SESSION ON PROPULSION
CAVITATION

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Discussion of the Report and draft Recommendations of the CAVITATION COMMITTEE

I. DISCUSSIONS

Y. LECOFFRE - Neyrtec, Grenoble, France

Changes in nuclei concentration may affect cavitation behaviour and lead to discrepancies in performances of hydraulic components. Among the cavitation types described in the ITTC committee report, the most sensitive to this effect are bubble cavitation and, at a less extent, sheet cavitation. The influence of nuclei is also important in jet cavitation.

When bubble cavitation occurs in streamlined flows, two problems generally arise on the model:

- Detection of the inception conditions.
- Prediction of developed cavitation effects upon performance.

Cavitation inception is due to the action of the flow field on the weakest nuclei.

It depends on the "critical pressure" of those nuclei. When using the conventional σ parameter based on Pv for scaling, important errors may occur whenever the water does not contain very "weak" nuclei. Inception will generally be better defined by using a σ parameter based on $P_{c\ max}$, the critical pressure of the weakest nuclei also called "susceptibility" (Oldenziel, Teijema IAHR-1977 Leningrad).

$$\sigma_i = \frac{P_\infty - P_{c\ max}}{\frac{1}{2}\rho V_\infty^2}$$

At lower σ values, when cavitation is more developed, both static and dynamic effects will act on nuclei and bubbles. The number of vapour bubbles created will be dependent on the whole nuclei spectrum. Each nucleus can explode only if it is submitted to a pressure lower than its critical pressure. The dynamic effects govern the macroscopic growing of vapour bubbles.

The lift coefficient of a foil under given overall conditions is a function of the number N of vapour bubbles that travel over it at a given instant. This has been pointed out by BJÖRHEDEN and ALBRECHT (ITTC-1975) and by HENRY (IAHR-1978). Our own experiments showed that the average C_p distribution on similar bodies operating at same σ values was dependent on N. (F. DANEL, LECOFFRE IAHR-1976).

The scaling parameters for developed cavitation are as follows:

- The number N of vapour bubbles has to be the same at a given instant on model and prototype

$$N_m = N_p$$

- Model and prototype should operate at the same σ value based on vapour pressure

$$\sigma_m = \sigma_p$$

σ governs the dynamic behaviour of the cloud of growing bubbles.

Those similitude rules are valid in most cases. Problems may, however, arise when "screening" or viscous effects are likely to play an important role.

For cavitation inception tests, it is necessary to know both model and prototype $P_{c\ max}$ the critical pressure of the weakest nuclei. In that case, the σ_i value, referred to Pc max can be written:

$$\sigma_i = \frac{P_\infty - P_{c\ max}}{\frac{1}{2}\rho V_\infty^2}$$

In developed cavitation, a more important part of the nuclei spectrum is involved. The scaling relationships are:

$$\sigma_m = \sigma_p \qquad N_m = N_p$$

They will be satisfied if the ratio between model and prototype active nuclei concentrations, (respectively C_m and C_p) is equal to the third power of the scale ratio λ.

$$C_m = \lambda^3 C_p \qquad (\lambda = L_p/L_m)$$

This leads for reduced scale tests to higher concentration in the model water than in the prototype fluid. To be active, the model nuclei have to be weaker than the prototype ones.

In order to achieve the above requirements, it is necessary to measure the prototype nuclei and to control the model nucleation. Prototype nucleation has to be measured by using direct methods in which the nuclei actually give birth to vapour bubbles. Indirect methods do not measure critical pressures, but a dimensional parameter. The relationship between particle dimension and critical pressure is not directly deducible from RAYLEIGH's Law. Recent experiments performed at the Delft Hydraulics Laboratory showed that very few particles present in water can be active nuclei. The ratio between the concentration of active nuclei and measured particles can be as low as 10^{-6}.

The venturi system developed in the Delft Hydraulic Laboratory and NEYRTEC Research Center is described in the committee report. It appears to be convenient for such direct measurements. It can give a complete nucleation spectrum whenever the active nuclei concentration is less than $5/cm^3$.

For model testing, high active nuclei concentration is generally needed because of the λ^3 rule. Several methods for injecting micro bubbles as artificial nuclei are available. Electrolysis, high pressure supersaturated water injection or bubble column system are of normal use in different facilities.

For nuclei concentration measurements in model, either direct or indirect methods can be used. If the facility is equipped with a micro air bubble generator, a filtering system and a resorber the nature of active nuclei is known. In that case a convenient indirect method is the local diffraction (KELLER). It enables measurements of high concentrations of nuclei, up to several thousands/cm^3. When no artificial nucleation systems are available, direct methods have to be used.

Bubble cavitation test results can be affected by changes in nucleation. Inception conditions, performances, noise and erosion depend upon the concentration in active nuclei under given flow conditions.

In most practical cases, performances can be scaled using the (λ^3,σ) rule. For inception, σ_i has to be referred to Pc max.

Thus, prototype measurements of nucleation are needed in order to correctly control the nuclei concentration in model test facilities.

R.E.A. ARNDT - University of Minnesota, St. Anthony Falls Hydraulic Laboratory, Minneapolis, U.S.A.

The Committee must be congratulated for a most thorough review of an extensive body of cavitation literature. I agree in principle with the recommendations of the Committee and support them fully.

I must again call attention to the fact that proper consideration must be given to both the level of free gas and dissolved gas in the flow. This is especially important for cavitation erosion, noise and unsteady forces due to cavitation. It is not sufficient to consider only the relative level of saturation, rather the effects of gaseous diffusion must be scaled dynamically. The influence of dissolved gas on erosion is underscored in the paper by Stinebring et al/Ref.77/. Effects of dissolved gas on cavitation noise is considered in a recent paper by Arndt. It should also be mentioned that proper balance of free and dissolved gas is not an easy task, since in many facilities the two factors are interrelated, some discussion of this offered in References /9/ and /10/. I would also like to caution the Committee on the use of the correction equation used on page 303, since the various effects are interrelated and are not necessarily separable in the linear fashion depicted. In addition to this comment I would also like to call attention to a small misprint on page 317. The range of velocity studied in Reference /77/ was much wider than the range cited in the text of the report.

Finally, it would be useful to hear more about cavitation noise scaling with particular emphasis given to interpretation of the acoustic signal as a diagnostic for evaluating other cavitation scaling problems.

