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HEALTH & SAFETY LABORATORY

Literature review: Noise from high pressure water jetting

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EXECUTIVE SUMMARY

Background

Water jetting systems generate a very high pressure jet by forcing water through a small bore nozzle. The nozzle is mounted on the end of a jetting lance/gun which is held by the operator. The water is supplied via a hose from a jetting unit which has a source of water, a high pressure pump and a prime mover (e.g. a diesel engine). The water jet has very high energy and the potential to cause serious injury. It has a wide variety of applications in the offshore, marine, construction and manufacturing industries. For example: removing marine growth, scale, rust and old paintwork from offshore structures and ships; scabbling and cutting concrete; cleaning tube bundles, heat exchangers and boiler tubes; removing graffiti, paint, rust, cement, grease and oil from any surface.

Objectives

Water jetting systems emit high noise levels and have the potential to require a programme of control measures to ensure a water jetting operator does not exceed the exposure limit value under the forthcoming Control of Noise at Work Regulations 2005 [2]. This project is primarily concerned with noise from high pressure and ultra high pressure water jetting, that is equipment operating above 680 bar (10,000 psi). This report describes the first stage of the project which is primarily a literature search for existing information on noise emission from water jetting. An initial survey of water jetting manufacturers and suppliers is also presented.

Literature review

The literature search revealed very few reliable or relevant papers on noise emission from hand-held water jetting systems. The most convincing observations are as follows:

- High frequency energy (4000 to 8000 Hz) dominates the water jet noise spectrum. The jetting unit is the main source of low frequency noise.

- Water jet noise emission increases with increasing water pressure, mainly in the mid-high frequency range. An increase of 9 dB with increments of 20 MPa at frequencies above 1 kHz and an increase of 6 dB with increments of 20 MPa for lower frequencies have been shown.

- At constant water pressure, noise emission increases with increasing nozzle diameter. At mid frequencies, an increase of 10-15 dB from 0.5 to 1.2 mm nozzle diameter and smaller increases at high frequencies have been shown.

- Noise propagation typical of a point source (6 dB decrease per doubling of distance) is apparent within an arc in front of the nozzle. This behaviour changes with increasing angle from the nozzle and probably behaves more like a line source (3 dB decrease per doubling of distance).

- There is a relationship between noise emission and the stand-off distance between the nozzle and the target material: noise is proportional to the length of the exposed jet. It has been shown that for a round jet nozzle, mid-high frequency noise increases with increasing stand-off distance. For a fan jet nozzle, the mid-frequency noise increases with stand-off distance but high-frequency noise rises then falls with increasing stand-off distance.

Conclusions and recommendations for further work

1 The literature search has uncovered very little information in terms of absolute noise levels incident on an operator using hand-held equipment. Similarly, the survey of water jetting companies has not extracted any useful noise data. The noise measurements by HSE show that water jetting operators are exposed typically to greater than 100 dB(A) showing that they are at a high risk of hearing damage. In addition, the water jet noise spectrum is dominated by energy around 4000 Hz, which is the frequency region of greatest acuity and where, in general, hearing loss first appears. Therefore, employers have a duty to minimise this risk to as low a level as is reasonably practicable. However, with no specific information on water jetting noise emission, noise exposure risk assessments may be unreliable. It is recommended that HSE investigates how manufacturers can best advise customers on noise emission from water jetting systems (which is particularly challenging when the system components can be sourced from different manufacturers and can operate at a wide range of pressures). The noise measurement method specified for high pressure water jetting in the Noise Emission in the Environment by Equipment for use Outdoors Regulations 2001 [6] (NEEEOR) does not include the flow noise from the water jet. The method only measures the noise from the jetting unit (the engine and pump). This is a significant omission in terms of the reliability of using a NEEEOR noise marking for an operator's noise exposure assessment.

2 The literature search has revealed preliminary research into noise emission characteristics of water jetting. However, this research has not yet progressed to developing noise control design and operating techniques to reduce exposure. Research involving laboratory-controlled noise measurements would be required to progress this.

3 A paper published in 1982, concluded by presenting three possible nozzle silencer designs to be assessed in the next phase of their research. It would be interesting to find out whether the effectiveness of these silencers have been tested.

4 In the absence of water jetting noise control (other than at the jetting unit) most water jetting operators are relying on hearing protection. There can be difficulty with the compatibility of hearing protection and the rest of the head and body protection. A study could be carried out to determine the most effective and compatible type of hearing protection for water jetting operators.

5 Remote controlled water jet machines are not used for many types of water jetting operations. It would be worthwhile finding out more about the practicality of this technology. Reducing the need for hand-held water jetting would distance the operator from the water jet and therefore reduce the operator's noise exposure.

1 INTRODUCTION

1.1 OBJECTIVES

A research proposal by Mr Damian Stear (Specialist Inspector, Offshore Safety Division of the Health and Safety Executive) was sent to the Noise & Vibration Section of HSL in December 2003. The research proposal was entitled: Exposure to noise during high pressure water jetting, with particular emphasis to use offshore. The main objectives were:

1) To compile typical noise levels and exposures during the use of high pressure water jetting equipment.

2) To examine the action taken by manufacturers, suppliers and users to minimise noise generation at source.

3) To advise on what more could be done to prevent or control noise exposure.

It was agreed that the project should be carried out in stages so that it can be amended and refined after each stage. This report describes the first stage of the project: a literature search and contact with manufacturers and suppliers.

1.2 BACKGROUND INFORMATION

1.2.1 Preferred terminology

The UK's Water Jetting Association use the internationally recognised definitions of water jetting as shown in Table 1.

Table 1 Water jetting definitions

Descriptor	Pressure		
	PSI	**bar**	**MPa**
Low pressure water cleaning (also known as power/pressure washing)	< 5000	< 340	< 34
High pressure water cleaning (also known as high pressure washing)	5000 - 10000	340 - 680	34 - 68
High pressure water jetting (also known as high pressure hydroblasting/waterblasting	10000 - 25000	680 - 1700	68 - 170
Ultra high pressure water jetting (also known as ultra high pressure hydroblasting/waterblasting/hydrodemolition)	> 25000	> 1700	> 170

This project is primarily concerned with noise from high pressure and ultra high pressure water jetting.

1.2.2 The equipment and how it works

A water jetting unit consists of an engine that drives a pump. Water from the pump is transported through a reinforced hose to a gun. The gun has a pistol shaped handle with a trigger to control the flow of water. By squeezing the trigger the water is diverted from a dumping circuit to the gun and out through a nozzle. The restriction of the water flow caused by forcing the water through the small bore nozzle causes the back pressure to build up to the working pressure of the pump. Then as the water flows across the orifice, its pressure drops to atmospheric. The effect of the large pressure drop across the orifice, equal to the working pressure of the pump, results in the water stream being accelerated to very high, often supersonic velocities. The resulting high-velocity jet carries the energy to the surface where the impact results in compressive and shear forces sufficient to break up the surface deposits or cut into the surface.

1.2.3 Jet patterns

The continuous jet is the most common type (as opposed to pulsed or cavitation jets). It is a jet composed of a continuous stream of liquid (water only or water and abrasive) travelling at up to 900 m/s.

A flat fan jet pattern is formed by the use of an elliptical orifice to distribute the liquid as a flat or sheet type spray. Fan jets are preferable for aggressive washing operations, where the jet can force its way between the deposit and the surface, peeling it off. Surface coverage is quicker than with a round jet, but they have a typical energy loss of 50% in the nozzle. The cleaning power falls off rapidly as distance from the nozzle to the target material increases (stand-off distance). Work rates can be increased by jetting at the correct angle of attack. Soft deposit build up generally peels off between 30° and 60° from the plane of the target material and hard deposit build up generally shatters between 60° and 90°.

A round jet is a uniform stream of liquid emitted through a circular hole. This is the most powerful and concentrated of all the jet patterns. Round jet nozzles have a typical energy loss of 20%. Steep angles concentrate the power into a small area. Shallow angles result in larger impact area with reduced power. Round jets are more effective on hard, brittle deposits which shatter when hit by the jet.

A rotating jet nozzle uses two or more forward pointing high velocity jets, off-set from the nozzle's axis and at an angle from the straight ahead position. These nozzles rotate at 1000 rpm and above, producing quick and effective cleaning of many surfaces well above that achieved with a standard fan or round jet.

1.2.4 Jet power

The power in the jet at the exit of the nozzle is a function of pressure, flow and nozzle size. Power output is more sensitive to changes in nozzle diameter than pressure: doubling the nozzle diameter increases the jet power by a factor of 4, whereas doubling the pressure increases the power by a factor of 2.8. The application influences which is more effective: for general cleaning, increasing nozzle size is more effective, whereas for cutting, pressure would have a greater effect.

1.2.5 Jetting gun types

The dump type gun is designed with a dump tube to allow for depressurisation at the cleaning site. With the dump gun valve closed, the gun is activated in the jetting mode - water passes through the gun and out through the nozzle. With the dump gun valve open, the gun is placed in the dump mode - water bypasses through the dump tube to waste, safely at almost zero pressure.

The shut-off type of gun is designed to be used only with a pressure regulator/unloading valve. With the shut-off gun valve open, the gun is activated in the jetting mode - water passes through the gun and out through the nozzle. When the operator releases the trigger to close the valve, water ceases to flow through the gun and the water is then bypassed at the pressure regulator/unloading valve.

1.3 APPLICATIONS

Typical applications of water jetting are listed below. Most of these examples are taken from a questionnaire that was used to find out about the water jetting industry before 1995 [1].

Offshore

- Topside and underwater blasting to remove marine growth, scale, rust and old paintwork.
- Dredging (cutting through compacted clay or hard sea bed material).
- Removing concrete protective weight coatings on submerged pipelines.

Marine

- Removal of barnacles, marine growth and scale from hulls.
- Cleaning of cargo storage holds and tanks.
- Cleaning of boilers, heat exchangers, evaporators etc.

Construction

- Restoring building surfaces: concrete, brick, sandstone, limestone, granite, marble, terracotta.
- Cleaning laitance from concrete and removing concrete splatter.
- Cutting reinforced concrete.
- Scabbling concrete in preparation for concrete bonding.
- Removing concrete and earth from excavators, dozers, dumpers, bulk cement/concrete mixers.
- Steel and pipework preparation for painting.
- Removing tar and asphalt spillages.

Process and manufacturing

- Cleaning tube bundles, heat exchangers, boiler tubes.
- Internal cleaning of pipes and process lines and removal of blockages.
- Cleaning interiors and exteriors of storage tanks and reaction vessels.
- Removal of product waste and spillages from floors, walls, gratings, machinery etc.
- Removal of grease and built up waste from rolling mill equipment.
- Removal of rubber, latex and other tenacious compounds.
- Cleaning of cooling towers.
- Cleaning of oil well drilling equipment.
- Cleaning of roll, meshes and pulp vats in paper mills.
- Cleaning of curing vessels and food processing plant and machinery.
- Removal of residues from meat processing and cooking plant.
- Removal of ceramic and sand core materials from aluminium, brass and ferrous castings.
- Removal of cement clinker from rotary kilns and cooler hearths.
- Cleaning cement industry kiln preheater columns.
- Cleaning drill pipe internals and threads.

General maintenance and repair

- Removing graffiti, paint, rust, cement, grease and oil from any surface.
- Removal of dirt, old paint, rust and corrosive residues from steel prior to painting.
- Cleaning sewers and drains.
- Cleaning of concrete and metal bridges, gantries, buildings, roadways etc.
- Removal of defective concrete expansion joints.
- Testing of long pressurised pipelines, providing high volume and required test pressure.
- Cleaning of railway engines and rolling stock prior to repair.
- Removal of rubber deposits or spillages on aircraft runways.
- Removal of built-up deposits of impacted leaves from railway lines.
- Water jet cutting.

Other innovative uses include:

- Dealing with old munitions.
- Fire fighting by producing an atomised spray.
- Surgery.

2 LITERATURE SEARCHES

2.1 HSE INFORMATION CENTRE

A literature search was conducted by qualified information specialists and trained information assistants at the HSE Information Centre, Sheffield during the first week of January 2004.

The literature search was for global literature related to water jetting noise, specifically:

- high pressure water jetting 10,000 - 25,000 PSI (680 - 1700 bar)
  also known as high pressure hydroblasting/waterblasting

- ultra high pressure water jetting > 25,000 PSI (> 1700 bar)
  also known as ultra high pressure hydroblasting/waterblasting/hydrodemolition

The full description submitted on LIBFORM 8 is given in Appendix A. Descriptions of the databases that were searched are also given in Appendix A.

The most relevant papers were selected from the results of the literature search. Reasons for ignoring some papers were because they referred to underwater water jets (associated with submarine propulsion), low pressure water cleaning or mining. The papers that were read are listed in Appendices B and C. The papers that were worth summarising are listed in Appendix B. Some of the literature search results were non-English papers with/without English abstracts. The papers with English abstracts that may be worth translating are listed in Appendix D.

2.2 WATER JET CONFERENCE PROCEEDINGS

Two major sources of information that were not included in the databases searched by HSE, were the American waterjet conferences hosted by the WaterJet Technology Association (WJTA) and the international water jetting conferences hosted by the BHR Group. Contents lists from these conferences dating back to 1991 (and a few further back) were acquired and several useful papers were found. The conferences that were searched are listed at the end of Appendix A.

2.3 INTERNET SEARCH

The following websites dedicated to water jetting were found:

The Water Jetting Association	www.waterjetting.org.uk
The WaterJet Technology Association	www.wjta.org
The Water Jetting Directory	www.waterjettingdirectory.com
BHR Group Limited (formerly The British Hydromechanics Research Association)	www.bhrgroup.com

Some of the websites listed in Appendix E contain extensive information about water jetting.

3 LITERATURE REVIEWS

From the papers selected to review, the most relevant and useful papers are summarised here. The full details of the papers are given in Appendix B.

3.1 JET NOISE MEASUREMENTS ON HAND HELD CLEANING EQUIPMENT (Barker, Cummings and Anderson, 1982)

This paper contains relevant information regarding noise emission to operators of hand held water jetting equipment. However, there are two drawbacks:

i) The equipment operates up to 68.9 MPa (10,000 psi), whereas high pressure water jetting operates above 68.9 MPa.
ii) The noise measurements are 22 years old. Therefore, any conclusions drawn from the data need to take this into account.

The paper describes research into the noise characteristics of typical jets operating in air and impacting against a surface. This research leads into developing engineering controls in order to limit water jetting noise emission. Engineering control is recognised as the primary goal in preference to management controls and personal protective equipment options.

3.1.1 Jet operating pressure

The variation of jet noise to operating pressure was measured for a tungsten carbide nozzle (1.42 mm exit diameter). The location of the microphone in relation to the jet is shown in Figure 1. This location means that the noise data is not necessarily representative of the noise levels incident on the operator. However, it is reasonable to expect that the changes in noise with pressure would be the same at the operator's position.

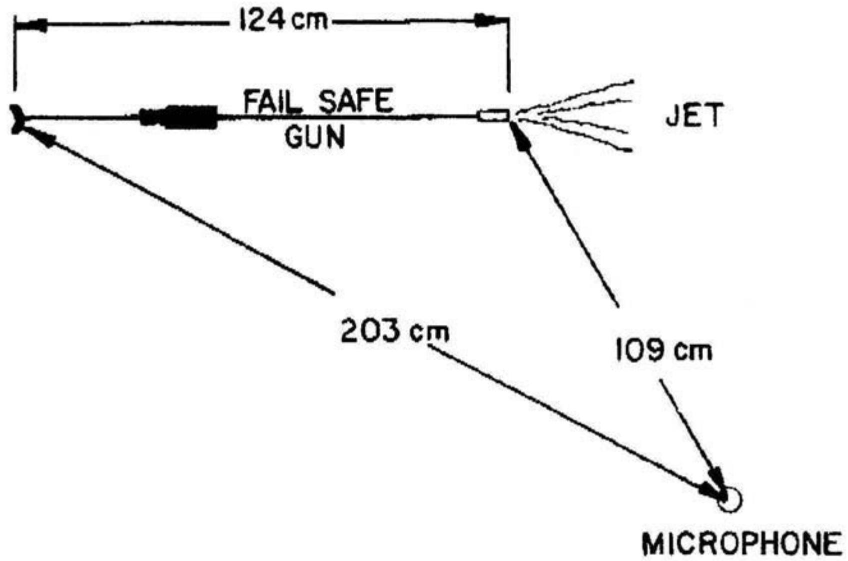


Figure 1 Location of microphone for Table 2 results

The measured sound pressure levels are reproduced (to the nearest dB) in Table 2 and summarised in Figure 2.

