The Development and Initial Testing of the Ice Pig Cleaning Method for Nuclear Reprocessing Plants – 15363

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ABSTRACT

There are numerous situations throughout the nuclear industry where it would be advantageous to clean out enclosed systems, e.g. ducts and pipes, to remove sediments and radioactive contamination. However, conventional flushing methods result in the production of significant volumes of contaminated liquor. The wall Shear achieved with water flushing is insufficient to remove and carry dense deposits often found in nuclear facilities. Conventional mechanical pigs can be propelled through the duct by application of a driving medium such as compressed air or water. These are able to achieve very high wall shears, but can also get physically stuck where there is variation in the pipe / duct diameter or small radius bends. The field of application is best suited to straight constant diameter systems with no discontinuities such as Tee pieces, valves and in-pipe instrumentation.

Driven by the desire to clean and displace radioactive materials from complex topology ducts and pipes, without the risk of having conventional pigs becoming lodged in a plant and coupled with the need to minimize effluent volumes, the UK Nuclear Industry led by Sellafield Limited (on behalf of the UK Nuclear Decommissioning Authority), has worked to demonstrate and underpin the use of the ice pigging technology for the nuclear industry.

It is found that high ice fraction slurries flow as viscous liquids that exhibit a number of mechanical properties that offer much higher shear rates. The 'Ice Pig' exerts shear rates on pipe walls which are typically 1000 times greater than those achieved with water flowing at the same velocity. The 'Ice Pig' is able to negotiate almost any topology, flow through pipe networks of vastly differing diameter, through heat exchangers and in-line instrumentation etc.

Experimental data and operational experience from other industries demonstrates that whilst there is high shear, the 'Ice Pig' does not damage the surface of the pipe wall. A further attractive characteristic of the 'Ice Pig' is that it eventually melts rendering it a simple effluent for processing by downstream processes.

Due to the special nature of ice slurry, its unique rheological and physical characteristics, together with the complementary underpinning experimental work undertaken by Sellafield Limited enables the Ice Pigging process to move from an 'interesting' technology to one suitable for use by the nuclear industry for operations, Post Operational Clean Out (POCO) and decommissioning.

INTRODUCTION

Cleaning manufacturing equipment is one of the basic activities undertaken in the process industry. Typical cleaning processes involve flushing material contained in the equipment out with water; these attempt to remove most of the 'soiling material'. This may be followed by further hot water washes or flushing with chemicals. These typical cleaning processes suffer from the so-called 'ratting' phenomenon, where the low viscosity water appears to find a low pressure drop hydraulic path through the material, leaving an annulus of waste adjacent to the pipe walls. In order to remove this annulus, the cleaning fluid has to be pumped at relatively high velocities (in an attempt to increase the shear at the wall), and for long periods of time (resulting in prolonged cleaning periods and large volumes of dilute effluent).

Pigging would alleviate much of this problem as it could potentially remove, by mechanical means, much of the material contained in the process equipment. Traditional pigging with piston-like objects works very well in straight pipe geometries or in geometries that have been constructed with pigging in mind at the design stage, but work badly in more demanding situations. For example, conventional pigs are not very good if there are many bends in the pipe work, and find it difficult to deal with contractions or expansions and impossible to address cleaning in heat exchangers and other complex process equipment (delivery nozzles, valves, metering devices and pumps). Pigging appears to offer much, but the mechanical rigidity of conventional pigs limits the application areas for the whole technology. This paper describes a simple yet elegant method in which thick ice slurries are used to act as an ice pigs.

fExperimental work has demonstrated that these slurries can behave as fluids, able to flow through orifice plates and around instruments. However, unlike simple fluids, these slurries do not have the propensity to rat through the material contained in the duct; rather the slurry tends to form a plug which snuggly fits the topology of the duct and pushes all the material in front of it in a similar manner to a piston. The ice pigging technology has now been demonstrated successfully in a number of industries. The work to date in the nuclear reprocessing sector indicates that it provide a potentially valuable technique enabling the removal of material from very ducts of complex topology using relatively small quantities of fluid. The work has also demonstrated other inherent benefits of the ‘ice pig’, such as it can never get stuck, it lends itself to easy integration with existing procedures and can easily be retrofitted into existing plant as an online and offline cleaning technology. The paper finishes with some imaginative extensions to the ‘simple’ ice pig, including ‘product pigs’ and ‘functional pigs’