G. KUIPER - Netherlands Ship Model Basin, Wageningen, The Netherlands

The inception data, as shown in Appendix A of the report of the Cavitation Committee, show very clearly that the experimental control of the inception process is still very poor. Apart from geometrical and dynamic similarity the only parameter used in practice for scaling of cavitation on ship propellers is the cavitation index. Three additional parameters are mentioned in the Committee Report which influence cavitation and especially cavitation inception, viz. nuclei effects, viscous effects and surface effects, but no means are available yet to incorporate these effects in the testing of model propellers. These three components of scale effect on cavitation inception have been studied recently in the NSMB Depressurized Towing Tank /1/,/2/ in an effort to improve the testing technique. Based on these experience some comments on the Committee Report can be made regarding sheet cavitation on model propellers.

1. As stated in the Committee Report the oil film technique can form a basis for scale effect studies. From a series of experiments, combined with calculations, it was found that the boundary layer on the suction side of a model propeller can be characterized as sketched in Fig. 1. In the region AB a short laminar separation bubble exists, followed by a turbulent boundary layer. The line BC forms a clear distinction between the turbulent region after separation and the laminar flow region, which radius will be called the critical propeller radius because of its importance for cavitation inception. In the region CD natural transition takes place, while near the hub laminar separation can occur at some distance from the leading edge, causing stalled propeller sections.
   The position of the points A to E on the propeller blade is of course very much dependent on propeller geometry and loading and on the propeller Reynolds number. Especially point B can vary from tip to hub with varying propeller loading, while point D can vary from C to E.
   The chordwise position of the transition region CD depends on the Reynolds number, shifting to the leading edge with increasing Reynolds numbers. An important observation, however, is that the line CD, and especially the point C, never comes close to the leading edge at Reynolds numbers practical on model scale (until about 10^6, based on section chordlength and local inflow velocity). This means that in the low pressure region of the model propeller blade only two types of boundary layer flow are present: laminar flow and laminar separated flow, followed by turbulent reattachment.

2. The cavitation behaviour of both flow regimes show considerable differences, especially with respect to the influence of nuclei. In the region with the laminar separation bubble a smooth sheet will be formed in those regions where the pressure is lower than the vapour pressure. The inception pressure is not known exactly but since this is a region with steep pressure gradients a deviation of the inception pressure from the vapour pressure generally does not result in large variations of the cavitation extent. There is, however, a threshold for the nuclei content, although this threshold is very low.
   When the nuclei content is below this threshold no inception takes place. This is especially apparent when there is little time for inception, as is the

case when a propeller blade passes a wake peak. In these situations electrolysis is found to have a "stabilizing effect" (see Refs. /13/ and /16/ of the Committee Report). When inception takes place a smooth sheet cavity is formed. In the laminar region no cavitation inception takes place. Remarkable is that nuclei do not expand in this region and addition of nuclei has no effect here. The reason is not known yet, but possibly some screening effect takes place. Sometimes streaks of cavitation occur in the laminar regions corresponding with turbulent spots in the boundary layer. The number of these streaks increases with Reynolds number, pointing to surface roughness, but in the NSMB Cavitation tunnel, where the number of spots was generally higher than in the Depressurized Towing tank, also microscopic contamination was found to cause streaks of cavitation.

An illustration of the different boundary layer regimes and their effect on cavitation inception is shown in Fig. 2, where the critical radius at this blade position for blade 1 is 0.8. Outside the critical radius a sheet cavity occurs and this sheet occurred at every revolution when electrolysis was applied. Without electrolysis the sheet occurred more or less randomly. Within the critical radius streaks of cavitation are observed. The radial extent of cavitation is often restricted by the critical radius. Since the critical radius is independent of the Reynolds number no effect can be expected from an increase in propeller Reynolds number.

The foregoing can have some importance for the practical interpretation of cavitation on model propellers, e.g. because the occurrence of laminar separation on model propellers is very sensitive for the shape of the leading edge. The practical example, given in the Committee Report, where a few wipes of sandpaper on the leading edge changed the inception speed with 2 knots can be caused by the fact that a change in the shape of the leading edge changed the critical radius, and thereby the inception speed. If this is the case, however, scale effects on cavitation inception caused this drastic variation of the inception speed and the results should be considered with caution.

3. From the foregoing it is seen that the process of cavitation on model scale is different from that on full scale, where natural transition takes place near the leading edge. It is therefore obvious to try to establish full scale conditions on model scale. This was done by applying roughness of 35 and 60 μm grainsize in a very small region at the leading edge (± 0.5 mm), which was sufficient to create turbulent boundary layer flow, at least over the suction side of the model propeller. This way of stimulating transition hardly affected the propeller performance, but it removed the restricting influence of the critical radius, causing inception near the vapour pressure. A disadvantage of this method of course is that the leading edge is affected, which can have a profound effect on the local minimum pressure, as this is the case with isolated roughnesses. Little is known, however, about the effect of roughness on the boundary layer near a sharp pressure minimum on a propeller blade. Calculations and comparisons with full scale, however, indicate that the total scale effect on inception is small when roughness is applied near the leading edge. When the blades are thus roughened no effect of nuclei content could be seen any more. Since some nuclei are considered necessary to create inception it is suspected that the threshold for the nuclei content is

very low in the case of stimulated transition. This means that the control of the nuclei spectrum becomes less important when the blades are roughened since the threshold will probably be lower than can be obtained in the test facility.

4. Some closing comments on the Committee Report are:
   - The distinction between spot and streak cavitation should be made more clear. Specifically it should be defined if the distinction is in the appearance, the origin or the location on the propeller blade. E.g. in Fig.3 of the Committee Report the spot cavity has a bubbly character, while the streak is a wedge-shaped sheet. The distinction then is in the appearance , but this is not clear from the description. Possibly one of both names will be sufficient.

   - When the effect of "nuclei seeding" (recommendation 2) is investigated, efforts should be made to determine also the condition of the boundary layer.

REFERENCES

1. G. Kuiper, "Cavitation Scale Effects - A Case Study -", International Shipbuilding Progress, Vol. 25, April 1978.
2. G. Kuiper, "Scale Effects on Propeller Cavitation Inception - Variation of roughness and nuclei content -", 12th Symposium on Naval Hydrodynamics, Washington, June 1978.

