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CAVITATION DAMAGE MEASUREMENTS BY RADIOTRACER ANALYSIS

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ABSTRACT

No method exists at present for continuous measurement of cavitation-erosion damage on metallic specimens. By using radioactive isotopes, the development of a technique that would give information not only on wear rate but on debris particle size and composition was attempted. Samples of 302 stainless steel and 1010 carbon steel were irradiated and exposed to cavitation in a venturi. Mercury and water were used as test fluids.

Meaningful data were obtained particularly with respect to particle size distribution and debris components, and their variation with particle size. In the water tests a useful measure of damage rate also was obtained. The mercury tests indicated the possible technological difficulties which may be encountered in the application of this method. These are primarily concerned with the capability of the liquid to wet the debris particles and to maintain a uniform slurry.

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I. INTRODUCTION

The use of irradiated tracers for measurements of erosion and wear rates for various devices is not new, and was in fact applied previously to the measurement of cavitation damage in water[1] by the present group. In addition to providing a potentially continuous and instantaneous record of damage rate, i.e., weight or volume loss, without disassembly and examination, this technique is capable of providing information on the size spectrum and components of damage particles. A measurement of damage rate as well as of particle size distribution for stainless steel specimens submitted to cavitating water flow in a venturi was in fact achieved in the previous experiment.[1] As far as is known, the latter measurement is still unique in the cavitation field.

The present paper describes an extension of the technique to steel specimens exposed to cavitating mercury in a venturi. Severe technological difficulties, as compared to the water experiment,[1] were encountered both in maintaining a homogeneous slurry of the mercury and debris particles, and in filtering the mercury. These difficulties were primarily associated with the lack of good uniform wetting between the mercury and the debris particles. They serve to emphasize the possible difficulty of extending this apparently attractive technique to liquids whose behavior may not, in all instances, be easily predictable. Nevertheless, as developed later, certain significant new information did result from the mercury tests, particularly with regard to debris size spectrum and components.

II. DESCRIPTION OF FACILITY

The previous[1] and present experiments were conducted in a closed-loop facility (Fig. 1) described previously.[1,2] Originally operated with water, it is now operating with mercury. The applicable significant features are summarized below.

Cavitation occurs in a plexiglas venturi (Fig. 2), and damage is observed on two small tapered test specimens (Fig. 3), inserted parallel to the flow through the wall of the diffuser section. By suitable control of pressure and flow, the termination of the cavitation region, in these tests, was set at the axial midpoint of the specimens ("Standard Cavitation"). Throat velocity was set at ~70 ft./sec. for the water tests,[1] and ~34 ft./sec. for the mercury tests. Fluid transit time around the loop is only a few seconds in either case, and Reynolds' number is in the highly turbulent range everywhere. Fluid temperature in all cases was approximately ambient.

The loop (Fig. 1) is powered by a vertical, overhung shaft, centrifugal, sump pump (Fig. 4). As discovered in the mercury tests, there is a strong separating effect upon foreign matter of density less than mercury due to the centripetal action of the impeller. Such material tends to escape from the main stream into the sump, where it is trapped and floats to the surface.

