THE UNIVERSITY OF MICHIGAN

College of Engineering

Department of Mechanical Engineering

Cavitation and Multiphase Flow Laboratory

Report No. UMICH 01357-19-T

EFFECTS OF GAS CONTENT UPON CAVITATION INCEPTION, PERFORMANCE, AND DAMAGE

by

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Financial Support Provided by:

National Science Foundation
Grant No GK-1889

June 1971

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ACKNOWLEDGMENTS

The author would like to thank Messrs. J. Arnault and A. Legrand, both engineers of SOGREAH, for their assistance in the preparation of this report, and also acknowledge the financial support of the National Science Foundation in the USA and SOGREAH, Grenoble, France, during the preparation of this work.

ABSTRACT

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The major past and on-going studies of the effects of gas content upon cavitation are reviewed. 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 a more basic nature. Finally, those studies pertinent to a prediction of the effects of gas content upon cavitation damage are discussed. In view of the overall situation as it appears at present, conclusions where possible and recommendations for future directions of research are appended.

I - INTRODUCTION

In the Leningrad meeting in 1965 of the Section for Hydraulic Machinery, Equipment and Cavitation of IAHR it was decided to form 3 Working Groups as follows : WG1 - Cavitation Scale Effects between Model and Prototype ; WG2 - Oil Mechanisms and Governing Forces and Capacities in Turbines ; WG3 - Causes and Dynamic Effects of Unsteady Turbine Draft Tubes (Including Effect of Air Admission). The history of WG1 is reviewed in further detail in ref. 1, but in short, there have been 3 subsequent meetings : 1966 in Brunswick, 1968 in Lausanne, and 1970 in Stockholm. During this period 2 major decisions pertinent to the present report were taken :

1) WG1 should concentrate first on a single one of the various possible subjects within its overall scope and,

2) First subject should be the effects of air content upon cavitation.

The above decisions were made immediately subsequent to the 1968 Lausanne meeting and information on this subject was then requested from all members.
Although the input was not large, the present writer prepared a summary report on the status at that time for the 1970 Stockholm meeting. At that meeting further input was requested from the Working Group members, and it was decided that a final report on the subject would be prepared in time for the 1971 Paris meeting. The present document is the first draft of that report. Once the report is finalized and accepted by the membership, the group can then turn its primary attention to the next subject which it has been agreed will be "Effects upon damage rates in machines, due to change in velocity or head and size of machine".

II - AIR CONTENT EFFECTS

The effects of air content (or gas content in general) upon cavitation can be considered under 3 main headings of which the first is probably the most important, i.e.,

1) Effects upon cavitation inception sigma,

2) Effects upon flow regime, torque, power, head, efficiency, noise, vibration, etc. for well-developed cavitation,

3) Effects upon cavitation erosion.

There is of course evidence of important effects of air content under each of the 3 categories above ; however, a major portion of the research has been concentrated under item 1 and theoretical treatments are more possible in that category than under the others.

The available information can also be divided in another manner : that which is directly applicable to the prediction of field and laboratory performance and that which is primarily of the nature of basic research which can hopefully be used to clarify the observed trends or to make meaningful predictions from observed data not directly applicable. Very partial listings of material of both sorts was made in ref. 1. This division will be followed in this report and the effects of air content upon both inception and well-developed cavitation will be considered together as often the same documents treat both. Damage effects will be considered separately.

A - DATA DIRECTLY APPLICABLE TO SIGMA AND PERFORMANCE EFFECTS OF AIR (Damage not considered)

There have been numerous fairly systematic and comprehensive studies of the effects of air content upon sigma for cavitation initiation and upon its effects, after initiation, upon performance parameters such as efficiency, power, torque, head, lift and drag for foils, etc. Even so, 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 parameters has not been recognized until very recently, and it seems quite probable even now that insufficient understanding of the phenomena involved exists to define and construct a basic test which would provide data entirely applicable to various prototype or model devices at this time. In the writer's opinion there are two primary difficulties in this regardx:

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 without doubt develops the audible and visible cavitation, the effects of which are measurable upon machine performance, etc. The entrained "nuclei", important in this regard, probably cover the approximate diameter range of 10^{-5} - 10^{-3} cm, thus being generally too small to be visible to the unaided eye. It has been demonstrated repeatedly that knowledge of the total gas content is not sufficient in itself.

Theoretical difficulty

It is not possible at present to describe in sufficient detail actual flow patterns in order to be able 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 under item (1) above. The realistic problem is necessarily 2 or 3 dimensional (depending upon the type of device), essentially biphasic in nature (even if it is a question only of cavitation inception) since the trajectory of the low-density entrained nuclei is not even approximately that of the liquid if important pressure or velocity gradients exist, and finally turbulence must be considered since turbulent fluctuations importantly influence gas diffusion effects into and from the nuclei as well as affecting the likelihood of cavitation inception through the application to the gas nucleus of instantaneous pressure which may be considerably below the time-mean pressure.

Items (1) and (2) above seem, in the opinion of the writer, to preclude at the present time a complete solution of the air effects problem such as would be efforted if it were possible to predict by calculation the cavitation inception sigma (or the effects upon other measurable parameters) of a given, and measurable, entrained gas nuclei population, size, and location distribution, and if it were then possible to verify the result experimentally in a few selected cases, so that the theory could then be applied with confidence to cases as yet untested. However, an improving theoretical understanding of the phenomena, the increasing availability and economy of large-scale computers, and the continuing development of instrumentation techniques continues to substantially reduce the gap between the possibilities of basic investigations and their direct application to model and prototype devices. Thus comprehensive experimental programs planned today are likely to be considerably more fruitful in providing information of more general applicability than those planned and carried out many years ago. At the very least the earlier investigations have proved beyond doubt the existence and importance of air effects upon cavitation inception and performance parameters in certain cases, and thus motivated the continuing study of this problem. In général, the studies of the effects of air content upon cavitation date to the 1930(s) to the writer's knowledge. It seems most useful to consider these under the relatively large-scale efforts of various institutions, universities, companies, etc. rather than as isolated papers by individuals. Of course only a few key people are generally associated with each such group. The groups and their investigations of which the writer is aware are listed and discussed in the following paragraphs. Many individual papers and authors have of course been omitted, but it is the present intention to present the main trends of investigations only. The order of the listing has no significance other than presenting a roughly chronological arrangement.

1 - F. NUMACHI AND T. KUROKAWA, INSTITUTE OF HIGH SPEED MECHANICS, TOHOKU UNIVERSITY, SENDAI, JAPAN (2 - 7)

Numachi and Kurokawa in the late 1930(s) conducted the earliest comprehensive investigation known to the writer of the effects of total air content upon cavitation sigma. Their tests included both a venturi test section and an isolated profile, and were conducted in distilled water, tap water, and salt water (2-6). Water temperature covered the range 10 - 40°C, and air content from about 0.3 to 1.3 saturation at standard temperature and pressure. Air content was measured using an instrument devised for the purpose, much like the Van Slyke type instrument used in many laboratories today. In this type of instrument, dissolved gas is removed from a sample of known volume of test liquid under vacuum, using mechanical agitation. The removed gas is then compressed into a much smaller known volume resulting in an increase of gas pressure to a conveniently - measurable range. The pressure and temperature of the gas are then measured so that the mass of gas can be computed, assuming type of gas is known, i.e., air, nitrogen, oxygen, etc. Since the device is unable to distinguish between types of gas, it must be assumed that the dissolved gas is primarily a mixture of nitrogen and oxygen in equilibrium proportions, e.g. This may not of course be actually the case, but knowledge of the total volume of gas which the device does measure is probably more important from the viewpoint of cavitation inception than knowledge of the precise nature of the constituent mixture. At least in the writer's opinion a total gas measurement is preferable to precise knowledge of one constituent alone as e.g. is given by the chemical Winkler method for oxygen, and then use of the unsupported assumption that the other gases are in the expected proportion. This is often not even closely the case because of the widely differing chemical affinities of oxygen, nitrogen, and other gases of interest.

The data of Numachi and Kurokawa is presented in terms of cavitation sigma vs. air content for various water temperatures. In general they obtained a fairly linear rise of sigma with increasing air content over the range tested (see above), with the effect being greater for lower temperatures than for higher. The change in sigma in these tests is substantial, ranging from a maximum in the venturi tests of up to 10-fold to 20 - 50 % in the profile tests, while the air content relative to saturation at standard temperature and pressure is increased from a minimum of about 0.3 to a maximum of about 1.3. Fig. 1 and 2 are typical of their results from a venturi and an isolated profile.

In view of the foregoing results it is apparent that at least for the test conditions of Numachi, sigma cannot be expressed independent of air content. Thus the notion of a "critical pressure" to replace vapor pressure in the usual expression for sigma, and to reflect the effect of air content and perhaps other variables is suggested. Gutsche

(1939, ref. 7) reduced some of Numachi's experimental data into this form, where sigma is defined in terms of "critical pressure" which is in turn the pressure at which cavitation actually occurs. Fig. 1 presents some of Numachi's venturi data in this form, where it is shown that the "critical pressure" increases in relatively uniform fashion with relative air content, but is fairly independent of temperature (range of 5 to 50°C).

The writer owes much of the above discussion, as well as the material from Gutsche, to the very fine summary of Numachi's work presented by Edstrand (8) in English.

2 - H. EDSTRAND, H. LINDGREN, AND C. A. JOHNSON, SWEDISH STATE SHIPBUILDING TANK, GOTEBORG, SWEDEN, (8 - 10)

A very comprehensive series of experiments upon the effects of air content on cavitation sigma and other performance parameters of marine propellors in both tap water and sea water has been reported by H. Edstrand from the Swedish State Shipbuilding Tank (ref. 8 and 9, 1946 and 1950). Quite recently additional data on air content effects has been obtained at the same installation on various International Towing Tank Conference (ITTC) head forms : see Lindgren and Johnsson, 1966, ref. 10.

Fig. 4, taken from ref 8, shows typical results from the propellor tests in tap water upon the torque, thrust, and efficiency. It is noted that a variation of relative air content from about 0.23 to about 0.73 has a substantial effect upon these parameters. For example, as the air content is increased over this range, the efficiency drops from 0.62 to 0.46 for a given advance coefficient and sigma (1.5 in this case). Fig. 4 is also generally typical of the type of results obtained for seawater (9).

The tests of Edstrand, etal, involving both tap water and seawater on propellors allow a comparison of the effect of these two different fluids with the results of Numachi, for an entirely different geometry, i.e., a venturi. In the present tests it was found that there was a distinct difference between the performances in tap and sea water in that the effect of cavitation upon thrust and torque becomes evident earlier in sea-water, i.e., at higher sigma. However, the difference between the two fluids for propellors was not nearly so great as that noticed by Numachi in a small (1 mm dia.) glass venturi. This comparison is shown in Fig. 5 which is taken for convenience from ref. 9. It is of special interest in that it emphasizes the strong effects of geometry and perhaps absolute size in measuring gas content effects.

A much more recent series of tests from the same laboratory upon ITTC comparative head forms by Lindgren and Johnsson (1966 - ref. 10) presents additional data on the effects of air content on sigma, showing the relatively large scatter in sigma at given air content obtained from different laboratories testing the same shape. Another interesting and related result of this investigation is shown in Fig. 6 (reproduced from ref. 10) which illustrates the effects upon inception sigma of the *rate* of lowering of pressure to obtain cavitation. This effect is shown to be especially pronounced for high gas contents and low velocities. Both of the points discussed above from ref. 10 indicate that cavitation inception sigma is not determined only by the conventional flow parameters and *total* air content, but in addition the disposition of this gas, which is of course affected by rate of pressure lowering while the total gas content is not.

Some of the visual observations made in these tests, as well as observations made elsewhere to be discussed later (11), help to clarify the situation to some extent. It was observed by Edstrand (8) in his propellor tests that the importance of the air effect depends very much on the type of cavitation which is involved. To quote Edstrand directly, "with burbling cavitation, large alterations in characteristics occur at different air content values, but with laminar cavitation"- - presumably cavitation involving a relatively steady-state pocket rather than a multiplicity of bubbles - - "on the contrary, the variation in - - (torque, thrust, and efficiency parameters) - - is unimportant even with great differences in the amount of dissolved air". However, it appears to the present writer that it would be very difficult to predict in advance the type of cavitation to be encountered in a given machine, and thus be able to predict the likely importance of air content effects. The above appears related to the observation of Mr. Vuskovic (1940, ref. 11) to be discussed next.

3 - ESCHER-WYSS AND I. VUSKOVIC (11)

A relatively comprehensive series of tests on air content effects related both to performance parameters and erosion is reported (1940) from Escher-Wyss by I. Vuskovic (11). The damage portion of that investigation will be discussed later under that subject. However, his observations concerning the effects of air content on the performance of a Kaplan turbine seem closely related to the somewhat later and independent observations of Edstrand (discussed above) for marine propellors. Vuskovic makes a distinction between "real" cavitation (that which is presently called "vaporous cavitation") and the presumed dissolution of air from the liquid presumably into small entrained microbubbles (today called "gaseous cavitation"). Related observations, primarily those of Holl and colleagues at Pennsylvania State University, USA, to whom the present English nomenclature is due, will be discussed later.

Vuskovic's tests were made in a Kaplan turbine wit transparent casing so that the incidence of cavitation could be observed and photographed with stroboscopic lighting. His photographs show that the first "cavitation", i.e., appearance of bubbles, is of the tip vortex type generated in the region between blade tips and housing. It is this phenomenon which he feels is not the true vaporous cavitation, but rather is "gaseous cavitation", to use present-day terminology. He describes the "true" cavitation as comprising a heavier and whiter cloud. He finds that incident sigma for the tip-vortex cavitation depends substantially on air content (Fig. 7, reproduced from ref. 11), but that the later "true" cavitation does not. He further finds that there is little observable effect from the tip-vortex cavitation upon the conventional turbine performance parameters. Thus, in his tests, there is only a slight effect of air content upon the Kaplan turbine performance parameters, a result consistent with later tests reported by Fallström (45). However, Vuskovic's results differ from those of Edstrand, etal in this regard (which may not be surprising since different machines are tested) in that Edstrand did find a substantial effect of air content on the propellor performance parameters, (Fig. 4, e.g.).

The observations of Vuskovic on the one hand and Edstrand on the other are similar, if it is assumed that Vuskovic's tip vortex cavitation (which he considers simply gas dissolution) is similar to Edstrand's "burbling cavitation (comprised of individual bubbles as is presumably the tip vortex cavitation, rather than a relatively steady pocket as Edstrand's "laminar" cavitation). At least it can be stated at this point that both the tip vortex cavitation and the "burbling" cavitation are much more sensitive to air content than are the more fully-developed types of cavitation ("true" cavitation for Vuskovic and "laminar" cavitation for Edstrand).

4 - VARIOUS OTHER VENTURI TESTS - CRUMP (12 - 13), WILLIAMS AND McNULTY (14), ZIEGLER (15)

In the 1940(s) and 50(s) various relatively isolated tests of the effects of total air content upon cavitation inception are reported, e.g., ref. 12-15. These tests are rather similar to the earlier tests of Numachi (2-6), although the results of the various investigators do not agree quantitatively, and much scatter appeared in each individual set of data. In général, it was found that for reduced air content, inception sigma was also reduced, and that for the lowest air contents tensions were sometimes found in the liquid. The results of Crump (Fig. 7) e.g., show a very large air content effect as did those of Numachi previously discussed, whereas those of Williams and McNulty, Fig. 8, show a much smaller effect. These authors also comment on a "hysteresis effect" in the data. In the present writer's opinion, these results further illustrate the impossibility of obtaining a clear representation of the effects of air in terms only of *total* air content and the conventional flow parameters.

5 - WATER TUNNEL INVESTIGATIONS IN USA - PENNSYLVANIA STATE UNIVERSITY, UNIVERSITY OF MINNESOTA, CALIFORNIA INSTITUTE OF TECHNOLOGY (16 - 22 AND 62)

Work in the United States on the effects of gas content upon cavitation inception upon submerged objects has been conducted largely since World War II, and has been concentrated in the large water tunnels at Pennsylvania State University (Penn State), University of Minnesota U-Minn, and California Institute of Technology (CIT) While the writer does not know of any study of air contents effects specifically at CIT, this group has generated much excellent data on the effects of velocity and size upon inception sigma for various submerged shapes (16, 17, e.g.) which has served as a good basis for comparison for other investigators.

The work of these various investigators pertinent to the present discussion has centered on the observed difference between sigma for inception and "desinence", as eventually named by Holl (18), i.e., the difference between sigma obtained when the pressure is lowered until cavitation occurs in the conventional test (incipient sigma), and then raised until its disappearance (desinent sigma). In general, it was found that the desinent sigma exceeds the incipient sigma, so that a "hysteresis" effect exists. This difference in the sigma values appears to decrease with increase in velocity or size and thus hysteresis is a scale effect. As previously mentioned, a hysteresis effect was earlier reported by Williams and McNuulty (14). It is also found that there is much less data scatter if the data are based upon desinent sigma rather than upon incipient. Further, there is a time-delay effect involved (19), in that cavitation inception may occur at a given sigma if the test conditions are maintained at that value over an extended period. Thus inception sigma depends upon the *rate* of lowering of pressure, as previously discussed in this report in connection with the work of Lindgren and Johnson (10).

It appears that all the above effects are closely bound up with the details of the nucleation process from entrained or stationary gas nuclei, so that they can be understood only if detailed knowledge of the distribution and size spectra of these nuclei is available. Work in this direction at the University of Minnesota has continued over the past decade. Ripken and Killen (19) found that free gas in a closed-circuit water-tunnel system reached a stable value after each change in tunnel operating pressure if sufficient time were allowed. Further, they found no hyteresis when tests for both desinent and incipient cavitation were made under conditions where the amount and characteristics of the free gas were stabilized. These investigators monitored continuously the concentration and gas-bubble-size distribution of the circulating free gas during the cavitation experiment, using its effect upon the velocity of propagation of a pressure pulse as the monitoring technique (20). Their method did not include gas attached to the fixed boundaries. Further work by the same group is described in ref. (21, 22 and 23). It appears from this work that hysteresis can be eliminated as a scale effect if the entrained gas population is maintained constant throughout the test. The above description is largely taken from ref. 24. More recent work attempting to measure entrained gas spectra and correlate with cavitation sigma in a venturi is in progress at the University of Michigan and will be described later.

