Discussion

S. L. Kerr. The author has made a very interesting contribution, extending the preliminary work which he did in the laboratory on the inception of cavitation to a field comparison on a full-scale hydroelectric unit.

The correlation between laboratory and field of cavitation and cavitation erosion has not been well established and any step toward this accomplishment is most welcome.

The author states that the weight-loss technique used in the magnetostriction testing has not been applied to flow systems. It should be noted, however, that the original work on weight-loss technique for establishing the degree of cavitation erosion in flow systems was carried out extensively in the 1920's and 1930's; in fact, it was the original laboratory procedure. The late Dr. Thoma did work of this type in Munich and there were the so-called "venturi cavitation stands" at Massachusetts Institute of Technology and also at the Pennsylvania Water and Power Company, Holtwood, Pa. The tests made at this latter installation were described at length by Mr. Mousson. Much stress was laid on different types of welded materials which were used in the repair of eroded runners.

The time for carrying out these tests by the venturi method was quite long, requiring from 60 to 100 hr to secure substantial weight losses. This was later reduced to 16 hr for some materials, but the power consumption of the pumping units to produce flow was still considerable.

The magnetostriction technique for establishing the relative resistance of materials to cavitation erosion was first applied to a broad program in 1935 and 1936, as described in a paper by the writer. This technique largely supplanted the venturi method for economic and other reasons.

The author's use of a relatively standard material as a reference for damage evaluation follows the magnetostriction practice. The effect of velocity on damage is of considerable interest.

In actual installations, however, there are many other variables which affect cavitation, particularly the range of turbine operation, the tailwater elevations, and the duration of exposure, together with the amount of time a unit is operated at substantial overloads or under fluctuating loads.

One of the very interesting methods of establishing such relationships in actual field operation is described in a paper by Kjell Rosenberg. The use of a radioactive isotope (arsenic-As76) permitted the measurement of the loss of material due to cavitation when running at different loads over substantial periods of time. The horizontal units at Vamma Power Plant in Norway were tested in this manner by applying a varnish containing the radioactive material and measuring the loss in radiation periodically.

Radioactive techniques would seem to offer a very excellent means of establishing the rate at which cavitation was causing damage. The results as shown in the article referred to indicate that the rate of loss increases rapidly with the turbine output, being about zero at 4000 kw; 13 per cent at 6000 kw; 38 per cent at 8000 kw; 60 per cent at 9000 kw; all related to 100 per cent at the full gate capacity of 9300 kw.

It would appear that the same technique could be applied to large vertical-shaft units if the instrumentation could be provided for in the design of the plant.

The areas usually affected by cavitation erosion are fairly well known from experience for different types of runners or else have been established from laboratory testing in the manufacturer's plant. The intensities, as between laboratory and full-scale installation, are indicated in this paper and it is hoped that more of this type of information will be available in the future.

John Farmakian. Inasmuch as this paper describes a new technique for measuring cavitation intensity by means of field tests of very short duration, it might be of interest to observe

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the nature of the cavitation-damaged area at one of the locations used for the test after a long period of operation. Fortunately, a pictorial record of the cavitation at Vane 6 on unit No. 2 is available at the position referred to in the paper as (b) on the vane immediately downstream from the entering edge adjacent to the shroud fillet. Fig. 6 is a view of the cavitated area on the high-pressure side of the vane, and Fig. 7 shows the cavitated area on the low-pressure side of the vane after the initial 3 years of continuous operation. At this vane, the cavitation actually produced a hole through the vane. A somewhat similar pattern of cavitation also was present near the same location at all of the other vanes of all of the units. Normally the Bureau of Reclamation does not permit the turbine runners to cavitate to this degree prior to rewelding with stainless steel. However, there was a severe shortage of power in the Southwest during the early years of World War II, and it was not convenient to shut down any of the units to make the repairs until after this unit had operated continuously for about 3 years. Fig. 8 shows the low-pressure side of the vane during the repairs. The area was first chipped out to solid metal and the hole plugged with solid steel. Layers of stainless 18-8 were then welded on until the original contour of the runner vane was re-established. It should be noted that at large gate openings the wicket gates of these units overhang the turbine-runner shroud by 6 to 8 in. It is the writer’s opinion that the blunt bottom of the wicket gate, due to the overhang and the subsequent lack of streamlining of the flow, also contributes to the heavy cavitation damage at this location. These units have presently been in operation for about 14 years. The amount of stainless-steel welding which now has to be done annually due to cavitation is relatively small.