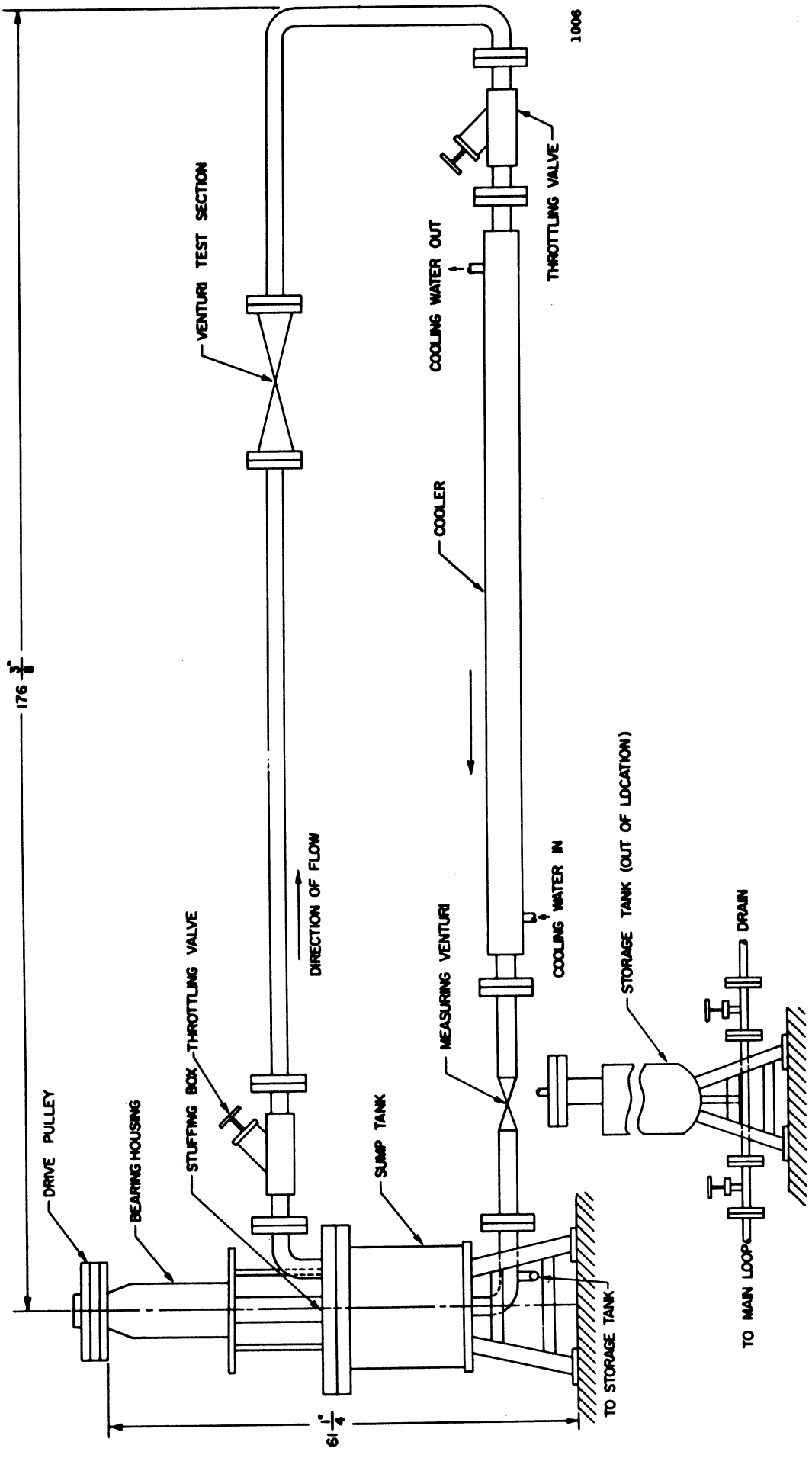

Figure 1. Sketch of overall liquid metal loop.

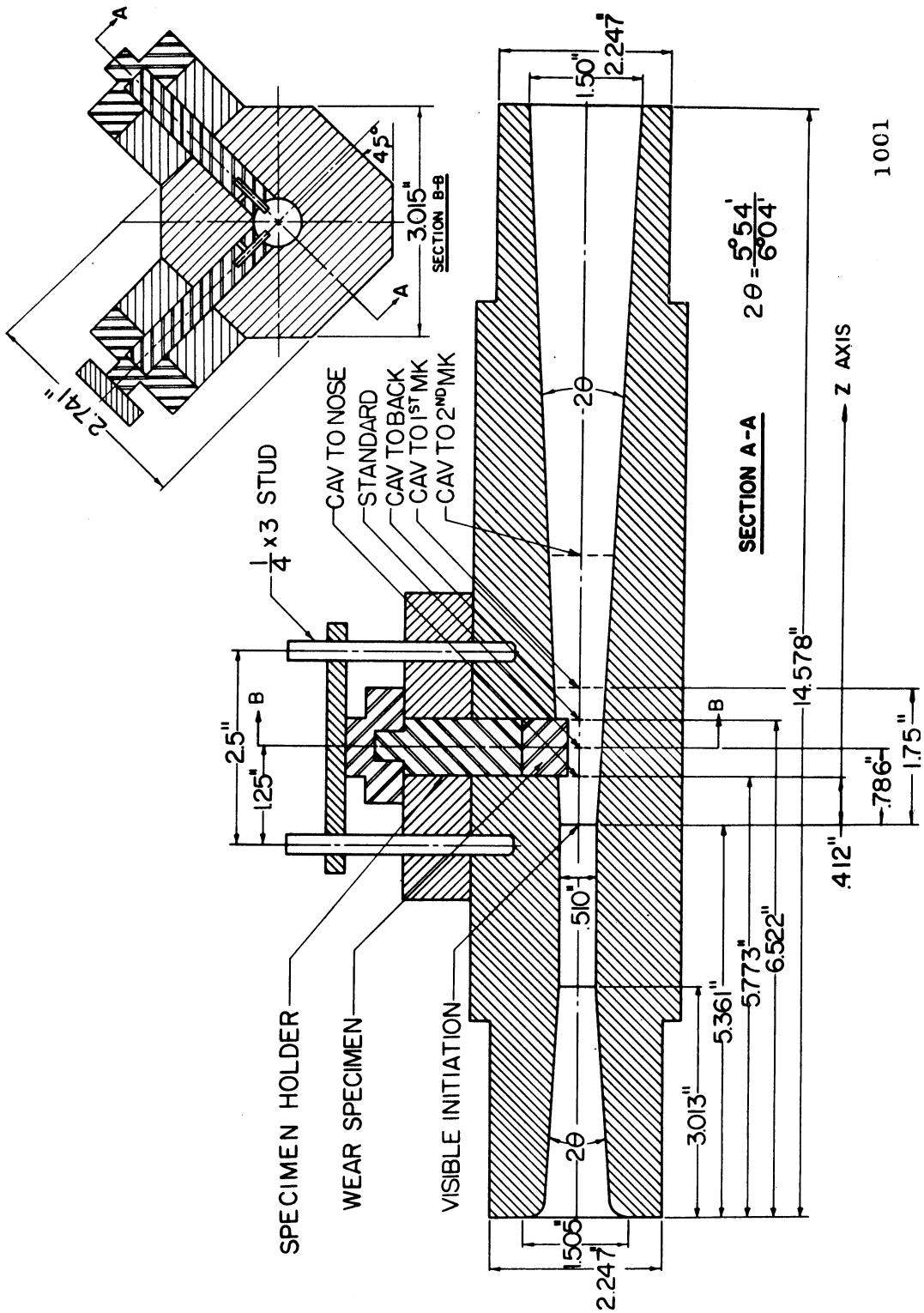

Figure 2. Drawing of the damage test venturi showing location of specimens, specimen holders, and cavitation termination points.

