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NOISE AND EROSION OF SELF RESONATING CAVITATING JETS

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SYNOPSIS

Self resonating jets have been developed which take advantage of the natural tendency of a jet to organize in large structures. Tests have shown that these jets are both highly erosive and a source of a discrete frequency high level noise. The erosion and noise effects are harnessed for improved cutting, drilling, and cleaning, as well as for sound generation. Simultaneous investigations of the noise and erosion of these jets have been conducted and have shown a definite trend toward correlation. For instance, time evolution of volume removal rates of an impacted surface and RMS readings of a transducer have been found to be correlated. Similarily, shifts in the relative importance of the various frequencies have followed the advancement of erosion. These results could be of great advantage in the determination of the evolution of a jet cutting operation in progress. In this paper jet noise and erosion correlaiton tests will be described and the results analyzed.

INTRODUCTION

Cavitation is mainly known for its harmful effects, namely, loss of performance, erosion, and noise. The usual procedure to prevent these deleterious effects is to avoid the phenomenon by proper design and by limiting the operating conditions. However, attempts to induce and harness cavitation for useful purposes have been increasingly successful. In high-pressure jets, cavitation has for some time now been purposely induced in order to increase their drilling, cutting, and cleaning capabilities[1-2]. The noise associated with cavitation is being used as a means of sensing cavitation when it becomes destructive and, hence, could allow for alleviating its damaging effects. More recently, a more direct utilization of cavitation noise in jets for sound generation was proposed and demonstrated[3-4].

The occurrence of cavitation in the high-volume flows of sodium in fast neutron reactors has prompted the C.E.A. to undertake a large research program on cavitating sodium flows[5]. This was prompted primarily by the importance of the phenomena to the sodium pump development program. Because of the lack of sufficient understanding of cavitation erosion and its scaling laws in sodium, excessive safety margins are presently used for pump design. It is therefore highly desirable to develop techniques to discriminate between erosive and nonerosive cavitation events and flow conditions. Since optical detection of cavitation in sodium flowing at very high temperatures is not feasible, acoustic detection instrumentation (CANASTA) was developed at the Cadarache Nuclear Research Center.

Acoustic detectors and signal processing instrumentation (CANASTA) capable of handling the high-frequency signals created by cavitation has been developed at CEN/CADARACHE. The ability of this instrumentation has been demonstrated using a liquid sodium test loop[6]. However, due to the extremely long time periods required to create measurable erosion in any traditional flow tunnel and therefore in the Cadarache sodium cavitation tunnel, test runs have been expensive and data collection somewhat difficult. In the work described here, erosion due to self resonating cavitating jets is used to gather data which allows discrimination between the noise patterns created by erosive versus nonerosive cavitation. The high erosive capability of these jets which significantly shortens experimentation time relative to a cavitation tunnel was the incentive to conduct this investigation.

In the work reported here, controlled erosion experiments on stainless steel have been conducted. The time evolution of the erosion and the emitted noise were measured simultaneously. The objective was to evaluate the possibility of discrimination between erosive and nonerosive cavitation.

SELF RESONATING CAVITATING JETS

Experimental observations of submerged jets show the tendency of the turbulent eddies in their shear layer to organize in large structures. Excitation of an air jet with periodic acoustic signals produced upstream of the nozzle by transducers or loudspeakers shows a remarkable change of the jet structure into discrete ring vortices when the excitation frequency, f, matches the predominant natural frequencies of the non-excited jet.

The potential of such a phenomenon for suberged water jets was recognized[1-3], and a unique technology was developed related to achieving useful submerged jets having very high amplitude, periodic, oscillatory discharge without using moving parts in the supply system. The passive excitation is obtained hydroacoustically and structures the shear layer of the jet into discrete, well defined ring vortices when the excitation frequency, f, matches the jet's preferred values. This can be obtained by (a) feeding the final jet-forming nozzle with various types of acoustic chambers (for example, Helmholtz chambers or organ-pipe tubes) tuned to

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resonate at the desired frequency; and (b) shaping the nozzle so as to feed back the pressure oscillations which occur at the exit. Such devices are forms of "whistles" which self-excite and thus are totally passive. These STRATOJETs have shown enhanced erosivity from increased cavitation activity. The large pressure oscillations associated with the intensification of cavitation, with resonance in the nozzle assembly, and with the production and disappearance of large vortical structures greatly improve the erosion and cleaning capabilities of the jet and make a very effective noise generator[4-5].

EXPERIMENTAL SETUP

The tests described here were conducted in the Tracor Hydronautics High Pressure Cell (HPC). The pressure in this cell can be varied up to 207 bar with independent variation of the nozzle pressure up to 690 bar. Therefore, wide ranges of cavitation intensity and cavitation number can be achieved in this facility. When the jet is allowed to impact on surfaces, erosion can be obtained with various cavitation numbers in a controllable manner. By adjusting the standoff distance of the impacting jet, one is able to control the erosion intensity with a fixed erosive strength for the jet. Therefore, the potential discrimination of erosive versus non-erosive cavitation noise patterns can be investigated.

Detailed descriptions of the Cell can be found elsewhere[7]. A drawing of this cell can be seen in Figure 1. The flow into the cell enters through a removable lid which is bolted to the main cell and sealed with an O-ring. The ambient pressure within the cell is controlled by a valve. The cell rated pressure capacity is 20.7 MPa.

The main circulation pump used in these tests was a diesel-driven high-pressure pump, manufactured by American Aero. It has five plungers and is rated for 112kW and yields 1.27 ℓ/s at 690 bar.

