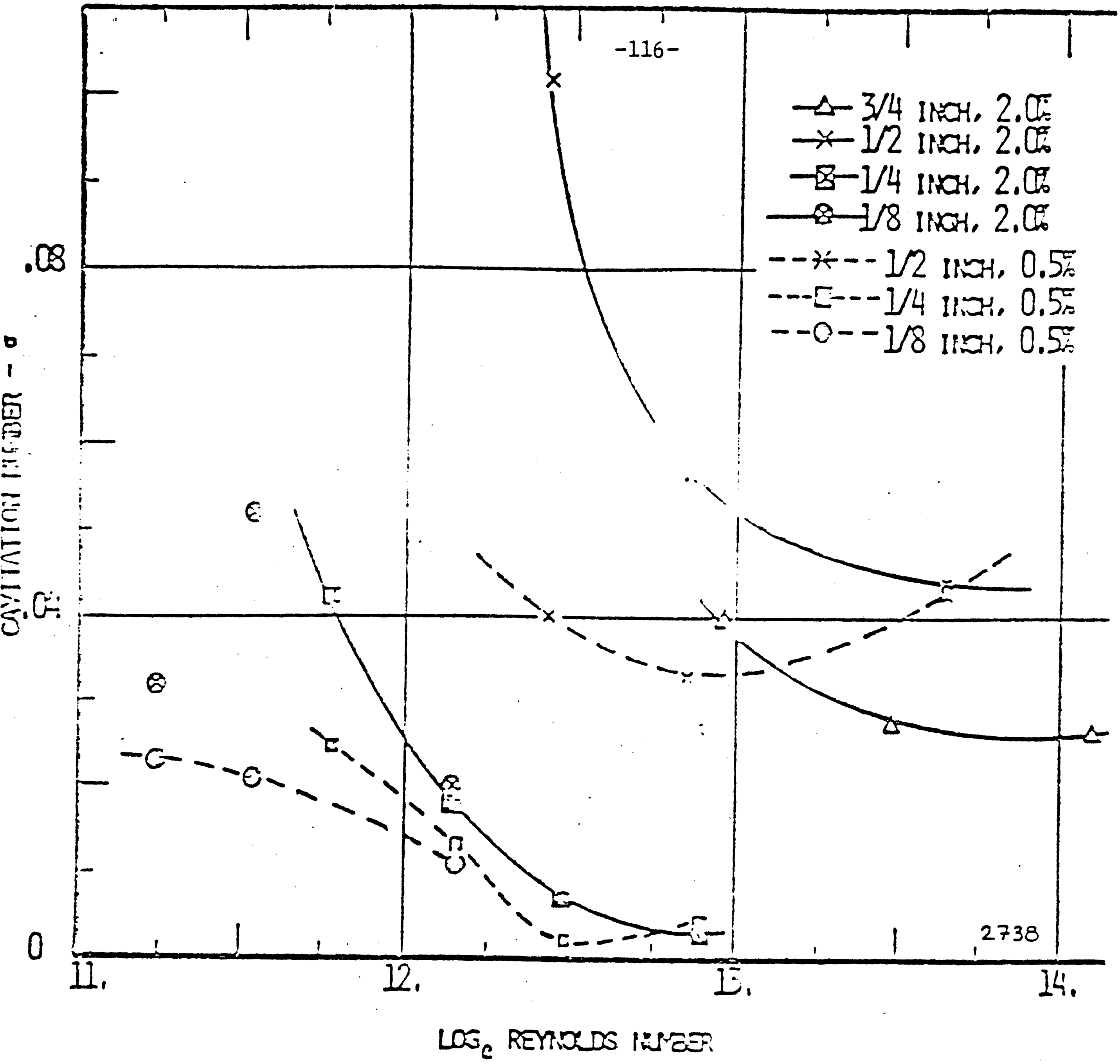


Fig. 7–b Inception Sigma vs. Reynolds Number, University of Michigan Venturis (1/8 to 3/4 inch throats). Hammitt, etal. (80–82)

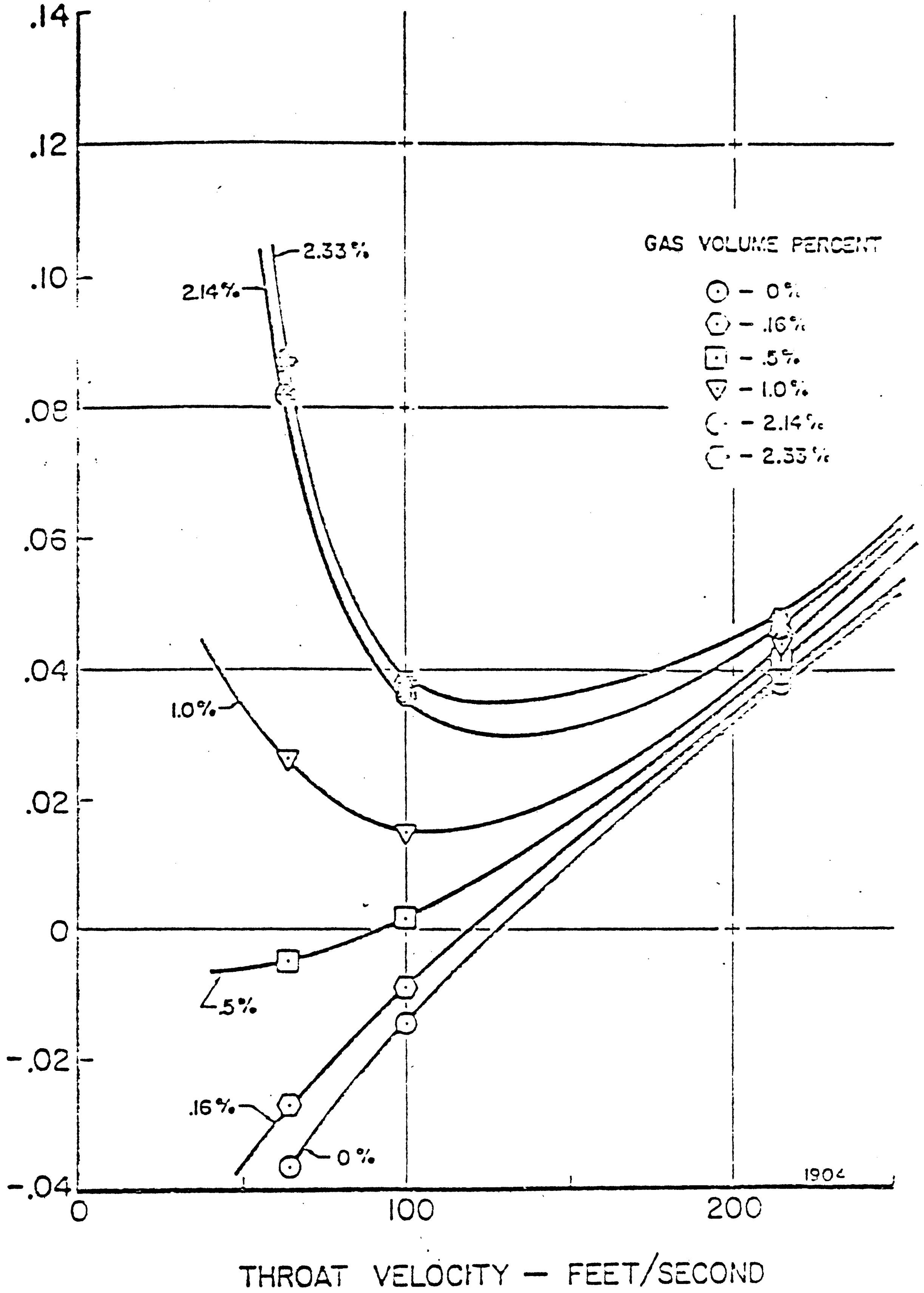


Fig. 8 Cavitation Inception Sigma vs. Throat Velocity - 1/2 inch Venturi, Hammitt, etal. (80-82)

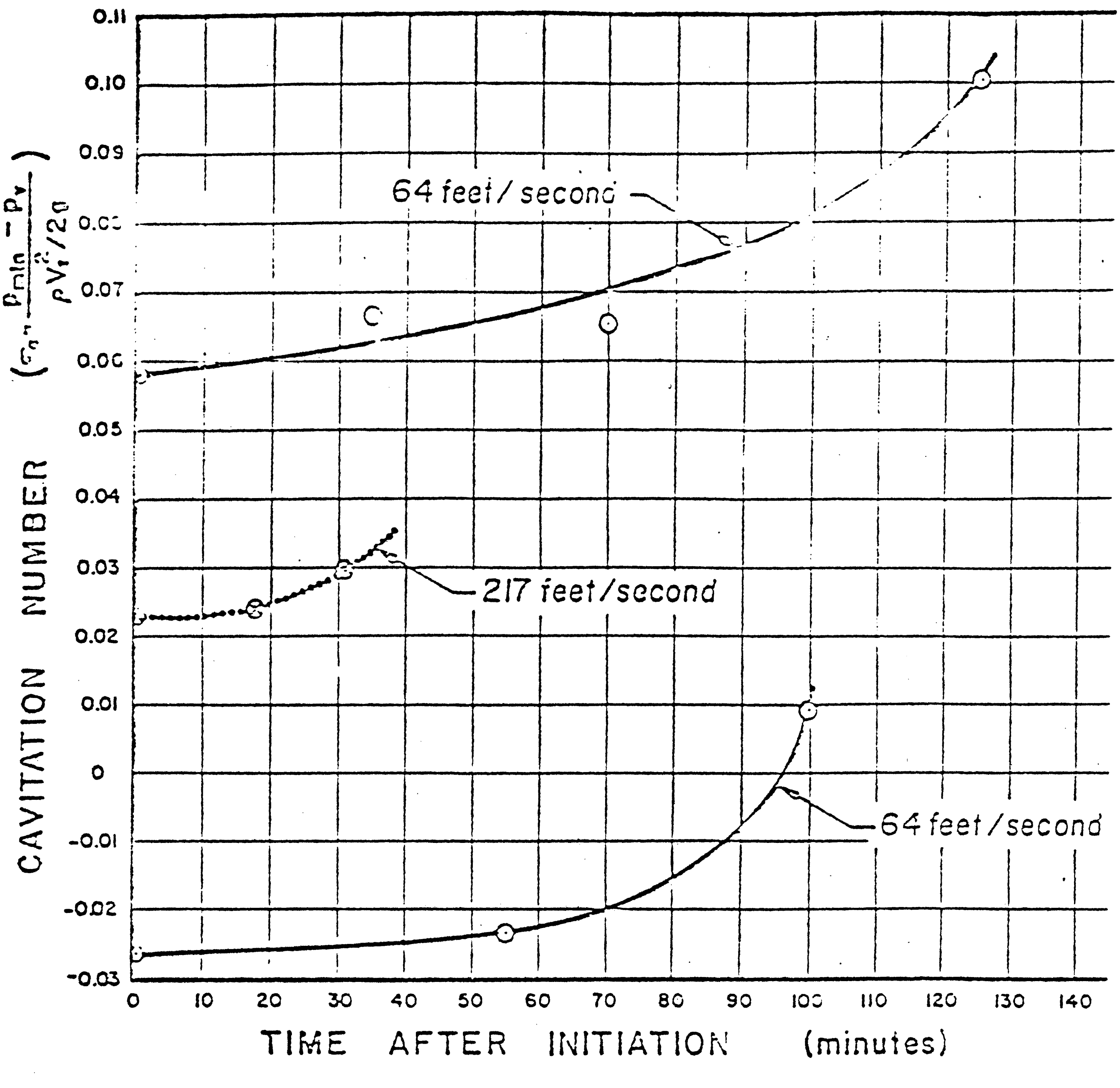


Fig. 9. a Prepressurization Effects on Cavitation Sigma, 1/2 inch Venturi, Hammitt, etal. (80-82)

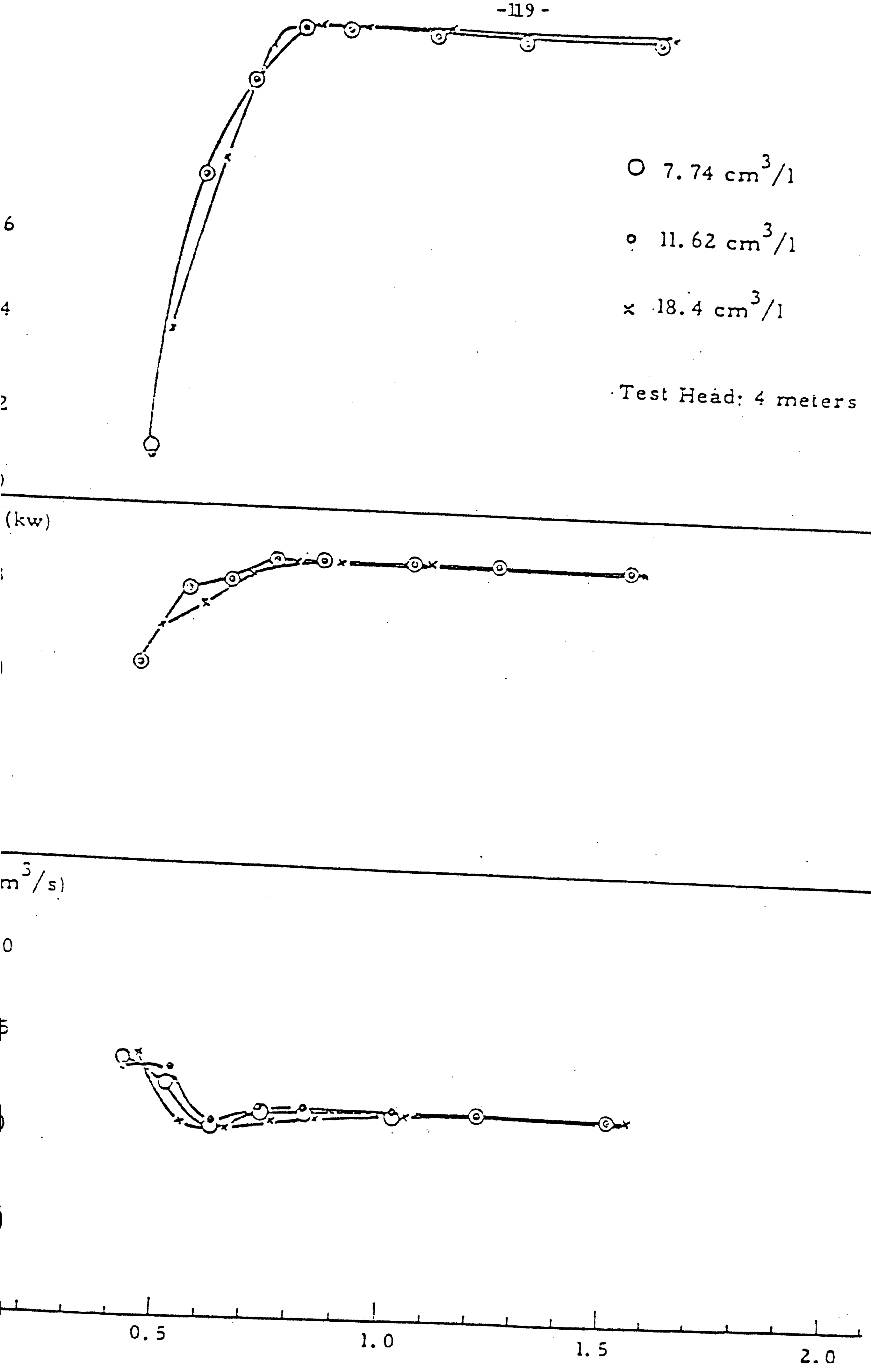
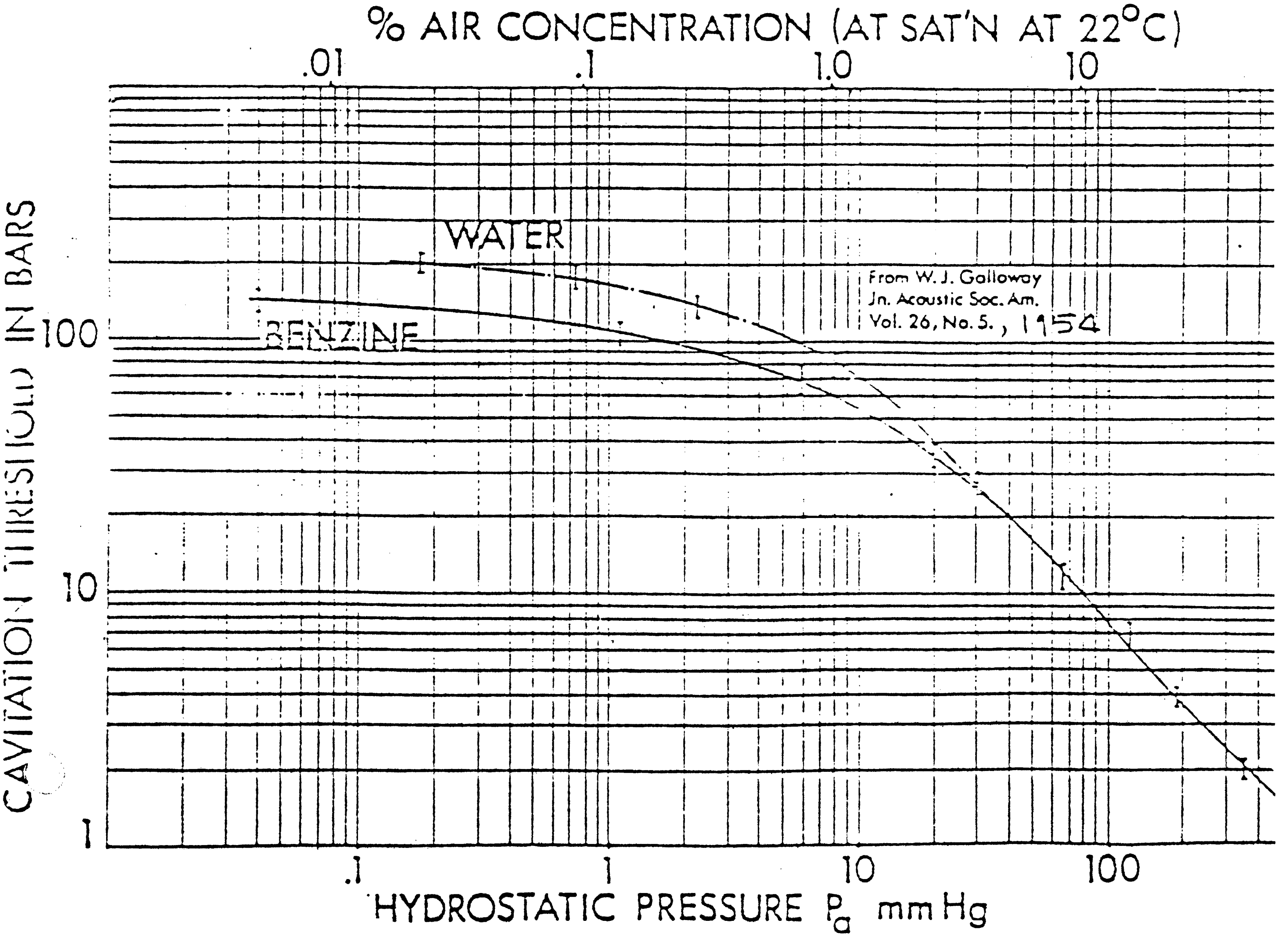


Fig. 10 Air Content Effects on Kaplan Turbine, Fallstrom (84)

Test Head: 4 meters

Fig. 11 Cavitation Threshold of Water and Benzine as Function of Relative Air Content (compared to STP), Galloway (91)



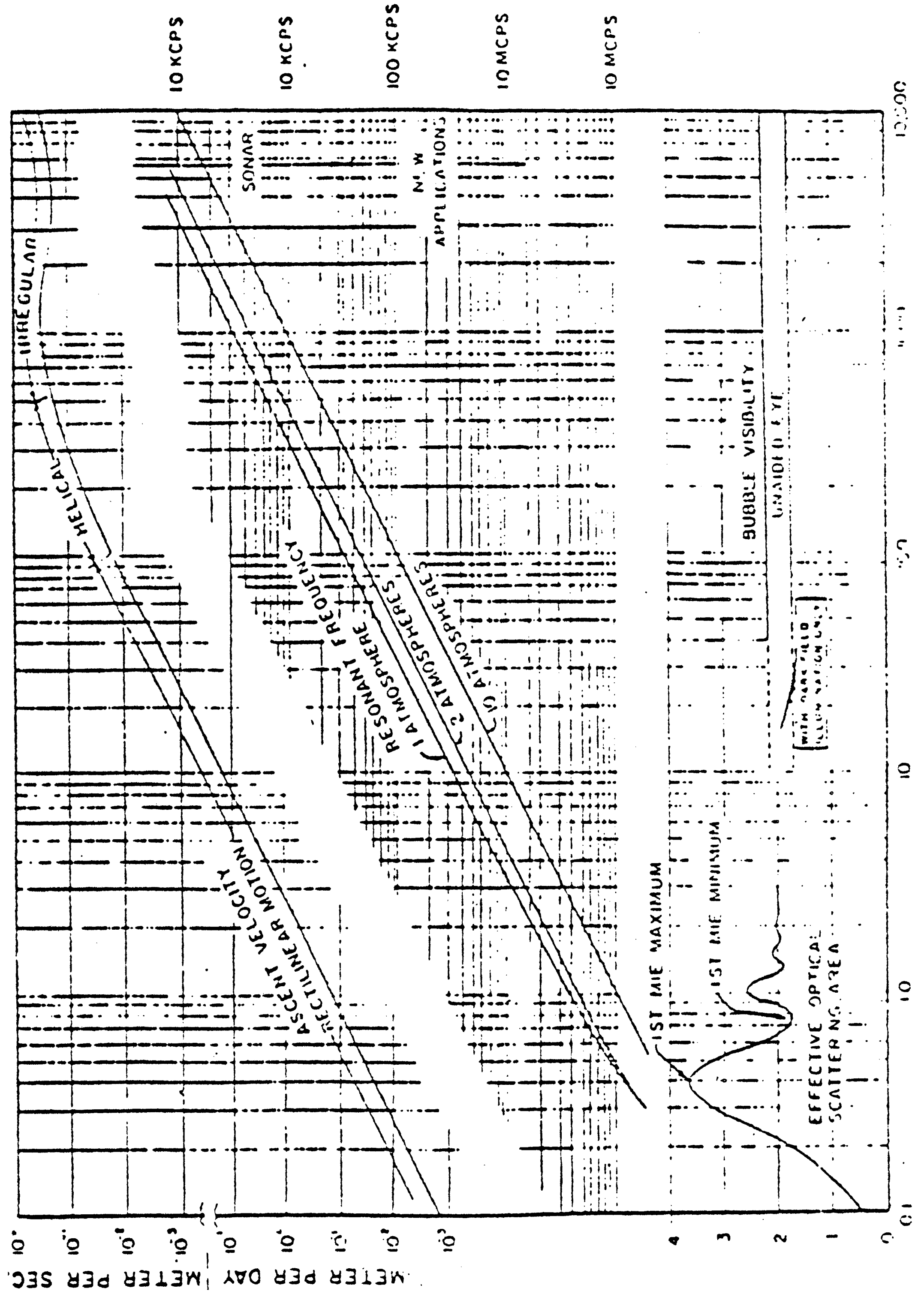


Fig. 12- Classification of Bubble Size (from ref.104, Vitro Laboratories.