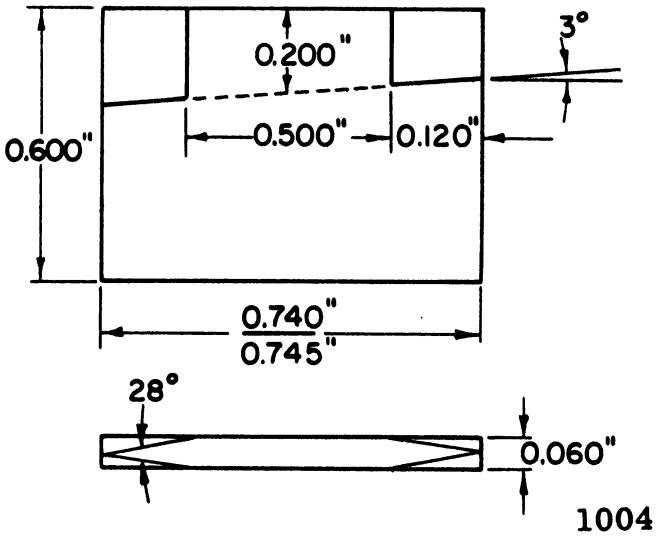

Figure 3. Drawing of damage test specimen.

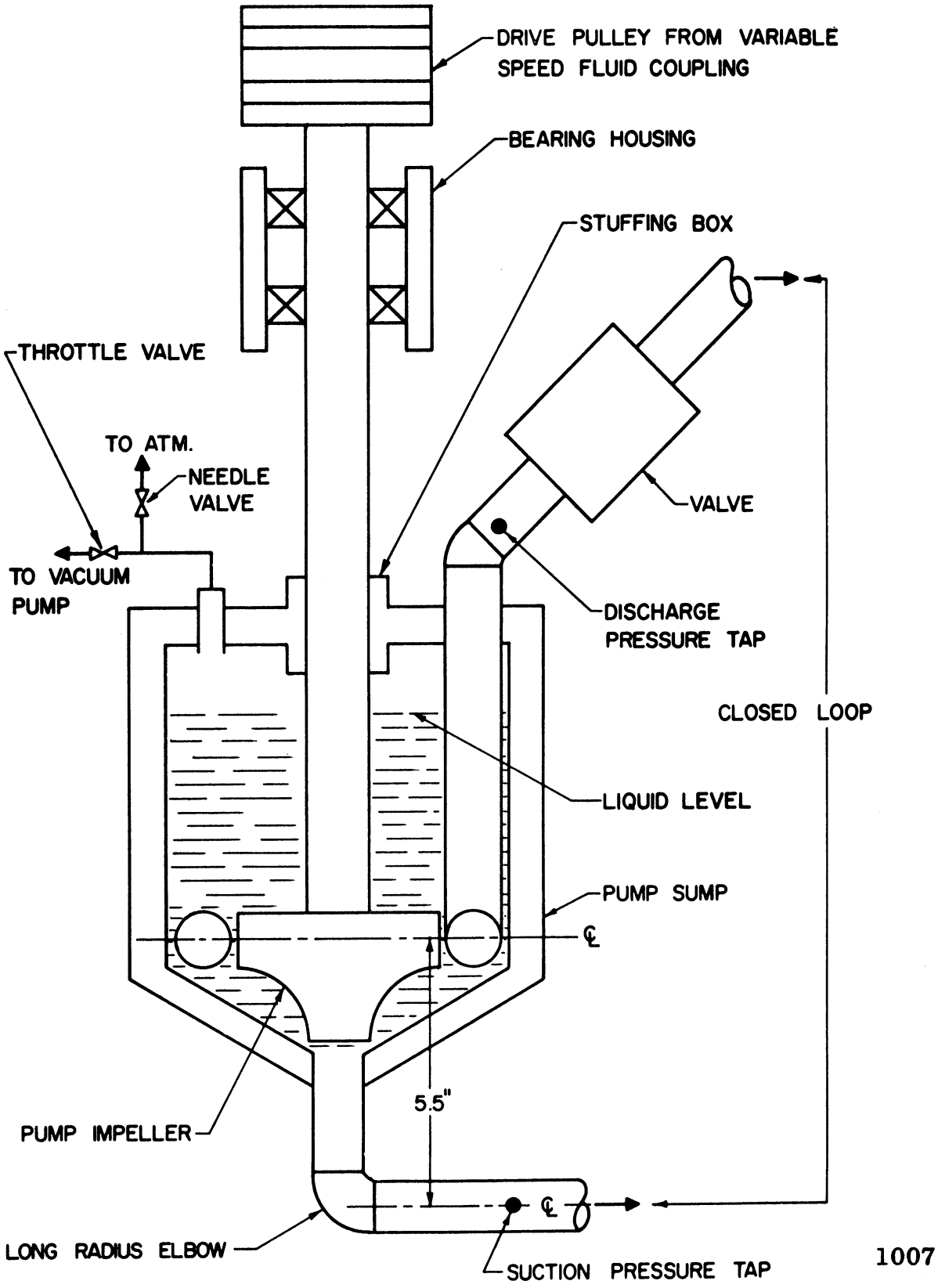

Figure 4. Schematic of pump in mercury loop.

III. EXPERIMENTAL PROCEDURE

A. Summary of Water Tests[1]

At the conclusion of the water test, part of the loop water was by-passed through a filter rack, holding four filters of graduated pore sizes in series, while the main circulating stream was held at full velocity to maintain agitation. Two such runs were made. A final run was made with the main stream essentially stagnant to determine whether settling rates and/or entrapment were significant. (They were not.) The relationship between weight of debris and counts per minute from the filters was determined by calibration with a standard solution, using a carefully weighed and dissolved piece of one of the radioactive specimens.