BACKGROUND, DRIVERS AND THEORY FOR ICE PIGGING

Conventional Pigging and Innovative Ice Pigging

The hydrocarbon recovery industry was the first to recognize the need and the potential benefits of pigging (1). The original purpose of pigging was to allow a pipeline to operate as efficiently as possible. Using a pig to clean a line removes deposits that can restrict flow or contaminate product within the pipe. The oil industry quickly identified another use for the technology: product separation. Two fluids flowing within a pipe will tend to mix since the fluid flowing through the centre of the pipe travels faster than the fluid at the pipe wall. Using a pig to separate fluid flows helps to eliminate any mixing that might otherwise occur. This results in increased integrity of the product and less waste or further cost involved in treatment of the products.

However, the introduction of any solid body such as a conventional pig into a pipeline carries with a number of disadvantages and makes a number of pre-requisite demands on the pipelines and associated infrastructure. Firstly there is always the risk that the pig may get stuck or trapped, or that the pig may break up and contaminate the product in the pipe. Next, there is a need for complex pig launching and receiving stations. Lastly, the pipeline itself has to be fairly straight and of sufficiently constant diameter with no internal obstructions for the pig to pass easily along it. These difficulties are exacerbated in a nuclear reprocessing environment where there are many more bends, pipe diameter changes, monitoring equipment and valves per unit length of pipeline than in a typical oil pipeline. The current position is that pigs are not commonly used in the nuclear industry because of the complex nature of the pipelines and the unacceptable consequences of getting a pig stuck in a pipeline. However, increasing pressure is being brought to bear to reduce waste volumes and costs associated with processing and storage activities. Hence pigging systems are now being considered for such plants. Pigging would also look attractive if it could be applied retrospectively to existing plant with minimal demands of a launch and receive station, and if the technology could cope with the complex topologies found in reprocessing plants and could be guaranteed never to get stuck. The melted ice can then be collected in existing plant equipment. The ice pig is being specifically studied and developed to ensure that it can satisfy these nuclear reprocessing related needs.

Experimental and theoretical work (2, 3, 4, and 5) has shown that thick ice slurries have rheological properties which make them suitable for use as pigs; the slurries are able to flow through pipes with minimal mixing, pushing other fluids ahead of them and separating these fluids from fluids flowing behind them. Being a semi-solid, the slurry is able to flow (like a liquid) through small apertures, but when it can it tends to 'knit' itself together and move more like a solid plug. Although the thick ice slurry has a high effective viscosity, it tends to generate a lubricating film of liquid water at the wall surface; it does not adhere to the pipe wall and very little residual liquid is left on the pipe wall.

Experimental and Theoretical Underpinning for Ice Pigging

Solid pistons able to move smoothly in pipes of correct dimensions make good pigs and are able to separate product and recover materials within the pipe, however, it is difficult/impossible to maintain good mechanical seals between the piston and the ducts, if the topology of the duct changes along its length. Fluids are able to 'flow' and always fill the offered topology. They are able to maintain excellent contact with whatever topology they are made to flow in. However fluids may not make particularly good pigs because Newtonian fluids flowing in a pipe have flow distributions in which the fluid in the centre of the pipe travels faster than that near the pipe walls. This results in a spectrum of residence times for fluid traveling through a duct, the central fluid spends a lot less time than that closer to the walls. If two fluids are pumped through the same duct in sequence, the fluids will mix, irrespective of the flow regime, the fastest central fluid 'ratting' through the slower annular fluid layer. However, non-Newtonian fluids, exhibiting critical yield stresses (Bingham-like fluids), may be less prone to ratting; with most of the velocity gradients occurring near the walls, and the central region moving more like a plug. Experimental and theoretical studies (6) show that slurries exhibit non-Newtonian rheological properties. The effective viscosity appears to increase rapidly with particulate fraction.

