THE UNIVERSITY OF MICHIGAN

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CAVITATION AND EROSION DAMAGE MEASUREMENTS WITH RADIOISOTOPES

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I. INTRODUCTION

Cavitation and erosion investigations are hindered by the lack of a reliable method for the continuous measurement of the rate of material removal. This damage rate is essential as a criterion in the determination of (1) the cavitation and erosion resistance of structural materials, (2) the effects of various liquids, and (3) the effects of varying certain parameters (such as experimental geometry, temperature, etc.).

In the case of metals, cavitation (and erosion) damage appears in the form of pits on those surfaces which are exposed to the flowing liquid. Direct weighing methods for determining the weight loss of pitted test specimens are usually difficult due to the very small amounts of metal worn off in a convenient test interval, the effects of corrosion (which may actually result in a weight increase), and the need for periodic dismantling of the equipment. Other methods of characterizing damage rates are usually time consuming, non-continuous, and inaccurate.

In this experiment, a radiotracer technique has been developed for the continuous measurement of cavitation-erosion wear in a closed-loop venturi facility. Using this method, the wear rate of type 302 stainless steel due to a constant cavitation field has been determined as a function of time. In addition, a particulate size determination of the cavitation wear debris has been made.

II. CAVITATION WEAR MEASUREMENTS WITH RADIOISOTOPES

This method for determining wear rates involves the irradiation of metal test specimens in a nuclear reactor creating certain radioactive isotopes in the material. With sensitive (but commercially available) electronic instruments, the activity of extremely minute amounts of this metal may be measured. For homogeneous metals, the activity is directly proportional to the weight of radioactive metal present.

In the present experiment, two irradiated stainless steel wear specimens were exposed to a constant cavitation field in a venturi section, located in a closed-loop water tunnel containing 6.6 gallons of recirculating water. The facility is described in detail in Reference 1. When wear occurs on the specimens and bits of metal are worn off, the water in the system becomes radioactive. Assuming homogeneous mixing, the radioactivity of the water is directly proportional to the amount of wear occurring on the metal specimens. Due to the high rate of flow (40 GPM) and the consequent agitation to the system, the assumption of homogeneity is justified.

The radioactivity level of the water can be determined at any desired time by withdrawing a small sample and testing in a well-type scintillation counter or similar instrument. In the present system, over 25 water samples of the required volume (~5 ml) may be taken without changing the total volume of water in the tunnel by 1 percent. It was found to be inconvenient from the viewpoint of handling and safety to use specimens irradiated to the level where direct counting of activity in the main stream, using an externally mounted counter, would be practical.

The system may be calibrated by preparing a standard solution of the radioactive metal by dissolving a small weighed piece from one of the specimens in a known volume of acid. The activity of a measured portion of the solution is determined with the counter on the same day that the radioactive water is tested. Thus, corrections for radioactive decay, crystal efficiencies, etc. are avoided. The total cumulative weight loss from the specimens may then be calculated at a given time, and the wear rate determined by differentiating the weight loss versus time curve.

III. PARTICULATE SIZING OF WEAR DEBRIS

A direct measurement of cavitation wear particles, nearly impossible using ordinary methods, has not been made previously as far as the authors know. The particles are extremely small and indistinguishable ordinarily from other system impurities. However, after a radioactive wear run, the fluid in the system contains wear particles which now may be identified by means of their radioactivity. The only radioactive particles present are the cavitation wear particles from the irradiated test specimens.

The size of the particles may be determined by pumping the radioactive fluid through a series of filters arranged in order of decreasing pore size (with respect to the direction of flow). The filter rack is carefully dismantled and the individual filters tested for activity level. The activity level represents the relative weight of cavitation debris stopped by that filter, but which had passed through the pores of the previous filter. From this information, an estimate of the particle size distribution may be made.

Very special filters are required for these measurements. It is important that the filters do not catch an appreciable number of those particles <u>smaller</u> than the filter rating. This sieving effect can be obtained only if the size of the pores in the filter is controlled to a high degree of precision.

