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DEVELOPMENT AND CALIBRATION OF WAVE-GUIDE ACOUSTIC PROBE SYSTEM FOR BUBBLE COLLAPSE SPECTRUM MEASUREMENT IN VIBRATORY AND VENTURI SYSTEMS

by

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ABSTRACT

The development of a system for measuring cavitation bubble collapse pulse spectra in a vibratory horn cavitation field is described. It is verified that such pulse count spectra can be obtained using either a standard submerged micro-probe or a "wave-guide" probe, where the active element is remote from the liquid so that high temperature operation is possible. Calibration curves showing pulse count rate vs pulse energy for four such wave-guide probes, obtained using the cavitation field from a 20 kHz vibratory horn, are included.

I. Introduction

The sodium cavitation damage program at the University of Michigan, Cavitation and Multiphase Flow Laboratory (U-M) and at Westinghouse ARD as supported by ANL requires the development of acoustic wave guide probes and the concommitant electronic chain to produce a final output of counts per second vs. pulse strength. The probes themselves (Fig. 1) have been fabricated by U-M, and are as identical as is possible. Two of these probes (nominally identical) have been furnished to ARD by U-M (probes No. 3 and No. 4)* Two other nominally identical probes (Probes No.1 and No. 2) have been retained at the U-M for our use. All four of these probes have been calibrated by U-M in terms of output vs. pulse strength using our vibratory cavitation facility with water (ambient temperature and pressure) for the acoustic source. Horn amplitude for these tests was 1 mil (peak-to-peak) and frequency 20 kHz, which are the conditions to be used for our eventual sodium tests. These water tests will then form a basis for comparison with our eventual sodium tests in terms of both pulse height spectra and damage rate of 304 SS. They will also form a common basis (with us) for comparison with the ARD venturi sodium tests.

"Probe calibration" necessarily also includes calibration of the "electronic chain" between probe and eventual output. This "chain" as used in our laboratory (Fig. 2) commences with a "charge amplifier" which is a commercially available item. This is probably the most critical item in the chain, and hence must be duplicated between ARD and U-M. For this purpose one of the 2 available U-M amplifiers was temporarily lent to ARD so that they could calibrate their own unit with it. Basically the other units in the chain (Fig. 1) are a high-pass frequency filter, an oscilloscope on which output can be displayed, and a counter

*Ceramic active elements differ due to inability to obtain old material for probe No. 4.

with which pulses of selected strength can be counted. A multi-channel analyser (MCA) would be ideal for this purpose, but the function can be accomplished with other instruments which may be available in a given laboratory, and it is because of these limitations that our own arrangement was chosen. The calibration curves (Fig. 3-6) have been made for different low frequency cut-offs, starting with 20 kHz. Since our vibratory horn input is at 20 kHz, a minimum cut-off frequency of this value is required for our case, to suppress the input signal, and to allow counting of the actual bubble collapse pulses. Since the harmonics of the input signal must also be eliminated as far as possible, it appears desirable to operate with a low-frequency cut-off of at least 40 kHz, so that either this value or 60 kHz cut-off* appears desirable for ultimate comparison. It is of course necessary that the ARD measurements provide data at the same high-pass frequency settings so that direct comparison of results can be made. In addition, the elimination of low frequencies is desirable for the flowing system also, to suppress machinery and turbulent flow noise. This mode of operation is possible, since past work shows that cavitation bubble collapse noise exists up to very high frequencies, and the duration of final bubble collapse is only a few microseconds. It seems desirable at this point to make the spectra data for low-frequency cut-offs at both 40 and 60 kHz, to give more generality to the results, and this is in fact the mode of operation for the U-M tests.

II. Acoustic Probe Tests and Calibrations

A. Probe Calibration Results

Figures 3-6 are calibration curves for acoustic wave guide probes No. 1-4, respectively. As previously mentioned, Probes No. 3 and No. 4 were sent to Westinghouse-ARD, and No. 1 and No. 2 retained here for our use in the forthcoming damage tests.

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* 60 kHz cut off appears preferable to 40 kHz since it also eliminates the low energy count decrease paradox discussed later.

The calibration curves are in the form of pulses/minute (x10^{-3}) vs. "energy setting" of the electronic counter used (Fig. 2). Curves for different settings of the "high-pass filter" are included, ranging from 20 to 80 kHz. In general (as expected) lower cut-off frequency settings produce larger pulse-count rates. All the calibration curves (Fig. 3-6) are made for 1 mil double amplitude ($\sim$ 51 μm) vibratory horn amplitude at 20 kHz (nominal) horn frequency. The "gain setting" for the "charge amplifier" differs for probe No. 4 since its ceramic is more sensitive, as listed on the curve-sheets. The "energy settings" correspond to dial settings on the counter. These are linearly proportional to pulse energy as inputted to the counter. The absolute pulse energy values are not known to us at this point, but can be determined by later calibration of the counter. The counter is essentially a low-energy cut-off device in that the counts include all pulses received for energies above each specific setting. Thus the curves should theoretically decrease monatonically as "energy setting" increases. This occurs in general, except for the low energy end, where in some cases, particularly for lower frequency cut-offs, the count rates also decrease, so that in some cases a maximum in the count-rate curve appears. This is obviously not physically realistic, and is apparently a "quirk" of the overall "chain" which includes the wave-guide probe and the electronics. It may be due to a cancelling effect for low-energy pulses which occurs in their passage through the relatively long wave guide. However, the use of this type of probe is necessitated by the requirement for high-temperature performance in sodium, and the unavailability of developed high-temperature probes for this type of service. However, this anomaly in the results is essentially unimportant for the present purposes, i.e., correlation between pulse-count spectra and cavitation damage rate, since it is presumed that only the higher energy portion of the pulse-count spectra contributes to the damage. A plausible relationship between these spectra and damage is as follows:

$$\text{Damage Rate} = C\,(E-E_o)^n \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

where C is a constant depending upon the material eroded, E is the total energy delivered by the bubble collapse pulses, i.e., area under the spectrum curve, E_o is a low-energy cut-off below which presumably the pulses do not deliver sufficient energy to the eroded surface to contribute importantly to the damage, and n is an exponent to be determined empirically. "n" as well as "C" and "E" may well depend upon the properties of the material to be eroded. It is of course the general purpose of this investigation to determine best values for C, E_o, and n for a given material, such as 304 stainless steel, e.g. Of course Eq. (1) may not be of the optimum form for this purpose, which will be determined later when more data is in hand. At least it is a "plausible" form for the moment. "Damage Rate" can be defined, for simplicity, as maximum "MDPR" (mean depth of penetration rate). Since the typical damage vs. time curve is "S-shaped" rather than linear, a more detailed definition of "Damage Rate" may be desirable eventually. The simplest, and most generally accepted, "figure of merit" for cavitation damage resistance of a material is $1/MDPR_{max}$.

B. Development of Acoustic Wave Guide Probes

1. General

At the start of this project there were two major unknowns to be resolved. It was not known whether or not standard submerged acoustic probe with pieozoelectric ceramic as the active element, which would be located within the test liquid and in the vicinity of a vibrating horn, would in fact be able to register individual bubble collapse pulses, which could then be counted and sorted as to energy by a suitable electronic circuit. Similar work of other investigators in this field (Japanese and Russian) was unknown to us at that time. If meaningful pulse counts could in fact be made by a "standard" microprobe of this sort

(Kistler Mod. No. 603A, Quartz Pressure Transducer, e.g., which we used), it was still not known whether or not these could be transmitted through a "wave-guide" probe consisting of $\sim$ 1 ft, long bar of stainless steel with the active (piezoelectric) ceramic at the far end. This probe design is of course necessitated by the requirement for its use for high-temperature sodium. No previous work pertinent to this latter problem yet exists to our knowledge. Our present successful calibration of these probes, as well as their present use for this purpose at Westinghouse-ARD, indicates the successful resolution of this second problem.

It is also interesting to note (Fig. 3-6) that the number of counts registered is "reasonable", i.e., within the expected "ball-park". We count typically a total of about 10^6 pulses/min. Since we have approximately the same number of cavitation cycles per min. (20 kHz), this would indicate about 1 bubble collapse of sufficient energy to be counted per cycle. Photographic studies over the years (4, eg.) have indicated that only 1 of $\sim 10^4$ bubbles seen to collapse in a given region are sufficiently energetic to be damaging. Since high-speed photos (5, eg) show the presence of $\sim$10 relatively large bubbles per cycle for our vibratory cavitation device, our count of about 1 per cycle is at least reasonable. Of course the number of relatively high-energy pulses is much less than the total counted. Also, for the present purpose, it is sufficient if the pulse count rate is merely proportional to the actual pulse rate existing in the cavitation field. Hence there is good hope at this time that the sought correlation between pulse count spectra and damage rate will be realized. Work of the earlier investigators (1-3) indicated some success in this regard for water and aluminum to which their tests were restricted.

2. Comparisons between Wave-Guide and Standard (Submerged) Probes

As previously discussed, it was necessary at the start of this research to validate the feasibility of measuring cavitation bubble collapse pulse spectra in a vibratory horn cavitation field. Since the driving frequency for the production of the cavitation is ~20 kHz, it is not certain a priori that bubble collapse pulses can be distinguished in a feasible manner from this "carrier-wave" frequency. This problem does not exist for a flowing system (as a venturi). A system working properly for the vibratory horn should work then without difficulty in the venturi system. Our later discovery of related work in Japan and Russia (1-3), using a vibratory horn, strengthened our initial hypothesis that the approach was feasible. In any case, our first work here on this project was the development of the necessary apparatus for the measurement of bubble pulse-count spectra using the simplest and most direct type of acoustic probe, i.e., a submerged piezoelectric Kistler pressure micro-transducer. The tests were limited to cold water, since this type of transducer is limited to low temperature operation. Since this was primarily a feasibility study, an existing cavitation-horn set-up was used, where the probe was inserted into the cavitation field from below. In the eventual sodium set-up the wave-guide probe (Fig. 1) must be inserted from above through the argon blanket, to minimize sodium-sealing problems. Hence the latter geometrical arrangement (Fig. 2) was used for the wave-guide probe calibrations already discussed. Figure 7 shows typical results for different frequency cut-offs obtained from the Kistler probe in this original set-up. These are compared with results from wave-guide probe No. 1, taken at the same time. No direct comparison between the two probe outputs can be made at this time since the crystal sensitivities are different, and their orientations with respect to the vibrating horn are not identical.

