The Potential of High-Frequency Forced Pulsed Waterjet for Nuclear Decommissioning – 15367

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ABSTRACT
Forced Pulse Water Jetting (FPWJ) has been demonstrated in other works as a credible and consistent method for removing coatings or otherwise preparing surfaces across numerous industries. Its applicability to the nuclear industry as a powerful tool for decommissioning and waste treatment has only recently being recognized and underpinning study is required before any deployment can be considered.

Use of FPWJ within the nuclear sector for decommissioning and waste treatment, requires a different degree of surface finish to achieve a decontamination effect or an assured performance. This necessitates a greater erosion of the base metal than in other industries. The addition of a Forced Pulse Modulation Unit (FPMU) to a high pressure water jetting system offers performance shifts akin to the differences between High Pressure (HP) and Ultra High Pressure (UHP) water jets.

Trials have been undertaken in a controlled environment to establish the number of cycles to achieve a given mass loss and or depth of penetration that would otherwise provide decontamination of mostly flat or simple geometry surfaces using a robotic arm for consistency and safety. It has also been shown that metalwork can be readily penetrated without risk of explosion, for example to allow draining of a gas cylinder.

Most nuclear facilities have a plethora of pipe systems spanning various diameters. A considerable portion of the UK Sellafield site has 2 inch bore pipe. The FPMU technology is being adapted to consider applications in enclosed systems, such as decontamination of pipes. Exploratory works to date show there to be many physical attributes that influence performance that include, standoff of the jet, established propagated forced pulse jet length, interference from resultant water spray and angle of attack. Comparatively small changes to these parameters can have a profound effect on performance.

The process is capable of removing 10's microns to several mm's of metal progressively and repeatedly. This enables a credible potential treatment of plant and equipment at Intermediate Level Waste and High Level Waste thresholds. In considering this as a treatment method, a balance between performance, cost and environmental impact of effluents must be made and will be studied further during future active trials.

INTRODUCTION
Forced Pulse Water Jetting (FPWJ) is a variation of traditional High Pressure Water Jetting (HPWJ) that offers enhanced surface interaction for surface preparation, erosion or coatings removal; by induction of pulses into the water jet. The technology has been industrially applied in the aerospace industry for coatings removal and high grade surface preparation for aerospace paint applications. Such applications are deployed in an ex-situ manner in booths equipped with FPWJ equipment mounted on robotic devices.

Pulsation of the water jet is induced by a <2kW fixed (or variable) frequency unit as part of a bespoke water jetting head unit that is quite large. The effective pulsed jet manifests itself in the water jet after ejection from the nozzle (see Figure 1). The means by which this occurs is protected by patents and presented in the literature, typically, [Refs 1 to 3]. The effective range of the pulsed water jet is relatively short and equivalent in most respects to the stand-off distances in Ultra High Pressure Water Jetting (UHPWJ) surface preparation jets, circa 25-50mm. A 'droptest' is employed to determine the ideal stand-off distance for a robot mounted unit to maintain see Figures 2 & 3. The pattern of the fully developed FPWJ varies with the standoff distance (S_d) as shown in the last photograph of Figure 1. This corresponds directly with the performance of the FPWJ. If the sample were placed close to the orifice, the pulsated jet will not have established, too far and the dispersive effects from breakdown of the jet pattern will also not offer optimal performance.

Figure 1 – High speed photographs of a traditional water jet and the establishment of a FPWJ.

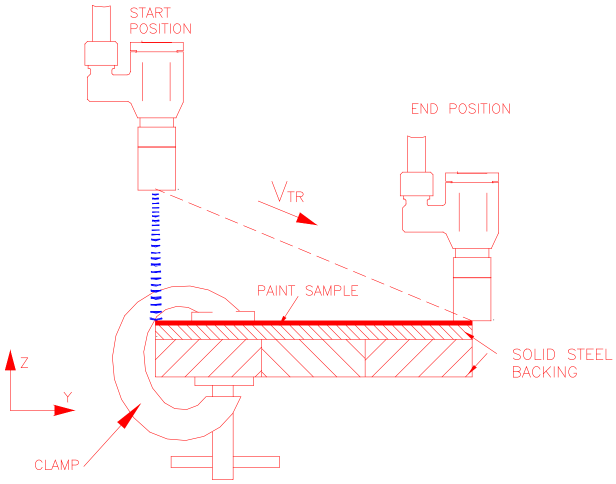

Figure 2 – Illustration of 'drop test'.

