Maintenance Free Fluidic Transfer and Mixing Devices for Highly Radioactive Applications — Design, Development, Deployment and Operational Experience

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ABSTRACT

Power Fluidics is the generic name for a range of maintenance-free fluid transfer and mixing devices, capable of handling a wide range of highly radioactive fluids, jointly developed by British Nuclear Group, its US-based subsidiary BNG America, and AEA Technology.

Power Fluidic devices include Reverse Flow Diverters (RFDs), Vacuum Operated Slug Lifts (VOSLs), and Air Lifts, all of which have an excellent proven record for pumping radioactive liquids and sludges. Variants of the RFD, termed Pulse Jet Mixers (PJMs) are used to agitate and mix tank contents, where maintenance-free equipment is desirable, and where a high degree of homogenization is necessary.

The equipment is designed around the common principle of using compressed air to provide the motive force to transfer liquids and sludges. These devices have no moving parts in contact with the radioactive medium and therefore require no maintenance in radioactive areas of processing plants. Once commissioned, Power Fluidic equipment has been demonstrated to operate for the life of the facility. Over 800 fluidic devices continue to operate safely and reliably in British Nuclear Group’s nuclear facilities at the Sellafield site in the United Kingdom, and some of these have done so for almost 40 years. More than 400 devices are being supplied by AEA Technology and BNG America for the Waste Treatment Plant (WTP) at the Hanford Site in southeastern Washington State, USA.

This paper discusses:

- Principles of operation of fluidic pumps and mixers.
- Selection criteria and design of fluidic pumps and mixers.
- Operational experience of fluidics pumps and mixers in the United Kingdom.
- Applications of fluidic pumps and mixers at the U.S. Department of Energy nuclear sites.

INTRODUCTION

Power Fluidics is the generic name given to the technology involved in pumping, in-tank agitation, and flow control of radioactive process fluids, by means of specially designed devices that use compressed air as the motive force and have no moving or electrical parts in contact with, or close to, the radioactive material. Power Fluidics technology was initially developed by the aerospace industry in the 1960s as a way of replacing unreliable mechanical components, but was then overtaken in that industry by the rapid advent of solid state electronics.

British Nuclear Group, its parent company British Nuclear Fuels (BNFL), and partner AEA Technology (AEAT) recognized the potential uses of Power Fluidics in British Nuclear Group’s nuclear processing plants at the Sellafield site in northwest England. In conjunction with Sheffield and Cardiff Universities and several U.K. engineering companies, British Nuclear Group and AEAT developed systems for the transfer and mixing of fluids that used no moving parts and thus required no maintenance.

The use of Power Fluidic devices is consistent with British Nuclear Group’s extensive employment of “dark cells” for its radioactive plants, whenever this is practicable. A dark cell is a concrete shielded and sealed enclosure in which the installed process equipment requires no maintenance through the life of the plant. There is no expectation of man-entry to a dark cell during the life of the plant, and neither is there any need for such entry. In the unlikely event of a leak or malfunction, secondary containment of radioactivity is provided by the stainless steel lining of the cell, together with a low point sump equipped with level monitoring, sampling systems and pumps. Cameras and remotely operated equipment can be introduced into the cell via roof hatches if this becomes essential. The dark cell arrangement can be contrasted with the “canyon” system developed for US radioactive plant, where process plant is remotely accessible and dismantle-able behind the concrete shielding via overhead cranes and removable “jumpers” are used to connect vessels and pipes to allow their removal for maintenance. More details of the design principles of dark cell are given elsewhere.[1]

Fluidic devices include: Reverse Flow Diverters (RFDs), Double-Diode Pumps, Pulse Jet Mixers (PJMs), Air Lifts, Vacuum Operated Slug lifts (VOSLs), Steam, Water & Air Ejectors, Vortex Scrubbers, Vortex Strippers, Vortex Amplifiers and Vortex Mixers. All of these devices have been employed in Sellafield plants, with some in continuous use since the early 1960s. In total there are now over 800 such devices in successful routine use. These devices have no moving parts, no seals that would require routine adjustment and replacement and all are fully compatible with a wide range of aggressive fluids.

There was a major program of additions to the Sellafield site facilities from the late 1970s through the late 1990s, when some 20 first-of-a-kind irradiated fuel and nuclear waste processing and cleanup facilities were designed, constructed, commissioned and put into routine operation. For these new facilities, British Nuclear Group worked with AEAT to develop new, more sophisticated, fluidic pumps, agitators and control systems. This work resulted in the installation and successful use of over 430 PJMs and RFDs at Sellafield. Experience with the use of these devices has shown that plant lifetime operational costs are significantly reduced in comparison with their mechanical equivalents through:

- Eliminating replacement costs of failed components, and thus reducing secondary wastes.
- Eliminating routine maintenance and the associated workforce radiation exposure.

Sellafield experience has shown that, once commissioned, Power Fluidic equipment in the dark cells operates reliably for the life of the plant, in a safe and stable manner with minimal operator intervention. Materials of construction, system modeling prior to design and fabrication, and dynamic testing at works, insure satisfactory operation for the transfer and homogenization of a wide range of fluids, with challenging chemical, radiological, and physical properties. Much has been learned about the performance of fluidic devices in recent years, both experimentally, and by studying their performance in radioactive (hot) service. Proprietary computer models have been developed and verified against the performance of actual pumps in operation. These models simulate plant physical conditions, and take account of fluid physical properties to predict system performance.

This successful experience has enabled BNG America (British Nuclear Group’s US-based subsidiary), in conjunction with AEAT, to introduce Power Fluidic devices to several waste treatment plants in the USA. This includes the Waste Treatment Plant (WTP) at Hanford where AEAT and BNG America have a contract with Bechtel National Inc (BNI), the prime contractor, for the design, supply and pre-installation performance testing of over 400 fluidic components for the PJMs and RFD pumps. It also includes the Phase I design for the Salt Waste Treatment Plant at the Savannah River site.