6 - BASSIN D'ESSAIS DES CARENES, PARIS (25-27)

A comprehensive series of water tunnel test data on the effects of total air content upon cavitation initiation for various ogives, hydrofoils, and propellors have been reported over the past decade by Bindel and his associates (25-27) from the Bassin d'Essais des Carènes of the French Navy in Paris. Total oxygen content was measured discontinuously by the Winkler method, and total gas continuously with a Cambridge meter. The results are reported in milligrams of oxygen per liter (saturation is 10.1 for atmospheric pressure and 15°C, which corresponds to 20 cm^3 air per liter), and generally cover the range 2 - 5 mg-O_2/liter, i.e., 20 - 50 % of saturation. Typical data are shown in Fig. 9, taken from ref. 27.

Perhaps the most important conclusion from these tests, in agreement with the conclusions of the Escher-Wyss group previously discussed (Vuskovic - 11) and the Swedish State Shipbuilding group (Edstrand etal - 8-10) is that the effect of total air content, as well as velocity depends very strongly upon the type of cavitation involved. Bindel, etal noticed 3 distinct types of cavitation : bubble cavitation (presumably the "burbling cavitation" of Edstrand (8)), cavitation by lamina ("laminar cavitation" of Edstrand (8)), and vortex cavitation (also discussed by Vuskovic - 11). Bindel's group observed "burbling" and vortex cavitation on all objects tested, i.e., ogive, hydrofoils, and propellors. However, laminar cavitation was observed only on the hydrofoils and propellors. They observed that burbling cavitation was only very slightly influenced by total air content or velocity (Fig. 9). For laminar cavitation the effect exists, and is not always well-defined, but generally an increase in air or velocity favors cavitation. Vortex cavitation behaves in a manner similar to laminar (Fig. 9).

The foregoing results for burbling and laminar cavitation differ directly from those of Edstrand (8), (whose results were limited to these two cases) who found little effect of air with burbling cavitation and large effect with laminar. They also are counter to the results of Vuskovic (11), who found only very slight effect of air content on vortex cavitation (in a Kaplan turbine rather than a propellor). While Edstrand etal covered a larger range of air content but one common with Bindel, Vuskovic used only air contents above those of Bindel.

It is further observed by Bindel, etal that velocity and total gas content effects are not independent in that in those cases where velocity effects are important, air content effects are also, and vice-versa. However, in all cases where there is an effect of air content, an increase therein favors the apparition of cavitation ; the direction of the effects of velocity depend upon the type of cavitation involved. A final recommendation of considerable practical interest is that tests should be run at as high a velocity as possible to minimize the velocity scale effect, and at a moderate total air content. A value of approximately 30 % saturation at STP (3 mg-O_2/liter) is suggested. Very low air contents can at least theoretically be expected to reduce sigma substantially, and extremely high air content may result in masking vaporous cavitation entirely, producing in its stead "gaseous cavitation". This statement is in fact closely related to the observations of Vuskovic (11). The observation of Bindel that increased velocity tended to reduce scale effects is consistent with that of Holl (18) previously mentioned that "hysteresis" effects are reduced if velocity is increased, and also with the conclusions of the University of Michigan investigation discussed later.

7 - NATIONAL PHYSICAL LABORATORY WATER TUNNEL TESTS (28)

A series of tests for the effect of total air content on propellor performance has been reported by Silverleaf and Berry (28). Total air content was measured using a Van Slyke type instrument, and an ultrasonic transmission method to distinguish entrained from dissolved gas, similar to that of Killen and Ripken previously discussed (21) was tried unsuccessfully. The intention to further pursue this latter method is stated. While no inception sigma results are reported, the overall trend of the observations is similar to that reported in the previous discussions of cavitating propellors (sections 2 and 6) in that generally cavitation is favored by an increase in total air content. The results are limited to effects upon thrust and overall performance, and appear conflicting in some aspects.

8 - COLORADO STATE UNIVERSITY WATER TUNNEL (29)

A recent set of data upon cavitating orifices ranging in size from 1 to 40 in. diameter has been reported by Tullis (29). A substantial size scale effect is found as expected, but there seems to be little effect upon inception sigma even though substantial differences in the quality of water exist. For most of the tests an open system through which lake water is discharged was used, but in one case a closed recirculating loop was employed. Though no measurements of air content were made, it is reasonable to assume that the total contents differed substantially and, more importantly, the entrained portions,

9 - SOGREAH - GRENOBLE, FRANCE (30 - 34 AND 36 - 38)

Over the past 5 - 10 years a study of scale effects including air content in various cavitating flows has progressed at SOGREAH. As a first step a relatively comprehensive series of tests were conducted on cavitating orifices of various shapes to investigate the effects of velocity and Reynolds Number as well as total air content on initiation sigma for cavitation induced in regions of strong shear such as those downstream of an orifice (30-33). A Reynolds Number variation greater than that obtained by variation of the velocity over the relatively narrow range available was obtained by using also a small variation in temperature. No size variation was included. Total gas content was varied by varying the pressure in the downstream tank of the loop in which there is a large free surface. Dissolved oxygen content was measured with a Beckman meter, and from this total gas content estimated assuming the appropriate equilibrium relations to apply. The possible disparity between dissolved gas as measured by the Beckman meter and total gas (which includes the entrained portion also) may not be important. Recent work in the writer's laboratory (34) has shown that the entrained volume, although believed all-important in cavitation initiation, is a virtually negligible portion of the total. However, the estimate of total air from a measurement of oxygen alone may be a more important source of error, as previously discussed.

It was found in these experiments that variation either in the form of the orifice (i.e., free jet shape) and/or in Reynolds Number did not greatly affect inception sigma. However, there was a substantial effect of total air content (Fig. 19), particularly in the range of moderate air contents (30 - 60 % saturation at STP). Also, it was found that the previous pressure history of the water strongly affected sigma for a given oxygen content. Such a comparison (Fig. 11) indicates again the impossibility of describing inception sigma in terms only of total gas content, and of course the other conventional flow parameters. This point was realized by the SOGREAH group, who included a reference two-dimensional venturi ("veine etalon") in their tests to assure the same size and population distribution of gas nuclei, for all tests, i.e., if the previously observed relation between total oxygen content and sigma did not exist for the "veine etalon", the test was not valid for the profile, orifice, or whatever test shape was used.

Continued efforts by the SOGREAH group since the shear flow cavitation experiments has been concentrated on the development of techniques for overcoming the difficulties of performing meaningful inception sigma tests, if only total gas content, rather than the population and size distribution of entrained gas, is known. They have followed two paths in this work :

1) Development of improved "veines etalons" to allow a standardization of the water for each series of tests, at least as far as those parameters which affect inception sigma are concerned, and,

2) Development of a "bubble microscope" (36, 37) capable of distinguishing gas "nuclei" in the 1 - 100 micron range which is pertinent to the nucleation of cavitation in most cases. A direct measure of entrained gas particle population and size distribution can be obtained in this manner since suitable photomicrographs can be made. The direct counting and classification of particles is possible but tedious, and the volume sampled in a single photograph is very small because of the high resolution and magnification of the instrument. Thus an automated counting procedure is required, and this appears to be a possibility.

A further aspect of the study by the SOGREAH group has been the survey and comparison of the various existing methods for the measure of total gas content (38).

10 - UNIVERSITY OF MICHIGAN - VENTURI STUDIES (34, 39 - 43)

A relatively long and comprehensive series of studies of both damage and performance effects in venturi test sections in the writer's laboratory at the University of Michigan (34, 39 - 43, e.g.) has been performed over the past decade. While the damage work has not involved specifically the effects of air content, considerable work has been done on gas effects upon cavitation sigma for both water and mercury. Liquid metals such as mercury are interesting in the context of this study, in that their solubility for gases is extremely small compared to that of water, so that only the effects of *entrained* gases are involved.

The scale effects investigations at Michigan have been divided into two parts :

1) Cavitating venturi tests for geometrically similar venturis with cylindrical throats of 1/8 to 3/4 inch diameter and 6° divergence angle in all cases, using water and mercury as test fluids, with temperature variation in both cases over a considerable range, but with total gas content measurement only, using a Van Slyke meter (39 - 42, e.g.).

2) Development of an instrument for the measurement of entrained gas nuclei population and size distribution (35 - 43), and correlation of these parameters with cavitation sigma. A modified Coulter-Counter system with sampling probe has been developed. The system operates satisfactorily (35) and has so far shown, e.g., that the volume of entrained gas in a typical case is an extremely small portion of the total gas volume ($1{:}10^6$). Presumably the proportion in an actuel case depends upon many things including the pressure history of the water over the previous few hours, which has also been illustrated by these tests (43).

Studies of the effect of velocity, size, temperature, previous pressure history, and total gas content upon cavitation sigma for geometrically similar venturis of the type employed have not produced any clear-cut relations even for this simplified flow pattern. Fig. 12-A shows the 1/2 inch throat venturi, which is typical. For example, a correlation of inception sigma with Reynolds Number was only successful for a given fluid and venturi (39, 42). Fig. 12-B for water is typical. It shows that in general an increase in gas content causes an increas in sigma. Fig. 13, extracted from the authors discussion ref. 44, compares sigma correlations for water and mercury with Reynolds Number in the same venturi.

The Michigan studies of this type have produced data on air content effects which are more readily explicable than those relating to other types of scale effects, such as are discussed in the foregoing. Fig. 14 shows inception sigma against throat velocity for the 1/2 inch throat venturi in water for various gas contents, ranging up to about 120 % saturation at STP. Very similar results were obtained for the 1/4 inch venturi in water but apparently did not apply to mercury. The following significant points are noted :

1) For high gas contents, sigma decreases strongly with velocity, passes through a minimum, and then increases. Incidentally, this behavior is similar to that observed by Jekat (44) for a cavitating axial pump using air-satured water.

2) For low gas content, sigma increases monatonically with velocity.

3) The separation between the curves of constant total air content is much greater at low velocity than at high consistent with previous observations by Holl (18) and Bindel (25-27), already discussed. Close examination shows that in fact the separation between the curves is approximately inversely proportional to kinetic head. This implies that the gas pressure in the bubbles is constant over the velocity range tested.

Using an approach suggested by Holl (19), it is possible to consider sigma as the summation of a sigma component due to gas effects, i.e., gas pressure within the entrained "nuclei", and the sigma which would apply for very small gas contents, eq. (1). As further suggested by Holl (19), the gas pressure within the nuclei may perhaps be considered as roughly proportional to the total gas content. Then :

$$\sigma = \sigma_o + \sigma_{gas} \quad ; \quad \sigma_{gas} \cong \frac{k\ p_{gas_{SAT}}}{\rho\ V_t^2/2} \quad ; \quad p_{gas_{SAT}} = \text{gas pressure to which water is exposed.}$$

k = Proportion of saturation pressure actually in bubble.

The present data shows that the internal gas pressure does not depend upon velocity and is constant for a given total gas pressure for these tests, since the sigma differential between curves of constant total gas content is approximately inversely proportional to velocity head. From the present data it is possible to compute the proportionality constant k in eq. (1). For the water tests the scatter in k is considerable, presumably partly because of the inexactness of the presumed model, and largely because of differences in previous pressure histories of the water used. Fig. 15 shows this effect. However, for water, k averages 0.009 and for the mercury tests, 0.058. Within its probable error, the above model allows the calculation of air content effects upon inception sigma for various velocities in a given geometry, provided the air content portion of sigma has been obtained by test for one velocity.

The most recent portion of the Michigan study has for its objective the development of a system for measuring the entrained gas nuclei population and size spectra. A modified Coulter Counter system has been used (35) wherein a continuous sample of the water-gas mixture is drawn through a micro-orifice of diameter only one order of magnitude larger than that of the nuclei to be measured (1 to 100 microns in this case). The passage of a gas "nucleus" through the orifice, which is of electrically-insulating material, results in a partial and instantaneous interruption of the electrically conducting path through the test fluid* which also passes through the orifice. The resultant electrical pulse can be suitably amplified, counted, and recorded. So far the system appears to operate satisfactorily with no insuperable difficulties becoming evident. Also, its application to other fluids of interest seems feasible. Fig. 16 shows a schematic of the apparatus plus typical results obtained for our water tunnel for 2 different gas contents and for different pressure pre-histories of the water. Both parameters have an important influence on the number and size distribution of gas "nuclei".

* The electrical conductivity of tap water is adequate for this purpose.

11 - SWEDISH STATE POWER ADMINISTRATION (45)

Fig. 17, comprised of data reported by Fallström (45) of the Swedish State Power Administration from tests upon a Kaplan turbine performed by KMW of Kristinehamn, Sweden, is consistent with the conclusions of Vuskovic (11), previously discussed, from tests upon a Kaplan turbine at Escher-Wyss, that variations in air content do not affect the performance of a machine of this type significantly. It is Fallström's stated opinion (45) that air content only affects sigma applying to the first appearance of bubbles in a machine of this sort, and thus presents only a problem of academic interest for Kaplan turbines.

12 - NATIONAL ENGINEERING LABORATORY, EAST KILBRIDE, SCOTLAND (46 - 48 AND 61)

To the writer's knowledge, no data relating to air content effects upon sigma have been reported from the water tunnels at NEL. However, some relatively basic work relating air content and nucleation phenomena in liquids (water and organic liquids) under non-flowing conditions has been financially supported by NEL (46 - 48 and 61). The work was actually performed at King's College, University of Durham, Newcastle-upon-Tyne, England by Richardson, Iyengar, and Mahrous. Nucleation thresholds in static samples under ultrasonic irradiation were studied as a function of total air content, pre-pressurization history, and other forms of pre-treatment such as centrifuging. Generally, it was found that nucleation thresholds (analogous to inception sigma for flowing tests), were strongly influenced for a given total gas content, by the condition of the gas in terms of the repartition between entrained "nuclei" and the dissolved portion, and nuclei diameter distribution. In certain of the tests it was found that there was no effect due to the dissolved portion upon thresholds and that only the entrained nuclei were of importance (48). This is illustrated by Fig. 18 over a range of total gas content from 50 to 95 % saturation.

Realizing the importance of detailed measurements of nuclei population and size distributions, they developed a technique for this purpose (46-48) based upon the strong attenuation of an ultrasonic beam caused by gas bubbles of a size resonant with the imposed frequency. In principle it is possible with this type of device to measure population of bubbles of chosen diameter by the attenuation of an imposed sound field of the appropriate frequency. By the use of different frequencies it is of course possible to survey the entire diameter range of interest. The instrumentation developments of this group are of course closely related to those of the University of Minnesota group previously discussed (20, 21, e.g.). They also experimented (61) with a light-scattering technique for the same purpose.

13 - MISCELLANEOUS NUCLEATION STUDIES FOR NON-FLOWING SYSTEMS (49 - 57)

A - Galloway (49)

Various isolated studies of the type supported by NEL and described above have been reported. Fig. 19 shows cavitation threshold as a function of total air content for water and benzine when exposed to an ultrasonic field as reported by Galloway (49). He shows a strongly increasing threshold (i.e. sigma decreasing into strongly negative regions in terms of a flowing test) for decrease in total air content from about 20 % saturation to about 0.02 % saturation. For such very low gas contents one might expect an approach to the order of magnitude of the actual tensile strength of the pure liquid, and Galloway's results (Fig. 19) do indicate very substantial liquid tensions, though admittedly the observation is only for high-frequency excitation. At the high-gas-content end of his curve, the threshold approaches the values normally expected. These results are not in disagreement with Iyengar and Richardson (ref. 48, Fig. 18), who showed no effect of dissolved air upon cavitation threshold, since their results are for a much higher gas content range (50 - 95 % saturation).

B - Hayward (50)

A somewhat related study performed at NEL is that of Hayward (50) who found through pre-pressurization experiments that only water, from a group of liquids including water of varying degrees of purity and various organic liquids, appeared to contain "nuclei" of the type originally postulated by Harvey (51), which could be destroyed or substantially suppressed through pre-pressurization of the liquid. He then concludes that in general Harvey-type "nuclei" cannot provide a major cavitation-nucleation machanism. In our opinion, this conclusion does not seem warranted.

C - Ward, Balakrishnan, and Cooper (52, 53)

In an entirely theoretical study, Ward, etal (52) postulate the possible substantial importance of dissolved rather than entrained gas, as is usually supposed. However, this viewpoint is disputed by various other investigators in a discussion of this paper (53). The above paper and various others pertinent to the subject appear in a *Symposium Booklet* (54) and later *Discussion Booklet* (53), both available from ASME. The Symposium was entitled "The Role of Nucleation in Boiling and Cavitation"; its existence indicates the growing activity in the field. Ref. 55 in the Symposium Booklet is of particuler interest in that it surveys the present knowledge of nucleation as it applies to cavitation.

D - Nystrom and Hammitt (56)

Nystrom and Hammitt (ref. 56, one of articles in Symposium Booklet, ref. 54) have investigated the effects of applied frequency and temperature upon nucleation in molten sodium under the influence of an applied ultrasonic pressure oscillation. Fig. 20 shows typical results which indicate that the cavitation threshold increases strongly with a frequency increase from 13 to 25 kc/s, and with a temperature decrease of the sodium. The trend with frequency is due to the increasing importance of inertia for high frequency. Presumably the low frequency end of the curve should approach results obtained in steady-state tests, and this was in fact observed. The increasing threshold for low temperature sodium may be due to an increasing surface tension at low temperature and perhaps increased sodium purity. Perhaps also an increasing effect of rectified diffusion is involved at high temperature (57). Threshold studies in liquid metals such as sodium, as compared with fluids such as water and organic liquids, are of interest because the gas dissolution effects are negligible or minor for the liquid metals because of very low solubility coefficients (57).

B - MAJOR BASIC RESEARCH TRENDS (DAMAGE NOT CONSIDERED)

The overall objective of relatively basic research into the effects of air or other gas content upon cavitation sigma or other machine performance parameters must be the development of an ability to predict these effects in advance of tests upon the specific apparatus, or to predict the effects upon a prototype from model tests. It is clear that in general this objective has not been attained, so that much present and recent test work has been motivated by a largely empirical approach of measuring air content effects upon models of interest of various sorts and then hopefully presuming that the behavior of similar but not identical devices can be predicted from the data so gathered. A major portion of most of the studies already discussed in this report are of this type.

As pointed out in the introductory portion of (A) from this section of this report, there are major difficulties at present preventing the development of such a predicting capability. Obviously a basic approach must start with the individual "nuclei" from which the observable and technologically important cavitation originates. The following steps at the least would be necessary :

a) Measure (or compute from other considerations of the flow regime) the number and size spectra of gas nuclei upstream of the model or machine.

b) Compute their trajectory as well as their growth or collapse rates during their passage between the region where the spectra have been measured and the region where cavitation occurs. The major difficulties of this step involving in general turbulent, two-phase, three-dimensional flows are obvious, and such a general calculation is no doubt beyond the realm of feasibility even of large present-day computers. To what extent mathematical models of this flow regime, adequately simplified for tractability, can provide useful results is of course the question at present.

c) Compute the effect of the two-phase flow regime, analysed under (2) above, on the performance of the pertinent model or machine.