However, the total counts seen by each probe are similar.

The Kistler output does not decrease for low energy pulses as does the wave-guide probe. This fact tends to verify our previously discussed assumption that the fall-off in pulse count for the wave-guide probes under this condition may be due to elimination or "blurring" of low energy pulses by interference phenomena in their traverse through the wave-guide rod. In any event these tests verify the feasibility of making bubble pulse-count spectra for the vibratory-horn cavitation field by both simple submerged probes and wave-guide probes. For each type of probe, the pulse count increases (as expected) with increased horn amplitude.

III. Conclusions

It has been verified that the measuring of cavitation bubble collapse pulse energy spectra in a vibrating horn cavitation field, using either a submerged micro-probe, or a wave-guide probe (for which the ceramic is distant from the test liquid) so that operation in high-temperature sodium is possible, is feasible. Such a system has then been developed under this project, and was used for the calibration of four wave-guide probes. Two of these were sent to Westinghouse-ARD for use in their sodium venturi tests, and two retained here for use in the U-M vibratory cavitation sodium tests.

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List of Figures

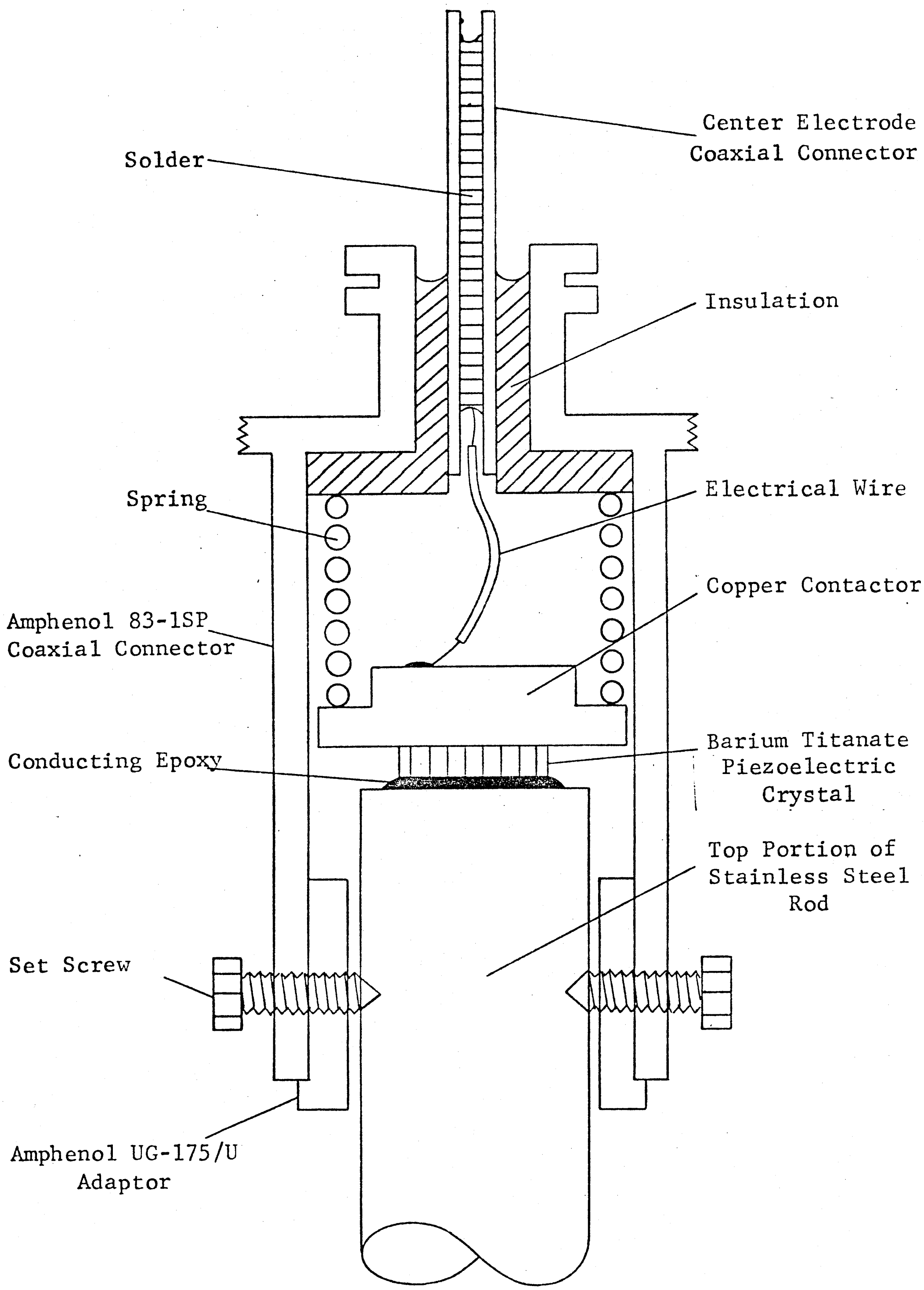

Figure 1. Schematic cross sectional view of the crystal assembly for wave-guide probe.