Figure 3 – Example of the stripe pattern from a 'drop test'. Yellow arrow indicates optimum standoff.

For a given ultrasonic power input (set by the amplitude on the generator), the value of ‘a’ (see Figure 4), pressure and flow rate, there is a certain distance at which the FPWJ is very powerful. The purpose of the “droptest” is to determine the zone where near optimum performance can be observed. As shown in Figure 2, the nozzle is programmed to traverse from left to right at a constant speed. For visual observation with the naked eye, a 12-in steel strip, as shown Figure 3 is employed. The arrow in Figure 3 shows the location where severe erosion occurs indicating near optimum performance of the FPWJ. This position varies with differing jet orifice size, pressure and flow rate.

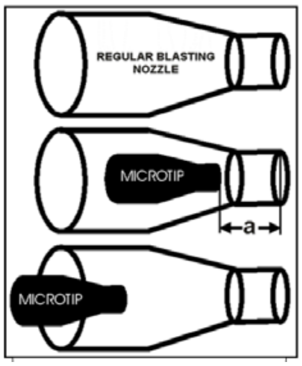

Figure 4 – Illustration of relative positioning of Ultrasonic transducer

The applicability of the technology for nuclear decontamination is being investigated, but fundamentally is a deviation from the surface preparation approach in that, reliable and meaningful quantities of the substrate material are needed to be removed to provide the required Decontamination Factor (DF) without regard for the resultant surface profile. The depth of removal will vary from one application to another however; will typically be from a few microns to 500 microns. The effects of the technology are repeatable in that multiple cycles can provide a cumulative effect.

The current application in the aerospace industry considers some simple geometry metallic items. Nuclear facilities are far more complex. Whilst planar surfaces can be treated now, facilities such as Sellafield, UK, host a vast array of plant types with many kilometers of pipe and duct systems. Hence, if such technology can be miniaturized to enter pipework or duct systems, the scope of application can be significantly expanded. Therefore, considering most nuclear fuel reprocessing facilities have a Highly Active liquor phase, there is the potential for High Active metallic wastes to be re-categorized to LLW, subject to acceptance of high water volumes. There are well known financial benefits for the long term costs of waste management by downgrading classification of wastes, albeit increasing the volume.

Whilst many of the effects seen by FPWJ can already be achieved by UHPWJ, the same effects are seen using High Pressures, hence identification of the benefits of the technology must be established and later benchmarked against the existing treatment methods before committing to introduction of the process at any given site in either an *in-situ* or *ex-situ* treatment context set against a backdrop of environmental considerations specific to any given nuclear site.

METHOD

All works were undertaken within a fully enclosed water jetting booth at the VLN Advanced Technologies Inc. works, making best use of their technical expertise and robotic control facilities. The fully enclosed booth (see Figure 5b) was fitted with a clamping turntable to support work with stainless steel 304 grade pipe sections.

Typical Parameters For FPWJ

There are many variables to consider in configuring a system for decontamination. These include:-

d: Water jet orifice diameter 0.04 to 0.065-in

H_p: Total hydraulic power: 46 to 84.6-hp

N_t: Rotational speed of the tube (pipe), RPM. (Only applicable to pipe samples)

P: Pump pressure: 8 to 15-kpsi

Q: Water flow rate: 5.1 to 11.60-usgpm

S_d: Standoff distance: 0.14 to 5.9-in

V_f: Feed rate of the nozzle, in/min

V_{tr}: 2.36 & 14.2-in/min (applicable to both pipe and plate samples.)

T: Relative position of the microtip (measured by turns): 1 to 4 (See Figure 4)

β: Angle of impact of the jet on to the surface (deg).

A short period of time (<2 seconds) is required to propagate and develop fully the pulsation effect as seen in Figure 1 that also shows the jet shape relative to a standard water jet at the same pressure and flow.

Defining Optimal Position – Drop Test

A robotic arm fitted with a water jet head configured for the desired parameters is moved across a test piece to determine the ideal stand off distance (S_d) and traversing speed (V_{tr}) as shown in Figures 1 & 2. This test provides a valuable example of the power of FPWJ but also how moderate variation in stand off (S_d) can affect performance. These tests are normally conducted with very slow traversing speeds (V_{tr}) to exaggerate the erosion effects to the naked eye. This test is repeated where there has been any change in the water jetting parameters, namely, pressure (P), flow (Q) or standoff (S_d).