At the present time, fully feasible techniques for implementing any of the above 3 steps are not available. However, various of the studies previously discussed can be considered as partially motivated in an attempt to improve capabilities in one or more of these areas.

1 - MEASUREMENT OF ENTRAINED GAS NUCLEI SPECTRA

Past progress and several on-going developments exist in this area. Techniques include :

a) Utilization of the effects of microbubbles upon sonic or ultrasonic transmission, either through attenuation in a narrow frequency band due to bubble resonance effects or reduction in the velocity of sound due to the presence of bubbles. The use of such techniques has probably been most wide-spread and successful so far by the group at the University of Minnesota (20 - 23). Related work was done by the NEL-supported group at the University of Durham (46-48). Also related work has been reported from Russia (58).

b) Sampling technique at University of Michigan, utilizing Coulter-Counter (35, 43), previously discussed. The measurement with this type of instrument is quite direct, but there is the difficulty of obtaining a true sample from the test section of the tunnel, and changes in the entrained gas population of the sample during transit to the instrument and processing by the instrument. For some of the other techniques discussed, including some of the sonic techniques above, these difficulties do not exist since the measurements are made "in situ".

c) Direct visual observation such as bubble microscope technique of SOGREAH (36, 37). The observation is certainly direct and is capable of providing fully detailed information on the nuclei spectrum. However, it is limited to transparent fluids.

d) Use of light-scattering properties of gas nuclei (59-61). Again the measurement is in situ and transparent fluid is required. Full detail of the size distribution and number of bubbles is not afforded, and calibration against an absolute measurement such as obtained from the bubble microscope technique or the Coulter-Counter is required. Once calibrated, read-out could be rapid and automatic. A laser light source may be required.

2 - BUBBLE AND FLOW CALCULATIONS

Items 2) and 3) listed in the beginning portion of this section, i.e., Section (B), both involve complex flow calculations upon two-phase turbulent flows, and will be considered together in the following, as in many cases it is impossible to separate these two aspects of the overall problem. Many studies related to these areas exist in the literature so that it is possible here to cite only a few of major importance, or those which are merely typical of many others.

a) Pennsylvania State University (Penn State) and California Institute of Technology (CIT)

Basic theoretical and experimental studies on cavitation nucleation have been conducted by these groups generally over the period since World War II. This has included consideration of the growth through gas diffusion of an individual bubble attached to a wall until it became large enough to be detached by the flow forces (16, 62 e.g. at CIT), and many studies of the behavior of gas bubbles entrained in the stream and approaching an area of cavitation. These studies involving primarily Holl and his colleagues (18, 19, e.g.), previously discussed in this report, have involved the investigation of fairly simplified mathematical models of bubble growth from nuclei including the effects of gas diffusion, pressure, and inertia. The models suggested appear tractible to some extent as already indicated in the discussion of their application to the University of Michigan data (40 - 42). However, important features such as the effect of turbulence upon gas diffusion rates have been neglected.

b) SOGREAH

At the present time the behavior of gas nuclei in a tunnel are being analysed at SOGREAH under contract to DRME* by a mathematical model which includes all apparently pertinent effects. At the time of writing of this report the calculations are not complete so that comments upon the results cannot be made. The study does not to the present include the trajectory of gas bubbles in pressure and velocity gradients, nor is any possible "slip" between the phases included.

c) Individual Bubble Studies

Numerous individual bubble studies exist in the literature, too numerous to allow a comprehensive list at this point. Many of these, however, are not pertinent to the problem of nucleation. They are pertinent rather to the following cases : bubble collapse as in cavitation erosion, bubble behavior under an oscillating high-frequency pressure field such as is encountered with ultrasonic cavitation damage devices, and bubble behavior under conditions where heat transfer effects predominate. Nevertheless, there are many studies motivated directly by the cavitation nucleation problem. One of the more comprehensive and applicable earlier studies is that by Gallant (63). Another of special interest in the present context is that by Johnson and Hsieh (64). This is one of the few studies presently available where the effects of pressure and velocity gradients upon bubble trajectory are considered.

C - AIR CONTENT EFFECTS UPON CAVITATION DAMAGE

Studies of the effects of air content upon cavitation damage are far more limited in number and scope than are those upon cavitation inception and performance of the type already discussed. However, it is clear that air or more generally gas content must have a substantial effect in at least some cases through the following opposing mechanisms :

* Direction Recherche et des Moyens d'Essais

a) Higher gas contents, as already discussed, in general favor the appearance and development of cavitation, thus providing an increased number of bubbles,the collapse of which may be damaging.

b) Higher gas contents within individual bubbles reduces collapsing wall velocities and pressure radiation into the surrounding liquid. Various relatively recent detailed numerical studies of individual bubble collapse (65, 66, e.g.) have shown that this is the case. Also it is generally accepted from field observations that injection of air in relatively large quantities into a damage-prone region tends to reduce damage (24, e.g.).

More detailed consideration of the above two conflicting effects of increasing gas content indicates the strong probability that in the realm of very high gas contents (saturation and above), an increase in gas content will reduce damage through its "cushionong" effect upon individual bubble collapses and perhaps also through a more rapid attenuation of bubble-collapse-generated shock waves in the surrounding (more gassy) liquid. On the other hand, for very low gas contents the cavitation threshold is very substantially increased if gas content is further reduced, i.e. sigma is increased, (48, e.g.), since for very low gas contents there are insufficient "nuclei" in the liquid. Thus for this range, a change of gas content strongly affects the cavitation field itself without having much corresponding effect on bubble collapse violence. In fact, in certain cases in this range an increase in gas content could well produce cavitation, which then could well be damaging, where formerly no cavitation (or damage) existed.

Beyond individual bubble collapse studies, the most comprehensive of which have been already cited, there are no theoretical studies to the author's knowledge of the effects of gas content upon cavitation damage, and only a few isolated experimental results. These will be discussed next.

1 - VENTURI TESTS AT HOLTWOOD LABORATORY*, USA, MOUSSON (67)

The earliest reported tests of the effects of air content upon cavitation damage to the writer's knowledge are those conducted by Mousson (67), which were reported in 1937. Typical results are shown in Fig. 21 as is the special damage venturi used for these tests. The results indicate that for substantial amounts of air injection (in the range of 1 - 2 % of the water flow rate - no measurement of actual air content was made) damage is very substantially reduced, consistent with the introductory remarks in this section. However, it appears that the relative percentage air flow must be greater for larger water velocities i.e., the power required for air injection is more than proportional to water flow rate.

2 - VENTURI TESTS AT ESCHER-WYSS, VUSKOVIC (11)

Tests on the effects of injected air on damage conducted at Escher-Wyss by Vuskovic (11) using a venturi of the same design which had been utilized previously by Mousson (67) were reported in 1940. His damage specimens were of copper, which was also the material used by Mousson. Vuskovic's test velocity was about 60 m/s, equivalent to the lowest velocity employed by Mousson. He did not make weight loss measurements as had Mousson, but merely shows photographs of the damaged regions after similar exposures to the cavitation field with different air contents (air content was measured as opposed to Mousson's measurement of only injection flow rates). Vuskovic reports a steady diminution of damage for air contents relative to saturation at STP increasing from 0.3 to 1.7. He reports that his results are entirely in agreement with those of Mousson (67).

3 - ROTATING DISC AND VENTURI TESTS, RASMUSSEN - (68, 69)

The next investigation known to this writer of the effects upon damage of air content variation is that by Rasmussen (68, 69), reported

* Safe Harbor Water Power Corporation

in 1955. He utilized both 1) a rotating disc apparatus (submerged circular disc, rotated at high velocity, and equipped with several cavitation-inducing through-holes near the outer periphery ; damage specimen is imbedded in the disc behind each such hole), and a special damage venturi wherein a small transverse cylinder is placed accross the high-velocity rectangular test section. The small cylinder also serves as test specimen and is damaged by its own cavitating wake. Air contents were measured as volume percents in a special device developed by Rasmussen for the purpose. Air content damage tests were made in both types of apparatus, and were upon cast iron and an aluminium alloy. Fig. 22, 23, and 24 show typical results for both types of apparatus. Consistent with the previously discussed results of Mousson (67) and Vuskovic (11), damage decreased continuously and substantially as air content was increased, in this case from near zero to about 10 % by volume (saturation at STP is about 1.8 % by volume), thus generally covering a range similar to that of the others. However, the proportionate decrease appears to depend upon both the material tested (Fig. 23 and 24) and the type of test (Fig. 22 and 23). It decreases for aluminium for an air content increase from near zero to about 4 by a factor of about 40 ; however, the decrease over the same gas content range for cast iron is by a factor of only about 4. Comparing Fig. 22 and 23, it is noted that an increase in air content over roughly the same range as above decreases damage to aluminium in the rotating disc apparatus by a factor of only about 3.6 vs. 40 (as stated above) in the venturi facility.

4 - NON-FLOWING, VIBRATORY DAMAGE TESTS - HOBBS (70, 71)

Much cavitation damage testing over the years has been performed with high-frequency vibratory devices wherein cavitation is induced on the face of the vibrating specimen in an otherwise static liquid by the very high negative accelerations of the specimen (order of 50,000 "g"), although the actual velocity and displacement are small. Hence it is of interest to consider air content effects upon damage rates for such tests.

The existance of substantial air effects in such devices had long been suspected because of the well-documented effect of temperature variation for such a test. It had been observed by numerous investigators (70-73, e.g.) that for a vibratory open-beaker test of this type, the damage rate maximizes for a temperature about mid-way between the boiling and melting point (apparently true for any fluid), and decreases strongly for either increasing or decreasing temperature from the maximum damage temperature. The decrease for high temperature is well-explained in terms of bubble heat transfer and thermodynamic effects (24, 70-73, e.g.) whereas that toward decreasing temperature remains largely unexplained. It had been suggested that this might be partly due to an increasing air content at low temperature because of the increased solubility of most liquids for gases at low temperature (73). Other possible reasons are increasing viscosity and changes in surface tension and other liquid properties. However, the first actual measurements of air content effects upon damage in a vibratory test, to the writer's knowledge, are those of Hobbs (70, 71). His results (Fig. 25) show that the effect of air over a relatively broad range (about 0.1 - 1.0 saturation at STP) is not very great for this type of test. Since the air effect is much less than that of temperature, it is apparent that increased gas solubility at low temperature is not primarily responsible for the reduction in damage at low temperature in the vibratory damage test as had previously been suggested (as discussed already). Hobbs's result is also interesting in that it does not show a continuous reduction in damage rate over the entire test range as gas content is increased, as had the previously discussed tests in flowing systems (67-69). Hobbs shows the conventional trend only for his higher gas contents. Thus this portion of his test is not inconsistent with the other investigators much of whose results were for gas contents well above the maximum employed by Hobbs.

At low gas content, Hobbs shows decreasing damage with decreasing gas content, consistent with the discussion in the introductory portion of the section on gas-damage effects. He ascribes this, in agreement with the present writer, to a probable lack of sufficient nuclei to allow cavitation to develop to the same extent as for the higher gas contents.

5 - CATHODIC PROTECTION AND GAS CONTENT (74, 75)

Cathodic protection to reduce cavitation damage was suggested by Petracchi (74) in 1944. He expected that its use would suppress the electrical-chemical effects perhaps associated with the high pressures and temperatures of bubble collapse, and would certainly help suppress ordinary corrosion, the effects of which, when combined with the mechanical attack of cavitation can be much more serious than when acting alone. His cavitation damage tests in a flowing system demonstrated a considerable reduction in damage when cathodic protection was used. However, later work by Plesset (75) suggested that the damage reduction was actually due primarily to the gas cushioning effect of the hydrogen released at the wall in the electrolytic process. Thus the demonstrated success of cathodic protection may be at least partially evidence of the reduction of damage by gas injection.

III - CONCLUSIONS AND RECOMMENDATIONS

Although obviously much remains to be done before a relatively complete understanding of the effects of air content upon cavitation has been attained, it is possible at this point to formulate certain important recommendations and conclusions. The first of these comes from a consideration of the question of where air content effects are important.

One can conclude from a consideration of all the work reviewed in this report that in general air content has little practical effect upon the overall performance of machines operating well in the cavitating region, but does often have an important effect upon sigma for the initiation of cavitation, in the sense that an increase in air causes an increase in inception sigma. It can thus importantly affect the prediction of inception sigma for a large-scale machine from tests upon a model, if there are differences in water quality with respect to gas content between model test and prototype. Thus gas content is similar to the ordinary "scale effects", in this sense.

Air content can importantly affect the rate of cavitation damage if, as stated above, it determines in some cases the existance or non-existance (and quantity) of cavitation itself. It is also well established that large amounts of air (usually well in excess of the saturation quantity) will substantially reduce cavitation damage, probably because of the reduced violence of bubble collapse if the bubbles in fact contain large amounts of non-condensable gas rather than only vapor.

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

Predictions of gas content effects upon cavitation are not possible if only total gas content (entrained plus dissolved portions) is known. It is necessary to assure water of similar population and size distribution of "nuclei" in addition to similar total gas content if gas content "scale effects" are to be avoided. The desired condition can be attained either by the actual measurement of entrained gas spectra in addition to total gas, or by a "calibration" of the water by a standard cavitating device. Both approaches are presently being pursued, though neither has achieved a fully satisfactory resolution as yet.

A general capability for a fully theoretical prediction of the effects of a known gas content distribution upon a cavitating flow regime, even though badly needed, does not appear to be within the present state of the art, since the general problem involves a two-phase multidimensional turbulent flow. In general, none of these three complicating features can be handled in a practical and feasible fashion even alone. However, more limited analytical approaches can and should be developed to increase understanding of the overall phenomenon and to at least indicate trends to be anticipated. Along this line much has been done and much remains to be done, for example, on the level of individual bubble studies in turbulence, in pressure and velocity gradients, and in multidimensional flow regimes in general.

Another capability which appears essential to the development of an increased ability for the prediction of gas content effects is that of the easy and practical measurement of the population, location, and size distribution of entrained gas nuclei in a flowing system. A partially alternative, but certainly complementary capability, is that for the "calibration" of the fluid using a standard cavitating device. Though this would not provide direct knowledge of the gas content distributions, it would allow the performance of model tests without air content "scale effects".

In conclusion, it appears from all the foregoing work that only rather vague guidelines can be drawn concerning the quantitative effects of gas content either upon inception sigma or damage rate for a condition as yet untested. However, fairly firm qualitative results can be utilized, which are consistent both with the experimental and theoretical studies previously discussed, and the applicable physical laws. Such hypothetical curves for both inception sigma and damage rate are shown in Fig. 25 (a and b). The curve for inception sigma (Fig. 25-a) is based upon the fact that for extremely low gas contents the tensile strength of the fluid becomes appreciable, and for very large gas contents, a large liquid pressure is required to prevent explosive growth of the gas bubbles, i.e., gaseous cavitation is encountered. The same concept leads also to the damage curve (Fig. 25-b) in that in a typical case no cavitation would occur if the gas content were indeed extremely low, since insufficient nuclei would exist. For somewhat higher gas content, the nuclei population would approach sufficiency, so that a further increase in gas content would not appreciably increase the number of cavitation bubbles and hence damage through this mechanism. For still larger quantities of gas, the gas cushioning effect upon collapse would become over-riding, and damage would decrease. The typical values shown in both curves (Fig. 25) are based upon the experimental results already discussed in the report.

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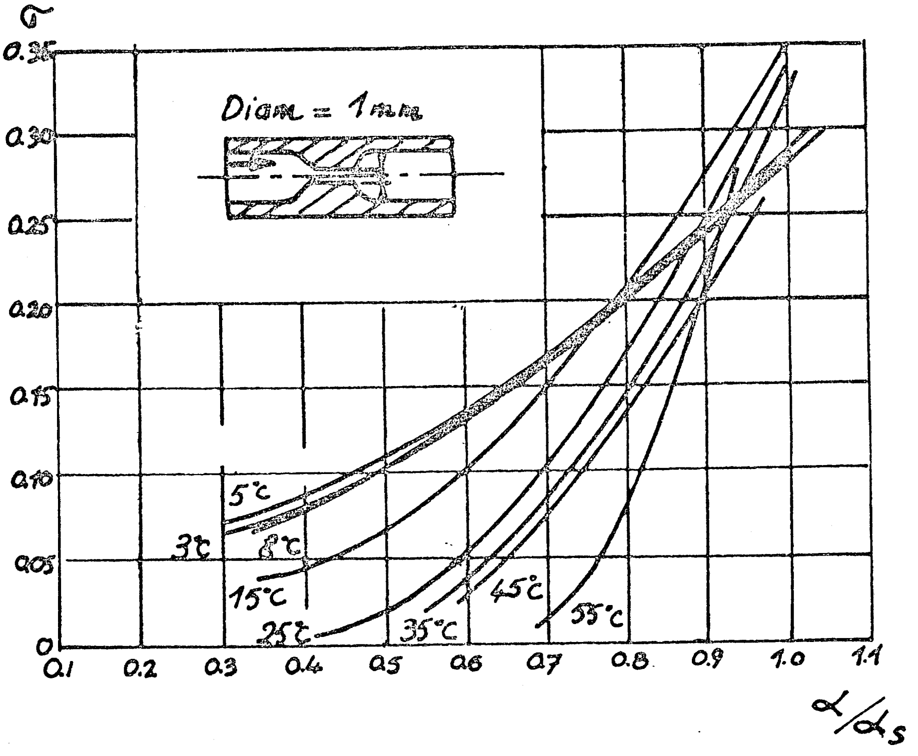

Fig. 1 Cavitation Inception Sigma in Venturi as Function of Relative Air Content Compared to Saturation at STP, Numachi Data (3 - 6).