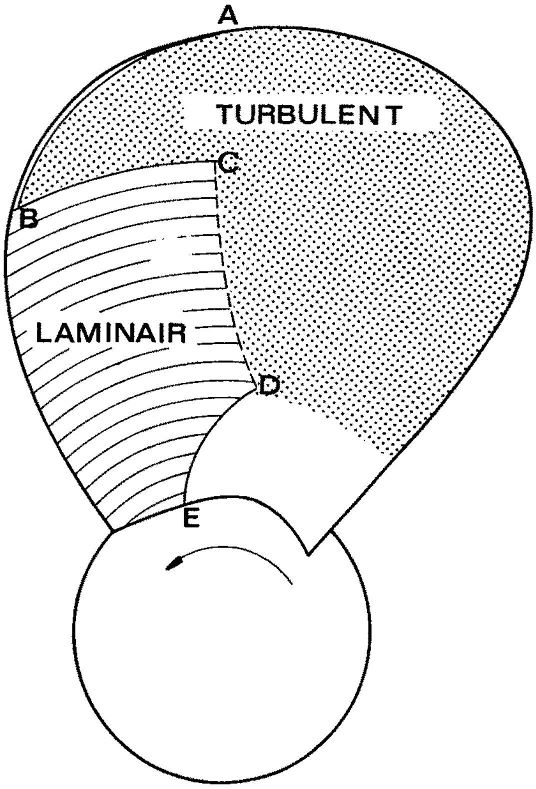

Fig. 1. Schematic representation of the boundary layer flow on the suction side of a propeller blade.

AB	Short laminair separation bubble
BC	Critical radius.
CD	Transition region.
DE	Laminair separation.

Fig. 2. Relation of the cavitation pattern with the boundary layer regime.

GÖRAN BARK - The Swedish State Shipbuilding Experimental Tank (SSPA), Göteborg, Sweden

In the studies of noise from unsteady propeller cavitation it has been found that sometimes sharp and high pulses are an important part of the signal. In the search for scaling laws of such pulses it is of interest to study the generation mechanisms in some detail. An appropriate way of starting is to use an oscillating hydrofoil to simulate the unsteady cavitation on a propeller operating in a wake.

The tests were carried out in SSPA cavitation tunnel No. 1 equipped with test section No. 1 (500 x 500 mm). The hydrofoil was located horizontally in the test section and was forced to oscillate around an axis fixed spanwise through the midchord point. The axis was driven by a connecting rod and an adjustable crankpin. The arrangement is shown in Figs. 1 and 2.

In these introductory experiments an existing hydrofoil, earlier used for studies in two-dimensional flow, was used. The profile has NACA 16 thickness distribution and the data are:

Mean line a = 0.8
Camber ratio = 0.0144
Thickness ratio = 0.0681
Chord length = 120 mm
Span = 200 mm

Two hydrophones (Brüel & Kjaer Type 8103) were placed in notches in a tube about 60 mm from the surface of the hydrofoil.

The requirements set up for the filming were that the film had to be synchronous with the noise recordings and permit measurements of cavity size as a function of time. The intention was not to measure the detailed behaviour of small or very fast events. The minimum duration of the filming was set to about one second.

These requirements were met by a Stalex VS 1C camera capable of 3 000 frames/s. For synchronization the camera could release a flash at a preset time. The flash-triggering signal was recorded on tape together with hydrophone signals and the flash was placed within the frame. The camera was also equipped with a crystal-controlled timemarker, making one light-marking every millisecond on the film. This meant good possibilities of identifying and following cavitation behaviour on film together with the corresponding pressure behaviour recorded on tape.

In Fig. 3 is shown pressure as a function of time. To the right are also sketches of the cavity pattern just before collapse. There are also indications of which parts (A, B etc.) of the cavities that generated the sharp pulses. The reduced frequency k_c is defined as

$$k_c = \frac{\omega c}{2U}$$

where ω = circular oscillation frequency
c = hydrofoil chord length
U = water velocity

In Fig. 4 the measured collapse time is shown for some different values of angles α_0 and $\tilde{\alpha}$. The time is normalized by the collapse time of a spherical bubble with a corresponding linear dimension.

In Fig. 5 the pressure generated at collapse is shown. The pressure is normalized by the distance between cavity and hydrophone (r), the maximum chordwise extension (l_{max}), and the pressure ΔP driving the collapse.

The figures indicate that when k_c exceeds a critical value in the interval 0.3-0.6 the collapse dynamics and generated pressure are changed.

Summary and conclusions

1. The generation of sharp pulses was dependent of the oscillation frquency. At low frequencies no high and sharp pulses were generated and above a certain frequency very high pulses were generated.

2. The sharpest and highest pulses were generated by cavities which separated from the main cavity and underwent a rather symmetrical and orderly collapse. Detailed studies showed, however, that a series of pulses was often generated, indicating that the collapses were not always simple at the very end.

3. Very high pulses could also be generated by cavities that were attached to the leading edge during the whole collapse.

4. The highest pressure generation efficiency was observed for spherical bubbles, which despite their smallness generated rather strong pulses.

5. The sharp pulses were generated during the very last part of the collapse.

6. Rebound of cavities was an important process for generation of sharp pulses. The most violent rebounds were obtained for separated cavities.

7. Low frequency noise was generated during growth, near the time of maximum cavity extent and during the rather

late stage of collapse. Because of a disturbing resonance the importance of collapse was, however, difficult to determine.

The basis of existing scaling laws for cavitation noise is mainly

1. Ideas from theory and experiment concerning the dynamics and radiation properties of a single cavity.

2. Ideas concerning statistical properties of the pulse-generating events.

The dynamics and radiation depend on cavity geometry, cavity size and the surrounding pressure. Scaling laws based on simple theory deal with model scale and magnitude of surrounding pressure, while similarity has to be assumed in cavitation behaviour.

It has to be accepted that complete similarity in cavitation behaviour will not occur, but if it is known which events in the cavitation process that are crucial for generation of important pulses, this also provides an indication of to which extent similarity is necessary for proper application of scaling laws.

Of course these introductory experiments cannot supply the final and complete answer,but the results indicate that one of the most important factors is that the separation of a cavity into parts is correctly scaled, the reason being that these separations are often the starting points for violent collapses. Especially when large parts are separated, this often begins at an early stage of the collapse, or is even initiated by disturbances during the growth of the main cavity.