Table 2 Octave band sound pressure levels from Figure 1 test

MPa	31.5	63	125	250	500	1000	2000	4000	8000	16000	Hz
27.6	75	76	76	78	81	83	86	88	87	81	
34.5	75	75	78	81	84	86	89	91	90	83	
41.3	78	76	79	82	86	88	90	92	92	85	
48.2	82	79	80	85	88	91	93	95	95	89	**dB**
55.1	83	80	83	86	90	93	95	97	97	91	
62.0	84	82	83	88	91	95	97	99	99	92	
68.9	86	82	84	89	93	96	99	101	101	94	

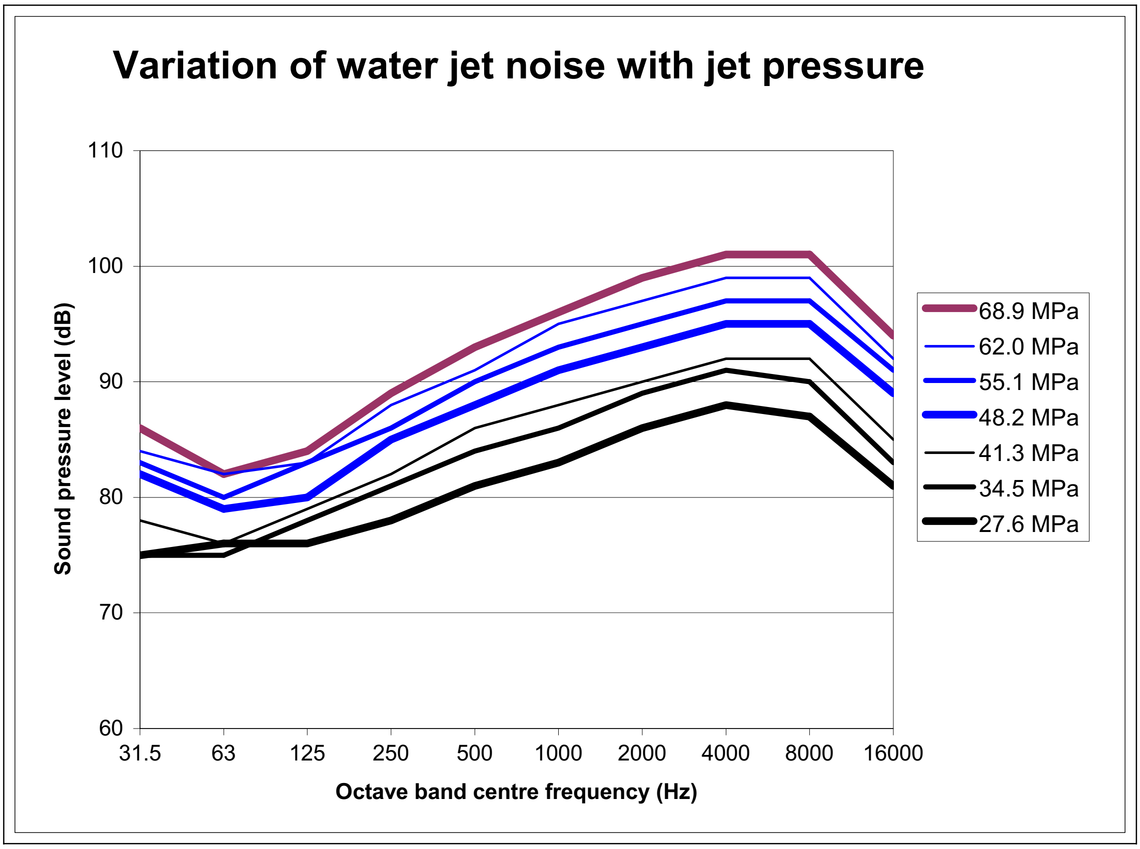


Figure 2 Graphical display of Table 2

The noise measurement results demonstrate two strong trends:

- High frequency peak around 4000 to 8000 Hz.
- Increase of 2 to 3 dB across the mid-high frequency range for each increment of 6.9 MPa.

The slight rise in levels at 31.5 Hz is due to pump noise which had a spectral peak at about 26 Hz.

3.1.2 Jet directivity

Using the same type of tungsten carbide nozzle as before, the directivity of jet noise was measured at a near field radius of 2.44 m and a far field radius of 13.7 m from the nozzle, as shown in Figure 3. The operating pressure was kept constant at 68.9 MPa.

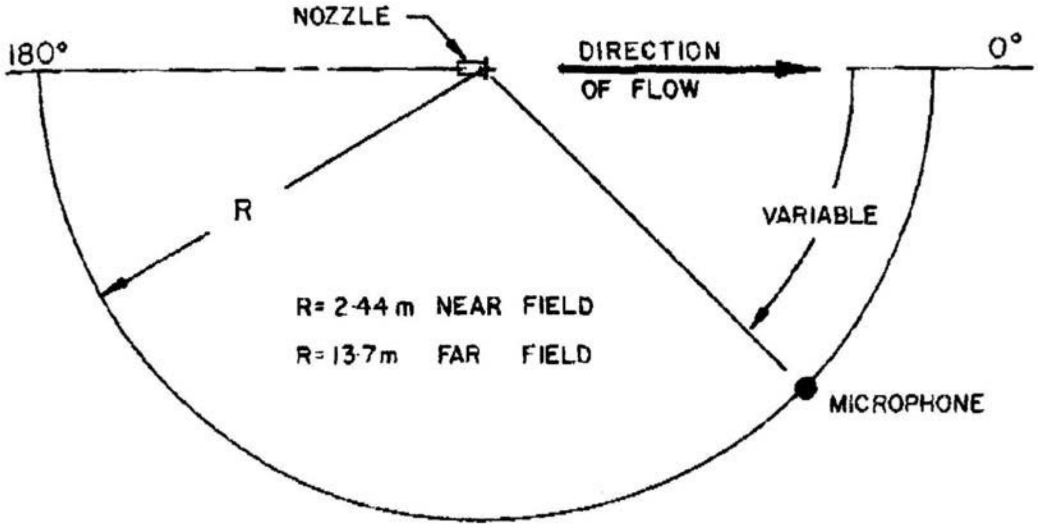


Figure 3 Microphone locations for Tables 3 and 4 results

This arrangement is intended to be representative of the noise levels that nearby personnel would be exposed to.

The near field noise measurement results are reproduced (to the nearest dB) in Table 3 and summarised in Figure 4.

Table 3 Octave band sound pressure levels from Figure 3 near field test

Deg	31.5	63	125	250	500	1000	2000	4000	8000	16000	Hz
7.5	104	104	99	98	103	108	111	114	113	103	dB
15	94	91	88	95	101	106	111	113	110	100	
30	84	79	82	91	95	100	103	105	105	99	
45	80	77	78	86	90	94	98	101	101	93	
60	77	75	75	81	86	92	96	99	98	89	
75	76	75	75	80	85	91	95	97	96	87	
105	78	76	76	78	84	90	93	96	95	85	
120	78	74	77	79	84	90	93	96	94	85	
135	78	73	78	78	84	89	92	96	94	85	
150	78	73	77	78	84	89	93	96	94	85	
165	79	77	75	78	83	88	92	95	94	84	
180	79	77	75	78	84	87	91	94	92	83	

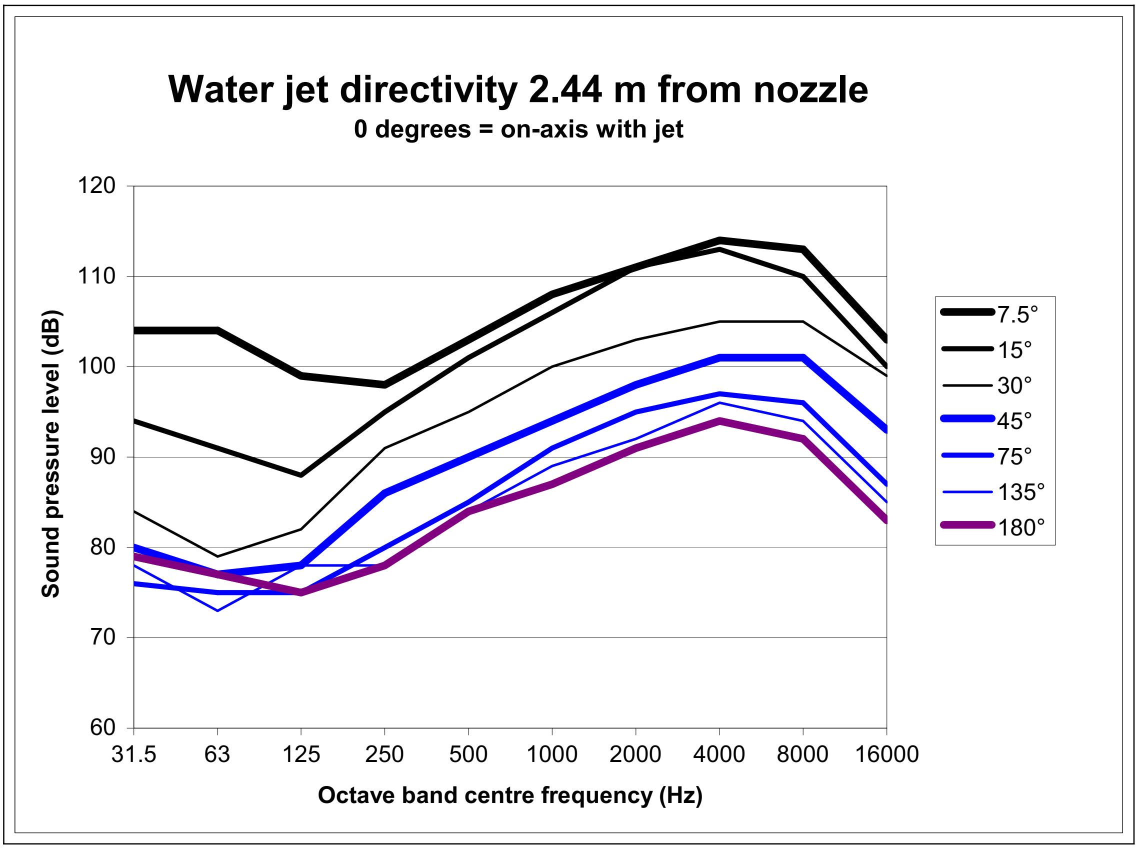


Figure 4 Graphical display of Table 3

The noise measurement results show a high frequency peak around 4000 Hz to 8000 Hz. It also shows an overall increase of about 20 dB from 180° to nearly on-axis with the jet (7.5°) across the mid-high frequency range.

The far field noise measurement results are reproduced (to the nearest dB) in Table 4 and summarised in Figure 5.

Table 4 Octave band sound pressure levels from Figure 3 far field test

Deg	31.5	63	125	250	500	1000	2000	4000	8000	16000	Hz
0	87	75	80	82	87	95	99	103	100	89	dB
7.5	84	75	77	83	87	95	102	105	102	90	
15	78	69	78	83	87	95	102	104	101	91	
22.5	78	70	77	83	88	95	101	104	101	90	
30	76	68	77	82	87	92	98	100	97	87	
45	74	69	77	80	83	87	93	95	93	85	
60	70	67	75	76	80	84	89	93	92	82	
75	68	66	72	73	77	82	88	92	91	80	
90	65	65	68	71	77	82	86	90	89	79	
105	67	67	69	72	77	82	85	90	88	78	
120	69	72	71	71	77	82	85	90	88	78	
135	70	69	72	71	77	81	86	90	87	77	
150	70	68	71	71	77	81	86	89	87	76	
165	70	67	71	71	77	81	87	89	87	76	
180	71	67	71	72	76	80	84	87	84	73	
Bkgd	63	65	65	57	53	50	45	41	37	27	

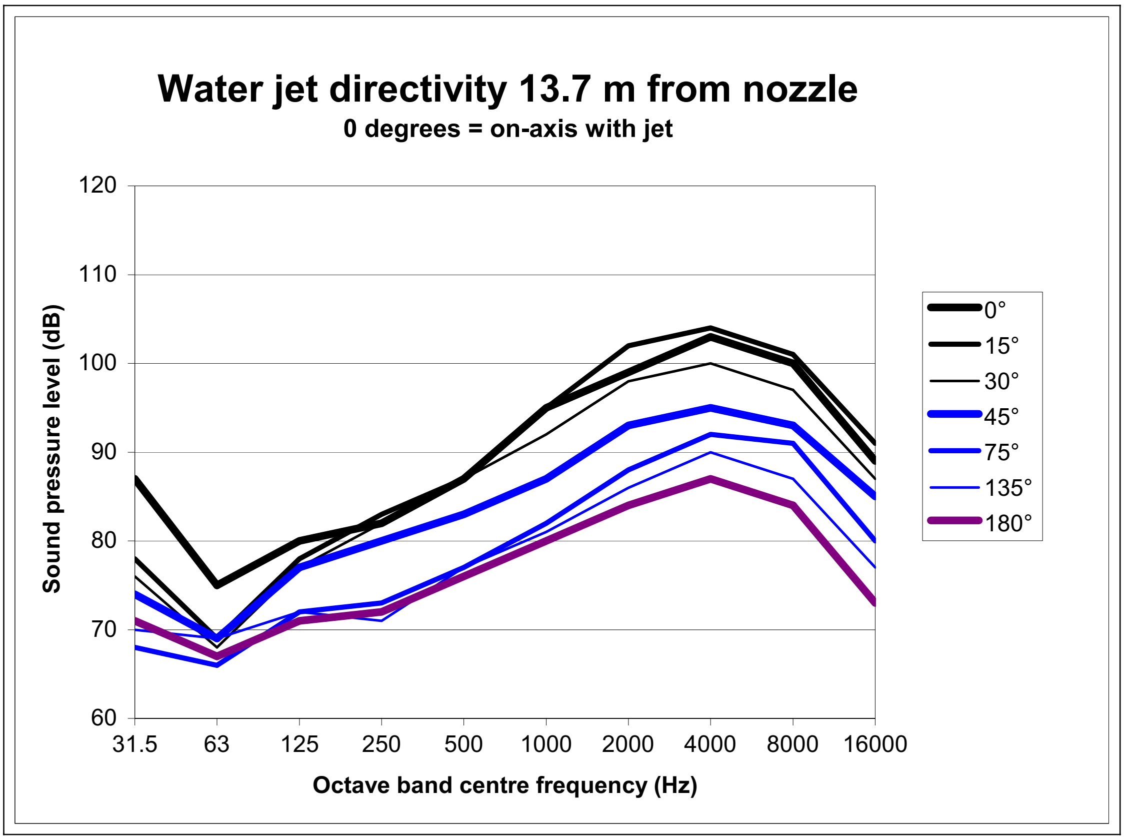


Figure 5 Graphical display of Table 4

The far field noise is 10 to 15 dB lower than the near field noise close to on-axis with the jet; this is compatible with point source noise propagation theory. Beyond 30° to the jet, the difference between near and far field noise is only 5 to 10 dB. This would seem to demonstrate that the nozzle does not radiate uniformly in all directions.

Figure 5 also shows an overall increase of about 15 dB from 180° to on-axis with the jet (0°) across the mid-high frequency range (compared to a 20 dB increase in the near field). It is harder to draw firm conclusions from the low frequency data because the background noise levels (probably pump noise) at 31.5 Hz, 63 Hz and to some extent 125 Hz are influencing the measurements. The background noise needs to be at least 10 dB lower than the noise source of interest to avoid contributing to the measurement.

The paper concedes that more detailed measurements would be needed to reliably quantify the radiation properties of the jet nozzle.

3.1.3 Jet length

In order to determine the change in noise along the length of the jet, the microphone was housed within a pipe and set into a screen which was parallel to, and 546 mm from the jet. The absolute noise levels at various distances along the length of the jet are presented in the paper. However, due to the way in which they were measured, it is only the change in noise levels which ought to be studied. Table 5 presents the noise level change using the spectrum at 0 mm from the nozzle as a baseline. In order to simplify the data further, the change in overall A-weighted level at each distance has been calculated and plotted in Figure 6. The A-weighted level is of interest because it takes account of the ear's differing sensitivity across the frequency range.

The operating pressure was kept constant at 68.9 MPa for this set of tests.