R. S. Quick.11 The author has described a most interesting means of confirming that cavitation taking place in the field is of the same basic character as in the laboratory.

As pointed out by the author, field units are seldom available for experimental use, so the manufacturer has to locate the area subject to cavitation by laboratory tests, or long-range observation and field experience, in order to determine, in advance, what surfaces of new equipment should be protected with special cavitation resisting materials.

Would it not be possible to develop a coating which could be applied readily to a model surface and which, after a reasonably short period of test, would indicate, by a change in appearance, where the regions of local cavitation were located? Some paints have shown promise in model and field testing but, to the best of the writer’s knowledge, have not been standardized to a point where they could be offered for general use. Red-lead primer will show evidence of cavitation environment after a short period of operation. Tests of such materials could be made advantageously under laboratory conditions where the degree of cavitation could be observed and controlled. More information on this subject would be welcome.

W. J. Rheingans. The new technique developed by the author for measuring the intensity of the cavitation attack is another big step forward in the solution of the problems associated with cavitation damage. The work described is just a beginning, but indicates the possibility of doing extensive field research work on cavitation characteristics.

Some specific comments on the paper are as follows:

The author uses a figure of 60 fps for the velocity in the field at the point of measurement and states that this is based upon the flow rate and the linear and angular dimensions of the machine. As a matter of fact, the velocity at the point of field measurement is somewhat greater than the average velocity based on his method of calculation; thus, instead of being 60 fps, it was probably closer to 65 fps. This is in the direction of a better agreement between the field and laboratory results.

The variation in pitting between the high and low-pressure sides of the runner blades indicates that the cavitation may originate from overhanging wicket gates. There have been several cases of pitting on propeller turbines (with no outer band or shroud ring on the runner) where pitting occurred on the stationary ring in spots corresponding to the number of wicket gates. This pitting occurred several feet below the wicket gates, but owing to location and number of pitting spots they could only be attributed to cavitation originating at overhanging wicket gates.

The four most important facts established by the author’s tests and previous experiments along the same lines are as follows:

1. After cavitation starts, intensity of cavitation attack is not dependent upon size or shape of guiding surface.
2. Intensity of cavitation depends upon velocity and varies approximately as the sixth power.
3. Rate of pitting per unit of cavitation width is independent of length of cavitation area.
4. There is a close correlation between laboratory and field pitting rates for similar velocities.

The success of this work in the field suggests a large number of additional tests. One of the first of these, which would be a simple continuation of the tests already made, would be to make a test run for various gate openings on the Parker unit. The author made a test at zero load showing no cavitation attack and a test at full load showing pitting. Further tests at other gate openings would show the load at which the cavitation attack starts and also might produce other interesting information.

Tests under various conditions of tailwater, net head, and at various locations in the turbine would also be of great interest.

The hydraulic-turbine industry would be missing a golden opportunity if the technique described were not used for continuing field research and experimentation.

The author should be congratulated upon having originated the idea of this technique and upon carrying it to a successful conclusion.

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The author is well known for his many fine contributions on the subject of cavitation. His investigations of the cavitation process have kept the subject extremely active and one is greatly indebted, therefore, for his efforts to present the latest attainments relating to cavitation intensity.

In this paper the author presents some thought-provoking ideas and it appears to be a step toward linking laboratory technique to field conditions. He makes no sweeping conclusions but, rather, sets forth certain implications derived from a single field test. It is in this same vein that the discussers present some of their thoughts as inspired by the paper. None of their views contradict those of the author but, rather, presents a different point of view.

The author is to be congratulated on the technique used to obtain a record of the cavitation effects on a metal test strip attached to a cavitating member of a hydraulic machine under actual operating conditions. The fact that such a record can be obtained in a test of only a few minutes' duration is of extreme interest. On the other hand, however, the advantages of a short test may be far outweighed, in many cases, by the time of preparation and waiting for an opportunity to shut down the plant.

It is suggested in the paper that the record thus obtained would be indicative of the "intensity of cavitation," the term not completely defined yet. Whether this intensity of cavitation will be a measure of all the bad effects of cavitation, namely, noise, vibration, damage to performance characteristics, and blade pitting, the paper does not state. Noise, vibration, and damage to head-capacity performance can be ascertained on the shop test of the machine and means of measuring these bad effects of cavitation are available. Usually, all the foregoing effects appear together—but any one of these, noise, for instance, is a sufficient cause for rejection of centrifugal pumps. Also, there is a wealth of test information on record giving the relative resistance of different materials to cavitation pitting. Even when and if the term cavitation intensity is clearly defined, and better means of measuring it are developed, practical application may yet have to be demonstrated. Perhaps this will come with time.

