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Accelerated Field Tests of Cavitation Intensity

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The purpose of this paper is to describe a new technique for measuring the intensity of the cavitation attack in a piece of hydraulic equipment operating in the field, and to present the results and conclusions of a preliminary trial of this method in a 30,000-kw hydraulic turbine. This technique has been referred to as an accelerated test because the time required for the test run is measured in minutes, and by careful planning the total outage time required for installation and removal of the test plates is short.

Background

THIS proposed method of measuring the intensity or damage potential of cavitation in field equipment is an outgrowth of the laboratory investigation of the mechanics of cavitation and cavitation damage with which the author has been engaged for some years. The major piece of apparatus that has been used in this study is the high-speed water tunnel in the Hydrodynamics Laboratory at the California Institute of Technology.[2-5]

Aluminum Test Plates. Recently considerable attention has been concentrated upon the damage area in an attempt to determine which portions of the cavitation process are responsible for the attack upon the adjacent guiding surface. One of the useful techniques developed during this period is the use of annealed pure aluminum for the guiding surface in the cavitation areas. The individual blows which constitute the hydrodynamic attack of cavitation on the guiding surface leave a record on this soft ductile material in the form of individual indentations or pits. Microscopic examination of these pits shows that no material has been removed. They are simply plastic indentations produced by a mechanical blow. Much can be learned about the cavitation process from the study of the sizes of the individual pits, the rate at which they are formed, and the location of the pitting area with respect to that of the cavitation. Such data directly supplement the information obtained through the use of high-speed motion pictures of the cavitation zone.

Wide Adaptability of Test-Plate Technique. Although this technique was first employed simply to delimit the damage area, it was soon found that it could be used to obtain much additional information. New applications are continually being found. For example, this technique already proved useful in studying the effect of absolute size on the cavitation characteristics of geometrically similar guiding surfaces, and in the investigation of the damage characteristics of different types of cavitation. One of the most promising uses of this technique is to measure the cavitation intensity. This particular use is made possible not only by the character of the record left on the surface (plastic deformation with no material removed), but also by the fact that fully annealed, commercially pure aluminum (Type 2S-O) has reproducible hardness characteristics that are little affected by the size and shape of the piece, or by any forming, machining, or finishing processes that take place prior to annealing. Furthermore, the plastic deformation resulting from the application of a given load is relatively unaffected by the rate of application of the load. Another advantage of this particular material is that the force required to produce a plastic deformation is considerably lower than that required to exceed the elastic limit of any of the metals normally used in the construction of hydraulic equipment. In nearly all cases it is even below the endurance limit. Hence all blows of sufficiently high intensity to physically damage normal hydraulic equipment will be recorded on the aluminum. The pitting record can be evaluated simply by counting the pits, either directly by the aid of a low-power microscope or by the use of low-magnification photomicrographs. Knowing the time of exposure, as well as the surface area, the pitting rate—pits per second per square inch—can be calculated. Experiments have shown that this pitting rate is constant for a given velocity, but that it varies extremely rapidly with velocity. Several independent sets of measurements indicate that the rate increases with at least the sixth power of the velocity.

Optimum Exposure Time. In the determination of the pitting rate, the optimum time of exposure of the test plate to the cavitation varies with the velocity of flow. The criterion for determining the optimum is very simple. It is the time required to obtain enough pits per unit of surface to permit easy and accurate counting, but with a low enough density so that only a negligible number of overlapping pits is present to cause confusion.

Pitting Rate as a Measure of Cavitation Intensity. Soon after the investigation of the mechanics of cavitation was well started, the author began to feel the need for a quantitative measure of intensity of cavitation attack. At that time the nearest approach to such a measure was the rate of removal of material per unit of surface area. This is principally employed as a measure of resistance to cavitation damage as determined by the magnetostriction technique. However, standard, brass test specimens are used to check the performance of the magnetostriction driver, so that, in a sense, the damage rate on these specimens was a measure of cavitation intensity. Apparently no attempt has been made to adapt this weight-loss technique to the measurement of cavitation intensity in flow systems. This is probably fortunate. At normal flow velocities the weight loss per unit time is so low that long test runs would be required to obtain significant measurements. Also, it is now apparent that the rate of loss of a given material is a function not only of the

[1] Professor of Hydraulic Engineering, Hydrodynamics Laboratory, California Institute of Technology. Mem. ASME.

[2] "Laboratory Investigation of the Mechanism of Cavitation," by R. T. Knapp and A. Hollander, Trans. ASME, vol. 70, 1948, p. 419.

[3] "Cavitation Mechanics and Its Relation to the Design of Hydraulic Equipment," by R. T. Knapp, James Clayton Lecture, Proceedings of The Institution of Mechanical Engineers, series A, vol. 166, 1952, pp. 150–163.

[4] "Recent Investigations of the Mechanics of Cavitation and Cavitation Damage," by R. T. Knapp, Trans. ASME, vol. 77, 1955, p. 1045.

[5] "Further Studies of the Mechanics and Damage Potential of Fixed Type Cavities," by R. T. Knapp, Proceedings, Symposium on Cavitation in Hydrodynamics, National Physical Laboratory, Teddington, England, September, 1955.

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cavitation intensity, but of the corrosion potential of the particular material-liquid system as well. The pitting rate recorded on the surface of a standard aluminum test specimen apparently has none of these disadvantages, since the testing time is short and the formation of the pits involves no material removal and hence is insensitive to corrosive conditions. Therefore, the author has proposed this pitting rate as a rough measure of cavitation intensity.