Two test plates made of 316 stainless steel were used as targets Their dimensions were 16.9 x 16.9 x 1.9 cm. Two transducer holes were provided on each plate with dimensions of 3.1 cm and 5.6 cm in diameter. The position of these holes with respect to the jet impact point is shown in Figure 2.

Two types of pressure transducers were used in the test runs. The transducers mounted in the test plate were provided by CEN/Cadarache. These were piezoelectric crystal transducers, and they had a rather large sensing area, about 3.1 cm and 5.6 cm in diameter, respectively. The large surface areas provided integrated signal over the surface. These transducers (Type 4540 and 4515) have been designed for withstanding high temperatures (up to 650°C) and their frequency range was up to 5 MHz. The third transducer, mounted on the wall of the high-pressure cell was a piezoelectric pressure transducer (PCB Model 101 M55). Its resonant frequency was 300 KHz, and sensing area was 0.635 cm in diameter. This transducer provided the overall pressure fluctuation, and thus measured the noise inside the HPC. A similar transducer was positioned in the feed pipe leading to the nozzle. Figure 3 gives a sketch of the location during the tests of these four transducers.

The CANASTA system was provided by the CEN Cadarache and was used to analyze the output of the transducers. The system counts during a measurement cycle the number of pressure spikes whose amplitude exceeds an imposed threshold. This number is related to the number of strong cavitation bubble implosions. Another output of the system is information on the detected pulses' "total energy." It is proportional to the time integrals of all the detected pressure bursts.

The signals from the transducers were also captured on a Nicolet 2090 Digital Oscilloscope and then stored on floppy disks for later analysis. This oscilloscope had a maximum digitizing rate of 50 ns per point and a bandwidth of up to 7 MHz. A Digital Equipment Corp. VAX 11/750 computer was interfaced with the oscilloscope allowing the digitized pressure-time information to be analyzed with a Fast Fourier Transform. A root mean square voltmeter, RMS HP 3466A, was also used to obtain information on the generated overall noise level. Figure 4 shows a schematic of the test facility and instrumentation.

TESTS AND PROCEDURES

In earlier tests the self resonating jet (STRATOJET) outperformed other jets. Very significant erosion depths were measured on commercial aluminum (up to 3 mm.) after five minutes of static impact. A pressure drop of 47.6 MPa was needed. Figure 5 shows comparative curves of mean depth of erosion versus ambient pressure for several types of nozzles. The STRATOJET nozzle of diameter 2.54 mm was chosen for the present study. A CENTERBODY CAVIJET was also used for comparative purposes. Its diameter was 2.72 mm, and the center body cylinder diameter was 1.36 mm. From the earlier tests, it was concluded that pressures in the range 48 to 70 MPa would produce measurable erosion imprints on stainless steel in a reasonable jetting time.

The ambient pressure in the High Pressure Cell was limited to 14.8 bar in order not to exceed the allowed maximum pressure of the CEA transducers' sealed elements. The pressure drop across the nozzles was 47.6 MPa for one set of tests, and 68 MPa for another set. The standoff distance between the nozzles and the plate was fixed at 9.5 mm when cavitation erosion was sought, and exceeded 89 mm in the nonerosion case.

Once the nozzle and the plate were positioned at the required standoff distance, the ambient pressure in the cell was set to 14.8 MPa, and the main pump was turned on to reach the required pressure: 47.6 MPa or 68 MPa. The following measurements were then taken during the jetting:

1. Sequential RMS readings of the three transducers mentioned above, plus periodic RMS readings of a fourth transducer located in the feed-pipe to the nozzle;

2. Sequential readings from the CANASTA for each of the three transducers.
3. Sequential high frequency recording of the transient signals from the three transducers on floppy discs of the Nicolet for later frequency analysis; and
4. Sequential frequency spectra of the three transducers' signals.

The following procedure was followed. The CANASTA system was allowed to integrate the signal of one transducer for fifteen seconds. Then, during a five-second intermission period the detection was shifted to the following transducer. While the CANASTA was integrating the signal of a given transducer, readouts were taken of the RMS and frequency values of the signals from the other transducers. After a selected period, ΔT, was completed, jetting was stopped, the HPC lid was opened, and the plate was visually inspected. Measurements and photographs of the erosion pattern were then taken if a detectable change from the preceding testing increment was observed. ΔT was varied from 140 seconds up to 2180 seconds. Erosion quantification was achieved by measuring mean and maximum depth of erosion as well as an equivalent diameter of the eroded area. Mean depth and equivalent diameter were obtained from measurements of the erosion imprint using statistical averaging. When erosion became significant, volume removal was determined by using a graduated syringe and filling the eroded imprint with a liquid. For the purpose of this study, surface tension was reduced by the use of a surfactant but no additional effort was made to correct for surface tension effects in the pippete. Recording of the transient signals on floppy discs was done at least once for each transducer during each ΔT period. These signals were then analyzed using the VAX 11/750 computer.

RESULTS AND INTERPRETATION

Several tests using the method described above were run and the main results are summarized here. Additional details can be found in Reference 8. Since the two CEN transducers were located symmetrically with respect to the jet the differences in their signals reflected only differences in their sensitivities and frequency responses. This was not the case for the PCB transducer which was located much farther from the jet and therefore from the collapsing and eventually eroding bubbles. Differences between signals from this transducer and the two CEN transducers were therefore due not only to differences in their characteristics but also to differences in the actual pressure signals they observed from their different positions. The "large" transducer detected the highest number of spikes due to the large dimension of its sensitive area over which the pressure pulses are integrated. The "cell" transducer came in second position even though its sensitive area was much smaller and its distance to the sound source much larger. This was probably due to its very high sensitivity. Since the CANASTA responds to signals stronger than a trigger level fixed by the operator, a more sensitive transducer detects, for the same acoustic source and trigger level, a larger number of spikes than a less sensitive transducer.