IV. EXPERIMENTAL FACILITY

The cavitating venturi allowed the insertion of two metal test specimens (3/4 inch x 1/2 inch x 1/16 inch) into the cavitating region for damage tests. About 0.15 inches of the 3/4 inch dimension projected into the stream, so that a metal surface area of 0.317 square inches was exposed to cavitation per specimen.

A filter rack, accommodating four 47 mm. diameter filters in series, was inserted into a by-pass stream of the cavitation loop. The filter stages were sealed in such a manner that <u>all</u> the water entering the filter system must pass through each filter. By suitable valve adjustment, any desired fraction of the circulating water may be passed through the filters.

Silk bolting cloth filters are commercially available down to a 64 micron pore size. Membrane filters are available in 16 porosity grades ranging from 10 millimicrons to 10 microns.(2) The membrane filters are composed of a thin cellulosic porous material containing millions of capillary pores per square centimeter of filter surface. These pores are essentially direct channels through the filter and are controlled to an extraordinary degree of precision. For example, the total range of pore size distribution in one type of filter, with a mean pore size of 0.45 microns, is plus or minus 0.02 microns. The distribution is shown in Figure 1. These pore sizes are precisely measured in manufacture by means of high pressure mercury intrusion studies and by actual filtration tests with particles of known size such as specific bacteria and viruses.

The pores which pass through the cellulose matrix occupy 80-85 per cent of the total filter volume. Consequently, extremely high flow rates are possible. For example, the flow of water through the above filter is 20 GPM per square foot at 15 psi.

V. EXPERIMENTAL PROGRAM

A. Choice of Experimental Conditions

Stainless steel Type 302 was selected as the material for the wear specimens since it had been tested extensively previously in the facility, because of its high technological importance as a structural material, and because of its favorable nuclear properties relative to irradiation.

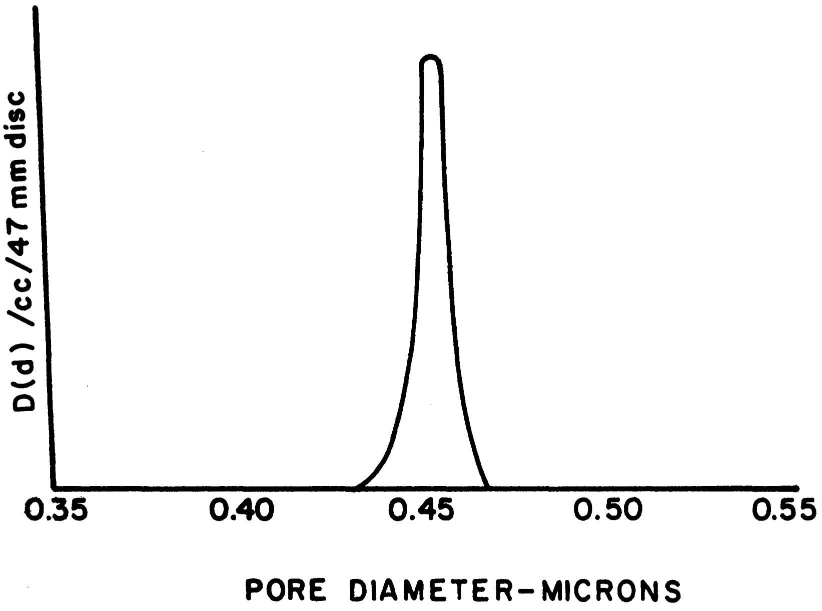

Figure 1. Millipore Pore Size Distribution - Skau-Ruska mercury intrusion.

1. Irradiation Properties of Stainless Steel

The effect of irradiating stainless steel, or any commercial material, is complicated by the presence of trace components and impurities, some of which have large neutron activation cross-sections and consequently contribute substantially to the radioactivity. As an example, Table 1 is a summary of the pertinent nuclear properties of the 24 isotopes occuring in stainless steel.

Fortunately, no appreciable amount of alpha radioactivity is formed in this case, simplifying the radiological health problems. The only high-energy-gamma emitter formed is Fe^{59}; however, various beta-emitters are involved.