Laboratory Versus Field Intensities. One of the problems that stimulated the proposal to use pitting rate to measure cavitation intensity concerns the relationship between the intensities experienced in the laboratory and in the field. In this connection, some of the pitting-rate studies carried out in the tunnel were very suggestive. For example, experiments with a given guiding surface showed that if the velocity were kept constant, the rate of pitting per unit of cavitation width (width being measured normal to the flow and parallel to the surface) is independent of the length of the cavitating area. This is surprising because the corollary to this statement is that the rate of pitting per unit area decreases as the size of the cavitation zone increases. Again, experiments on similar shaped surfaces of varying sizes gave no clear indications of appreciable differences in the pitting rates. Both of these results imply that the characteristics of the cavitation attack are determined more by the velocity and the physical properties of the flowing liquid than by the size or shape of the guiding surface, provided only, of course, that cavitation does occur.[6]

It must be remembered that these are implications rather than conclusions. The possible variations in size and shape of the guiding surface that can be investigated in a given water tunnel are relatively limited. However, such implications emphasize the importance of making comparable measurements in large hydraulic machinery operating under standard field conditions. Two important questions that arise out of these implications are (*a*) how do the laboratory and field pitting rates compare for the same flow velocity, and (*b*) what are the relative sizes of the pits in the two cases?

Need for Pitting-Rate Measurements in Field. A consideration of the possibilities of adapting this method of measuring cavitation intensity to field testing showed that if it could be carried out successfully, it should be able to give answers to these and similar important questions that up to this time have defied previous observers. Many of the potential advantages of this method are related to the short time of testing required to obtain a quantitative record. Obviously, hydraulic machines which may operate under cavitating conditions are constructed of the most cavitation-resistant material that can be justified economically. With such materials cavitation damage occurs rather slowly so that the rate of damage must be estimated by comparing observations made at relatively long time intervals. Unfortunately, these intervals are so long that usually they cover quite a wide range of operating conditions. Hence, it is difficult to be sure whether the damage was taking place all the time that the machine was operating or whether the attack was concentrated over a comparatively short time for one particular condition of operation. Occasionally, machines of identical design, installed under comparable conditions, have been found to have quite different rates of cavitation damage. Usually, however, in both installations the range of operating conditions has been too wide to make it possible to draw any conclusions as to the cause of the differences. Such questions should be answerable if a method could be found for determining quickly and easily the location and intensity of the cavitation attack.

[6] It is important to make a clear distinction between the terms, "inception," "degree," and "intensity" of cavitation. Inception means the first appearance of a cavitation zone. The flow conditions under which inception takes place are determined by the shape of the guiding surface, and, in the case of a vane or similar discontinuous surface, the angle of attack at which the liquid meets the leading edge. At least in the first approximation conditions for inception are independent of both size and velocity; that is, they follow the laws of geometric and kinematic similarity.

The degree of cavitation is the length of the cavitating zone along the direction of flow. It depends not only on the size and shape of the guiding surface, but also upon the amount that the system pressure is dropped below the value for the inception of cavitation. Again, in first approximation, the degree of cavitation obeys the laws of geometric and kinematic similarity.

Intensity of cavitation refers to the intensity of the hydrodynamic attack of the liquid on the guiding surface in the zones of cavitation. Since this is apparently unaffected by either size or shape of the guiding surface but is extremely sensitive to the velocity, it obviously does not obey the similarity laws.

Plan of Field Tests

General Requirements. It is one thing to try out a new technique in the laboratory and quite another to do it in the field. Laboratory equipment exists for the purpose of making experiments. However, hydroelectric power plants and pumping stations are installed to give service, and any experimentation that interferes is apt to be looked upon with disapproval. On the other hand, the development of a new technique is often a slow, tedious process. The fact that it is new means that there is a high probability of encountering unforeseen difficulties in putting it into operation. Thus many more factors have to be considered in planning the development of new techniques in a large field installation than are involved if the technique has been perfected already. It was felt that the development of this particular technique would be feasible only if a field location having the following characteristics could be found:

1 The test should be carried out on a machine known to be operating under cavitation conditions.

2 There must be enough time available in the operating schedule for several trials of the technique so as to permit the inevitable "debugging."

3 It is necessary to have the interest and co-operation of all of the personnel associated with the field installation because without this there is little possibility of obtaining satisfactory results.

4 The location should be reasonably close to the laboratory.

All four of these conditions were satisfied at the Bureau of Reclamation Power House at Parker Dam. Owing to a long series of low run-off years, the available flow in the Colorado River was below normal. Although this was bad for power generation, it offered two advantages to the proposed testing program:

(*a*) The turbines are known to cavitate during full-load operation when the tailwater is low.

(*b*) The river flow was so low that the plant had to be operated at part capacity. Hence time was available for the installation and test of this new method without causing any loss of generating capacity.

The Parker Dam plant also satisfied admirably the other two conditions since everyone concerned with the plant was interested in cavitation problems. Furthermore, Parker Dam is only about 5 hr driving time from the Hydrodynamics Laboratory.