FIG 2

BLOCK DIAGRAM OF THE ULTRASONIC VIBRATORY FACILITY.

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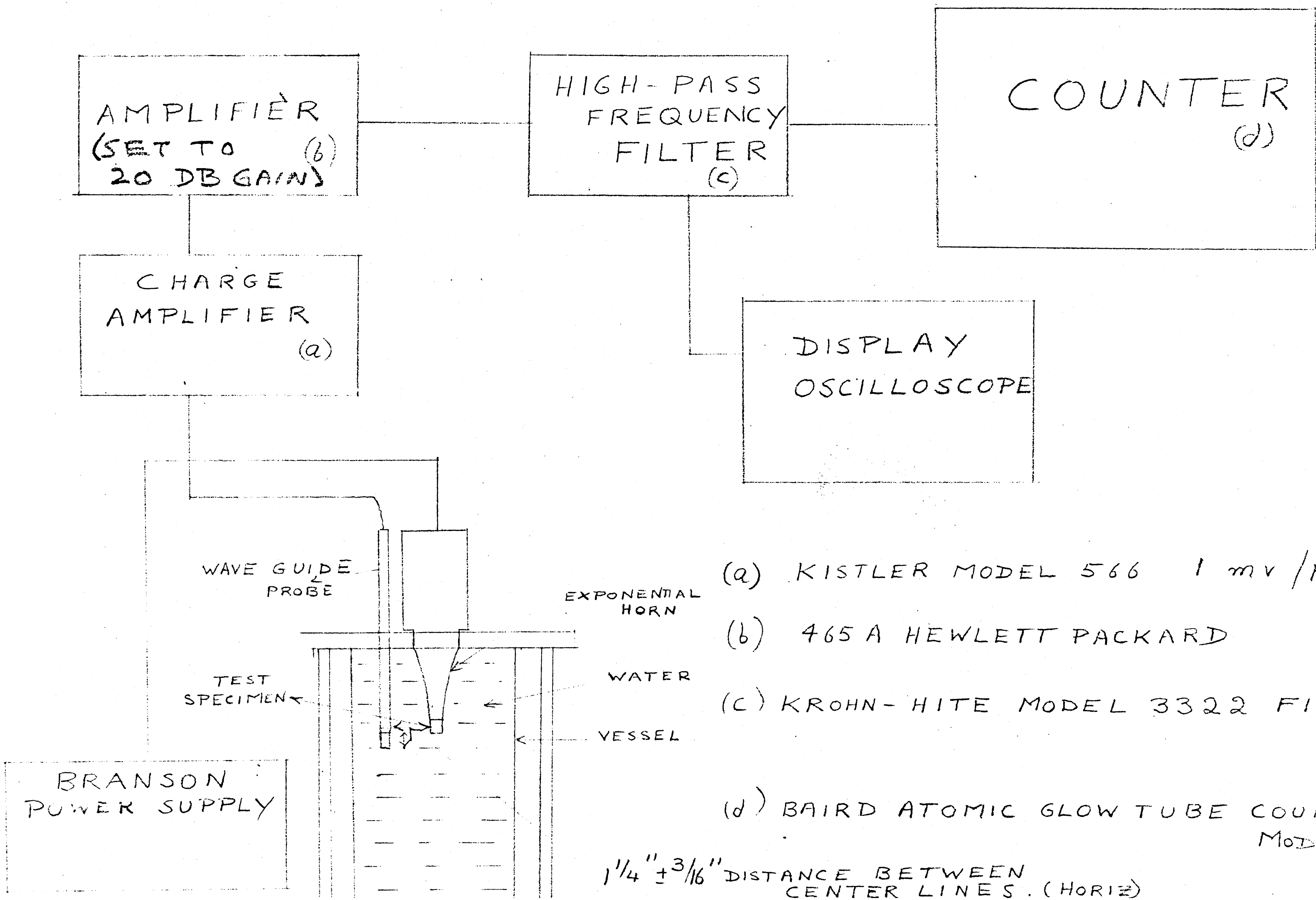

(a) KISTLER MODEL 566 1 mv/pcb

(b) 465 A HEWLETT PACKARD 20 db.