Parameters that determine tendencies to separation of cavities are only studied to a limited extent, but it is clear that the combination of a long (chord-wise) cavity and high reduced frequency causes extensive separation of large parts from the main sheet. From the plots of collapse times and pressure generation efficiency $p^+r/\Delta P1_{max}$ as functions of reduced frequency it can be concluded that within special regions it is important that the time variations of the surrounding pressure are properly scaled. Such a scaling may be critical for the onset of separation of large cavity parts from the main cavity.

REFERENCE

Bark, G & van Berlekom, W (1978): Experimental Investigations of Cavitation Noise. Twelfth Symposium on Naval Hydrodynamics, Washington D.C., June 1978.

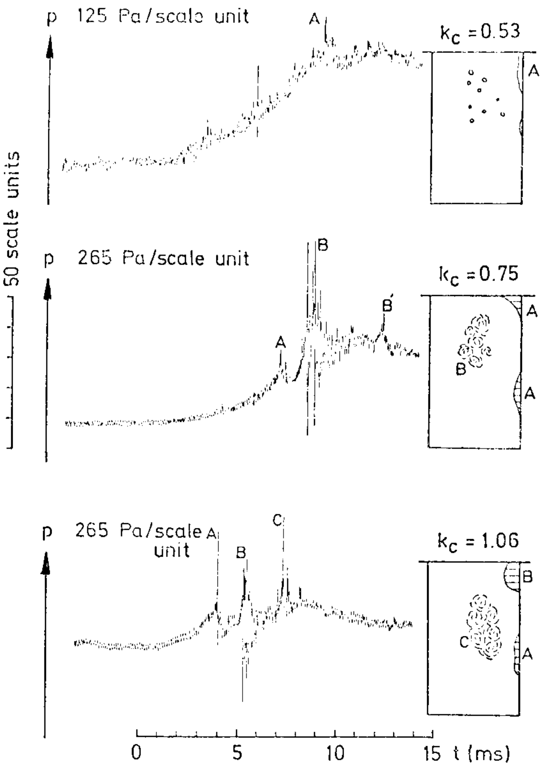

Fig. 3 - Pressure signals during collapse

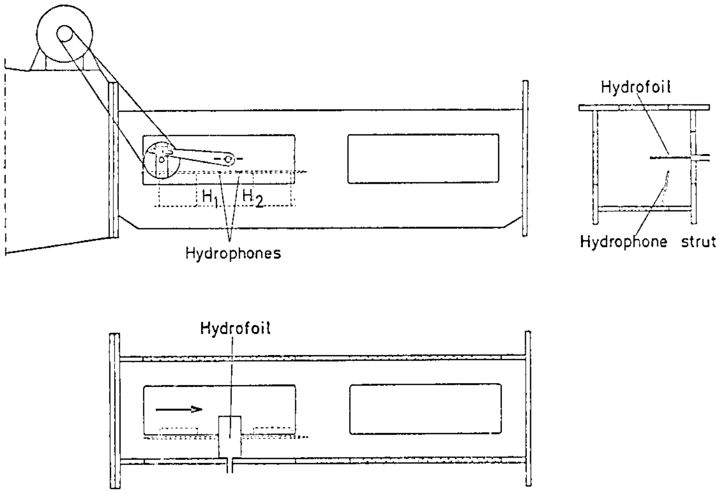

Fig. 1 - Experimental set up

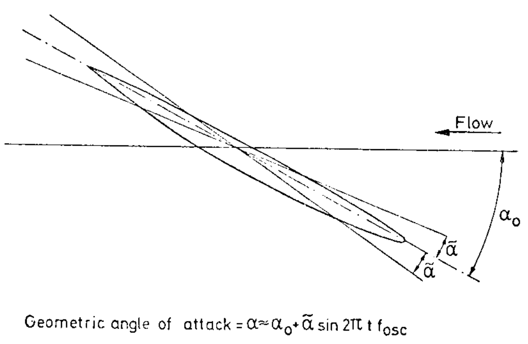

Fig. 2 - Oscillating hydrofoil

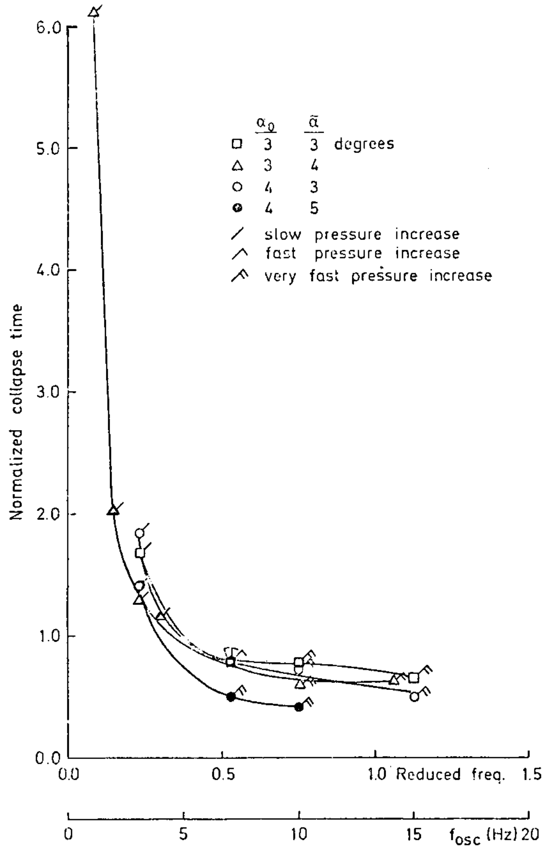

Fig. 4 - Normalized collapse time

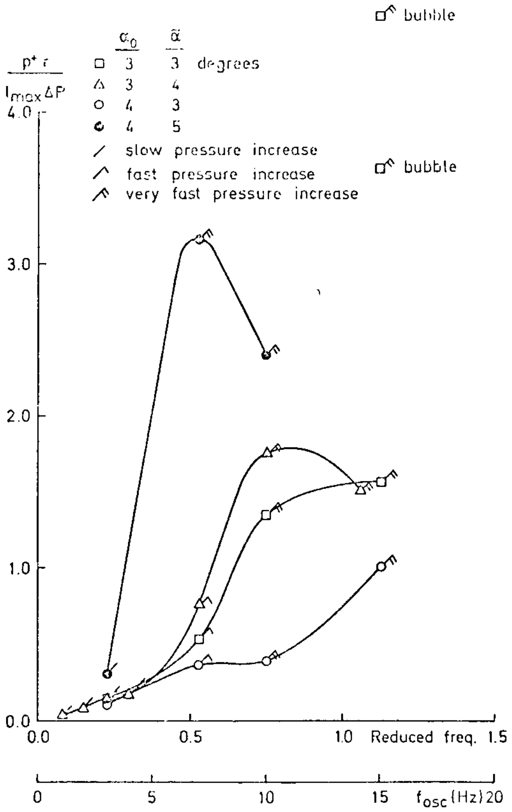

Fig. 5 - Normalized pressure p^+ at collapse

K. TAMURA and T. SASAJIMA - Mitsubishi Heavy Industries Ltd., Nagasaki Technical Institute, Nagasaki, Japan

As for the prediction of cavitation erosion from model tests, the Committee reported that all the participating establishments obtained satisfactory results in the use of SSPA stencil ink. But it should be reminded that the satisfactory results could not have been obtained without utmost efforts of the participants to overcome difficulties in dilution and coating of the ink.

It is recommended therefore to search for a material more adequate for soft surface technique, taking account of the response to the strength against cavitation erosion, the easiness of handling and the effects of coating on cavitation pattern on propeller blades.

S. TAMIYA - University of Tokyo, Department of Naval Architecture, Tokyo, Japan

As to "the Description of Cavitation Appearances" the committee report writes that all terms relate to visual observations only. Actually, however, we are usually looking at the phenomena (possibly changing very quickly) under the flash lights of stroboscope with a predetermined periodicity.

If there are supposed to exist any influences on the visual images due to, for example, the duration of flashing light, the committee would be kind enough to call attention in the report.

R. SATO - Research Institute, Ishikawajima-Harima Heavy Industries Co., Ltd., Yokohama, Japan

SSPA stencil ink coating method, which was recommended for prediction of cavitation erosion by ITTC, was applied to full scale ship propeller before sea trials. The process and the results are described briefly in this report.

Stencil ink coating method was tried on a four bladed controllable pitch propeller equipped on a cargo ship built at IHI shipyard. Method of cleaning of propeller blades, application and drying ink layer is as follows:

Surfaces of the propeller blades were cleaned with the ink conditioner prepared for the stencil ink S-1 in the dry dock before the sea trial. After drying the conditioner stencil ink S-1 was applied with a roller on both sides of No. 1 and No. 3 blades of the propeller. S-1 was used without dilution to avoid local thickening of ink layer at the blade edges. Ink layer was not so thick that it does not affect on the cavitation performances of the propeller.