During the tests, the CANASTA trigger level was, for practical reasons, kept the same for the three transducers and maintained constant throughout a test run. This level was chosen such that a good response without saturation could be obtained for all transducers. Very good correlation between the CANASTA processed signals of the three transducers was observed as long as saturation did not occur. In the corresponding erosion tests volume removal from the target plate through erosion was either absent or moderate and therefore changes in the sound characteristics were moderate. However when erosion was intense and jetting time relatively long the trigger level became inadequate for the CEN transducers. No obvious correlation was then seen between the three signals. Another important reason for the absence of correlation comes from the phenomenon itself. Once an erosion pattern is imprinted on the surface of the target plate, the flow field on the plate is modified. This modification becomes very substantial when the imprint becomes deep. Secondary cavitation and erosion is generated, and a large separation region can be formed. For the transducers imbedded in the target plate, such an occurrence has a more dramatic effect than for the far-field transducer. This implies that these embedded sensors will not necessarily detect acoustic pressures for more intense erosion. The presence of separation bubbles or cavities could isolate these sensors from the noise sources or attenuate the incoming signals. All indications from the present tests are that this has occurred and that a location of the transducer far from the erosion region is preferred.

Figure 6 shows a comparison of the RMS readings of the three transducers for a set of tests. Since the readings were made using a true RMS meter on signals filtered only for the very low frequencies (f<60Hz), they give a very good indication of the overall pressure sound level. This figure compares two tests A and B. In test B (X = 95 mm), the nozzle was far away from the target plate, hence no erosion was occurring, and the three transducers detected no significant changes in the RMS pressure levels as a function of time However large variations with time of the RMS readings were seen during test A where X = 9.5 mm. All four transducers show corresponding peaks and valleys in the RMS signals time histories. These "oscillations" are, however, most intense for the transducer located in the cell. These oscillations indicate acceleration and saturation periods of noise generation and, as we will see later, high rates of erosion followed by erosion saturation periods. The intensification of the RMS readings during the initial erosion phase and the tendency to return to the nonerosive value seem to indicate the generation of a separated region on the plate.

The time history of the signal of the large transducer has an overall trend quite different from the other transducers. As indicated also with the CANASTA signals a detrimental event has happened at t≈4500 seconds. The RMS signal of this transducer takes an overall continuous downslope which is not observed with the other transducers. This deterioration of the signal is confirmed at the end of the tests (t≈10,000 seconds) by the complete "death" of the transducer. This transducer was replaced by a second similar one for the following tests.

The time variation of the mean pressure fluctuations are compared in Figure 7 with the evolution of the total volume removed from the target plate. The test corresponding to this figure Test A, used the very erosive STRATOJET nozzle and was conducted for a long enough per od to observe significant erosion and noise modification. Figure 7 shows simultaneously the RMS pressure fluctuations measured by the "small" CEN transducer and the PCB "cell" transducer. The volume removed was determined for this figure by measuring "mean" eroded diameters and depths (see Figure 8). The qualitative agreement between the general trend of the total volume removed curve and the RMS signal evolution of the cell transducer is very satisfactory. Additional information is provided in Figure 7. In this figure, simultaneous representation of time variations of RMS pressures, total volume removed, volume removal rate, and the CANASTA counts can be seen. The volume removal rate is obtained by fitting polynomial curves through portions of the curve of total volume removal versus time and by computing the time derivative of these polynomials.

From these observations, we can tentatively say that following the initial incubation period, both RMS pressure fluctuations and total volume removal increase with time until the first saturation period. The comparison between rate of volume removal and RMS pressures is much more striking for this initial phase. When saturation of total volume removal and the saturation of RMS readings were achieved, a very high erosion rate was attained and then terminated by a spike in the RMS readings (e.g., t = 4000 s.). One would have liked to be able to continue to observe the erosion in a more monotonic fashion ..probably a relatively large piece of metal was removed at that point, and a new incubation period restarted on the newly bared metal. This can be deduced from the sudden flattening in the total volume removal curve and by the sharp drop in the volume removal rate The following phases look like periodic repeats of the initial phase. A lag between two successive periods is related to incubation periods for the newly bared surface metals. Drops in the RMS pressure readings (Figure 9, t>6000 s), which are difficult to explain by considering the total volume removed, seem to be related to negative slopes in the volume removal rate.

Comparison of the CANASTA processed signal with the other signals shows that peaks and troughs do correspond, but the general trend of increasing RMS pressure is not seen. The most comparable curve seems to be the volume removal rate curve. However, the shift between the spikes and mostly that between the peak at t=4000 s observed in the removal rate curve and that at t = 5500 s observed in the CANASTA signal does not have a satisfactory explanation at this time. Errors in the evaluation of the volume removal rate as well as in the total volume measurement might explain these differences

Frequency spectra of the signals detected by the transducers in eroding and noneroding cavitation conditions were analyzed. All the spectra were obtained by applying to the recorded signals a Fast Fourier Transform. Before erosion was significant, the only main frequency component was the self resonance frequency of the STRATOJET which is about 7.3 KHz. This was also the case when the plate was away from the nozzle. A second frequency (24.4 KHz) was also present but was less important. When erosion developed, the signal became much richer in frequency. For case A presented in this paper, after 5220 seconds the energy of the signal was mainly contained in the frequency band 7.3 to 24 KHz. Some other higher frequencies also appeared. However, the relative importance of the main frequency to the others changes significantly with erosion. The main indication of the erosive process seems to be reflected in all three transducers by the strong enforcement of the frequencies in the range 24 to 45 KHz.