Pipe Applications

Rotation of the sample is achieved using a turntable in place of a spinning jet head. The test piece is mounted vertically and clamped into position, see Figure 5. This allows for the robotic arm and water jetting head unit to traverse upward and downward according to a defined computer programme. This introduces new a parameter, jet traversing speed across the inner circumference of the pipe sample (N_t). This was calculated to 3,700-in/min at 50-RPM (turntable) for the chosen pipe diameter.

Figure 5 – a) Clamping arrangement and b) pipe section configuration.

Overlapping

Since the traverse speed (V_{tr}) of the nozzle downward (assuming start jetting at the top of the pipe) is quite slow compared to the peripheral speed of the pipe, overlapping occurs. The overlap factor is an indicator of the ratio of the traverse speed of the jet along the axis of the cylinder versus the rotational speed of the pipe. Assuming a water jet traverses a given distance (Lo) in one revolution of the pipe, and the width of the jet is dj, the overlapping factor can be quantified. In most respects this would be comparable to the dwell time or number of passes for conventional surface preparation water jetting.

Mass Loss

Using the same method for drop tests, small sections of metal were prepared to assess the mass loss following exposure to FPWJ. This becomes important when considering the concentration of metals and or particulates in any resultant effluent stream. A drop test sample piece was prepared into 21 off 0.5 x 1.0 in Sections that were weighed before and after using a conventional mass balance to offer an indication of loss. The operating conditions used are shown in Table I.

Table I – Test conditions for mass loss determinations.

Parameter	Condition A	Condition B	Condition C	Condition D	Condition E
P	10	15	8	11	15
V_{tr}	2.36	2.36	2.36	2.36	14.14
Q	7.90	9.67	9.86	11.57	9.67
H_p	46.06	84.62	46.04	74.22	84.62
T	1	1	2	2	1
D	0.055	0.055	0.065	0.065	0.055

Angle Of Incidence

As with traditional water jetting, the angle of incidence can have some impact on performance. A brief set of trials were undertaken to determine the susceptibility of FPWJ to such phenomena at 30° and 0° (perpendicular). Quantification of performance is the degree of mass loss in a manner similar to the above.

Cutting

To further demonstrate the power of the FPWJ technology, an arrangement similar to pipe sections was employed to restrain a gas cylinder. A computer programme was created to cut small sections from the cylinder without risk of ignition. Demonstration of this capability could also be applied to nuclear decommissioning.

RESULTS

Examples of the test runs are shown in Figure 6. The banding reflects the various test conditions employed, and when observed from a side profile, the extent of erosion can be clearly seen against the untreated interspacing sections.

Unlike other industrial applications, the residual surface finish is not of concern to the nuclear industry, rather radiological decontamination to support dose reduction activities or aid waste re-categorization for disposal. The surface roughness increases markedly with dwell time / exposure to the water jet.

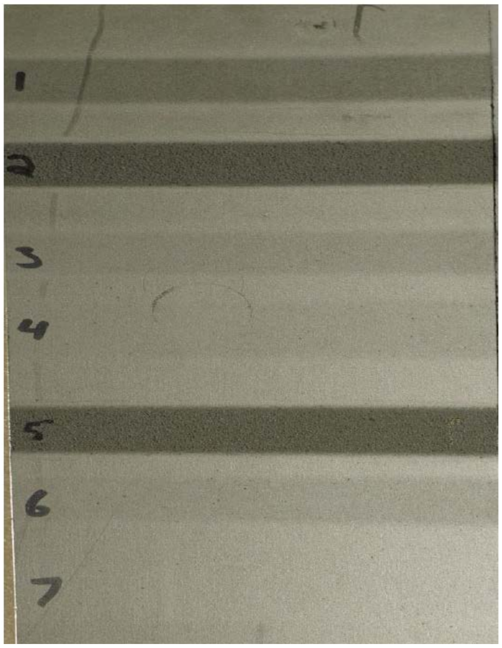

Figure 6 – Shows the banding effect from changing parameters, against a series of trial runs. Darker bands show greater degrees of erosion that correspond to more overlap (equivalent to jet dwell time).

Mass Loss

Mass loss determinations were made with a simple mass balance against the table of operating conditions listed in Table I (repeated below). Table II shows the mass loss per sample and the operating condition. Figure 7 illustrates this more clearly.