Description of Test Turbine. The machine made available for the test was Unit No. 2, a Francis-type turbine with a rating of 40,000 hp at 94.7 rpm. The runner has 15 vanes, the case 20 gates. During the program the operating head was 80 ft, the rate of flow approximately 5800 cfs, and the tailwater level was from 1 to 3 ft below the discharge edges of the runner vanes. It was necessary only to shut the gate and drain the penstock to make the entire vane area accessible.

Preparations and Plans. The entire program was organized to minimize the down time of the turbine and cause the least possible interference with plant operation. The general features of the proposed plan were to inspect the turbine and select test areas on the first visit to the field; preform a series of interchangeable test plates in the laboratory to fit each test area; then return to the field, install the test plate, and make a series of measurements. Before the first field trip, several methods of determining the contour of the test areas were tried and techniques were developed to preform the test plate. After studying the size and shape of the runner vanes and passages, it appeared that the test plate should be at least $^1/_8$ in. thick, and that it could be fastened directly to the vane without interfering appreciably with the flow and cavitation patterns. It was decided to make a cast of the vane areas selected for test, then return to the laboratory, make a replica of the vane surface from this cast, and preform the plate to fit the replica. Several techniques of making the cast were tried out in the laboratory before the first field trip. The most satisfactory results were obtained with plaster of paris applied in several layers before setting was complete until sufficient thickness was built up to give the necessary rigidity. It was found that light reinforcing rods could be imbedded in the plaster during the layering process. These greatly increased the rigidity and strength of the cast. A suitable release agent for use with relatively rough iron surfaces was found to be the colorless "light mineral oil" sold in drug stores. With this oil the cast adhered tightly to the surface until setting was complete, after which it could be removed easily.

First Field Trip. The laboratory crew found upon arrival at Parker Dam that the turbine was drained and opened for inspection. Two cavitation regions on the runner vanes were found suitable for the installation of test plates; namely (a) on the low-pressure side of the vane near the discharge edge, and (b) on the vane immediately downstream from the entering edge adjacent to the shroud fillet. Both areas show evidence of moderate cavitation pitting. The cause of cavitation at (a) appeared to be the vane design. At (b) it seemed to be due to a combination of the contour of the leading edge and shroud interference. It was decided to install the first test plates in location (b) primarily because of accessibility, and secondarily because here the problem of fastening the plate and of fairing-in the leading edge could be simplified greatly by bending the plate in hairpin form around the leading edge, thus insuring a strong mounting and avoiding all discontinuities in the flow. Vanes Nos. 6 and 8 were selected for test. Measurements showed that these vanes were so similar that a single drilling template might suffice for both. Plaster casts were made of both vanes, and each cast was marked to show the area to be covered by the test plate.

Construction of Test Plate and Drilling Template. At the laboratory vane replicas were made from the two plaster casts, using a hard, strong material called "Hydrostone." Some difficulty was experienced in finding a suitable release agent, since most materials are absorbed too rapidly by plaster of paris. Liquid soap was found to be satisfactory. A vane replica and the cast from which it was made is seen in Fig. 1.

The test plates were made from factory-polished 2S-O aluminum sheet. As received, the polished side of this sheet is covered with a tough, stripping-type adhesive paper. The plates were first bent around the leading edge of the replica, and then finish-formed, using a rubber hammer and a rubber protective sheet. The test plates were then annealed in an electric oven at 650 F for 2 hr. The protective paper was removed carefully before heating, and replaced after the annealing process was complete. After annealing, hardness is approximately 21 Brinnell. Fig. 2 is a test plate ready to install on the turbine vane.

Surface Characteristics of Test Plate. As previously stated, the aluminum sheet from which the test plates were made was factory-polished. This finish is far from ideal for these tests. Examination with a low-power microscope shows that it is covered with scratches and other imperfections. However, it is comparatively