In addition samples withdrawn from the loop periodically during the test were analyzed. The results obtained[1] included a particle size measurement as well as an indication of rate of weight loss from the specimens.

B. Estimate of Required Irradiation for Mercury Tests

Based on previous knowledge of cavitation damage rates in the present facility, and detailed information on the irradiation properties of the materials as explained later, required radiation exposures were estimated. To reduce test time and increase precision the maximum allowable irradiation is desirable. This is governed by two factors:

i) Irradiation damage to test specimen - Too high an irradiation will alter the mechanical properties of the material to be tested and thus destroy to some extent the validity of the test. Fortunately

the limit for metallic materials (Stainless steel Type 302 and 1010 carbon steel were used in these tests.) is quite high compared, e.g., to plastics, other organics, etc. No measurable change in the mechanical properties of steels is expected for irradiation below about 10^{18} nvt fast flux.[3,4] It was estimated that the stainless steel specimens in these tests received about 1.5×10^{17} fast nvt and the carbon steel about 0.5×10^{17}. Thus the margin for a further increase in irradiation is small, so that this limitation even for metals may be significant. It may well be prohibitive for some non-metallic materials.

ii) Safe handling - In the present case no difficulty was encountered. Rather than posing an absolute limitation, this limitation is a function of the equipment on hand, and in most cases can be easily met.

C. Irradiation Properties of Steels

For the Type 302 stainless steel used a chemical analysis was obtained. It was determined that of the forty radioactive isotopes found only five are significant: Fe-59, Mn-56, Cr-51, Ni-65, and Co-60. A similar analysis was not made for the 1010 carbon steel, but it is likely that the same isotopes would be important due to the presence of at least trace quantities of these elements.

IV. EXPERIMENTAL RESULTS

A. Stainless Steel Test

Two Type 302 annealed stainless steel specimens were used. It was estimated from post-test microscopic observation, comparing with previous tests for which weight loss had been measured, that the weight loss was $\sim$ 2.4 mg, about as expected. Inadvertently a direct weight loss measurement omitted. Run duration was 26 hours.

Samples of mercury were withdrawn periodically throughout the test both from the pump sump and from the main loop stream. It was attempted to filter these using the rack previously described. In some cases only one filter was used (pore size 0.2μ); in others, four filters in series in order of decreasing pore size (0.2, 0.8, 10, and 53μ).

The filtration of mercury proved difficult, and it is not certain that filtration was actually achieved in all cases. The difficulties are apparently due to the following:

i) Mercury does not "wet" the filter material. Hence the pressure differential due to surface tension to force it through the small pores is high, and it becomes difficult to prevent leakage around, or rupture of, the filters.

ii) Debris particles almost necessarily lighter than mercury quickly float to the surface. For a vertical down-flow arrangement as used the mercury may pass through the filters but leave behind the floating debris. An up-flow arrangement, for which other difficulties were anticipated, was not tried.

Nevertheless, a certain amount of debris was left on the filters, although not necessarily primarily from the cavitation specimens. In any case, no appreciable activity (beta or gamma) was found on the filters. Further, an external check of the loop with a Geiger counter revealed no evidence of radioactivity. This result is inconclusive because of the shielding effect of the mercury and piping.

Finally, a 100cc sample was withdrawn from the loop, distilled, and the residue counted, again with negative results. At this point there was the possibility that the cavitation damage was actually much less than estimated. However, this hypothesis disagreed with the results of visual and photographic examination of the specimens.

B. Carbon Steel Test

At the conclusion of the stainless steel test, no knowledge of the disposition of the radioactive debris, if any, existed. Hence, it was decided to try carbon steel for which, from previous non-irradiated specimen data, the damage should be considerably greater. The purpose of the carbon steel test was to determine the feasibility of subsequent tests and the disposition of the radioactive debris. For this "feasibility test" the procedures were not as elaborate.

However, this time the specimens were weighed ($\sim \pm$ 0.1 mg repeatability), both before and after exposure to 50 hours of cavitation. During the test their weight decreased by 2 to 3 mg. The irradiation achieved for these tests (contact dose after four days about 2 r/hr.) was about half that of the stainless steel specimens.

Before and after photomicrographs show that extensive damage did occur, as indicated by the weight loss. It is probable from the

microscopic observations that the weight loss was several times that in the stainless steel test.

With a Geiger counter, radioactivity was detected at two locations:

i) In the pump sump at approximately the level of the mercury surface,

ii) At flanges having vertical taps for pipe connections.

However, a 15 cc sample from the loop again showed essentially no radioactivity.

The loop was disassembled at the above location, and substantial radioactive debris recovered from the sump:

i) Along the inside wall at the mercury surface, where there was a deposit of dust-like material of relatively high radioactivity,

ii) In the debris floating on the mercury.

Samples from these location were collected on paper and calcined at 1300°F., leaving a residue of yellowish powder. This was mixed with water and filtered successfully, using filter openings of 53, 10, 2, and 0.45μ. It is believed that the high temperature used should not substantially affect the dimensions of the steel cavitation debris. The residue on the filters was counted using a multiple channel analyser. Spectra substantially above background (Fig. 5), which is included in all curves, were found for the 53 and 10μ filters. No radioactivity was found on the 0.45μ filter, and that on the 2μ filter was only slightly above background.