Thus, given that fluids are able to fill any topology, but have the propensity to 'rat', and that pistons do not 'rat', but cannot provide hydraulic sealing in changing topologies, there appears to be a need for some hybrid, with the properties of both fluid and solid. The evidence suggests that this hybrid is likely to be a highly non-Newtonian fluid. A thick slurry, such as an Ice Pig may just fit the bill. For economic, environmental, safety and hygiene reasons, the slurry should be inexpensive, non-toxic, naturally occurring and be able to blend back into the environment in a seamless manner. The simplest and most appropriate slurry is that generated by freezing water into a high ice fraction homogeneous mixture of small ice crystals and cold water. This is essentially the 'ice pig'.

The Simple Ice Slurry Pig

The hydrodynamic complexity of slurries further increases if the system has memory or is changing with time due to physical or chemical reactions. An example from the natural world would be a moving glacier. The solids content may be so high, that the system behaves almost as a solid, however, it is still able to exhibit some of the properties associated with fluids partly as a result of shear strain relations and partly due to sacrificial melting-freezing. One of the attractive features of a glacier is that the glacier itself disappears into background water when it has finished doing its cleaning job.

Rather than using a water ice slurry mixture, work at Bristol University, UK, (Quarini(3) and Shire (6)) has demonstrated that an ice slurry containing a freezing point depressant, for example a salt has the desirable property of maintaining slurry-like properties for longer periods of time. The freezing point depressant is needed to slow down the tendency of the small ice crystals to weld together and form chunks of ice which would be difficult/impossible to pump through complex geometries.

Ice Pigs are measured by a parameter known as Ice Fraction. This is a calorific measure of the quantity of ice crystal in a given slurry and hence its relative viscosity. Ice Fraction can also be measured using light compression in a simple vessel, such as a cafetiere. This simpler and realtime measure is more often used. Previous study of calorific and ‘cafetiere’ shows a strong linear relationship, where calorific ice fraction is approximately 0.58 that of ‘cafetiere’.

Experimental work has demonstrated that to achieve piston or pig like characteristics the ice fraction has to be greater than say 40%. Below 30%, and the slurry appears to behave like Newtonian fluid with transport properties similar to those of water. It has also been found experimentally that it is difficult to handle ice slurries with ice fractions much greater than 90%. Indeed, at these ice fractions, the slurries tend to lock up and they can become very difficult, to push into the inlet ports of pumps; bridging and dewatering of the ice slurry occurs. As ice fraction is increased the wall shear observed increases rapidly, and by about 50% ice fraction, the shear is approximately one order of magnitude greater than that of water, Shire (7), as seen on Figure 1.