In the method of recording the mechanical effects of cavitation as described in this paper, there are a number of factors which were taken for granted prior to the actual testing. The machine was known to cavitate, the location of the place where most of the cavitation damage was expected was definitely known, and it was known that the unit operates through a wide range of the performance curve. This latter condition cannot be changed even if it is ascertained that most of cavitation does occur when the machine operates far from the rated point. It would seem that the method described will not help to locate easily the places subject to cavitation.

The term cavitation intensity invites further comment. It will be noticed that all phenomena in the nature to produce a measurable effect involve a transfer of mass and energy. In fluid machines fluids are used as carriers of energy. To produce any effect there must be a "driving force" or "potential" which causes the effect to appear. The measured effect depends upon the mass involved and is usually expressed as a product of the potential and the rate of transfer of the energy or mass. The cavitation effects, i.e., noise, vibration, damage to performance, and loss of metal, also depend on two factors; one representing potential, and the other representing the "volume of cavitation," or size of the machine. From the paper one gets the impression that the author's term cavitation intensity is intended to unite both of the factors; i.e., potential and rate of producing the bad effects of cavitation. The writers cannot clarify the author's concept of cavitation intensity. In the writers' opinion, cavitation in a hydraulic machine is caused by the local pressure drop below that corresponding to the saturation pressure at the existing liquid temperature. The resulting thermal unbalance causes liquid to vaporize. Thus the deficiency in NPSH or excess temperature of the liquid is the potential causing the appearance of cavitation. The effect of the volume of cavitation can be seen from the fact that large machines (say, centrifugal pump) would produce considerable noise and vibration while a small one, operating under the same head and the same velocities, would have no objectionable cavitation effects.

Nothing is mentioned in the paper about the pressures, or submergence under which the test tunnel and the water turbine were operated. The discussers differ from the author on the meaning of the velocity in producing cavitation phenomena. To them, increased velocity is only one means to reduce the absolute pressure at the cavitation zone to the saturation pressure at the prevailing temperature. Provided that the absolute pressure is low enough, cavitation effects at low relative velocities may exceed those at higher velocities. While the author's presentation of the subject of cavitation leans heavily on the dynamic side of the phenomenon, certain aspects of cavitation are easier to visualize and better to define in terms of thermodynamic side of the process. For instance, "incipient cavitation" conditions exist when the pressure in the cavitation zone becomes equal to the saturation pressure of liquid at the prevailing temperature.

For the same dynamic conditions, cavitation effects are governed by the thermodynamic properties of the liquid. Furthermore, under the same dynamic conditions, (homologous machines under the same head) the "degree" of cavitation depends upon the time it takes for the liquid to pass the cavitation zone; thus in a larger machine the degree of cavitation is greater as the path is longer. There is experimental evidence to this effect.

Among other things, the tests described in the paper aim to establish a basis for a comparison of cavitation conditions for two geometrically dissimilar systems. A theoretical justification for such a procedure is not available yet. The experimental evidence presented in the paper is not sufficient to indicate the type of problems to which this method may be applied profitably. It may be pointed out at the same time that experimental evidence is accumulating to show that, for systems geometrically and dynamically similar, deviations from the Thomas law (sigma is constant) appear due to effects of time and physical properties of the liquid.

In his footnote 6, the author connects the intensity of cavitation with the "intensity of the hydrodynamic attack" of the liquid on the guiding surface in the zone of cavitation. Could not then intensity of cavitation be measured by the pressure on the vanes developed by the process of the vapor bubbles collapsing? Such pressures have been measured by several investigators, the results showing a great variation of such pressures. It is believed that the destructive effect of the bubble collapse depends on the absolute pressure of the system.

In their experience with centrifugal pumps the discussers have found it necessary to distinguish between two types of cavitation. The first occurs when the flow is approaching the impeller vanes with zero angle of attack, and the pump is operating at the design point. A slight variation of NPSH from that corresponding to incipient cavitation is sufficient to produce or suppress cavitation under such conditions. With a small deficiency in NPSH the vapor pressure is established across the whole impeller channel and the pump head-capacity curve drops off abruptly.