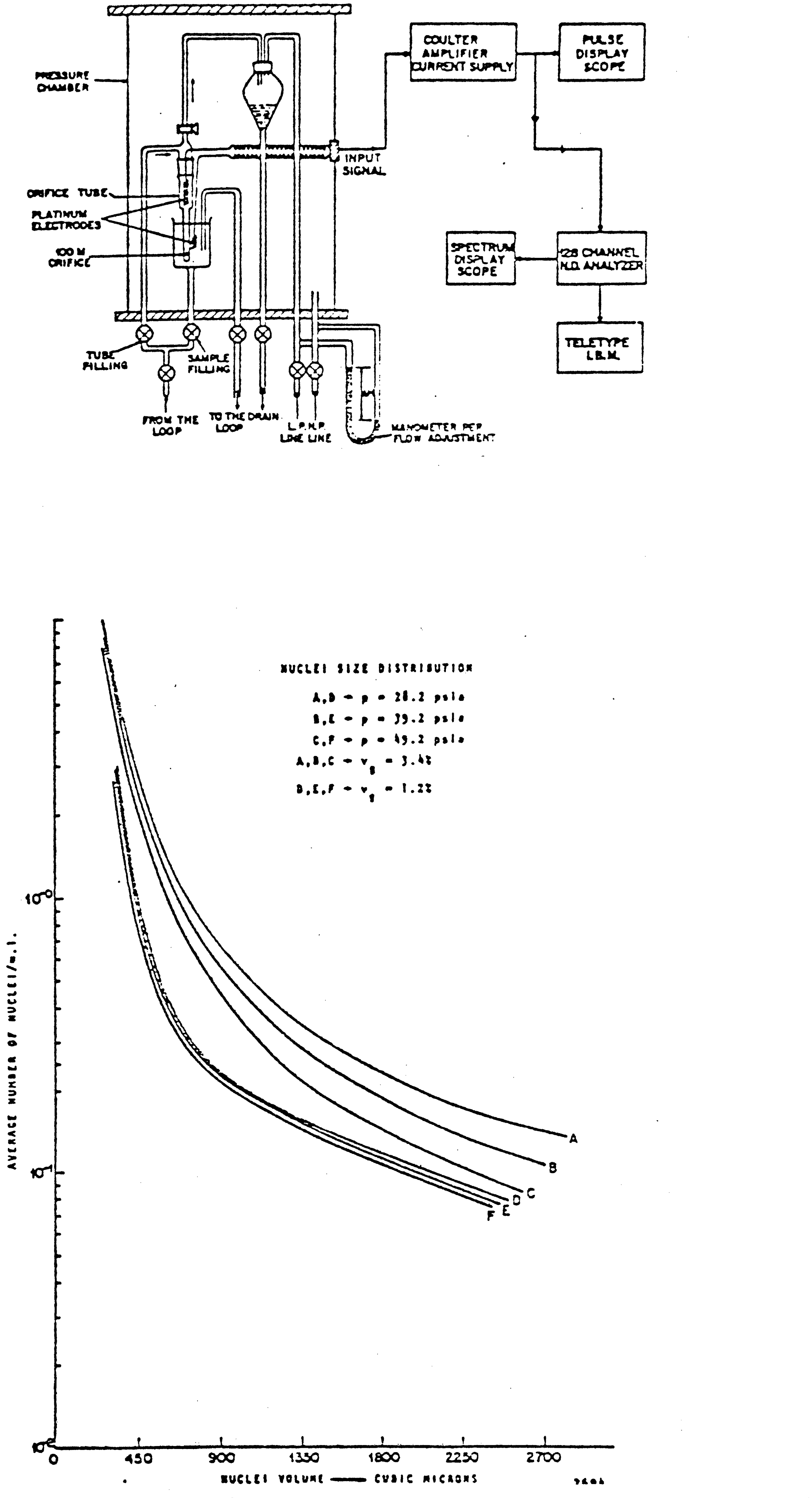
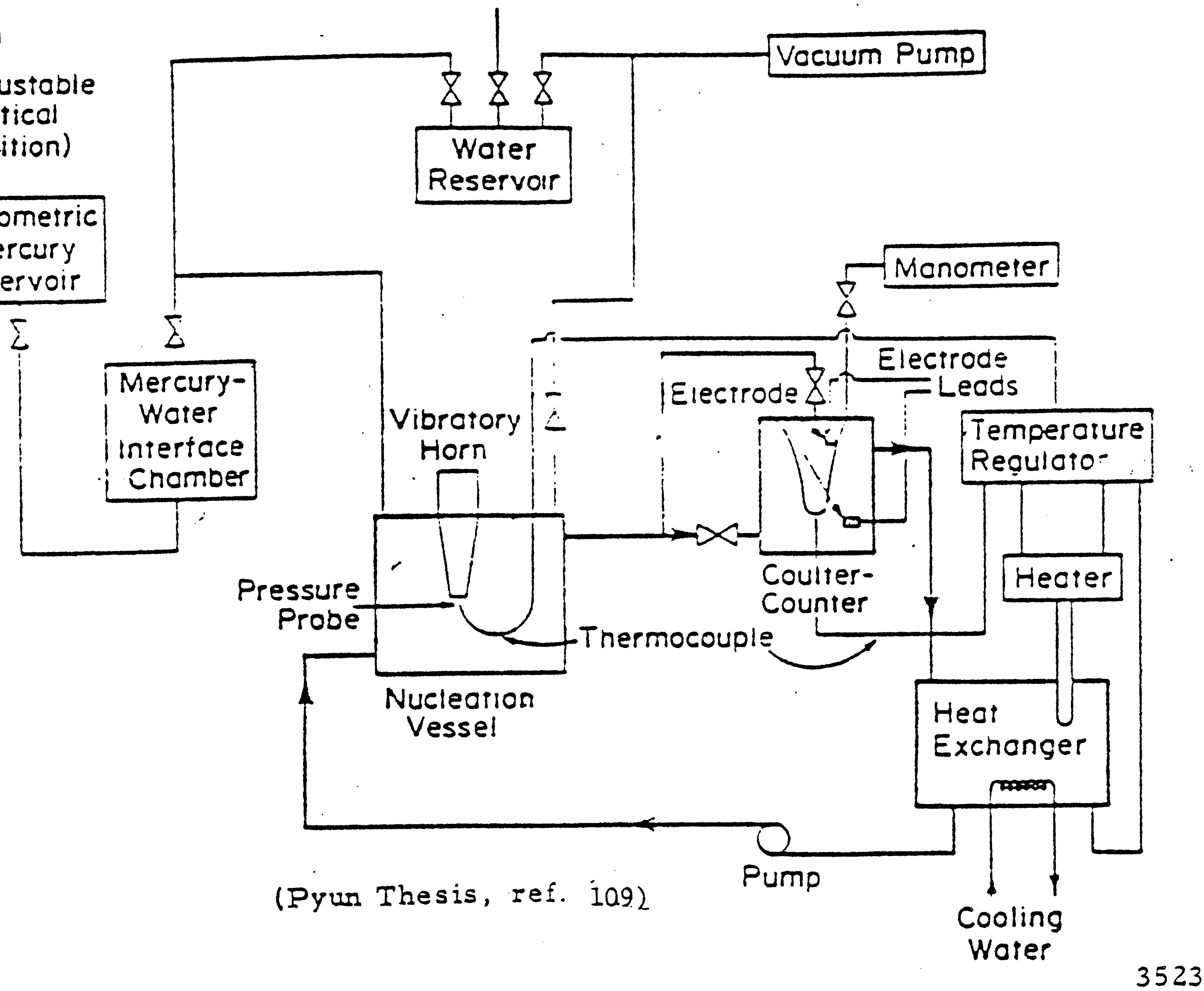


Fig. 13 - University of Michigan Coulter-Counter, Schematic Diagram and Nuclei Size Spectrum, Ahmed and Hammitt (37)

Fig. 14-a *SCHEMATIC DIAGRAM OF VIBRATORY HORN NUCLEATION STAND*

(WATER)

MECHANICAL SYSTEMS



(Pyun Thesis, ref. 109)

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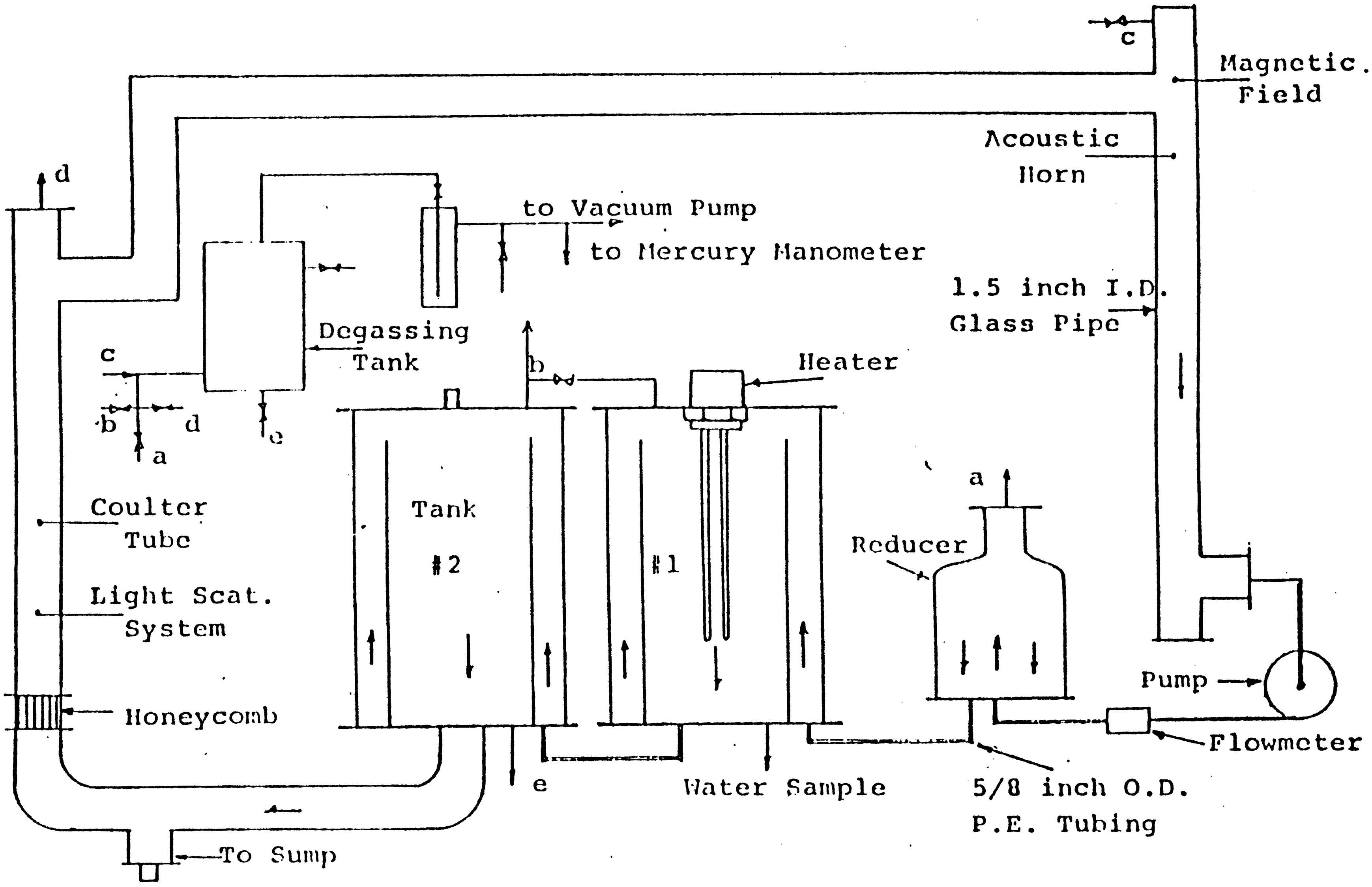

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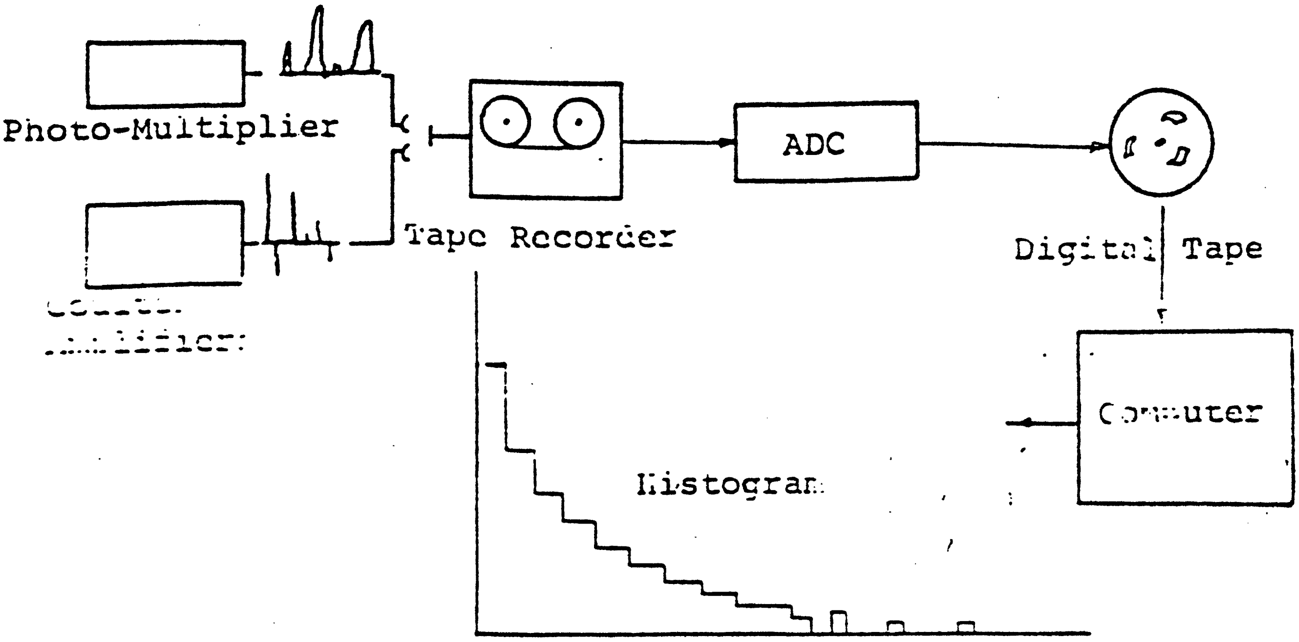
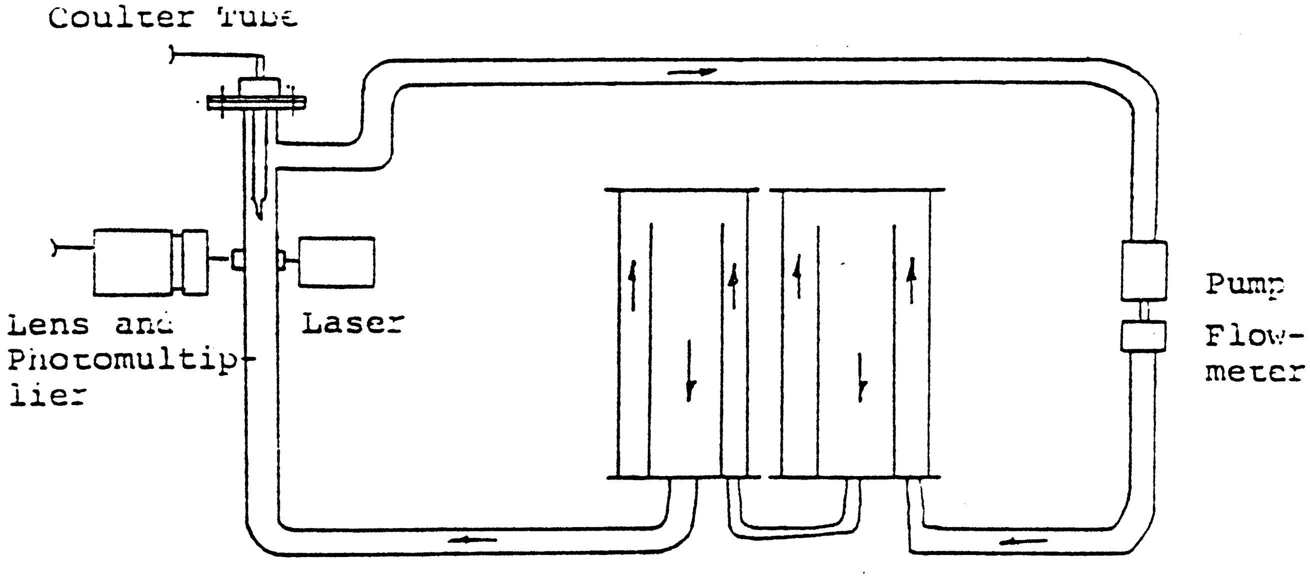
Fig. 14 b, Schematic Diagram of the Water Loop.



Block diagram for pulse processing



Sketch of the experimental set-up

4943(a, b)

Figure 14- c

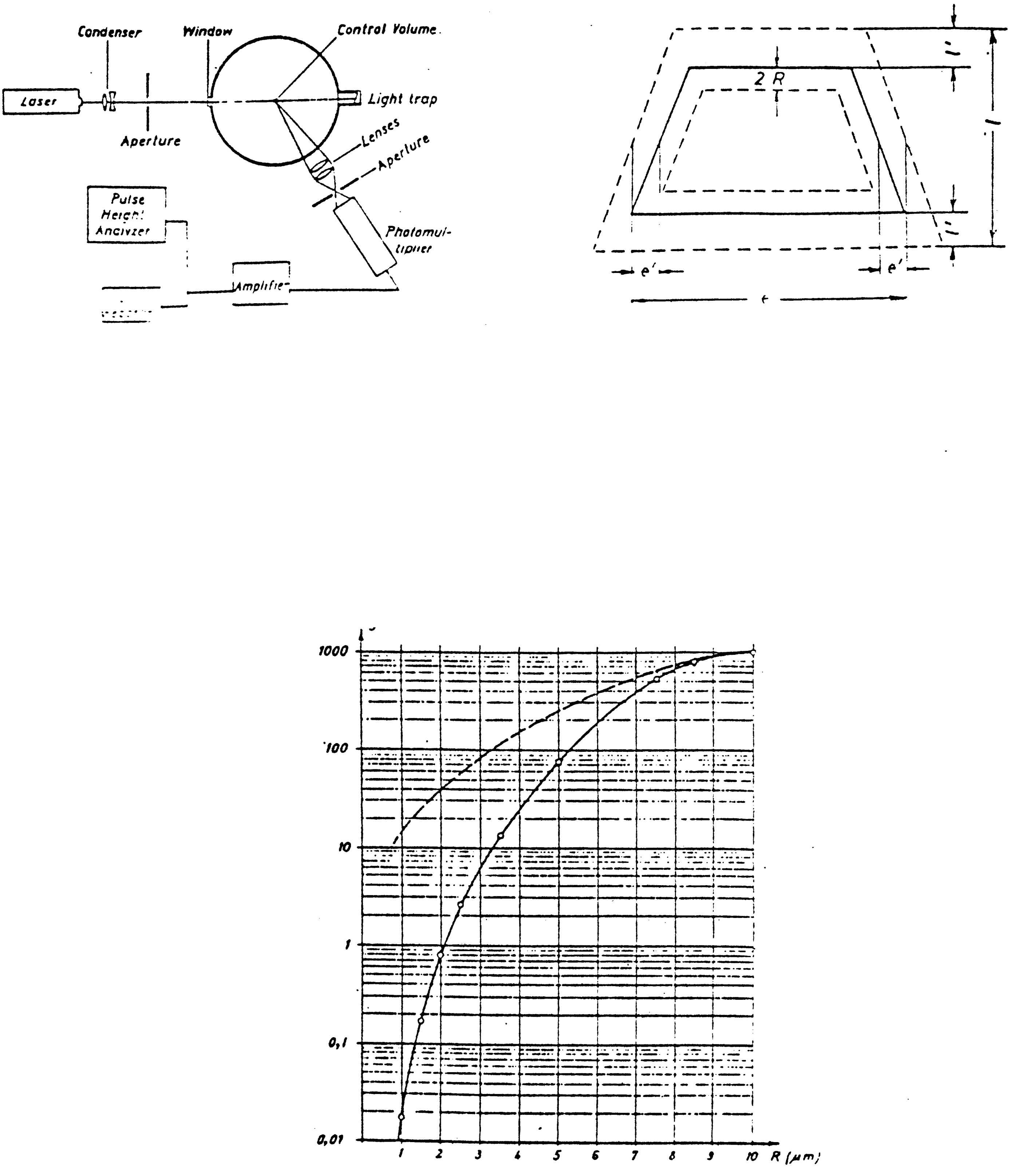


Fig. 14. d. Basic Layout and Calibration of Optical Measuring Device, Yilmaz (111)

4941 a-c)