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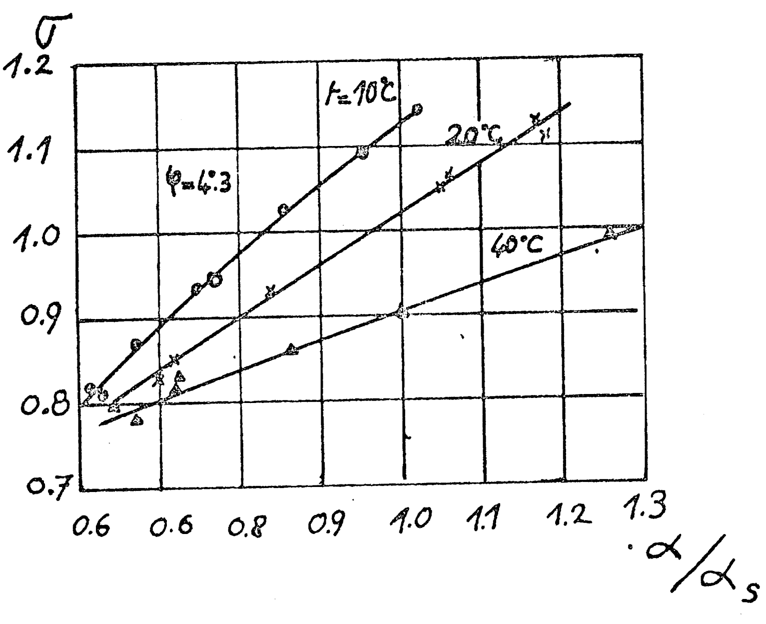

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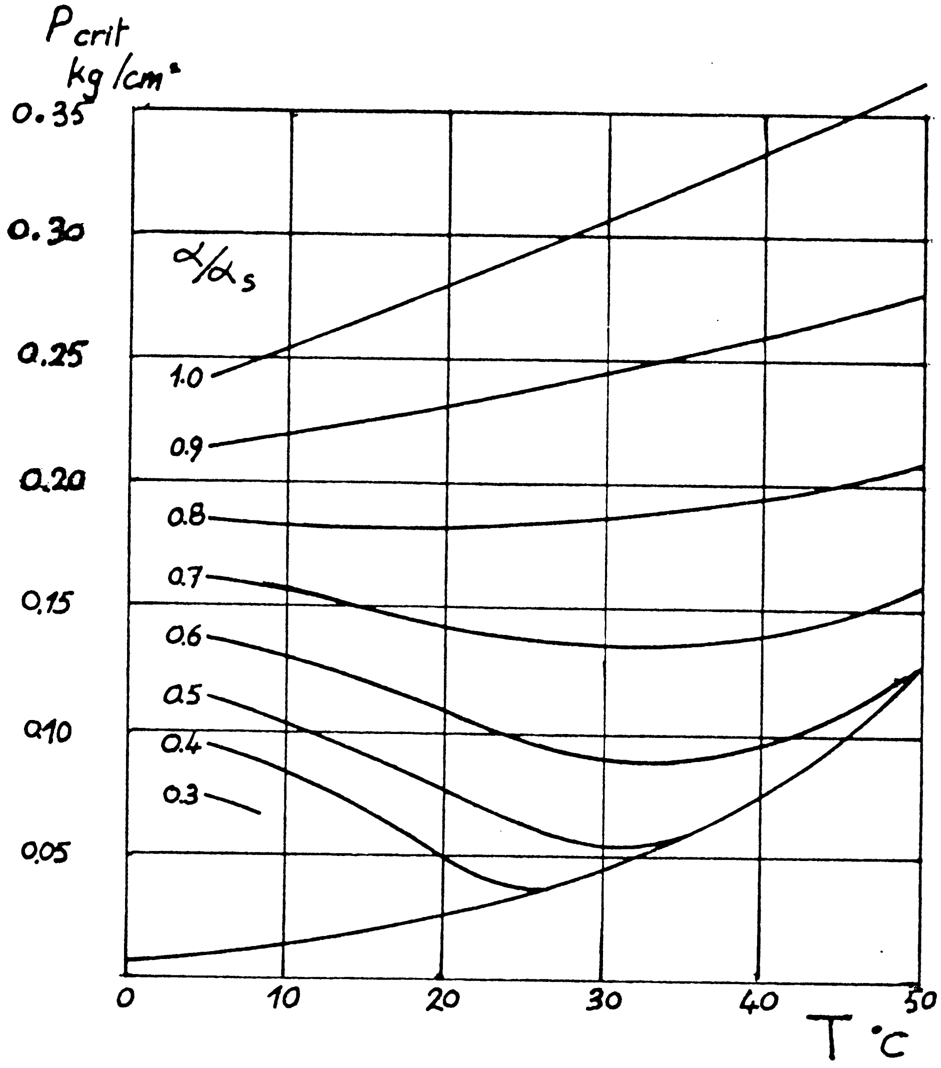

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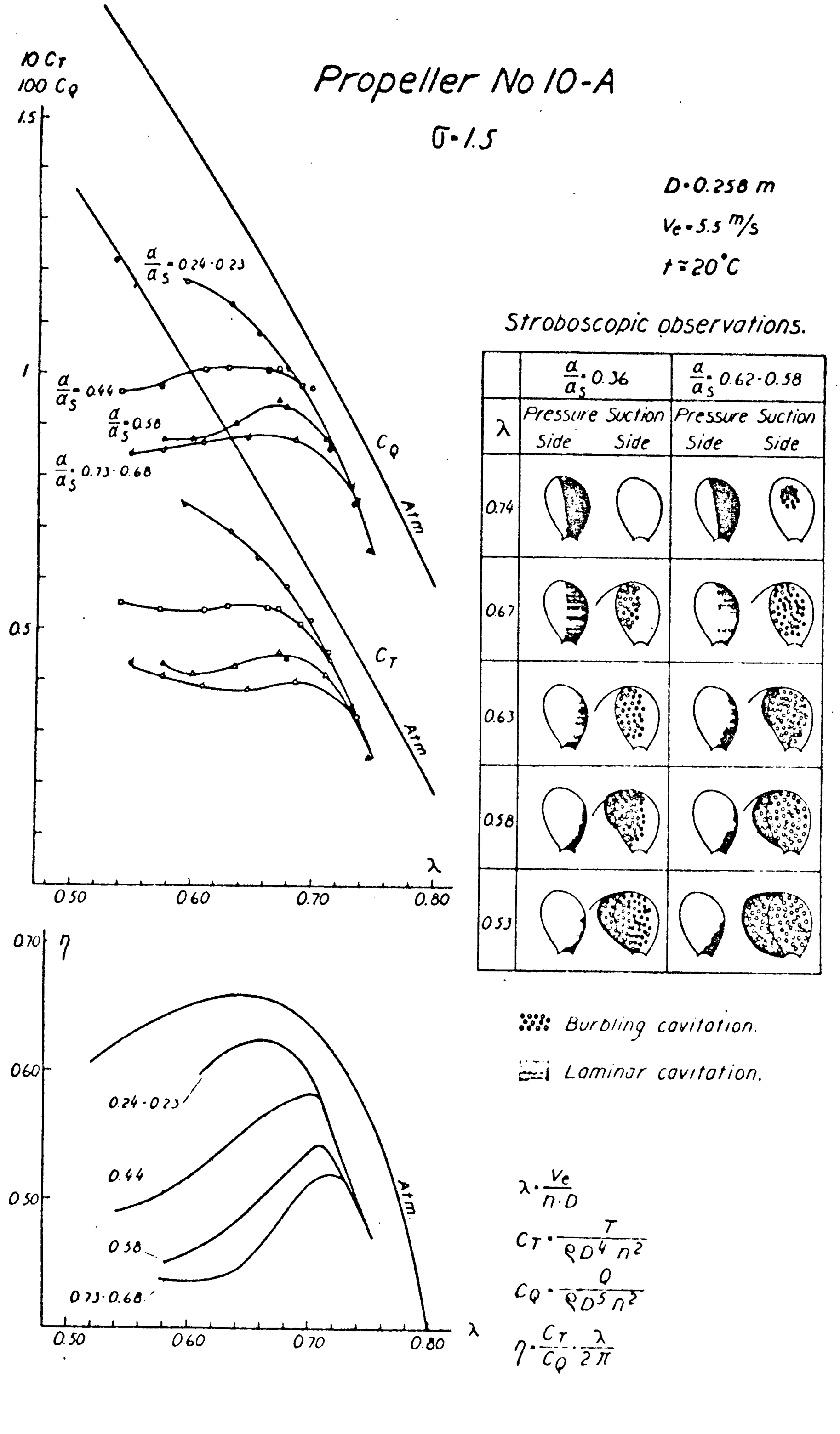

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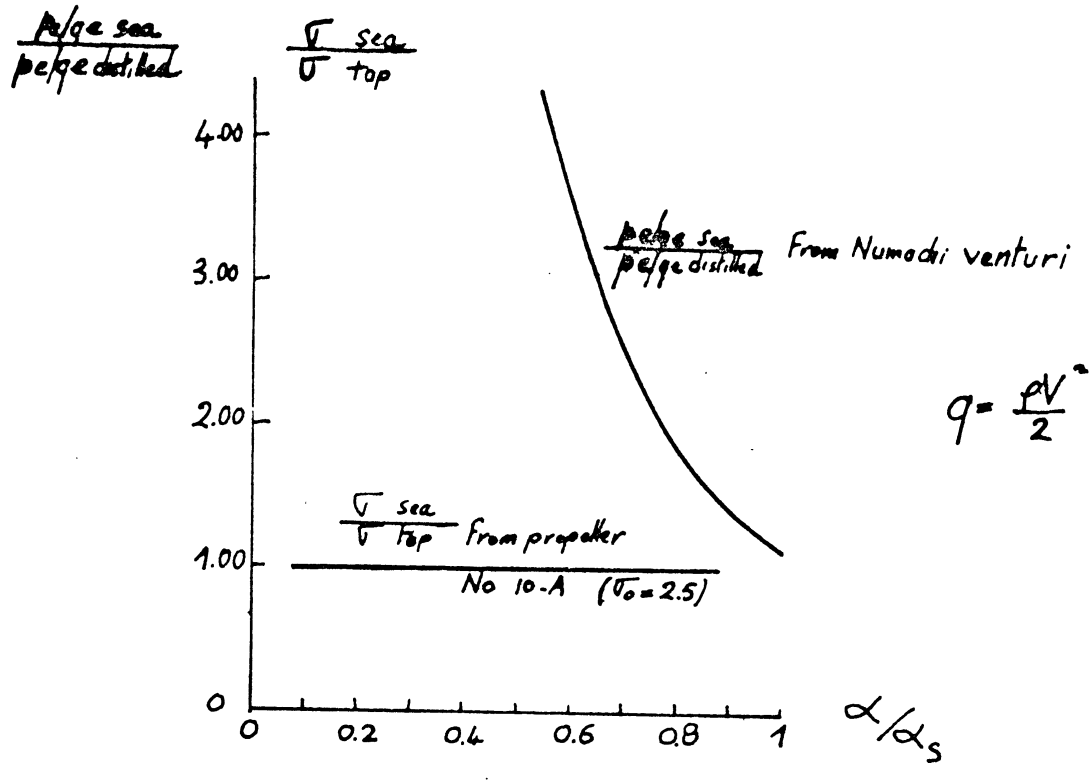

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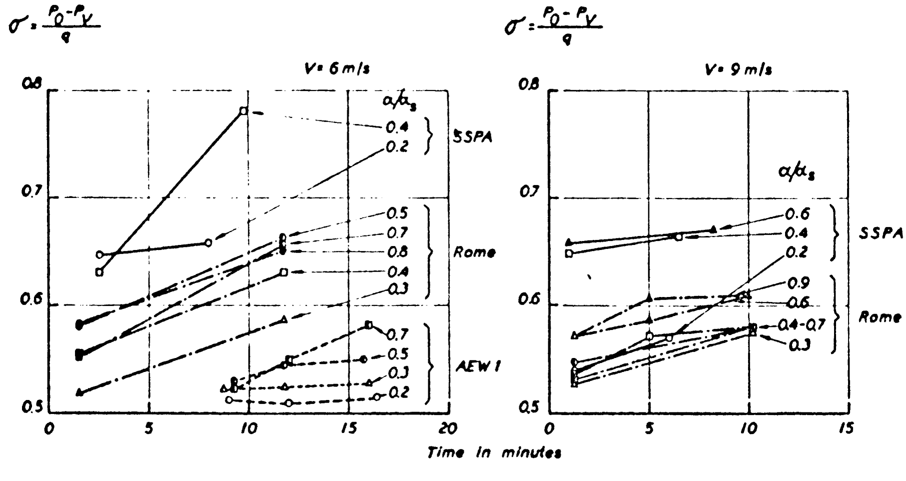

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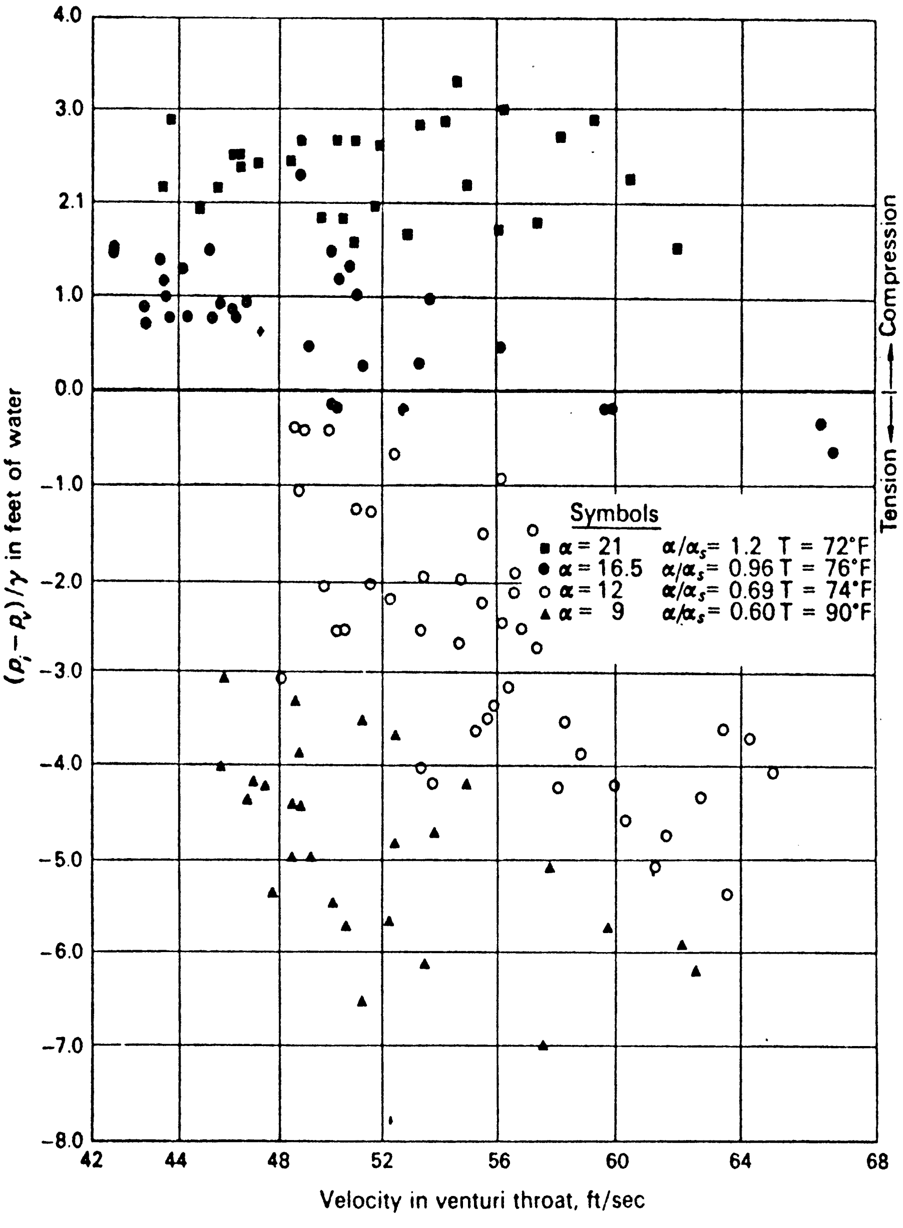
L'effet du taux de réduction de la pression sur le σ de début pour des teneurs en air différentes, Lindgren et Johnson (10).



a = absolute air content (mm /liter)
corrected to standard temperature and pressure
a_s = saturation air content (mm /liter)
corrected to standard temperature and pressure

Fig. 7 Effect of Relative Air Content on Pressure at Inception of Cavitation in Venturi, Crump (12 and 13).

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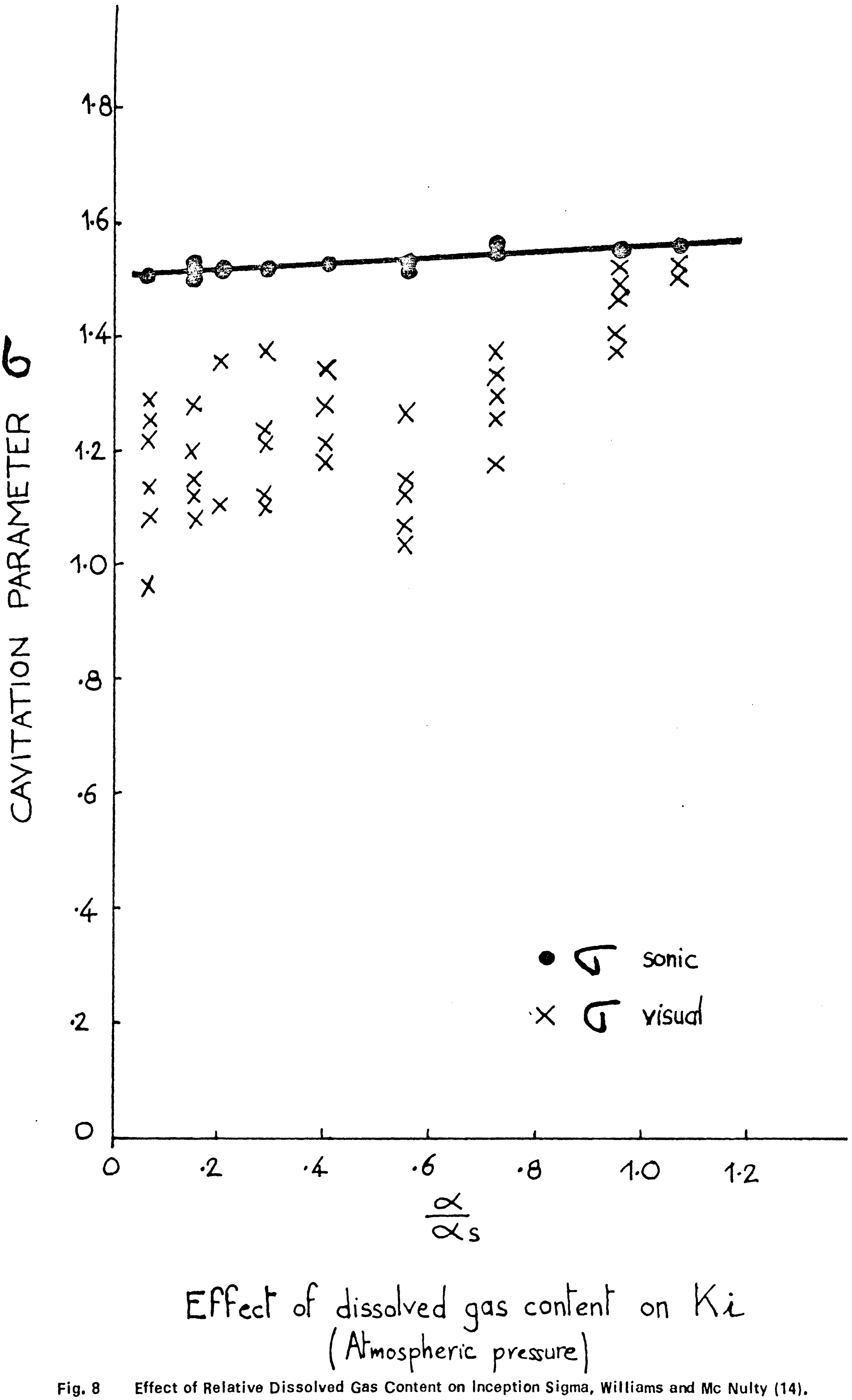