(c) KROHN-HITE MODEL 3322 FILTER

(d) BAIRD ATOMIC GLOW TUBE COUNTER MODEL 1283

$1\frac{1}{4}'' \pm \frac{3}{16}''$ DISTANCE BETWEEN CENTER LINES. (HORIZ)

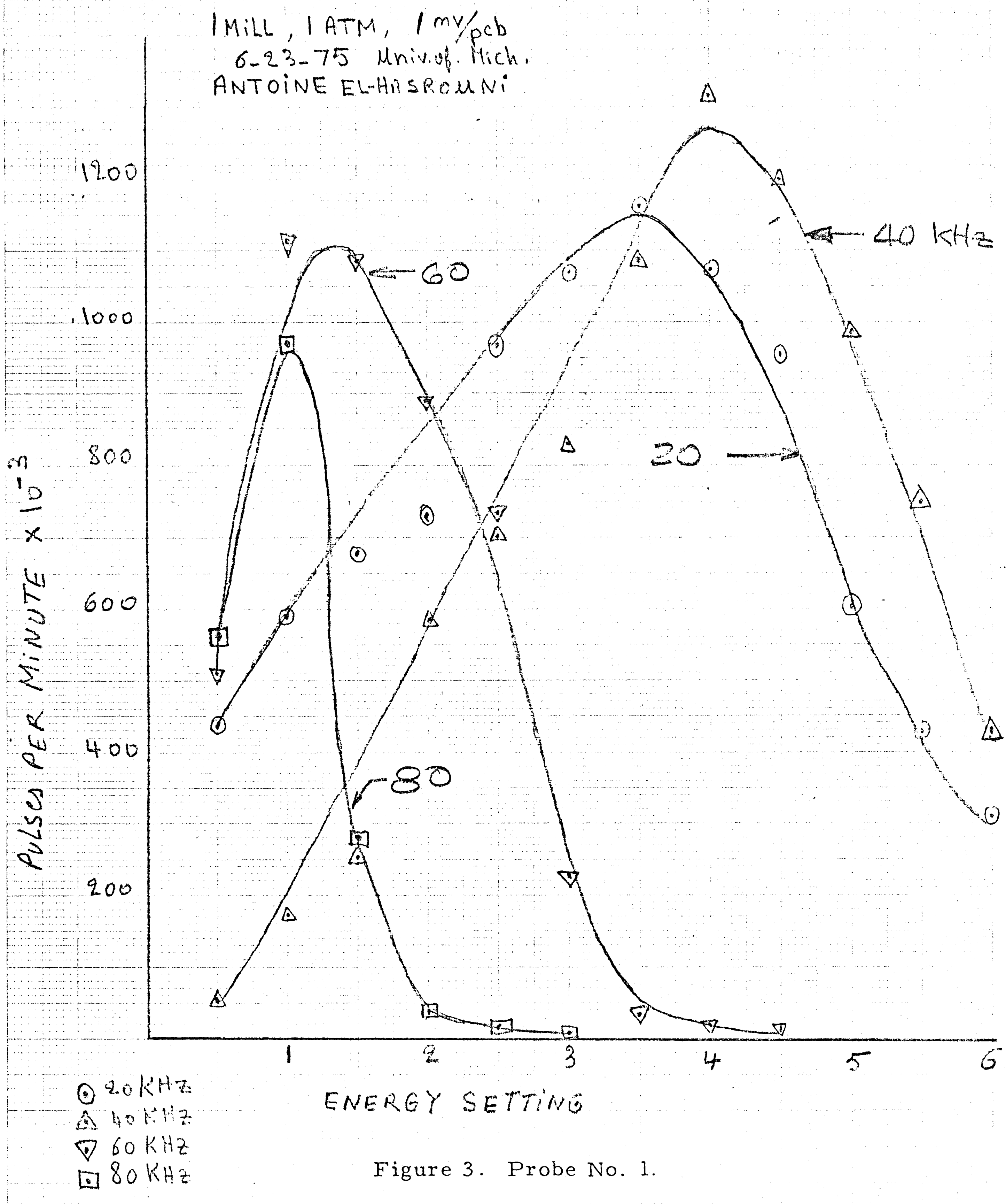

Figure 3. Probe No. 1.