Table I – Operating conditions for mass loss determinations.

Parameter	Condition A	Condition B	Condition C	Condition D	Condition E
P	10	15	8	11	15
V_{tr}	2.36	2.36	2.36	2.36	14.14
Q	7.90	9.67	9.86	11.57	9.67
H_p	46.06	84.62	46.04	74.22	84.62
T	1	1	2	2	1
D	0.055	0.055	0.065	0.065	0.055

Table II – Actual mass loss of from each sample piece.

Sample	Standoff (S_d) inches	Mass Loss (g)				
		Condition A	Condition B	Condition C	Condition D	Condition E
21	0.14	0.00	0.00	0.00	0.00	0.00
20	0.43	0.27	0.00	0.22	0.00	0.00
19	0.72	0.67	0.00	0.31	0.02	0.00
18	1.01	0.79	0.25	0.65	1.19	0.00
17	1.30	0.79	0.91	0.60	1.17	0.00
16	1.58	0.69	1.76	0.37	1.15	0.01
15	1.87	0.51	1.63	0.15	1.09	0.26
14	2.16	0.27	1.52	0.03	1.07	0.63
13	2.45	0.07	1.42	0.01	0.75	0.53
12	2.74	0.00	1.21	0.00	0.62	0.46
11	3.02	0.00	1.02	0.00	0.37	0.17
10	3.31	0.00	0.83	0.00	0.09	0.04
9	3.60	0.00	0.47	0.00	0.02	0.00
8	3.89	0.00	0.19	0.00	0.00	0.00
7	4.18	0.00	0.04	0.00	0.00	0.00
6	4.46	0.00	0.00	0.00	0.00	0.00
5	4.75	0.00	0.00	0.00	0.00	0.00
4	5.04	0.00	0.00	0.00	0.00	0.00
3	5.33	0.00	0.00	0.00	0.00	0.00
2	5.62	0.00	0.00	0.00	0.00	0.00
1	5.90	0.00	0.00	0.00	0.00	0.00

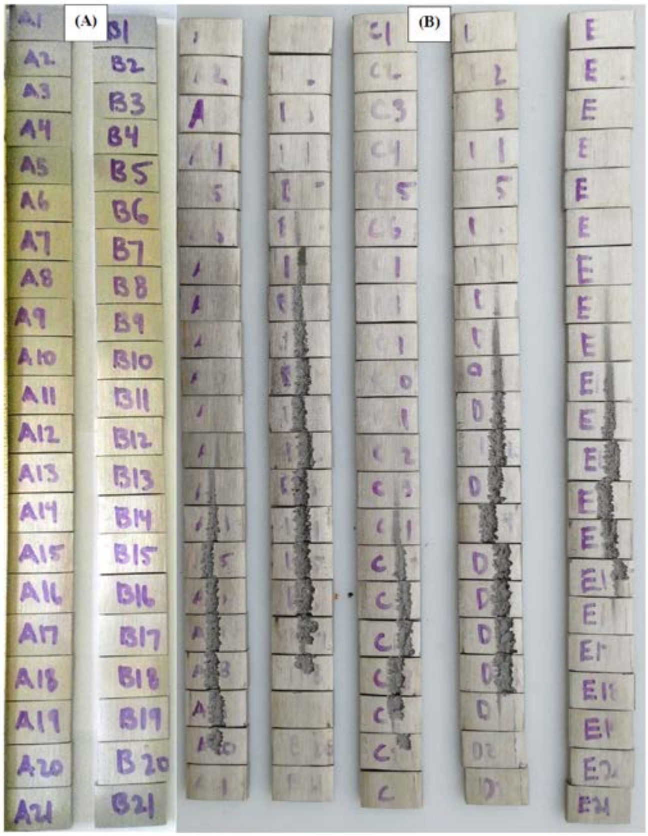

Figure 7 – Photograph of samples following drop test procedure for mass loss determinations. (A) before, (B) after.

Angle Of Incidence

The angle of the jet with respect to the target substrate as in traditional water jetting also has significant impact on performance as shown in Figure 8. The angle of incidence vs sample number is shown in Table III.