2. Determination of Reactor Time

An estimate of anticipated damage rate is necessary to specify a radioactivity level of the stainless steel which would provide a measurable water activity after a reasonably brief cavitation run. The approximate estimates used in the present case led to samples more highly irradiated than actually necessary. In this particular case a reactor time of 140 hours was used (thermal neutron flux of about 5×10^{12} nv). With the degree of irradiation attained, the presence of 1 billionth of a gram of the stainless steel could be detected with the low-activity gas flow proportional counter used.*

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* NMC Gas Flow Proportional Counter, Model PC-1.

TABLE 1

Isotope	% Abundance in Stainless Steel 302	Thermal Neutron Activation Cross-Section, Barns	Product Isotope Formed in Reactor	Type of Disintegration of Product Isotope	Half-Life of Product
Fe-54	4.13	2.5	Fe-55	EC	2.94 yr.
Fe-56	65.00	2.6	Fe-57	IT	10 sec.
Fe-57	1.54	---	Fe-58	--	----
Fe-58	0.22	0.98	Fe-59	Beta-Gamma	46 days
C -12	0.15	3.3 mb	C -13	--	----
C -13	0.002	0.9 mb	C -14	Beta	5568 yr.
Mn-55	1.50	13.3	Mn-56	Beta-Gamma	2.58 hr.
Si-28	0.55	---	Si-29	---	----
Si-29	0.024	---	Si-30	---	----
Si-30	0.018	110 mmb	Si-31	Beta	2.62 hr.
Cr-50	0.775	13.5	Cr-51	Gamma	27.8 days
Cr-52	15.08	---	Cr-53	---	----
Cr-53	1.72	---	Cr-54	---	----
Cr-54	0.43	0.38	Cr-55	Gamma	2.1 hr.
Ni-58	6.10	4.2	Ni-59	EC	80,000 yr.
Ni-60	2.35	---	Ni-61	---	----
Ni-61	0.11	---	Ni-62	---	----
Ni-62	0.33	15.0	Ni-63	Beta	85 yr.
Ni-64	0.10	1.6	Ni-65	Beta	2.56 yr.
P -31	0.03	0.19	P -32	Beta	14.3 days
S -32	0.02	1.8 mb	S -33	Alpha	2,000 yr.
S -33	0.001	15 mb	S -34	----	----
S -34	0.08	0.26	S -35	Beta	87.1 days
S -36	Negligible	0.14	S -37	Beta	5.0 min.

3. Cavitation Conditions

The cavitation field in the venturi was such that the downstream termination of the field was located at the mid-point of the test specimens. Through-velocity was about 70 feet/second of cold water.

B. Description of Test Methods

1. Cavitation Wear Run

Two radioactive wear specimens were inserted into the venturi, and the cavitation field was obtained. The system was allowed to run continuously for 20 hours. Each hour, a 5 ml water sample was withdrawn from the loop into a well-counter lucite thimble. At the completion of the experiment, the activity levels of the 20 water samples were determined with a scintillation detector and the gas flow counter.

2. Particulate Size Determination

At the completion of the test, part of the circulating water was passed through the filter rack. During this operation the main circulating stream was held at full velocity to maintain agitation. For the first run, the filter rack was loaded with filters rated at 0.45, 0.80, 7.5, and 64 microns. For a second run, it was loaded with filters rated at 1.2, 5.0, 10.0, and 64 microns. A third run was made with the main stream essentially stagnant using the same filters as the first run to determine possible settling rates and/or entrapment. At the end of each