Table 5 Sound pressure level change along length of jet (round nozzle)

mm	31.5	63	125	250	500	1000	2000	4000	8000	dB(A)	Hz
0	0	0	0	0	0	0	0	0	0	0	
25	1	0	1	4	5	6	4	-1	-3	4	
51	2	2	2	5	5	6	3	-1	-1	3	
102	2	1	3	6	7	11	7	3	4	8	
152	4	3	4	5	4	4	3	5	7	4	
254	7	6	8	11	12	13	13	14	16	13	
356	8	10	11	13	14	16	16	18	19	17	
457	10	13	14	15	16	16	16	18	19	17	**dB**
559	14	20	21	23	22	21	21	22	21	21	
660	16	24	26	26	24	23	22	23	21	23	
762	19	27	29	29	26	24	23	23	20	23	
914	22	28	30	29	25	22	20	20	16	21	
1067	22	28	28	28	24	21	19	18	15	20	
1219	28	35	36	32	27	21	17	17	12	20	
1372	25	30	30	27	22	16	15	14	10	16	

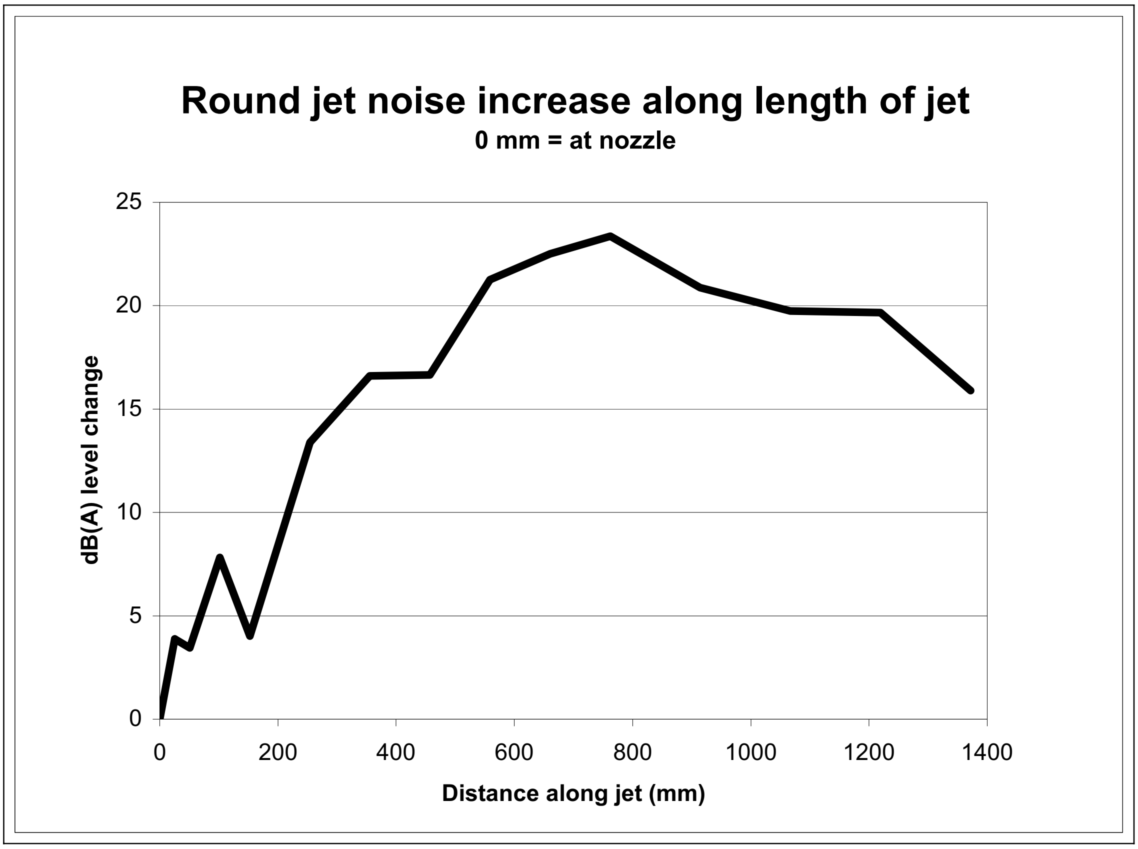


Figure 6 Graphical display of A-weighted level change (Table 5 results)

From Table 5, it can be seen that the low frequency energy is greatest, far from the nozzle (~ 1219 mm), whereas high frequency energy is greatest, much closer to the nozzle (~ 762 mm). The predominance of high frequency energy at 600 - 800 mm is also to be seen from Figure 6. The reason for this may be due to the directivity of the nozzle since the angle between the line drawn from the nozzle to the microphone and the jet axis will decrease with increasing distance along the jet.

This test was repeated for a 15° fan jet nozzle. The results are shown in Table 6 and Figure 7.

Table 6 Sound pressure level change along length of jet (fan nozzle)

mm	31.5	63	125	250	500	1000	2000	4000	8000	dB(A)	Hz
0	0	0	0	0	0	0	0	0	0	0	dB
25	1	2	2	2	0	0	1	2	3	1	
51	3	4	4	4	4	4	5	6	7	5	
102	4	5	5	6	5	6	8	10	10	8	
152	5	6	6	7	8	8	10	12	13	10	
254	6	9	10	12	13	11	13	15	14	13	
457	10	20	22	23	16	8	10	10	6	11	
660	23	32	33	29	19	7	3	0	-6	13	
762	19	30	29	22	10	4	3	0	-4	7	
914	24	33	34	29	18	5	-1	-3	-5	13	

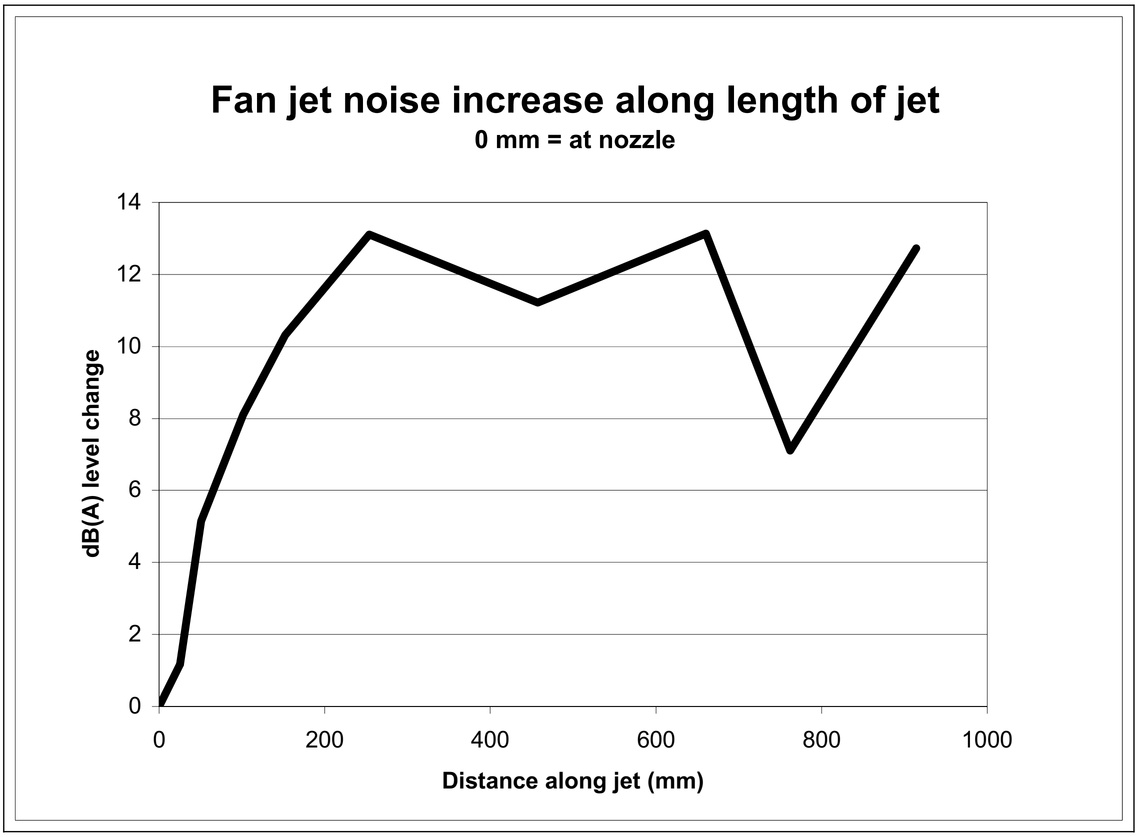


Figure 7 Graphical display of A-weighted level change (Table 6 results)

Similar results are true for the fan jet nozzle. However, the high frequency energy is greatest even closer to the nozzle (~ 254 mm) and seems to drop more dramatically at greater distances (this may indicate a problem with the measurements e.g. background noise influence).

3.1.4 Jet striking metal plate

For the last set of measurements, the jet was mounted on a stand and directed to strike a steel plate normal to its surface. The microphone was positioned where the operator's head would be. For a round jet nozzle operating at 68.9 MPa, the noise measurement results are reproduced (to the nearest dB) in Table 7 and summarised in Figure 8.

Table 7 Sound pressure levels at different stand-off distances (round nozzle)

mm	31.5	63	125	250	500	1000	2000	4000	8000	dB(A)	Hz
25	82	72	74	80	85	91	99	106	108	110.5	
102	76	76	79	83	87	90	97	107	110	111.7	
178	74	82	82	82	86	91	100	109	112	113.8	**dB**
254	75	77	75	80	87	94	104	113	113	116.5	
381	73	73	75	79	87	96	107	114	113	117.3	

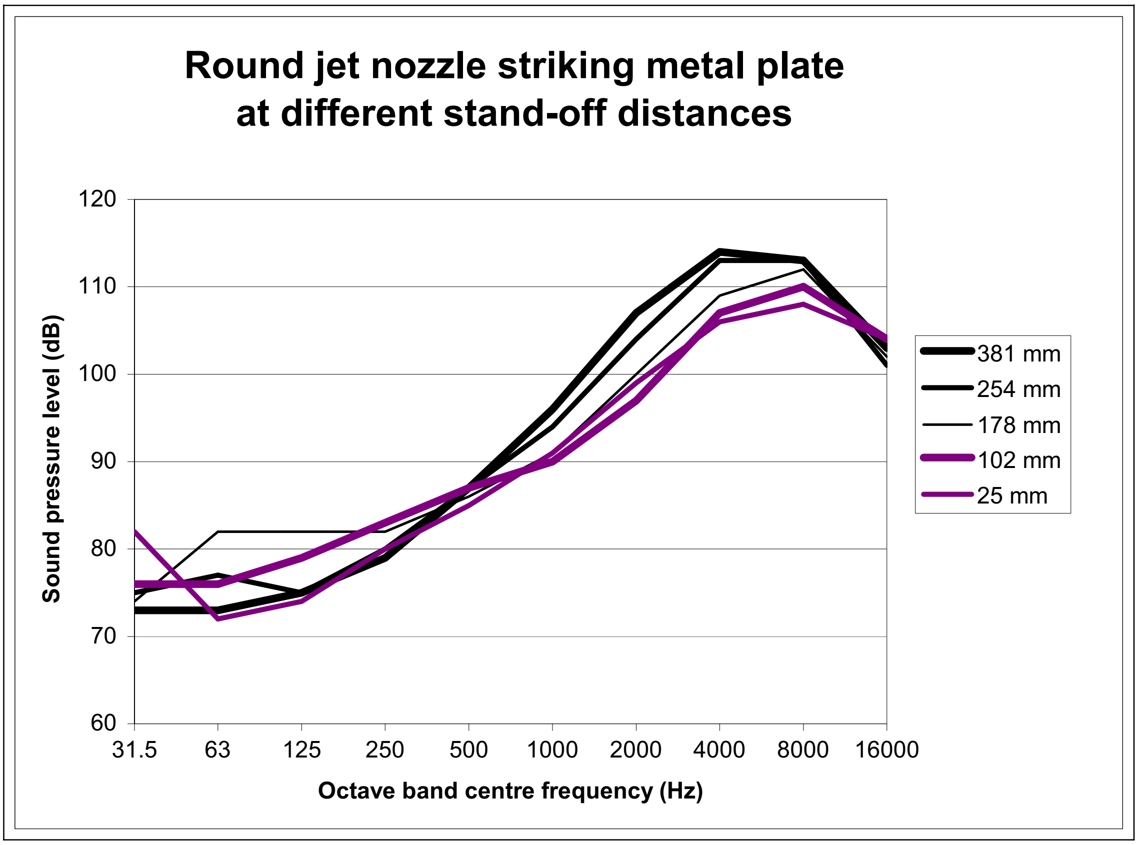


Figure 8 Graphical display of Table 7 results

In general, the mid-high frequency energy increases with increasing stand-off distance, which is also apparent in the overall A-weighted levels. These levels are clearly high enough to require a programme of control measures to ensure the operator does not exceed the exposure limit value under the forthcoming Control of Noise at Work Regulations 2005 [2].

This test was repeated for a 15° fan jet nozzle operating at 68.9 MPa, the results of which are reproduced (to the nearest dB) in Table 8 and summarised in Figure 9.

Table 8 Sound pressure levels at different stand-off distances (fan nozzle)

mm	31.5	63	125	250	500	1000	2000	4000	8000	dB(A)	Hz
25	75	73	76	78	86	86	92	97	101	102.7	
102	75	74	74	77	84	94	103	110	110	113.7	
178	75	79	80	81	89	100	108	111	109	115.0	**dB**
254	74	78	77	83	94	104	109	109	107	114.3	
381	77	76	79	91	101	104	106	106	104	111.9	

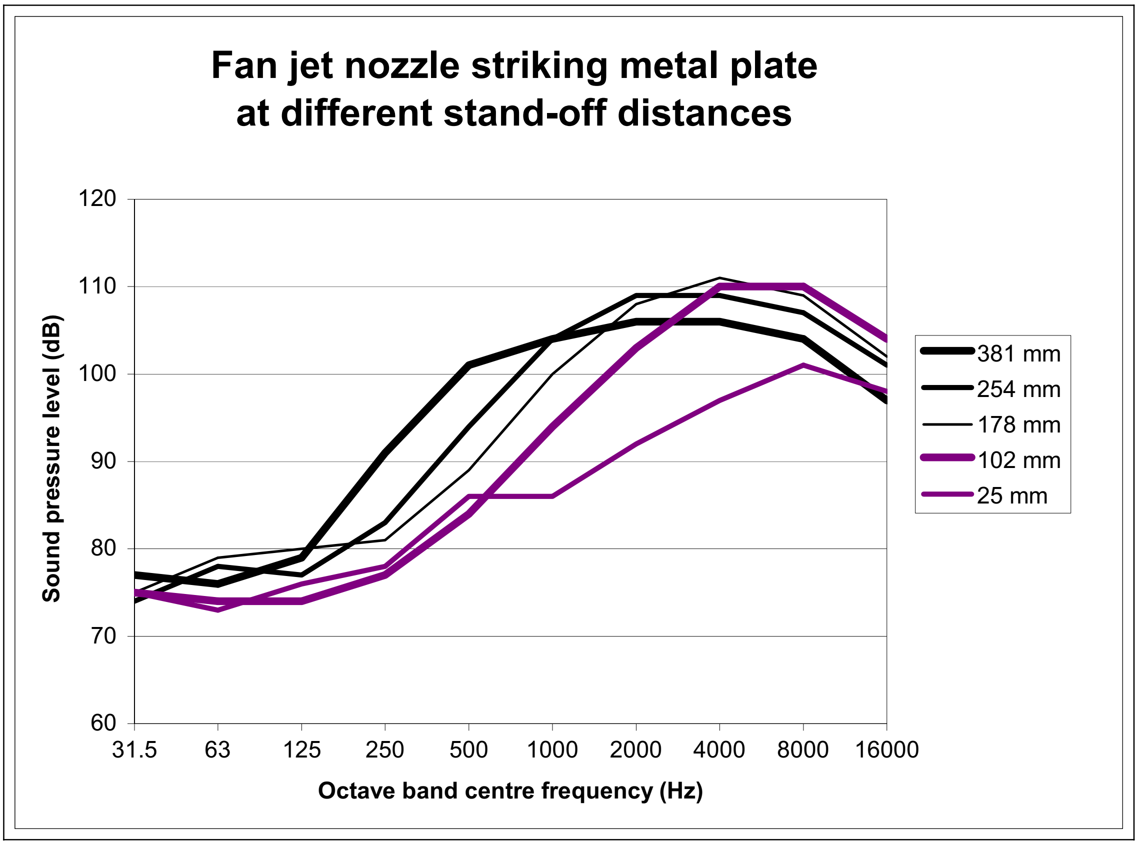


Figure 9 Graphical display of Table 8 results

The results for this fan jet nozzle show that increasing stand-off distance causes an increase at mid-frequencies only. The relationship doesn't seem to exist at higher frequencies (unlike the round jet nozzle), which is also reflected in the A-weighted levels. The peak frequency range for the round jet nozzle is consistently around 4000 Hz to 8000 Hz, whereas the peak frequency range for the fan jet nozzle becomes broader with increasing stand-off distance. This could be because the acoustic reflection from the steel plate is less focussed for the fan jet nozzle.