Ink layer was dried in open air for 24 hours. Drying time was sufficient for this application. Checking the perfect drying of ink layer, the ship departed to sea trials.

The trials were conducted for about 2 weeks and the propeller was operated for about 150 hours at propeller rotation number N_p = 130 RPM and 85 RPM. Moreover, the propeller was operated at N_p = 130 RPM for 30 minutes under neutral condition and at N_p = 130 RPM, 30 % MCR for 40 minutes at low pitch angle $\beta = 7.4^{\circ}$. These conditions are not desirable from the view of face cavitation erosion.

Ink removal pattern on each side of the blade was photographed in dry dock after the sea trials. Ink removal pattern on each side of the propeller blades is shown in Fig. 1. According to the extent of ink removal, ink removed area was grouped into two classes. Slightly removed area is denoted degree 1 and heavily removed area degree 2 in this figure.

The pressure side of No. 4 blade, where stencil ink was not applied, was damaged by cavitation slightly at 0.8-0.9 r/R in circular area of about 200 mm diameter. The damaged position is also indicated by D in Fig. 1.

Ink removal areas along the leading edge on the pressure sides of No. 1 and No. 3 blades are supposed to be caused by face cavitation occurred under neutral condition during the sea trials. Because

1. These ink removal patterns on the pressure sides of No. 1 and No. 3 blades show close agreement with cavitation pattern observed on the pressure sides of the corresponding model propeller operated in the cavitation tunnel.
2. Damaged position on the pressure side of No. 4 blade coincides with ink removal position on the pressure sides of No. 1 and No. 3 blades.

Ink removal areas along the blade edge on the suction sides of No. 1 and No.3 blades agree with cavitation pattern observed on the corresponding model propeller operating in the cavitation tunnel.

Finally it is possible to predict satisfactory cavitation pattern and erosions on full scale ship propellers with the aid of the stencil ink coating method.

Last but not least it has to be noted that a series of work, i.e., cleaning of propeller blades, applying of the stencil ink, operation of the propeller and observation of ink removal patterns, must be done as quickly as possible and that ink layers are not be left in sea water for a long time not only before but also after the operation of the propeller.

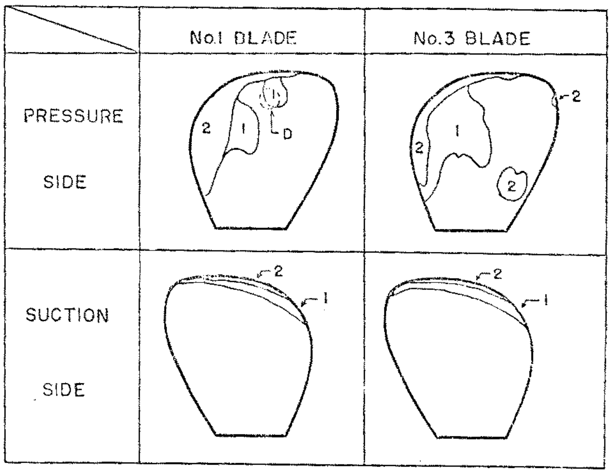

Fig. 1. Ink removal position.

J.W. ENGLISH - National Maritime Institute, Ship Division, Feltham, United Kingdom

On pag. 321 of the Cavitation Committee Report it is stated that acoustic attenuation caused by bubbles in water may be used to find bubble size spectra, however, the method does not show sufficient sensitivity for practical application. On pag. 324 it states "There is no acoustic technique that can be recommended by the Cavitation Committee for the measurement of free gascontent and bubble size spectra", while on page 325 it suggests a monitoring technique consisting of an acoustic projector driven by a broad band source with a receiving hydrophone opposite.