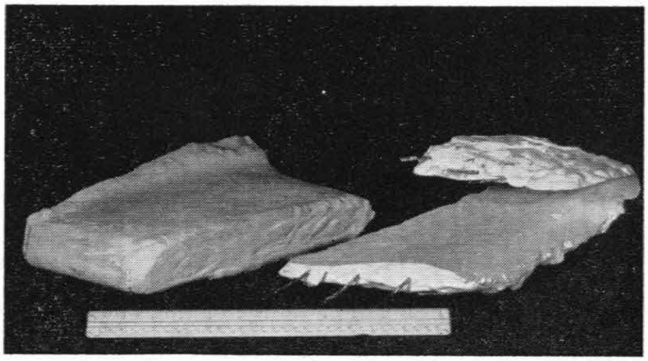

FIG. 1 VANE REPLICA AND FIELD CAST

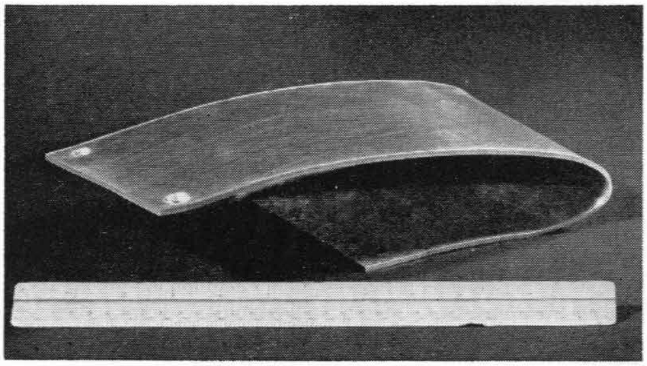

FIG. 2 PREFORMED TEST PLATE

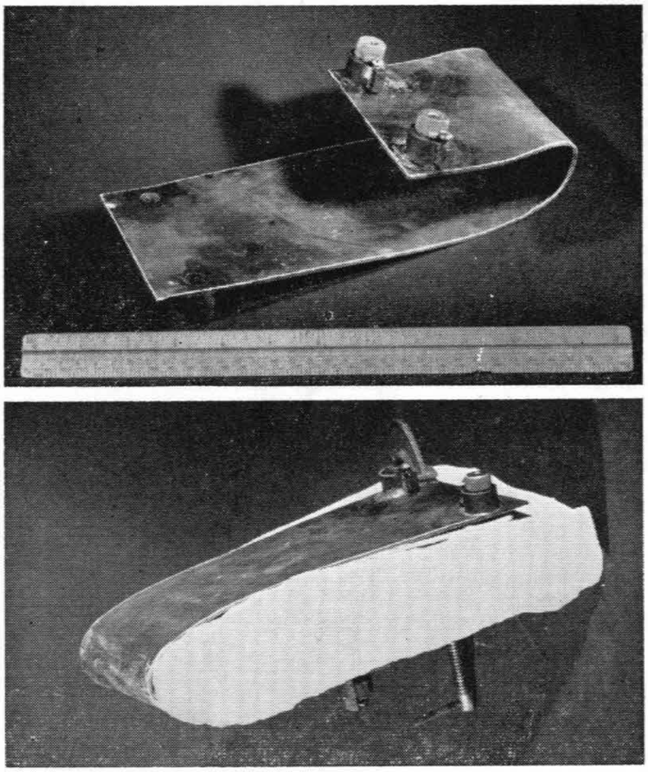

FIG. 3 DRILL JIG, WITH AND WITHOUT SPACER

free from blemishes that might be mistaken for cavitation pits. Since it is extremely difficult to obtain a satisfactory metallographic polish on a material as soft as this aluminum, it was decided not to try to improve the surface finish for these exploratory tests. The test plates were re-examined after forming and annealing. The area of the sharp bend had been so overstressed that the surface had developed a dimpled, "orange peel" appearance. Since this was not considered to be an area of potential cavitation damage, no attempt was made to hand-polish it at the risk of spoiling the plate.

It was decided to fasten the test plate to the vane with four $^1/_4$-in. 28-thread flathead hexagon socket screws. A drilling jig was constructed to fit the test plate, using interchangeable drilling bushings for the tap and body drills. To make it possible to use the same jig to drill both the vane and the test plate, one of the latter was used as a spacer when drilling the vane. Fig. 3 shows the drilling jig both alone and mounted on the vane replica with spacer in place.

One step in the water-tunnel technique of using aluminum test surfaces is to preselect the area to be evaluated and to make photomicrographs of this area before the test. These are used as references during the subsequent analysis of the area to determine whether given blemishes were present before the test or formed during the test. This is simple in the water-tunnel runs because the location of the damage zone is known accurately. This is not the case in the field tests. Although the test-plate location was an area of known cavitation, there was no way of estimating just how much and what part of the plate would be covered by cavitation at the particular load of the test run. Since it is impractical to photograph the entire area even at the lowest usable magnification, this step was omitted from the trial runs.

Test Procedures

When these preparations had been completed, a second trip was made to Parker Dam. The objective of this second trip was to drill the vanes, install the plates, and make some test runs. Although trouble had been anticipated in drilling and tapping the vanes, luckily none developed, so it was possible to install the two test plates and make the first run in one day. Three additional runs were made the second day, thus completing the series successfully. It was found that a complete cycle could be made in $2^1/_2$ to 3 hr. This included shutting down the unit, closing the penstock gates, draining the penstock and case, mounting the test plates, closing and filling the unit, raising the gate, bringing the unit up to synchronism, loading, making a test run, and shutting down the unit. This was very pleasing because it represents a minimum interference with plant operation.

The schedule of test runs is given in Table 1.

TABLE 1 SCHEDULE OF RUNS

Run no.	Test Plate Vane 6	Vane 8	Load	Duration, min
1	6A	8E	Full	5
2	6B	8F	0	10
3	6B	8F	Full	10
4	6C	8D	Full	20

Objective of Run No. 2. Runs Nos. 1, 3, and 4 were normal test runs. No. 2 was a check run to determine if any detectable cavitation occurred during the starting, stopping, synchronizing, and running of the unit at "no load." Approximately 5 min were required to bring a unit up to speed and synchronize it at no load. Another 5 min were taken to bring the machine to rest from the loaded or unloaded condition. The time required to apply the load was approximately $^1/_2$ min. Observations made of the wicket-gate-control-piston movement showed that the first audible indication of cavitation occurred at approximately 80 per cent of full-load gate opening. This implies that the test plate is subject to cavitation attack only while the unit is running at full load. However, since the time of starting, stopping, and applying the load is comparable to the full-load running time, it seemed better to get some direct evidence in this matter. The procedure for run No. 2 was identical with that of the other runs except that after the machine was synchronized with the line it was run under no-load conditions for 10 min, and then shut down for inspection. A careful examination of both sides of each plate was made, especially in the critical damage areas found on the test plates of run No. 1. A relatively high-power hand magnifier and extension light were used. No signs of pitting were found. Hence it may be concluded that the pits on the test plates of runs Nos. 1, 3, and 4 were all formed during the full-load operation.