This paper explains the design principles and operational characteristics of RFDs, PJMs, Double-Diode Pumps, Air lifts and VOSLs, presents selection and design criteria, describes operational experience and discusses specific applications, including those in WTP.

NOMENCLATURE

AEAT	AEA Technology Inc
BNFL	British Nuclear Fuels plc, parent company of British Nuclear Group
BNFL Inc.	US subsidiary of BNFL (now renamed BNG America)
BNG America	British Nuclear Group’s US-based subsidiary
BNI	Bechtel National Inc
DOE	US Department of Energy
DIODAS	Diode Pump Design and Simulation
EARP	Enhanced Actinide Recovery Plant at Sellafield
Floc	Flocculent
FLUMP	Fluidic Pump simulation model
gpm	US gallons per minute
HALES	Highly Active Liquid Evaporation and Storage plant at Sellafield
JPP	Jet Pump Pair
MAC	Medium Active (evaporator) Concentrate
PJM	Pulse Jet Mixer
RFD	Reverse Flow Diverter
SARDAS	Single Acting RFD Design and Simulation
STP	Solvent Treatment Plant at Sellafield
SEC	Salt Evaporator Concentrate
Thorp	Thermal Oxide Reprocessing Plant at Sellafield
VOSL	Vacuum Operated Slug Lift
WEP	Waste Encapsulation Plants (grouting of irradiated fuel hulls) at Sellafield
WPEP	Waste Packaging and Encapsulation Plant (grouting of ferric floc from EARP)
WTP	Waste Treatment Plant at Hanford
WVP	Windscale Vitrification Plant (Lines 1,2 and 3) at Sellafield

PRINCIPLES OF POWER FLUIDIC DEVICES

The Reverse Flow Diverter

The general arrangement of the Reverse Flow diverter (RFD) and Pulse Jet Mixer (PJM) installation in a typical tank is shown in Figure 1. The RFD element is a chamber, submerged into the tank liquid with two opposing nozzles set into it, and with an opening to the tank liquid at the bottom. This element is connected on one side to the liquid discharge pipework and on the other to the Charge Vessel. The Charge Vessel is connected to the Primary Controller Jet Pump Pair (JPP) located inside the dark cell, and the JPP is in turn connected to a compressed air supply via the Secondary Controller solenoid valves located outside the cell in a shielded “bulge” (and thus accessible for maintenance). A barometric head between the maximum liquid level in the vessel and the Primary Controller insures that radioactivity cannot reach the Secondary Controller located outside the cell.

Operation of the pump is cyclic, and the flow of liquid from the pump is therefore not continuous. This may be overcome with the use of multiple RFDs operating in sequence, or by creating a liquid hold-up in a breakpot. There are three phases in the pump cycle; suction, drive, and vent.

Suction

A Secondary Controller solenoid valve is opened by an electronic controller to admit compressed air to the Suction Jet Pump in the JPP. This draws air through the Drive Jet Pump from the Charge Vessel, and the Charge Vessel thus draws tank liquid in through the RFD element.

Drive

When the charge vessel is full the first solenoid valve shuts and a second one opens, this time to admit compressed air to the Drive Jet Pump. The air pressurizes the Charge Vessel and drives the liquid out of it to the RFD element. Because of the geometry of the opposing nozzles in this element, the liquid does not return to the tank but instead flows via the discharge nozzle to the receipt vessel. The fast-moving jet of liquid also entrains further liquid from the tank.

Vent

The second solenoid valve is closed, and the system reaches equilibrium as air in the charge vessel passes back through the Drive Jet Pump, and vents via the Suction Jet Pump into the active ventilation extract system. The system is then ready for the next cycle. The duration of a pumping cycle varies with pump geometry, and is typically between 20 and 100 seconds.

The Double Diode Pump

The Double Diode Pump is a variation on the RFD, in which the RFD element is replaced by two vortex diodes. Vortex diodes are circular chambers with one tangential and one axial liquid port. Because of the rotation of the liquid within the chamber caused by liquid movement into the tangential port, these devices have a resistance to liquid flow that is some 10 times higher in one direction than the other. They thus act as slightly leaky one-way valves. In the Double Diode Pump the Charge Vessel and the two vortex diodes therefore operate in the same way as in a standard force lift pump, but without the mechanical valves, piston or piston seals needed by the latter.