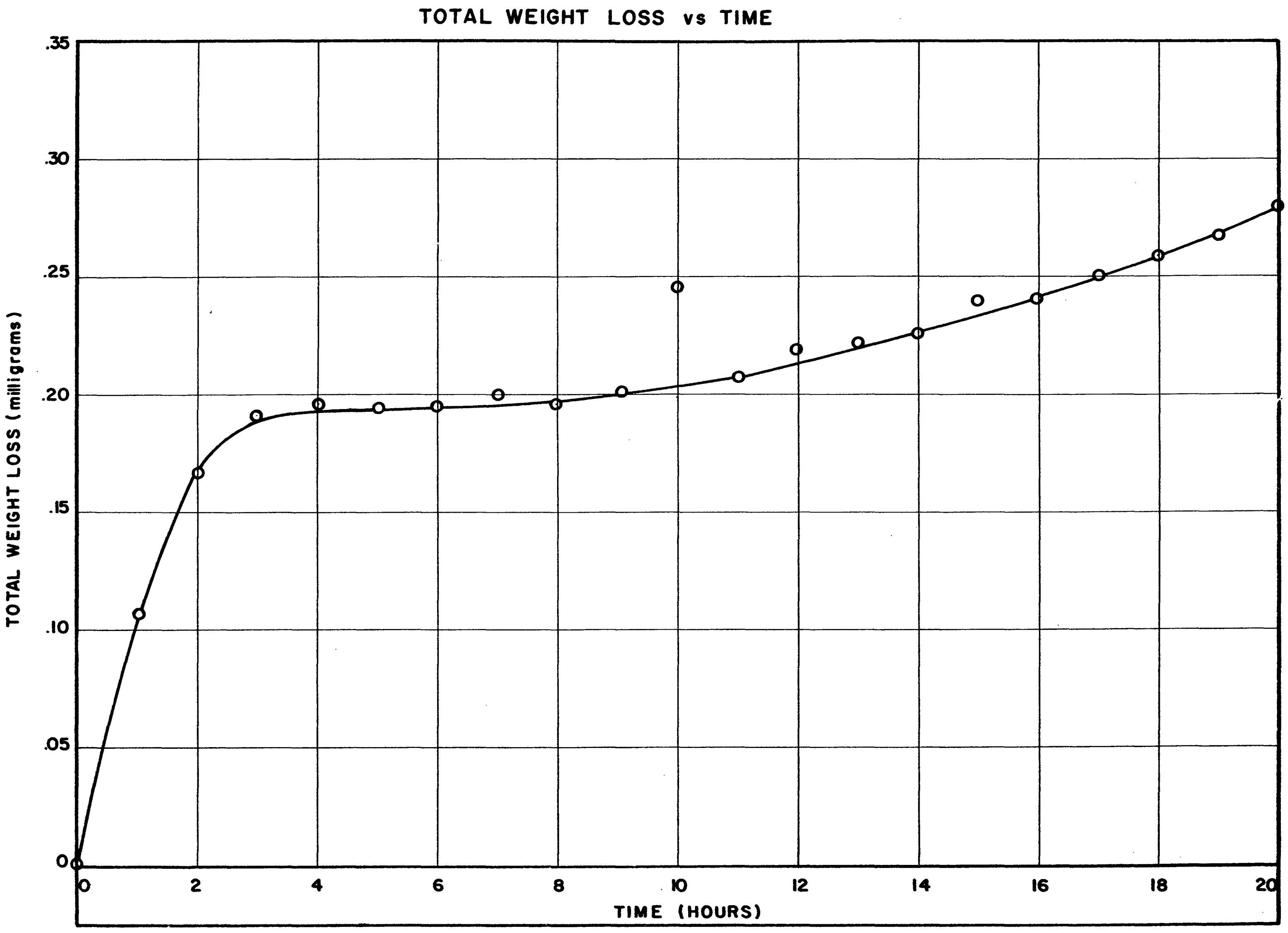

Figure 2. Total Weight Loss vs Time.