The paper provides the following possible explanation:

"There is a general tendency for the noise level to increase as the distance between the steel plate and the jet nozzle increases. If one speculates that the noise caused by impingement is relatively small, then the major effect of the plate will be to "cut off" the region of noise sources at the point at which the plate is situated. The structure of the jet between the nozzle and plate is probably affected relatively little by the presence of the plate. This speculation is, at least, consistent with the trend in the measurements."

3.1.5 Silencers

The final section of the paper describes three possible silencer designs. The authors recognise that the silencer must be designed in such a way that does not appreciably interfere with the use of the water jet and does not obscure the operator's view of the target material. Also, any enclosure around the nozzle must not result in premature jet break-up (from the interaction between the jet and the ambient air). However, these restrictions have been put aside in order commence the first stage of possible silencer designs.

Figure 10 shows the simplest possible enclosure configuration of a tube with/without a water-retardant sound-absorbing liner (labelled as Kevlar). The paper explains that:

"In the event that the jet is disrupted by the tube, two air passages are drilled through the collar to allow a natural aspiration to occur. If the air passages are required, the sound path back through the air holes will be modified by using sintered bronze air mufflers commonly used on air driven tools."

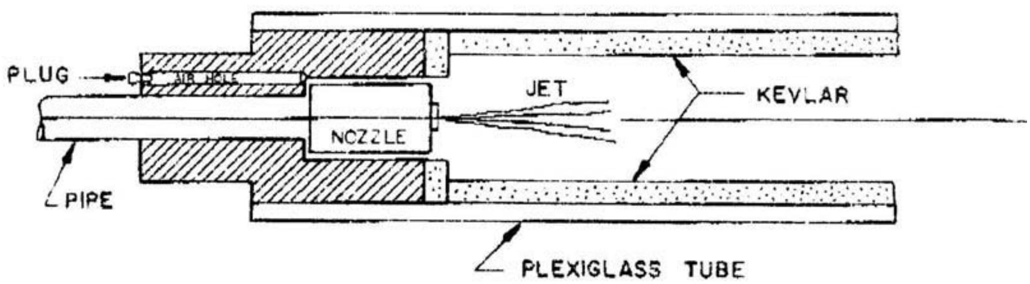


Figure 10 Silencer 1

Figure 11 is a modification of Silencer 1. The length of the tube and the diameter of the flange (with/without a Kevlar lining) could be varied to investigate the effectiveness of the silencer.

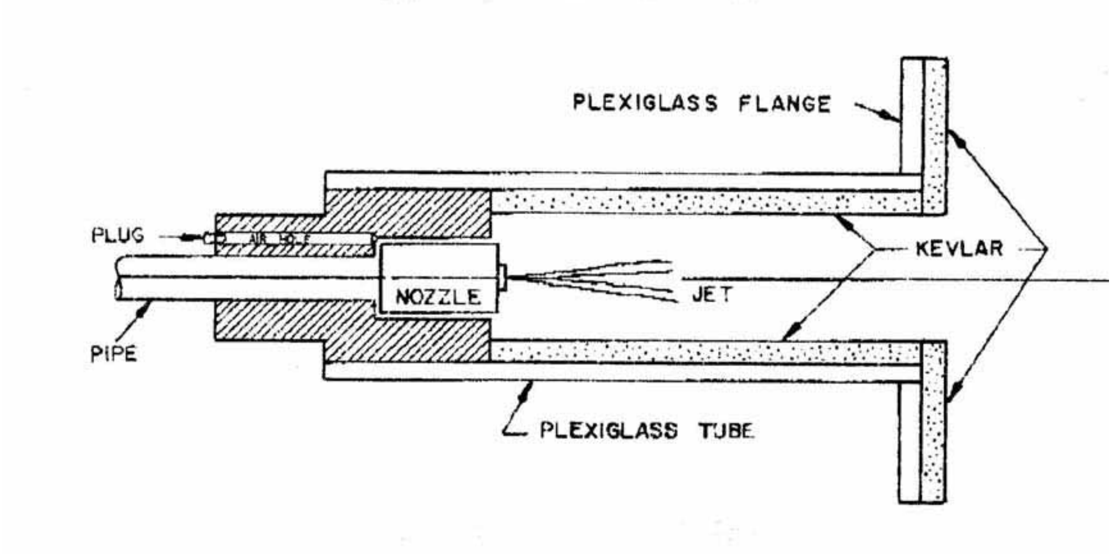


Figure 11 Silencer 2

Figure 12 shows a third possible silencer design. In this case a cavity has been formed between the inner tube and a larger outer tube. Again, some adjustment of the position of the silencer relative to the nozzle could be made to investigate noise reduction performance.

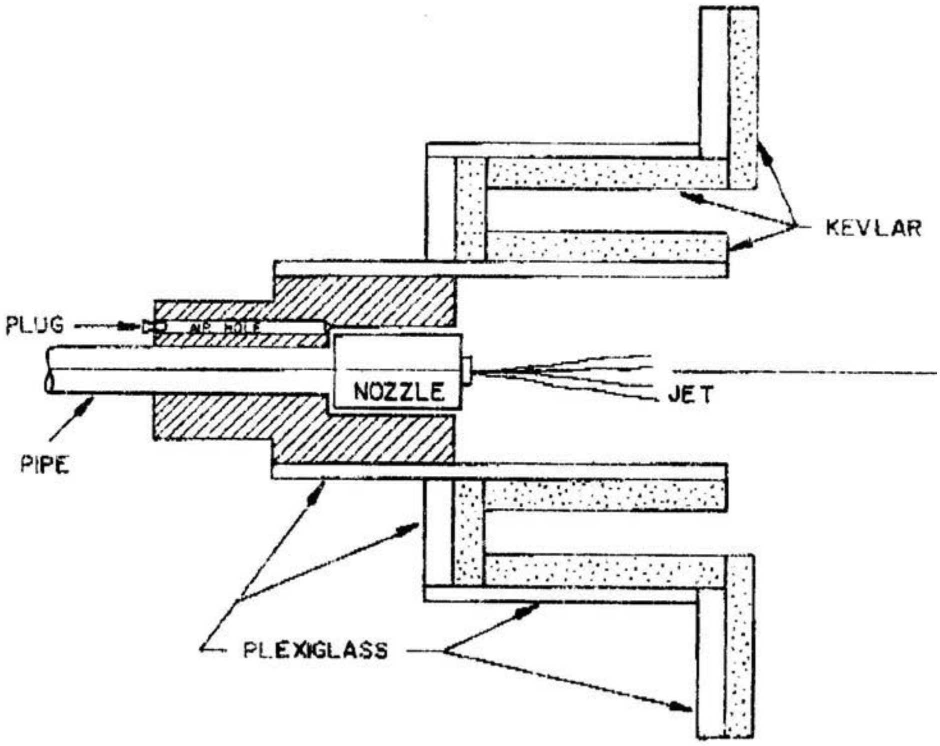


Figure 12 Silencer 3

3.1.6 Conclusion

This is one of only two papers with useful content on noise emission from water jetting. It is the only paper which presents an initial attempt at noise reduction design. The absolute noise data is unlikely to be of interest because the operating pressure is not high enough to be classed as 'high pressure water jetting'. However, the change in noise levels with different operating pressures and source-receiver orientations is likely to be valuable information. In the absence of a formally agreed noise measurement method for the water jet specifically, the measurement arrangements presented in this paper are interesting ideas, particularly for comparing the noise levels from different water jet nozzles and evaluating the effectiveness of noise reduction designs.

3.2 ACOUSTIC EMISSION OF PLAIN WATER JETS (Bortolussi, Ciccu et al, 2003)

This paper examines the correlation between the characteristics of sound power emission of plain water jets and operational parameters such as pressure, nozzle diameter and stand-off distance. The results are presented for pressures from 30 MPa to 120 MPa. The results above 70 MPa are of most interest because this is the high pressure water jetting range of operation.

The sound power emission was determined by sound intensity measurements according to ISO 9614-1: 1993 [3] (the British Standard equivalent is BS EN ISO 9614-1: 1995 [4]). The advantage of sound power data over sound pressure data is that it is independent of the acoustic environment. The measurement procedure involved taking an array of sound intensity measurements over a hypothetical surface (greater than 0.5 m from the source under test). A cylindrical measurement surface would seem to be most appropriate to accommodate the shape of the water jet. However, a parallelepiped measurement surface was used, presumably to take account of the reflective surfaces parallel to and below the water jet. The measurement arrangement in Figure 13 shows the water jet (pointing downwards), the microphone sound intensity probe and the grid of measurement points.

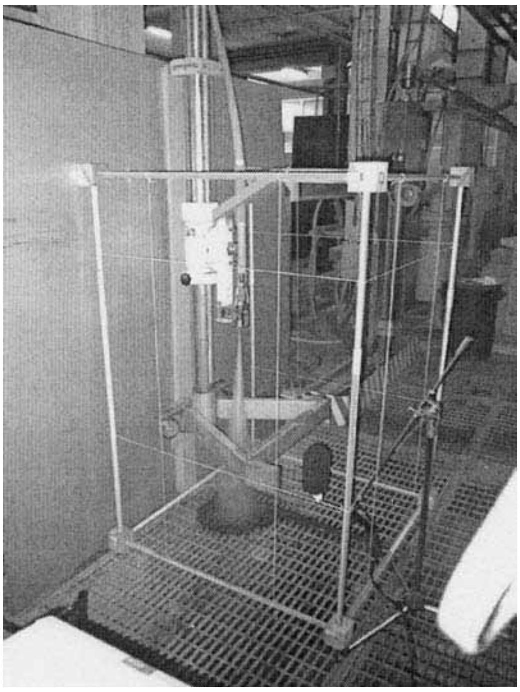


Figure 13 Sound intensity measurement set-up

Water pressure, nozzle diameter and exposed jet length were varied for each measurement in order to evaluate their influence on sound power level. The paper claims to present the maximum sound power levels from varying the exposed jet length up to 100 cm. However, this aspect of the test does not seem comprehensive, since for instance, the length increments are not the same for each operating condition. Therefore, Table 9 presents the results without labelling the sound power levels as maxima.

Table 9 Measured sound power levels and corresponding operating conditions

Pressure MPa	Nozzle Ø mm	Flow rate l/min	Jet velocity m/s	Jet power kW	Jet length cm	Total L_w dB	Total L_{Aw} dB(A)
30	1.2	10.4	238	5.2	100	104.8	104.4
50	1.2	13.4	307	11.2	100	112.4	112.5
70	1.2	15.8	363	18.4	100	119.3	119.8
70	0.5	2.7	363	2.9	50	108.7	109.3
120	0.5	3.6	475	7.2	100	118.2	118.7

3.2.1 Pressure

The linear and A-weighted one-third octave band sound power level spectra are shown in Figure 14 to demonstrate the influence of water pressure on noise emission.

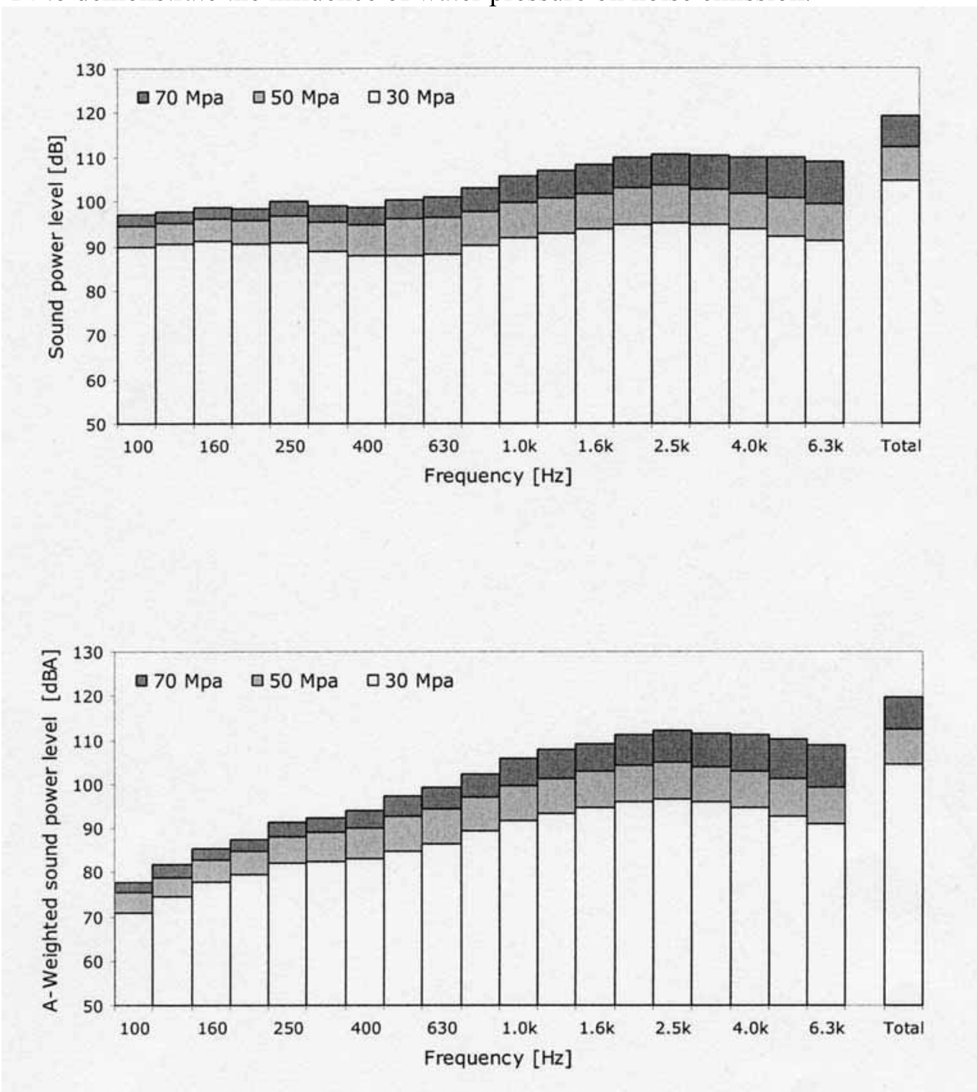


Figure 14 Linear and A-weighted sound power levels
1.2 mm nozzle diameter, 100 cm exposed jet length

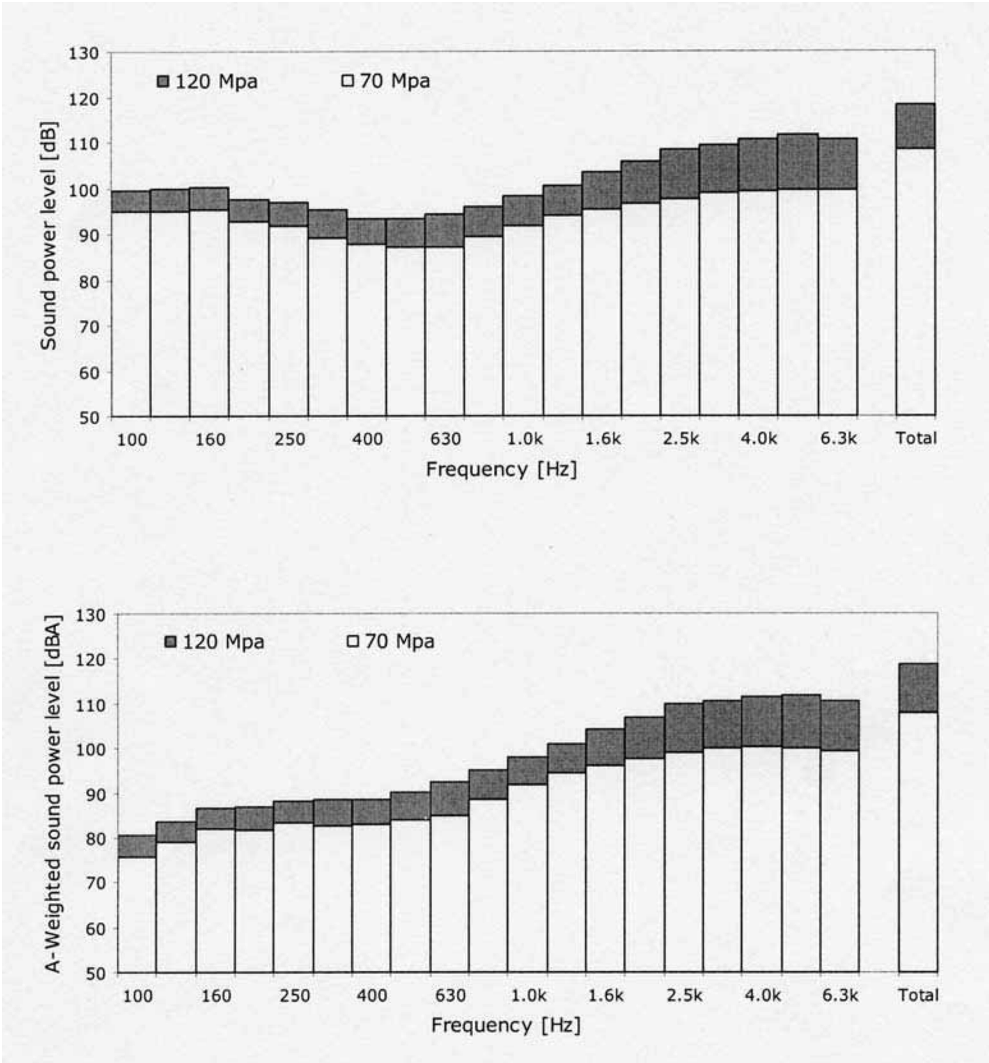


Figure 15 Linear and A-weighted sound power levels
0.5 mm nozzle diameter, 100 cm exposed jet length

Figures 14 and 15 show that increasing pressure causes an increase in sound power level in all one-third octave bands. The increase is about 9 dB (with 20 MPa increment) at frequencies above 1 kHz and about 5-6 dB (with 20 MPa increment) for lower frequencies. The increase in overall A-weighted sound power level is about 11 dB(A) with 20 MPa increments. The reason offered for this trend is that increased pressure causes increased fluid velocity which has the effect of increased turbulence and rate of droplet formation within almost the same volume of water. Table 9 demonstrates that an increase in pressure from 30 MPa to 120 MPa, with only a small increase in jet power between nozzle diameters of 1.2 mm and 0.5 mm, causes a significant increase in sound power level (14.3 dB(A)).