This is mostly reflected in the "cell" transducer. As we have seen in the preceding sections,this "cell" transducer gave the best correlation with erosion. Here, indications are given that this transducer, probably because of its size, location, and response was the most able to detect the frequency range most sensitive to erosion.

CONCLUSIONS

We have investigated in this paper the correlation between noise and erosion of cavitating jets. Comparisons between volume removal of 316 stainless steel and acoustic signal analysis of various transducers have produced the following preliminary conclusions. Some of these conclusions corroborate earlier results, but most of them need confirmation through additional testing and variation of the experimental configurations.

(a) The location of the noise detecting transducer is a key factor in a good noise-erosion correlation technique. A transducer distant from the eroded region seems to be significantly more sensitive to the erosion versus time variations.

(b) A transducer of small size, high sensitivity, and flat frequency response is recommended for the correlations.

(c) The time variation of the root mean square values of the detected sound pressure seems to give the best correlation with the total volume removal.

(d) The frequency contents of the erosive and nonerosive cavitating conditions investigated here seem to be similar. The major influence of erosion is to shift the importance of the various frequencies. The main resonance frequency of the jet becomes of secondary importance when erosion is occurring.

(e) Significant acoustic pressure variations are only detectable when significant erosion is occurring. Volume removal has to take place and modification of the secondary flow over the erosion imprint is probably needed

(f) RMS sound pressures and CANASTA readings increase with increasing volume removal rates and total volume removed. These readings decrease following saturation of material removal and a drop in the volume removal rates. The overall tendency of the noise to increase with the total volume removed is however only correlated with the RMS readings.

The results of this study are very encouraging in showing the possibility of correlation between noise and erosion. They add a significant amount of data, information, and evidence to earlier CEA studies on the subject. An outcome of a reliable correlation between noise and erosion would be the detection of potential erosion in an installation and its control. An additional outcome, which shows more promise at this point in time is the monitoring the evolution of a jet cutting operation. The conclusions drawn above indicate that it is possible, when direct observation is difficult, to remotely assess the progress of erosion

ACKNOWLEDGEMENTS

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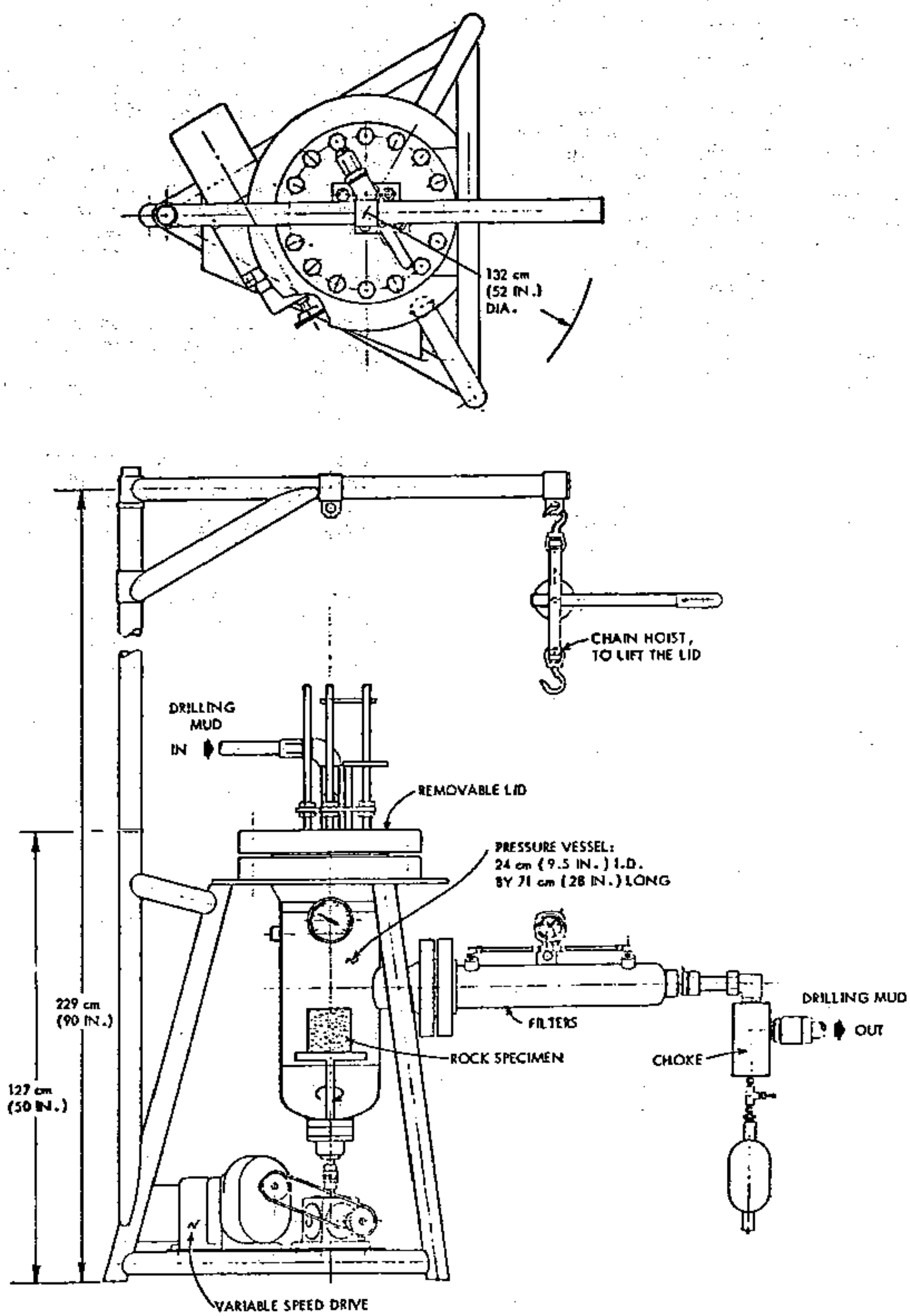
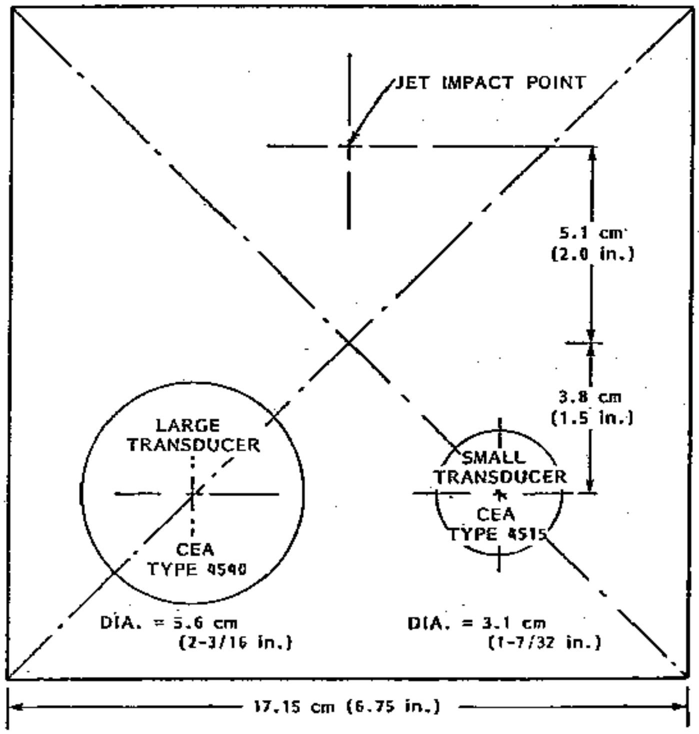