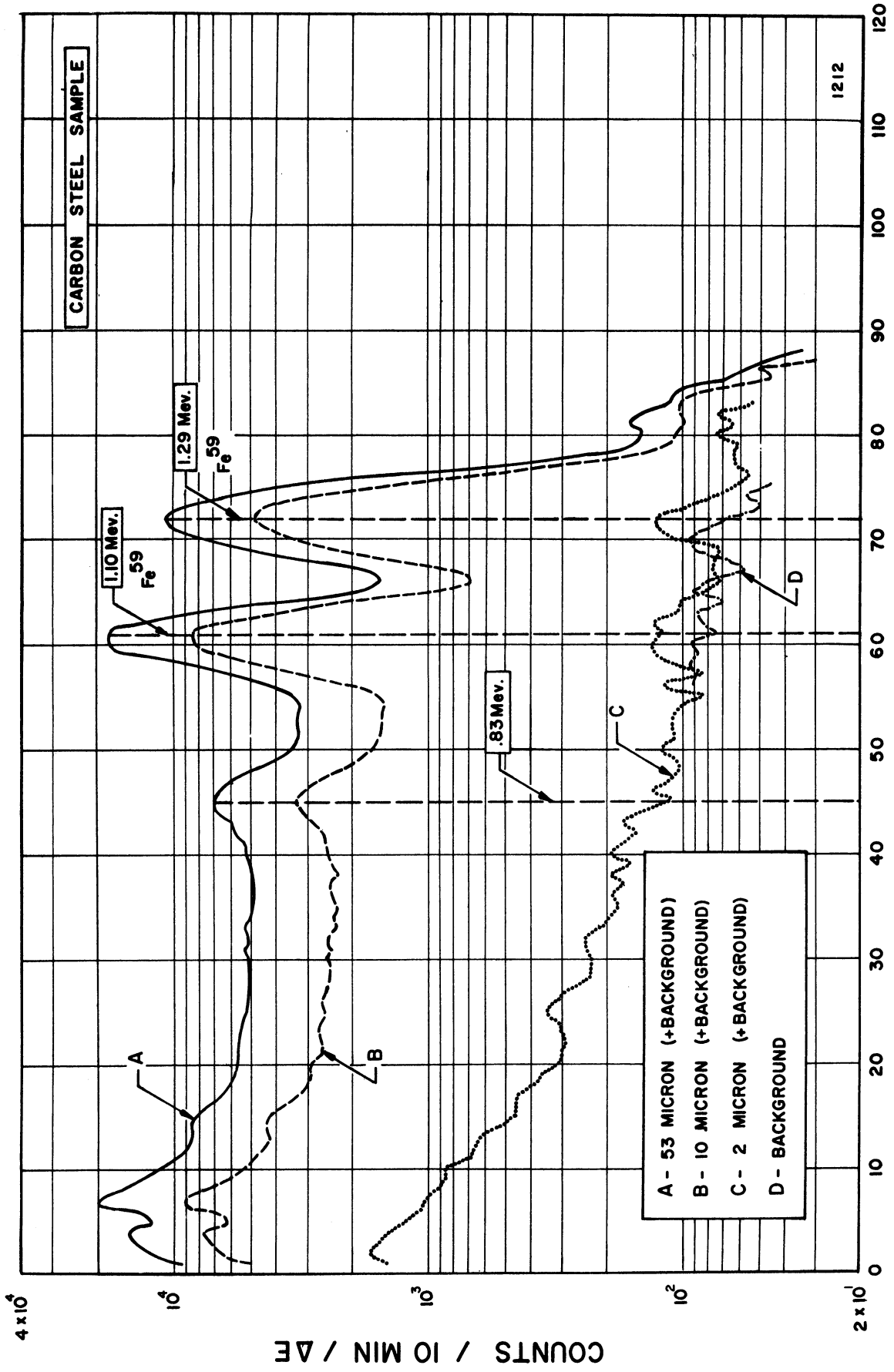

Figure 5. Differential radioactive curve of debris retained by the different pore size filters.

After the test, one of the test specimens was dissolved in concentrated hydrochloric acid. A standard sample of the resultant solution, suitably diluted, was counted (Fig. 6). Comparison of the photopeaks of Fe-59, as well as the remainder of the spectrum for the curves shown in Figs. 5 and 6 indicated that the debris components do not differ, within the accuracy of these tests, from those of the parent material, and do not depend upon particle size.

Finally a differential characteristic curve was also obtained from a small piece from the stainless steel test specimens (Fig. 7).