Since no pitting occurred during run No. 2, the test plates 6B and 8F were left undisturbed on their respective vanes, and run No. 3 was started immediately.

Subsequent Treatment of Test Plates. Experience with 2S-O aluminum in the water tunnel indicated that, after exposure to cavitation attack, this material has a tendency to surface corrosion. The test plates were therefore removed from the vanes as soon as the turbine could be shut down, carefully rinsed with distilled water and oven-dried to remove all moisture. After cooling, they were wrapped in abrasive-free paper to prevent damage, and taken to the laboratory to be photomicrographed.

Provisions for Future Tests. The only alterations of the turbine that were required for these tests were the four $^1/_4$-in. tapped holes drilled in each vane. It is planned to weld these full at the completion of the work. Since additional tests on this unit are contemplated within the year, flush plugs were cut from a threaded stainless-steel rod to fit each hole and a slot made in one end for a screwdriver. These were lubricated with pipe dope and set snugly. This technique seemed advisable since the holes are adjacent to cavitating areas, and thus, if left open, might focus the cavitation attack and not only destroy their future usefulness, but also increase the damage rate.

Test Results

Behavior of Test Plates. Although the test plates had been fitted carefully to the contour of the vanes, at the end of each run they were found to be bowed out on the low-pressure side. The fit on the high-pressure side was unchanged. The maximum amount of this bowing was approximately $^3/_4$ in. This is obviously enough to change the local effective curvature of the vane. It is probable that the effect of this change was to reduce the degree of cavitation upstream from the point of maximum bowing, and to increase it downstream from this point. It is believed that the over-all effect was to shift the area of cavitation damage slightly downstream and perhaps change its size. However, judging from the water-tunnel results, the total number of pits per unit width of a cavity should not be affected. Obviously, this bowing is undesirable and should be eliminated, probably by installing additional "hold-down" screws before further tests are made. However, it seems unlikely that its effects could have been great enough to cause any significant change in the over-all character of the results or to alter the conclusions that have been drawn from them.

Pitting Zones. All tests plates from one vane showed consistent performance. However, an appreciable difference was observed between the pitting record from the different vanes. The test plates from vane No. 6 showed fairly heavy pitting on the low-pressure side; only slight traces of pitting were found on the high-pressure side. On vane No. 8 the pitting was quite light on the low-pressure side; whereas on the high-pressure side it was noticeably heavier. Of course, both vanes have the same design shape. The difference in performance must therefore be due to variations in shape introduced during manufacture. During the initial inspection, noticeable variations in the shape of the entering edges were observed near the shroud. One reason for selecting vanes Nos. 6 and 8 was that they appeared to be more similar in shape than many of the others. Apparently, the remaining differences were sufficient to cause the shift in pitting pattern. The fact that some pitting was observed on both sides of each vane implies that at full load the inlet angle of the water is nearly equal to the design angle. It also implies that the curvature of the edge is a little too abrupt for best cavitation performance.

Size of Pits. First the test plates were examined visually under the microscope. The pitting zones appeared quite similar to those produced in the water tunnel. Photographs were then taken of selected areas, and pit counts made using the same four classifications of pit size as those employed in the water-tunnel tests:

Pit classification	Small	Medium	Large	Extra large
Diameter range, in.	Below 0.0025	0.0025 to 0.005	0.005 to 0.010	Above 0.010

This classification proved to be adequate. However, it soon became apparent that the size distribution was significantly different in that the relative number of pits falling into the three larger classes was higher.

The water-tunnel results had indicated that the relative number of large pits increased with increase in velocity. Although the relative velocity of the flow with respect to the vane could not be measured during the turbine tests, a rough estimate of 60 fps was made for this velocity on the basis of the flow rate and the linear and angular dimensions of the machine. The water-tunnel tests at 60 fps produced no pits in the three upper size groups. At 100 fps, 5 per cent of the pits fell in this size range. In the turbine runs the average of the pit counts on the three test plates of vane No. 6 showed 20 per cent of the pits in the three upper size groups. Furthermore, one fourth of these, or 5 per cent of the total, were in the extra large classification.

Pitting Rate. These pits are smooth, round indentations. It is always difficult to obtain satisfactory illumination to make such details stand out clearly in a photomicrograph. Thus small differences in the angle of incidence of the illumination has a great effect on the pitting visibility. By chance, the photomicrographs of the test cylinders from the water tunnel showed two symmetrical bands of excellent illumination in which reliable pit counts could be made. It proved to be very difficult to get equally satisfactory micrographs of the flat turbine test plates, chiefly because of the poor surface of the factory-polished aluminum. The micrographs in Fig. 4 compare, at the same magnification, the final result with the best counting area of the laboratory test specimens. Owing to the roughness, counting the small pits was slow and difficult. Hence time permitted counts only on the low-pressure side of vane No. 6. The same areas were counted for runs Nos. 1, 3, and 4, which were, respectively, 5, 10, and 20-min runs. Duplicate counts were made by two observers. The average of the six counts is 5.05 pits per sec per sq in., with maximum and minimum counts of 7.24 and 3.21.