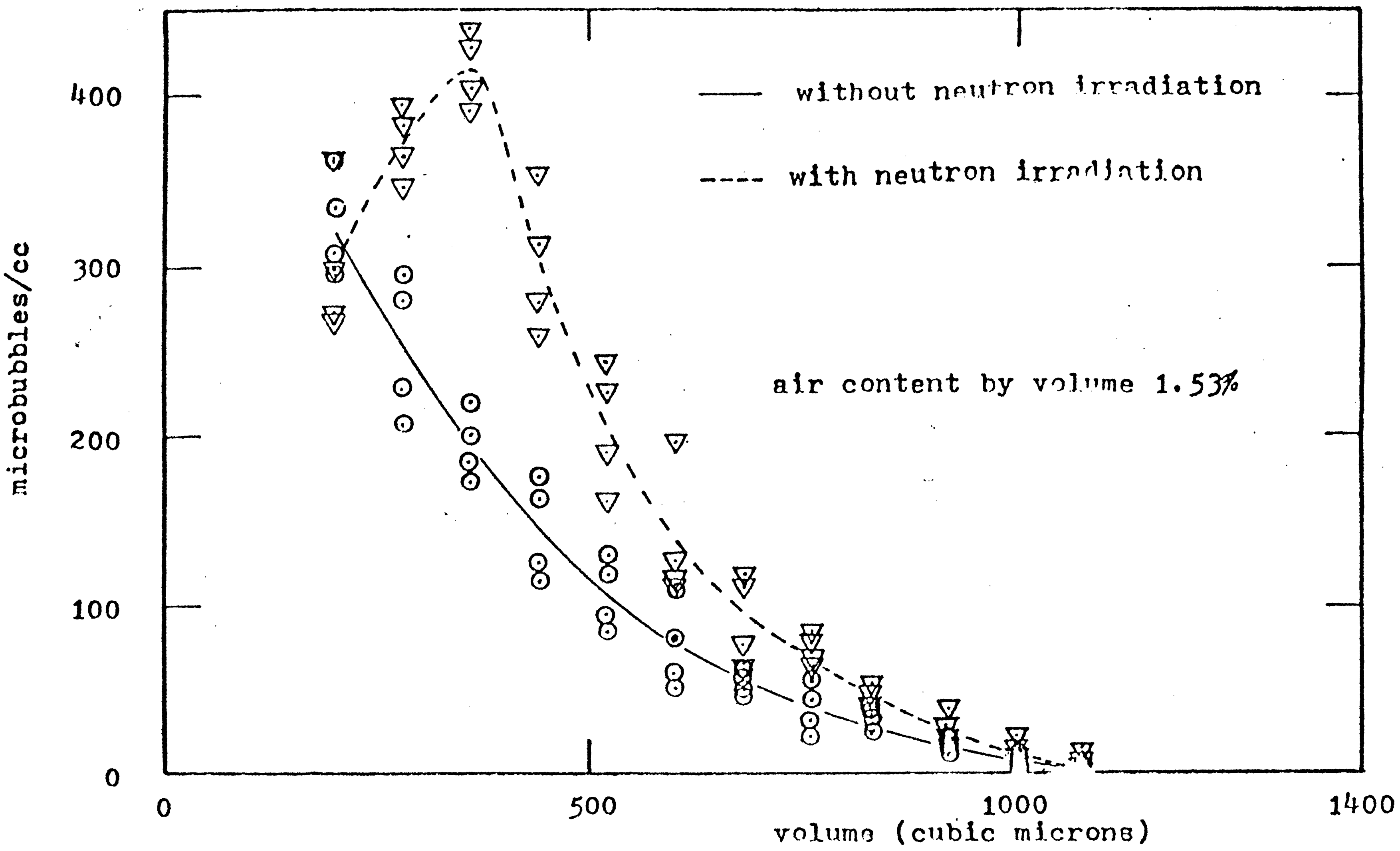
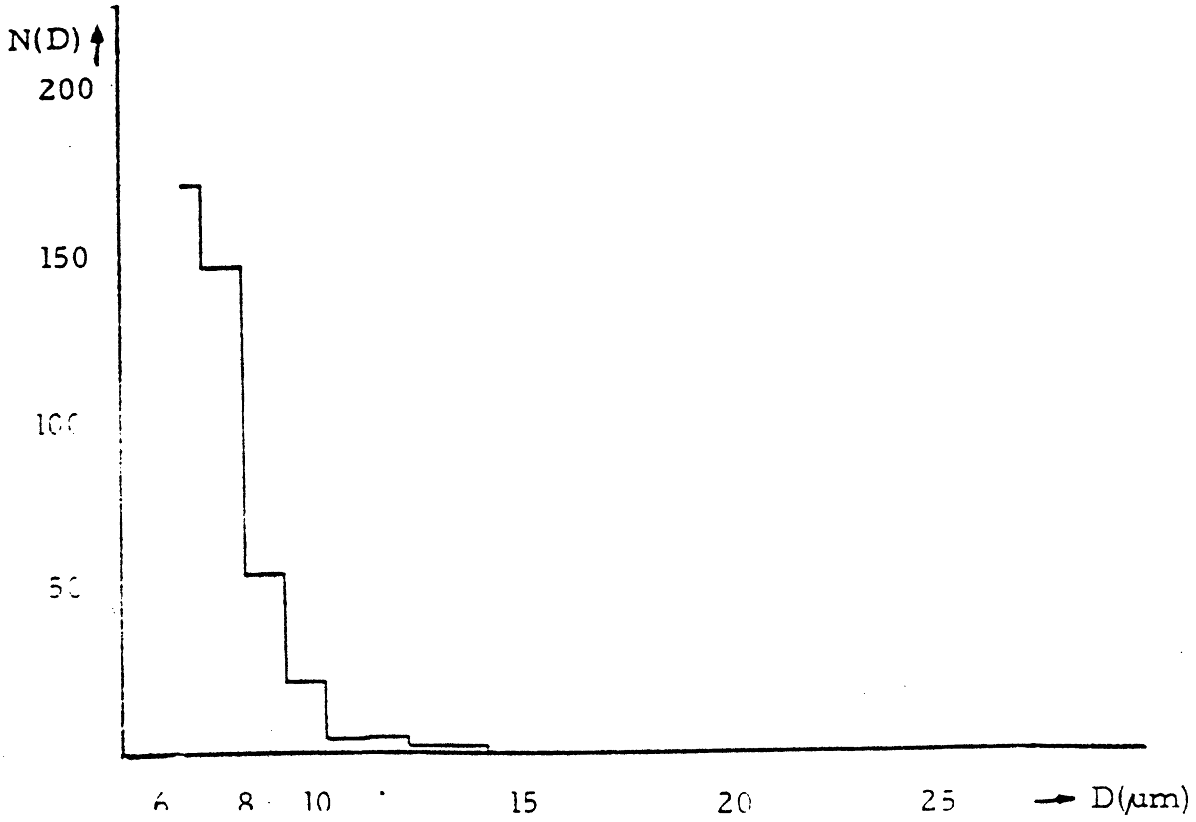
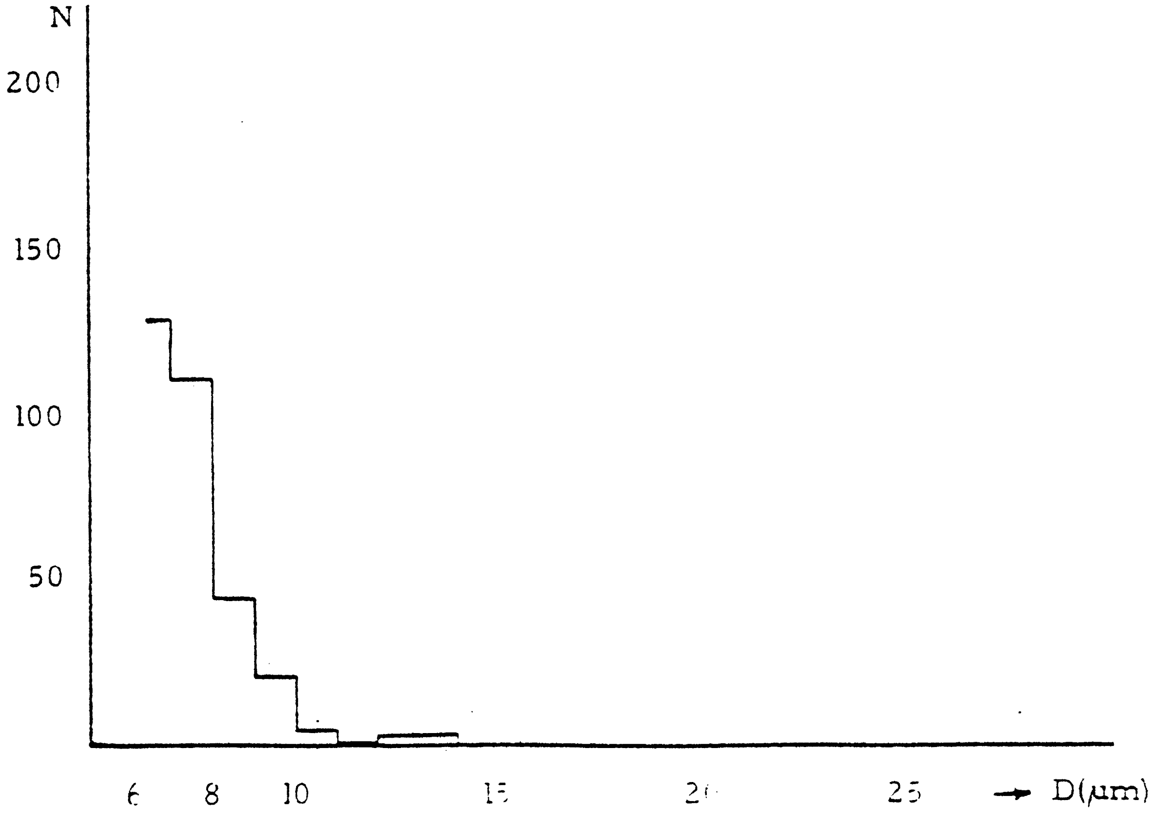


Figure 3-15 Microbubble Spectrum in a given Sample of tap Water at P = 15.8 psia, T = 70°F & t = 24 Hours 3591



Untreated Tap Water



Degased Tap Water

Fig. 16 Nucleus Size Histograms of Untreated and Degased Tap Water: Obtained with the Optical Method, Yilmaz (111) 4949 a, b

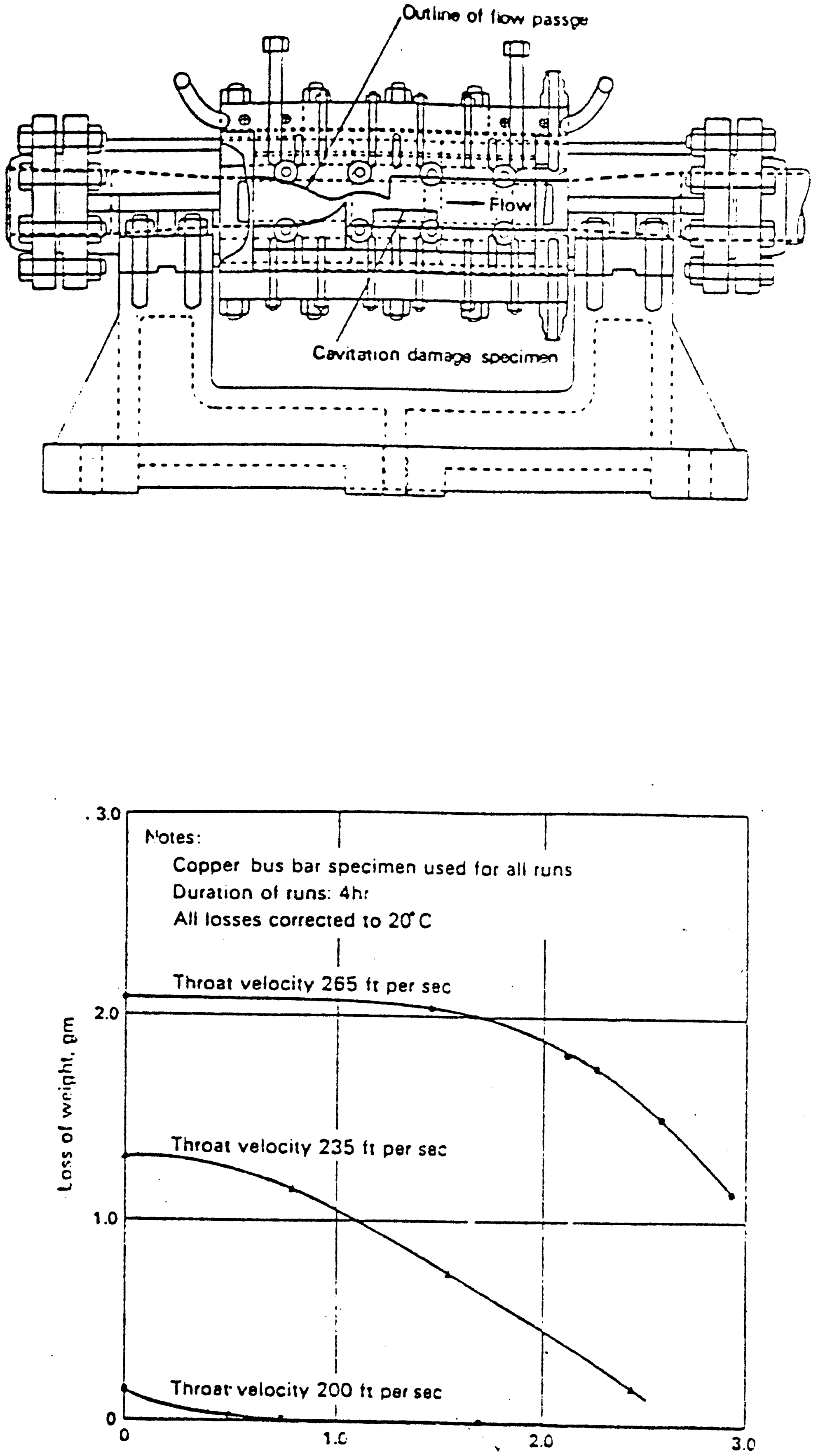


Fig. 17 Effects of Air Injection Upon Cavitation Damage in Venturi, Mousson (127)

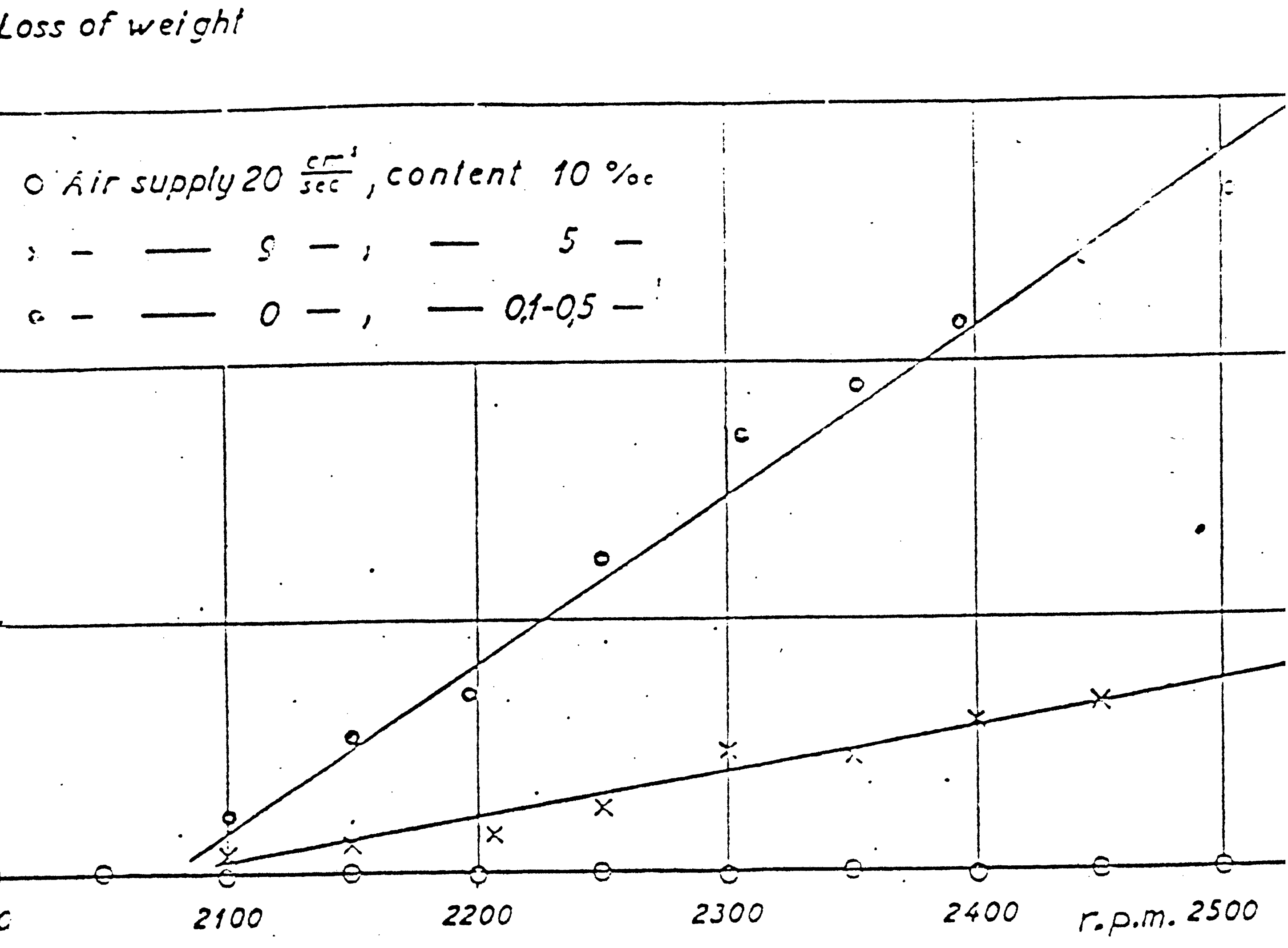


Fig. 18 Effects of Air Content Upon Cavitation Damage in Rotating Disc Apparatus, Rasmussen (128,129)

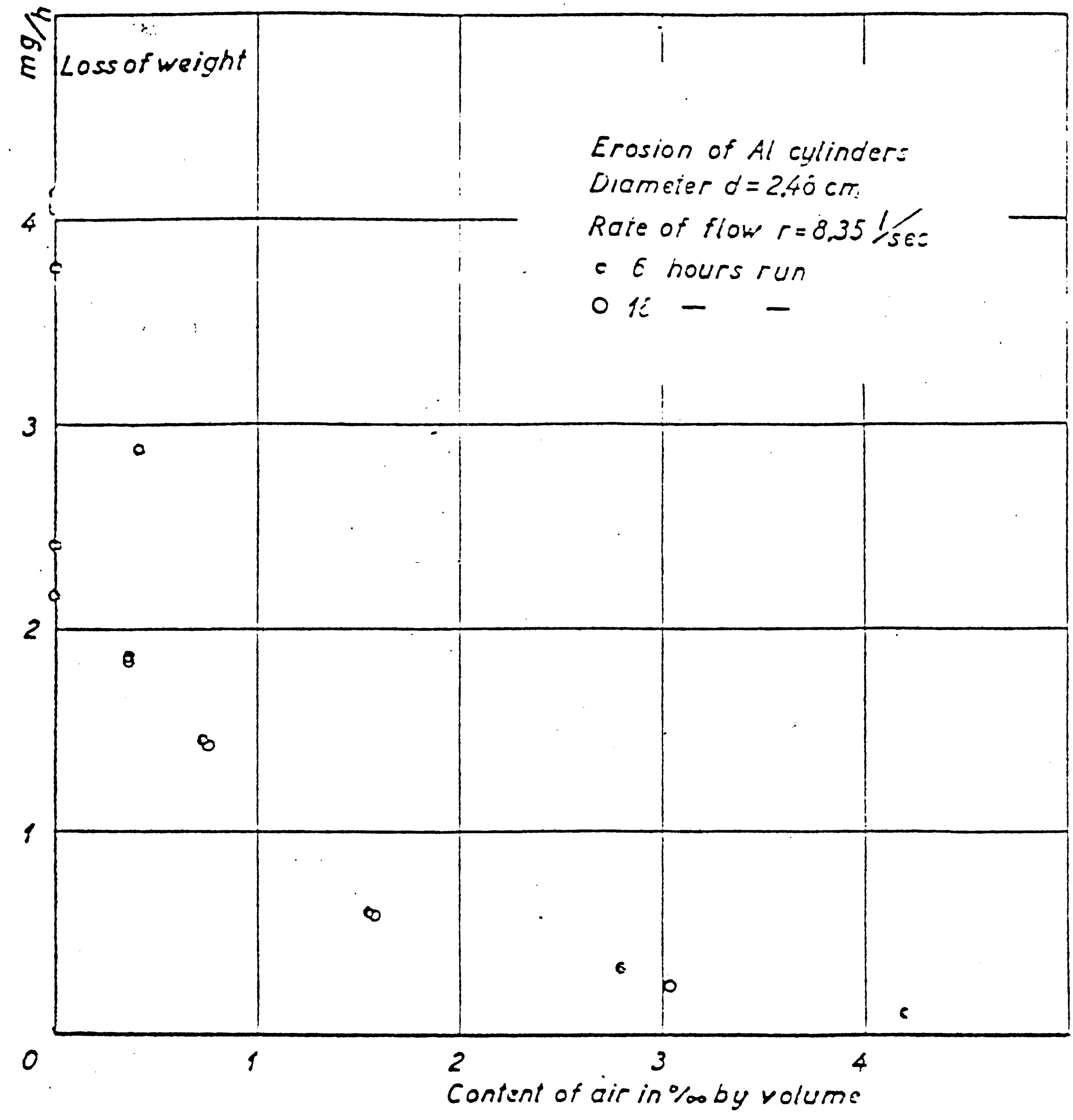
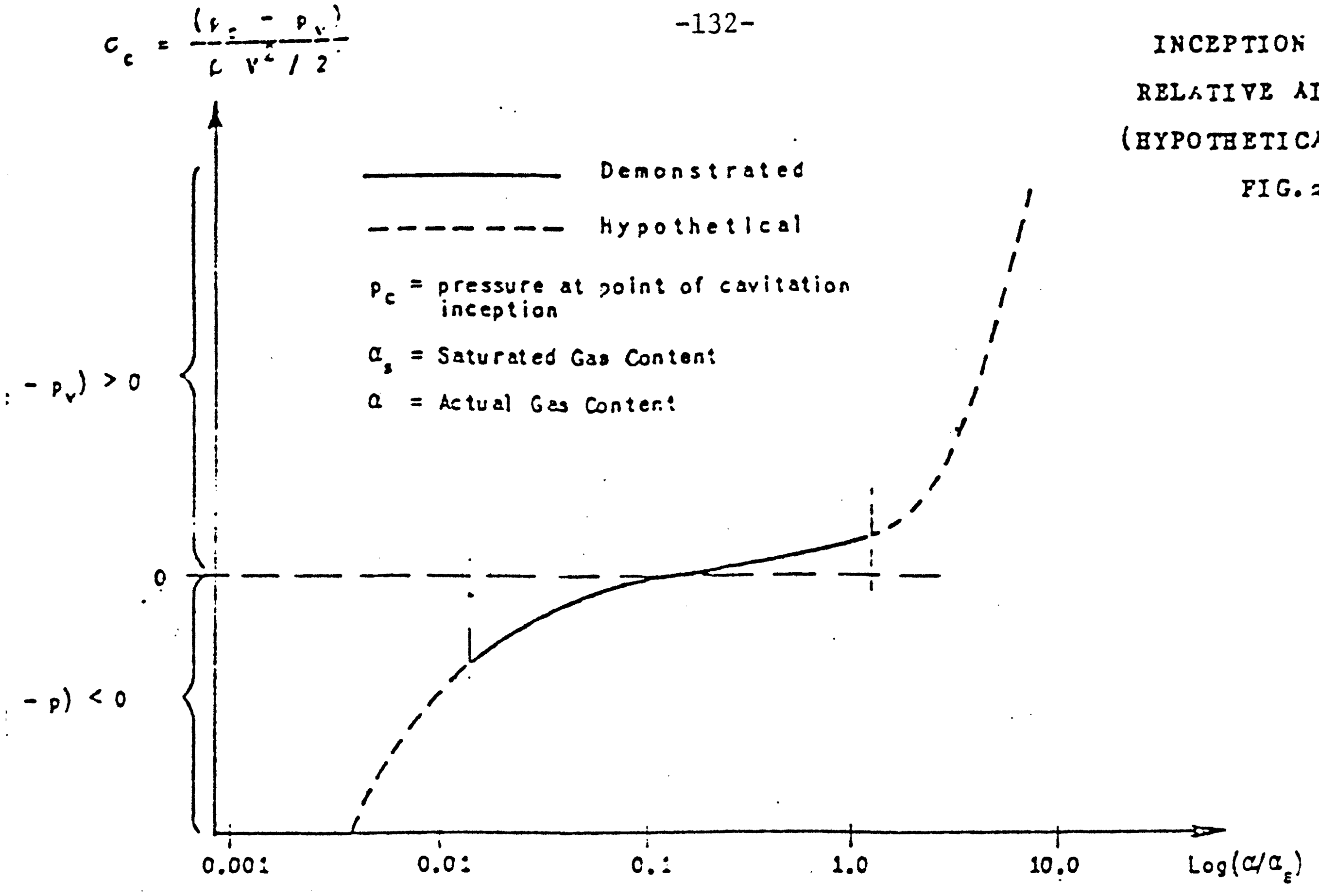
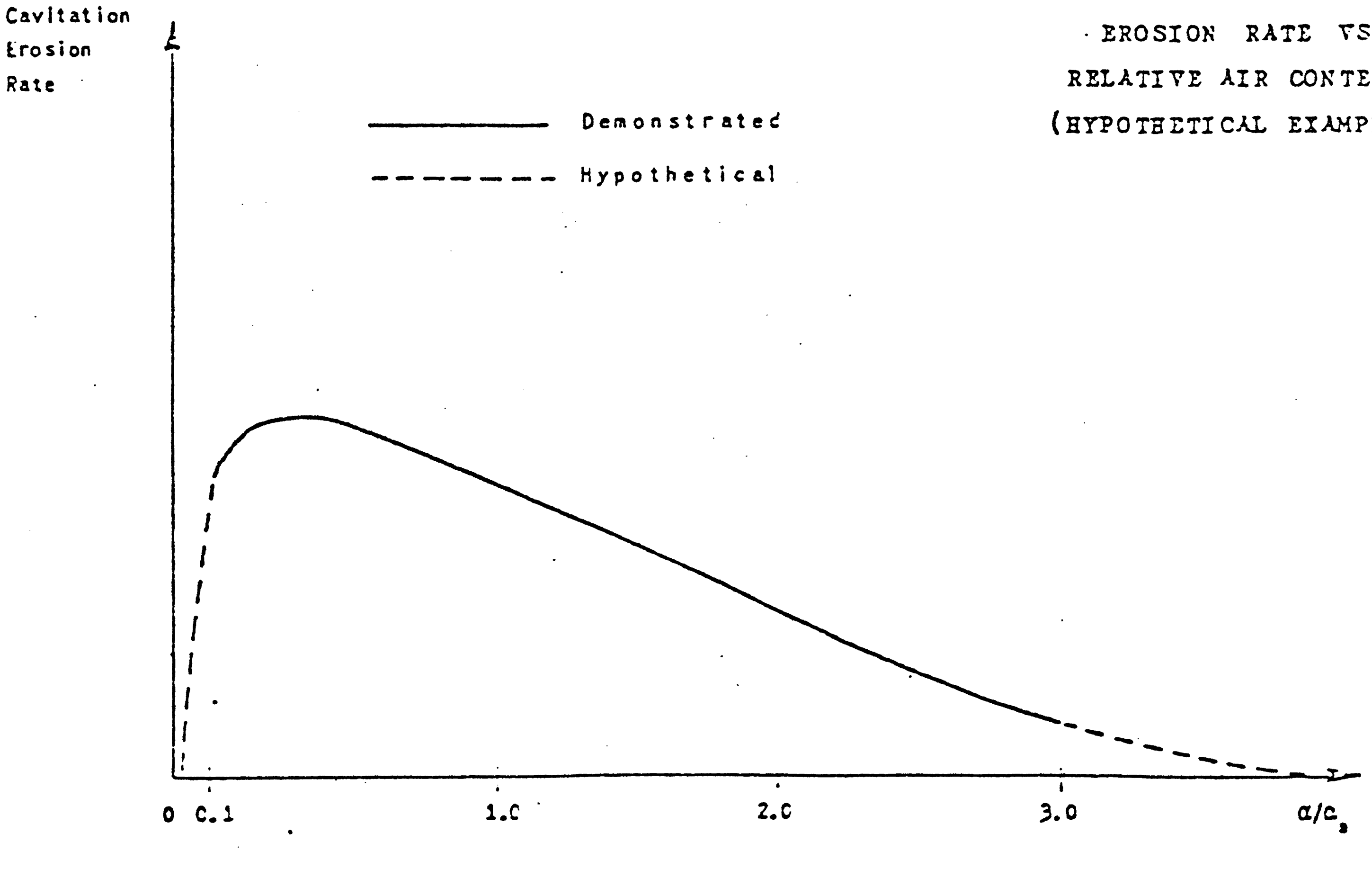