My question is, in view of Medwin's success in measuring bubble size spectra acoustically in the sea, and the success of others, should the acoustic approach be written off at this stage?

I commend the report for suggesting the acoustic monitoring device as a relatively simple and practical means of ensuring that the water conditions are not too different when subsequent measurements are taken. Is the 5 dB deviation quoted based on experience or is it an educated guess?

A.M. STUURMAN - Ministry of Defence (Navy), The Hague, The Netherlands

On page 324 of the report under the heading of Proposed Future Procedures it is stated that the objective is to obtain estimated free-field sound pressure or sound power levels.

As a user of model basin test results I need noise data for two design considerations:

1. underwater radiated noise levels
2. inboard airborn sound levels

The source for both levels is the fluctuating cavity volume on the propeller. The sound path in both cases depends on

- water quality and water depth
- afterbody shape and construction
- inboard lay-out and finishing of spaces

We have methods available to calculate inboard sound levels and underwater noise levels if we know the sound source.

Therefore I would like to suggest that noise data be presented in the form of cavitation volume variations.

J.W. HOYT - Naval Undersea Center, San Diego, U.S.A.

The foil head-form combination described in the committee report may eventually become a "standard" cavitator for intercomparison of results between various organizations. However, the size of this device makes it unusable for the smaller tunnels. I recommend that the span of the device be reduced so that

1. it can be used in smaller tunnels
2. blockage effects become less important for all tunnels.

D.M. OLDENZIEL - Delft Hydraulics Laboratory, Delft, The Netherlands

Today we know that the onset of cavitation is a function of the water quality. Nevertheless the velocity field and pressure field determine the type of cavitation and its intensity. When also the water quality has been known the cavitation intensity can be detected, unambiguously. As shown in Figure 1, the water quality can be defined by two parameters: free-gas content and dissolved-gas content.
The free gas exists as well in the form of small bubbles which are dynamically stable but unstable with respect to mass transport across the bubble surface as in the form of small gas pockets stabilized in crevices of small solid particles suspended in the liquid.

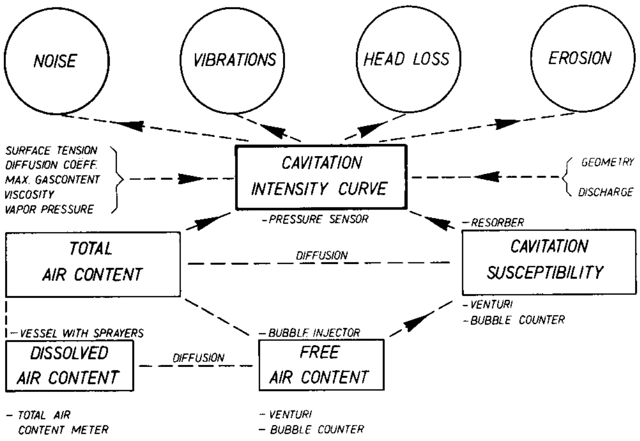

Figure 1 Relation between cavitation intensity and water quality

At the Delft Hydraulics Laboratory measurements have been carried out to investigate the relation between the cavitation-intensity and the water quality. Figure 2 shows examples of cavitation-intensity curves. The type of cavitation considered was free-flow cavitation behind a butterfly valve with constant pressure difference and constant discharge. The free-gas content

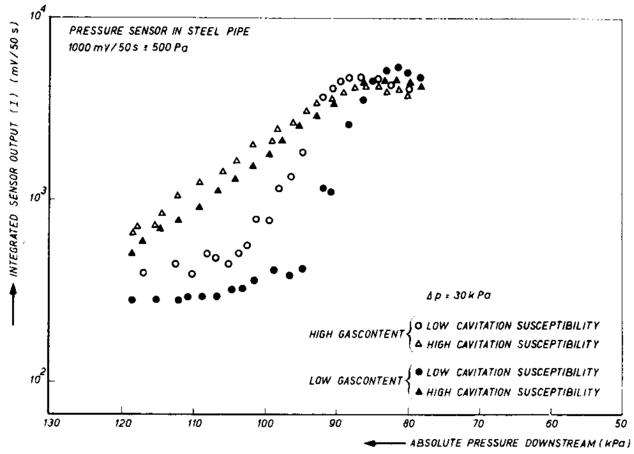

Figure 2 Influence of cavitation susceptibility and gas content on cavitation inception

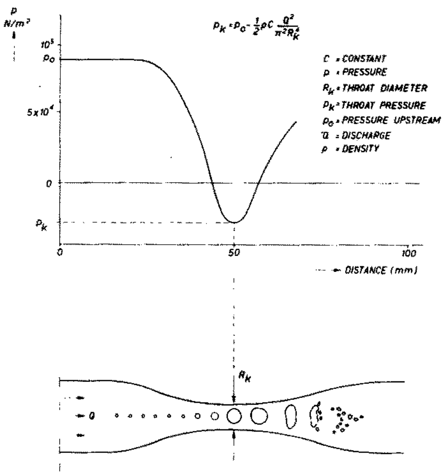

Figure 3 Pressure distribution and bubble explosion in the throat of the venturi tube

(cavitation susceptibility) as well as the dissolved-gas content have been varied. The cavitation intensity is defined here as the number of bubble implosions per unit of time (vertical axis in Fig. 2). On the horizontal axis the absolute pressure at the downstream side of the valve has been plotted.

The tensile strength of water is determined by counting exploding bubbles in the throat of a small venturi tube. The negative throat pressure at which the biggest bubbles or the weakest nuclei explode is defined as the cavitation susceptibility of water.