Fig. 5 shows how this pitting rate compares with the water-tunnel measurements. In this figure the solid and dashed curves show the results of the water tunnel tests. Two experimental points are plotted for each velocity at which the test was made—the cross giving the pitting rate in the zone of maximum damage and the circle, the average rate over the entire damage area. The triangular points plotted at 60 fps are the field measurements from the turbine tests. In the water tunnel the extent of the cavitation zone could be determined accurately by direct visual observation. In the field tests it can only be assumed that the cavity springs clear near the leading edge of the vane. The pit-count area covers only the portion of the cavitation zone in which the pit density is relatively high. Hence this count is probably more representative of the maximum than the average pitting rate.

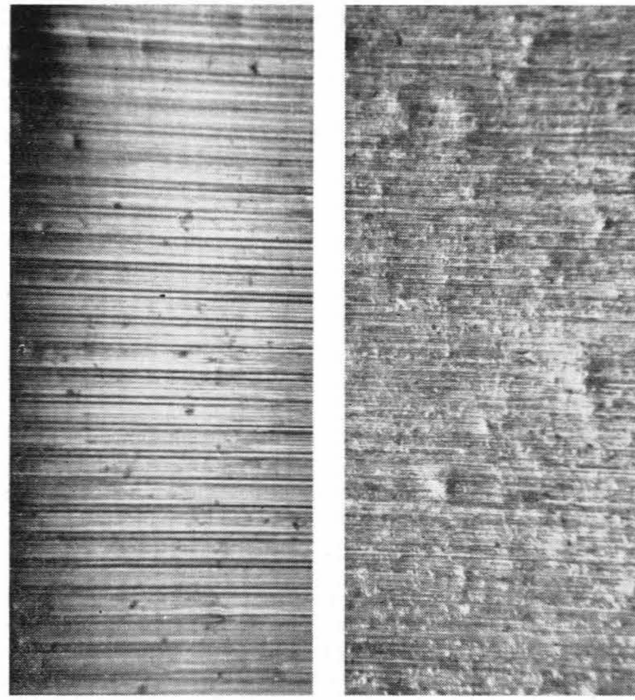

Fig. 4 Comparative Appearance of Laboratory (*left*) and Turbine (*right*) Pitted Test Surfaces

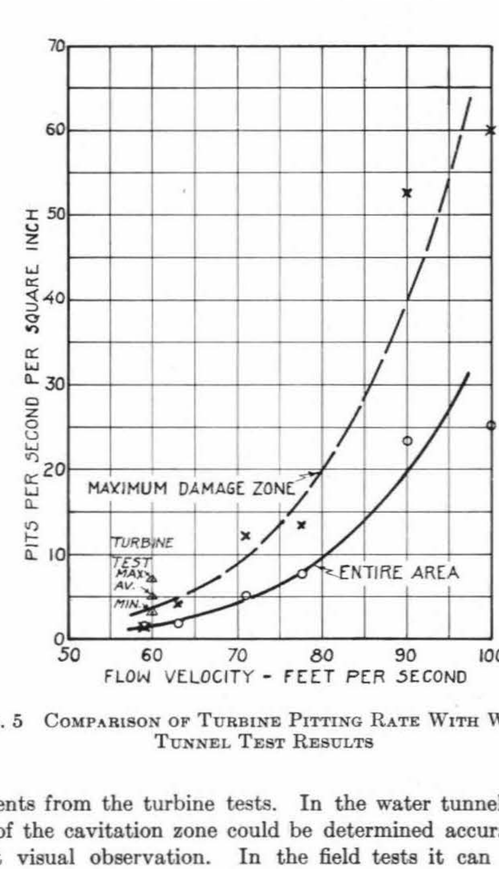

Fig. 5 Comparison of Turbine Pitting Rate With Water-Tunnel Test Results

Discussion of Test Results

Test Procedure. These preliminary tests have demonstrated the feasibility of this technique for use in studying the cavitation characteristics of operating machines. The $^1/_8$-in. aluminum plate is apparently heavy enough to give a satisfactory pitting record. The plate must be fastened securely, especially in exposed locations. The planning of the tests to minimize shutdown time worked very satisfactorily. The preforming of the test plates and the use of the drill jig were major factors in eliminating excessive down time.

Relative Significance of the Pitting Record. These results were obtained in one short series of tests under a single operating condition. However, although it would be unwise to base any extensive set of generalizations upon them, they have clarified several important points:

1 The soft aluminum test plates, and presumably other ductile materials in the same range of hardness, give useful pitting records under field-cavitation conditions known to be severe enough to cause appreciable damage to the machine.

2 Adequate pitting records can be obtained with runs of very short duration.

3 The fact that, within the limits of accuracy of the field tests, the pitting rate for a given flow velocity is the same in the laboratory as it is in the large turbine, tends to confirm the previously expressed concept that the pitting rate is primarily a function of the flow velocity and the properties of the liquid rather than of the physical size of the guiding surface.

4 Qualitatively, it is not surprising that at the same flow velocity the percentage of large pits is much greater in the field tests than in the laboratory. Investigations in the water tunnel showed that, velocity remaining constant, the relative number of larger pits increased with cavity length, while the total rate of pitting remained constant. The statement made that in the water tunnel no large pits were found at the 60-fps velocity of the turbine test, was based on cavity lengths of 1 or 2 in. The probable length of the cavity in the field test was 6 to 8 in.; thus more large pits would be expected. However, an increase from practically nothing to 20 per cent cannot be explained by this factor alone. Another possible reason for the number of large pits recorded in the turbine tests is that probably there was a higher concentration of large nuclei in the turbine flow than in the water tunnel, in spite of the fact that Colorado River water was used in both cases. The water flowing through the turbine at Parker Dam is untreated in any way. It has a relatively high sediment content and a high concentration of dissolved salt. However, the Metropolitan Water District softens and filters the portion of the aqueduct flow that is used for domestic and industrial purposes in the Los Angeles metropolitan area. Hence the nucleus content in the water used to fill the tunnel in Pasadena is much lower than in the original river water, and presumably the average size of the remaining nuclei is much smaller. Furthermore, it is believed that the continued recirculation in the water tunnel, at least a portion of which is with cavitation in the working section, tends to reduce the gas-nucleus concentration still further.