5228

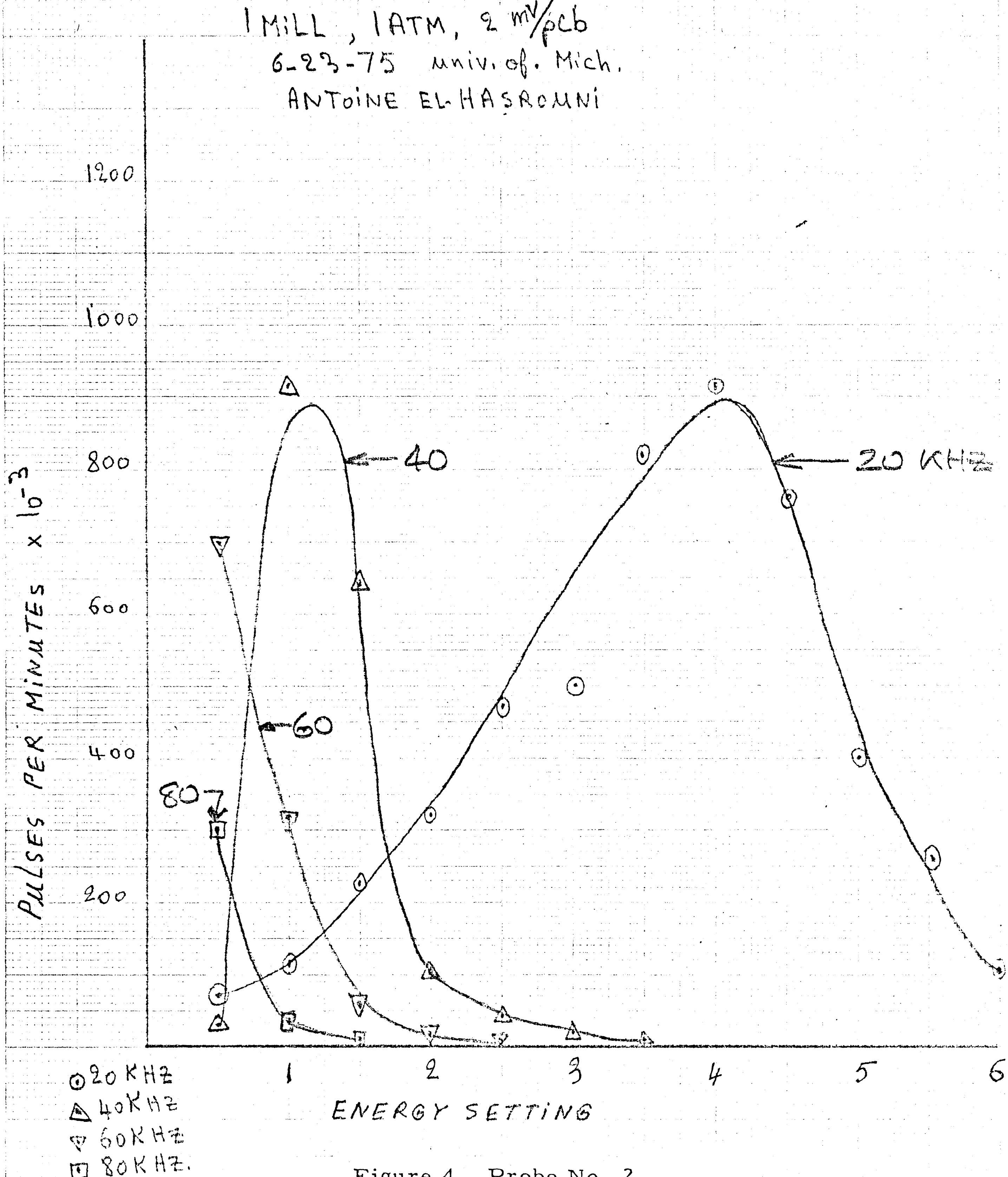

Figure 4. Probe No. 2.