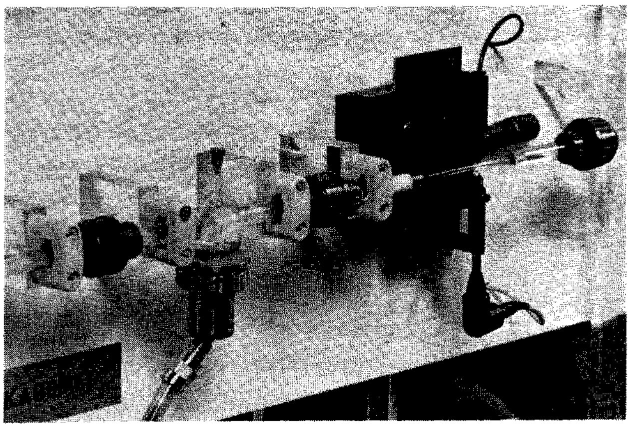

Figure 4

Venturi tube in the cavitation-susceptibility meter developed at the Delft Hydraulics Laboratory

The principle of this system has been shown in Figure 3. The Delft Hydraulics Laboratory uses a venturi tube made of glass (inlet diameter 10 mm, throat diameter 2 mm); the exploding bubbles are detected optically. See Figure 4. At Neyrtec a venturi tube is used with about the same size but made of stainless steel; the exploding bubbles are counted acoustically (implosions). See Figure 5.

At the Delft Hydraulics Laboratory an acoustic Doppler system (4.4 MHz) has been developed, to detect suspended sand particle or bubbles in water. The principle of this system has been drawn in Figure 6. In the shaded volume particles or bubbles scatter a part of the acoustic waves from the transmitter in the direction of the receiver. The velocity of the object, which scatters the acoustic waves, causes the Doppler frequency shift. The intensity of the Doppler signal is proportional to the concentration of bubbles or nuclei in the shaded volume. The size of the bubbles has to be known. Figure 7 shows the acoustic transmitter and receiver in a pipe segment.

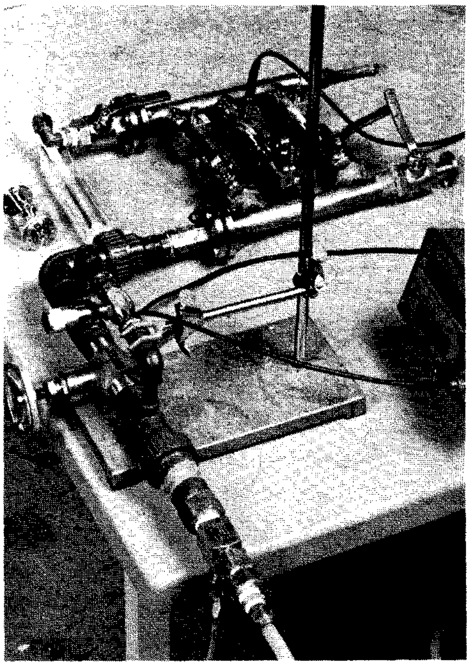

Figure 5 Cavitation-susceptibility meter developed at Neyrtec, Grenoble

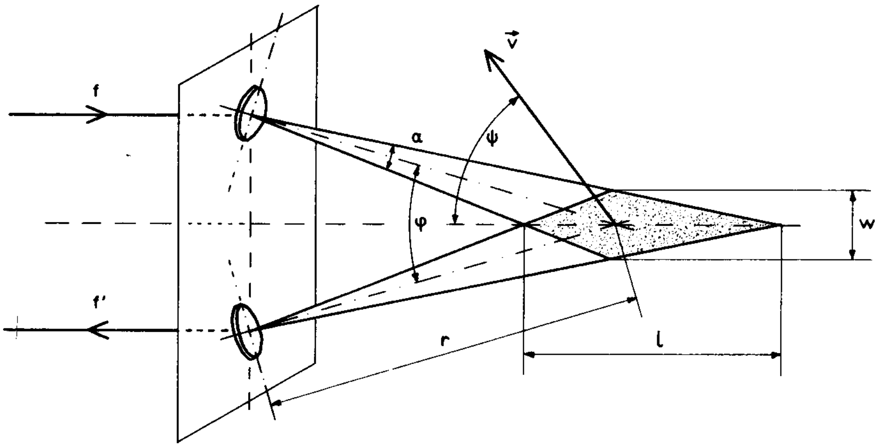

Figure 6.

Principle of the acoustic Doppler bubble concentration meter

Figure 7. Segment of perspex pipe with the acoustic transmitter and receiver.

C.A. JOHNSSON - Swedish State Shipbuilding Experimental Tank

I just want to endorse the recommendation made by Mr. Kuiper that recommendation No. 2 of the Committee should be expanded so as to include viscous effects with special reference to the influence of roughness on different cavitation phenomena.

I have a feeling that many laboratories (including the one I belong to) apply roughness in a rather non-scientific way as a last attempt to obtain agreement between model and full scale, and very often with success. In our case for instance we have, like NSMB, applied it in connection with merchant propellers in wakes. Further we successfully applied it to supercavitating propeller models, thereby getting a very pronounced effect both on cavitation patterns and thrust and torque characteristics, in both cases increasing considerably the agreement with full scale observations.

If the next Committee could be recommended to collect and co-ordinate information of this kind may be, we will know better at next Conference how this matter should be handled and the reasons why we get improvement in many cases.

H. TAKAHASHI - Ship Research Institute, Tokyo, Japan

I would like to give some comments on the stencil ink and the soft surface.

To use the stencil ink is not so difficult, if you are familiar with it. For example, repeatability tests under the various conditions were performed in SRI and good results are obtained. The problem on the stencil ink, however, is "how to taking account of response to the strength against cavitation erosion", as pointed out by Mr. Tamura (MHI).

We performed the preliminary soft surface experiments in using quite a new material developed by the Film company in Japan. This material is sensitive to pressure and the original colour of this material is white. And deepness of colour changes due to the strength of pressure. Advantageous point of this material is that the strength of cavitation can be measured approximately by the deepness of colour. Disadvantageous point is that this material is very weak in water. Therefore, we must cover this material with a special paper. I think this new material can be of use in the near future, especially for testing two-dimensional models.

REPLY OF THE CAVITATION COMMITTEE

The Committee appreciates the contribution by *Mr. Lecoffre* on the importance of the correct nuclei content for model testing. The use of the critical pressure instead of the vapour pressure in the definition of the σ-parameter for incipient bubble cavitation has the disadvantage that the value of the critical pressure is usually not known. In the Committee Report it is stated that no measuring technique is as yet available for routine use. Mr.Lecoffre's conclusion that the model fluid has to be weaker than the prototype fluid is important and stresses once more the importance of nuclei seeding in cavitation facilities.