5 There is nothing inconsistent in the findings that the pitting rate is the same in the tunnel and in the turbine, whereas the percentage of larger pits is much greater in the turbine. In the first place, the high-speed motion pictures of cavity surfaces show that such surfaces are usually completely covered with small traveling cavities. On the average they seem to reach their final size near the upstream end of the cavity. However, a few appear to continue their growth over a longer path at the expense of the surrounding cavities; i.e., these become smaller. Hence neither the number of cavities nor their average size is affected appreciably by this growth. The fact that the cavities surrounding a growing one are probably forced to decrease in size should have little or no effect on the pitting rate, since the probabilities are that these cavities are smaller than the minimum size that can cause damage. The water-tunnel investigations showed that for a velocity of 90 fps only about one in 20,000 traveling cavities was of the proper size to produce a pit of any kind.

Conclusions

In general, this technique for determining pitting rate seems to be as feasible for use in the field as it is in the laboratory. Pitting rate is believed to be the most suitable measure yet available of the relative intensity of the cavitation attack. It is not anticipated that pitting rate alone will furnish a sound basis for the prediction of damage rate, because no account is taken of the important contributing factor of chemical or electrochemical corrosion. It would seem that a similar measure of the corrosion potential should be attainable by chemical tests of samples of the liquid and the material of the guiding surface. It is not unreasonable to hope that in the future a good prediction of damage rate may be obtained by combining these two measurements.

The relationship between pitting rate and cavitation intensity needs further investigation. Although the concept "cavitation intensity" is not yet clearly defined, it would be desirable to so define it that there would be a 1:1 correspondence between intensity and rate of removal of material from a standard test surface. It is rather improbable that the simple concept of pitting rate will fill this qualification. It seems likely that a more sophisticated measure which takes into account the area or volume of the pits formed as well as number per unit of time will be necessary.

These preliminary field investigations should be extended to cover a wide variety of conditions, in particular, a wide range of the flow velocities in the cavitation regions. These first results imply that the pitting rate may be independent of the size or design of the equipment, affected only by changes in velocity or in physical properties of the liquid. If this should prove to be true, it would be an extremely important finding with far-reaching implications in the design and operation of hydraulic equipment.

Acknowledgments

The author wishes to thank the organizations and individuals whose active help and co-operation have made this study possible. In the Bureau of Reclamation Mr. L. N. McClellan, Chief Engineer, personally approved the undertaking and made the turbine available for the study. Mr. John Parmakian, Head, Technical Engineering Analysis Section, not only helped with the detailed arrangements for carrying out the tests at Parker Dam, but freely shared his wide experience in testing large units. Mr. F. H. Sweany, Chief, Parker Dam Field Division, his operators and maintenance crew, gave their wholehearted co-operation in making the tests a success. Mr. R. B. Diemer, General Manager and Chief Engineer, Metropolitan Water District, extended the hospitality of the field headquarters to the laboratory staff during their field trips.

Thanks are also extended to the Mechanics Branch of the Office of Naval Research for permission to use a portion of the time of the staff of their project NR062-166 on these tests, and to the project members themselves for their interest and co-operation.

Discussion

S. L. Kerr.[7] 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.[8] 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.[9] 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.[10]

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.

[7] Consulting Engineer, Flourtown, Pa. Fellow ASME.

[8] "Pitting Resistance of Metals Under Cavitation Conditions," by J. M. Mousson, Trans. ASME, vol. 59, 1937, pp. 399–408.

[9] "Determination of the Relative Resistance to Cavitation Erosion by the Vibratory Method," by S. L. Kerr, Trans. ASME, vol. 59, 1937, pp. 373–397.

[10] "Wear of Francis Turbines Due to Cavitation Effects. Studies During Operation by Means of Radioisotopes," by Kjell Rosenberg, World Power Conference, Vienna, Austria, June, 1956. Paper No. 192/H/44.

John Parmakian.[11] 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

[11] Head, Technical Engineering Analysis Section, Bureau of Reclamation, Denver, Colo. Mem. ASME.