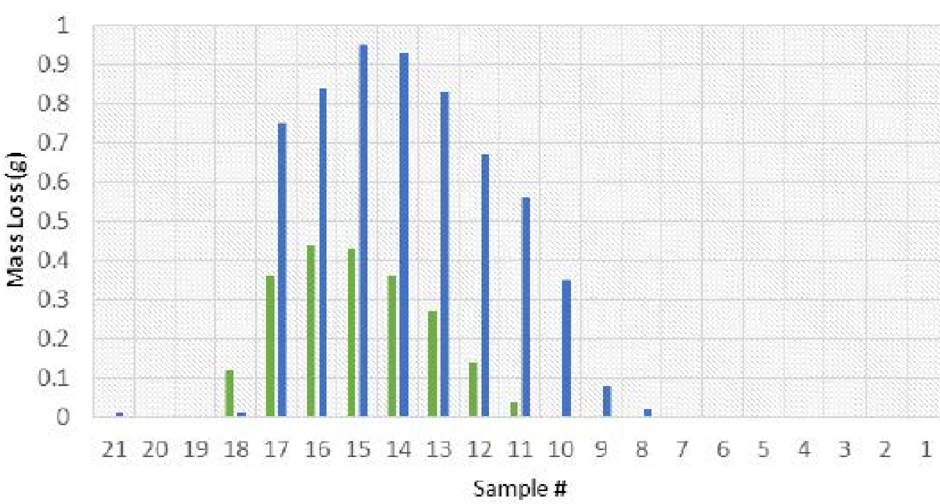

Figure 8 – Mass loss for angled and perpendicular jets.

Table III shows the mass loss (g) per sample piece at 0 & 30° angle of incidence.

Sample	Mass Loss (g) β = 30°	Mass Loss (g) β = 0°
21	0.00	0.01
20	0.00	0.00
19	0.00	0.00
18	0.12	0.01
17	0.36	0.75
16	0.44	0.84
15	0.43	0.95
14	0.36	0.93
13	0.27	0.83
12	0.14	0.67
11	0.04	0.56
10	0.00	0.35
9	0.00	0.08
8	0.00	0.02
7	0.00	0.00
6	0.00	0.00
5	0.00	0.00
4	0.00	0.00
3	0.00	0.00
2	0.00	0.00
1	0.00	0.00

Cutting

As a proof of concept or capability trial, a triangular section approximately 2.5 x 1.5 x 3in was cut from the cylinder using FPWJ. Operating conditions were P = 15kpsi at S_d = 3.25 and V_{tr} = 10 in/min. Edges of the cut section were rough as can be seen in Figure 9.

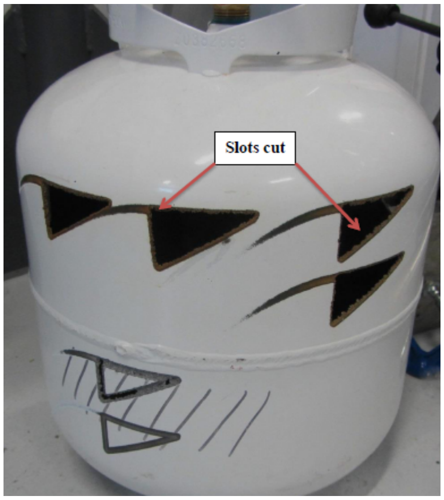

Figure 9 – Photograph of sections of cylinder selectively cut out using FPWJ.

DISCUSSION

Operating water jetting systems in nuclear facilities has many challenges. Any process that can make water jetting a more effective tool for a given pressure and flow rate, would be welcomed, if it can be shown to be deployable within a plant (*in-situ*). The opportunity to treat waste in a booth based system, as per VLN, creates opportunities for credible ILW waste re-categorization.

Larger pipe, duct and other simple geometry systems can therefore be treated where the assessment against other processes, such as (U)HPWJ, chemicals, abrasives etc permit, so called optioneering. As can be seen in Figures 7 & 9, many mm's of metal can be eroded from the path of the jet. Thus, very aggressive treatment of waste can be considered, for example highly active materials. In selecting or considering such options, there must be an acceptance of the higher effluent volumes to achieve >100 micron surface removal.

It can be assumed that the rate of erosion of metal from the test piece is linear if eroding a large area. The rate of mass loss can be determined from the experiments to further demonstrate the control of the process (see Table IV). When considering single channels or cuts as shown in the exaggerated droptests, other factors such as the accumulations of water in deeply eroded channels will interfere with the incoming water jet and thereby reduce performance. The resultant roughness of the metal may prevent further reuse of the pipework or surface due to the additional surface area and crevices etc to harbor contamination.