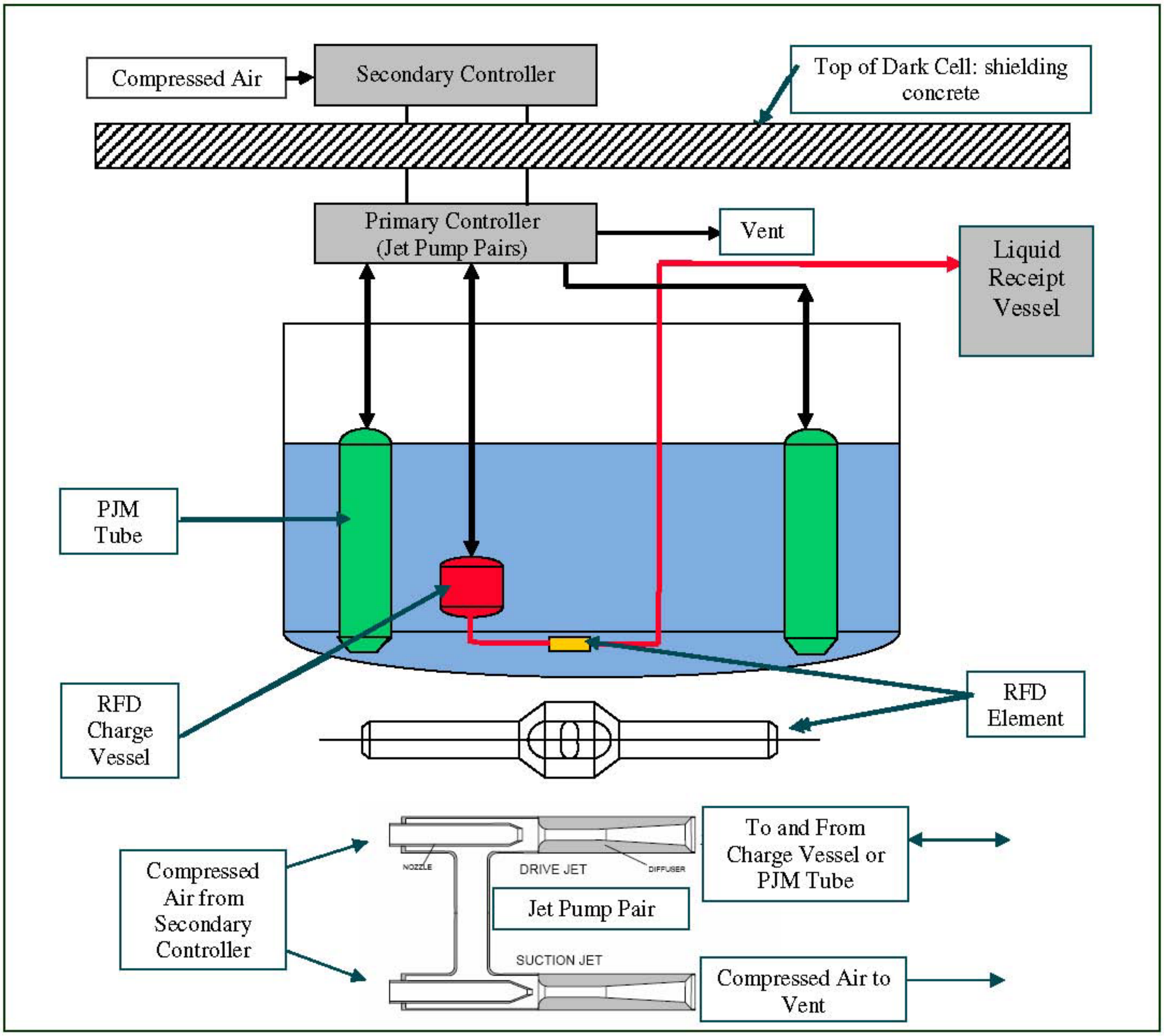

Fig.1. Schematic of an RFD pump and pulse jet mixer tubes

The Pulse Jet Mixer

The Pulse Jet Mixer (PJM), also shown in Figure 1, operates in a similar way to the RFD pump. A PJM tube replaces the RFD Charge Vessel and liquid is drawn into this tube and expelled from it by the same actuation of the JPP that was described for the RFD pump. In this case however, the liquid is driven out of the pulse jet mixer tube via a nozzle towards the base of the tank. By suitable nozzle design and placement of the tubes around the circumference of the tank, and in the center for larger diameter tanks, efficient scouring of the tank bottom and mixing of the tank liquid can be achieved. Variations that can be used include allowing the liquid to exit the tubes by gravity (for pulse jet tubes that extend above the maximum liquid level in the tanks), and allowing the tubes to fill by gravity (if they are fully immersed).

A typical installation arrangement of PJM tubes and RFD pumps within a radioactive liquid tank is shown in Figure 2. The combined PJM Tubes typically displace a volume equivalent to 5-10% of the total tank volume, depending on the intensity of mixing required and the density of the liquid or slurry. The PJM Tubes can be “fired” in sequence or simultaneously, depending on the agitation action required. Simultaneous firing provides very effective agitation that is especially suitable for non-newtonian slurries, but the resulting pressure pulses as the exhausted air enters the ventilation and filtration system require careful design of the ventilation system. Pulsed Jet Mixers are used in nuclear facilities to:

- maintain solids in suspension.
- re-suspend solids that have been allowed to settle.
- homogenize liquids and slurries prior to sampling operations and analysis.
- blend different materials within a tank.
- provide contact between reagents or process fluids to promote reaction.