Fig. 1 High pressure cell for Elevated Ambient pressure studies of CAVIJET nozzles



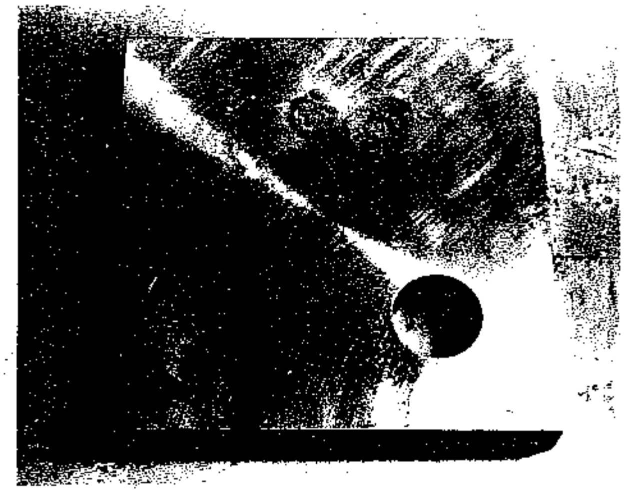


Fig. 2 Test plate used in Noise/Erision tests

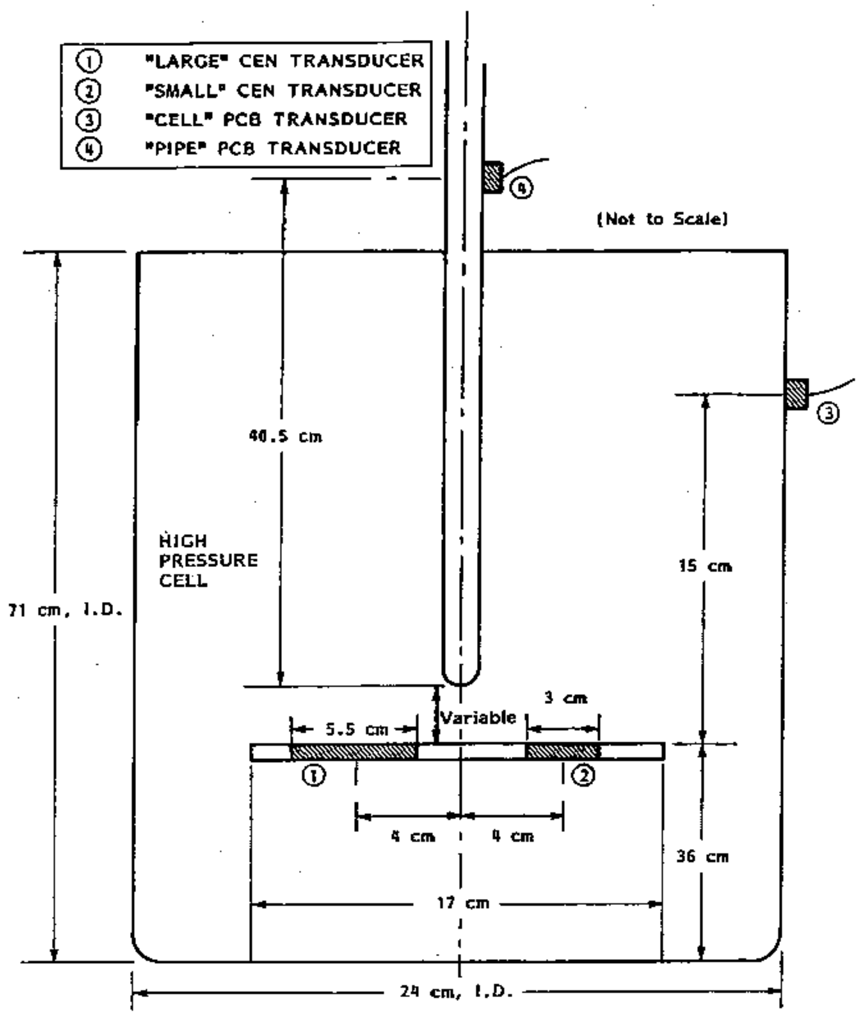


Fig. 3 Sketch of pressure transducer location in the high pressure cell