In the second type, cavitation appears as a result of "separation of flow resulting from a bad angle of attack, as occurs at partial
capacities in centrifugal pumps operating with ample NPSH to
develop the normal head-capacity characteristics. In this the
cavity is confined to a relatively small part of the impeller
channel. As a result, although noise, vibration, and metal pitting
appear, the head-capacity-curve continuity is not disrupted.
The cavitation due to separation does not respond to small
NPSH changes, the velocity and angle of attack being predomi-
nant factors. However, a change in inlet-vane angle is an effec-
tive means of reducing or eliminating cavitation caused by separa-
tion.

Thus, to have dynamically similar cavitation conditions, it is
necessary that two pumps operate at the same specific speed on the
head-capacity curves. When making cavitation observations
in the case of geometrically dissimilar systems it is not clear what
basis should be used for comparison of cavitation effects. It is
felt that a constant velocity certainly is not a sufficient criterion
for this purpose. It would be instructive to run the tests similar-
to those described in the paper under different pressures on the
system.

E. B. Strouhger. Professor Knapp's new technique appears
to promise good results in determining the intensity of cavita-
tion attack in hydraulic turbine runners. It makes use of proto-
type conditions and therefore should prove dependable in deter-
miming potential trouble spots of pitting on a runner. It does
not, however, answer the question of what metal to use to best
withstand the attack. For this the laboratory test should be
useful. Its principal use would be to determine where cavita-
tion might be expected to occur, for the purpose of improving
the design or determining where to apply a protective coat of
material more resistant to pitting than the parent material.
The present cavitation guarantees made by the manufacturer
are not very satisfactory from the user's point of view. The
runner is normally guaranteed against excessive pitting for one
year from the date the unit is placed in service provided the tail-
water level is not more than a stated distance below the center-
line of the distributor. Excessive pitting is defined as the removal
from the runner of metal aggregating more than a stated number
of pounds. The number of pounds stated is usually much larger
than would be satisfactory from the users' point of view.

Having determined by Professor Knapp's method that there
are areas of high intensity of cavitation attack on a particular
runner installation, the setting being fixed, about the only thing
that can be done to obviate pitting is to see that the areas so
determined are covered with material of high pitting resistance.
This knowledge will be useful to the manufacturer in indicating
how to improve conditions on the next job where this particular
runner is used, i.e. by modifying the bucket shape and/or lower-
ing the setting of the unit.

Author's Closure

One characteristic of a complicated physical phenomenon is
that it can be studied from several points of view, all realistic
and productive of factual information. Consequently, investi-
gators who study different aspects of the same phenomenon tend
to analyze its characteristics from their own viewpoints and to
overlook equally sound approaches. When two such individuals
discuss their conclusions with each other, it often develops that
while they feel that they are considering the same features, ac-
tually they are talking about different aspects of the phenomenon.
This seems to be the situation with regard to Mr. Kerr's discus-
sion of the author's paper.

It appears that the author has failed to make clear to Mr. Kerr
that the entire paper is concerned with field measurements of the
intensity of the hydrodynamic attack, not with the relative re-
sistance of various materials to cavitation damage. It is cer-
tainly true that flow systems have been used repeatedly to study
relative resistance of materials. The author saw such a system
demonstrated by Professor Föttinger in Berlin in 1929. In one
experiment he removed an appreciable amount of glass from the
wall of a venturi section by the action of cavitation, thereby con-
vincing the author that cavitation damage could occur without
any chemical action. However, such flow systems have been
used primarily to compare the relative cavitation resistance of
different materials under carefully standardized flow conditions.
There is little evidence of quantitative study of the intensity of
the hydrodynamic attack of cavitation as a function of velocity
or of using as a measure of intensity, the weight loss from spec-
imens of a single, carefully standardized material.

Mr. Kerr states that "the author's use of a relatively standard
material as a reference for damage evaluation follows the mag-
netostriiction procedure." The author wishes to emphasize once
more that no attempt was made to evaluate damage, and that,
unlike magnetostriiction tests, no material was removed from the
test specimens. The pits on the aluminum surface were plastic
indentations only.

Mr. Kerr feels that many variables affect cavitation [damage]
in addition to velocity, such as range of operation, tailwater
elevation, duration of operation. This is quite true, but also
quite irrelevant to the paper. The author's experiments seem
to indicate quite clearly that, for a given machine, whenever
cavitation occurs the cavitation intensity is primarily a function
of velocity.