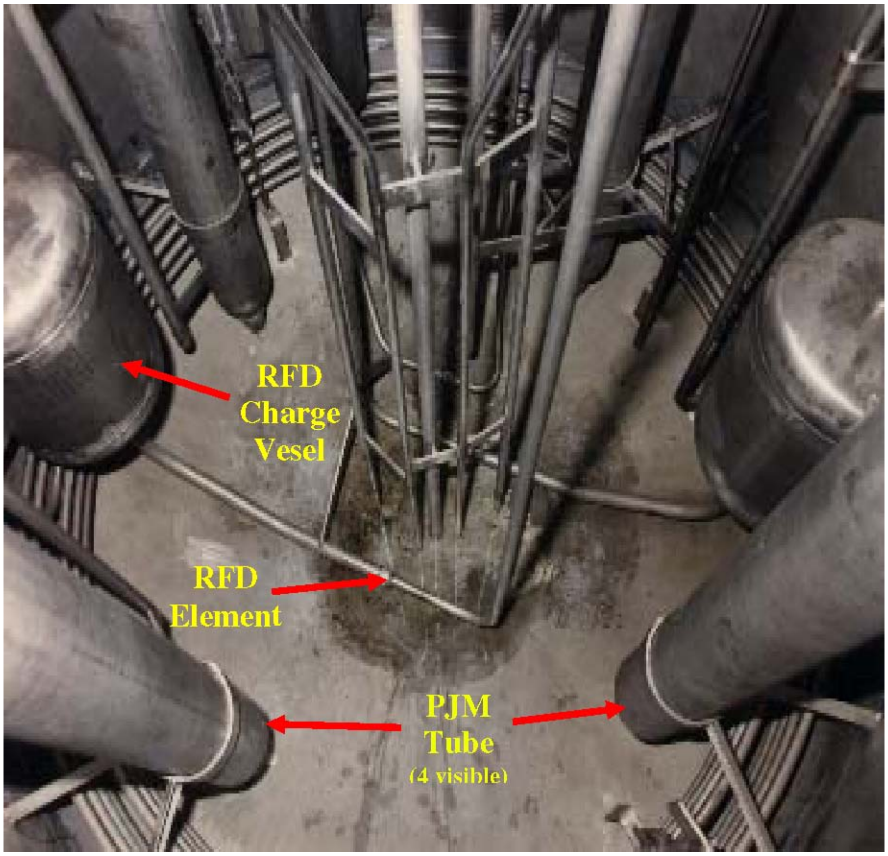

Fig.2. Arrangement of PJM tubes and RFD pumps within a process vessel

Unlike mechanical mixers, PJMs still operate efficiently with low liquid levels in the tank thus providing more versatility during facility operations.

RFD and PJM Control Systems

For proper control of RFDs and PJMs it is necessary to actuate the solenoid valves in the Secondary Controller when the Charge Vessel or PJM Tubes are full following the suction cycle, and when the liquid is near to the bottom of these vessels following the drive cycle. Overblow during the drive cycle and “oversuck” during the suction cycle will not cause any radioactivity to exit the primary containment or the dark cell and so are both safe. However, they will mix air with radioactive liquid thus causing radioactive aerosols that may challenge the ventilation filtration system and so are undesirable.

The necessary control can be achieved by simple timers that are calibrated during commissioning and this is often the most straightforward approach for pumping liquids that do not vary greatly in density. However, such timers have to be calibrated for the lowest possible tank level for the drive cycle and the highest possible level for the suction cycle and thus can potentially lead to some reduction in pumping capacity. AEAT therefore developed for British Nuclear Group a more sophisticated sensing system, PRESCON™, which determines when the charge vessel and PJM tubes are empty and full and hence sets the datum points for each cycle. It accomplishes this by analyzing the pressure signals from the compressed airline and so is totally non-intrusive. The controller automatically compensates for variations in the system (e.g. changes in tank liquid level and specific gravity) and so maintains the fluidic system operation at optimum efficiency. In addition, the enhanced software monitors process loops, checking for drift of pressure transducers, integrity of signal loops and other inputs and provides a continuous health check on the system. The PRESCON™ control system can be installed as a standalone device for each fluidic system, or can be incorporated as software into the overall control and monitoring system for the facility, such a the Distributed Control System used on many Sellafield facilities.

The Air Lift

Air lifts have been used for many years both in the nuclear industry and in the general process industries. They are of simple construction and operation, have no moving parts in contact with the process fluid and do not cause dilution or heating of the liquid as do steam ejectors. Airlifts consist of a riser pipe leading from the supply vessel to a disentrainment vessel at a higher elevation within the dark cell (Figure 3).

Compressed air is injected continuously at the base of the riser via a simple tee piece. This effectively reduces the fluid density within the riser. The level of aerated fluid rises in order to restore the hydrostatic head balance between the liquid in the supply vessel and in the riser. Transfer of fluid occurs when the two-phase flow enters the disentrainment vessel.

Operation of the Airlift

Initially, the airline is flooded to the same level as the fluid in the supply vessel and riser. A low flow rate of air is admitted to the airline, which displaces the fluid. Air begins to enter the riser at the air injection point and normally displaces a small amount of fluid towards the supply vessel. This effect is known as “blow back” and always occurs at start up. As the airflow increases, the two-phase mixture changes from “bubble” to “slug” to “churn”, and finally to “annular” flow, where air occupies completely the center of the pipe, with the fluid forming an annulus around it against the pipe walls. The liquid flow increases progressively with airflow until “churn flow” is established at which point a continuous delivery of fluid is achieved. Raising the air flow-rate further, into the annular flow region, results in a decrease in liquid flow rate. Air supply for the airlift is provided from a cabinet outside the dark cell which incorporates pressure and flow control equipment.

The sizing of pipework associated with Airlifts is a specialist function and will depend on the facility arrangement and the supply vessel dimensions and position in relation to the discharge elevation. Although air lifts are well known devices, British Nuclear Group found that little hard design data was available to enable pipework to be sized, airflows calculated, disentrainment vessels to be designed and minimum blowback lengths to be determined, the latter enabling the required lute depth below the supply vessel to be calculated. Because of this, British Nuclear Group worked with AEAT to design and build an Air Lift Test Facility with riser diameters from 15mm (0.5 inch) to 80mm (3 inch) and total riser heights up to 35m (115 ft). Operation of this Facility produced a systematic set of design criteria and rules for air lifts. This work showed that, although liquid lift heights up to 25m (82 ft) were possible with liquid densities of 1 gm/cm^3, this could achieved only with excessive air flows, and that the normal lift height limit was about 12m (40ft). It was also found from this work that, given a constant submergence of the air injection point, which can be arranged with a constant head vessel fed by an RFD pump, an air lift is an excellent metering device, providing a precise relationship between air injected and liquid flow achieved. They are thus useful where precise flow control is required but conventional control valves are unsuitable because of their need for maintenance, and where alternatives such as Constant Volume Feeders are unsuitable because their bulk liquid holdup is unacceptable for criticality reasons.