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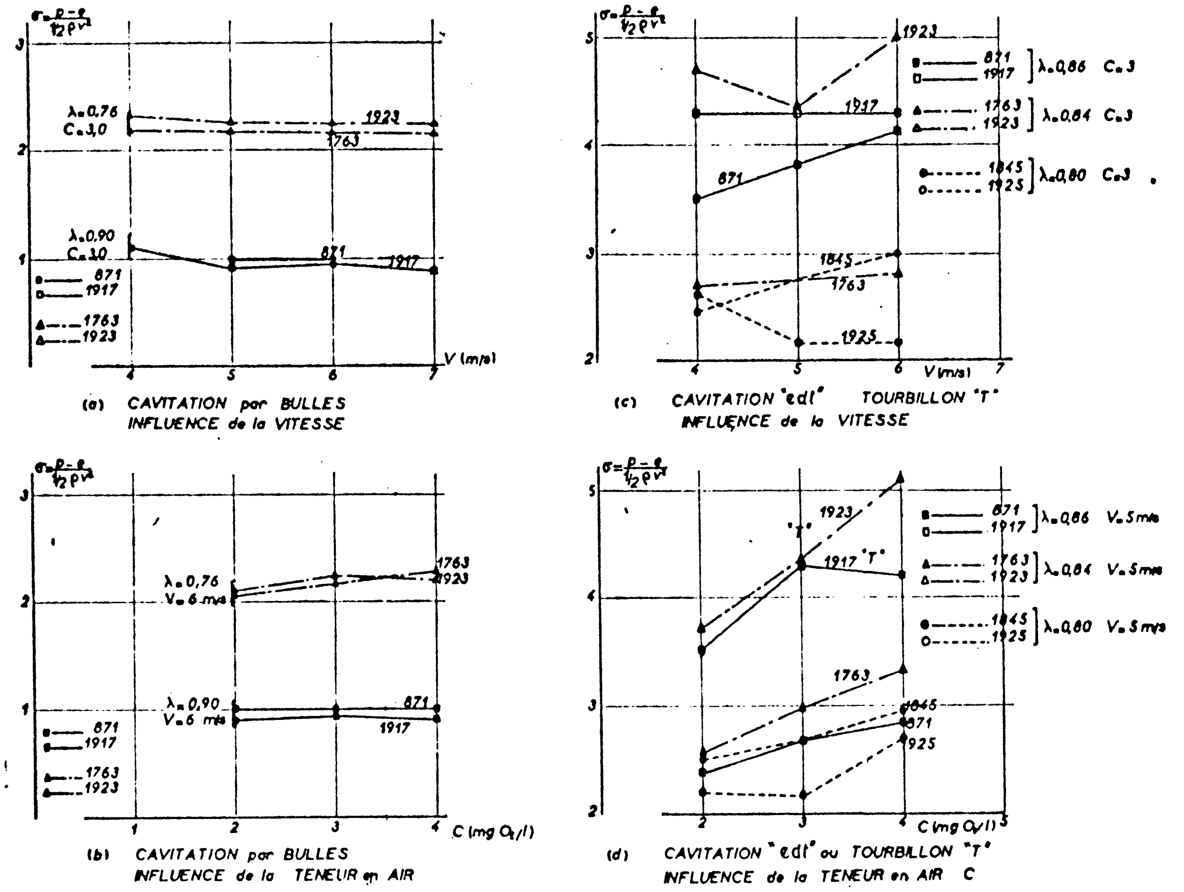


FIG. (*a* et *b*). — Hélices : Effet d'échelle.

FIG. (*c* et *d*). — Hélices : Effet d'échelle.

Types de cavitation observés.

Fig. 9 Types of Cavitation Observed on Propellors and Effects of Oxygen Content and Velocity on Inception Sigma, Bindel and Riou (27).

Les types de cavitation observés pour les hélices, et les effets de la teneur en oxygène et la vitesse sur le σ de début, Bindel et Riou (27).

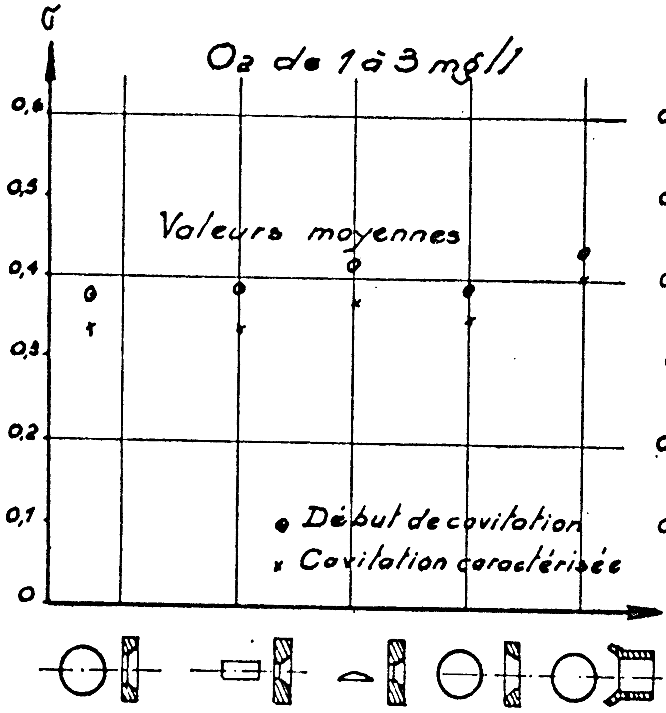


Fig. a — Influence de la forme de jet et de la buse.

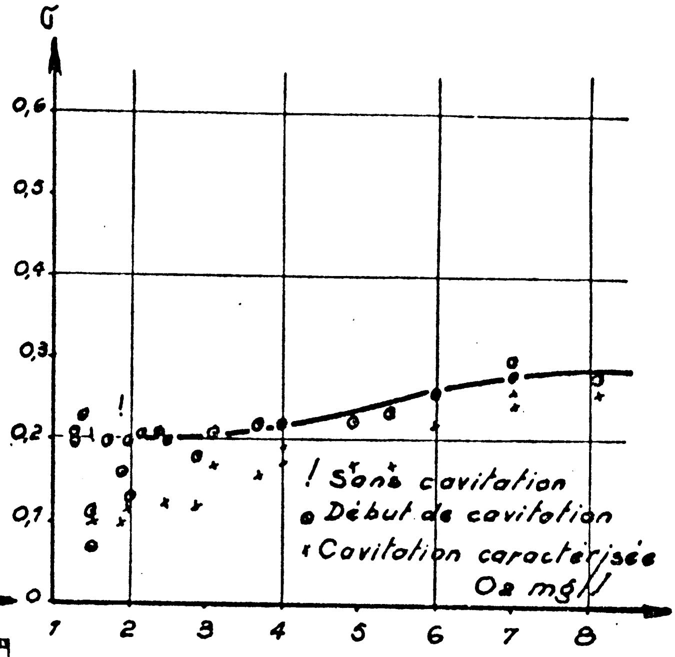


Fig. c — Influence de O_2 (Veine de référence).

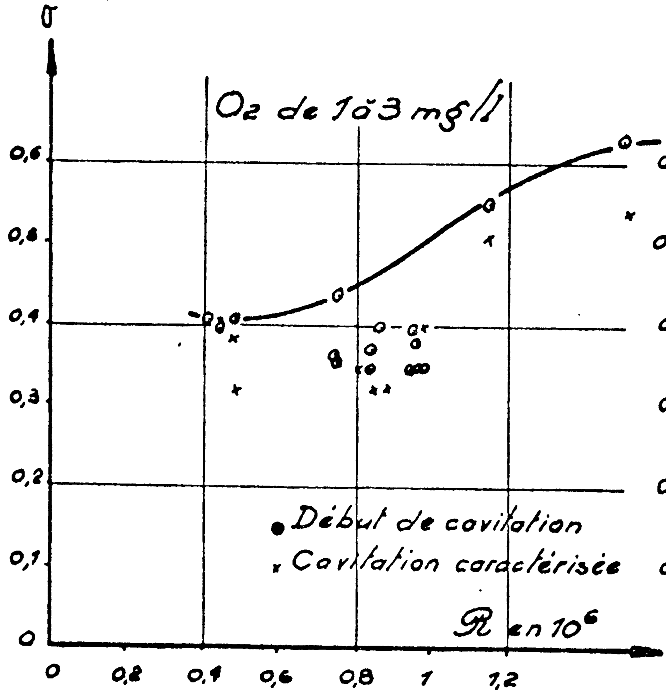


Fig. b — Influence du nombre de Reynolds (Diaphragme circulaire).

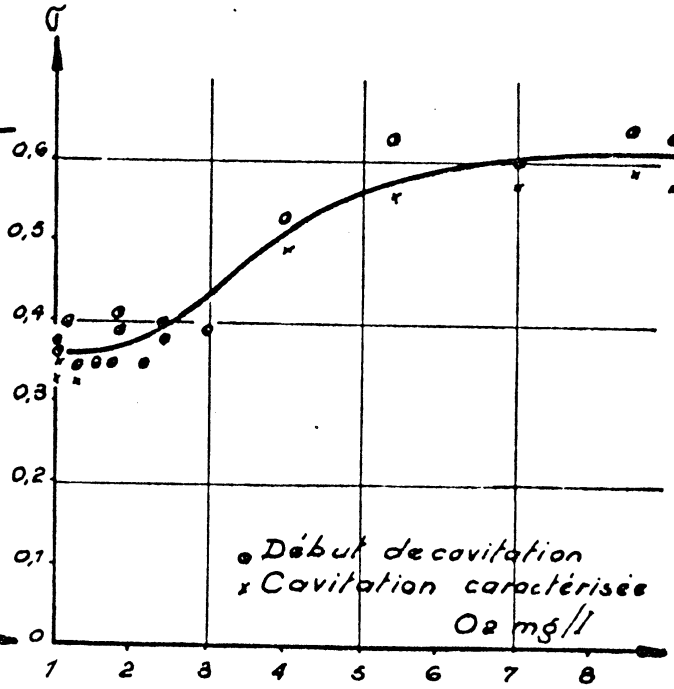


Fig. d — Influence de O_2 (Diaphragme circulaire).

Fig. 10 Influence of Oxygen Content and Reynolds Number for Various Orifice Shapes on Inception Sigma, Duport (34).

Les effets de la teneur en oxygène et le nombre de Reynolds sur le σ de début pour des types d'orifices différents, Duport (34).

ORIFICE CAVITATION

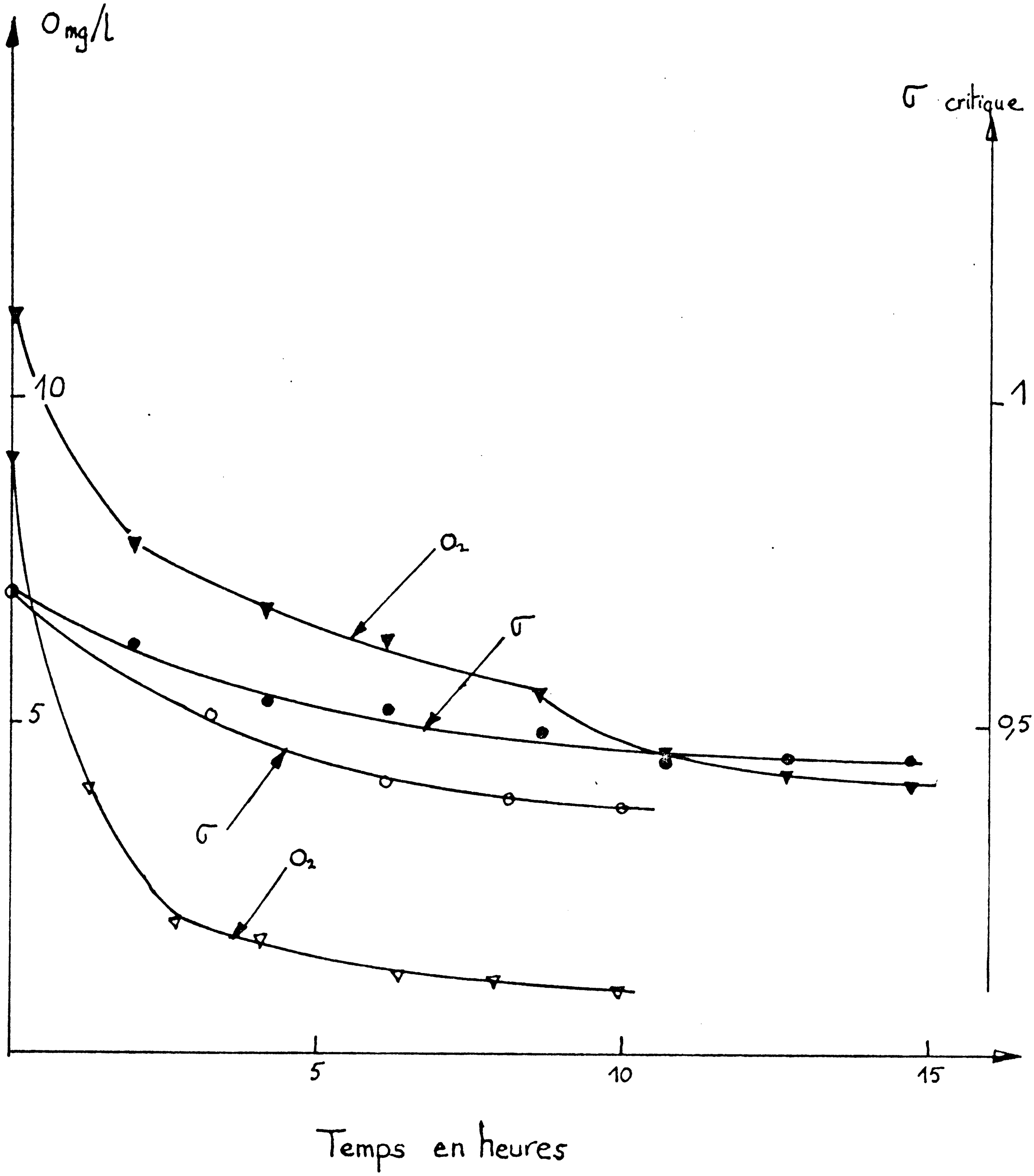
– circuit initial –

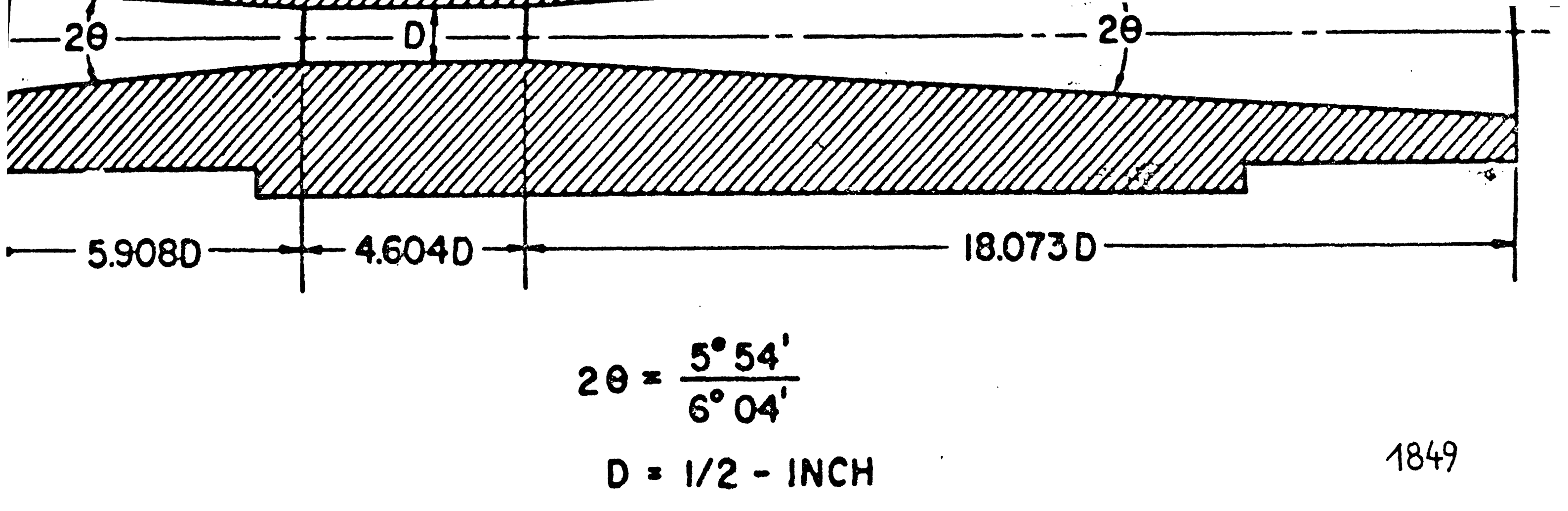
– Fig. 11 –

INFLUENCE DU DEGAZAGE

sur σ critique et la teneur en oxygene (mg/L)

▽ ○ degazage avec $h_3 = 0{,}7$ m d'eau
▼ ● degazage avec $h_3 = 5$ m d'eau





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Dessin de venturi de l'Université de Michigan (1/2 pouce col), Hammitt, etal (42).