3.2.2 Nozzle diameter

When pressure is kept constant but the jet power is increased by enlarging the nozzle diameter, the sound power level increase is more significant at mid-low frequencies (although it is still the high frequencies which dominate the A-weighted spectrum). This trend is shown in Figure 16.

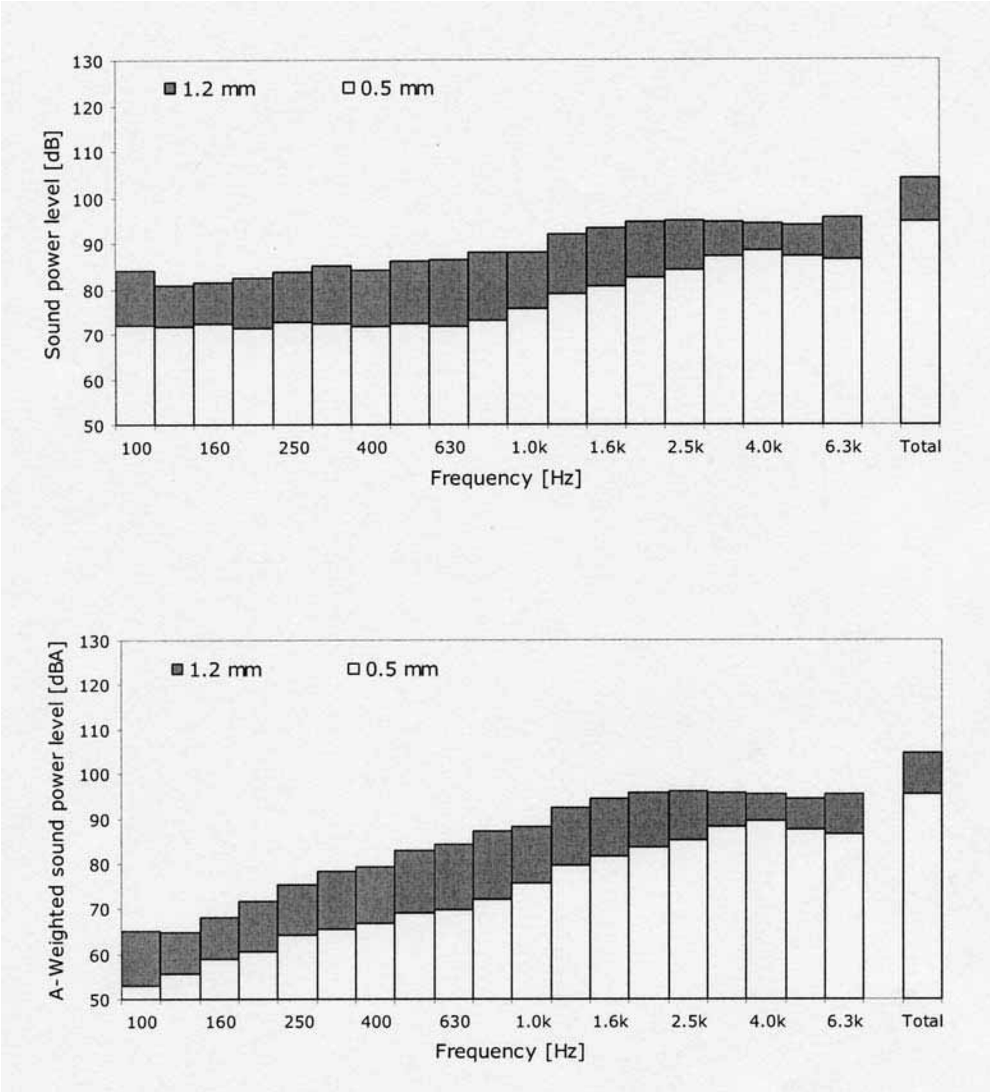


Figure 16 Linear and A-weighted sound power one-third octave band levels 70 MPa pressure, 10 cm exposed jet length

The paper offers the explanation that, for the same pressure, a larger nozzle diameter implies a higher volume of turbulence, while the intensity remains at the same level. As a result of this, an increase in jet power of 15.5 kW (0.5 mm to 1.2 mm nozzle diameter at constant pressure) produces an increase of 10.5 dB(A) in the overall A-weighted sound power level whereas an increase in jet power of 13.2 kW by increasing pressure causes a larger increase of 15.4 dB(A). This implies that enlarging the nozzle diameter to increase jet power is preferable to increasing the pressure. However, the paper does not point out that these results are at two different exposed jet lengths which also influences the measured sound power level.

3.2.3 Exposed jet length

Figure 17 shows the effect of increasing the exposed jet length (or stand-off distance) for three different levels of jet power.

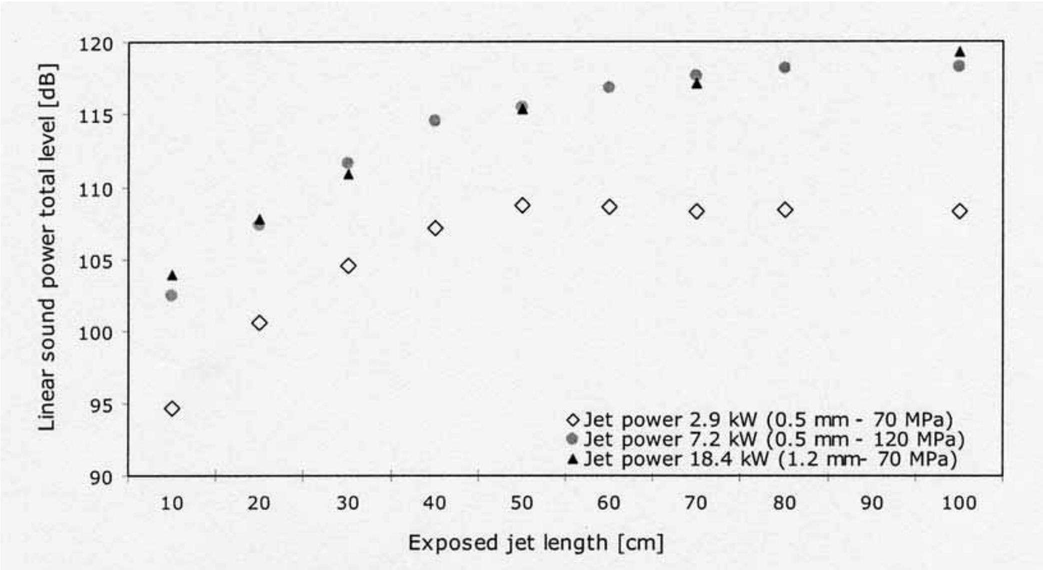


Figure 17 Overall linear sound power levels vs exposed jet length

Figure 17 shows that linear sound power level increases with exposed jet length up to about 50 cm. Above 50 cm, the trend seems to flatten out at 2.9 kW and increase less significantly at higher jet powers. The paper presents further results (but with less clarity) to demonstrate that stand-off distance has a significant influence on sound power emission.

3.2.4 Conclusions

The following conclusions are drawn from the tests:

- An increase in pressure causes an increase in sound power emission, especially at high frequencies (where the human ear is most sensitive).

- An increase in nozzle diameter causes an increase in sound power emission, especially at mid-low frequencies (where the human ear is less sensitive).

- Therefore, increasing jet power by increasing the nozzle diameter causes a smaller increase in overall A-weighted sound power level, than increasing the pressure.

- Up to a certain length, an increase in exposed jet length causes an increase in sound power emission. The limiting length depends on jet power and it would seem that the higher the jet power the higher the limiting length.

3.3 WATERJET RELATED NOISE AND ITS COUNTERMEASURES (Katakura and Miyamoto, 1997)

The introduction to the paper states that little quantative information related to noise from water jetting was found from a bibliography search. Therefore, noise measurements were carried out in order to assess the noise hazard from the water jet and the water jetting equipment. Also "countermeasures" are recommended to reduce noise exposure.

The paper proposes the following components of water jet noise:

1 Breakdown of the work object.
2 Hitting of drops of water to the solid surface of the work object.
3 Flow turbulence induced by the collision of the jet and the work object.
4 Cavitation noise.
5 Jet noise.

Table 10 presents the two water jetting systems that were measured.

Table 10 Water jetting system specifications

System	A	B
Pump unit delivery pressure	5 MPa	200 MPa
Nozzle shape	cylindrical	cylindrical
Nozzle diameter	1 mm	0.25 mm
Work object	cement block	aluminium block
Stand-off distance (nozzle to work object)	5 - 30 cm	2.5 - 28 cm
Microphone distance from "noise sources"	~ 90 cm	~ 2 cm

Figure 18 shows the microphone positions in relation to the nozzle and work object.

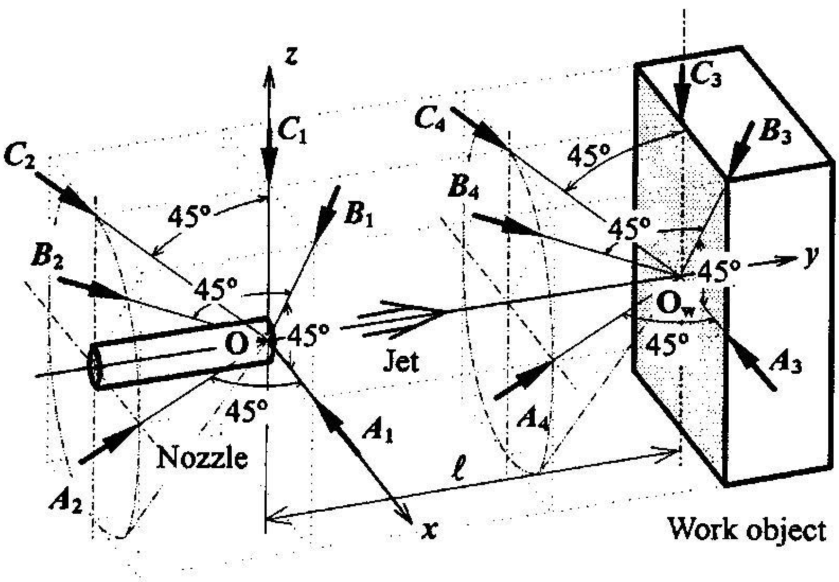


Figure 18 Noise measurement microphone positions

The results of the noise measurements are scattered throughout the paper and unfortunately, the translation to English affects the clarity of the noise measurement descriptions.

The paper states that:

"In order to separate the noise radiated from a certain point from the others, a circular straight tube of 83 cm in length and 7.5 cm in outer diameter was applied in some experiments. The internal surface of the tube was covered with fiberglass wool of about 1 cm in thickness to absorb the noise different from the selected. The internal diameter of the circular opening that noise passes through was about 4 cm. This tube is called 'focussing tube' in this report."

The focusing tube was used between the noise source and the sound level meter at each measurement position. It is reasonable that the authors are interested in separating the different components of noise, but this method does not seem to be a reliable way of doing it. It also seems illogical to do this and then present an overall average level across all the measuring directions. Noise measurements in the selected positions without the focusing tube would have been more practical information. Therefore, the noise data will not be reproduced here. System A is of limited interest anyway as it cannot be classed as high or ultra high pressure jetting.

The noise levels surrounding the surface of the work object (at microphone positions A_4, B_4 and C_4 shown in Figure 18) were found to be much higher than the noise levels radiated from the nozzle (at microphone positions A_1, B_1, C_1, A_2, B_2 and C_2).

Figure 19 illustrates the difference in noise levels at B_4 for different stand-off distances. It also shows that the noise level at B_4 reduces by 7-8 dB(A) in the first 3 minutes, then reduces more gradually until it is fairly constant after 10 minutes, with an overall reduction in noise of between 5 and 15 dB(A) depending on stand-off distance.

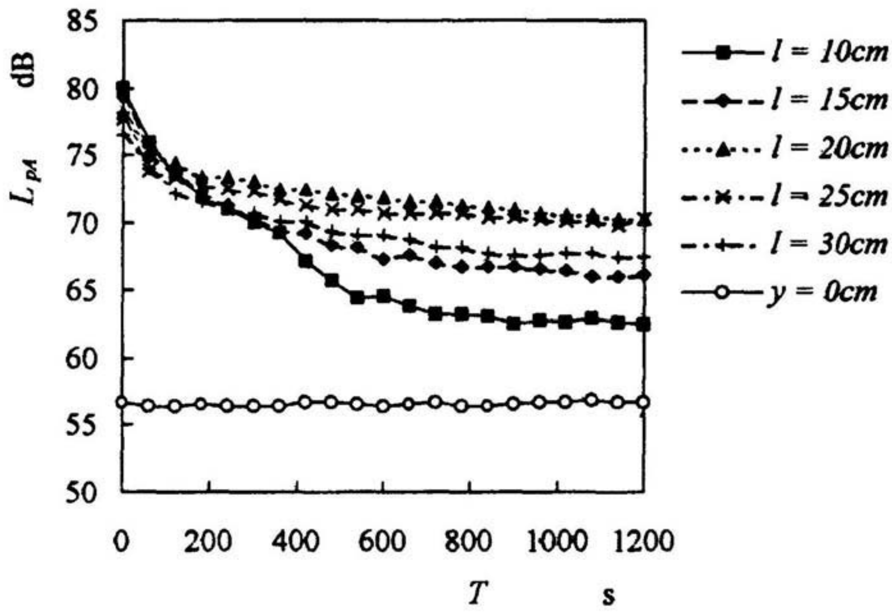


Figure 19 System A
A-weighted noise level at position B_4 (with focusing tube) vs duration of jetting
l = stand-off distance (between nozzle and work object)

Figure 20 shows octave band spectra measured at B_4 at 5 minute intervals. In general, high frequency energy is about 15 to 20 dB more than low frequency noise energy. There is a difference in spectral energy distribution between the start of the jetting (at 0 min) and after 5 minutes. This may be due to the difference in reflected noise once the work object has been cut significantly.