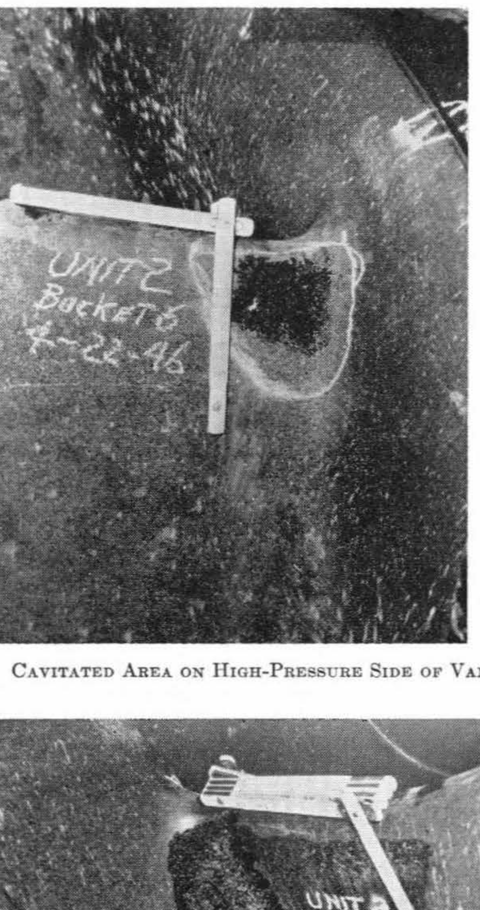

Fig. 6 Cavitated Area on High-Pressure Side of Vane 6

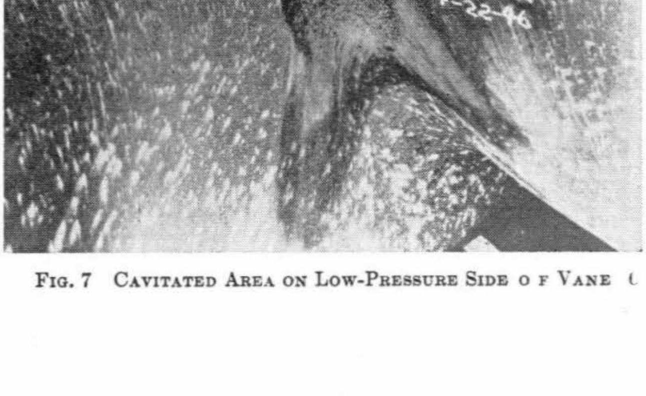

Fig. 7 Cavitated Area on Low-Pressure Side of Vane 6

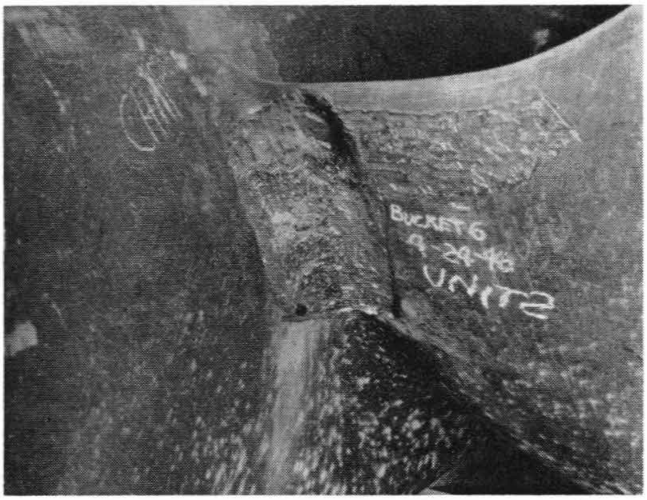

FIG. 8 LOW-PRESSURE SIDE OF VANE 6 DURING REPAIRS

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.[12] 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.

[12] Consulting Engineer, Baldwin-Lima-Hamilton Corporation, Philadelphia, Pa. Fellow ASME.

W. J. RHEINGANS.[13] 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 cavitating area.

4 That 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.

[13] Manager, Hydraulic Department, Allis-Chalmers Manufacturing Company, Milwaukee, Wis. Mem. ASME.

A. J. STEPANOFF[14] AND H. A. STAHL.[15] 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 contradicts 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, its 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 cavitating 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 Thoma's 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

[14] Development Engineer, Cameron Engineering Department, Ingersoll-Rand Company, Phillipsburg, N. J.

[15] Ingersoll-Rand Company, Phillipsburg, N. J.

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 predominant factors. However, a change in inlet-vane angle is an effective means of reducing or eliminating cavitation caused by separation.

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. Strowger.[16] Professor Knapp's new technique appears to promise good results in determining the intensity of cavitation attack in hydraulic turbine runners. It makes use of prototype conditions and therefore should prove dependable in determining 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 cavitation 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 users' 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 tailwater level is not more than a stated distance below the centerline 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 lowering 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, investigators 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, actually they are talking about different aspects of the phenomenon. This seems to be the situation with regard to Mr. Kerr's discussion 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 resistance of various materials to cavitation damage. It is certainly 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 convincing 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 specimens 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 magnetostriction procedure." The author wishes to emphasize once more that no attempt was made to evaluate damage, and that, unlike magnetostriction 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 Hafland[10] 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 received 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 paint, 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 discharge. The discharge is a fairly close measure of the relative velocity between the water and the guiding surfaces of the runner where the radioactive paint was applied. Thus, these pits seem to be a remarkable check on your [the author's] experimental data indicating that the intensity of cavitation varies as the sixth power of the velocity."[4,5] Rosenberg, in discussing his own results, states that undoubtedly 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 conclusion 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

[16] Chief Hydraulic Engineer, Niagara Mohawk Power Corporation, Buffalo, N. Y. Mem. ASME.

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 readers have 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. This should reduce the number of aluminum test plate runs needed to determine 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 contents 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 overall 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 so measured 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 measurements 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 to 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. Stepanoff 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.[4] 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

$$V_c = V_a(K + 1)^{1/2}$$

where

V_c = 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. Stepanoff 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 employs 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 these 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.