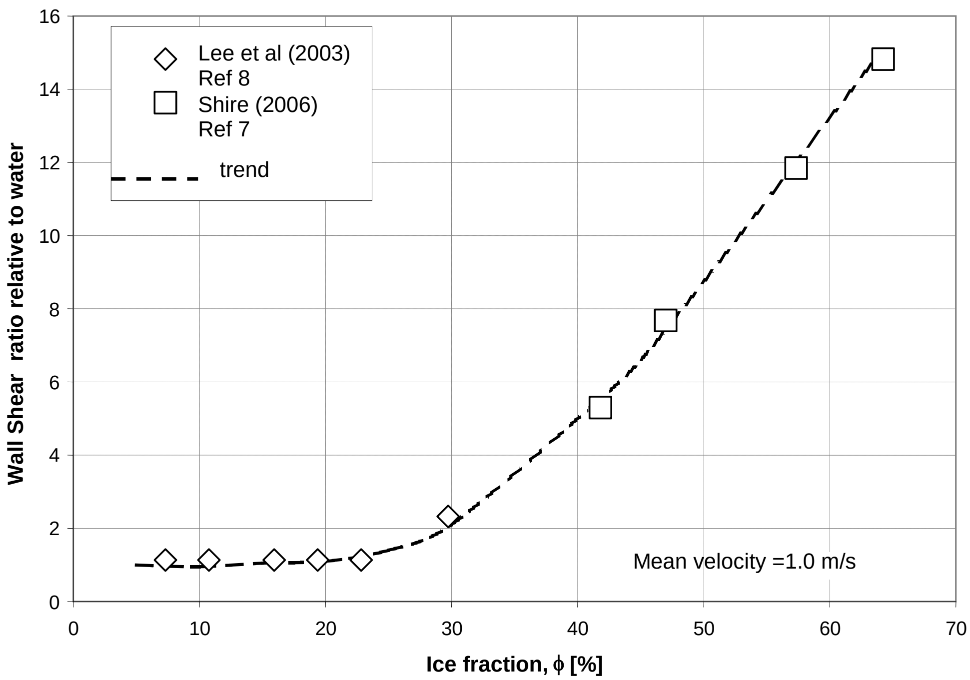


Figure 1. Normalised pressure gradient in 25mm diameter smooth pipe as a function of ice fraction, for a mean velocity of 1 m/s.

Experimental work (Quarini (3, 7)) has demonstrated that the ice slurries appear to be stable and hold themselves together for much longer than anticipated when pumped in ducts with fluids in front of and behind them. This stability is explained by the seminal work of Taylor (10), who examined the stability of the interface between two immiscible fluids in a duct. Essentially, Taylor pointed out that for immiscible fluids exposed to a driving pressure gradient within a duct, the interface between them could be expected to be stable (flat and well defined) or unstable (with break-through and penetrating ‘fingering’ flows), depending on the densities and viscosities of the fluids and on their relative position in the duct, as indicated in Figure 2. The underlying reasons for this are that the less dense fluids have higher acceleration than denser ones, and, the less viscous fluids move at higher velocities than more viscous ones, when exposed to the same driving pressure gradients. Continuity and incompressibility then ensure that the interface will be stable, provided the denser, more viscous material is behind the less dense and less viscous fluid. The opposite being true when the positions are reversed.

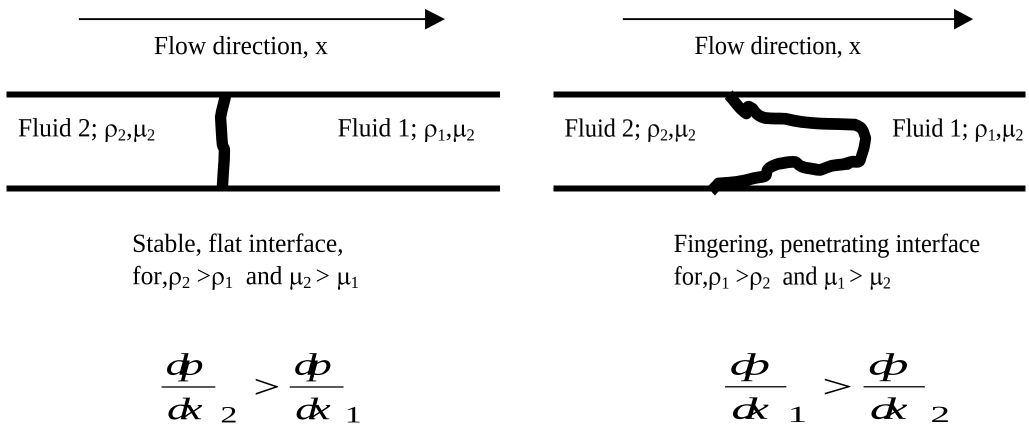


Figure 2. Sketch depicting the criteria for interface stability from Taylor (10).

Thus, provided that the upstream fluid is denser and more viscous than the downstream one, the interface between them is likely to remain well defined. In the case of an ice slurry separating two fluids, the situation is rather more complex.