5229

Squares to the Inch

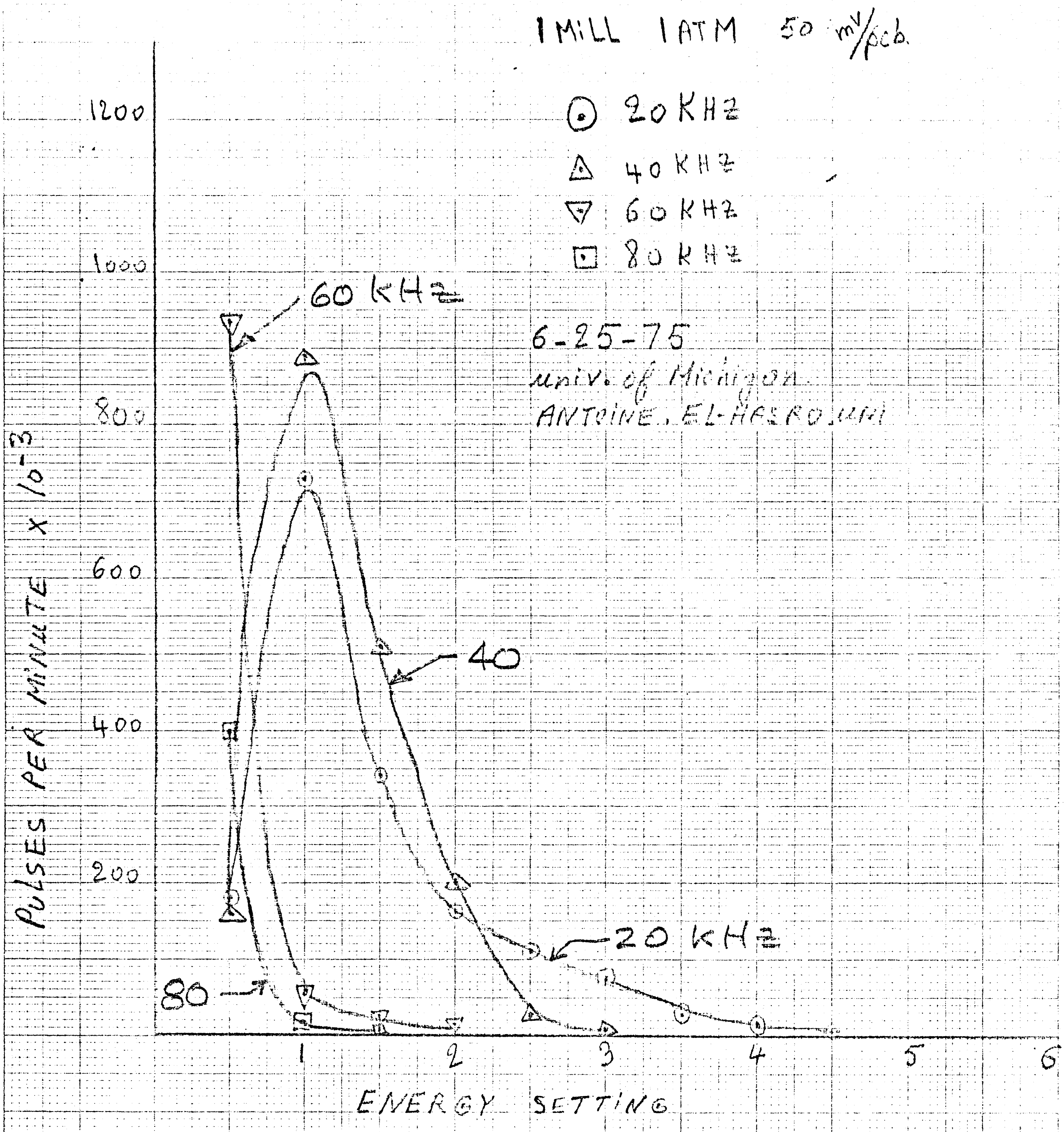

Figure 5. Probe No. 3.