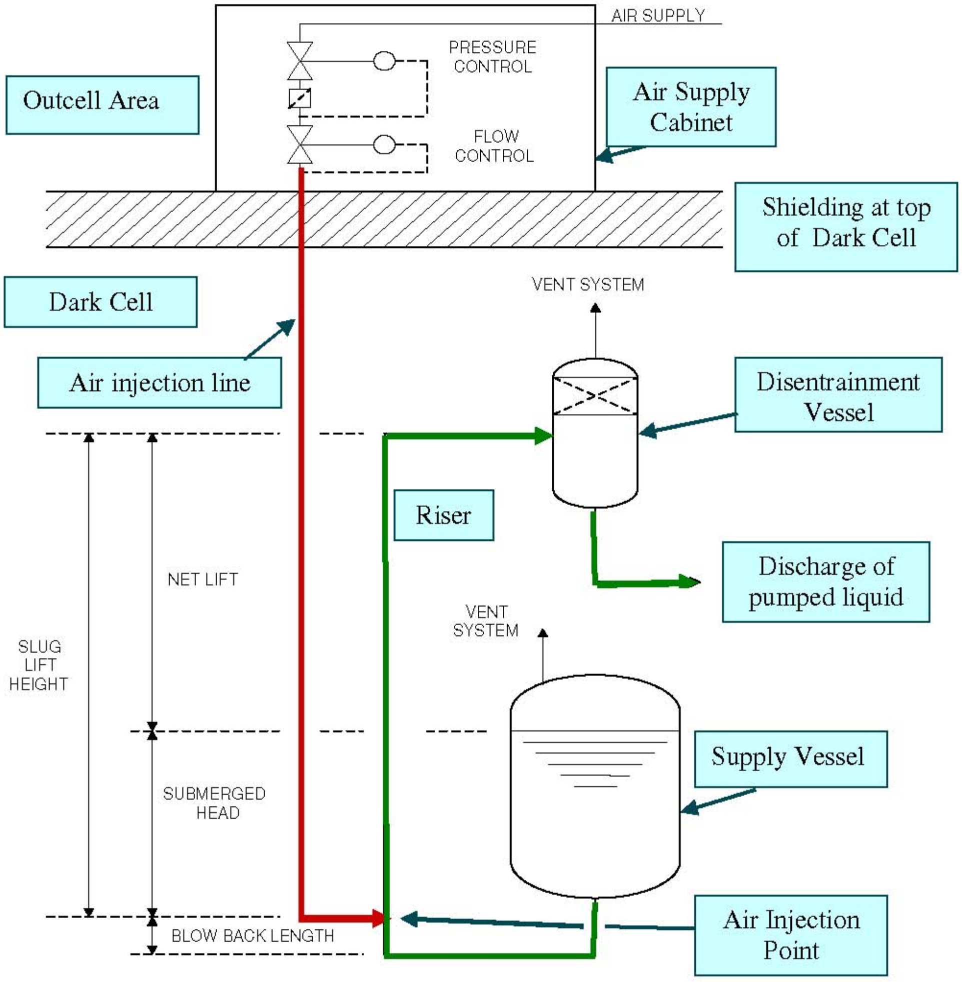

Fig.3. Schematic of an Air Lift

The Vacuum Operated Slug Lift (VOSL)

The Vacuum Operated Slug Lift is effectively a vacuum-assisted air lift. A vacuum is applied to the disentrainment vessel and this produces an increased submergence of the air injection point, producing a higher liquid flow for a given air flow, and also allowing the lute below the supply vessel to be eliminated. However, the Disentrainment Vessel outlet does of course require a vacuum seal lute and this reduces the achievable lift height to some extent. Nevertheless, a VOSL can routinely lift liquid to heights up to 20m (66ft), with a maximum lifts achievable of approximately 25m (82ft). The application of vacuum to the liquid being pumped does however limit its maximum temperature to about 15°C (27°F) below its boiling point.

The Constant Volume Feeder

Although not a fluidic device, the Constant Volume Feeder is often considered as a potential alternative liquid pumping and metering device and is described here for completeness. A Constant Volume Feeder consists of a rotating disk, mounted on a hollow shaft with open liquid containers around its circumference. It is mounted so that as it rotates it dips into a reservoir of the liquid being pumped, filling the containers which then discharge into the hollow shaft as the disk continues to turn. The rotational driveshaft normally passes through the dark cell wall so that the drive motor is mounted outcell and accessible for maintenance. Although not capable of high pumping heads, constant volume feeders provide precise metering of liquid flows and are a good alternative to conventional control valves which require in-cell maintenance. For nuclear plants they have the disadvantage of requiring a large liquid reservoir which cannot be made critically eversafe and are therefore not considered further in this paper.

SELECTION CRITERIA AND DESIGN OF FLUID TRANSFER SYSTEMS

Liquid Pumping

For a typical nuclear facility handling radioactive liquids and slurries, liquid pumping can be achieved by conventional centrifugal pumps, fluidic RFDs or double diode pumps, Air Lifts ands VOSLs.

A comparison of the advantages and disadvantages of these fluid transfer devices for nuclear processing plants is shown in Table I. In selecting a transfer device for a particular application it is necessary to consider the flow rate, suction and discharge heads that are required and the type of maintenance that is possible. For medium to highly active pumping duties with moderate suction and discharge requirements, an RFD or double diode pump is usually preferred, and experience at Sellafield has shown that such pumps provide the lowest lifecycle costs because of the elimination of maintenance. For specialist metering pump duties, where a constant submergence can be provided and only low flow rates are required, Air Lifts and VOSLs are highly effective. They show the same lifecycle savings as do RFDs, and are very simple to design and install.