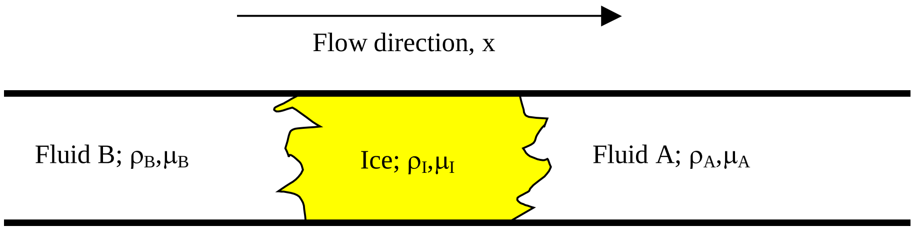


Figure 3. Ice pig, I, with fluid A in front and B behind

Most liquids encountered in the nuclear industry tend to have densities close to that of water and ice, hence there tends to be little difference in the density values of ρ_A, ρ_I and ρ_B, (see Figure 3 for nomenclature). However, the effective viscosities of these materials can be very different, and often are. It has been found (Shire(6)) that when ice slurries are used to separate liquids, the front of the ice slurry tends to become ill defined and mixing occurs with the downstream fluid, whilst the back of the ice slurry tends to remain well defined, with little mixing occurring with the upstream fluid. The explanation offered for this experimental finding is that as some of the ice melts, the water rich fluid (having a lower viscosity than the ice slurry) is accelerated to the front of the 'pig', where it mixes with the pig front and the downstream fluid producing the ill-defined front. Water rich material accelerating away from the body of the pig ensures that the pig remains firm (maintains a high ice fraction). If the upstream fluid has a lower viscosity than the pig, it will tend to be accelerated into the pig, however, the pig is at a relatively cold temperature, typically at –3 to –8 ºC, depending on the ice fraction and the freezing point depressant concentration. Such cold temperatures tend to freeze water rich fluids which attempt the go through the pig, thus maintaining a reasonably well defined interface between the back of the pig and the upstream fluid.

Demanding Topology

The great challenge cleaning out nuclear reprocessing ducts and associated processing units is the geometric complexity of the equipment. To illustrate both the ability of the ice pig to deal with complex topologies and its remarkable ability to ‘hold-together’ an experiment was undertaken in which the ice pig (white ice slurry) was pumped through a 3 inch diameter duct containing a static mixer, as shown in Figure 4 a, b and c. These three pictures show a time elapse sequence. The flow is from left to right in the one inch tube at the bottom of the pictures, the tube then goes through a 180 degree bend so that the flow is then from right to left, when the tube enters the 3 inch tube containing the static mixer. Whatever material is seen in the 1 inch diameter tube, will within 5 to 6 seconds find itself in the 3 inch tube. Hence in Figure 4a, the 1 inch tube is full of ice, this ice is seen to have almost completely filled the 3 inch tube, Figure 4b. At this point in time, the 1 inch tube has red water flowing in it, and this is seen to be displacing the ice in the 3 inch tube in the third picture, Figure 4c. Note, the interface between the back of the ice pig and the water is still sharp.

4a *4b* *4c*

Figure 4. Time lapse sequence of an ice pig passing through a 1inch diameter pipe 46a), entering the 3 inch diameter duct containing the static mixer, whilst water flows in the 1 inch pipe (4b), and, finally the ice pig half way down the 3 inch duct, negotiating the static mixer, whist still maintaining a sharp back interface with the water, (4c).

Another complex topology is the plate heat exchanger. The flow paths within these units are complex and simply impossible to pig these with traditional pigging systems. Within a laboratory environment a limited series of experiments have been undertaken on both a model plate exchanger unit and a real plate exchanger. Figure 5 shows a Tetra Plex C6-SR exchanger with 12 plates of dimensions 250 by 1000mm, (a type that might be found for pond water cooling systems) with an equivalent hydraulic diameter between the individual plates of 7mm, connected via stainless steel flexible hoses to ice slurry supply lines. The initial tests were undertaken with the primary aims of demonstrating that the ice pig could be made to flow through the unit and to obtain preliminary indicative pressure drop characteristics for the unit during ice pigging operations. Ainslie (12) has reported on a number of laboratory experiments in which ice pigging was used to clean plate and shell-and-tube heat exchanger geometries.