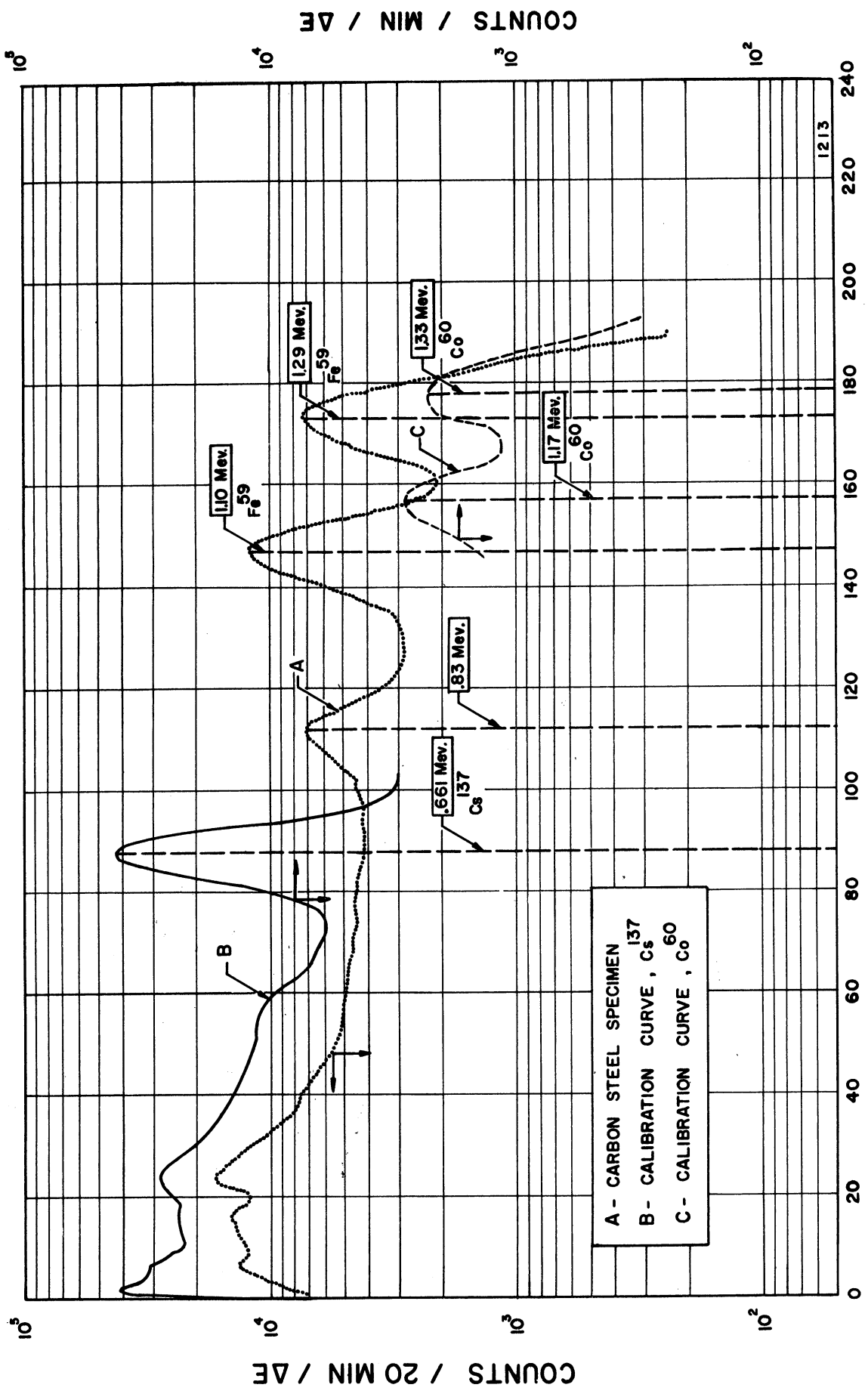

Figure 6. Differential radioactive curve of carbon steel specimen.

V. DISCUSSION AND REDUCTION OF RESULTS

A. Mass of Debris Recovered and Particle Size Distribution

Since the material of the radioactive debris and that of the specimen are essentially the same and were irradiated at the same time, the mass of material in each size range was computed by comparing the corresponding count-rate at a given energy to the count-rate of the standard sample at the same energy (Table I). The details of the calculation are given elsewhere.[6,7] However, to summarize, the areas under the higher photopeak of Fe-59 (used because of its better resolution) are computed assuming a Gaussian distribution from each size-group of debris (Fig. 5) and compared with the similar area from the differential curve of the standard carbon steel sample (Fig. 6), corrected to the same chronological time.

It was assumed that all the radioactive debris had originated from the carbon steel, since seven and one-half months had elapsed between the stainless and carbon steel tests so that the stainless steel activity would have decreased very considerably, and the mass of debris from this test was estimated to have been considerably smaller.

Table I also shows the number of particles in each size range, assuming them to have been spherical. For the largest category it was assumed that the particle diameter was equal to the specified filter pore size, tending to balance the following factors:

i) Some smaller particles will be retained because of non-uniformity of pores and particle shape, partial blocking by other debris, etc., and,

ii) All particles bigger than the pore size will also be retained. However, from microscopic examination of the pits, only a few particles much larger than 53μ (2.08 mils) could have existed.

For the smaller filter sizes the upper cut-off is determined by the next larger filter size. For these sizes an approximate numerical average between the limiting sizes was assumed.

Even though most of the mass was retained on the largest filter (Table I), the number of particles is much less than that for the 10 micron filter, which is in turn less than that for the 2 micron size. This numerical distribution is consistent with the visual pit counts which have been performed on numerous non-irradiated specimens.

The particle size distribution, in terms of percent mass passing a given filter, is presented in Fig. 8 for the carbon steel* and previous stainless steel[1] tests. It is indicated that the percent mass passing a given filter is always less for mercury than for water, i.e., the cavitation debris particle sizes from the mercury test are apparently larger than for the water tests. This is not consistent with information from pit observations which show the opposite trend. The discrepancy may be due to the different filtering techniques used, and the possible lack of a representative sample, particularly in the mercury tests as explained below.

The curves converge for the larger pore sizes. Thus, for either fluid most of the debris would pass an 80 micron (3 mil) filter.

* The 2 micron point is not shown on this logarithmic point since the percent passing was zero.