It should also be noted that the pulsation can be phased to allow for traversing speeds for a given depth of removal and offers a degree of assurance for plant management against breach of integrity for any given pipe / vessel.

Alternatively, the process may also be used to water jet cut metals in a safe manner, without risk of explosion e.g. gaseous atmospheres, as there are no sparks from abrasive materials to ignite such an atmosphere.

Table IV – Indicative mass loss rate against various operating parameters.

Sample	Standoff (S_d) inches	Mass Loss Rate (g/s)				
		Condition A	Condition B	Condition C	Condition D	Condition E
21	0.14	0.00	0.00	0.00	0.00	0.00
20	0.43	0.02	0.00	0.02	0.00	0.00
19	0.72	0.05	0.00	0.02	0.00	0.00
18	1.01	0.05	0.02	0.04	0.08	0.00
17	1.30	0.05	0.06	0.04	0.08	0.00
16	1.58	0.05	0.12	0.03	0.08	0.00
15	1.87	0.04	0.11	0.01	0.07	0.10
14	2.16	0.02	0.10	0.00	0.07	0.26
13	2.45	0.00	0.10	0.00	0.05	0.22
12	2.74	0.00	0.08	0.00	0.04	0.19
11	3.02	0.00	0.07	0.00	0.03	0.07
10	3.31	0.00	0.06	0.00	0.01	0.02
9	3.60	0.00	0.03	0.00	0.00	0.00
8	3.89	0.00	0.01	0.00	0.00	0.00
7	4.18	0.00	0.00	0.00	0.00	0.00
6	4.46	0.00	0.00	0.00	0.00	0.00
5	4.75	0.00	0.00	0.00	0.00	0.00
4	5.04	0.00	0.00	0.00	0.00	0.00
3	5.33	0.00	0.00	0.00	0.00	0.00
2	5.62	0.00	0.00	0.00	0.00	0.00
1	5.90	0.00	0.00	0.00	0.00	0.00

Given nuclear sites have a large inventory of pipe work of varying diameters, for the scope of FPWJ application to be wider; some fundamental design issues must be addressed. Outline works have shown such a system can be created in 8-in diameter pipes. However, with much of the process pipe work in a nuclear reprocessing facility using 4-in diameter or smaller, efforts to consider the re-shaping and flexibility of the system to maximize scope / field of use will require much more development. From the standoff – metal loss data reported in this paper, there will also be a compromise between performance and ability to insert a system into smaller pipe work systems.

Factors that would be considered include, rotating head systems, changes to the method of pulsation initiation and propagation, amongst others. It would therefore be helpful to consider the willingness of other nuclear sites to consider FPWJ as a decontamination method before investment in the process.

CONCLUSIONS

These early works examining FPWJ have shown that meaningful depths of metal can be erosively removed to an extent superior to equivalent High Pressure water jetting systems. In radiological terms, this represents a high probability of being able to remove contamination from the bulk of a metallic substrate, which could realize re-categorization from Highly Active to Low Level Waste thresholds. However, this will not work for activated materials. There must also be an acceptance of high liquid effluent volumes to achieve high depth erosion (i.e. decontamination). Furthermore, visual observation of the degraded surface following FPWJ, has been quantified using mass loss against a range of operating parameters.

Angle of incidence is also important in determining performance. A near perpendicular angle is needed to maximize efficiency of the FPWJ. Deviation by more 30° can give rise to significant reduction in performance.

The extent of erosion / removal of metal can be readily controlled in a manner similar to traditional water jetting, namely by pressure, flow, stand off, number of passes / dwell time and angle of incidence. The droptests have shown that sensitivities to standoff and to ensure a consistent degree of treatment, a robotically deployed system would demonstrate ALARP principles for conventional and radiological safety. The rough surface from heavily eroded FPWJ treated items is likely to prevent any re-use of the material hence; items treated with FPWJ are likely destined for disposal or recycle.

If a FPWJ is left static or has a low traversing speed (V_{tr}), it can also be used for cutting metals without abrasives in a timely manner. Without any abrasive material, there is no spark, hence can be considered for use in hazardous environments.

The technology has been shown inactively to be effective as a means of decontaminating metallic materials. If this is to be adapted for pipework or other small enclosed systems, a significant effort will be required to re-design of the jet head and pulsation system. With many kilometers of such pipework on a typical nuclear fuel reprocessing plant, the option for assured decontamination is worthy of further investigation.

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