Fig. 19 Effects of Air Content Upon Cavitation Damage in Venturi Upon Aluminum Alloy, Rasmusser (128, 129)



INCEPTION SIGMA VS
RELATIVE AIR CONTENT
(HYPOTHETICAL EXAMPLE)
FIG. 25-a



EROSION RATE VS
RELATIVE AIR CONTENT
(HYPOTHETICAL EXAMPLE)

Fig. 20 · Hypothetical Overall Dependence of Inception Sigma and Erosion Rate on Relative Air Content (43)

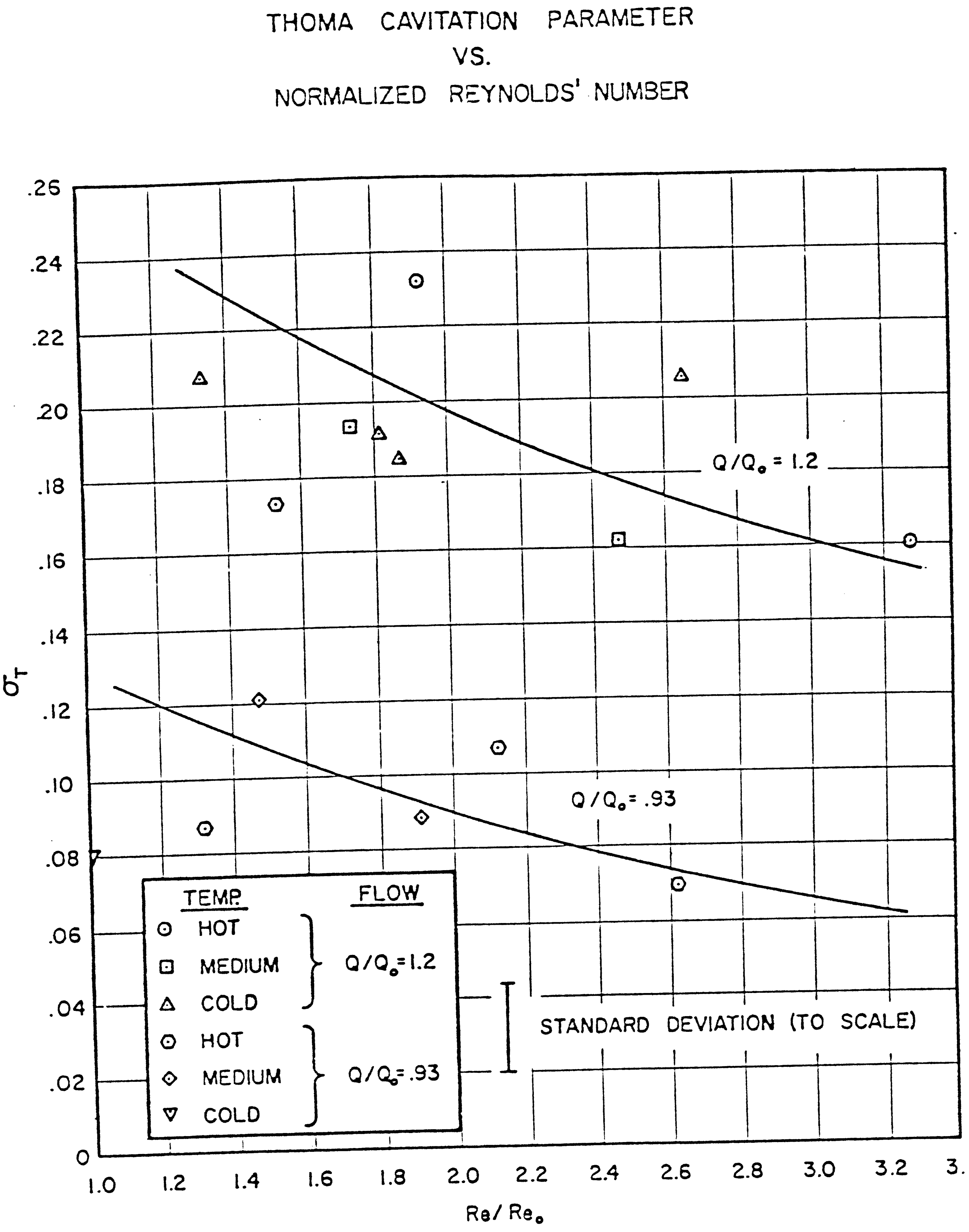


Figure 21 Thoma Cavitation Parameter vs. Normalized Reynolds' Number. U-M tests (46,47)

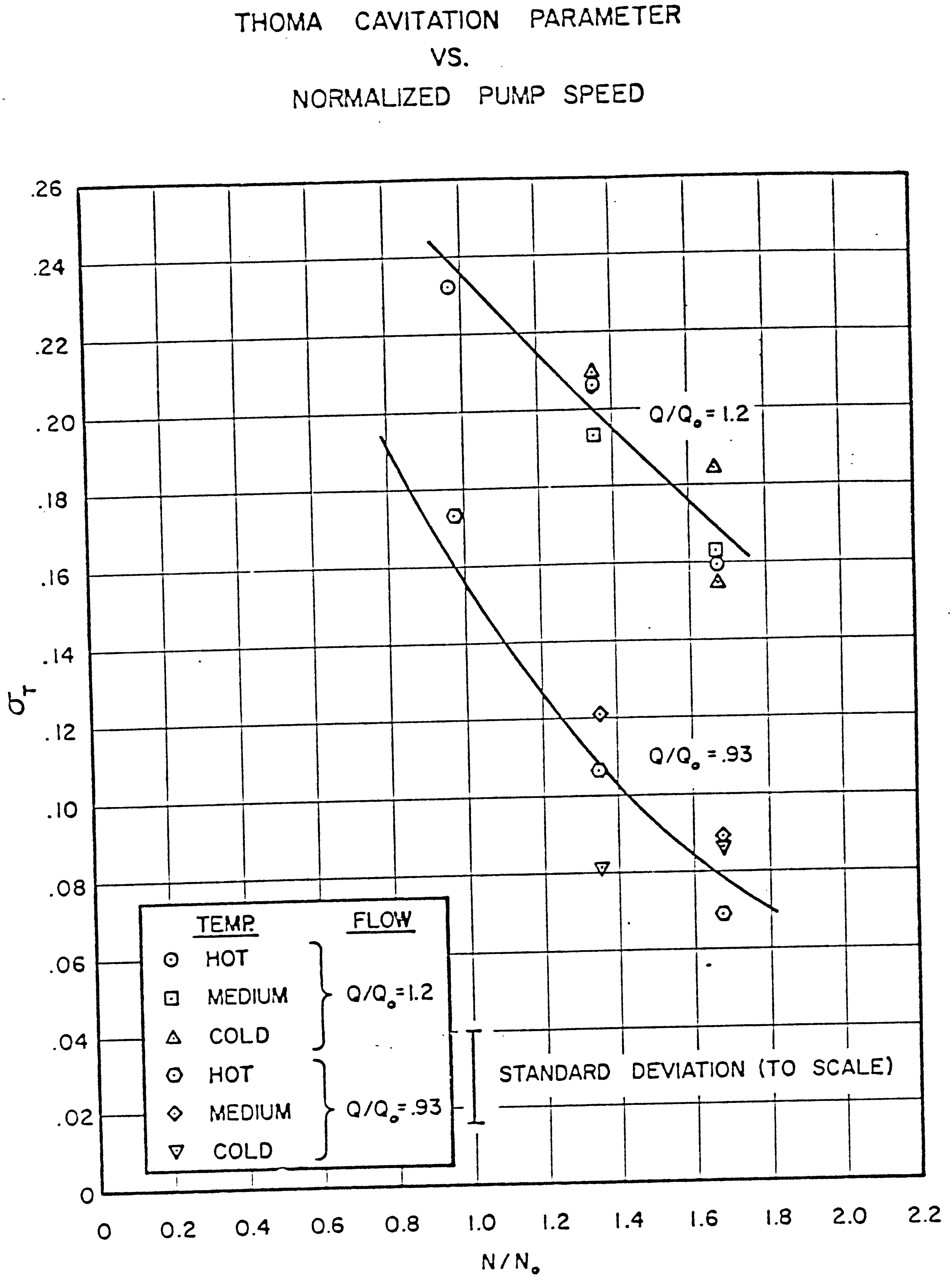


Figure 22. Thoma Cavitation Parameter vs. Normalized Pump Speed.

U-M tests (46,47)

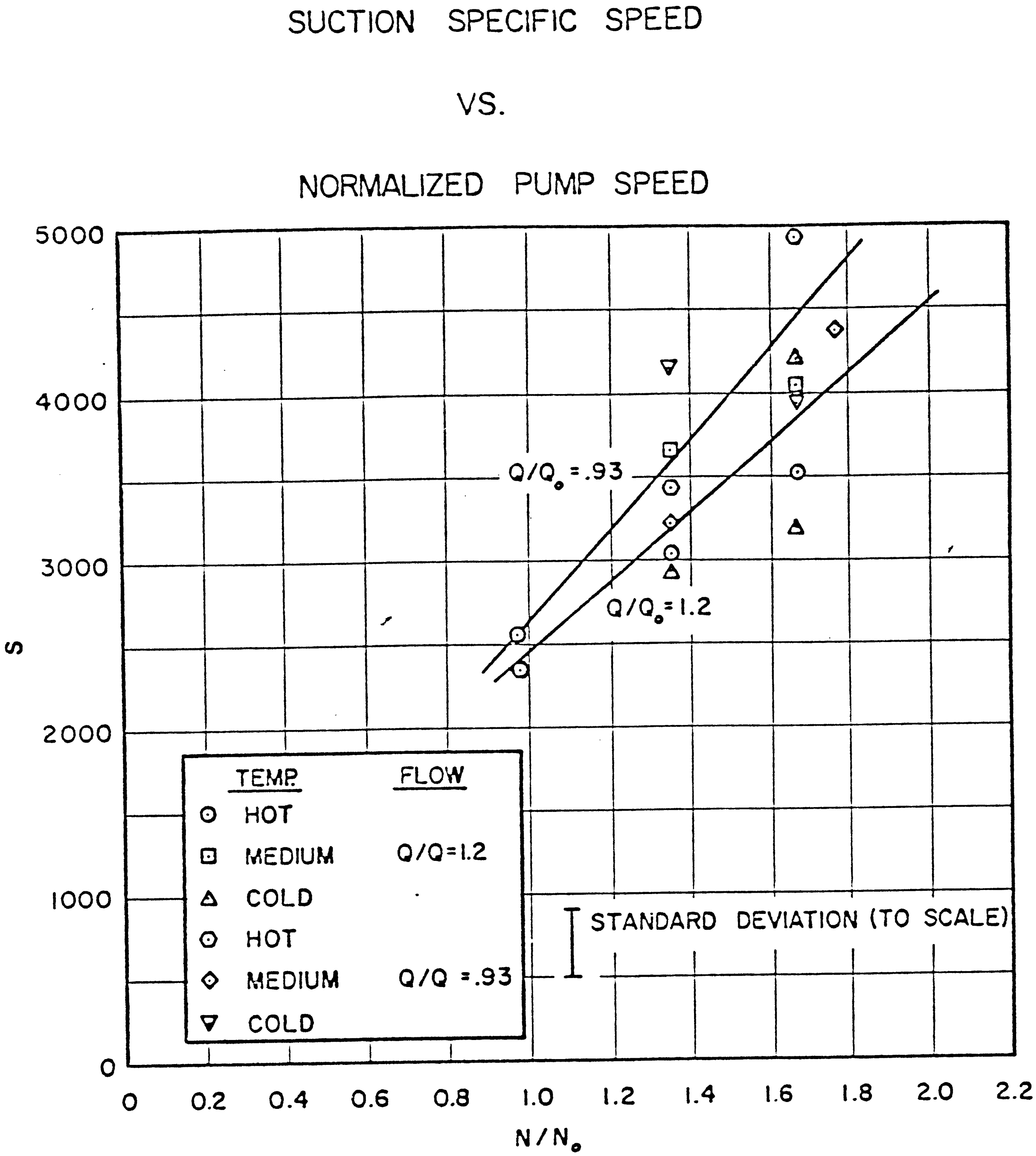


Figure 23 Suction Specific Speed vs. Normalized Pump Speed.

U-M tests (46,47)

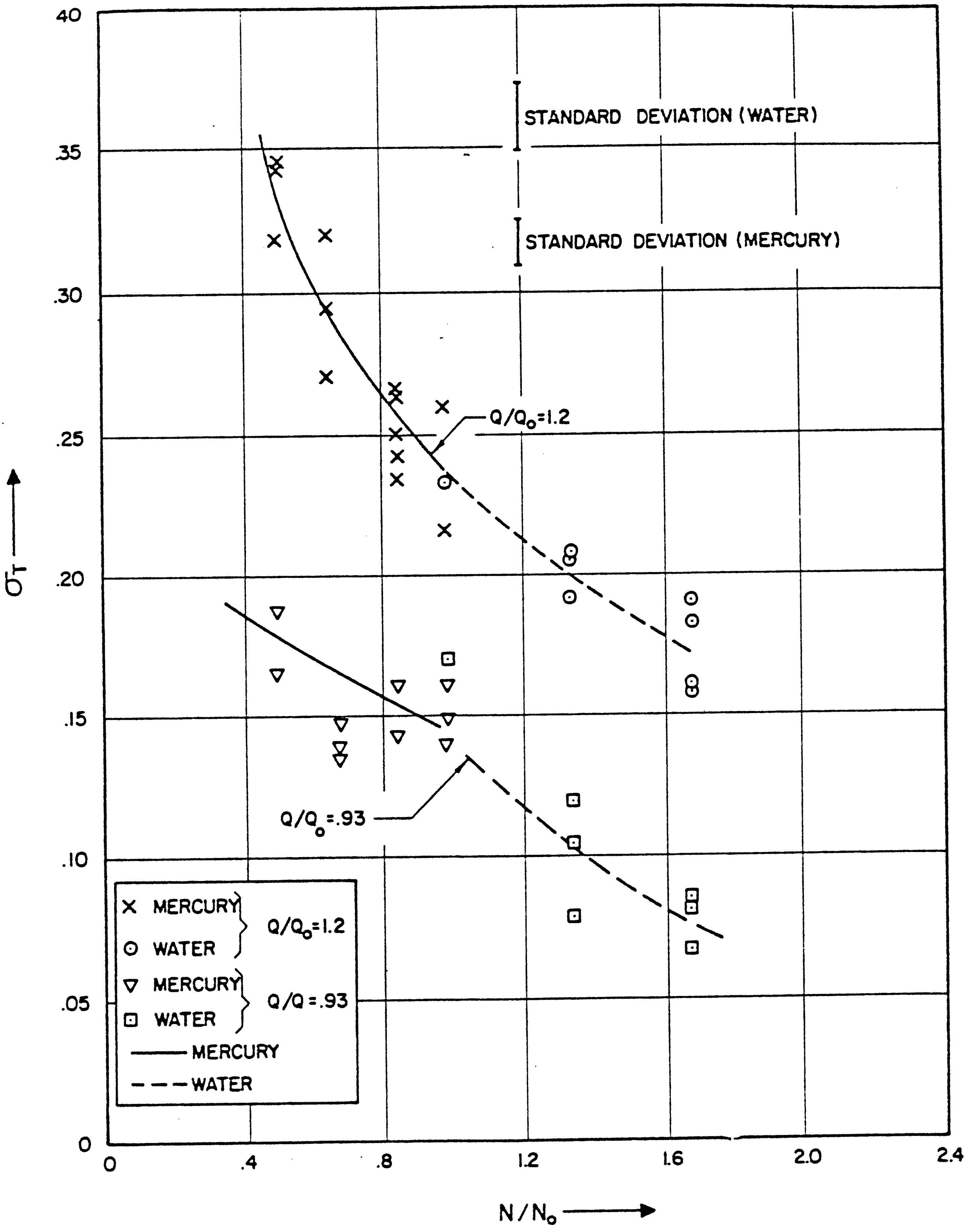


Figure 24 Thoma Cavitation Parameter vs. Normalized Pump Speed.

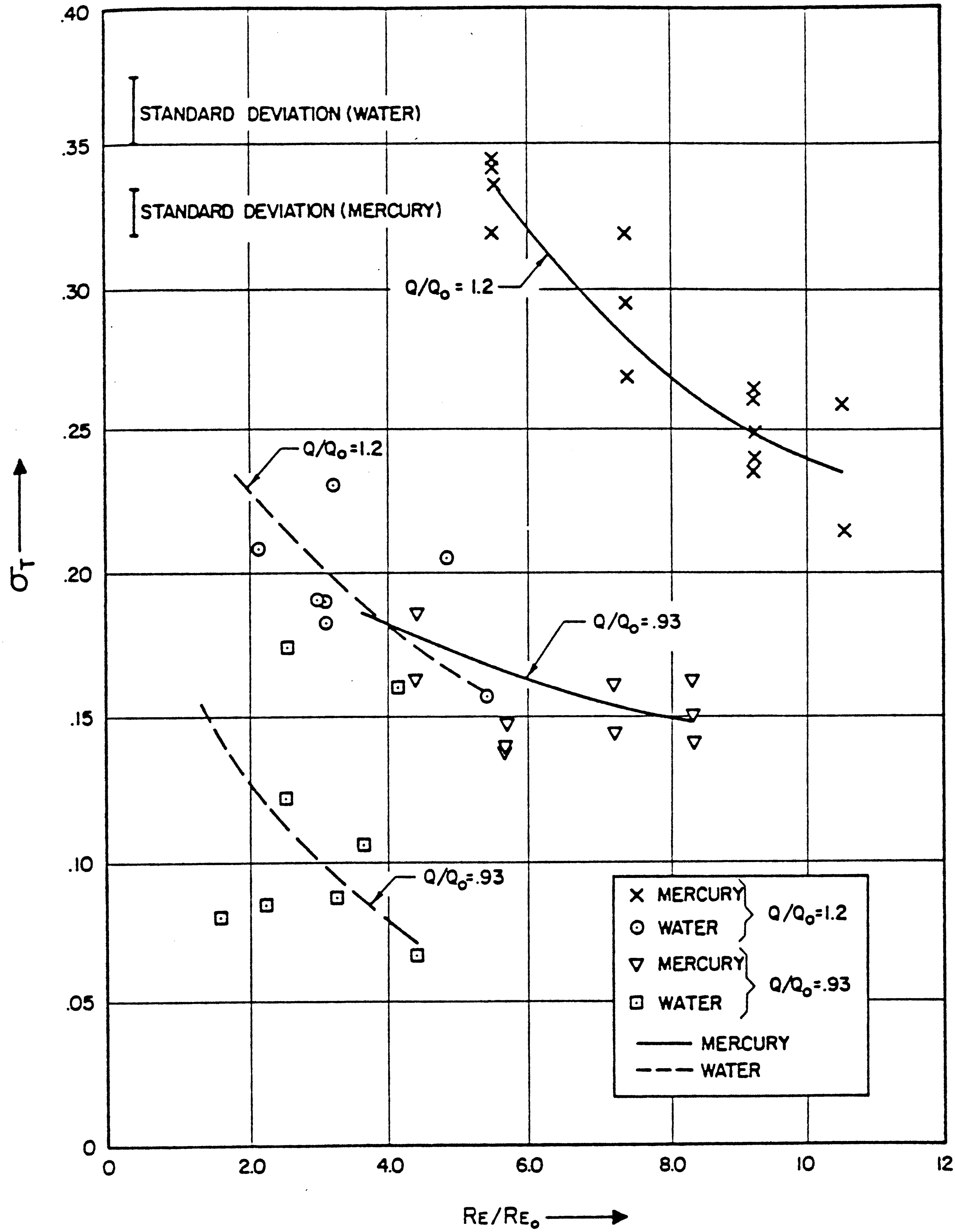


Figure 25 Thoma Cavitation Parameter vs. Normalized Reynolds' Number.

