Progress with K Basins Sludge Retrieval, Stabilization and Packaging at the Hanford Nuclear Site

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ABSTRACT

This paper shows how Fluor Hanford and BNG America have combined nuclear plant skills from the US and the UK to devise methods to retrieve and treat the sludge that has accumulated in K Basins at the Hanford site over many years. Retrieving the sludge is the final stage in removing fuel and sludge from the basins to allow them to be decontaminated and decommissioned, thus removing the threat of contamination of the Columbia River.

A description is given of sludge retrieval using vacuum lances and specially developed nozzles and pumps into Consolidation Containers within the basins. The special attention that had to be paid to the heat generation and potential criticality issues with the irradiated uranium-containing sludge is described. The processes developed to re-mobilize the sludge from the Consolidation Containers and pump it through flexible and transportable hose-in-hose piping to the treatment facility are explained with particular note made of dealing with the abrasive nature of the sludge.

The treatment facility, housed in an existing Hanford building is described, and the uranium-corrosion and grout packaging processes explained. The uranium corrosion process is a robust, tempered process very suitable for dealing with a range of differing sludge compositions.

Optimization and simplification of the original sludge corrosion process design is described and the use of transportable and re-usable equipment is indicated. The processes and techniques described in the paper are shown to have wide applicability to nuclear cleanup.

INTRODUCTION

The Hanford nuclear site occupies some 151,000 hectares (585 square miles) in Washington State in the northwest of the U.S.A. It operated from the middle 1940s up to the late 1980s to produce nuclear materials for defense use by the irradiation of uranium metal in a series of water-cooled nuclear reactors. The site was chosen principally for its remoteness and for the ready availability of cooling water from the Columbia River that runs through the site. Chemical processing and the production of nuclear materials ceased in 1989 and, since then, the mission of the site has changed to one of decontamination, decommissioning, cleanup and safe, contained disposal of the radioactive waste material.

The uranium irradiated in the reactors was enclosed in aluminum alloy or zircaloy containers or “cans” to form fuel elements and, after removal from the reactor, it was necessary to store these elements for a short period of time to allow the more intense radioactivity to die away prior to chemical processing. The 100 Area K East (KE) and K West (KW) Basins were built in the early 1950s to provide this temporary storage by placing the elements underwater. Each basin is approximately 46m (150 ft) by 24m (80 ft) by 6m (20 ft) deep and contains approximately 5 million liters (1.3 million US gallons) of water. The two basins are located close to the Columbia River at the north of the Site.

When chemical processing ceased in 1989 about 2100 metric tons of the fuel was left within K Basins. During the 1990s, breaches in the zircaloy and aluminum cladding of the fuel caused during fuel discharge operations were exacerbated as the uranium metal fuel oxidized and expanded. This in turn has allowed some dissolution of uranium, transuranics and fission products into the basin water. K Basins are now beyond their design life, the potential for leaks of the basin water threatens contamination of the nearby Columbia River and decommissioning is therefore a priority. From December 2000, Fluor Hanford, the operating contractor for the part of the Hanford Site containing K-Basins, has progressively removed all of the 105,000 fuel elements, vacuum dried them in a purpose-built Cold Vacuum Drying Facility (CVDF) and placed them in on-site dry cask storage. Removal, cleaning, packaging, drying and storing of the approximately 1.8 million kilograms (4 million pounds) of spent fuel was successfully completed in October 2004.

Remaining within the basins is a highly radioactive sludge formed from the corrosion of the cans and the partial dissolution of the transuranics and fission products as well as wind blown sand and spalled concrete from the basin walls. Retrieving, stabilizing and packaging this sludge is an essential precursor to basin decommissioning. These processes are difficult to achieve because of the highly variable nature of the sludge, from very light particles through to highly abrasive metal fragments, because of the obstructed nature of the basin floor, because uranium particles in the sludge continue to corrode and thus release hydrogen, because of the residual heat release from the fission products and because of potential criticality issues with some of the sludge. Fluor Hanford and BNG America have therefore worked together to develop and implement processes to mobilize, remove, stabilize and package the sludge so that it can be long-term stored in safe containment. Fluor Hanford and BNG America have worked together to optimize the treatment processes, to make maximum use of existing buildings and facilities on the Hanford site and, wherever possible, to utilize modular, transportable equipment that does not itself require extensive decommissioning after its mission is complete. During this work BNG America has drawn on British Nuclear Group's extensive experience of sludge mobilization and transfer gained from operations at the Sellafield nuclear site in the UK.

The initial processes designed to mobilize, retrieve and stabilize the sludge were described in previous papers [1,2]. Since then, considerable work has been done to simplify and optimize these initial designs, based on the results of practical development work and mathematical modeling. This paper describes this optimization work and shows how initially fairly complex waste cleanup processes can be simplified by the application of experience and sound process engineering principles.