5230

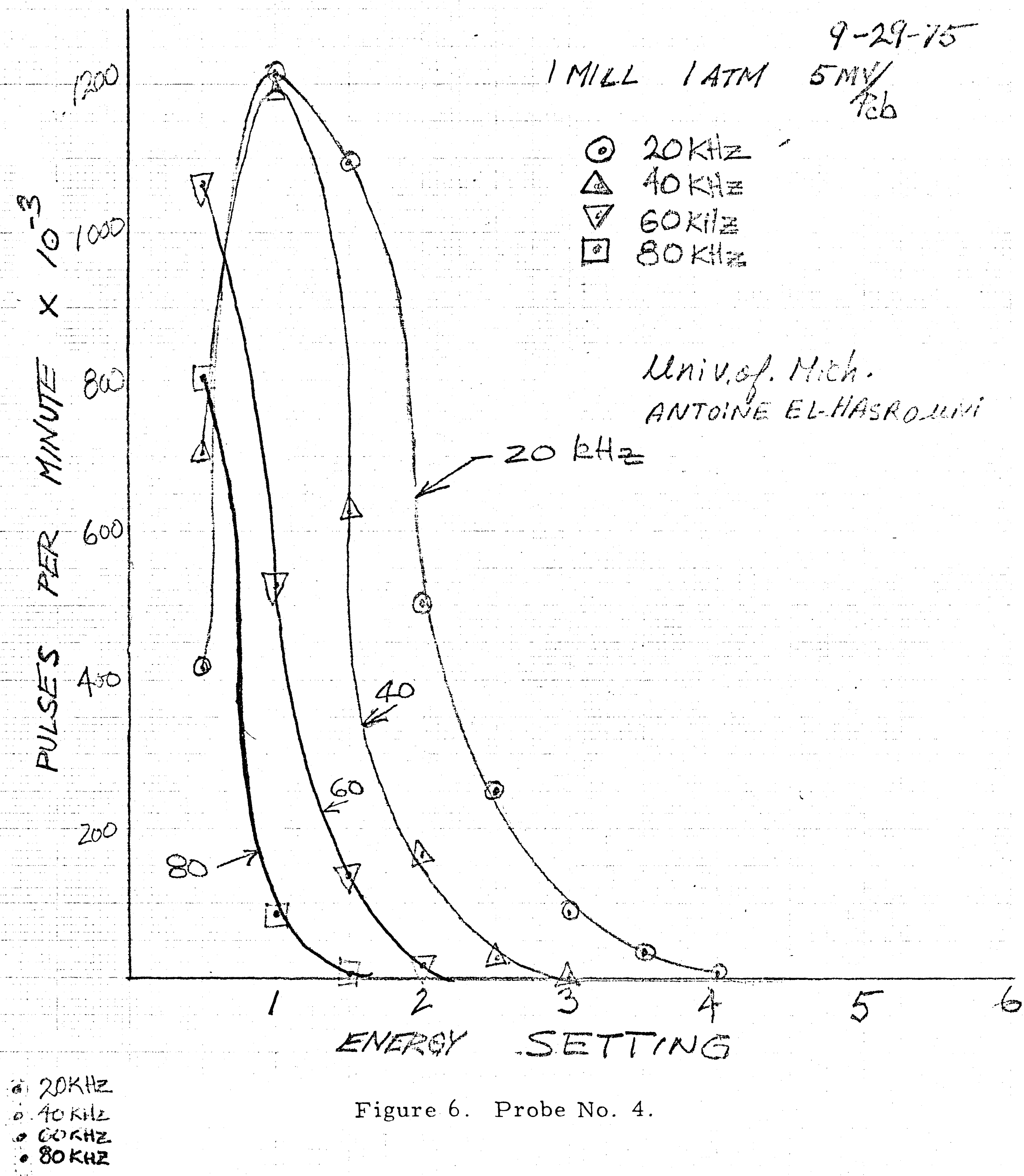

Figure 6. Probe No. 4.

5231

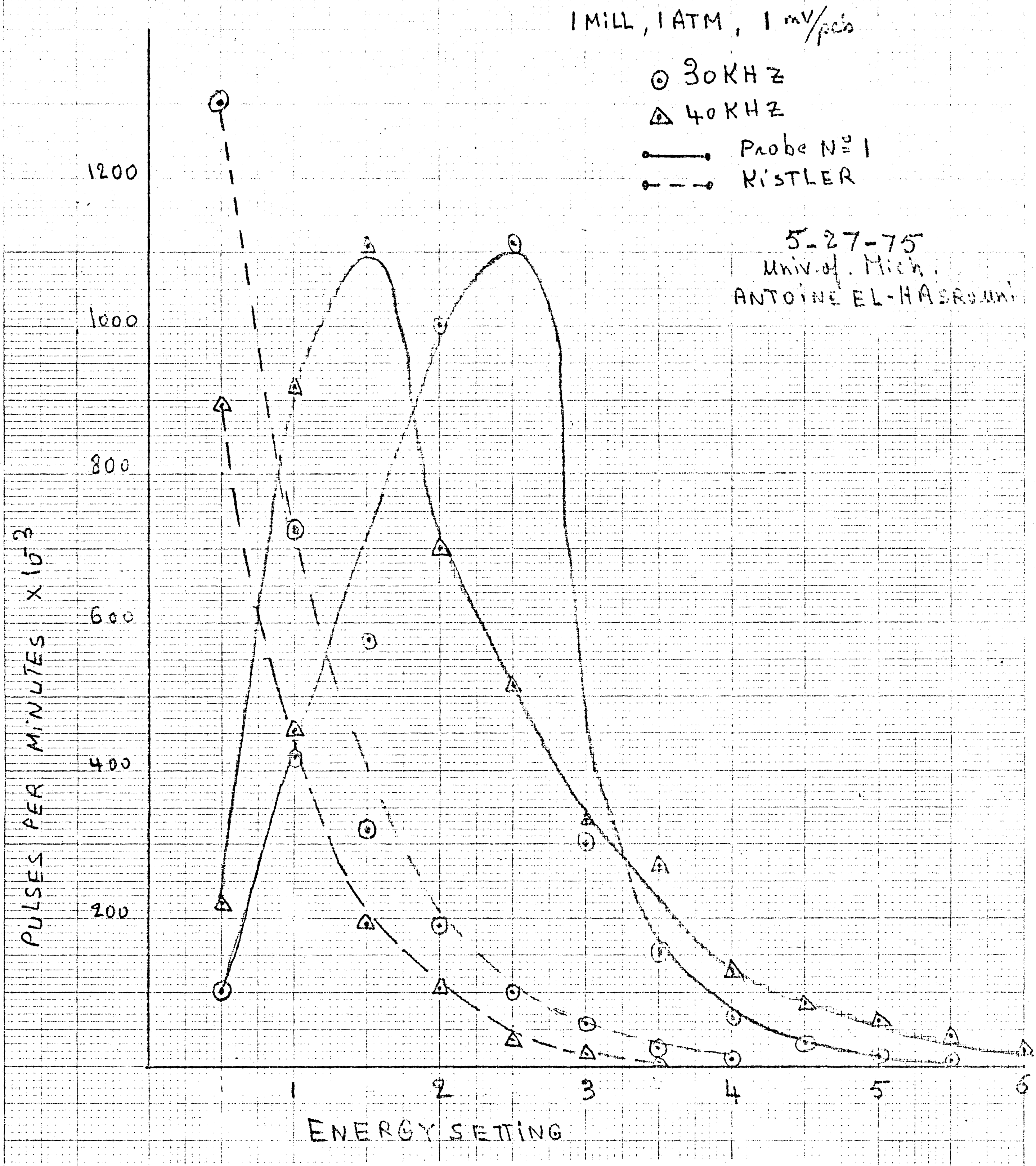

Figure 7. Probe No. 1 and kistler.