The Committee would like to thank *Prof. Arndt* for his appreciation of the Committee Report and for his support to the recommendations. The Committee agrees with Prof. Arndt that both the free and dissolved gas content are important parameters to be considered. It is felt, however, that the interrelationship between the two parameters in many cavitation facilities may lead to a meaningful use of the total gas content ratio α/α_{st} when considering vortex cavitation inception. The influence of dissolved gas on phenomena related to cavitation, such as noise and erosion, is another important aspect. The Committee is well aware of the fact that the correction equation on page 303 is a rough simplification intended only to analyze further the needs for a proper standard cavitator.

The contribution by *Mr. Kuiper* is a most valuable one. In particular the observation that no cavitation appeared in the laminar region on the model propeller deserves full attention. With regard to applying sand roughness to induce early transition to turbulence, the Committee feels that this may be an effective way of reducing viscous scale effects when the roughness only affects transition. However, as pointed out by Mr. Kuiper, the roughness is also affecting the leading edge shape. Besides, the roughness elements may cavitate themselves and thus trigger other types of cavitation. Hence, the effects produced by the roughness should be studied in more detail before final conclusions can be made. The Committee feels that the problem of a laminar separation bubble along the leading edge may be particularly important in testing high-skew propellers which are being designed for the very purpose of suppressing cavitation and reducing vibrations. The adequacy of such design is evaluated in model scale cavitation tests. However, the nature of these designs, with their swept tips, introduces secondary flows in the boundary layer which will be different if a laminar separation bubble exists. This could well lead to misleading results in evaluation of their performance. With regard to the distinction between spot and streak cavitation, the Committee presents the following, revised definition of spot cavitation:

- spot cavitation (formed at isolated roughness spots or surface imperfections).

The contribution by *Mr. Bark* is a very worthwhile addition to the subject of unsteady cavitation and cavitation noise. The Committee regrets that a copy of the complete paper he presented at the 12th Symposium on Naval Hydrodynamics in Washington, June 1978, was not available when the Committee Report was still in manuscript form. His description of cavities separating from the main cavity could be inferred to be cloud cavitation. As such, his conclusion that the formation of the cloud cavitation be correctly scaled is a point the Committee would also like to emphasize. If the development of various types of cavitation is not simulated on a model, there is little possibility that the noise or erosion intensity can be scaled. Mr. Bark's conclusion that the time variation of the surrounding pressure must be properly scaled supports the results reported in Ref. /58/ where it was shown that the angular pressure gradient is an important parameter:

$$\xi(k) = \left(\frac{dC_p}{d\alpha}\right)_{\text{unsteady}} / \left(\frac{dC_p}{d\alpha}\right)_{\text{steady}},$$

where k is the reduced frequency, C_p the pressure coefficient and α the angle of attack. It is hoped that Mr. Bark will continue his research on this subject and since for certain conditions of cavity length (l/c), with k = 0, the cavitation can also be unstable in a manner similar to that observed by Mr. Bark, it is hoped that his future work will include comparisons for both k = 0 and k>0.

The Committee appreciates the remarks by *Mr. Tamura* and *Mr. Sasajima*. If full advantage is to be taken of the work of SSPA, each establishment will probably need to use the stencil ink method several times in order to obtain a standard for comparison. It should be emphasized, however, that the Committee Report did not make a suggestion on recommending any specific coating for general use.

Prof. Tamiya makes the point that what is seen depends on the lighting, what may appear as a sheet may be unsteady discrete cavities. This was referred to in the 1948 Conference, the first Conference to consider cavitation, but needs to be repeated at intervals.

The experiments by *Dr. Tasaki* and *Mr. Sato*, in which stencil ink has been used on the ship propeller as well as the model, are very interesting, not only for the support they give to the use of stencil ink but also in demonstrating how well the coating adheres in the absence of eroding cavitation.

The Committee would like to thank *Dr. English* for calling specific attention to the usefulness of characterizing bubble populations acoustically. None of the organizations contacted are currently using acoustics to measure bubble size spectra in their test facilities. However, since Medwin /11/ had considerable success with this method in sea water and since various facilities are now "seeding" their facility water, it appears that this technique should be reconsidered. Monitoring the change in the acoustic attenuation property of the water requires less sensitive and sophisticated instrumentation. This latter procedure is considered very important by the Committee when cavitation noise measurements are made. The Committee also recommends that when the attenuation properties of the water change by 5db, then the measurements should be terminated. The original suggestion was 3 db, but several organizations stated that 5 db would be more appropriate at the present time.

The Committee appreciates the interest *Mr. Stuurman* has with regard to documenting the cavitation noise measurements in a manner that would also allow their use in full scale performance predictions. Since the radiated noise is dependent on the rate of change of the cavity volume, $\frac{\delta^2 V}{\delta t^2}$, it may in practice be difficult to measure this volume change directly. However, with procedures for documenting model cavitation noise measurements similar to those outlined in the Committee Report, the possibility exists for better cavitation noise predictions in the future.

Dr. Hoyt's suggestion to reduce the size of the foil-headform combination had to be considered carefully when the final size of a standard cavitator was selected. For the new set of hydrofoil tests proposed by this Committee the size will be the same as chosen earlier, i.e. the total span will be 300 mm. This size is close to the one normally used for model propellers.

The Committee appreciates the contribution by *Mr. Oldenziel* on the influence of free gas content and dissolved gas content. The free gas content of the liquid is "translated" into cavitation susceptibility and the committee regards this as an interesting approach. The Committee welcomes comparisons between the venturi tube device and other "nuclei meters", and is anxious to hear the results of such comparative studies recently made at the Delft Hydraulics Laboratory.

Mr. Johnsson's suggestion to expand recommendation No. 2 of the Committee Report has been followed. As stated earlier in the reply to Mr. Kuiper's discussion, the Committee's opinion on applying roughness is that all effects produced by roughness should be studied in detail, so as to obtain early transition to turbulence without inducing other, disturbing effects.

Dr. Takahashi's successful use of a new film or paper covering which will indicate pressure intensity by colour changes opens up a new field of investigation and it is fortunate that the results became available just in time for this Conference.

In closing, the Cavitation Committee would like to express its gratitude to all discussers for their valuable contributions. In the discussions many new ideas have been put forward and this will undoubtedly be a stimulus for the work of the next Cavitation Committee.