Mr. Kerr refers to an interesting technique recently developed
by Rosenberg and Hafland10 for the study of cavitation damage
in turbines. He states that it is useful in establishing the effect
of factors other than velocity on the cavitation damage rate.
Previous to the arrival of Mr. Kerr's discussion the author re-
ceived a letter from W. J. Rheingans with a copy of Rosenberg's
paper. Mr. Rheingans commented as follows: "In Fig. 3 he
[Rosenberg] has plotted the wear of materials, as determined
by the radioactive point, against the turbine load. We have
determined the turbine discharge for these various loads and plotted
the discharge against the wear. This has indicated that the wear
is somewhere between the 5.4 and the 7.3 power of the dis-
charge. The discharge is a fairly close measure of the relative
velocity between the water and the guiding surfaces of the runner
where the radioactive point was applied. Thus, these pits
seem to be a remarkable check on your [the author's] experi-
mental data indicating that the intensity of cavitation varies as the
sixth power of the velocity." Rosenberg, in discussing his own
results, states that undoubtly the rate of loss of the radioactive
paint measures the cavitation intensity, and concludes that
"probably [it] also gives a true picture of the relative loss of
steel from the runner." He goes on to say that more experimental
study in suitable apparatus would be necessary to demonstrate
whether or not this assumption is correct. The author's con-
clusion is that Rosenberg's technique and the one proposed in the
present paper basically measure the same characteristics, i.e.,
the relative intensity of cavitation. They have many similarities
and a few differences. The radioactive paint has the advantage
of ease of application, but there is doubt as to the reproducibility
of its resistance to cavitation between different batches of the
paint applied to surfaces of different textures. The techniques
have one failing in common: They measure relative intensity
only.

Mr. Rosenberg feels all cavitation probably has high enough
intensity to damage structural materials. On the other hand,
the author feels that it has been demonstrated that the minimum
cavitation intensity at which damage begins varies widely with different material, and probably these limits are all above the intensities at which both of these proposed techniques give positive readings.

The author thanks Mr. Parmakian for supplying valuable additional information about the cavitation history of the turbine used in the experiments. This is a good example of the value of keeping adequate performance records. The Bureau of Reclamation is to be complimented upon this practice. The author agrees with Mr. Parmakian that in these tests the cavitation probably originated on the squared bottom end of the overhanging wicket gates and collapsed on the leading edges of the runner vanes, thus producing damage in a location that otherwise would have been cavitation-free.

Mr. Quick asks about the possibility of developing a coating to be applied either to a model or to a field machine to locate all the local cavitation regions for various conditions of operation. In the author's opinion, such a procedure would be more useful for field testing. In the laboratory it should be as easy, as well as more informative, to construct the model so that all cavitation-susceptible surfaces could be inspected visually, using stroboscopic or photographic techniques, to determine directly the size and shape of the cavitating regions. It is impractical to do this in the field; hence a diagnostic coating would be valuable. The author has had no experience with such coatings and hesitates to comment on the possibility of standardizing such a technique. He feels, however, that the best chances for success would be to use such a coating to define the area of the cavitation attack and to use independent methods for determining the intensity.

Mr. Rheingans in his formal discussion, increases the author's indebtedness to him for his interest in the paper. It is indeed rare for an author to have a discusser point out that the agreement between sets of experimental results is better than that shown in the paper! If, in accordance with Mr. Rheingans' suggestion, the three turbine test points (the triangles in Fig. 5) are shifted to the 65 fps line, they will straddle the laboratory curve in the maximum damage zone.

Mr. Rheingans, like Mr. Parmakian, suggests that the cavitation originated on the wicket gates. He cites as evidence cases of pitting on the stationary ring of propeller turbines in spots corresponding to the number of wicket gates, although the spots occurred several feet below the gates. The author has observed such cavitation zones in models of Francis turbines. Using stroboscopic illumination, the cavities from the lower end of the wicket gates were observed to extend down to the runner, and traveling cavities from these zones could be seen to impinge on the pressure sides of the runner blades, apparently collapsing there.

Mr. Rheingans' four-point summary of the most important experimental facts brought to light by the author's recent researches on cavitation damage is very clear and concise. It is feared that the papers were not as clear as this summary, and that the average reader has not been able to give them as much consideration as Mr. Rheingans has done. The suggestions made for additional tests are welcome. It is planned to extend the tests in these directions as soon as possible. It may be feasible to amplify the technique to include acoustic equipment capable of detecting the inception of cavitation. Such a technique would be valuable in determining the limits of cavitation-free operation. The author sincerely hopes that the entire hydraulic machinery industry, including manufacturers and operators, will not only read Mr. Rheingans' next to last paragraph, but will agree with it, because such a technique can be developed into a useful tool only with the co-operation of the industry.