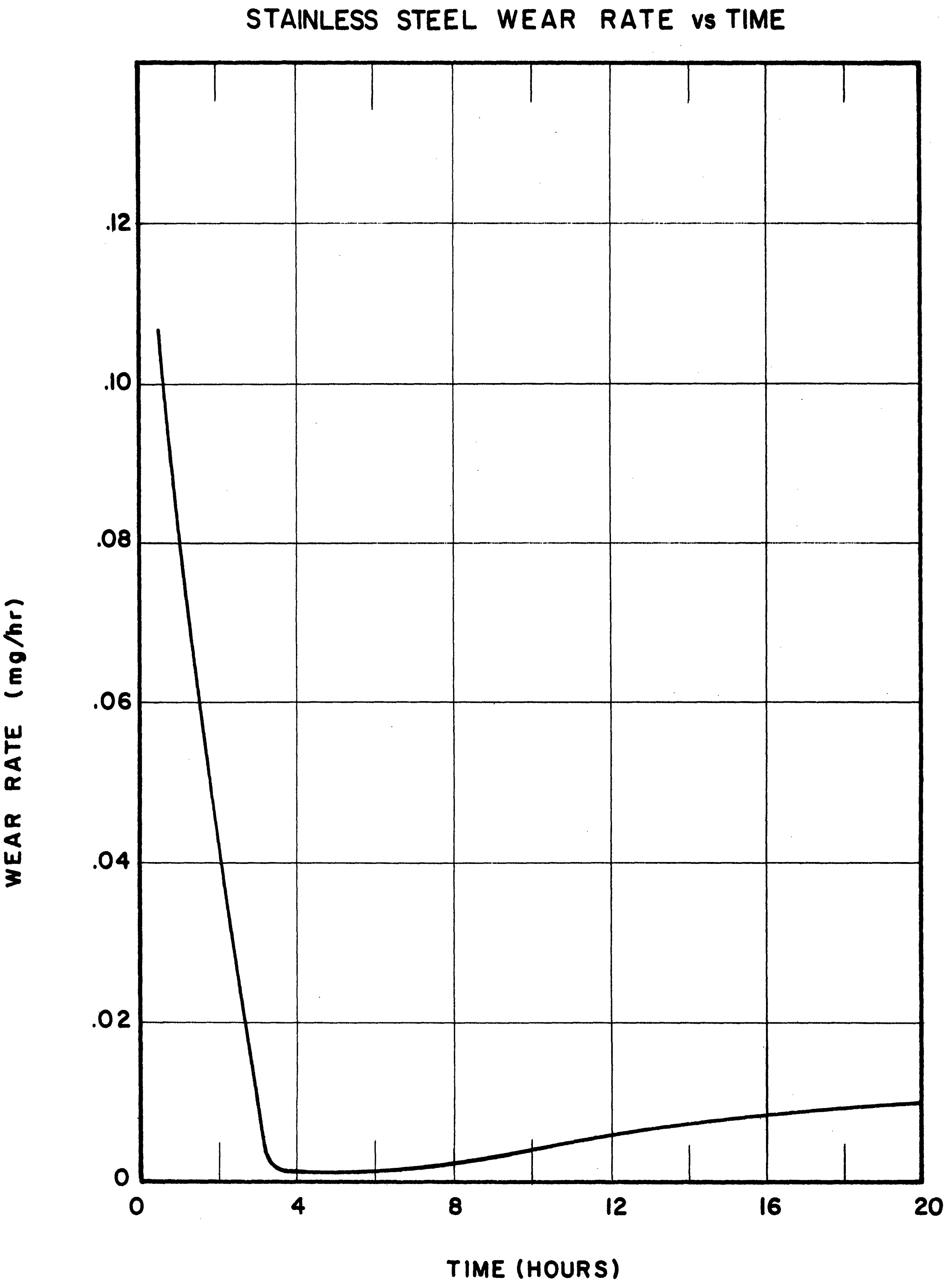

Figure 3. Stainless Steel Wear Rate vs Time.

filtration test, the filter rack was carefully disassembled and the activity level of each filter determined with the electronic counting apparatus.

3. Calibration with a Standard Solution

A small piece was cut from one of the radioactive specimens and weighed accurately on an analytical balance. The metal fragment was dissolved in concentrated hydrochloric acid and diluted to three known concentrations. One ml of each of these solutions was then tested for activity level using the same counters which were used for the water samples. From this data, the relationship between milligrams of metal and cpm was determined.(3)

VI. EXPERIMENTAL RESULTS

A. Radioactive Wear Run

Figure 2 shows the total weight loss from the wear specimens as a function of time. Cavitation damage was extensive during the first three hours with a total of 0.19 mg worn off in that time. By the fourth hour, the damage rate had become much less severe with the weight loss per unit time only 1/100 of that observed initially. After the fourth hour, the damage rate increased slowly and by the end of the experiment, it had reached a level which was about 1/10 of the initial wear rate. At the completion of the 20 hour experiment, a total of 0.28 mg had been lost from the stainless steel wear specimens.