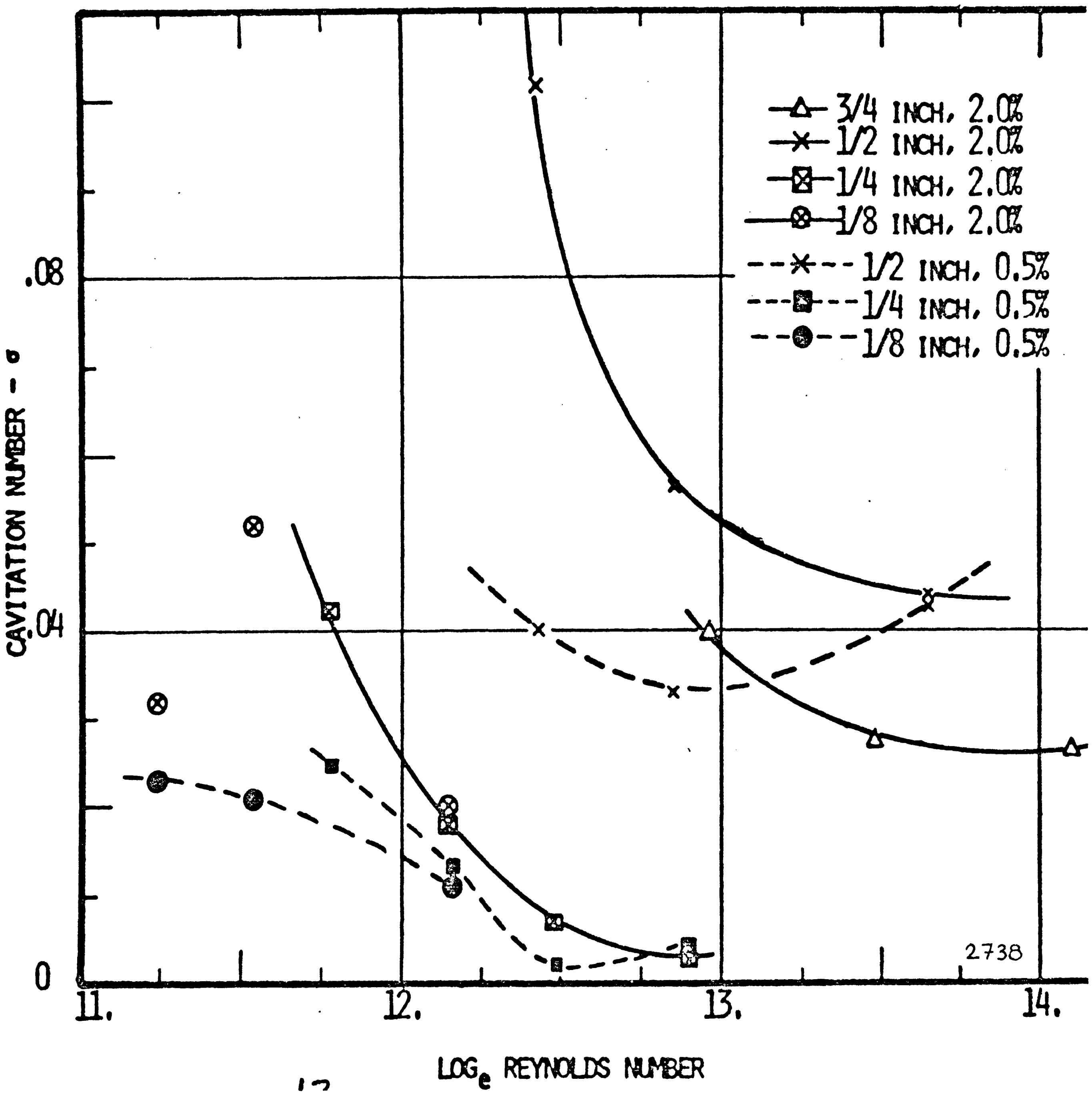


Fig. 12-b Inception Sigma vs. Reynolds Number, University of Michigan Venturis (1/8 to 3/4 inch throats), Hammitt, etal (42).

Le σ de début en fonction du nombre de Reynolds en venturi, Université de Michigan (1/8 - 3/4 pouce cols), Hammitt, etal (42).

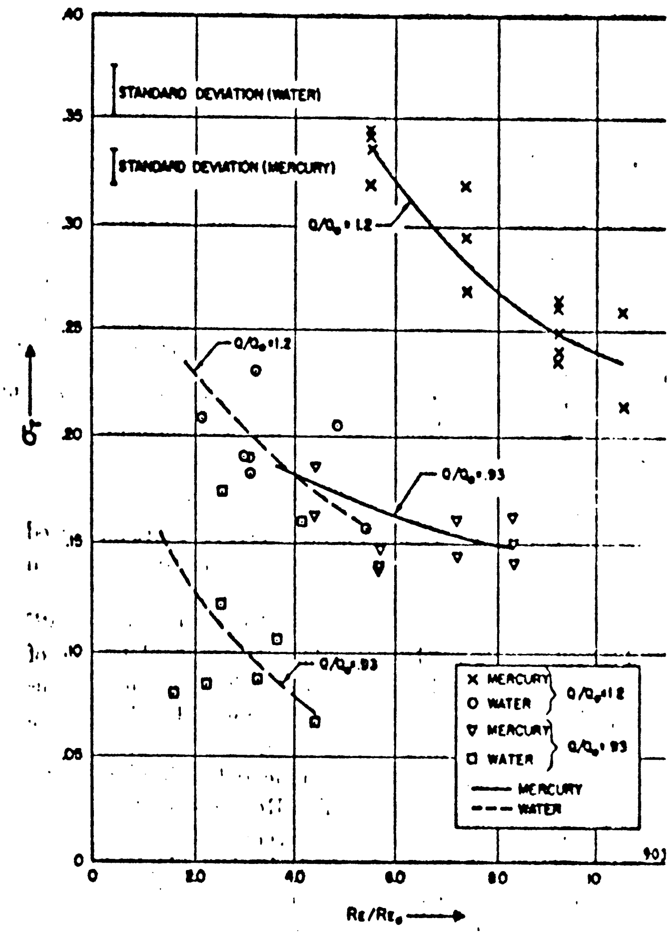


Fig. 13 Centrifugal Pump Performance - Thoma Cavitation Number vs. Normalized Reynolds Number for Water and Mercury as Pumped Fluids ; Pump Specific Speed about 720 in English Units, Hammitt (44).

La performance d'une pompe centrifuge - Nombre de cavitation de Thoma en fonction du nombre de Reynolds normalisé pour l'eau et le mercure (Vitesse spécifique de pompe est ~ 720 en unités anglaises), Hammitt (44).

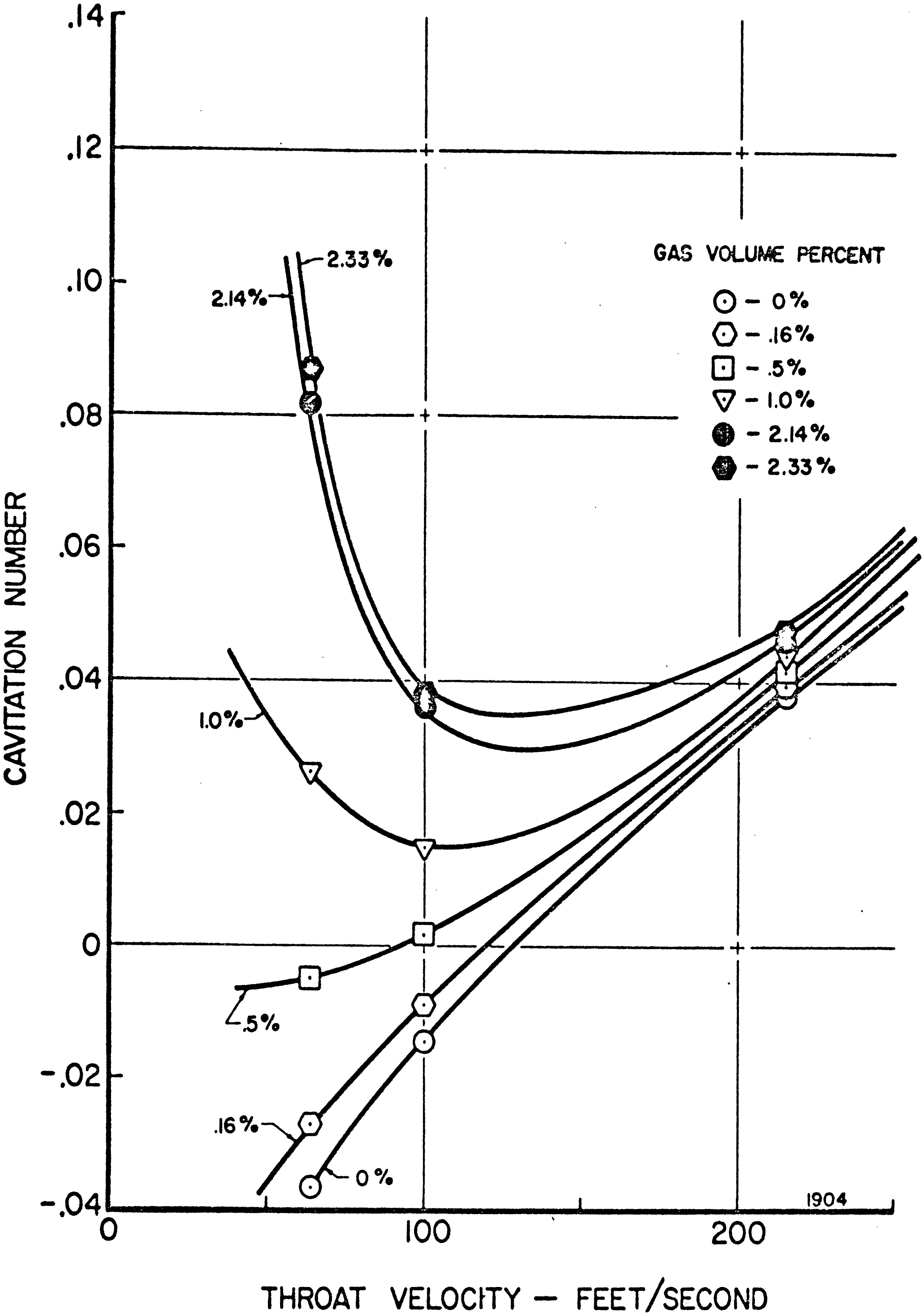


Fig. 14 Cavitation Inception Sigma vs. Throat Velocity - 1/2 inch Venturi, Hammitt, etal (42).

Le σ de début de cavitation en fonction de la vitesse au col d'un venturi de 1/2 pouce, Hammitt, etal (42).

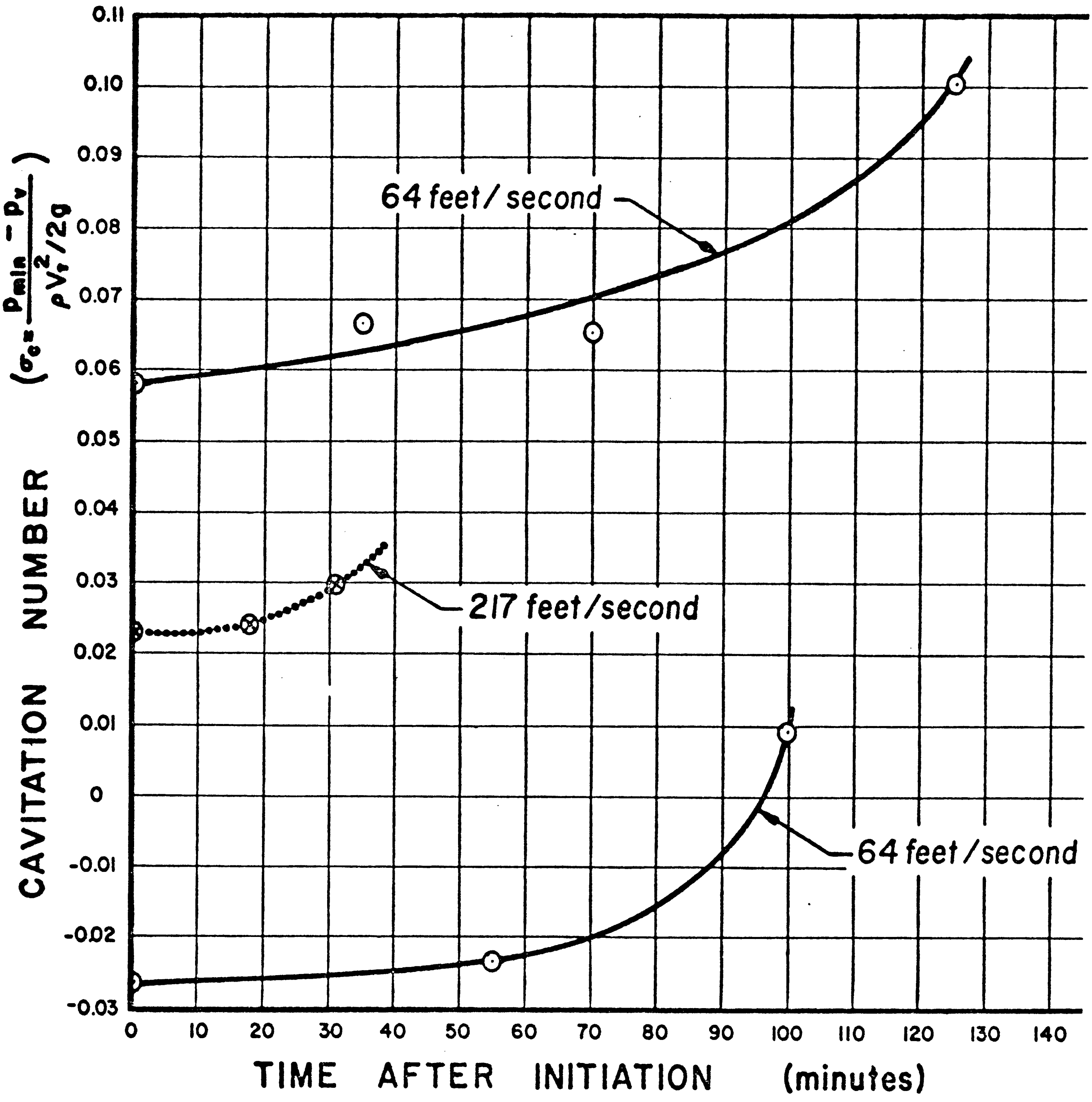


Fig. 15 Prepressurization Effects on Cavitation Sigma, 1/2 inch Venturi, Hammitt, etal (42).

Les effets de la pré-pression sur le σ de début de venturi de 1/2 pouce col, Hammitt, etal (42).

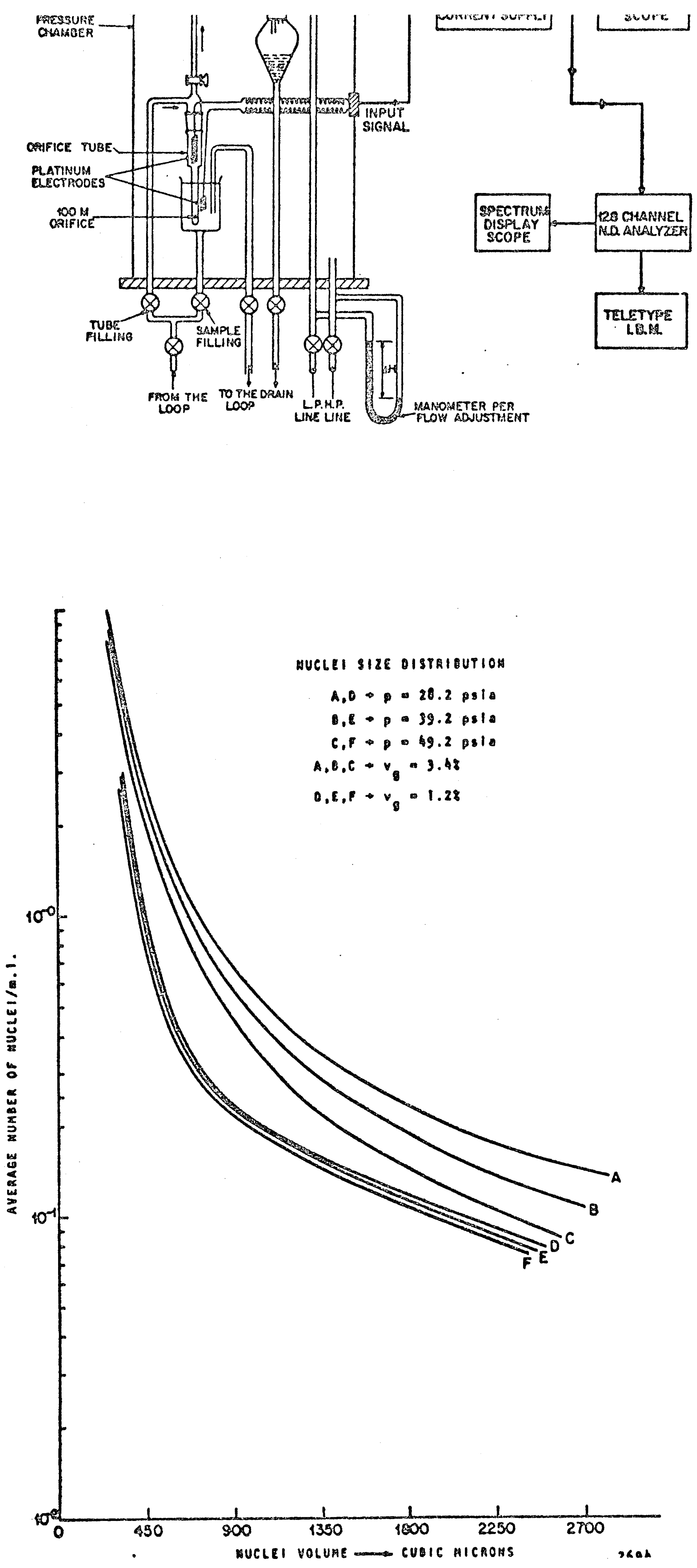


Fig. 16 University of Michigan Coulter-Counter, Schematic Diagram and Nuclei Size Spectrum, Ahmed and Hammitt (43).

Coulter-Counter de l'Université de Michigan, un schéma et la répartition des germes, Ahmed et Hammitt (43).