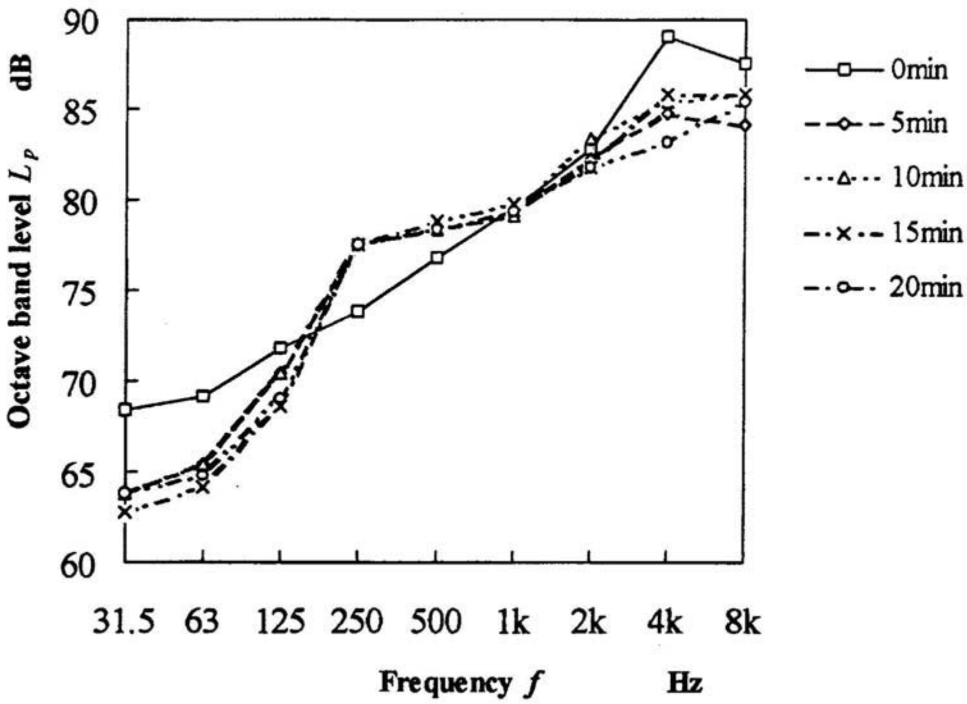


Figure 20 System A
noise spectrum at position B_4 (without focusing tube)
stand-off distance = 20 cm

Figure 21 shows A-weighted levels at C_3 for different stand-off distances over the first 5 minutes of jetting using system B. The noise levels are significantly higher compared to system A, which is expected due to the substantial increase in water pressure. In general, there is an increase in noise with increasing stand-off distance, although this relationship does not seem to be linear. From low to high noise, the order of stand-off distances are: 75, 25, 125, 280, 250 and 175 mm.

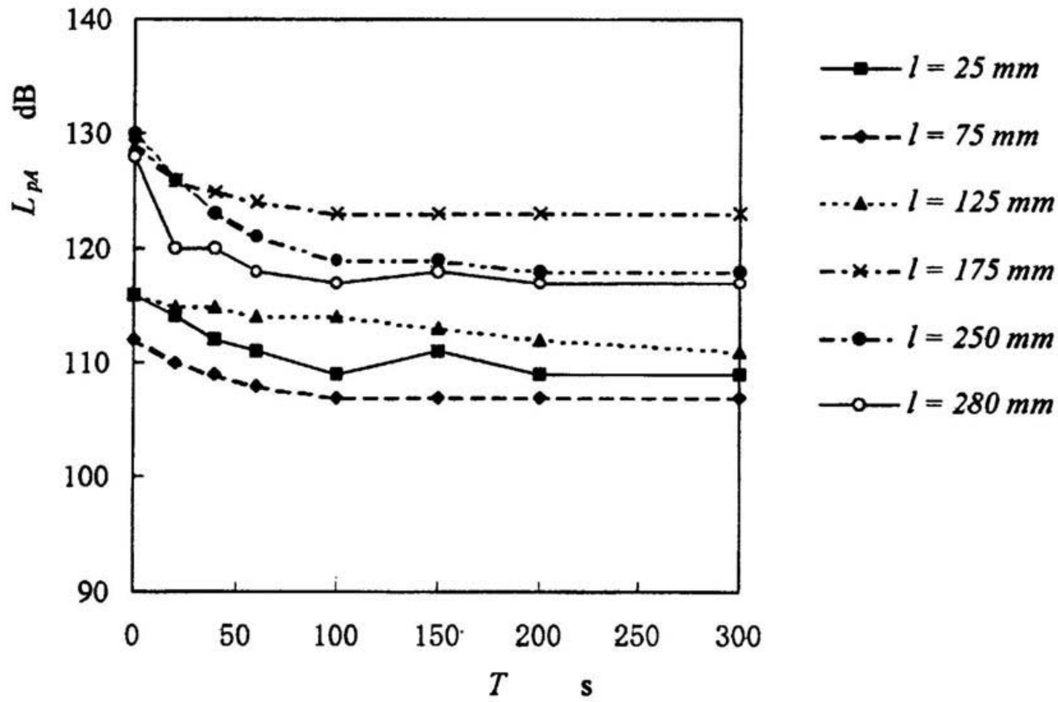


Figure 21 System B
A-weighted noise level at position C_3 (without focusing tube) vs duration of jetting
l = stand-off distance (between nozzle and work object)

Field measurements were carried out on water jetting equipment which was machine mounted and remote controlled. The water pressure was at 180 MPa with a flow rate of 0.8 l/s. The equipment was being used for internal surface preparation of a 5 m diameter pipe. The paper states that the noise in the pipe measured during the jetting was 112 dB(A) at about 3 m from the nozzle. This is of interest in so far as this type of work using hand-held water jetting equipment would subject the operator to very high noise levels.

The paper presents "noise countermeasures" in 4 categories:

Noise sources

The paper recommends using a low noise pump unit, operating at the lowest possible delivery pressure. It also recommends vibration isolation for the pump unit to minimise vibration propagation to other equipment. Also, the work object should be mounted securely to avoid generating vibration.

Noise propagating paths

The paper describes (laboriously) that noise from a point source attenuates at 6 dB per doubling of distance. There is also a slightly incorrect and simplified discussion of sound reduction theory for a panel. It does not suggest any noise control measures specific to water jetting. Noise control measures such as distance and barriers are only likely to be of use to machine mounted remote controlled water jetting equipment.

Around or on workers

The paper states that "human bodies...ears...ear canals are covered by materials which noise does not pass through". The paper discusses earplugs and earmuffs, of which the most pertinent advice is that earplugs could be worn with earmuffs fitted with telecommunications devices to allow communication between operators.

Management

The paper suggests alternating workers in order to limit the accumulation of noise exposure. There is also a reminder that education and training is important for operators, supervisors and managers to ensure that appropriate noise control measures are applied correctly.

3.3.1 Follow-up paper

A further paper by the same author in 1999, describes a very similar project. It is entitled:

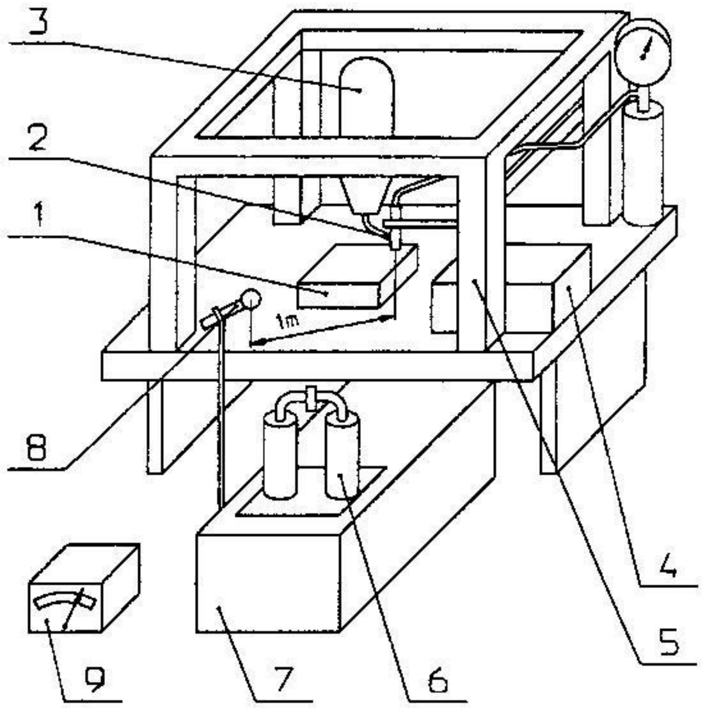
"Noise of jet flow of water in air during waterjet drilling - principal noise source and a tool to measure"

As before, the translation from Japanese makes it difficult to follow and occasionally ambiguous. The author has probably spent considerable time making various noise measurements and displaying the results in different ways. Unfortunately, the measurement methods are questionable. The aim of the research is supposedly to investigate noise exposure to water jetting operators, but the measurements are overly complicated and do not include a straightforward measurement representative of the operator's head position. The measured data at different positions around the nozzle and the workpiece, do not easily allow derivation of operator noise exposure at greater distances.

3.4 MEASUREMENT OF NOISE CHARACTERISTICS OF HYDRO-JET CUTTING TOOLS (Brenner, Pushkarev et al, 2000)

This paper describes an investigation of noise characteristics from commercial hydro-abrasive and water jet cutters of TSU design applied for destruction of rocks and building materials. Unfortunately, it is not clear what is meant by "TSU design". Figure 22 is the test rig. The 100 kW drive pump unit delivered oil at 20 MPa to the pressure intensifier, creating water pressures of up to 250 MPa. Quartz sand was used to form the hydro-abrasive suspension jet.

The positioning of the microphone implies that the equipment is operated by someone close by but is independently mounted rather than hand-held. The purpose of the investigation was to provide information about the noise level at the operator's position.



1 - sample under destruction
2 - hydro-abrasive (water jet) cutter
3 - abrasive delivery system
4 - pressure intensifier
5 - stationary frame construction
6 - water purifying unit
7 - drive pump unit
8 - microphone
9 - noise meter (RFT-00.023)

Figure 22 Test rig and microphone position

The results of the measurements are presented for various modes of operation. For each mode, the data is presented as "acoustic power levels, dB" from 63 Hz to 8000 Hz and an "equivalent acoustic level, dB". The data is not reproduced here because it is not known how to interpret these data descriptors. The paper confirms that the measurements were performed at the operator's position (with the microphone at 1 m from the equipment under control). It would be most logical to present the spectra as linear sound pressure levels along with an overall A-weighted sound pressure level. However, the "equivalent acoustic level" presented in the paper does not equate to a logarithmic addition of the spectrum, with or without A-weightings. The results are unlikely to be accurate sound power levels, because an array of microphones rather than just one microphone position ought to be used. If uniform spherical radiation from a point source is assumed, then sound pressure = sound power - $10\log 4\pi r^2$, where r is the radial distance in metres from the source (1 m in this case). However, using this relationship, the "acoustic power levels" do not give the "equivalent acoustic levels" given in the paper, with or without A-weightings.

Despite the lack of clarity regarding the data descriptors, a number of observations can be made from the changes in data for the different modes of operation:

- Mid and high frequency noise levels drop when the jet impacts a block of material rather than into free air.

- No significant difference in noise levels cutting blocks of concrete or limestone.

- Significant increase in noise levels across spectrum with increase in water pressure from 100 MPa to 250 MPa.

A "noise absorptive case" is used in the "free space between the cutter and the concrete block" which causes a slight reduction in low frequency noise levels and a more significant reduction in mid to high frequency noise levels. However, without a better description of this modification it is not possible to learn from this improvement.

3.5 ABRASIVE WATER JET SOUND POWER MEASUREMENT (Merchant and Chalupník, 1987)

This paper focuses on an abrasive waterjet machine process, i.e. machine mounted rather than held by a human operator, so it is of limited direct interest.

The main aim of the paper was to compare the noise levels from a water jet cutting system using a conventional water tank catcher, to that of the same system using a steel ball matrix catcher. The conventional water tank catches the jet exit stream below the workpiece. The steel ball matrix catcher is a more compact container filled with steel balls. The energy from the jet is dissipated by friction between the balls and by sacrificial abrasion of the balls in the catcher.

The measurements were conducted in-situ rather than under laboratory conditions. However, the measurement procedure described in the paper seems sufficient to achieve reasonable quality results. For instance, the reverberation time was increased and measured carefully in order to determine the minimum measurement distance from the source (i.e. where the diffuse field begins). Also, the presence of pure-tone components in the spectra were taken into account when establishing the matrix of microphone positions over the source.

The sound pressure level results have been converted to sound power levels using established room acoustics theory. The benefit of sound power level data is that it is independent of the acoustics of the measurement room, which means that sound pressure levels of the machine in any other environment can be predicted.

The narrowband analysis of the pump noise clearly shows the fundamental frequency at 210 Hz and its harmonics, corresponding to the piston discharge rate of the multi-cylinder pump. The pump noise spectrum was subtracted from the overall noise spectra to obtain spectra without the pump noise contribution. The spectra for both types of catching systems tend to peak at 12.5 kHz. The A-weighted sound power levels derived from the sound pressure level measurement results are given in Table 11.

Table 11 A-weighted sound power level results

Operation	**Sound power level dB(A)**	
	Water tank catcher	**Ball matrix catcher**
Idling (pump noise subtracted)	112.5	104.2
Cutting workpiece (pump noise subtracted)	109.8	103.4
Pump only	83.4	83.4
Test conditions		
Pressure	207 MPa	
Abrasive	0.5 kg/min	
Workpiece	13 mm aluminium	

The results show that the noise of the abrasive water jet cutting system using a steel ball matrix catcher is less than that of a conventional water tank catcher under both idle and cutting conditions. The improvement can be attributed to the fact that the ball matrix catcher intercepts the water jet near the nozzle whereas, the exposed jet is much longer when the water tank catcher is used. This suggests that the sound power is proportional to the length of the exposed jet.

3.6 ULTRA-HIGH PRESSURE WATER JET: BASELINE REPORT; GREENBOOK (CHAPTER) (U.S. Department of Energy, 1997)

This report is an evaluation of the health and safety issues of ultra-high pressure waterjet technology. The testing focused on dust and noise exposure. The dust exposure was found to be minimal, but noise exposure was significant. Other areas of concern included hand-arm vibration, ergonomics and communication between personnel due to the high noise levels.

The equipment tested was a hand-held Husky™ ultra high pressure waterjet cutting tool with a skid-mounted pump unit. At maximum continuous operation, the output volume was 33 litres/minute with an output pressure of 2720 bar.

Personal noise monitoring using dosemeters, was carried out for the pump operator and the lance operator in an open outdoor environment. The results of the noise measurements are scattered throughout the text of the paper. For greater clarity, the data has been organised into Tables 12 and 13 below. The United States uses different noise exposure criteria from the UK's noise exposure criteria. The Occupational Safety and Health Administration (OSHA) sets a maximum continuous exposure level of 90 dB(A) for an 8-hour working day. OSHA takes into account the recuperative powers of the ear during quiet periods between intermittent noise. The maximum allowed exposure time reduces by 50% for each 5 dB increase in noise level. If an employee works an 8 hour day then an exposure to a steady sound level of 90 dB(A) represents a 100% noise dose, similarly 95 dB(A) represents a 200% noise dose.

Table 12 Personal noise monitoring results

Operator	Monitoring (hours)	OSHA % noise dose	OSHA 8-hour TWA dB(A)	Projected to 8-hour shift	
				% noise dose	8-hour TWA dB(A)
Pump	2.05	16.54	77.0	64.37	86.8
Pump	7.86	108.21	90.5	133.74	92.1
Lance	7.88	875.10	105.6	1135.74	107.5
TWA: Time Weighted Average					

Table 13 Personal noise monitoring results

Operator	Monitoring (hours)	Average exposure dB(A)		Maximum dB(A)	
		80 dB cut-off	90 dB cut-off	Slow?	Instantaneous
Pump	7.86	92.2	91.3	108.6	137.7
Lance	7.88	107.5	107.5	121.9	140.6

Some of the noise data terminology in the paper is not very clear. For instance, "80 / 90 dB cut off" is assumed to mean that noise levels below 80 / 90 dB are not included. The "average exposure level" is described as the overall average of one minute noise averages. The time-weighting of the maximum sound level (which isn't instantaneous) is assumed to be slow.

The paper's final conclusion is that: "The safety and health issues discussed throughout this report could be reduced and in some cases eliminated if this type of high pressure water jet technology could be designed to operate remotely."

3.7 ENVIRONMENTAL AND SAFETY ATTRIBUTES OF WATERJET CUTTING (Burnham and Sepe, 1993)

This paper examines the environmental aspects of waterjet and abrasive waterjet technology compared to conventional alternatives. It is concerned only with machine mounted rather than hand-held water jetting equipment.

An extract of the brief discussion on noise is as follows:

"The amount of sound emitted from a waterjet or abrasivejet depends on the distance between the orifice and the material. If the jet stream is exposed to air for distances exceeding those outlined by manufacturers, the sound generated by a waterjet can exceed 85 dB. Most pumps manufactured for use with waterjet systems employ some type of limited sound-abatement equipment."

3.8 FIELD STUDY OF HIGH PRESSURE WATER JET FOR HIGHWAY SURFACE MAINTENANCE (Hilaris, 1980)

The aims of this field study were to demonstrate the advantages of water jetting technology over other concrete cutting techniques and to determine the design parameters for a remote controlled water jetting machine for highway surface maintenance.