Figure 3 is a differential plot of Figure 2 and shows the damage rate as a function of time.

The effect of particles settling in the circulating system was determined experimentally to be negligible. However, the data was corrected for a small rate of random entrapment which was observed. The justification for the above and the treatment of data is discussed in detail in Reference 3.

B. Filter Tests

The data compiled from the three filter runs is presented in Figure 4. Over 70 per cent of the metal debris by weight was found to consist of particles in the size range of 13-80 microns, corresponding to about 0.5 - 3 mils. Only trace amounts of radioactivity (less than 1 per cent) occurred in the particle sizes below 1 micron. Approximately one-half of the radioactive debris consists of particles larger than 47 microns.

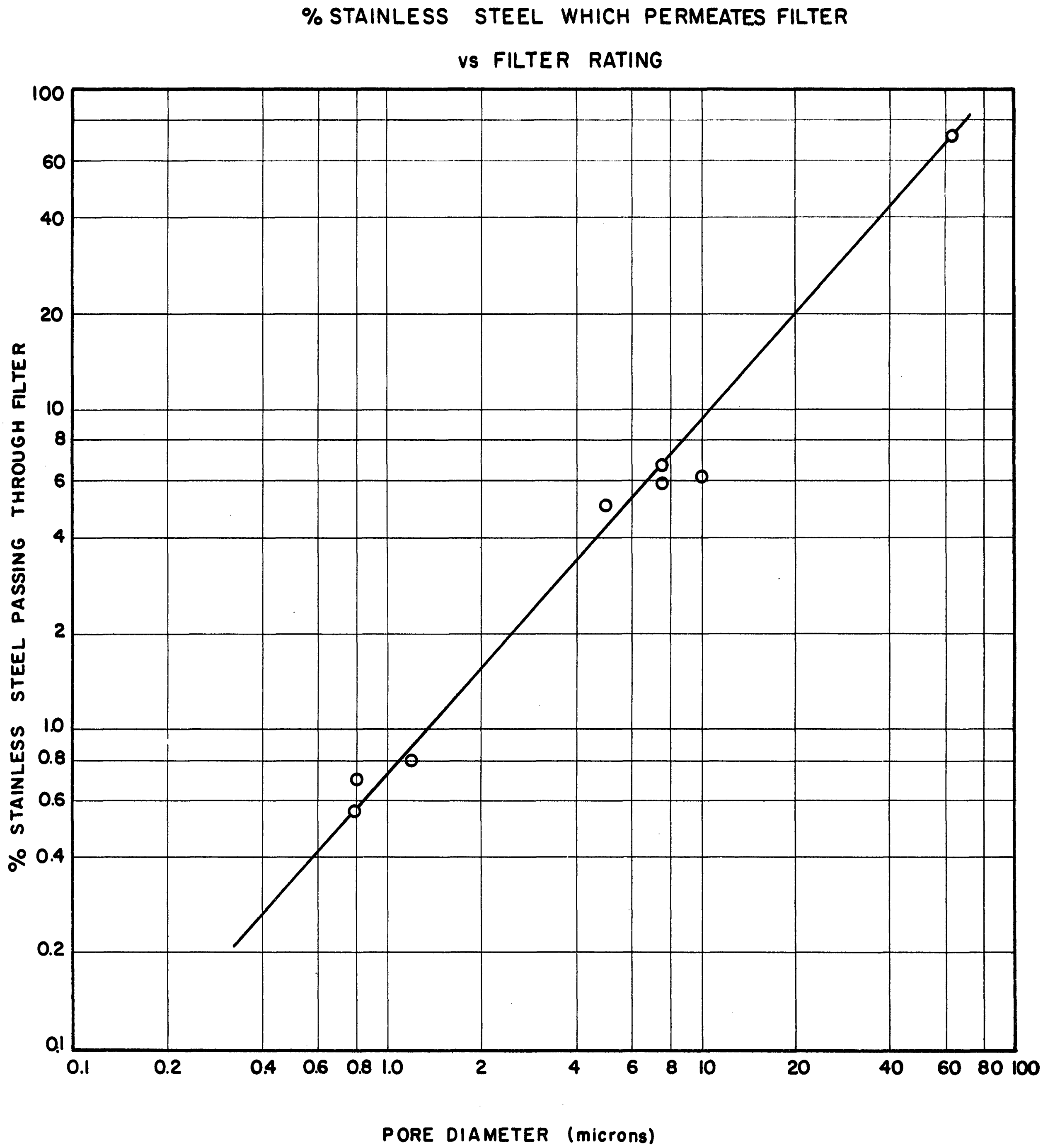

Figure 4. % Stainless Steel which Permeates Filter vs Filter Rating.

VII. DISCUSSION OF RESULTS

One of the principle results of this experiment is the successful development of a radiotracer technique for relatively accurate and continuous measurements of cavitation damage. Under the conditions of this experiment, as little as one-millionth of a gram of cavitation wear can be detected and accurately measured. According to the literature,(4,5) stainless steel undergoes no appreciable change in mechanical properties as a result of neutron irradiations of less than 10^{18} nvt fast flux (considerably in excess of flux required for irradiation). Consequently, the results obtained from radioactive wear experiments will be directly applicable to ordinary cavitation damage runs.

This technique makes possible the attainment of relatively accurate data for the beginning phases of cavitation damage. As a result, much may be learned concerning the basic mechanism of cavitation damage. The initial high rate of wear followed by a much lower wear rate indicates that many sites of surface weakness may have been available at the beginning of the experiment. As these "weak" points were exhausted during the first few hours of exposure to cavitation, the wear rate dropped rapidly to a relatively low level. The subsequent increase in damage rate may be explained by the assumption that pits from cavitation damage act as nuclei or accelerators for further cavitation damage by disturbing the local flow-streamlines. As continued damage occurs, more pits would be available and the damage rate would increase.