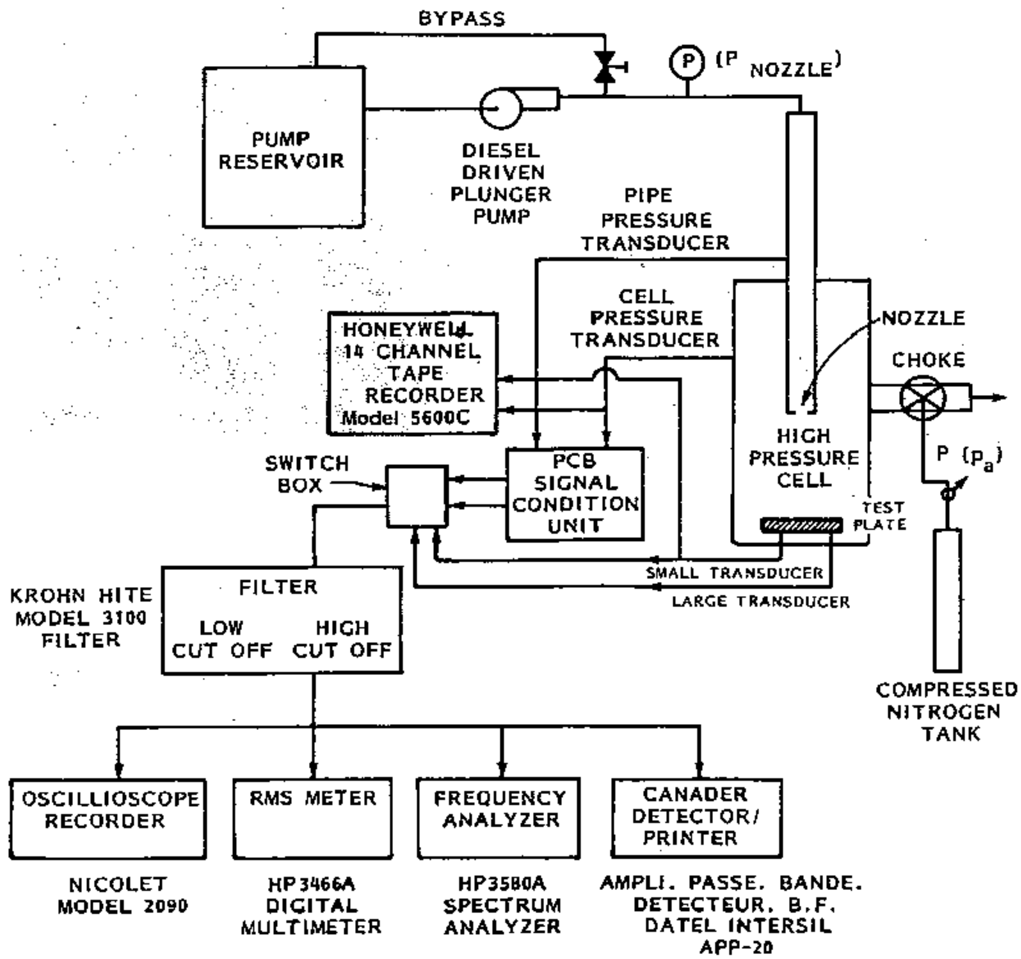


Fig. 4 Schematic of test facility and instrumentation

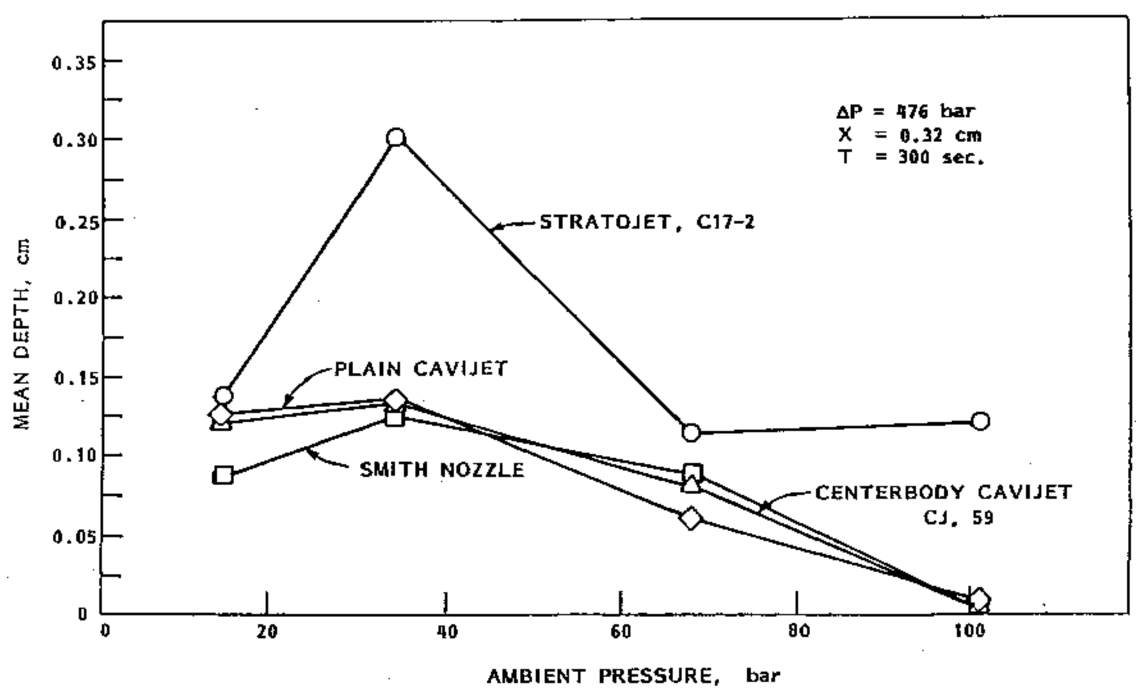


Fig. 5 Comparison of mean depth of erosion for four nozzles in Aluminum

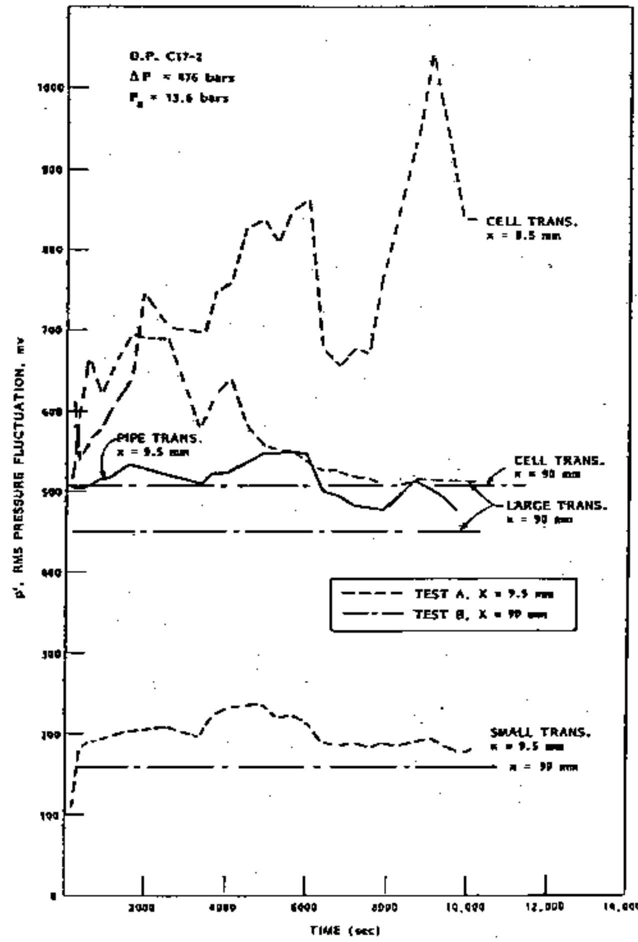