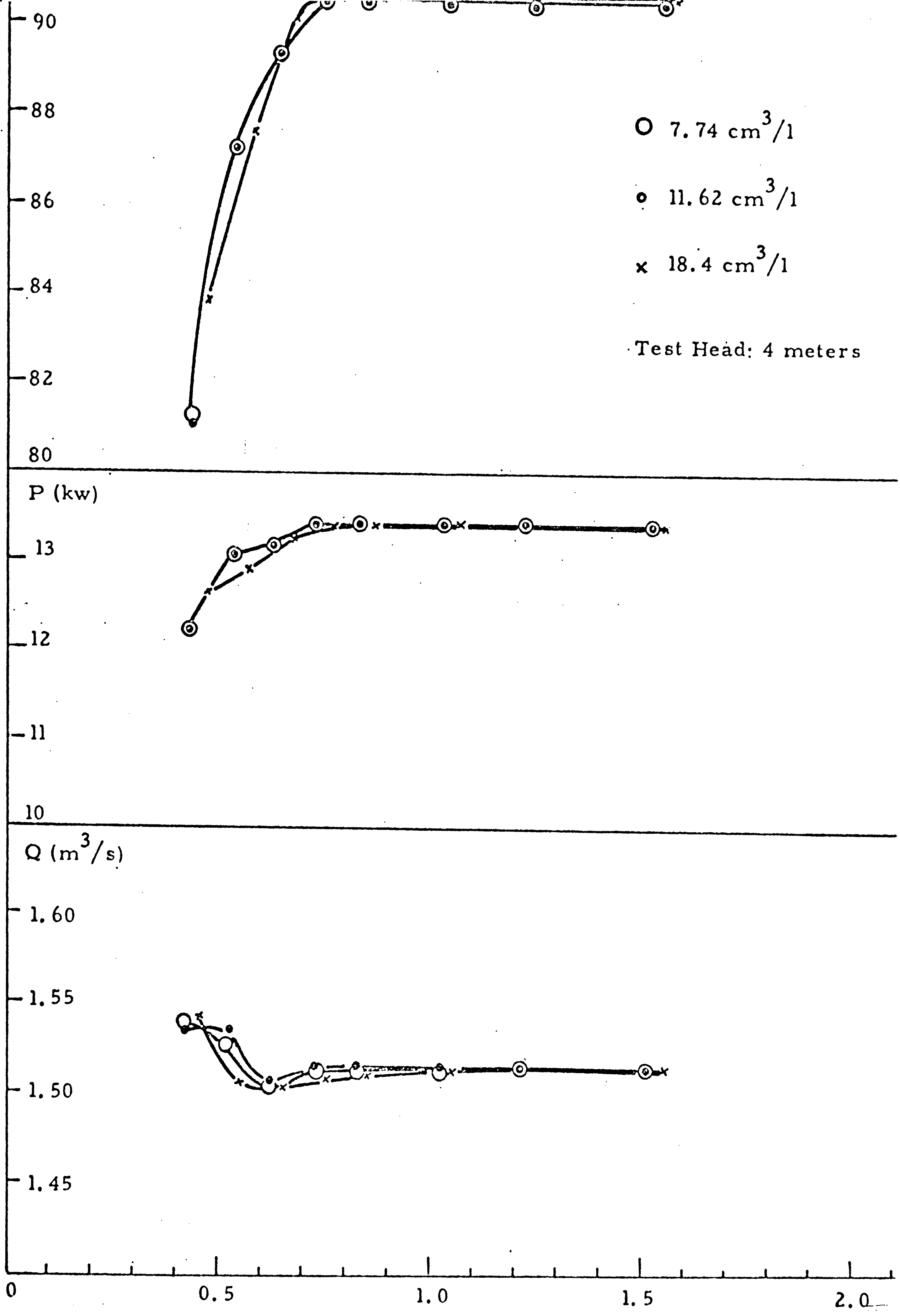


Fig. 17 Air Content Effects on Kaplan Turbine, Fallström (45).

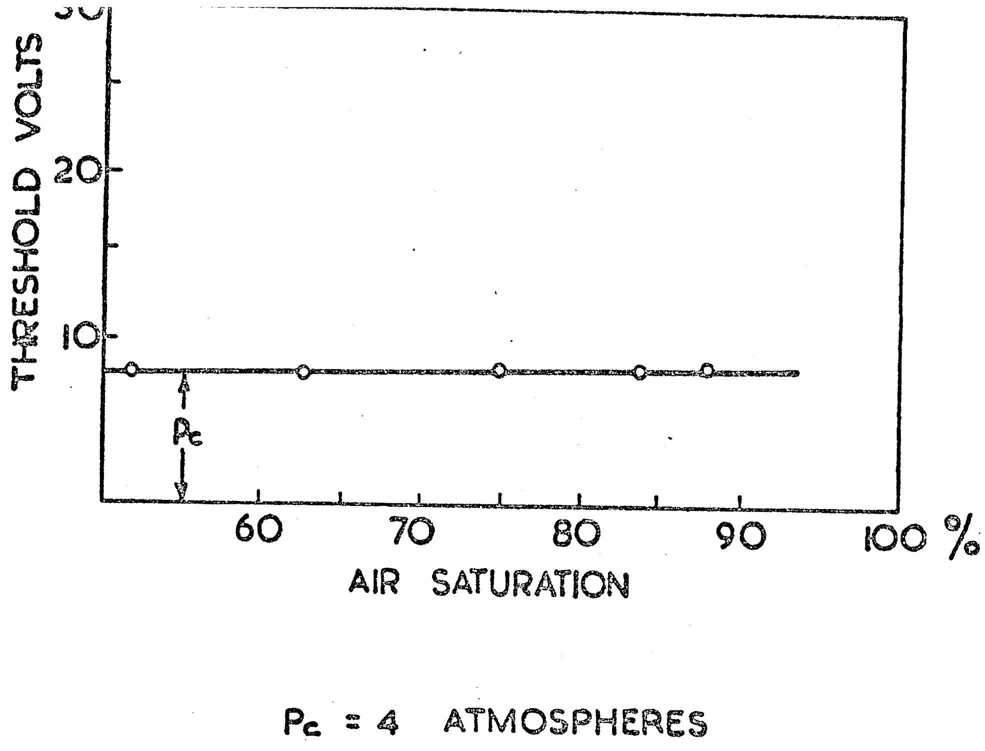


Fig. 18 Effects of Air Content on Ultrasonic Cavitation in Static System, Iyengar and Richardson (61).

Les effets de la teneur en air sur la cavitation ultrasons en système statique, Iyengar et Richardson (61).

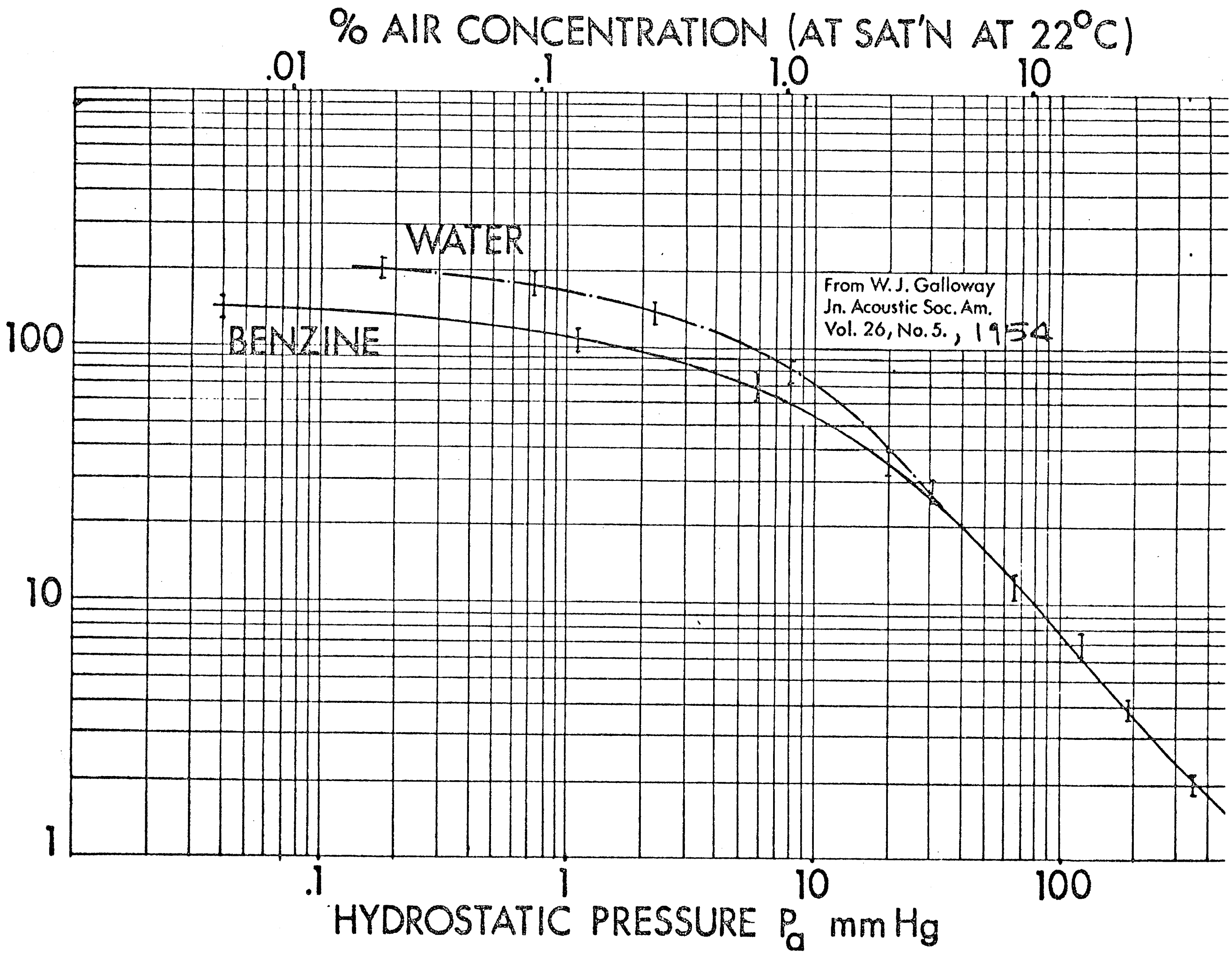


Fig. 19 Cavitation Threshold of Water and Benzine as Function of Relative Air Content (Compared to STP), Galloway (49).

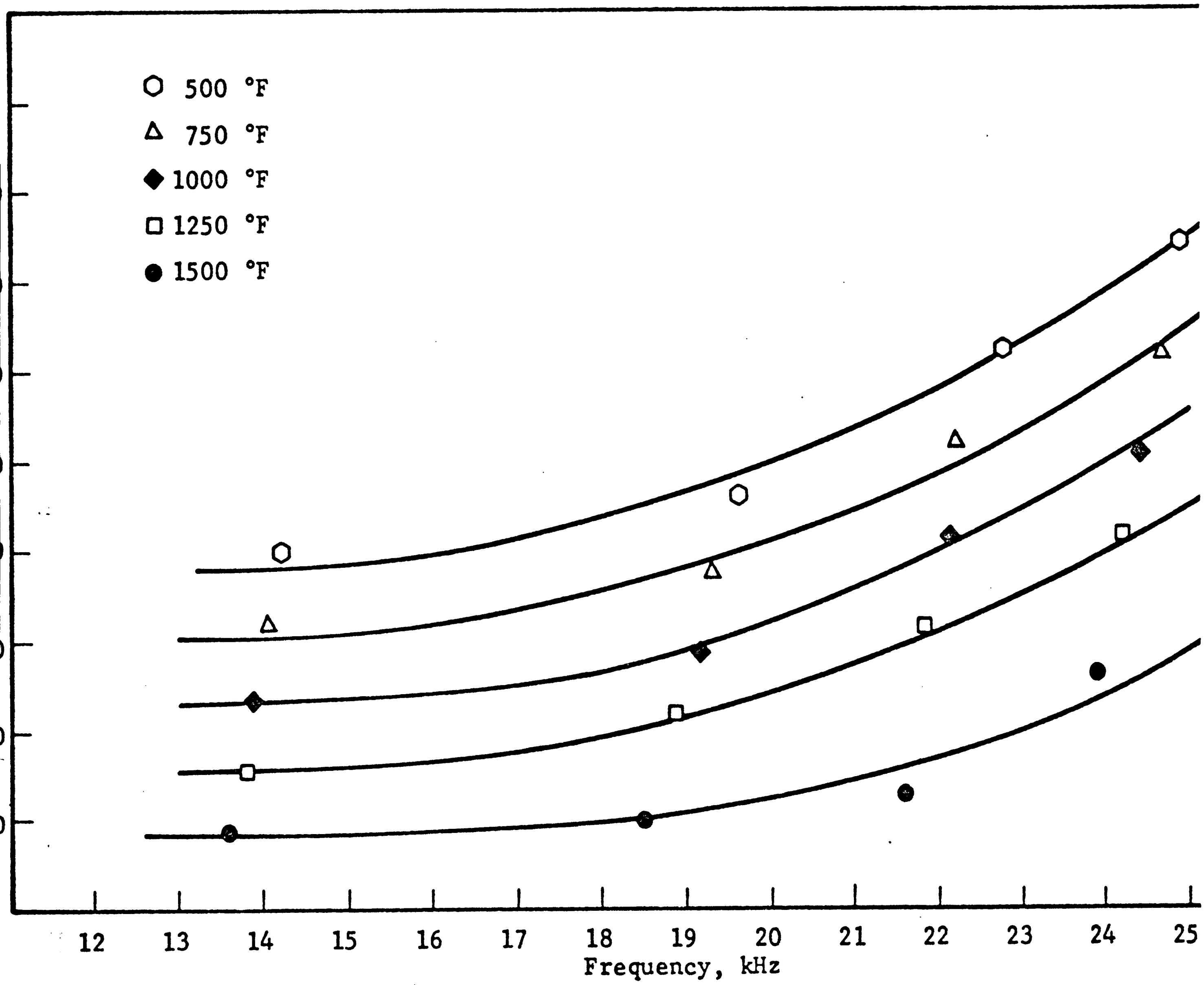


Fig. 20 Sinusoidal Pressure Amplitude for Cavitation Inception vs. Frequence for Liquid Sodium Temperatures of 500 - 1500 F, Nystrom and Hammitt (56).

L'amplitude de pression oscillante de début de cavitation en fonction de la fréquence pour le sodium liquide et pour des températures entre 500 et 1500°F, Nystrom et Hammitt (56).

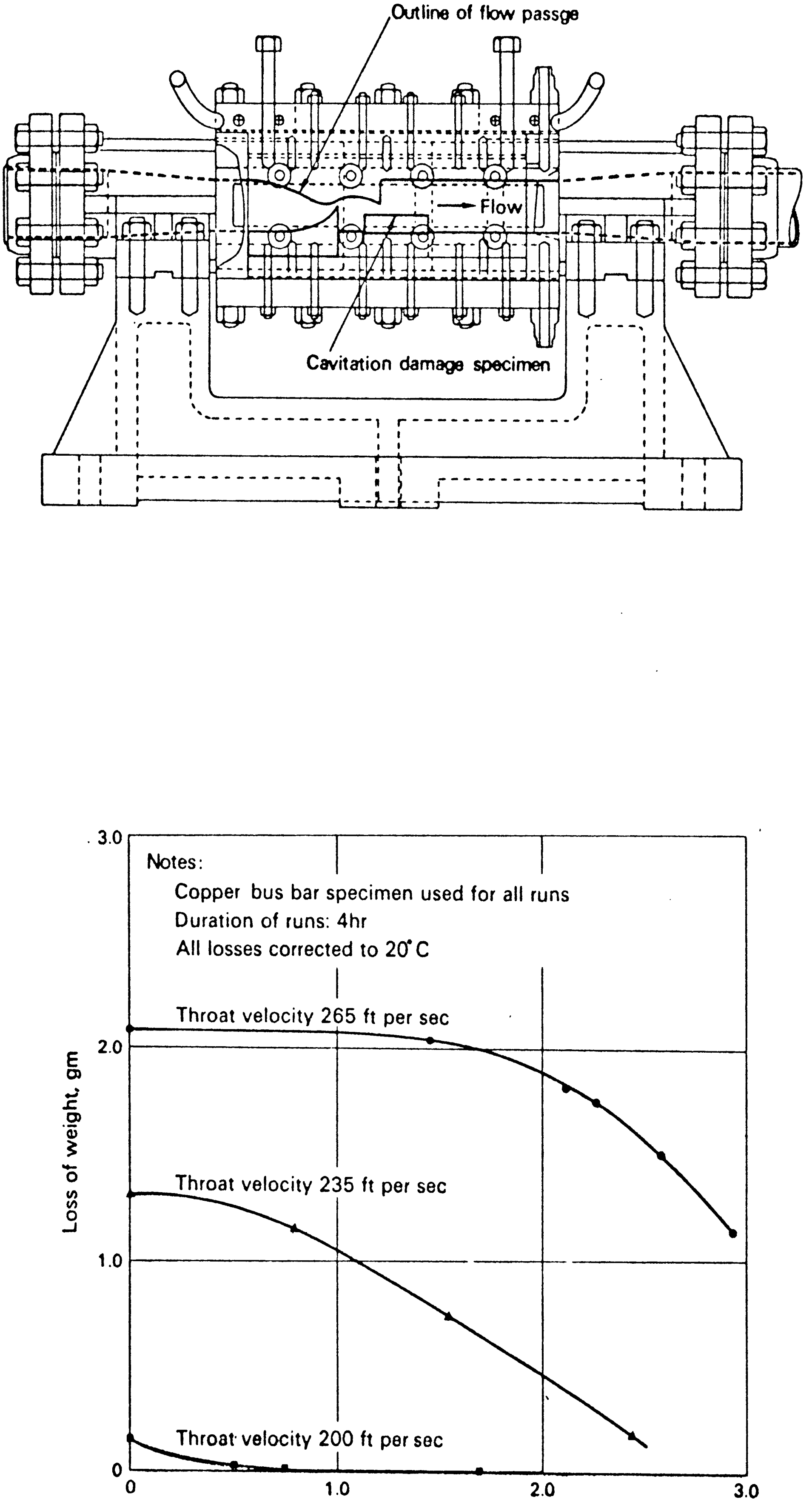


Fig. 21 Effects of Air Injection Upon Cavitation Damage in Venturi, Mousson (67).

Les effets de l'injection de l'air sur l'érosion de cavitation en venturi, Mousson (67).