Figure 5. Ice pigging in a small industrial plate heat exchanger.

ICE PIGGING FOR NUCLEAR REPROCESSING

The ice pigging methodology is environmentally friendly and quite adaptable since it contains only water and a freezing point depressant. Common salt (sodium chloride) is often used as the freezing point depressant (FPD), but other substances can be used such as sucrose, glycerol, sorbitol, ethanol, glycol, or acetic acid. For the nuclear reprocessing sector, potassium nitrate is seen as a good FPD, as it is inexpensive, easily available in high purity, compatible with stainless steel and most importantly, it is easy to process within conventional nuclear reprocessing plant's routine operations. These features make ice pigging very attractive, especially when it is noted that one does not need to construct special ducts or special launch and receive stations, and when it appears to be easy to retrofit into existing plants with minimal modification. Over the recent years, Sellafield Limited has sponsored and undertaken work in the laboratory to develop an understanding of and to demonstrate the technology in environments within boundary conditions relevant to nuclear reprocessing.

One of the attractive characteristics associated with ice pigging is its ability to deal with complex topologies. One of the test loops (shown on Figure 6) in which the ice pig has been made to flow gives a good indication of the geometric complexity that the ice pig can deal with. The loop has 3 inch, 2 inch and 1 inch diameter pipes splits, orifice plates, tee pieces, valves and flexible hoses. The ice pig is able to negotiate all of these with no difficulty, displacing whatever fluid is in the pipework as it moves through the ducts. The ice pig is also able to displace, pick-up and transport sediments like sand out of the pipes.

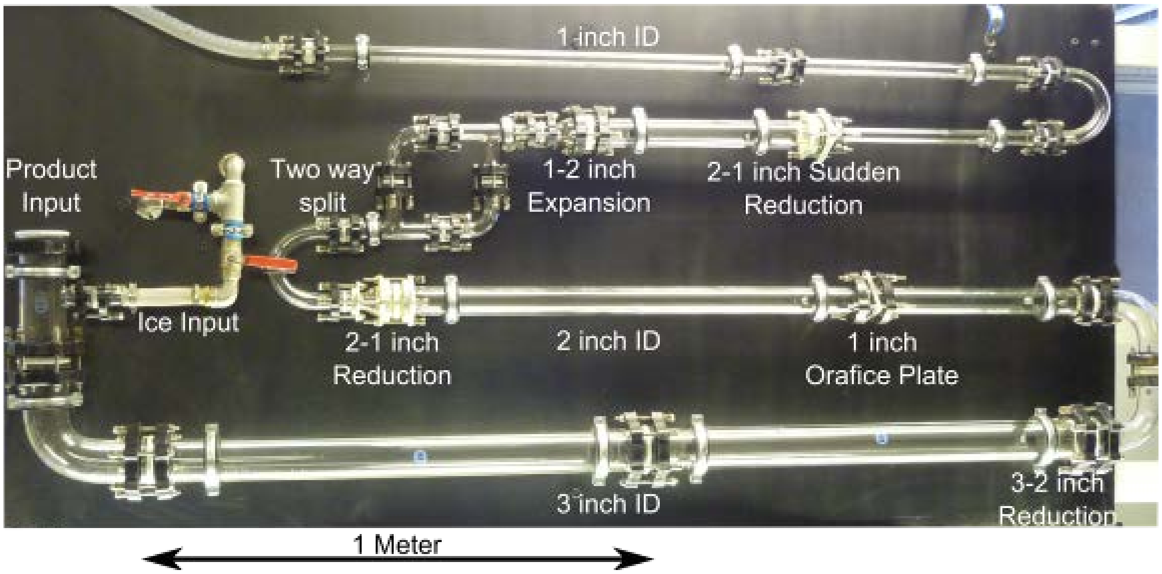


Figure 6 The experimental test rig used to demonstrate the ability of the ice pig to deal with complex topologies.