Fig. 6 Comparison of RMS readings of three Transducers. Tests A and B. Organ Pipe Stratojet, C17 – 2

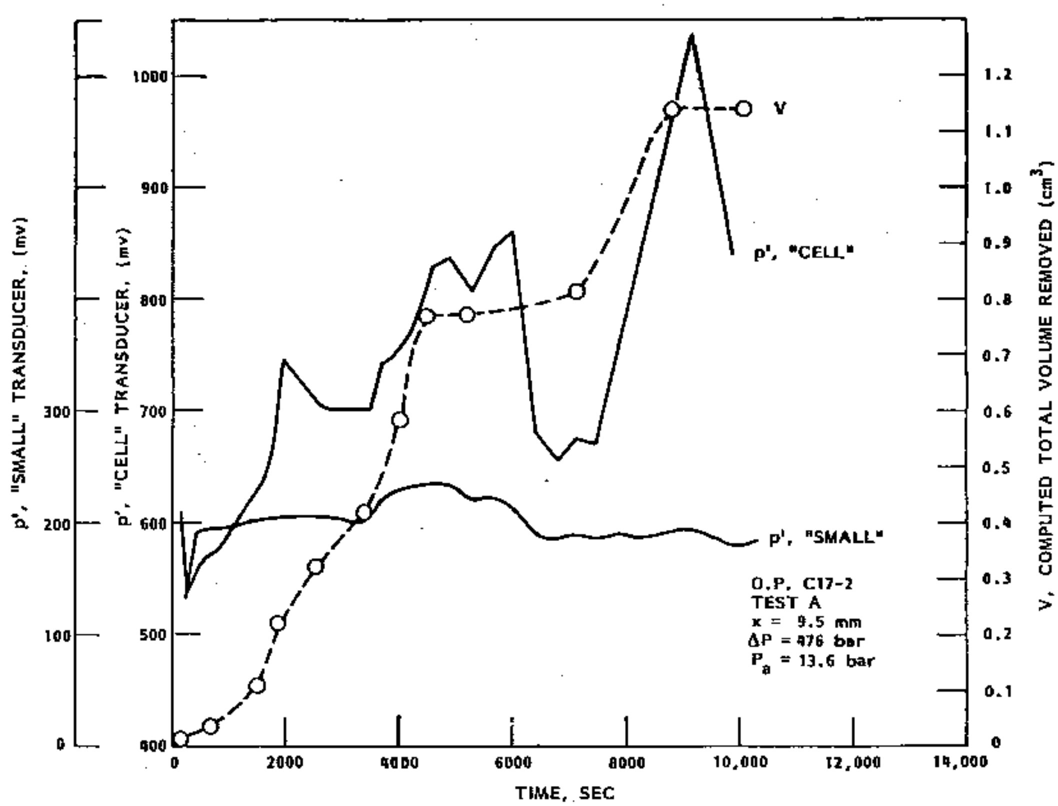


Fig. 7 Correlation between total volume removed and RMS readings of 'CELL' and 'SMALL' Transducers