The results from the filter experiments clearly indicate that cavitation pits in this experiment were formed by the tearing away (not necessarily by single bubbles) of single pieces, as opposed to an expected (but not observed) gradual enlargement of pits by many particle removals. This conclusion is based on the similarity between the sizes of the cavitation particles and the pits visually observed. As shown by high-magnification photographs of the metal surface taken at various stages of cavitation damage, the pits generally remain constant in size with additional damage appearing in the form of new pits.

Although most of the cavitation debris by weight was found to occur in particle sizes larger than 10 microns, it is believed that the great majority of cavitation particles are much smaller than 10 microns. A relatively large cavitation wear particle may weigh more than the combined weight of thousands of smaller particles.

The data presented in Figure 2 is fairly smooth with the exception of the 10 hour reading, which shows the water sample withdrawn at that time to have an abrupt increase in radioactivity. This was probably the result of a large cavitation particle in that water sample. The concentration of large particles is such that the catching of only one in the series of tests is not unreasonable.

VIII. CONCLUSIONS

A radiotracer method has been developed and tested for the continuous measurement of cavitation and/or erosion damage in a flowing system. Using this method, the damage rate of type 302 stainless steel was determined as a function of time for a constant cavitation field in a venturi, with water velocity at 70 feet/second. The highest wear rate observed during the 20 hour experiment was 0.15 mg/hr (the initial rate of damage) from a surface area of about 0.5 square inches. After about 4 hours of cavitation, the damage had become much less severe (about 0.001 mg/hr). During the last 16 hours of the run, a gradual increase of the wear rate to 0.01 mg/hr was observed.

A presently unique measurement was attained, using filter tests, to indicate that greater than 70 per cent of the wear debris consisted of particles ranging from 0.5 - 3 mils in diameter. Only trace amounts of cavitation particles were found which were smaller than 1 micron.

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