Table I. Comparison of Liquid Pumping Systems for Use in Radioactive Plants

	RFD	Double diode Pump	Air lift	VOSL	Centrifugal Pump
General Advantages	•Reliable & well proven in nuclear industry •No in-cell maintenance. •Capable of large single stage lift •No process liquid dilution or heating •Capable of handling fluids with high solids content	•As for RFDs •Can be installed outside tank •Capable of complete emptying of tank •Single stage lift can exceed that of an RFD •Overblow less troublesome if pump outside tank •Lower air consumption	•Reliable & well proven •Simple design & operation •No in-cell maintenance •No process liquor dilution or heating •Good liquid metering capabilities •No large volume vessels so critically eversafe	•As for Air Lifts •Does not require a lute below feed vessel, potential for blockage reduced •Can pump direct from inside feed vessel •Increased liquid flow for given air flow •Minimum penetrations into tank	•Reliable and well proven in general industry •Commercially available •Simple control system •Wide range of flow-rates and pressures available. •Can pump slurries

Table I. Comparison of Liquid Pumping Systems for Use in Radioactive Plants (continued)

General Dis-advantages	• Control system needed to prevent over blow • Air cons’n ~20 times the volume of fluid pumped • Pulsed flow, unless two RFDs or breakpot used.	• As for RFDs • Generally more expensive to fabricate and install	• Requires significant submergence. • Pipework forms a lute below tank which may be prone to blocking • Liquid-air contact, thus aerosol generation • Disentrainment vessel required • Not suitable for slurries • Lift height limited by liquid/air “slippage”	• Need for lute on discharge pipework • Applied vacuum limits temperature of liquid • Liquid-air contact, thus aerosol generation • Disentrainment vessel required • Not suitable for slurries • More expensive than Air lift • Lift height limited	• Requires periodic maintenance or replacement • Requires active isolation valve to prevent liquid draining out on pump removal. • Modification needed to facilitate in-canyon maintenance
Continuous liquid flow?	Only by use of breakpot or twin pumps	Only by use of breakpot or twin pumps	Yes	Yes	Yes
Controlled/ metered flow?	Yes, but dependent on control system	Yes, but dependent on control system	Yes, when submergence held constant	Yes, when submergence held constant	No
Maximum flow rate	No limit, but air pressure limits restrict to typically 570 l/min (150gpm)	No limit, but air pressure limits restrict to typically 570 l/min (150gpm)	200 l/hr (1 gpm)	200 l/hr (1 gpm)	Unlimited except by impeller speed
Typical air:liquid ratio	20:1	< 20:1	2:1 up to 20:1 depending on riser flow regime	2:1 up to 20:1 depending on riser flow regime	N/A
Maximum suction head	RFD element must be flooded. Charge vessel can be up to 9m (30ft) water above this	Up to 9m (30ft) water up to charge vessel. Diode placement is flexible	Air inlet must be submerged	Air inlet can be 9m (30ft) water above lowest liquid level	~23 ft (7m) water
Discharge Head	28m (90ft) normal limit	28m (90ft) normal limit	12m (40ft) normal limit	20m (66ft) normal limit	Unlimited except by impeller speed
Capability to empty tank	No, if usual internal placement of RFD element is used	Yes if diodes mounted outside and below tank	No (requires air inlet point submergence)	Yes	Not advisable, because of undesirability of running pump dry
Operation with slurries?	Yes	Yes	No	No	Yes, but wear on impeller & housing may be significant

Airlifts and VOSLs are particularly useful when criticality considerations rule out the use of Constant Volume Feeders. Conventional centrifugal pumps are sometimes essential where very high flows and heads are required but, unless special arrangements are made for their removal and maintenance, they are best suited for inactive or low radioactive environments.

Mixing and Homogenization

In radioactive facilities the mixing and homogenization of liquids and slurries can be achieved by conventional mechanical mixers, PJMs, air sparging and by liquid recirculation using a pump. Some of the advantages and disadvantages of each of these techniques are shown in Table II. Pulse Jet Mixers are the first choice for tank agitation and homogenization at Sellafield because of their effectiveness at remobilizing and keeping in suspension solid slurries, their effectiveness at scouring tank bases, and their consistent performance without in-cell maintenance over the 20 to 40 year operating life of the typical nuclear process plant. Most Sellafield tanks have height to diameter ratios not exceeding 1.2 and contain liquid and slurries of densities up to a maximum of 1.6 g/cm^3. For applications that exceed these norms, and particularly with "tall" tanks designed to reduce facility footprints, it is difficult to ensure the complete homogenization of the upper parts of a tank with many mixer types. For the Waste Treatment Plant (WTP) at Hanford, there are a number of such tall tanks, containing non-newtonian slurries. It is essential to homogenize completely the contents of these tanks prior to sampling, so as to confirm the correct compositions to meet stringent vitrified product specifications. For these tanks, a program of specific testing and development was carried out [2,3] that resulted in the design of PJM/air sparge combination systems to provide the required degree of homogenization.