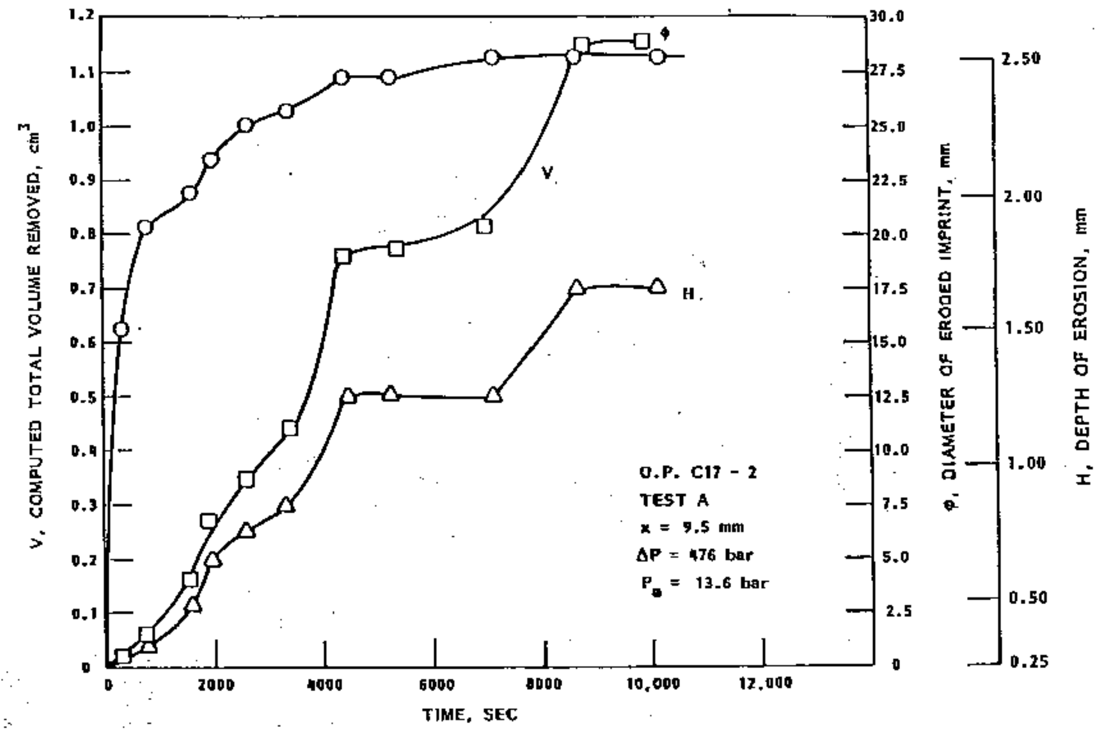


Fig. 8 Eroded Imprint characterisitics, test a Stratojet Nozzle

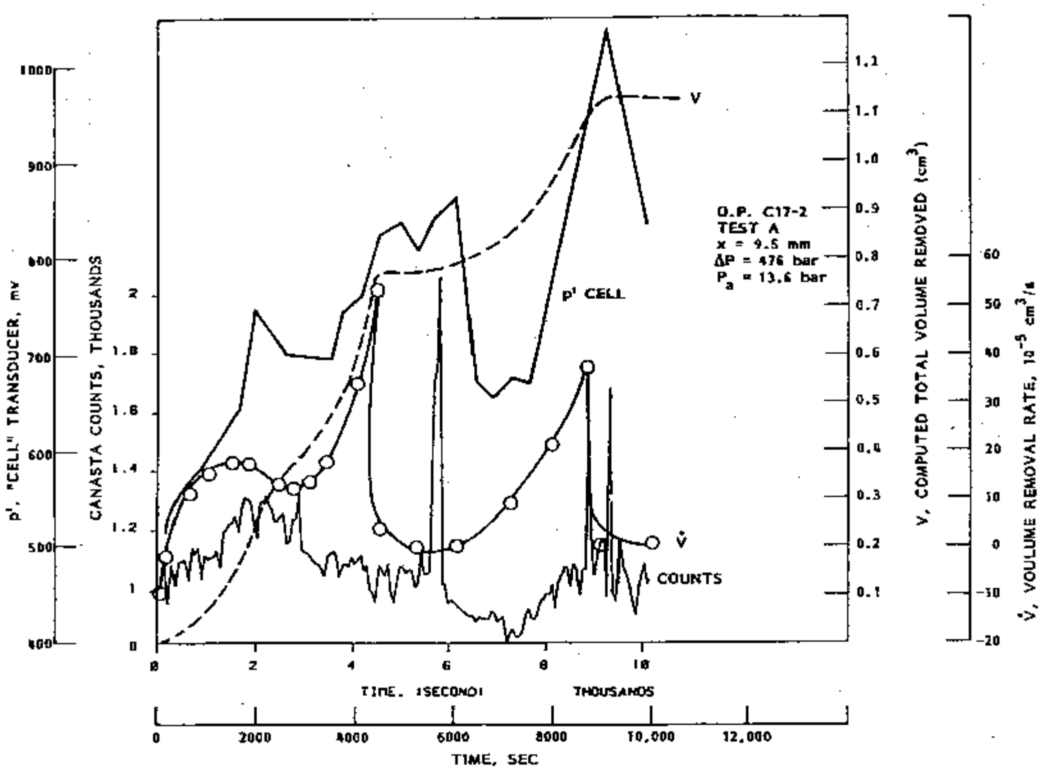


Fig. 9 Correlation between total volume removal, Volume Removal Rate, RMS Acoustic pressure time variations, and number of Canasta Impact counts