Messrs. Stepanoff and Stahl have prepared an interesting and extensive discussion. In it they advance some important physical concepts upon which the author will try to comment. In general, the author feels that these discussers have assigned a broader significance to the results than he had envisaged, so that some of the points raised can be answered only by going beyond the content of the paper.

The discussers are concerned about the meaning of "intensity" of cavitation. An attempt was made to define this in the first sentence: "This proposed method of measuring the intensity or damage potential......" This was intended to mean the potential of the cavitation attack to cause physical damage, i.e., removal of material from the guiding surface. Both "intensity" and "potential" imply an amount per unit area rather than over-all amount. This concept was used in the section on test results. Here the emphasis was on the comparison of laboratory and field results of the size distribution of the pits and the measurement of pitting rates; i.e., pits per sec per sq in.

The author is sorry that the discussers received the impression that "cavitation intensity" included both the potential for doing damage and the area covered by the cavitation attack. The area is not included in the concept of intensity.

This discussion again emphasizes that there is a demand for a technique to delineate cavitation zones in field equipment. This is certainly not the objective the author visualized in undertaking these tests, nor is he convinced that this technique is suitable for such an objective. In undertaking these tests, the author's thoughts were approximately as follows:

1. Laboratory investigations of the effect of the cavitation attack on standardized soft metal test specimens indicates that the attack produces plastic deformation of the surface in the form of indentations or pits and that the pitting rate is a logical, although rough, measure of the intensity of cavitation.
2. Physical reasoning indicates that there should be a relationship between intensity of cavitation and the removal rate per unit area of a given material.
3. Pitting rate measurement shows that the intensity of the cavitation varies very rapidly with velocity, i.e., approximately as the sixth power.
4. These measurements also imply that the pitting rate may vary with the physical size of the guiding surface.
5. Intensity measurement on field equipment using the same type of standardized test specimens should give information about the effect of change in size of the guiding surface on the rate of pitting and the size and type of pits.
6. Such a program might bring us a step closer to the goal of predicting the cavitation damage characteristics of a given field installation from the design flow velocities, the pertinent liquid characteristics, the materials of construction, and the location and extent of the cavitation areas as determined by properly constructed model tests.

The author and the writers differ fundamentally in their concepts of the physical nature of cavitation. The author believes that the formation and collapse of a cavitation void is primarily a hydrodynamic process in which the motion of the liquid is controlled by the relationship between the applied forces and the inertia of the liquid. This process may be complicated by thermodynamic transfer of energy which results from the hydrodynamic change. He views boiling, on the other hand, as a thermodynamic process in which a liquid is vaporized by the addition of heat. The process is complicated by the resulting motion of the liquid induced by the growth of the vapor bubbles. Based on the thermodynamic concept of cavitation of the writers, a liquid which had no vapor pressure could not cavitate; from the hydrodynamic viewpoint, such a liquid is ideal, as the cavitation process would occur with full vigor, unaffected by the damping due to heat transfer effects. Such cavitation would exhibit all
of the major effects observed in real liquids—loss of performance, vibration, noise, and damage to the guiding surface.

In the hydrodynamic concept of cavitation, a cavity forms when the liquid ruptures as a result of its inability to withstand tension. Some liquids normally have a finite tensile strength; practically all liquids have relatively high effective tensile strengths when completely free from undissolved gas. Such liquids do not cavitate when the pressure drops below the vapor pressure. These and similar considerations make it impossible for the author to accept either the writers' concepts of the nature of the cavitation process or their definition of incipient cavitation. The author prefers the most elementary meaning of inception: The beginning, that is, the inception of cavitation, is the development of the first tiny cavity. In clarifying these differences in viewpoint, the author has no intention of implying that the thermodynamic properties of the liquid cannot affect the cavitation process. Unfortunately, most hydraulic engineers start their thinking about hydraulic phenomena with the implicit assumption that the liquid involved is cold water. Since the vapor pressure of cold water is very low, the cavitation process is little affected by the thermodynamics of the liquid. However, in hot water and other high vapor pressure liquids, especially those with high latent heat, the heat exchange involved in the vaporization and condensation of the contents of the cavities can alter significantly the course of the cavitation process and modify its effects on performance, noise, damage, etc. Messrs. Stepnoff and Stahl have been leaders in pointing out these facts and the profession owes them a debt of gratitude. It is hoped that they pursue their investigations vigorously, since there is much unexplored territory awaiting them.