Table II. Comparison of Mixer Types

Mixer Type	Advantages	Disadvantages
PJM	•Efficient scouring of base of tank base •Capable of re-suspending settled slurries •No in-cell maintenance required •Lasts lifetime of plant	•Efficient homogenization restricted to tanks with height/diameter ratios of < 1.2 •Air pulses in tank vent •Oscillating motion imparted to tank
Air Sparging	•Simple and cheap to install •Can be used to augment PJMs, especially for higher height/diameter ratio tanks	•Only limited effectiveness when used alone •Aeration of liquid, potentially producing aerosols •Long term effectiveness may be degraded by wear at sparge tip
Recirculation	• Can often be installed at little extra cost by using existing pumping systems	•Needs specific design of discharge nozzle •Not very effective, even with such specific design •Can cause aerosols if discharge nozzle not immersed in tank liquid
Mechanical Mixer	•Well understood and characterized •Can be bought off the shelf •Motor can be located outcell, but requires long stirrer shaft •Can be designed to efficiently mix high height/diameter tanks	•Needs access for maintenance of motor and in-tank impeller •Not effective at re-mobilizing settled slurries •Does not scour tank base efficiently •Aggressive slurries can wear impeller

Development of Standardized Designs for Fluidic Pumps and Mixers

British Nuclear Group and AEAT have jointly carried out an extensive range of practical development work and computer simulation over the last 30 years to develop standardized designs for fluidic pumps, mixers and their working parts such as RFD elements, PJM tubes, and Jet Pump Pairs. The work for the Sellafield facilities falls into three categories:

- Facility Specific: large or full scale test rigs and simulants were used to test pump and mixer configurations for specific plant duties that were considered challenging.
- Equipment Specific: for example RFD element testing was carried out with water to validate the three computer design codes developed for fluidic devices.
- Generic: fluidic device component and assembly testing to produce a suite of standard RFD, Jet Pump Pair and PJM Tube designs.

Table III indicates the pattern of the work and shows how the plant specific and generic test work was integrated to produce a series of standard design components covering a wide range of conditions and from which a fluidic pump or mixer for a particular application can be designed. To help coordinate the results of the development work, three computer codes for fluidic pump design were developed: FLUMP (Fluidic Pump simulation model), SARDAS (Single Acting RFD Design and Simulation) and DIODAS (Diode Pump Design and Simulation).

It can be seen from Table III that the development work was carried out in three stages. Specific designs of fluidic pumps and mixers were initially tested at full scale with liquid simulates for the initial use of these devices in the Highly Active Liquid Evaporation and Storage (HALES) plant and Windscale Vitrification Plant Lines 1&2 (WVP) at Sellafield. A program of generic testing of fluidic components followed, leading to the production of standard designs plus the three computer codes to aid in fluidic pump and mixer design. Finally, as the expansion and modernization of the Sellafield site nuclear facilities commenced in the early 1980s, specific fluidic pumps and mixers were tested at full scale where it was considered that liquid density, solids content or tank & pump system geometry were particularly challenging. This work was carried out to support the Enhanced Actinide Recovery Plant (EARP), the Waste Packaging and Encapsulation Plant (WPEP), the Waste Encapsulation Plants (WEP), the Thermal Oxide Reprocessing Plant (Thorp) [1], the Solvent Treatment Plant(STP), and WVP Line 3.

Table III. Development Work at Sellafield for Fluidic Pumps and Mixers

Development Work	Details	1960 - 1970	1970 - 1980	1980 - 1990	1990 - Present
Full Scale Test Rigs Phase I	PJMs and RFDS for High Active Liquid Evaporation & Storage (HALES) plant PJMs for Windscale Vitrification Plant (WVP Lines 1&2)	━	━	━	
Generic Component Studies	Testing of a range of standard fluidic components, such as diodes, JPPs, RFD elements, to characterize them and produce standard design data	━	━	━	━
Development of Standardized Components	Production of designs for standard fluidic components and development of standard quality assurance tests			━	━
Computer Code Development	Development and validation of standard computer codes to aid in fluidic system design			━	
Full Scale Test rigs Phase II	Full scale testing of specific fluidic systems where configurations or liquids being pumped considered challenging.			━	━

The outcome of this development work was the production of designs for 12 standard RFD elements and 13 standard JPPs of different sizes to suit a range of pumping applications, together with a series of standard PJM tubes. Typical examples are illustrated in Figure 4. Together with the computer codes, this allows designers to select and develop with confidence fluidic pump and mixer designs for a wide range of plant applications bounded by:

- Tank height to diameter ratios up to 1.2
- Liquid densities up to 1.65 g/cm^3
- Liquid viscosities up to 1000 centipoise at 33Hz, 100 centipoise at 300Hz
- Solids content up to 60 wt%
- Temperatures up to 70°C (158°F)
- Flow rates from 6 to 570 liter/min[1](1.5 to 150 US gallons per minute).

Subsequent work by Bechtel International and Washington Group for the WTP project [2, 3] has extended these boundaries to include tanks with larger height to diameter ratios and to the mixing of non-newtonian liquids and slurries.

Fig.4. Standardized RFD Elements, Jet Pump Pair and PJM Tube

OPERATIONAL EXPERIENCE WITH FLUIDIC DEVICES IN THE U.K. AND THE U.S.

U.K. Experience

Fluidic pumps and mixers have been in use at Sellafield since the mid 1960s, with some 800 individual devices in long term successful use. This includes 141 Pulse Jet Mixers and 291 RFD/Double Diode pumps, together with Air Lifts, VOSLs, steam ejectors and fluidic ventilation system devices. The operational experience with the PJMs and RFDs is summarized in Tables IV and V respectively.