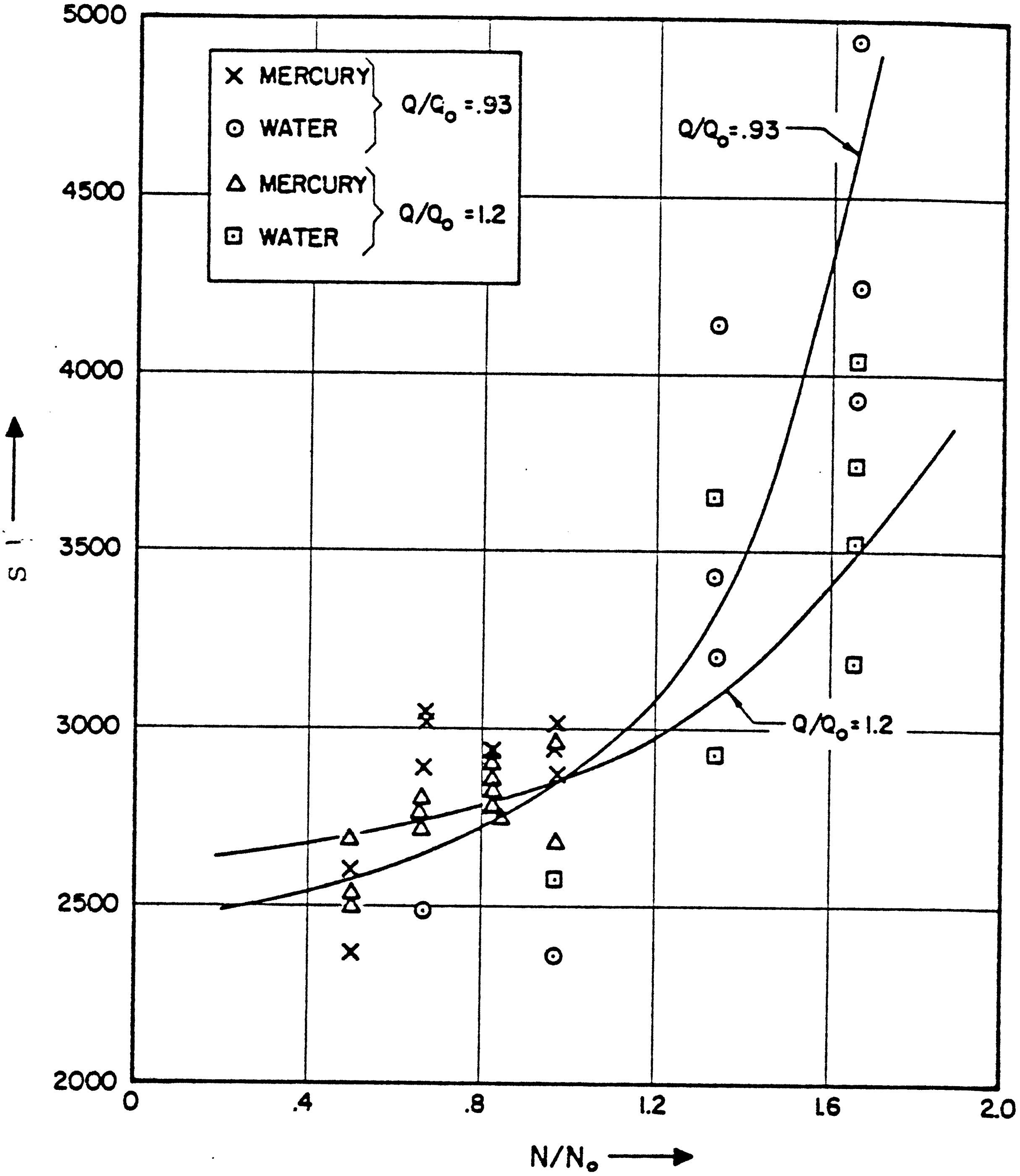


Figure 26 Suction Specific Speed vs. Normalized Pump Speed for Water and Mercury at Two Different Normalized Flow Conditions Using Berkeley Model 1 1/2 WSR Centrifugal Pump.

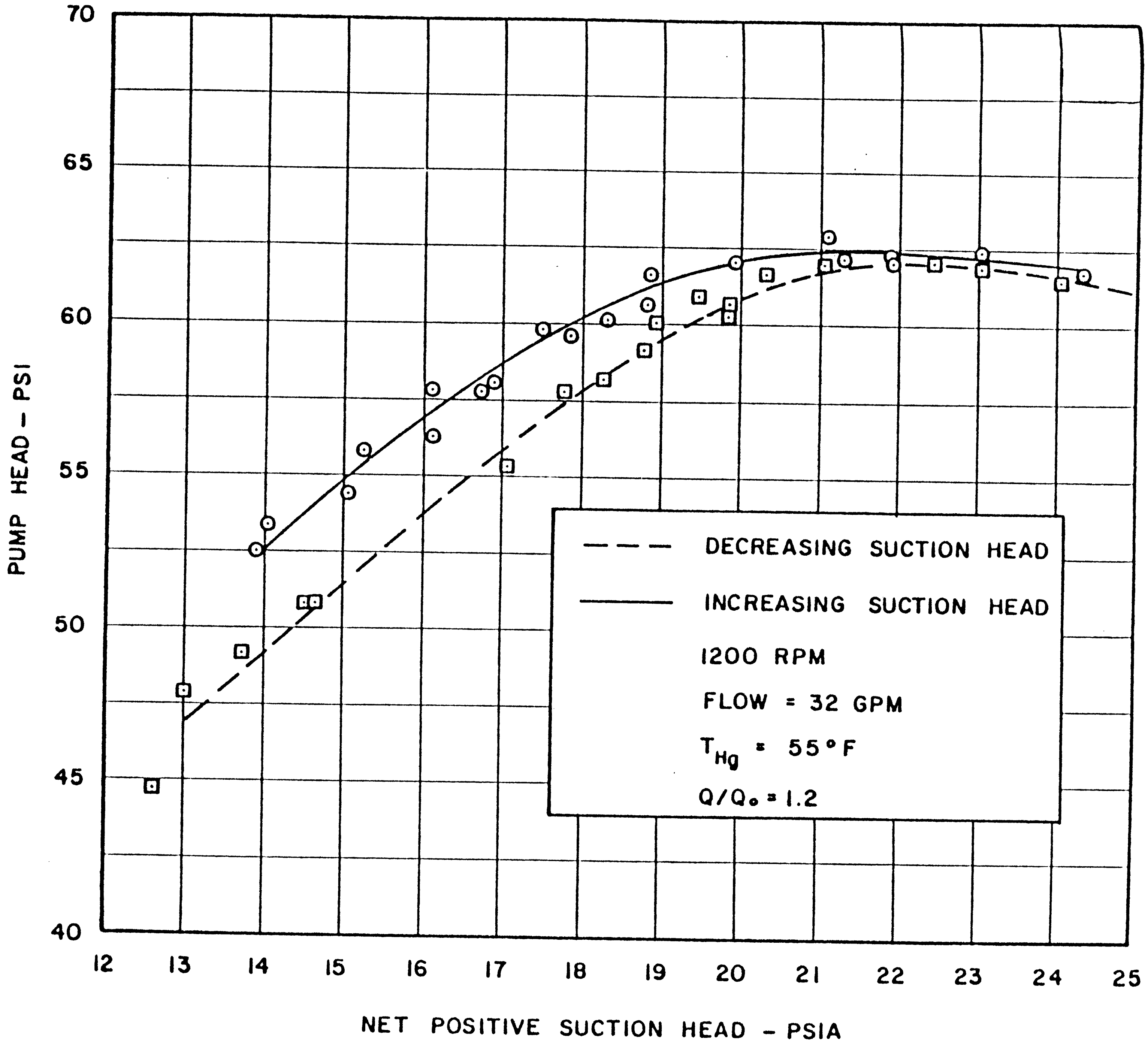


Figure 27 Net Positive Suction Head vs. Head Across Pump with Increasing

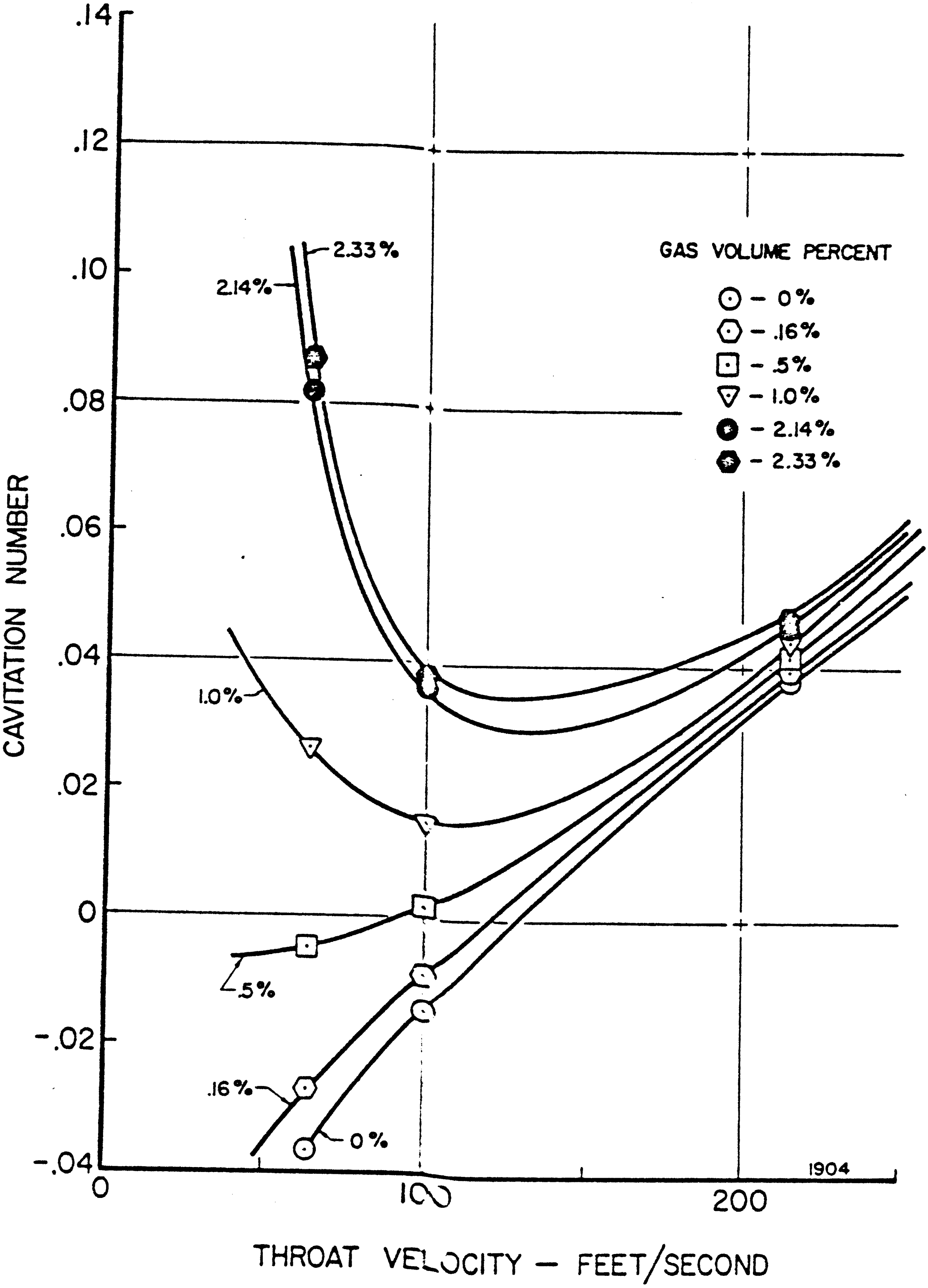


Fig. 28[illegible].--Cavitation inception number vs. throat velocity for 1/2" plexiglas venturi at room temperature and several air contents in water.

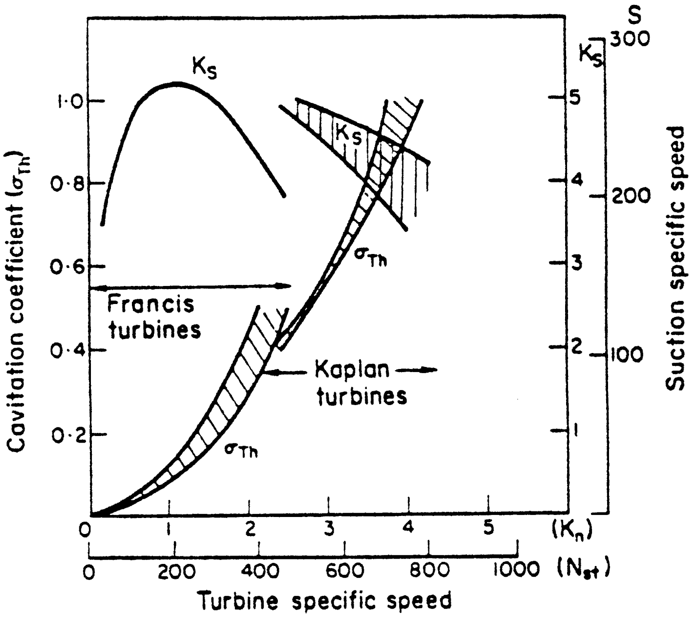


Fig. 29 *Cavitation limits for turbines*

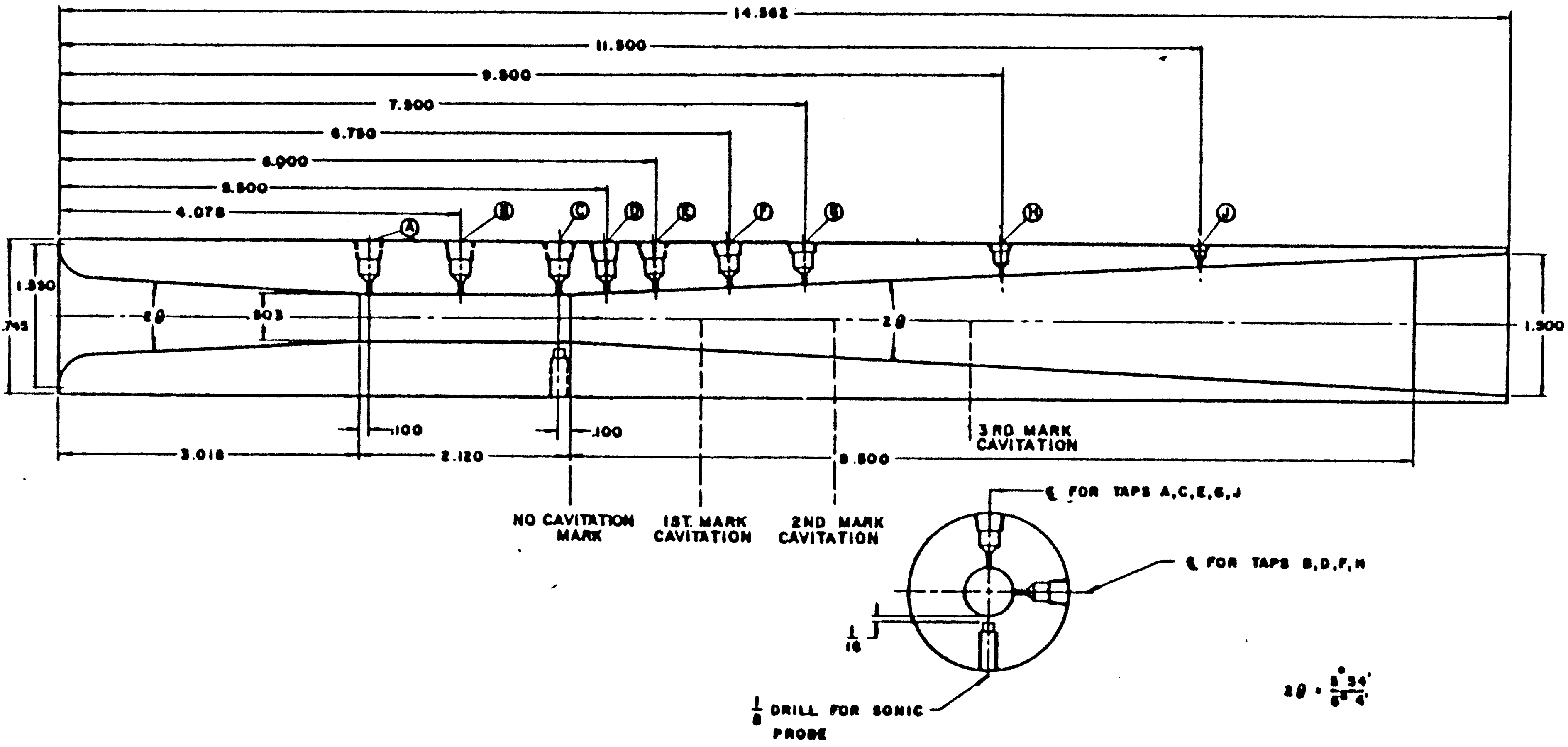


Figure 30 1/2" Cavitating Venturi Test Section

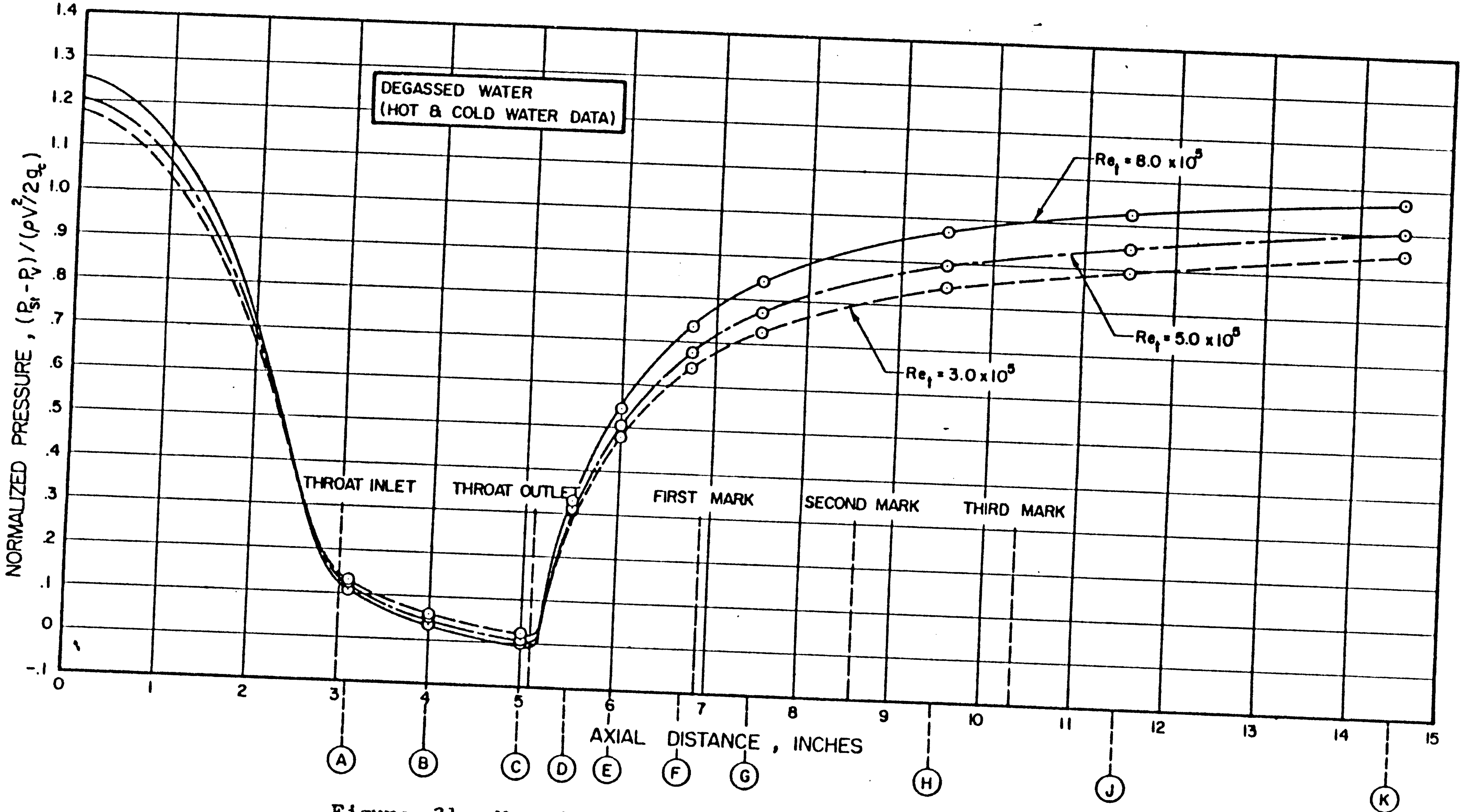


Figure 31 Normalized Pressure vs Axial Position, Sonic Initiation, 1/2" Test Section

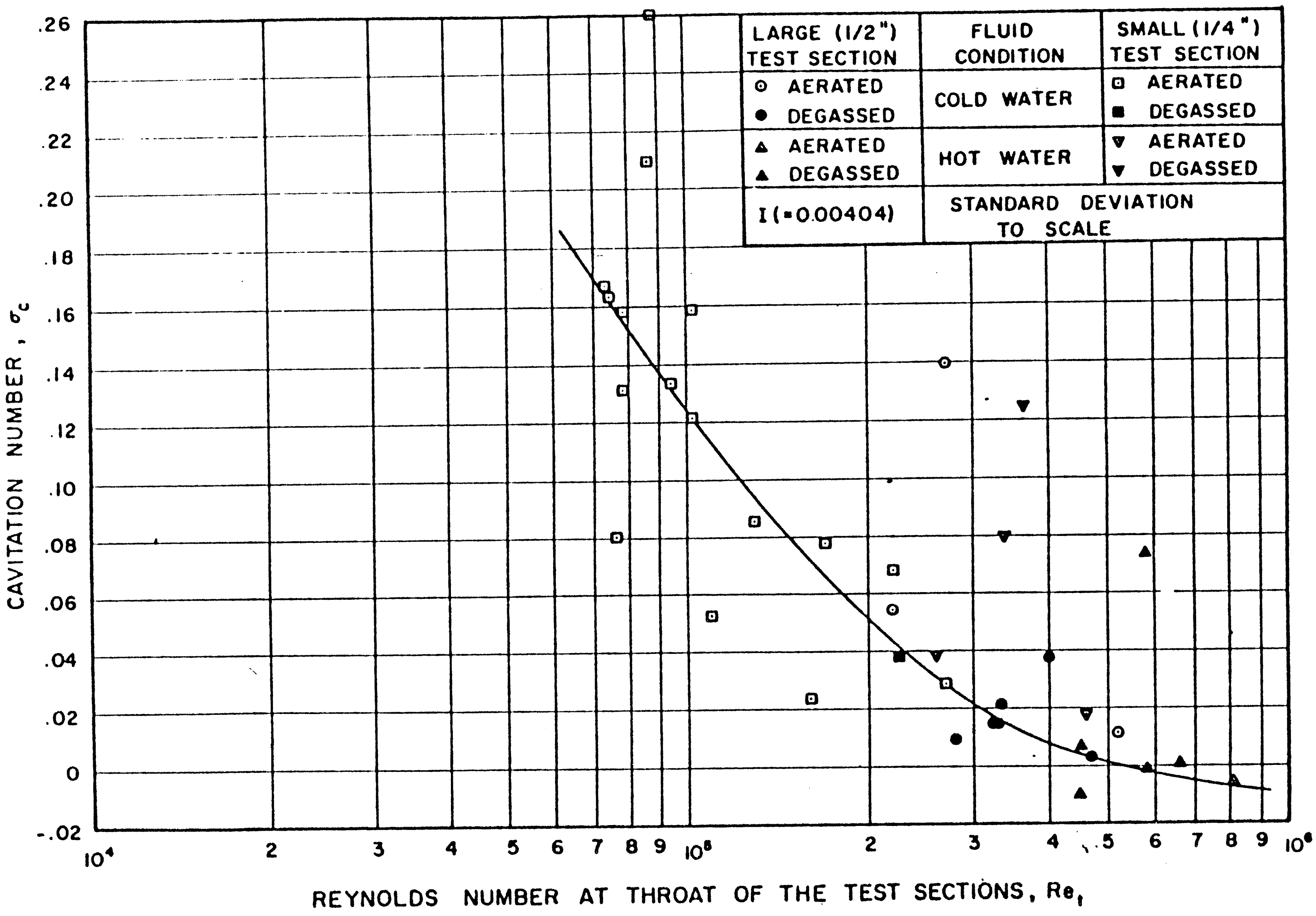


Fig. 32 Cavitation Number vs. Throat Reynolds' Number in a Cavitating Venturi for Sonic Initiation.