Some points raised in the discussion are primarily matters of definition, e.g., "degree." The author agrees that degree refers to the size of the cavitation zone and contrasts with intensity. However, such terms may be used either in the relative or the absolute sense. In discussing model versus prototype performance, it is convenient to employ them in the relative sense; thus the degree of cavitation would be the same in both machines when the same relative area was covered in each.

In referring to footnote 6 of the paper, the writers inquire as to the possibility of measuring intensity of cavitation by determining the pressure on the guiding surface. They add that several investigators have tried this with widely differing results. The author believes it is possible, although very difficult, to measure intensity in this manner. A cavitation blow capable of causing damage affects a very small area on the guiding surface, and the time between blows on the same area is measured in minutes. Thus the average pressure on the surface is meaningless since the damage is caused by the peaks alone. Many difficulties must be overcome in the development of an instrument capable of measuring infrequent high pressures of very short durations covering only minute areas. The only simple method that comes to mind is the pitting record itself. Since the physical properties of the test plate are known, the size and shape of the individual pit is a measure of the individual blow that caused it.

The writers state that two types of cavitation are observed in pumps—one occurring near the design point, and the other being typical of operating conditions well removed from the design point. The author believes that both are actually the same type and that the observed differences are due to change in pressure distribution in the flow, not to differences in the type of cavitation. The writers state that when operating at the design point, a small change in inlet pressure causes cavitation to develop across the entire impeller channel, thus seriously affecting the head-capacity curve. Although there is no doubt that cavitation can have a major effect on the head-capacity curve, it is questioned whether or not cavitation develops throughout the entire impeller passage. Such a condition implies that in this region the vanes exert no force on the liquid, otherwise there would be a pressure difference across the cross section. Even if such a condition did exist at the vane entrance, the cavitation conditions should worsen in the downstream direction as the vanes began to change the direction of flow. In other words, cavitation would have appeared earlier in this region and would have been heaviest on the low pressure side of the passage.

In the final paragraph, the writers outline requirements for dynamically similar cavitation conditions in different machines. The author feels that such requirements are irrelevant to the subject, that is, cavitation intensity. For low vapor pressure liquids, if cavitation occurs, the intensity is determined primarily by the velocity at the free surface of the cavitation zone. This velocity depends uniquely on the average velocity in the cross section and the cavitation parameter. The relationship is

\[ V_a = V_a(K + 1)^{1/4} \]

where

- \( V_a \) = velocity along the cavity interface, and
- \( V_a \) = average velocity in the cross section

This is independent of the absolute pressure on the system, thus calling attention to one more lack of agreement between the author and the discussers.

The question raised by Mr. Strowger has been partially answered in the author's reply to Messrs. Stepnoff and Stahl. The author feels that the intensity of the cavitation attack is one of the essential measurements which must be made before the question of what metal to use in the construction of the machine can be answered. The magnetostriction tests of the relative resistance to different materials employ a standardized cavitation intensity. This intensity is high enough to cause measurable damage to practically all materials in a relatively short time. It is known qualitatively that different materials have different thresholds of cavitation intensity below which they do not show damage. However, as yet the concept of cavitation intensity has been rather vague, with no accepted unit of measurement. The technique proposed in the paper offers a rough quantitative measure of intensity under existing operating conditions. What is still lacking is the determination, using this same scale, of the threshold intensities for damage on specific materials, and the relationship between intensity and damage rate after this threshold has been exceeded. It should be possible to correlate the measured intensity obtained with these aluminum test plates with the standard intensity used in the magnetostriction tests, but an expansion of the techniques of the latter tests might result in reliable information concerning the damage threshold. It is probable that many of the uncertainties Mr. Strowger describes would be eliminated if this chain of information could be obtained.

The author wishes to express his appreciation to all of those who have discussed his paper, and especially to those who have gone to the additional trouble of preparing these written discussions. The remarks made have pointed out some of the aspects of the paper which were not clear. Furthermore, the preparation of the answers to some of the points raised has forced the author to clarify his own thinking with regard to some of the more obscure aspects of the cavitation process.