Table IV. Sellafield Operational Experience with Pulse Jet Mixers

Sellafield Plant	PJMs	Number of Tanks	Years of Operation	Total PJM Years	PJM Failures
HALES (Tanks 9-12)	28	4	36	1008	Zero
HALES (Tanks 13-16)	28	4	29	812	Zero
HALES (Tanks 17-21)	35	5	16	560	Zero
WVP Lines 1&2	2	2	16	32	Zero
THORP Head End	30	13	12	360	Zero
THORP Chemical Separation	8	4	12	96	Zero
WEP	8	2	12	96	Zero
WVP Line 3	2	2	2	4	Zero
TOTAL	141	36	135	2968	Zero

Table V. Sellafield Operational Experience with RFDs and Double Diode Pumps

Sellafield Plant	RFD/Double Diode Pumps	Years of Operation	Total Pump Years	Pump Failures
HALES (Tanks 18 -21)	8	16	128	Zero
WVP Lines 1&2	6	16	96	Zero
THORP Head End	36	12	432	Zero
THORP Chemical Separation	168	12	2016	Zero
WEP	24	12	288	3
EARP	6	12	72	Zero
WPEP	4	12	48	Zero
STP	26	6	156	Zero
WVP Line 3	13	2	26	Zero
Total	291	100	3262	3

As can be seen, the reliability record for the PJMs and RFDs is very good indeed. After a total of 2968 PJM operating years there have been no failures at all, and after a total of 3262 RFD/Double Diode operating years that have been just three failures that were rapidly remedied without in-cell intervention. These three cases were common to the same vessel in WEP and were due to a temporary blockage of the RFD element by settled barium carbonate solids. This problem was traced to insufficient agitation of the solids, which itself was due to a design based on a simulant that had a less rapid settling rate than the real solids. The blockages were readily removed by higher energy pulsing of the RFD element, and the problem was prevented from re-occurring by increasing the agitation energy. The performance of both the PJMs and the RFDs/Double diodes has remained unchanged throughout their lives, indicating that there has been no significant change in internal dimensions of the fluidic elements due to erosion or corrosion.

Table VI summarizes the range of RFD pump sizes and liquids pumped at Sellafield, and shows the wide range of conditions under which RFD pumps have been consistently successful.

Table VI. Range of sizes and conditions for RFD Pumps at Sellafield

RFD Element Size (in)	Delivery Line			Process Fluid	S.G.	Average Pump Rate (gpm)
	Lift (ft)	Length (ft)	Dia (in)			
7/32	100	147	1	Water	1	3
1/4	27	49	1	Ion Exchange Resin	-	2
1/4	9	16	1	3M Nitric Acid + 3g/l stainless steel shavings	-	1
3/8	29	193	1	Ion Exchange Resin	-	1
3/8	13	29	1/2	Water	1	5
13/32	100	147	1	Water	1	8
7/16	14	49	1	Barium Carbonate	Up to 1.3	11
5/8	26	32	2	Floc	-	3
5/8	27	98	2	Barium Carbonate	-	2
5/8	100	147	2	Water	1	23
5/8	14	113	1-1/2	Barium Carbonate + Filter precoat + magnetite	-	7
3/4	16	111	2	Ferric Hydroxide Sludge	-	15
13/16	49	1515	3	Water	1	7
13/16	100	147	2	Water	1	35
13/16	19	82	1-1/2	Ferric Floc	1.1	10
13/16	19	65	2	Ferric Floc	-	11
13/16	19	65	2	MAC Floc	-	11
13/16	19	65	2	SEC Floc	-	11

Table VI. Range of sizes and conditions for RFD Pumps at Sellafield (continued)

RFD Element Size (in)	Delivery Line			Process Fluid	S.G.	Average Pump Rate (gpm)
	Lift (ft)	Length (ft)	Dia (in)			
13/16	16	131	3	Floc	1.1	47
13/16	16	131	3	BE7 Floc	1.08	18
13/16	16	131	3	MAC Floc	1.1	31
13/16	16	131	3	SEC Floc	1.1	26
13/16	16	131	3	China Clay + Bentonite	1.1	26
13/16	16	131	3	China Clay + Bentonite	1.1	26
13/16	16	131	3	China Clay + Bentonite	1.1	26
13/16	55	167	2	Water + Filter precoat + magnetite	-	15
1	100	147	3	Water	1	44
1	9	16	1-1/2	Water + dicalite + sand	-	8
1-1/8	N/A	98	3	Water	1	57
1-1/8	49	65	3	Uranyl Nitrate + Kieselguhr + Graphite	Up to 1.6	61

US Experience

In the last decade, Power Fluidics technology has been transferred to the U.S.A by BNG America and AEA Technology and applied in particular to radioactive liquid mixing and pumping requirements at US Department of Energy nuclear sites such as Hanford and Savannah River. Twenty full-scale systems have been designed, developed, tested and fabricated for the retrieval, mixing and sampling of radioactive wastes at these sites.

For the Waste Treatment Plant project at the Hanford site, BNG America and AEA Technology have the contract from BNI to design, fabricate and test more than 430 fluidic components for use in fluidic RFD pumps and PJMs within the Pretreatment, Low Active and High Active Vitrification plants. The scope includes the supply of 80 RFD elements and 356 JPPs, all produced to the standard designs. Each item is fabricated to NQA-1 nuclear standards and undergoes rigorous testing to verify its performance using a purpose-built test facility at AEAT’s premises in Charlotte NC.

CONCLUSIONS

Power Fluidic devices enable the mixing and pumping of aggressive and radioactive liquids and slurries while avoiding the use of any moving or maintainable components in contact with the liquid. Fluidic pumps and mixers have been developed over 40 years at the Sellafield site in the UK and during that time have proved themselves to be completely reliable. They can thus be installed with confidence in dark cells in radioactive plant, in the knowledge that they will continue to function satisfactorily without intervention throughout the life of the plant.

British Nuclear Group and AEAT have worked together using test rigs and computer simulations, and by using the experience from plant applications, to devise standard designs for the key fluidic elements, standard design methods for fluidic pumps and mixers and three computer codes. This means that, within a broad range of liquid and slurry characteristics, fluidic pumps and mixers can be designed with confidence, without the need for demonstration testing. Where there are particularly challenging liquid and slurry properties, such as high solids content or non-newtonian behavior, proving tests can readily be set up and the results interpreted using the computer codes.

Fluidic pumping and mixing is thus an established and mature technology that is ideal for radioactive plant use and is now finding increased applications at US DOE sites.

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