(refs. 22, 49)

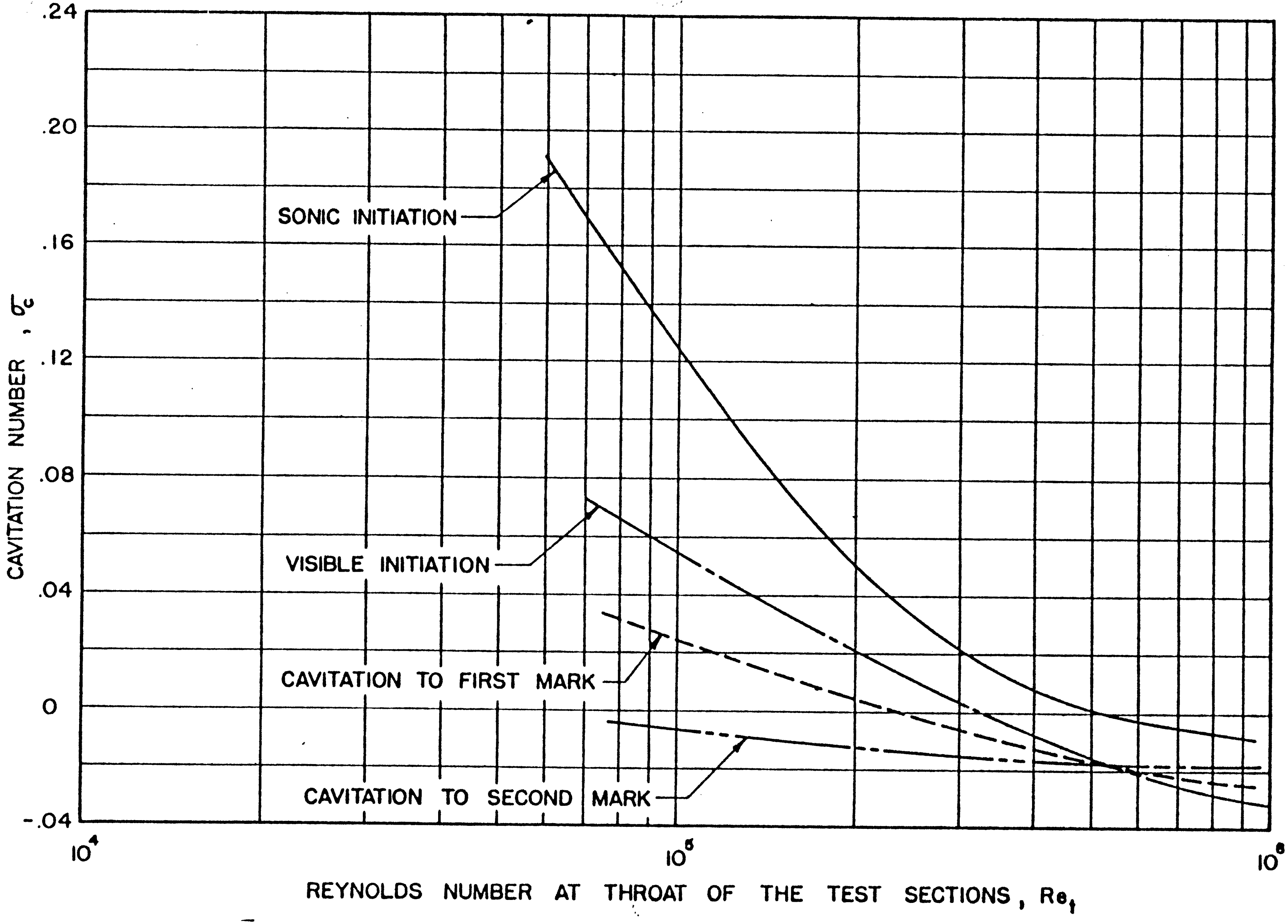


Figure 33 Comparison of Cavitation Number vs Throat Reynolds Number for Various Degrees of Cavitation

(refs. 22, 49)

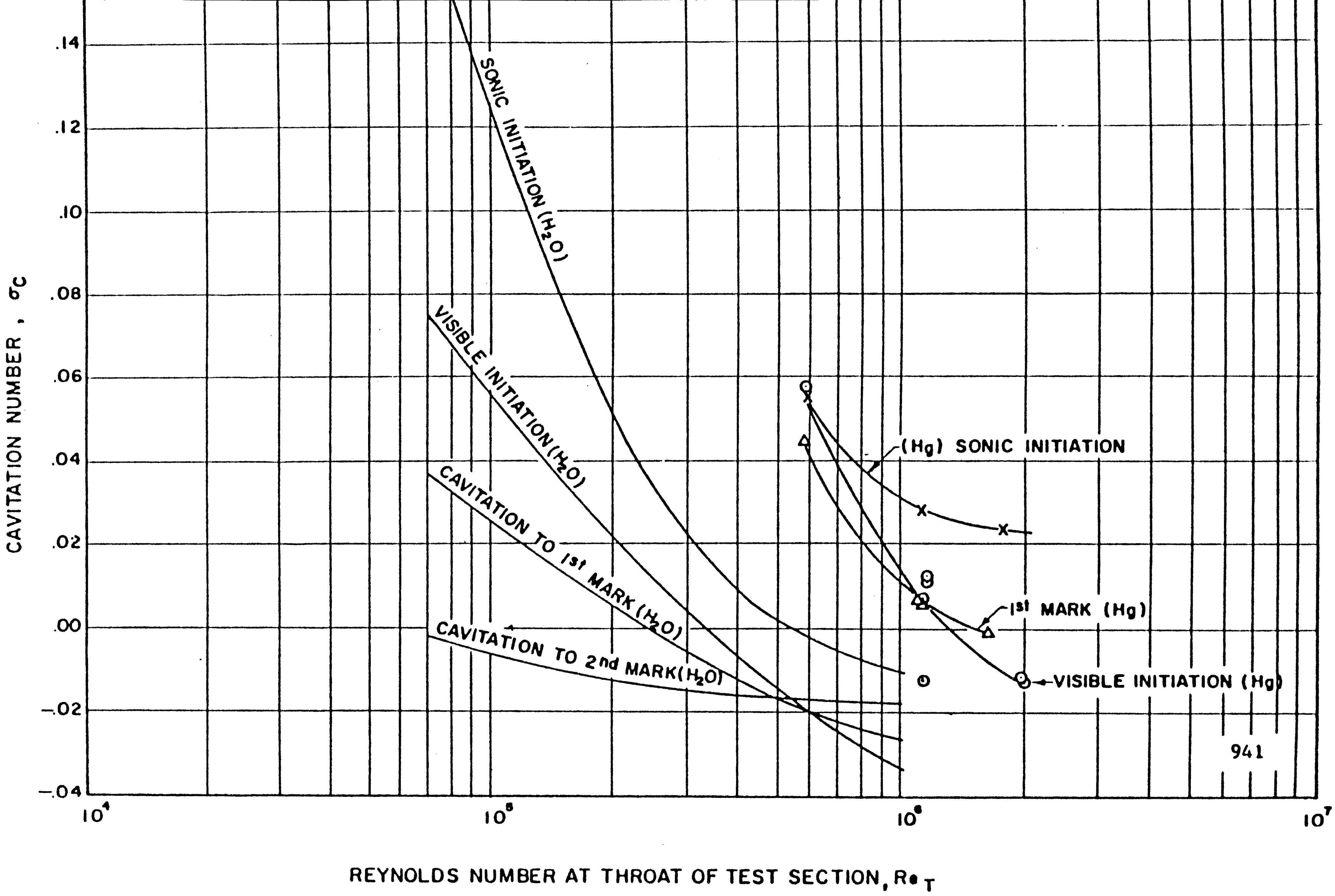


Fig. 34 -- Cavitation Number vs. Reynolds' Number for Several Cavitation Conditions with Mercury and Water. (1/2" Venturi)

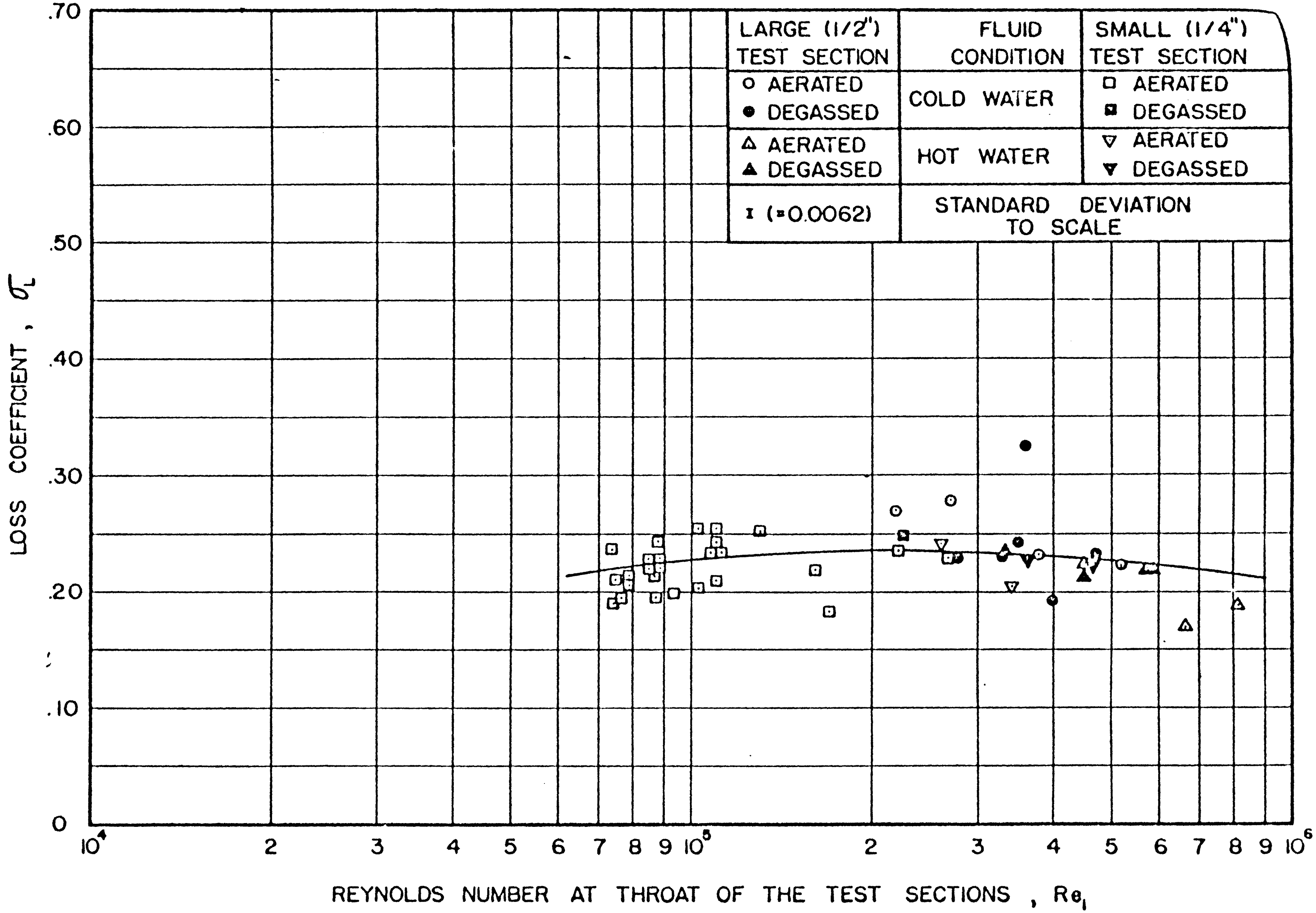


Figure 35 Loss Coefficient vs Throat Reynolds Number in a Cavitating Venturi for Sonic Initiation (refs. 22, 49)

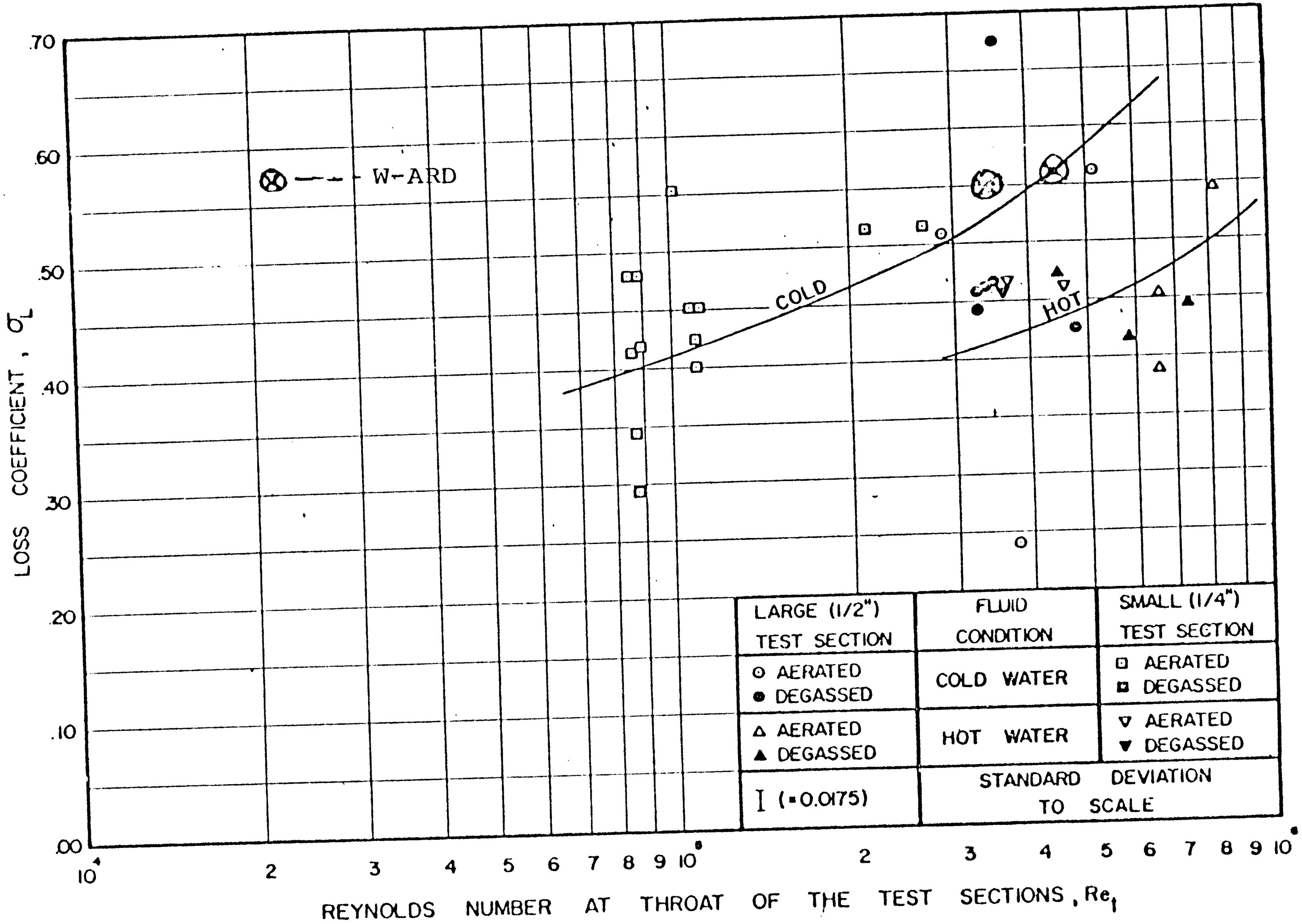


Fig. 3'6 Loss Coefficient vs. Throat Reynolds' Number in a Cavitating Venturi for Cavitation to First Mark. (ref.)

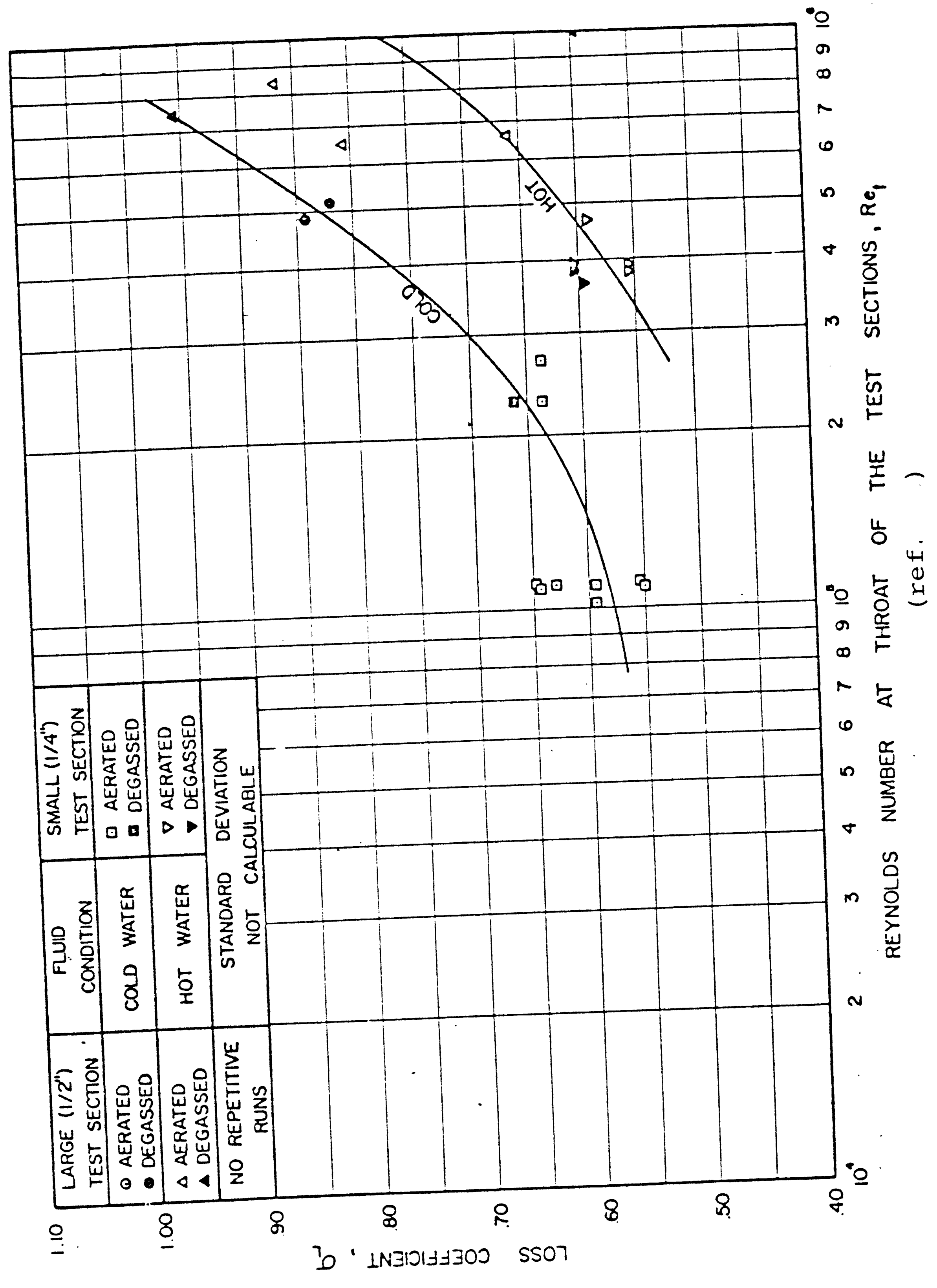
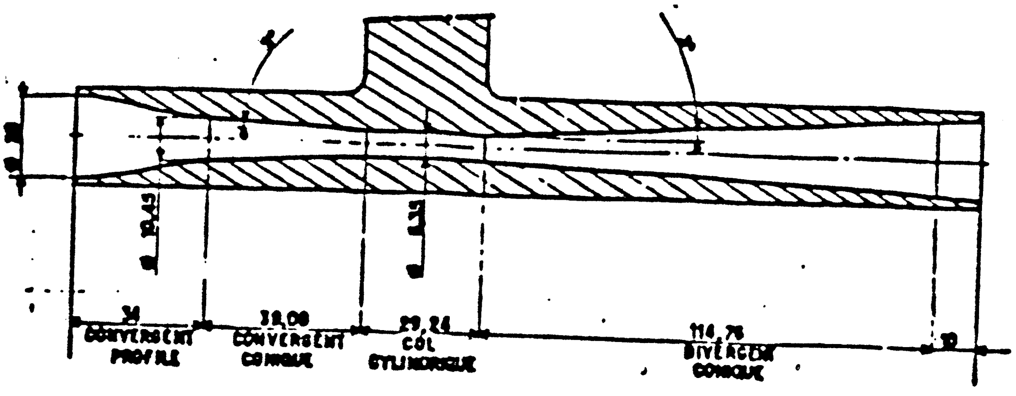


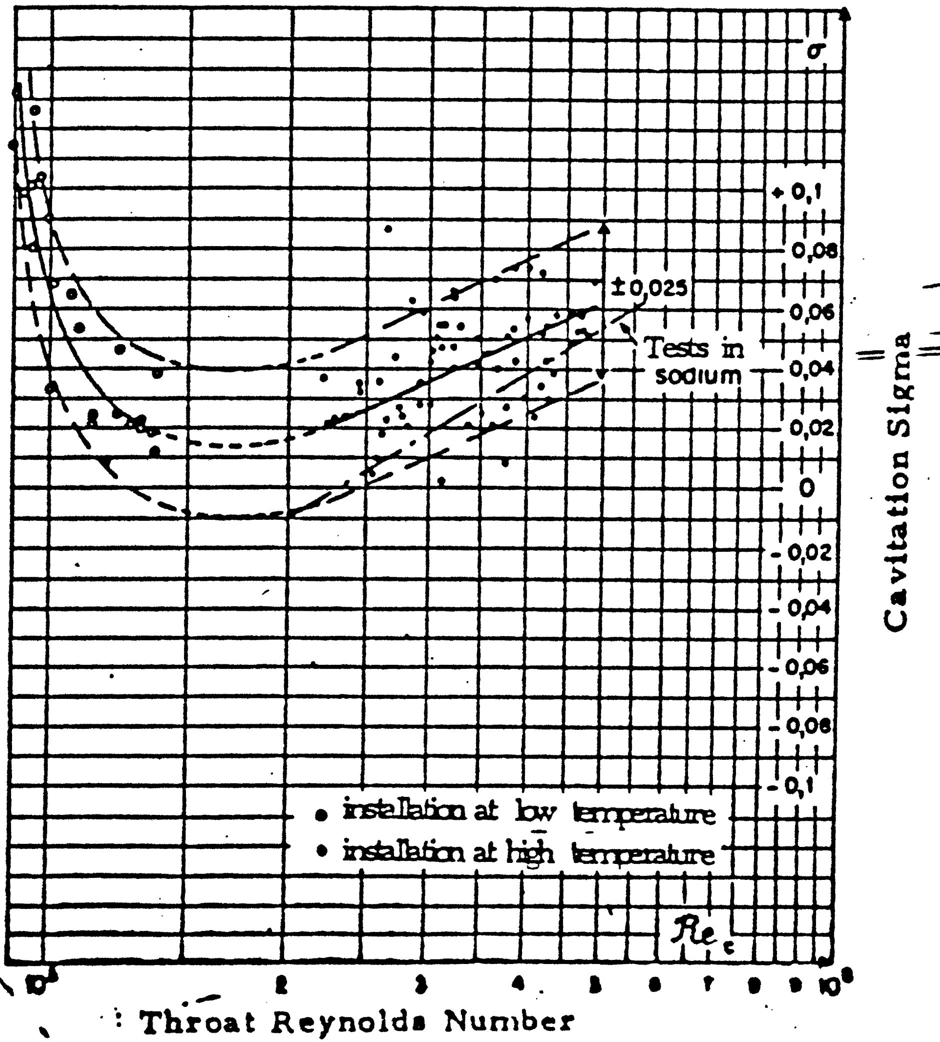
Fig. 37 Loss Coefficient vs. Throat Reynolds' Number in a Cavitating Venturi for Cavitation to Second Mark.