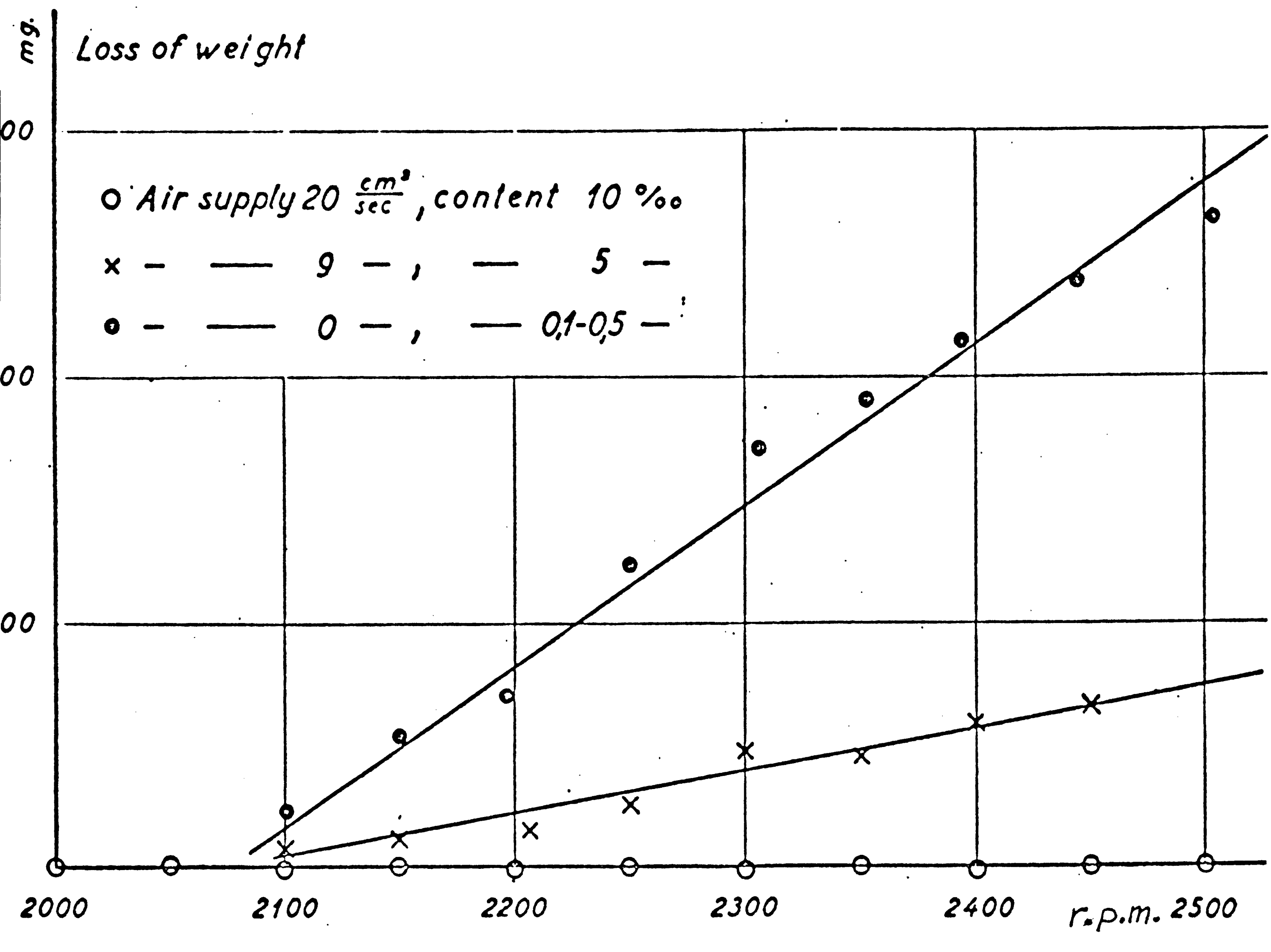


Fig. 22 Effects of Air Content Upon Cavitation Damage in Rotating Disc Apparatus, Rasmussen (68, 69).

Les effets de la teneur en air sur l'érosion de cavitation en disque tournant, Rasmussen (68, 69).

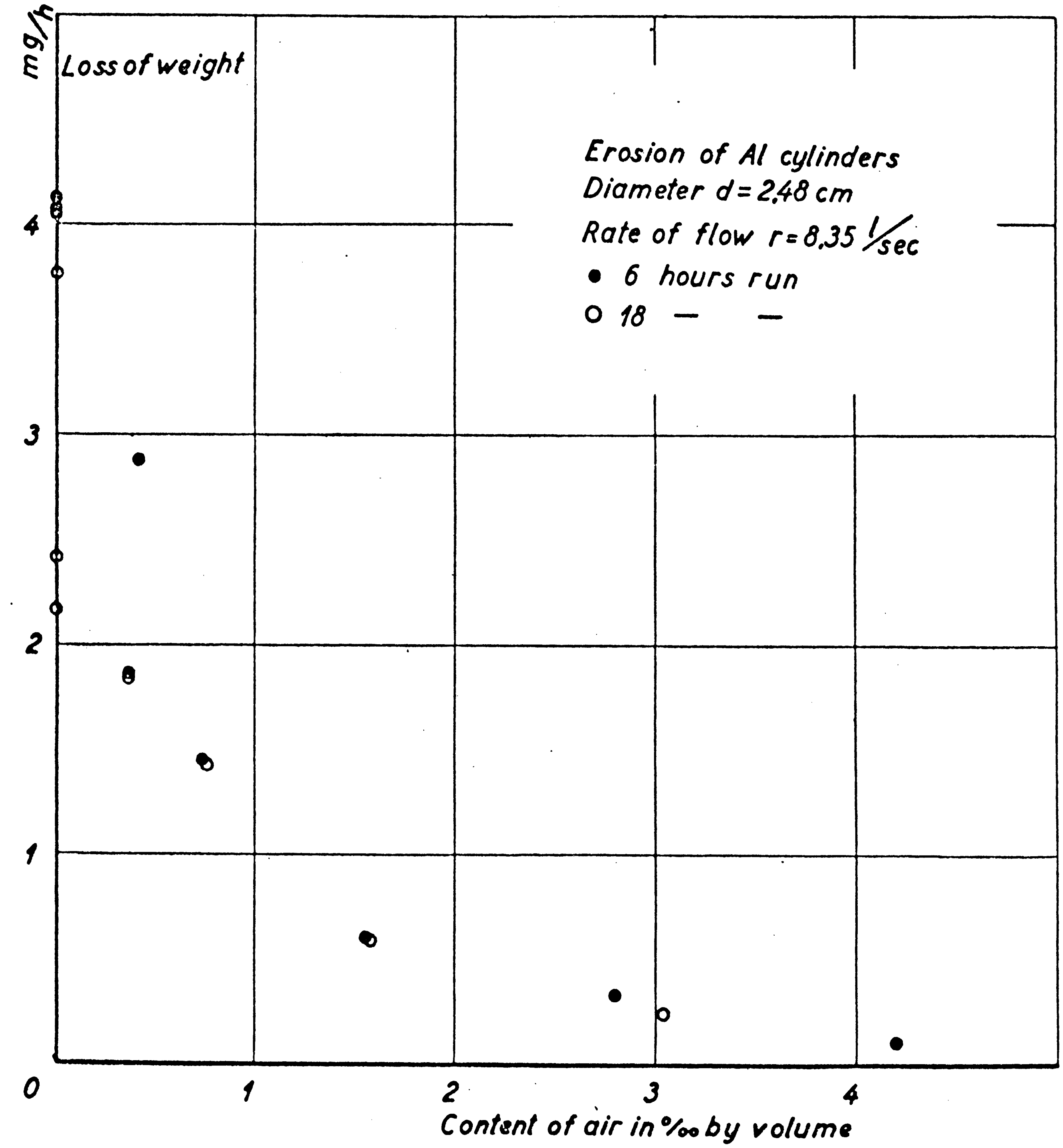


Fig. 23 Effects of Air Content Upon Cavitation Damage in Venturi Upon Aluminum Alloy, Rasmussen (68,69).

Les effets de la teneur en air sur l'érosion de cavitation en venturi sur un alliage d'aluminium, Rasmussen (68, 69).

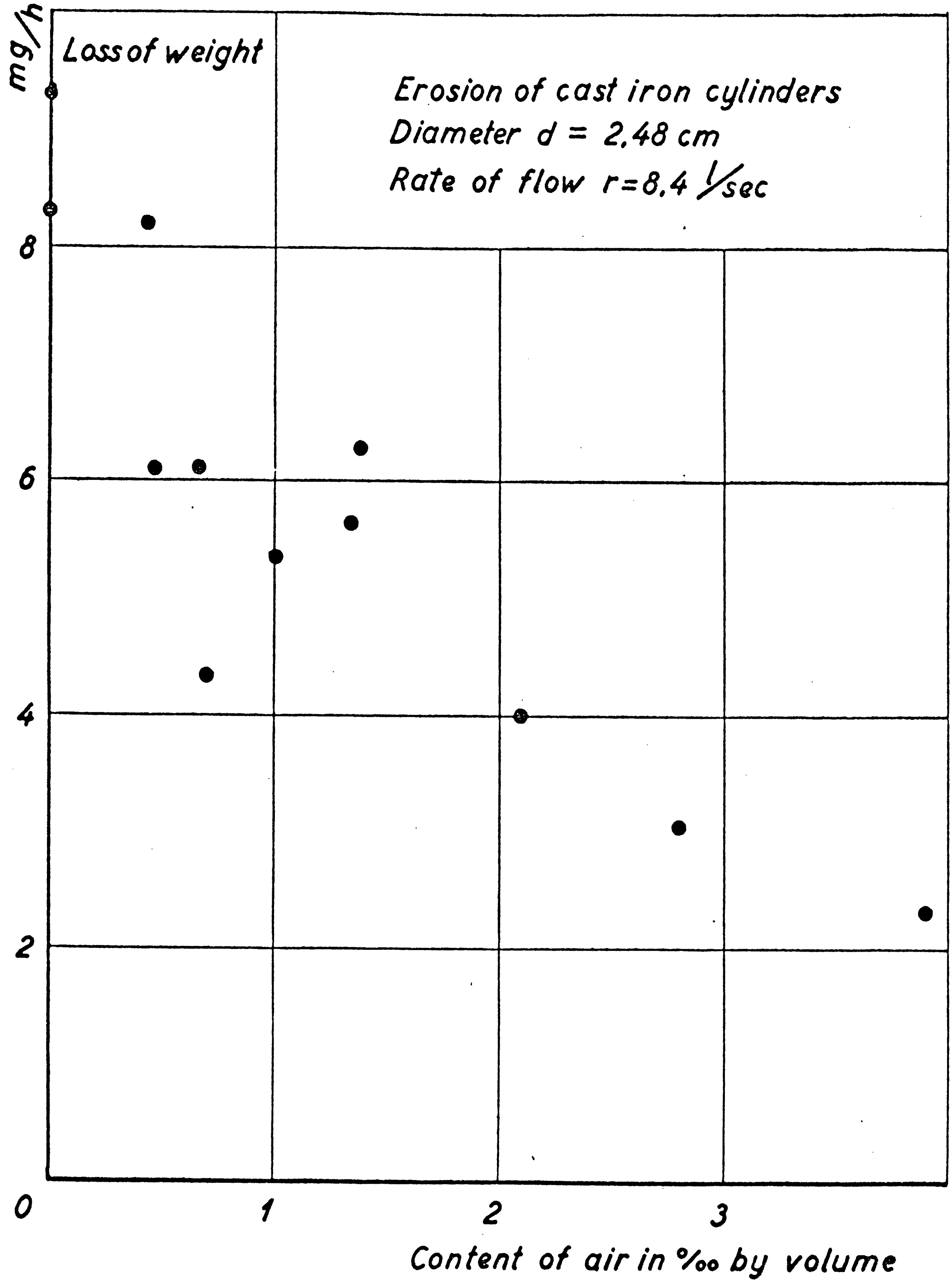
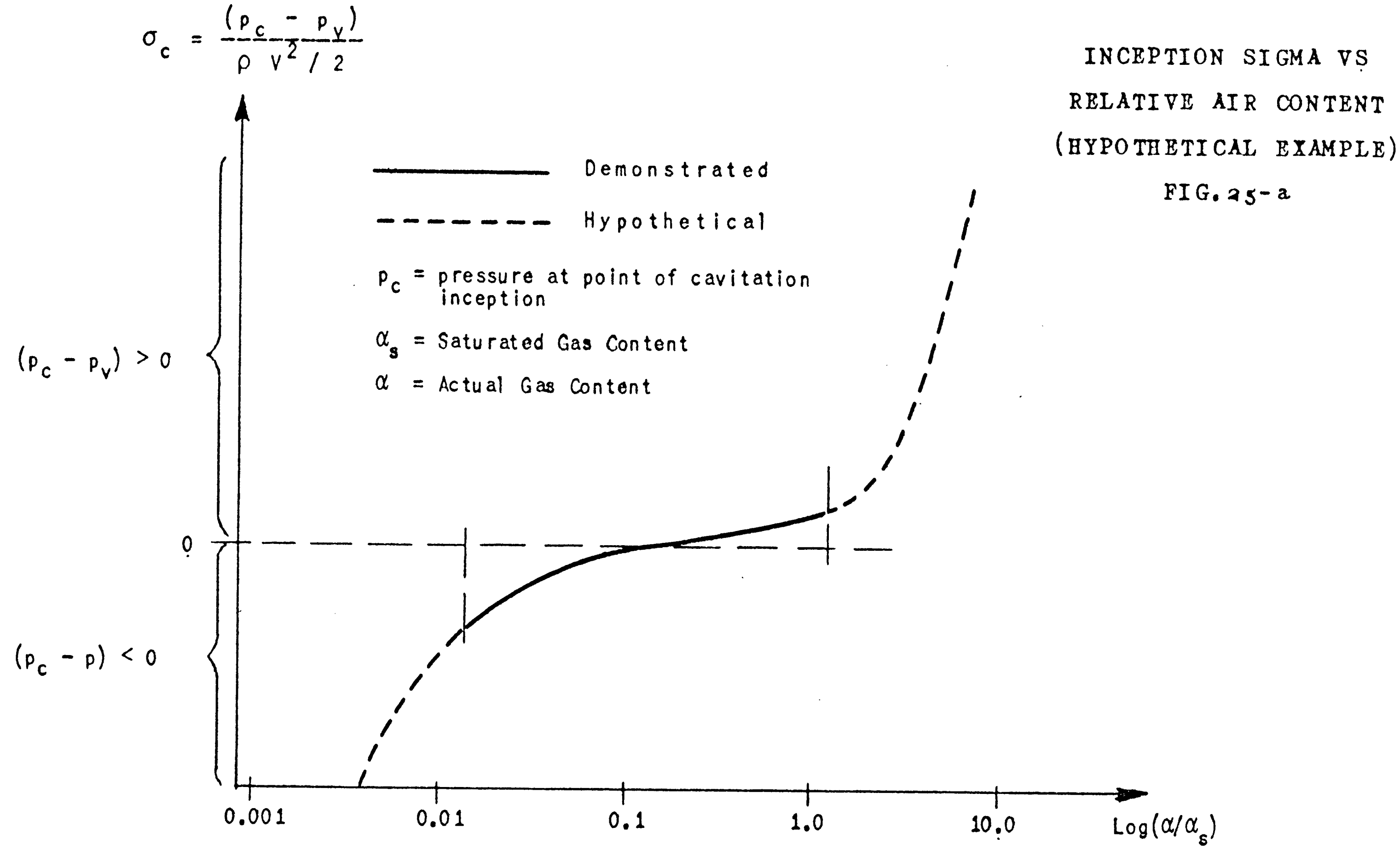


Fig. 24 Effects of Air Content Upon Cavitation Damage in Venturi Upon Cast Iron, Rasmussen (68, 69).

Les effets de la teneur en air sur l'érosion de cavitation en venturi sur la fonte, Rasmussen (68, 69).



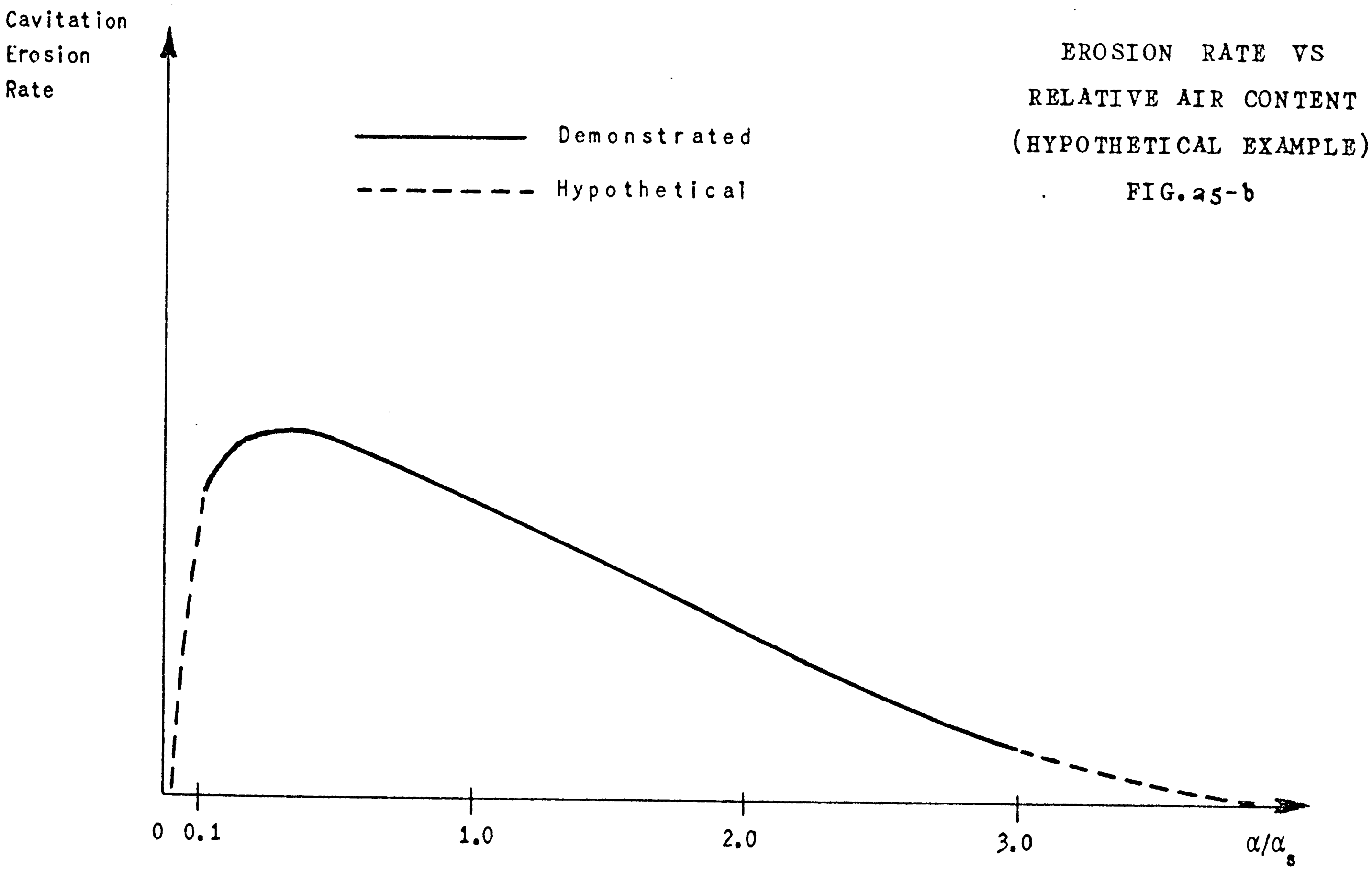


Fig. 25 - Hypothetical Overall Dependence of Inception Sigma and Erosion Rate on Relative Air Content

σ et taux d'érosion en fonction hypothétique de la teneur en air