This paper explains the main reasons for the speed advantage of jet cutting through concrete compared to a diamond saw:

i) None of the cutting hardware is in active resistance with the concrete as in the diamond saw blade.
ii) The jet relieves all binding forces due to the creation of a wide kerf or slot, whereas an extra relief cut must be made for the saw method to avoid blade damage due to binding.

The main jet parameters affecting cutting performance are:

- jet pressure
- traversing speed
- number of nozzles
- nozzle diameter
- nozzle rotational speed

The study found that water jet productivity was directly proportional to the water jet power, i.e. doubling the power, doubled the productivity.

Lower noise emission is mentioned as an advantage of water jetting over concrete breaking tools such as jackhammers. However, no data is given to support this assertion.

3.9 ABRASIVE WATER JET (AWJ) PROCESS IDENTIFICATION BY GENERATED SOUND DETECTION (Jurisevic and Junkar, 2002)

This paper focuses on AWJ machining processes, i.e. machine mounted rather than held by a human operator, so it is of limited interest. The paper describes how detection of the generated sound can be used as part of an Adaptive Control Constraint (ACC) system for increasing the automation of an AWJ machining process. This would allow for detection of critical situations such as abrasive jamming and mixing tube breakage. Ultimately, the control and optimisation of other machining parameters such as wear of the cutting head components, stand-off distance and cutting efficiency should be possible. It is recognised that understanding the sound generation mechanisms and the influence of process parameters and material properties is an important basis for developing an AWJ process control system.

The paper assumes that there are five major sound generation sources:

Source 1 The interface of the AWJ with the cutting head.

Source 2 The AWJ passing through the air from the cutting head to the workpiece.

Source 3 The interface of the jet with the workpiece in the material removal zone.

Source 4 The jet interface with the catcher tank after cutting.

Source 5 The noise propagating from the environment.

The mechanisms contributing to Source 1 include:

- the interaction between the high pressure water and the orifice,
- the mixing process of the abrasive and water jet in the mixing chamber,
- the air suction with the abrasive grains, and
- the interaction between the AWJ and the internal surfacing of the mixing tube.

The mechanisms contributing to Source 2 include:

- the jet surface fluctuation in the air,
- the expansion of the air sucked during the mixing process,
- the high speed particle interference with the air around the jet,
- the turbulence in the jet, and
- the vortex creation around the jet.

The mechanisms contributing to Source 3 are complex and depend on the process parameters and workpiece material properties. The sound is mainly generated by the impacts of abrasive particles on the workpiece surface and by cracks propagation in the material.

A range of experiments were carried out, mainly looking at the relationship between sound and stand-off distance (and the other sound generation sources were minimised).

The results are presented in terms of root mean square of the signal in the time domain and frequency amplitude cumulative sum of the signal power spectra in the frequency domain. So the results are not particularly accessible in terms of operator noise exposure. However, they do indicate a strong relationship between the generated sound and the stand-off distance: increased generated sound with increased stand-off distance (between 0.5 and 10 mm).

3.10 IDENTIFICATION OF ABRASIVE WATERJET NOZZLE WEAR BASED ON PARAMETRIC SPECTRUM ESTIMATION OF ACOUSTIC SIGNAL (Kovacevic, Wang and Zhang, 1994)

This paper focuses on abrasive waterjet (AWJ) machining processes, i.e. machine mounted rather than held by a human operator, so it is of limited interest.

The AWJ nozzle is one of the most critical parts that influences the technical and economical performance of an AWJ system. This paper presents an on-line technique for monitoring the nozzle wear based on monitoring the acoustic signals generated by the AWJ.

Nozzle wear can be quantified by the inside diameter of the nozzle which increases gradually, which makes the clearance between the waterjet and nozzle larger. The result of this is incomplete mixing of the abrasive particles with the waterjet, which causes a reduction in cutting ability and tends to produce unacceptable manufacturing quality.

An acoustic sensing system for nozzle wear is based on the hypothesis that a change in the nozzle inside diameter affects the flow of the AWJ and thus influences the level and the pattern of acoustic signal, monitored at the exit of the nozzle.

Three different conditions of an AWJ system were tested:

Water only

> An increase in nozzle inside diameter (1.27 to 1.52 mm), causes the acoustic signal level to increase but the spectral pattern to stay largely the same.

Water and abrasive without cutting

> The fluid flow mixed with abrasive becomes more chaotic than in the case of water only, due to the presence of the abrasive, however, the amplitude of spectra in the high frequency range (above 20 kHz) still depends on the nozzle inside diameter.

Water and abrasive with cutting

> In comparison with no cutting operations, the acoustic signal increases dramatically due to the addition of the acoustic source generated by the erosion of the workpiece and it is possible to distinguish the different nozzle inside diameters from the spectral amplitudes (increasing diameter causes increasing spectral amplitude).

4 NOISE MEASUREMENTS BY HSE

4.1 ULTRA HIGH PRESSURE WATER JETTING

4.1.1 Noise measurements in 2000

On 23 March 2000, a Specialist Inspector in HSE's Noise & Vibration Corporate Topic Group, carried out noise measurements on ultra high pressure water jetting equipment that was designed for surface preparation applications. The equipment setup was as follows:

Operating pressure	2000 bar (30,000 psi)
Flow rate	22 litres/min
Nozzle type	multiple jet rotating head
Stand-off distance	30 - 40 mm

The noise measurement results are summarised in Tables 14 and 15.

Table 14 Jetting noise measurement results

Jetting condition	Measurement location	L_{eq} dB(A)	L_{max} dB(A)	Duration seconds
Against side of steel portacabin	At operator's ear	108.0	110.9	47
Into free space	At operator's ear	109.7	111.4	41

Table 15 Jetting unit noise measurement results

Measurement location	Jetting unit doors	L_{eq} dB(A)
1 m from jetting unit	Open	100.6
2 m from jetting unit	Open	96.6
1 m from jetting unit	Closed	94.3
2 m from jetting unit	Closed	92.0

It can be seen from Table 14 that the noise level is steady because there is little difference between the L_{Aeq} and L_{Amax} levels. There is a small increase in noise when the water jet is directed into free space, rather than against the side of the portacabin. Table 15 demonstrates the benefit of keeping the noise-attenuating doors closed on the jetting unit.

4.1.2 Noise measurements in 2004

HSL visited the premises of two water jetting equipment manufacturers during April and May 2004. The primary objective was to carry out hand-arm vibration measurements to confirm that rotating jets cause higher vibration than straight jets. These visits were also an opportunity to record the operator's noise exposure. A tripod mounted microphone next to the water jetting operator and a dosemeter worn by the operator provided the noise data. The detailed results will be available in HSL Report No. NV/04/11 due to be published soon. In summary, the L_{Aeq} (A-weighted average noise level) varied from 95 to 127 dB(A) depending on the UHP equipment configuration and jet length.

4.2 HIGH PRESSURE WATER JETTING

On 11 March 1999, HSL carried out noise measurements on high pressure water jetting equipment that was designed for surface preparation applications. The operating pressure was 12,000 psi and the nozzle was a rotating head.

The noise measurement results are summarised in Table 16.

Table 16 Noise measurement results

Jetting condition	Measurement location	L_p dB(A)
Towards the ground	At operator's ear	95
Towards the ground	5 m away	87
Against metal box	At operator's ear	101 - 102
Against metal box	5 m away	94 - 95

5 LEGISLATION AND INDUSTRY GUIDANCE

5.1 NOISE AT WORK REGULATIONS

An operator exposed to an L_{Aeq} of 110 dB(A) during water jetting operation, exceeds the second action level under the current Noise at Work Regulations [5] within a few minutes. Therefore, the employer has a duty to keep the risk of damage to the operator's hearing to below that arising from exposure to the second action level.

Under the proposed Control of Noise at Work Regulations [2], this exposure will exceed the exposure limit value within a few minutes, in which case the employer has a duty to take action to reduce exposure to below the limit value.

5.2 NOISE EMISSION REGULATIONS

Regulation 3 of The Noise Emission in the Environment by Equipment for use Outdoors Regulations 2001 (NEEEOR) [6] requires 'high pressure flushers' and 'high pressure water jet machines' to have a noise marking along with the CE marking.

5.2.1 Equipment definitions

The definitions of the equipment are given as:

High pressure flushers

> A vehicle equipped with a device to clean sewers or similar installations by means of a high pressure water jet. The device may be either mounted on a proprietary vehicular truck chassis or incorporated into its own chassis embodiment. The equipment may be fixed or demountable as in the case of an exchangeable bodywork system.

High pressure water jet machines

> A machine with nozzles or other speed-increasing openings which allow water, also with admixtures, to emerge as a free jet. In general, high pressure jet machines consist of a drive, a pressure generator, hose lines, spraying devices, safety mechanisms, controls and measurement devices. High pressure water jet machines may be mobile or stationary:
>
> - mobile high pressure water jet machines are mobile, readily transportable machines which are designed to be used at various sites, and for this purpose are generally fitted with their own undergear or are vehicle-mounted. All necessary supply lines are flexible and readily disconnectable.
>
> - stationary high pressure water jet machines are designed to be used at one site for a length of time but capable of being moved to another site with suitable equipment. Generally skid or frame-mounted with supply line capable of being disconnected.

5.2.2 Noise measurement methods

The noise marking is in the form of a 'guaranteed sound power level'. For each type of equipment, the Regulations lay down the basic noise emission standard and general supplements for measuring the sound pressure level on a measurement surface enveloping the source and for calculating the sound power level produced by the source. The measurement methods for high pressure flushers and high pressure water jet machines are as follows:

High pressure flushers

Basic noise emission standard: BS EN ISO 3744: 1995 [7].

Operating conditions during test: The high pressure flusher shall be tested in a stationary position. The engine and auxiliary units operate at the speed provided by the manufacturer for the operation of the working equipment; the high pressure pump(s) is (are) operating at its (their) maximum speed and operating pressure provided by the manufacturer. Using an adapted nozzle the pressure reduction valve shall be just on the point of reacting. The flow noise of the nozzle shall not have any influence on the results of the measurements.

Period of observation: At least 30 seconds.

High pressure water jet machines

Basic noise emission standard: BS EN ISO 3744: 1995.
Parallelepiped measurement surface with measurement distance d = 1 m.

Operating conditions during test: The high pressure water jet machine shall be installed on the reflecting plane; skid-mounted machines shall be placed on a support 0.40m high, unless otherwise required by the manufacturer's conditions of installation.

The high-pressure cleaning machine shall be brought to its steady-state within the range specified by the manufacturer. During testing the nozzle shall be coupled to the high-pressure cleaning machine that causes the highest pressure if used according to the manufacturer's instructions.

Period of observation: At least 15 seconds.

The noise measurement method defined by NEEEOR does not include the flow noise from the water jet. This is a significant omission in terms of using this data to assess an operator's noise exposure. This problem is perhaps because NEEEOR is trying to provide noise data for use with environmental assessments on outdoors equipment. It could be argued that low frequency noise emission from the jetting unit is more of an issue, because the high frequency noise from the water jet will attenuate with distance more quickly than the low frequency noise.

5.3 WATER JETTING ASSOCIATION CODES OF PRACTICE

The Water Jetting Association maintains a Code of Practice (CoP) for manufacturers [8] which covers the health and safety requirements in the design, construction, installation and maintenance of pumps and pumping systems used for high pressure water jetting.

The noise-related normative references are listed as:

EN ISO 3746: 1995	Acoustics - Determination of sound power levels of noise sources using sound pressure - Survey method using an enveloping measurement surface over a reflecting plane
EN ISO 11202/AC	Acoustics - Noise emitted by machinery and equipment - Measurement of emission sound pressure levels at a work station and at other specified positions - Survey method in-situ
EN ISO 11688-1/AC	Acoustics - Recommended practice for the design of low-noise machinery and equipment - Part 1: Planning
ISO 4871	Acoustics - Declaration and verification of noise emission values of machinery and equipment
2000/14/EC	Noise emission in the environment by equipment used outdoors

The CoP makes the following references to noise:

Clause 5.4	Noise generated by the high pressure pump, water jet system, control valves as well as the emerging liquid jet, or by the liquid jet striking an object can pose a hazard to health.
Clause 6.3	The equipment should carry a permanent CE mark and sound power level mark.
Clause 7.3	The generation of noise and the emission of noise of high pressure water jet machines shall be reduced as far as is technically possible within commercial restraints.
Clause 17.8	The measured surface sound pressure level shall be in accordance with the Measured Envelope Surface Method at one metre distance, excluding the noise generated by the spraying device (EN 12639, ISO 3744 and 2000/14/EG)
Clause 18.1	For high pressure pumps and water jetting systems the following shall be clearly and permanently marked: The sound power level in accordance with Directive 2000/14/EG.

These clauses could be expanded to provide more comprehensive instructions to manufacturers on noise emission. Initial comments are as follows:

- Clause 5.4 could be expanded to include the risk of permanent hearing loss.

- Clause 6.3 could make reference to the Noise Emission in the Environment by Equipment for Use Outdoors Directive 2000/14/EC. If the CoP is aimed at UK readers only, there could also be a reference to NEEEOR.

- Clause 7.3 could make reference to the EN ISO 11688 standards.
- Clause 17.8 refers to ISO 3744 but lists ISO 3746 in the normative references section. In fact, there should only be reference to ISO 3744 because the measurement standard in NEEEOR is BS EN ISO 3744 (see section 4.1). This measurement standard only covers the jetting unit and not the water jet. The reference to the European Directive should be 2000/14/EC.

The Water Jetting Association also maintains a CoP for users of high pressure and ultra high pressure water jetting equipment [9]. It makes the following references to noise:

5.5 Noise levels will exceed 85 dbA [sic] in almost all applications and appropriate hearing protection must be used. In addition to the Jetting Gun operator this consideration will apply to the second man at the pump who may be exposed to even higher noise levels, depending on the location of the pump.

6.6.1 Most water jetting produces noise levels in excess of 85 dbA [sic] and hearing protection will be required. In some cases noise levels can be sufficiently high to require the use of ear defenders, for example when operating in a confined space.

As for the manufacturer's CoP, this document could be improved to provide more helpful guidance with regards to noise exposure risk assessments. It would also be an opportunity to highlight the fact that the NEEEOR noise marking only represents noise from the jetting unit and not from the water jet. An operator's noise exposure assessment ought to include the water jet noise source, particularly as it is the primary mid-high frequency noise source.

6 SURVEY OF WATER JETTING COMPANIES

An email requesting information about water jetting noise was sent to 31 companies in the high pressure water jetting industry including manufacturers, distributors and contractors. The email and the list of companies that were contacted are presented in Appendix E. Before the email was sent, the survey was approved by HSE's Survey Control Liaison Officer (SCLO) team. The email was sent on 16 February 2004 and at the issue of this report, there have been five replies, which are summarised below.

- A manufacturer has supplied noise data from their various jetting units, but they do not have noise data from the water jet itself. The contractor is expected to deal with this aspect because of the range of possible tasks and work environment that the equipment could be used in.

- A contractor has expressed interest in this topic and sent brief details of a noise survey carried out in 2002. However, as the measurements were part of an environmental assessment (presumably for a local authority) the results are not well suited to assessing an operator's noise exposure to water jetting. It seems likely that this particular company would be enthusiastic in assisting HSL with future water jetting noise measurements if appropriate.

- A contractor requested information (rather than offering any) but sounded keen to assist where possible. However, they tend not to operate at the high pressure end of water jetting.

- Two companies have sent holding replies, claiming to send information as soon as they can.

The poor response from this survey is perhaps due to the lack of noise data that water jetting companies possess or the ineffectiveness of this type of survey.

HSE's Utilities Section has also had little success in obtaining noise information from its industry contacts.

7 DISCUSSION

The following observations are drawn from the papers that have been reviewed:

- High frequency energy dominates the water jet noise spectrum.

  The paper summarised in section 3.1, demonstrates a peak around 4000 Hz to 8000 Hz. Similarly, the paper summarised in section 3.3 shows high frequency noise to be 15 to 20 dB higher than low frequency noise.

- Noise emission increases with increasing water pressure.

  Paper 3.1 shows a 2 to 3 dB increase with increments of 6.9 MPa (1000 psi) at mid-high frequencies. Paper 3.2 shows an approximate increase of 9 dB with increments of 20 MPa at frequencies above 1 kHz and an approximate increase of 6 dB with increments of 20 MPa for lower frequencies.

- At constant water pressure, noise emission increases with increasing nozzle diameter.

  Paper 3.2 shows an increase of 10-15 dB from 0.5 to 1.2 mm nozzle diameter at mid-frequencies and smaller increases at high frequencies. Paper 3.10 also shows this relationship with nozzle diameter.

- An associated noise source is the pump which emits low frequency noise.

  Paper 3.1 shows a rise in the spectrum at 31.5 Hz due to pump noise.