TABLE I

MASS AND SIZE DISTRIBUTION OF PARTICLES RECOVERED IN THE DIFFERENT FILTERS

Pore Size		Weight Recovered (mg)	% Recovered of Total Weight Loss	% Retained in Filter	% Passed Through Filter	Size of Particles		Counted Pits	Estimate No. of Particles
Microns	Mils					Number	Assumed Diameter		
53	2.08	.224	4.22	68.95	31.05	6000	53μ	23	6,000
10	0.39	.100	1.89	30.75	.307	14750	30μ	1,698	14,750
2	.79	.001	0.02	.307	0	18400	6μ	24,415	18,400
	Totals:	.325	6.13%						

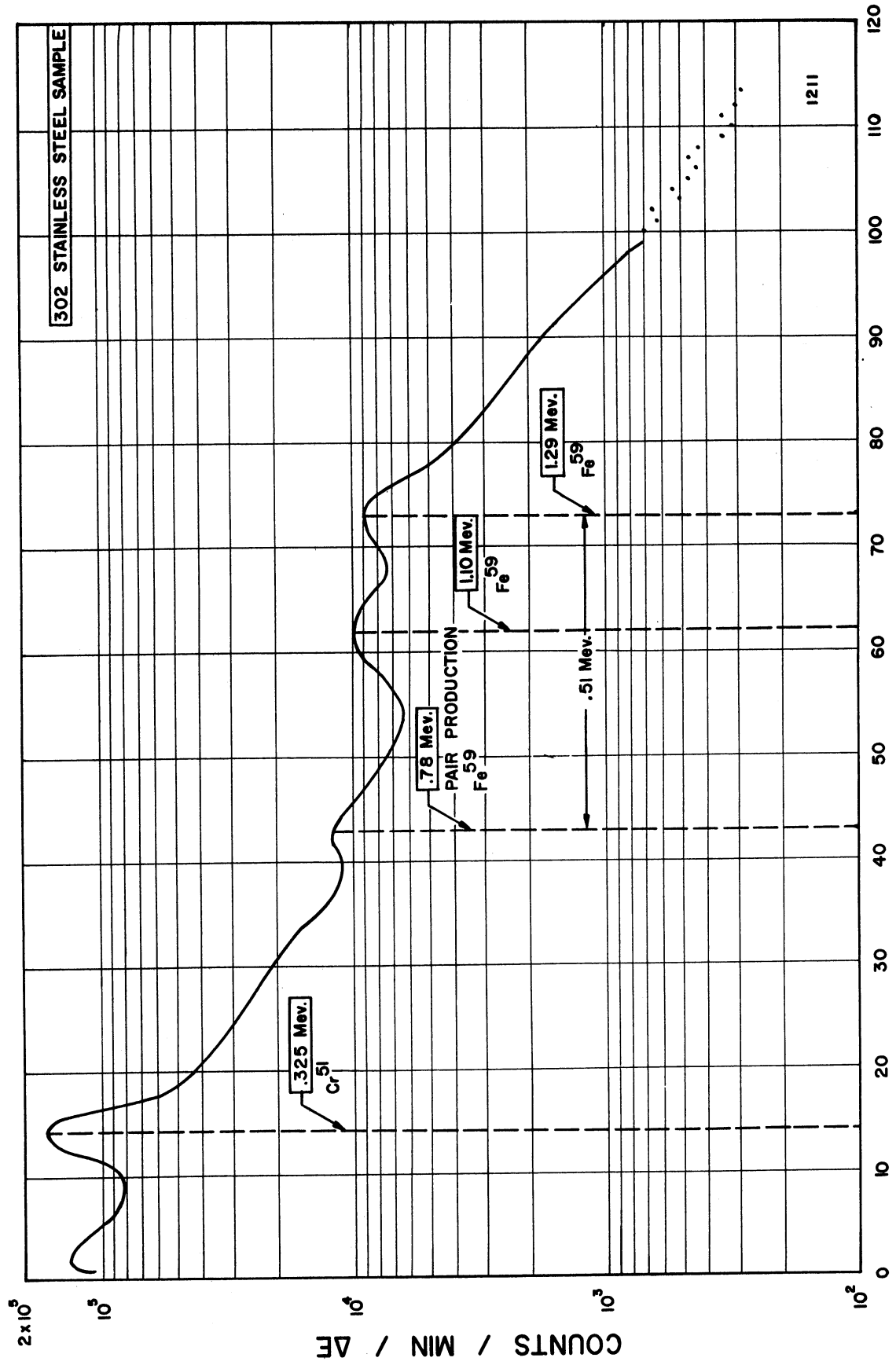

Figure 7. Differential radioactive curve for stainless steel.