Work has been undertaken to study the removal and transport of loose sediments and debris from pipe work in the context of Post Operations Clean Out (POCO) and decommissioning activities. In a comprehensive series of test, the ice pig was used to clean out pipes containing loose sand (ordinary builder's sand with a mean sand particle size of 0.5 to 1 mm). The experiments were designed to establish whether the ice pig was firstly able to move the high density sand, and then to establish whether it was able to transport it away in a manner which was not going to cause downstream difficulties such as accumulation of sand at downstream flow restriction, simple bulldozing of mounds of sand in front of the leading edge of the ice pig, so called "bulldozer effect".

Other materials displaced and removed from ducts were metal shavings and swarf, as shown on figures 7. Irrespective of the indigenous swarf material (carbon steel, stainless steel and aluminum), the ice pig was able to gently remove all the material at a flow speed that water was unable to mobilize.

Figure 7a Aluminum Swarf

Figure 7b Carbon Steel Swarf

Trials have also been undertaken where a thick paste of magnesium oxide/hydroxide was allowed to dry on the inside of a pipe before attempting to remove it using water flushing and ice pigging. It was found that magnesium hydroxide which had been allowed to set for 12 hours simple could not be moved by water flushing, but that the ice pig removed it by montonically taking layers of hydroxide off the walls until the pipe was clean. The incremental way the hydroxide was taken off and transported away suggested that “bulldozing” would not be a problem for this material with ice slurries of ice fraction used in these trials. The white magnesium hydroxide slurry was coloured red to improve flow visualization of the ice pigging process.

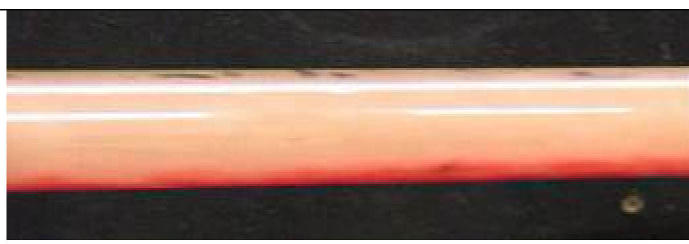
Time	
a) 30 sec.	
b) 35 sec.	
c) 40 sec.	

Figure 8 Ice pig removing fouling from within the test section. Videos of the ice cleaning show the beneficial behaviour of the ice pig more clearly; magnesium hydroxide slurry, now set to a weak grout-like material is taken off the wall in layers rather than bulldozed along. Water flushing had no discernible effects on the soft grout.

There are vastly different geometries and components used within the nuclear reprocessing sector which could benefit from the ice pigging technology. For example, work has been undertaken to study the performance of the ice pig in cleaning rust deposits from narrow high aspect ratio cavities where the availability and locations of possible inlets and outlets to and from the cavities are predefined or very limited. It has been found that in such geometries, typical model geometries being shown on Figures 9a and b, the ice pig does a better than expected job. The ice slurry rapidly spreads from the inlet port(s), quickly coving the whole of the channel flow area and then tends to move in a plug flow fashion until it reaches the outlet port. Limited experimental work has shown that it is capable of dislodging and transporting sediments and particulate from the bottom of narrow channels, even when the flow speed of the pig is very low (in the range of cm/s). The work has investigated how the performance of the ice pig varies with changing geometric scales and ice flow directions.

Figure 9a A small scale narrow cavity (nominally 120mm high, 400 long and 22mm thick)

Figure 9b A narrow cavity (nominally 600mm high, 2000mm long and 22mm thick). Both cavities have one adiabatic wall and the other wall kept at 40^0C. By changing the direction of flow of the ice pig the capability of the ice pig to remove debris and loose rust from the floor area was investigated.