- There is a significant noise increase in front of the nozzle compared to behind it.

  Paper 3.1 shows an increase of about 20 dB across the mid-high frequency range from 180° to 7.5° (where 0° is in line with the direction of the water jet) at 2.44 m radius from the nozzle.

- Noise propagation changes from a point source to a line source in an arc in front of nozzle.

  Noise propagation typical of a point source (6 dB decrease per doubling of distance) is apparent within an arc in front of the nozzle. This behaviour changes with increasing angle from the nozzle and probably behaves more like a line source (3 dB decrease per doubling of distance). Around 0° from the nozzle, paper 3.1 shows a difference of 10 to 15 dB between 2.44 to 13.7 m from the nozzle, but beyond 30° from the nozzle, the difference is only 5 to 10 dB.

- In general, mid-high frequency noise increase with increasing stand-off distance.

  Paper 3.1 shows that for a round jet nozzle, mid-high frequency noise increases with increasing stand-off distance between the nozzle and the target material. For a fan jet nozzle, the mid-frequency noise increases with stand-off distance but high-frequency noise rises then falls with increasing stand-off distance. Paper 3.1 speculates that, assuming the noise caused by impingement is relatively small, the major effect of the target material is to "cut-off" the region of noise sources within the water jet at the point at which the plate is situated. Paper 3.2 demonstrates that up to a certain length, an increase in stand-off distance causes an increase in noise emission. The limiting length for this behaviour seems to be proportional to the jet power. The measurements in papers 3.3, 3.5 and 3.9 also give similar results with stand-off distance.

8 CONCLUSIONS AND RECOMMENDATIONS

The literature search has uncovered very little information in terms of absolute noise levels incident on an operator using hand-held equipment. Similarly, the survey of water jetting companies has not extracted any useful noise data. The noise measurements by HSE show that water jetting operators are exposed typically to greater than 100 dB(A) clearly showing that they are at a high risk of hearing damage. In addition, the water jet noise spectrum is dominated by energy around 4000 Hz, which is the frequency region of greatest acuity and where, in general, hearing loss first appears. Therefore, employers have a duty to minimise this risk to as low a level as is reasonably practicable. However, with no specific information on water jetting noise emission, noise exposure risk assessments may be unreliable. It is recommended that HSE investigates how manufacturers can best advise customers on noise emission from water jetting systems (which is particularly challenging when the system components can be sourced from different manufacturers and can operate at a wide range of pressures). The noise measurement method specified for high pressure water jetting in the Noise Emission in the Environment by Equipment for use Outdoors Regulations 2001 [6] (NEEEOR) does not include the flow noise from the water jet. The method only measures the noise from the jetting unit (the engine and pump). This is a significant omission in terms of the reliability of using a NEEEOR noise marking for an operator's noise exposure assessment.

The literature search has revealed preliminary research into noise emission characteristics of water jetting. However, this research has not yet progressed to developing noise control design and operating techniques to reduce exposure. Research involving laboratory-controlled noise measurements would be required to progress this.

It is not known whether the authors of paper 3.1 have progressed their investigation of water jetting noise since they published the paper in 1982. It would be interesting to find out whether they have tested the effectiveness of the three silencer designs that are presented. Some of the noise measurement arrangements described in Paper 3.1 are worth considering for comparing noise levels from different water jet nozzles and evaluating the effectiveness of noise reduction designs.

In the absence of water jetting noise control (other than at the jetting unit) most water jetting operators are relying on hearing protection. There can be difficulty with the compatibility of hearing protection and the rest of the head and body protection. A study could be carried out to determine the most effective and compatible type of hearing protection for water jetting operators.

Remote controlled water jet machines are available but not used for many types of water jetting operations. It would be worthwhile finding out more about the practicality of this technology. Reducing the need for hand-held water jetting would distance the operator from the water jet and therefore reduce the operator's noise exposure.

A potential source of information which has come to light at the end of this investigation, but may be worth reviewing is a reference book entitled *Hydroblasting and Coating of Steel Structures* [10] published in 2003 which has a section on noise.

9 REFERENCES

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[2] Proposals for new Control of Noise at Work Regulations implementing the Physical Agents (Noise) Directive (2003/10/EC). HSE consultative document 2004.

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[4] BS EN ISO 9614-1: 1995 Acoustics - Determination of sound power levels of noise sources using sound intensity - Part 1. Measurement at discrete points.

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[6] The Noise Emission in the Environment by Equipment for use Outdoors Regulations 2001. Statutory Instrument 2001 No. 1701.
The Noise Emission in the Environment by Equipment for use Outdoors (Amendment) Regulations 2001. Statutory Instrument 2001 No. 3958.
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[7] BS EN ISO 3744: 1995 Acoustics - Determination of sound power levels of noise sources using sound pressure - Engineering method in an essentially free field over a reflecting plane

[8] Manufacturer's Code of Practice for High Pressure Water Jetting Equipment, Pumps and Ancillary Equipment, The Water Jetting Association, pre-publication draft issue 2, 17/06/02.

[9] Code of Practice for the use of High Pressure and Ultra High Pressure Water Jetting Equipment, The Water Jetting Association, 2002, ISBN 1874278024.

[10] Hydroblasting and Coating of Steel Structures, Andreas Momber, ISBN 185617395X.

APPENDIX A LITERATURE SEARCH

Literature search request to HSE Information Centre

Water jetting noise.

Specifically:

- high pressure water jetting 10,000 - 25,000 PSI (680 - 1700 bar)
also known as high pressure hydroblasting/waterblasting, and
- ultra high pressure water jetting > 25,000 PSI (> 1700 bar)
also known as ultra high pressure hydroblasting/waterblasting/hydrodemolition.

Particularly interested in water jetting used in petro-chemical, offshore and marine industries.

Applications include:

- removing graffiti, paint, rust, scale, marine growth, cement, grease, oil etc from any surface,
- preparing surfaces for painting,
- demolition e.g. cutting steel, concrete, glass, rubber etc,
- scabbling concrete in preparation for concrete bonding,
- restoring building surfaces: concrete, brick, sandstone, limestone, granite etc, and
- drain and sewer cleaning.

Looking for all noise related information, including: measured noise levels, predicted noise levels, noise control methods, noise exposure to humans, hearing/ear protection.

The components of water jetting noise are likely to be: drive unit noise (motor and pump), water jet noise from nozzle, impact noise of water on surface.

Noise data keywords: octave band, one-third (1/3) octave band, A-weighted, sound pressure level, sound power level, dB, dB(A), L_p, L_{eq}, L_{Aeq}, L_{max}, L_{Amax}, L_1, L_{A1}.

Noise control keywords: noise reduction, attenuation, insulation, absorption, isolation.

Noise synonyms: sound, acoustics.

Databases searched by HSE Information Centre

1) OSHROM which consists of the following databases:

HSELINE from the Health and Safety Executive.

CISDOC from the International Occupational Safety and Health Information Centre of the International Labour Organisation.

NIOSHTIC2 from the National Institute for Occupational Safety and Health, U.S. Department of Health and Human Services.

RILOSH (Ryerson International Labour, Occupational Safety & Health Index) from Ryerson Polytechnic University Library in Canada.

2) Medline - OEM (Occupational and Environmental Medicine) subset of Medline database.

3) Ergonomics Abstracts Online.

4) Ei Compendex. Electronic version of Engineering Index covering engineering and technological literature: civil, energy, environmental, geological and biological engineering; electrical, electronics and control engineering; chemical, mining, metals and fuel engineering; mechanical, automotive, nuclear and aerospace engineering; computers, robotics and industrial robots. Journal literature and conference proceedings are covered.

5) NTIS - National Technical Information Service. Database provided by NTIS, Office of Product Management, USA. Consists of summaries of U.S. government sponsored research, development and engineering, plus analyses prepared by federal agencies, their contractors or grantees. NTIS also provides access to the results of government sponsored research and development from countries outside the USA, including Japan, UK, Germany and France.

6) ICONDA - International Construction Database. Covers worldwide technical literature on civil engineering, urban and regional planning, architecture and construction. Sources include over 600 periodicals, books, research reports, conference proceedings, business reports, theses and non-conventional literature.

7) GeoArchive. Covers all types of information in geoscience, hydroscience and environmental science. Covers over 5,000 serials, books from over 2,000 publishers, geological maps and doctoral dissertations.

8) GEOBASE. Covers worldwide research literature in physical and human geography, earth and environmental sciences, ecology and related disciplines. Covers over 5,000 journals, over 2,000 books, monographs, conference proceedings and reports.

9) GeoRef. The database of the American Geological Institute covers worldwide technical literature on geology and geophysics. Indexes over 13,000 serials, covers over 3,500 journals as well as books and book chapters, conference papers, government publications, theses, dissertations, reports and meeting papers.

10) FLUIDEX (Fluid Engineering Abstracts). Global literature in the use, control and management of fluids for engineering purposes. Covers trade and scientific literature.

11) TULSA (Petroleum Abstracts). Scientific articles, patents, meeting papers and government reports of interest to geologists, geophysicists, petroleum engineers and other technical professionals and managers in the oil and gas exploration and production industry.

12) WATERNET. Index of the publications of the American Water Works Association and the AWWA Research Foundation. Includes books, proceedings, journals, newsletters, standards, manuals, handbooks and water quality standard test methods. Emphasis is on the technical reports and studies from water utilities, regulatory agencies and research groups in the United States and its territories, Canada, Mexico and Latin America. European and Asian data are also reported.

13) JICST-Eplus - Japanese Science and Technology. Covers literature published in Japan from all fields of science, technology and medicine. Covers over 6,000 journals and serials, in addition to conference papers, preprints, technical reports and other non-periodicals published by the Japanese government or local governments.

14) PASCAL. Produced by the Institut de l'Information Scientifique et Technique (INIST) of the French National Research Council (CNRS). It covers the world's scientific and technical literature.

15) Wilson Applied Science and Technology Abstracts. Covers more than 400 core English language scientific and technical publications. Non-English language periodicals are indexed if English abstracts are provided. Covers science and technology, from trade and industrial publications, journals issued by professional and technical societies, and specialised subject periodicals, as well as buyers' guides, directories and conference proceedings.

Other sources of information searched

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Proceedings of the 2nd U.S. water jet conference, 1983
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Proceedings of the 4th U.S. water jet conference, 1987
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Proceedings of the 11th international conference on jet cutting technology, 1992
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Proceedings of the 15th international conference on jetting technology, 2000
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APPENDIX B PAPERS REVIEWED AND SUMMARISED

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Katakura H. (Tokyo Engineering University, Japan) and Miyamoto H. (Keio University, Japan). Proceedings of the 9th American Waterjet Conference, August 1997, Paper 59.

Noise of jet flow of water in air during waterjet drilling - principal noise source and a tool to measure
Katakura H. (Tokyo Engineering University, Japan). Proceedings of the 3rd ASME/JSME Joint Fluids Engineering Conference, July 1999, FEDSM99-7257.

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Brenner V.A., Pushkarev A.Y., Golovin K.A., Chukov A.N., Sladkov V.Y. and Naumov Y.N. (Tula State University, Russia). Proceedings of the 15th International Conference on Jetting Technology, September 2000, ISBN 1860582559.

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APPENDIX C PAPERS REVIEWED ONLY

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Modelling of water-gun signatures
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The application of water jet technology in the construction industry
Akio S. (Kumagai Gumi Co. Ltd.). Wota Jetto (Journal of the Water Jet Technology Society of Japan), 1993, Volume 10, Number 3, ISSN 09100172.

Latest circumstances of demolition works. Non-polluting demolition method featuring low noise, no vibration and no dust using an ultra-high-pressure water jet. RECPAC method.
Fumi K. (JDC Corp.), Naotaka K. and Masakazu H. (Kako). Seko (Architectural Product-Engineering), 1992, Number 326, ISSN 03891879.

Investigations on industrial safety and health protection using devices working with jets of liquids on building sites in the construction industry
Petzschmann E., Jung D. and Watermann D. (Bundesanstalt fur Arbeitsschutz und Arbeitsmedizin). Wirtschaftsverlag NW, Germany, 2001, ISSN 3897016702.

APPENDIX E SURVEY

The following request was emailed to the companies listed in Table E.1. Most are members of the Water Jetting Association (www.waterjetting.org.uk).

The Health & Safety Executive (HSE) are aware that water jetting operators can be exposed to high noise levels. The Health & Safety Laboratory (HSL) have been asked by HSE to:

- get a better understanding of the typical noise levels from high pressure and ultra high pressure water jetting,

- investigate what action is taken or could be taken by manufacturers and suppliers to minimise noise generation,

- investigate what operating techniques are applied or could be applied by operators to minimise noise exposure, and

- investigate what sort of hearing protection is effective and how compatible it is with other personal protective equipment, such as eye and head protection.

We are interested in noise emission from all applications of high pressure and ultra high pressure water jetting (with or without abrasive) including cleaning, surface preparation and cutting. All sources of water jetting noise are of interest: the pump equipment, the water jet and the impact with the target surface.

Participation in this survey is voluntary. Any information you give will be treated confidentially and the results compiled anonymously. It will only be used for the purposes of developing helpful guidance on minimising the risk of hearing loss for water jetting operators. This guidance will be of benefit to all those involved with manufacturing, supplying or using water jetting equipment.

Information requests:

1. Please provide any measured noise levels you have for your water jetting equipment in use. Useful details to accompany each set of data include:

    - type of application
    - target surface
    - description of equipment components (nozzle, lance, pump)
    - whether the equipment is suitable for offshore applications
    - equipment settings (pressure, jet velocity)
    - type of abrasive if applicable
    - nozzle to surface distance
    - noise measurement position

2. What noise reduction measures do you make use of?

3. What operating techniques do you recommend/use to minimise noise exposure?

4. What type of hearing protection do you recommend/use?

5. Is your company a manufacturer, supplier or operator of water jetting equipment?

Table E.1 Water jetting companies

Company name	Website	Email
Aquablast Limited	www.aquablast.co.uk	sales@aquablast.co.uk
Balvac Whitley Moran	www.balvac.co.uk	info@balvac.co.uk
BHR Group Ltd	www.bhrgroup.com	fluid@bhrgroup.com
Brocol Consultants Ltd	www.brocol.co.uk	j.tucker@brocol-hq.co.uk
Calder Ltd	www.calder.co.uk	steve@calder.co.uk
Circle Technical Services Ltd	www.circletech.co.uk	info@circletechnical.com
Clearway Drainage Systems Ltd	www.clearwaydrainageuk.com	(submitted online)
Cristofoli International Ltd	www.cristofoli.net	cristojet@aol.com
DBI Group Ltd	www.dbigroup.co.uk	offshore@drainbrain.co.uk
DCS (Aquajet)	www.dcsuk.com	info@dcsuk.com
DIAJET Ltd	www.diajet.co.uk	jetting@diajet.co.uk
Ferro Monk Systems Ltd	www.ferromonk.co.uk	info@ferromonk.co.uk
Flowplant Group Ltd (Harben Neolith)	www.flowplant.com	sales@flowplant.com
Hawk 2000 (subsidiary of W & J Leigh & Co)	www.wjleigh.co.uk	enquiries@leighspaints.co.uk
Hydropumps Ltd	www.hydro-pumps.co.uk	jeffhaigh@hydro-pumps.co.uk
Jetchem Systems Ltd	www.jetchem.com	info@jetchem.com
L M Sorrell & Co	www.lmsorrell.co.uk	allendrury@lmsorrell.co.uk
Laser Special Projects Ltd	www.laser-group.co.uk	enquiries@laser-group.com
Longville Ltd	www.longville-group.com	(submitted online)
Luddon Construction Ltd	www.luddon.co.uk	enquiries@luddon.co.uk
Makers UK Ltd Civil Engineering Repair Division	www.makers.co.uk	cerd@makers.co.uk
Mourik UK/Euro Exchangers	www.mourik.com	admin@mourik.co.uk
Powerclean UK Ltd	www.powerclean-uk.co.uk	info@powerclean-uk.co.uk
Rentajet Ltd	www.rentajet.co.uk	sales@rentajet.co.uk
Rentokil Initial	www.initialcleaning.co.uk	(submitted online)
Rigblast (Aqua-Dyne Ltd)	www.rigblast.co.uk	mike.jamieson@rigblast.com
Roy Hankinson Industrial Services Ltd	www.hankinson.co.uk	info@hankinson.co.uk
Sureclean	www.sureclean.co.uk	ian.pirie@sureclean.co.uk
Tube Tech International Ltd	www.tubetech.com	info@tubetech.com
Tytan (Jetting) Ltd	www.tytan.co.uk	enquiries@tytan.co.uk
WOMA (GB) Ltd	www.woma.gb.com	david.clegg@woma.gb.com