4916

a.) Schematic of Venturi Tube (Dimensions in mm.)

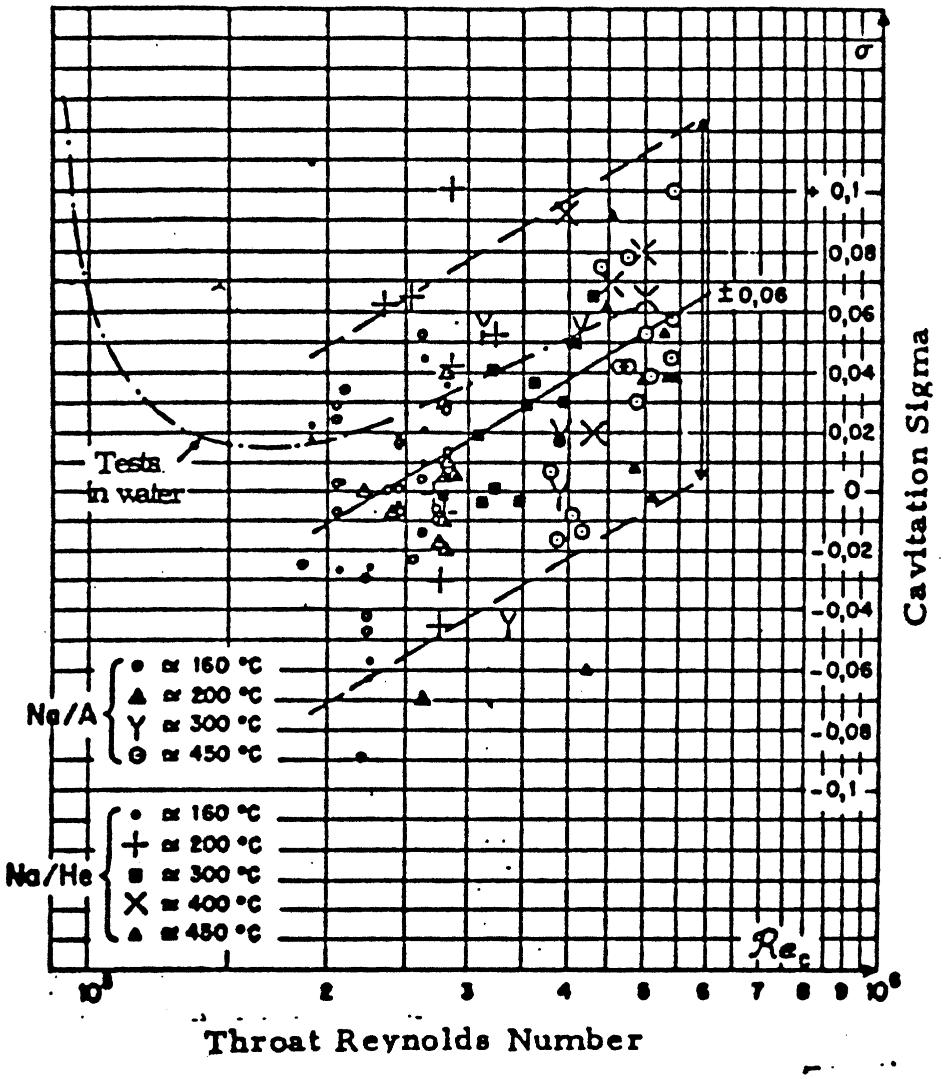
Electicite de France Tests (154)



4917

Fig. 38 b.) Water Cavitation Inception Tests

Electricité de France (154)



4918

Fig. 39 Sodium Cavitation Inception Tests
Electricité de France (154)

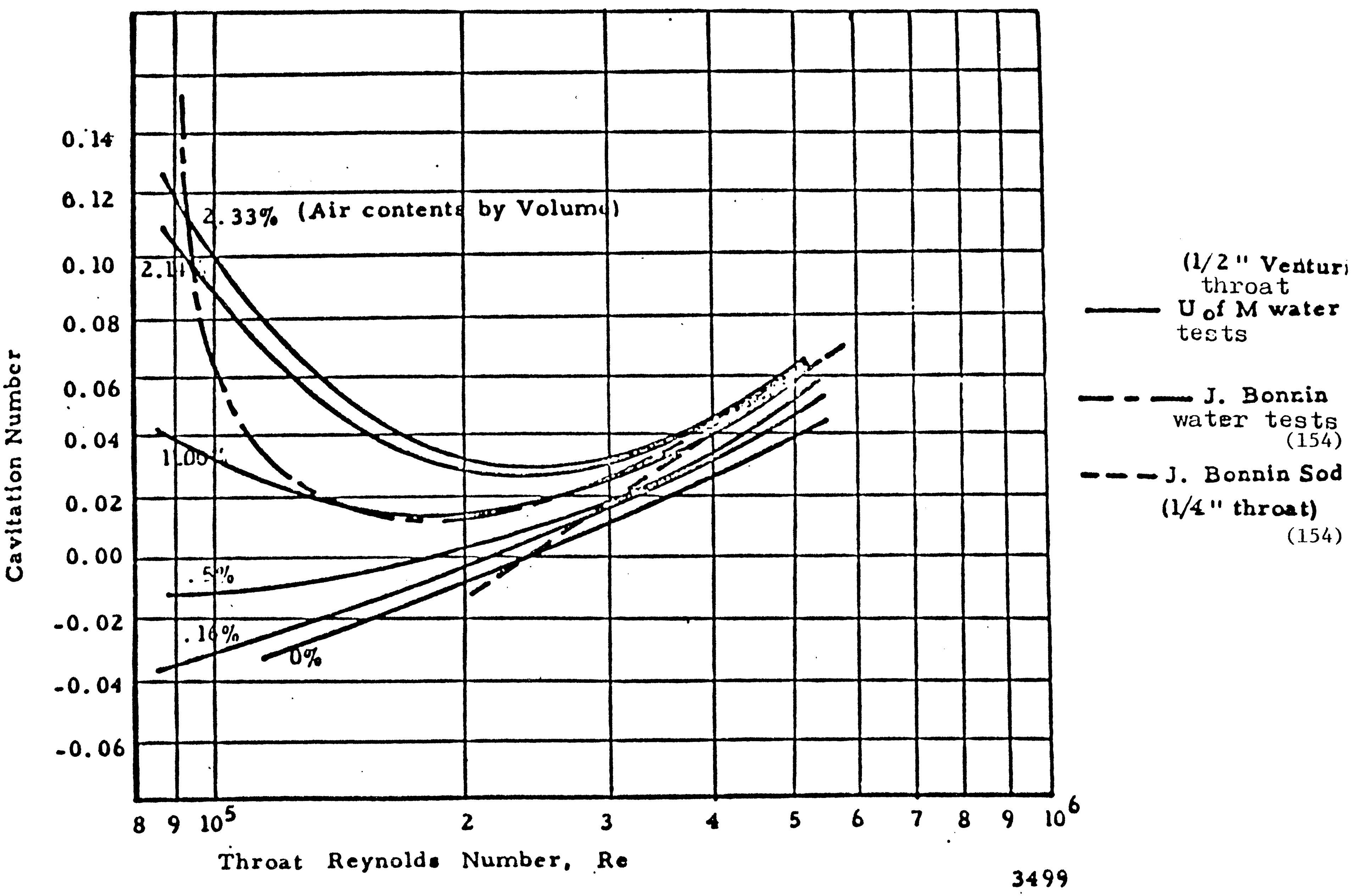


FIG 40 CAVITATION SIGMA VS. REYNOLDS NUMBER IN VENTURI FOR

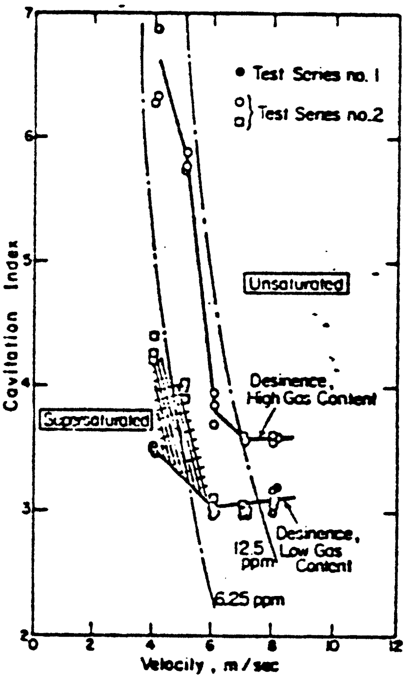


Fig. 41 Cavitation Desinence Data at High and Low Gas Content, 16 cm. Disk. (157)

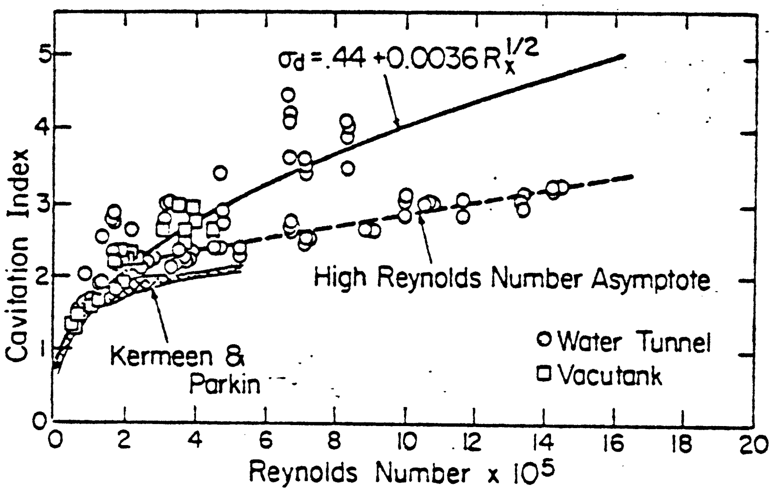


Fig. 42 Cavitation Desinence Data. (157)

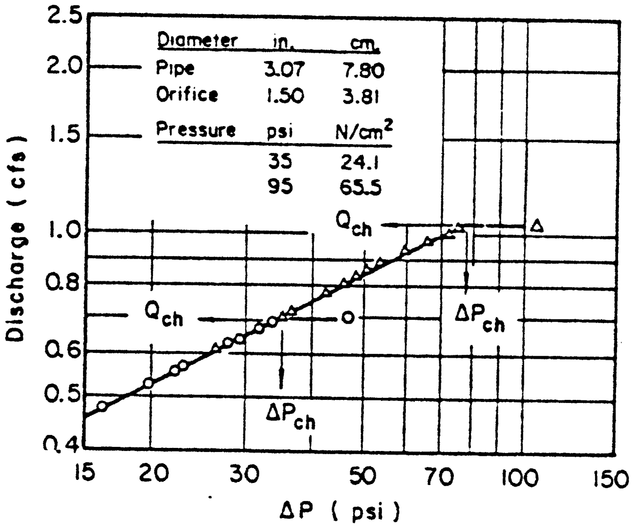


Fig 43 -GRAPHICAL EVALUATION OF CHOKING CAVITATION

(157)

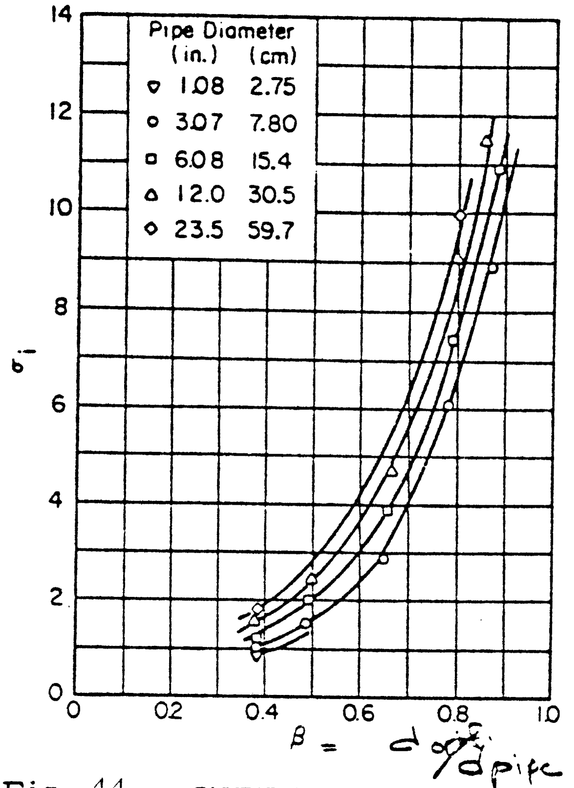


Fig. 44 .—INCIPIENT CAVITATION

(157)

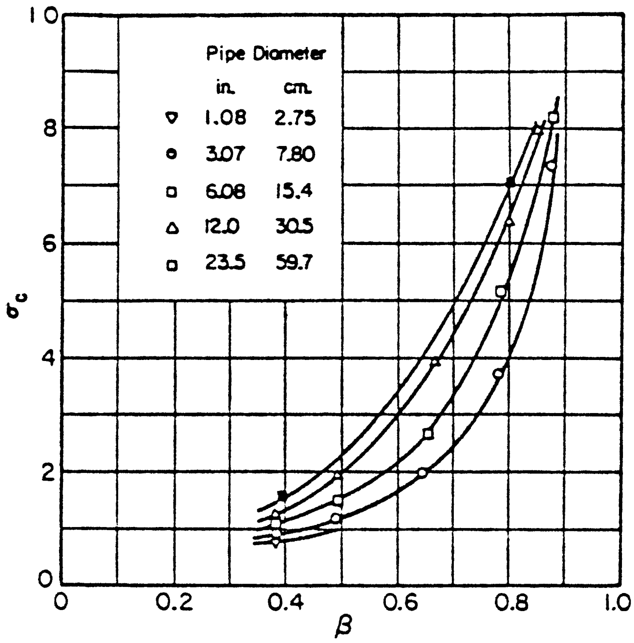


Fig. 45 —CRITICAL CAVITATION
(157)

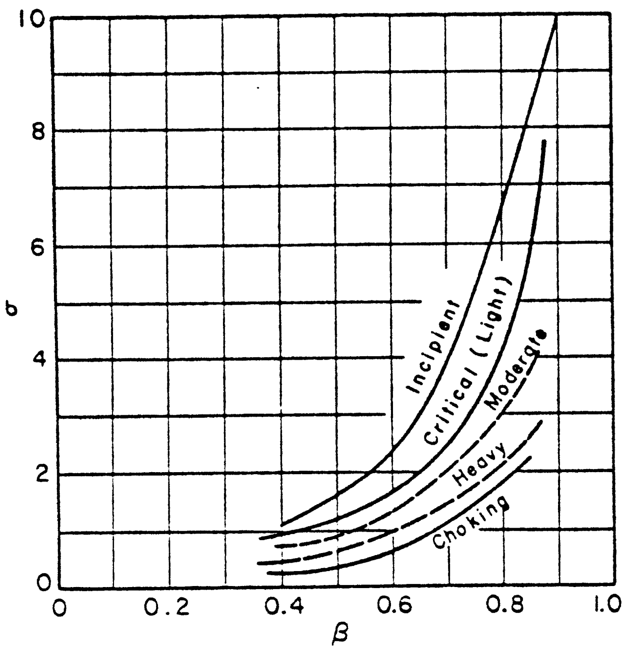
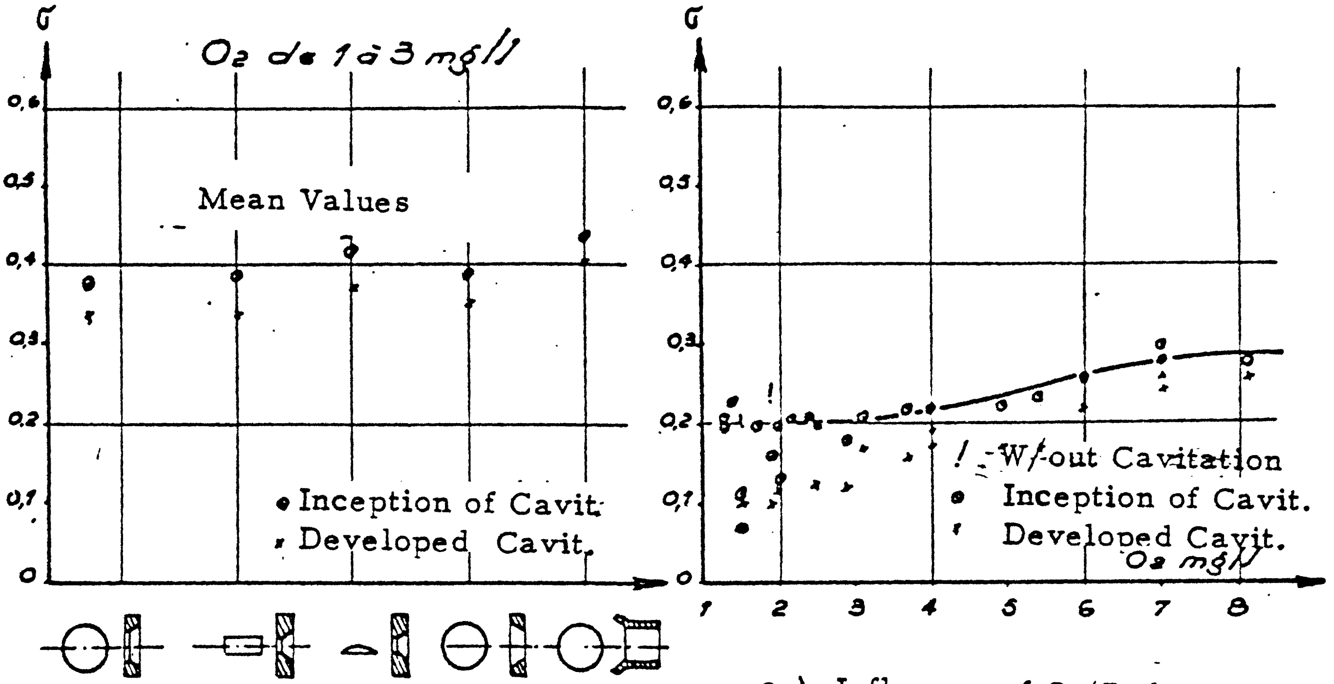


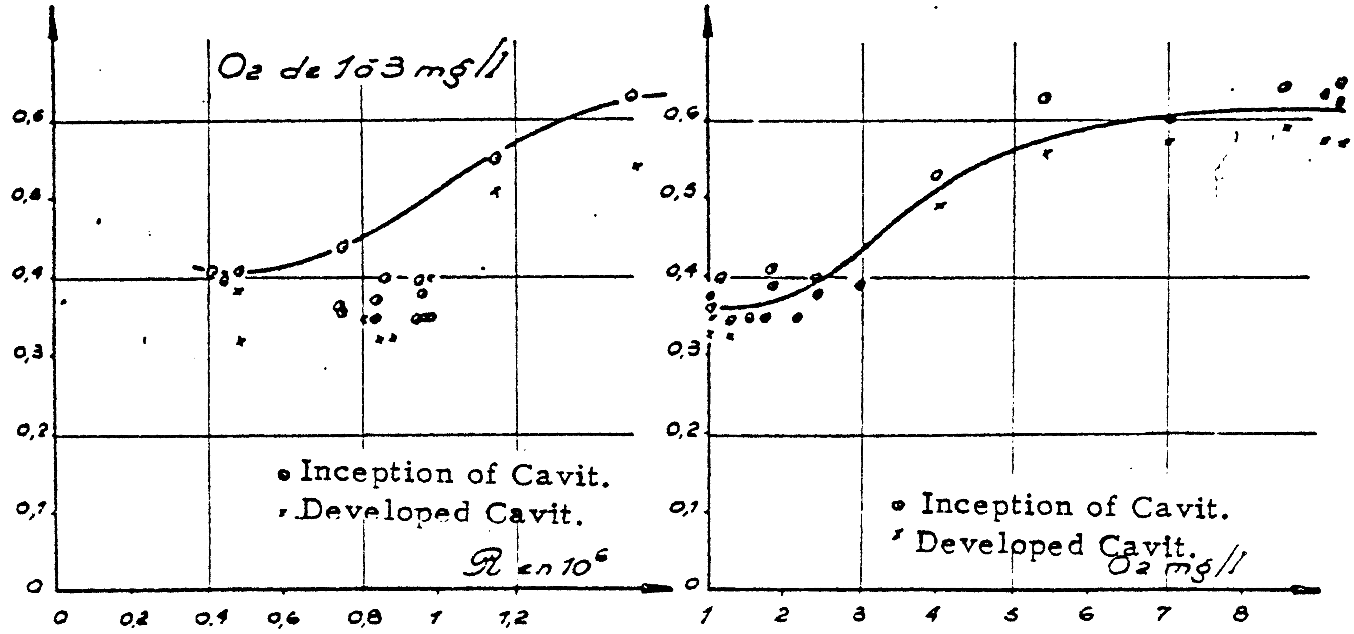
Fig. 46 -CAVITATION LIMITS FOR ORIFICES IN 3.07-IN. (7.62-CM) PIPE

(157)



a.) Influence of the Form of jet and of the nozzle.