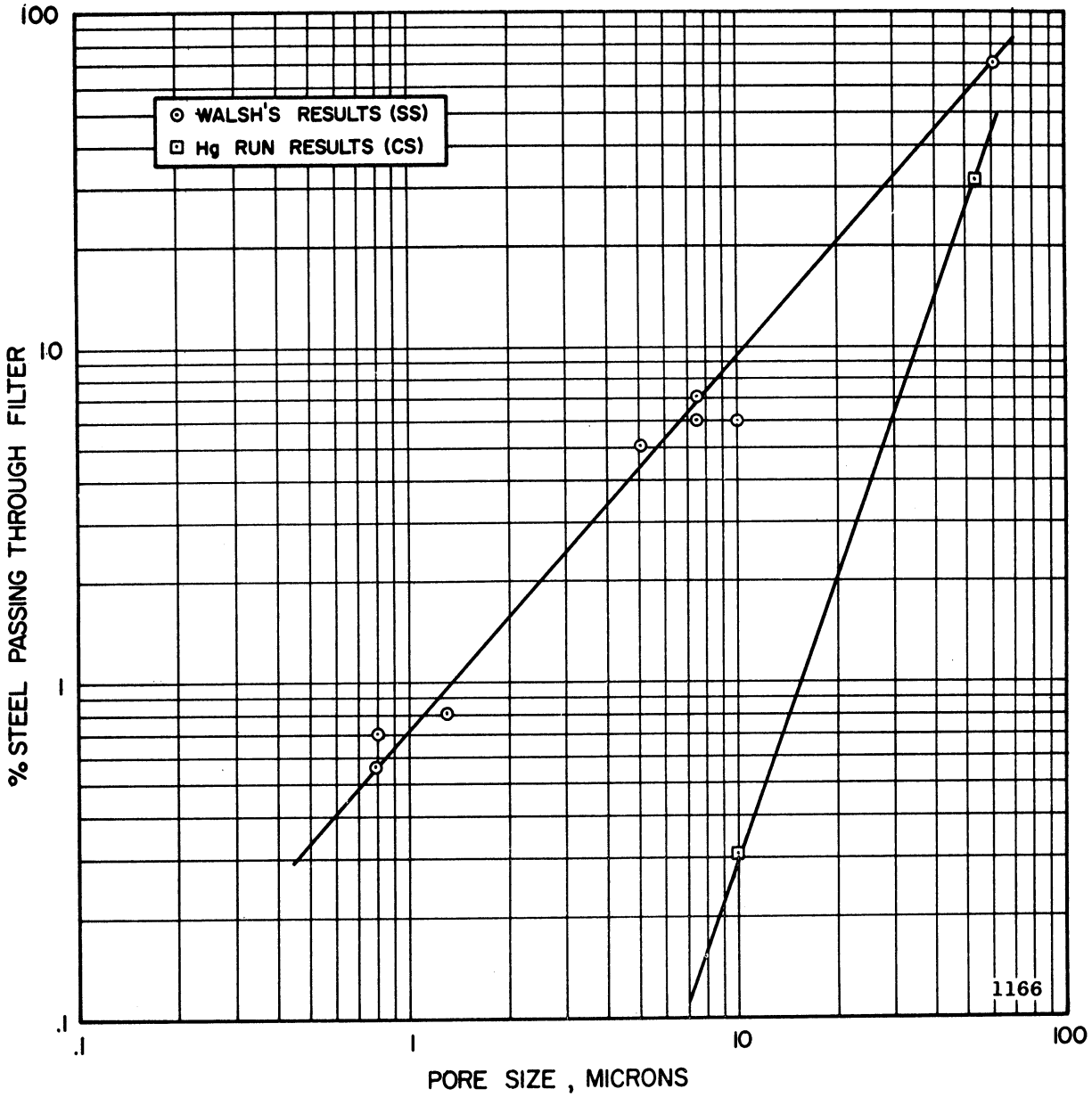

Figure 8. Percent of steel passing through filters vs. filter pore size.

On the other hand, only a fraction of a percent of mercury debris is of a size less than 6 to 8 microns, while about 7% by weight of the particles in water are below that size.

B. Representiveness of Sample

Visual pit tabulations in the various filter size categories for previously run unirradiated specimens have been compared (Table I) with the estimated numbers of particles from the mercury run filter results in the same size ranges. The absolute numbers are of course not significant. The particles and counted pits both become more numerous as the size decreases. However, it is noted that the effect is much stronger for the counted pits than for the estimated numbers of particles, so that there appears to be a disproportionate number of large particles in the filtered mercury run samples which thus may be truly representative. This is not unlikely since the samples were recovered from the pump sump, whence they had been centrifuged from the main stream. The larger particles would thus be preferentially represented.

C. Components of Debris

The tests indicate no selective attack on any constituent of the carbon steel, so that the relative components of the debris are the same as those of the original specimens. The shape of the spectrum curves are similar, independent of particle size, and they show the same peaks. Similar tests with stainless steel, where there may be a real possibility of selective attack by mercury or other liquid metals on the nickel or chromium, would be of interest for the future. Since

the mercury samples taken after the stainless steel test showed no radioactivity, it can be assumed that no substantial solution of stainless steel in mercury occurred.

VI. CONCLUSIONS

The major conclusions to be drawn involve both the feasibility of the method and various particular results from the present investigation.

A. Feasibility of Method

i) The irradiated specimen technique for cavitation-erosion studies for fluids for which disassembly and direct observation are difficult is potentially of great value. However, significant development may be required for its implementation depending upon the particular properties of the fluid-material system. Of particular importance in this respect are for the fluid: wettability, filterability, and likelihood of maintenance of homogeneous slurry (also depending upon flow system configuration); and for the test material, susceptibility to irradiation damage and existence of suitable isotopes for irradiation. In these respects water and steel is a much more favorable condition than mercury and steel. Alkali metals with stainless steel might prove relatively favorable because of the good wetting usually obtained.

ii) This technique represents a useful, and perhaps the only feasible method for determining particle-size distribution and relative components of the debris.

B. Significant Experimental Results

i) A particle-size distribution for cavitation damage in mercury on annealed Type 1010 carbon steel was obtained and compared with a similar measurement previously obtained for annealed Type 302

stainless steel in water.[1] The maximum particle size was about 3 mils in each case. The filtering of irradiated debris indicated that the mercury particle size range was not as great as that for water, showing fewer particles of minimum size. Since the reverse trend is indicated by visual pit counts on the damaged surfaces, it is believed that a non-representative sample was obtained for filtering. The probable explanation involves the centrifuging action of the centrifugal pump.

ii) Evidence that no selective attack occurred on the carbon steel was obtained by comparing the differential spectrum curves resulting from the debris and the original specimen. Also, within the accuracy of the data, the relative components of the debris did not vary with particle size. A similar test for stainless steel, unfortunately not completed, would be more meaningful and perhaps instructive.

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