The work briefly reported above provides confidence in the technology; specifically the work demonstrates that the ice pig can cope with the geometries encountered in nuclear reprocessing plants, it suggests that the technology could be used to remove quite dense waste materials for pipes and ducts. It could for example be used to flush out debris after maintenance operations where there is a risk that swarf and other materials might have unintentionally been left behind. The ice pig is also able to dislodge and remove wet grouts from ducts or minimize the volume of chemical used to dissolve cured grout, in a manner that is simply impossible to achieve with water flushing. Lastly, the work on the narrow cavity suggests that the ice pig is able to deal with much more demanding geometries than simple pipes and ducts.

ICE PIGGING IN OTHER INDUSTRY SECTORS

Over the past 8 years, ice pigging has progressed from successful laboratory trials into a viable commercial process capable of cleaning potable water trunk mains (Quarini (13)). After numerous laboratory trials and preliminary small scale trials on disused water pipes, a large scale (10 te) refrigeration/ice maker and a specific delivery unit has been used on live water feed lines (see Figure 10).

Figure 10 The ice-pig delivery lorry ready to undertake a live trial

DISCUSSIONS

The use of thick ice slurries to pig pipelines has been successfully tested and proven in specific laboratory and factory and field trials. The technique is currently being used commercially in for example, the water industry where well over 1000km of trunk water mains have already been cleaned using ice pigging, throughout the world. The success of the technology has led to keen interest from other potential users. These vary from the hydrocarbon recovery industry (14), through personal hygiene product manufacturers, to paint producers and power station operators.

The potential for this technology within specific parts of the nuclear reprocessing sector is promising. The work reported here clearly indicates there will be a role for this technology in nuclear reprocessing in helping to reduce effluent production and associated costs. There may also be a role for the technology to assist in plant life extension and equipment performance enhancement. The timescales for the adoption of this technology are unclear but will be derived from active plant trials.

Further benefits can be gained by the development of ice pigging based on liquors containing freezing point depressants that serve dual purposes: providing the standard freezing point depression effect, required to slow down Oswald ripening (the agglomerative effects on ice crystals over time), plus other desirable functional effects, such as the ability to chemical dissolve fouling deposits. This would mean that the pig would not only mechanically remove loose materials, but was also able to chemically break down strong physical bonds between the fouling material and the duct wall, making it easier for the ice pig to mechanically transport the bulk material away. Lastly, the technology offers the potential of delivering concentrated solutions to specific points in the plant by either combining the solution into the pig as the freezing point depressant, or by trapping the solution between two conventional ice pigs. In both cases the pigs would be pumped to the appropriate point in the plant where they would deliver their 'magic bullet' effects. This might enable plant operators to use very high concentrations of active ingredient, in the knowledge that when/if the ingredient is mixed with the rest of the plant inventory, the concentration will remain within acceptable operating levels.

CONCLUSIONS

Ice pigging, as a pumpable ice slurry, offers many desirable advantages. These include the potential to removal of loose particulates from within complex topologies, with minimal retrofitting requirements. This technology has the immediate knock on effects of reducing effluent production, with a guarantee that the pig will never get stuck. The successful implementation of this technology will reduce the time required for cleaning operations, increase plant availability and make previously unviable or undoable cleaning/decommissioning operations possible.

The technology offers more than simply a versatile pigging system, it potentially offers a paradigm shift in the way nuclear sites operate and decommission their plant. The successful development and implementation of 'functional' pigs and of 'delivery' or 'magic bullet' pigs opens up new ways of operating existing plant and equipment in safer manner, whilst improving performance and reducing the environmental impact of doing so.

Experimental data indicates that the ice pigging result in wall shears 100 to 1000 times higher than those expected with comparable water flushing, suggesting that the technique will be a very desirable. There is simply no doubt that ice pigging can and will reduce the volume of effluent produced in reprocessing operations with corresponding beneficial consequences (small storage tanks and reduced inventory volumes).

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