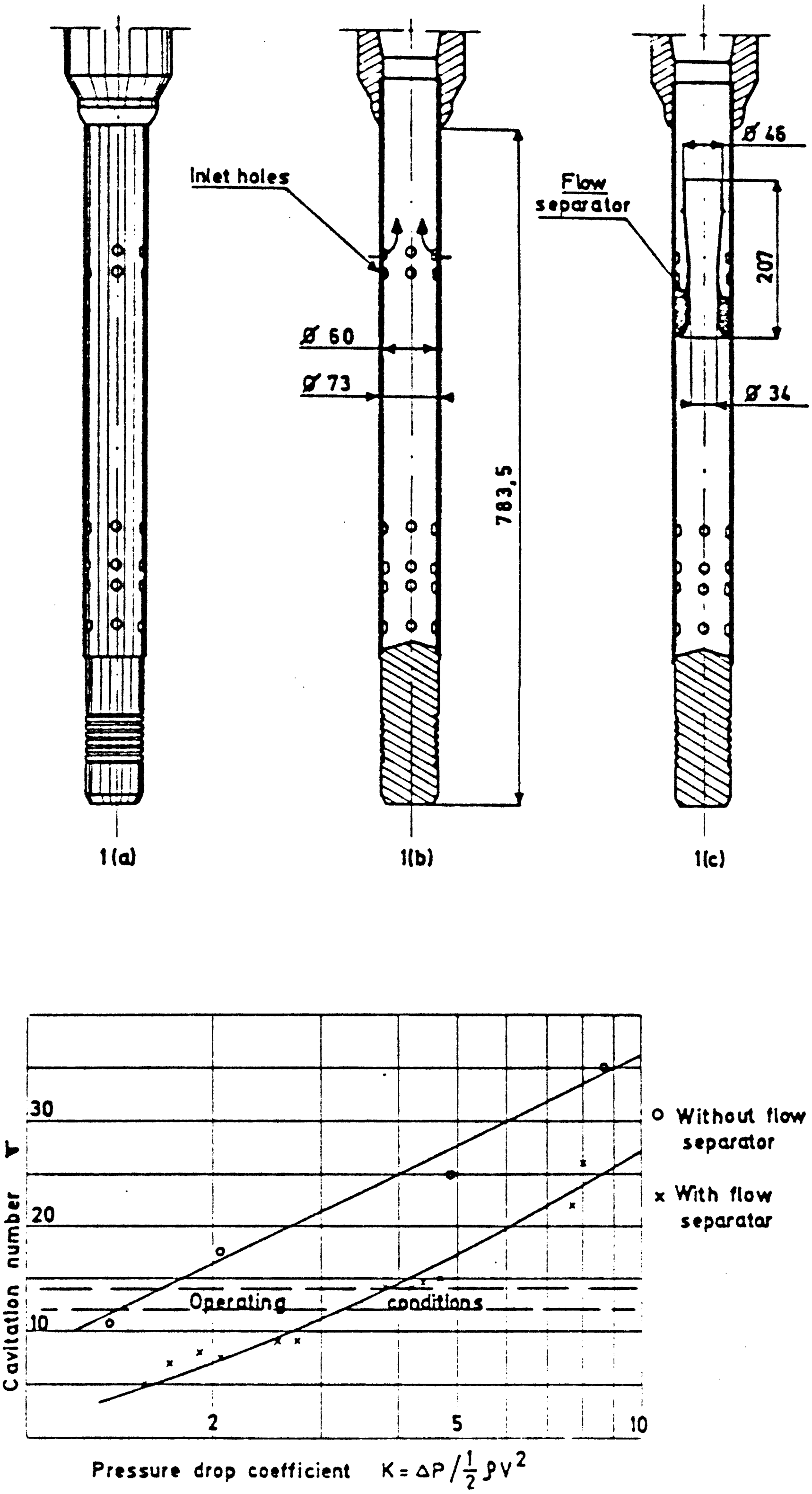
c.) Influence of O_2(Ref. Test Sect.)



b.) Influence of Reynolds' Number (Circular Orifice)

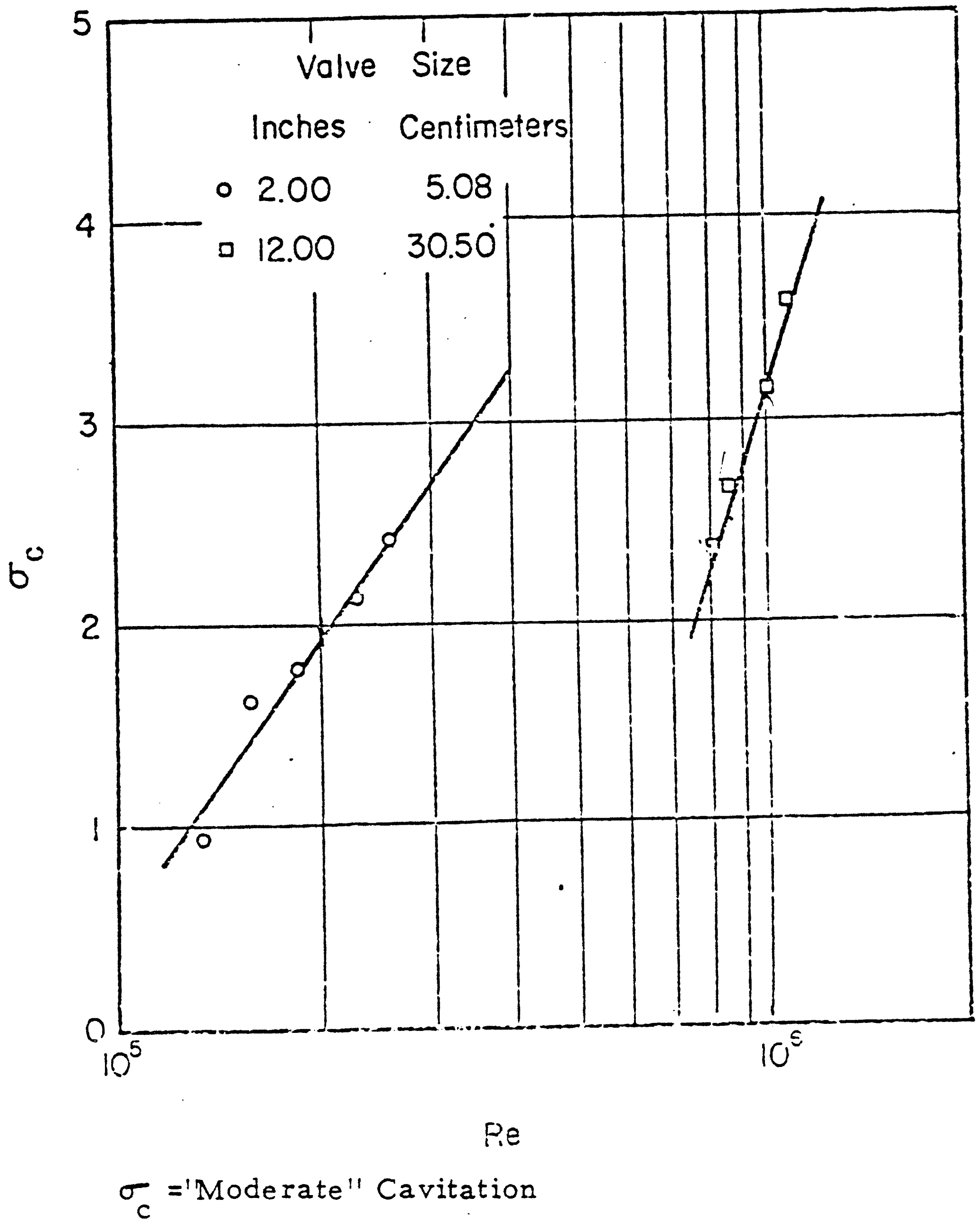
d.) Influence of O_2(Circular Orifice)

Figure 47 - SOGREAH Inception Sigma Tests (159,160)



(Ref. 161)

Figure 48 - Flow Distribution Devices of PHENIX Subassemblies



σ_c ='Moderate'' Cavitation

Fig. 49 Size and Pressure Scale Effects for Ball Valves.

(Ref. 162-165)

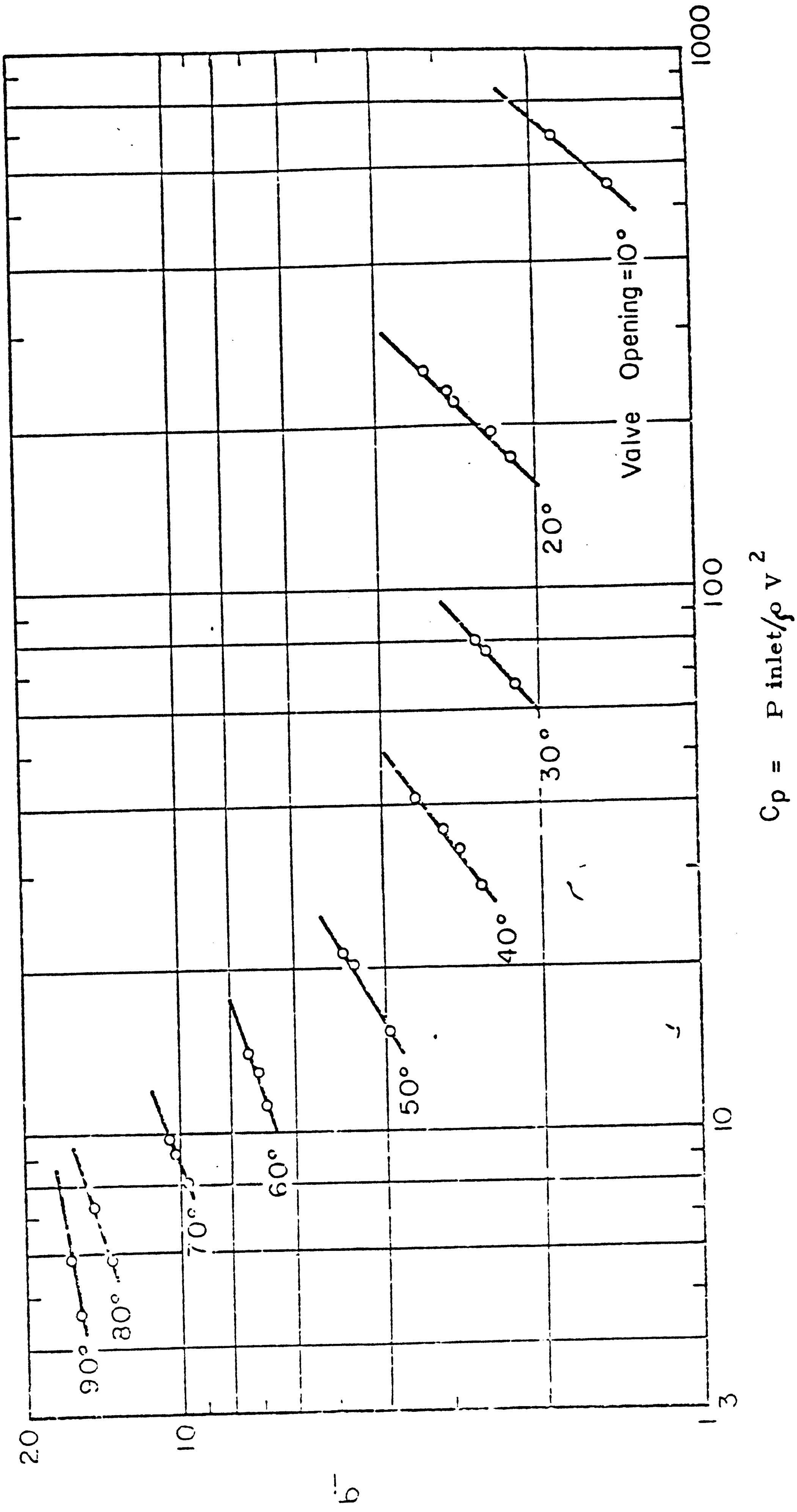


Fig. 50 - Pressure Scale Effects for Butterfly Valves.

(Ref. 162-165)

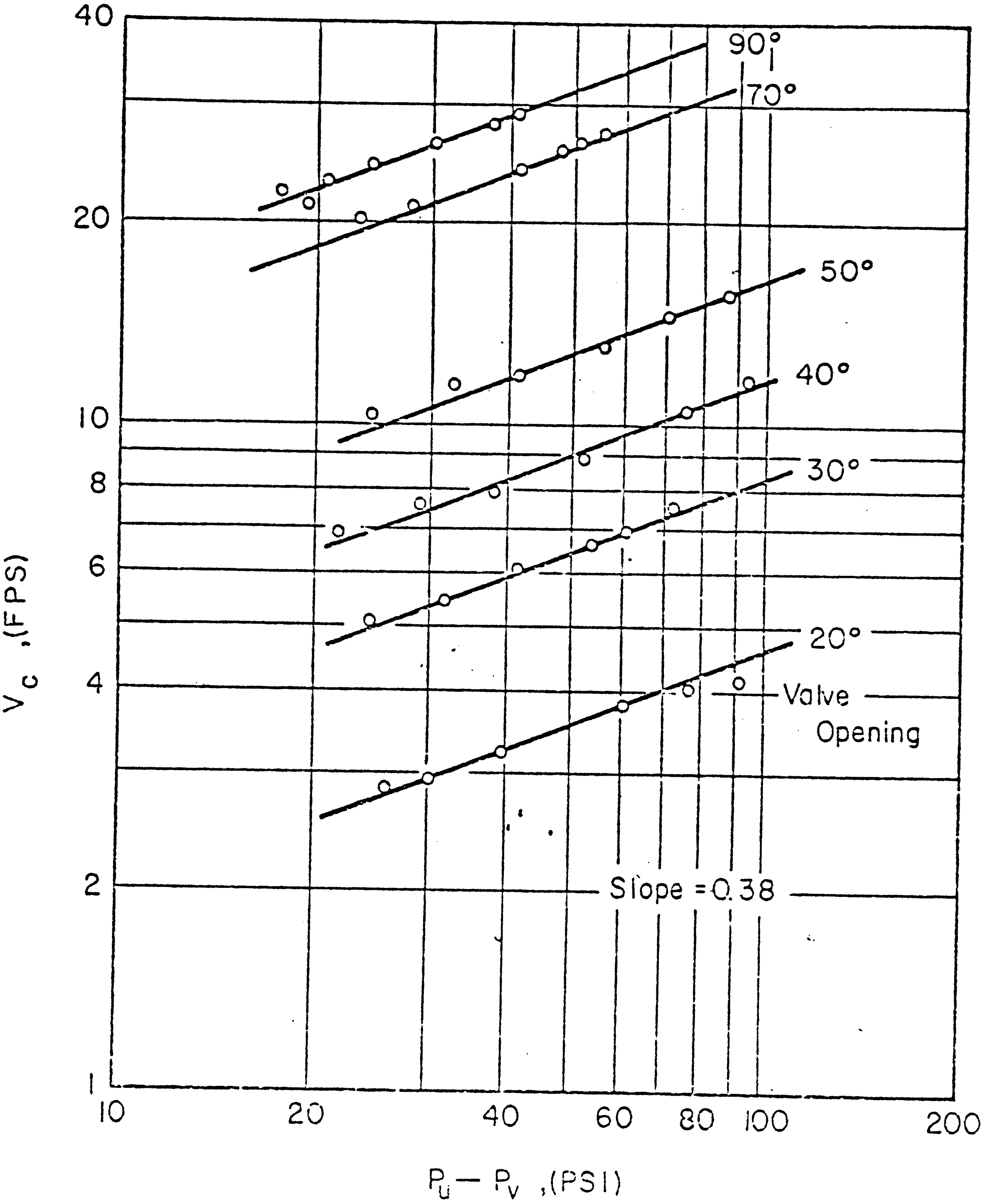


Fig.51 - Variation of V_c with P_u-P_v.

(Ref. 162-165)

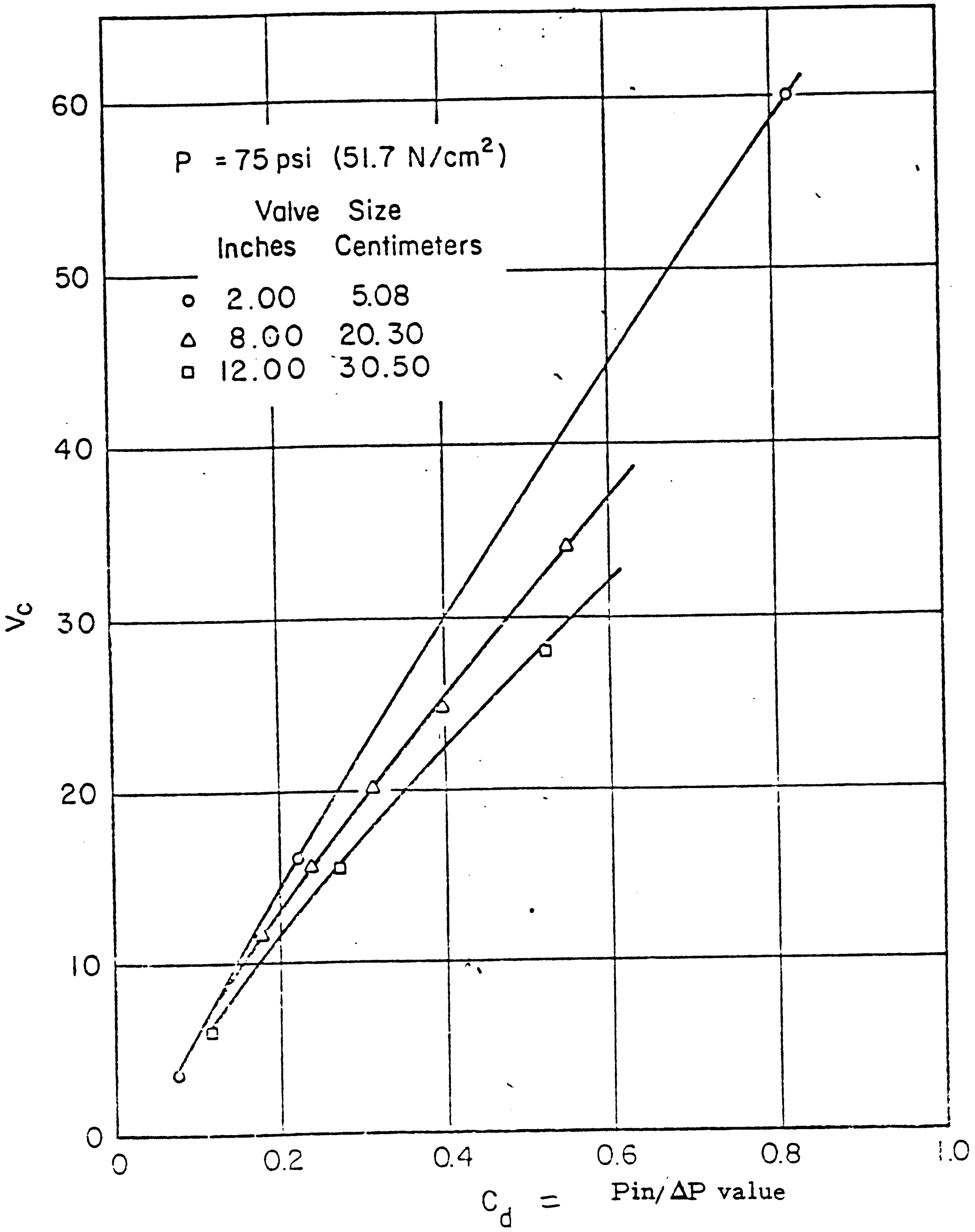


Fig. 52 - Effect of Size on V_c for Ball Valves.

(Ref. 162-165)

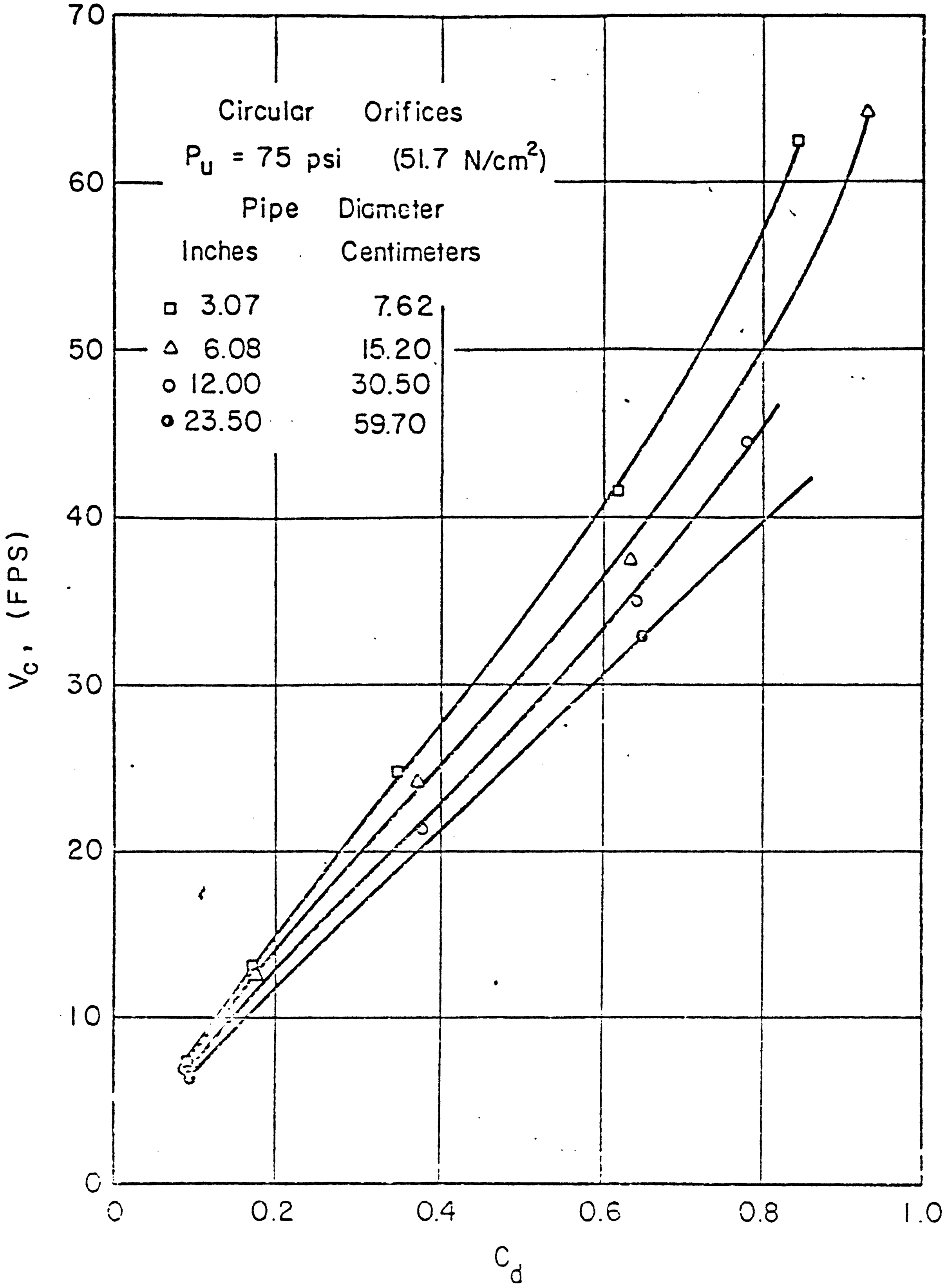


Fig. 53 - Size Scale Effects for Circular Orifices.

(Ref. 165)