NOMENCLATURE

BNG America	British Nuclear Group's US-based subsidiary
CVDF	Cold Vacuum Drying Facility
FGE	Fissile Gram Equivalent
FFV	Filter Feed Vessel (original design)
HIH	Hose-in-Hose (temporary liquid transfer system)
IPAN	Image Passive Active Neutron monitoring system
IWTS	Integrated Water Treatment System (used in KW Basin)
KE	K East Basin
KOP	Knockout Pot (in IWTS)
KW	K West Basin
LCV	Large Corrosion Vessel (original design)

LDC	Large Diameter Container
LOP	Loadout Pit
MOSS	Mobile Solidification System (grouting)
NLOP	North Loadout Pit (in KE Basin)
PCBs	Polychlorinated Bi-Phenyls
SCV	Small Corrosion Vessel (original design)
SOP	Stable Operating Point (in tempered uranium corrosion reaction)

K BASINS SLUDGE CHARACTERISTICS

Overall there are approximately 50m^3 of sludge, with 42m^3 arising from KE and the rest from KW Basin. The sludge contains:

- uranium metal and oxides from degraded fuel rods.
- plutonium, americium and fission products from the fuel rods.
- iron and aluminum corrosion products from the fuel cladding and from structures within the basins.
- spalled concrete from the basin walls.
- environmental particulates such as sand and organic media transferred from the site surroundings.
- small amounts of ion exchange media and traces of PCBs.

Sludge is defined as containing particle sizes up to 0.635cm (0.25 inches), and strainers of this size are employed in the sludge recovery equipment to reject larger particles. These larger particles are treated as fuel element scrap and dealt with separately, via the Cold Vacuum Drying route. Typical dose rates from the sludge are more than 0.05Sv/hr (5R/hr), mainly due to its cesium content.

Sludge samples were collected from 78 locations within K Basins during the period 1995 through 2003 under a sampling plan that defined sampling methods, locations, sample handling, laboratory analysis methods, QA and reporting requirements. The results were compiled into a Sludge Data Book [3] that forms the base data for all process design and that is accepted as being an authoritative source of sludge data. A summary of these data is shown in Table I. It is recognized however, that it is impossible to be certain that all the samples obtained are fully representative of the sludge and that it is possible therefore that some sludge batches may lie outside the range of characteristics in Table 1, particularly with respect to uranium particle size and thus reactivity to corrosion. It is therefore important that treatment processes are flexible and adaptable.

Table I. Summary of Sludge Properties

	Sludge Location in Basins				
	Location (1)	**Location (2)**	**Location (3)**	**Location (4)**	**Location (5)**
Volume, m^3	34.8	9.9	2.5	2.8	0.4
Wet Density, g/m^3	1.4	1.4	1.9	3	10.5
U metal, g/cm^3 of sludge	>0.001	~0.0001	>0.01	>0.10	>1.0
Decay Power, W/m^3	3.12	0.26	21.7	87.2	690

TRU, nCi/g	1.93E04	0.40E05	1.44E05	2.04E05	3.54E05
TRU, Bq/g	7.1E05	1.48E05	5.33E06	7.55E06	1.31E07

It can be seen from Table I that the physical and chemical properties of the sludge vary considerably depending on the origin of the sludge from within the basins. As the volume of the types of sludge decrease from locations (1) to (5), so the density, uranium metal content & decay power and TRU content increase. Most of the sludge was originally on the main floor of each basin, and within connected Load-Out Pits (LOP). Sludge within the open fuel element canisters in KE Basins was partially deposited on the basin floor when the fuel was removed. In KW Basin, the closed canisters prevented this and instead the sludge was collected via the Integrated Water Treatment System (IWTS). This cleaned the basin water periodically as fuel was being processed by drawing it through a screen to remove particles larger than 0.25 inches (0.63cm), Knockout Pots (KOP) (Location 5) to remove particles between 600 microns and 0.25 inch diameter, a series of settler tanks (Location 4) that removed most of the remaining sludge, and an ion exchange bed to remove soluble fission product cations. The cleaned water was returned to the Basin.

OVERVIEW OF SLUDGE RECOVERY, CONTAINERIZATION AND TRANSFER

The sludge recovery routes in KE and KW Basins remain essentially as described previously [1,2] and are shown in Figure 1, which also shows the previously used IWTS.

KE Basin Sludge Recovery

The approximately 6.3 m^3 of North Loadout Pit (NLOP) sludge in KE Basin was found to have relatively low uranium metal and fissile content, and a low decay power and therefore heat-generating ability. The NLOP was used during the life of KE Basin to transfer fuel out to the fuel chemical processing plant.

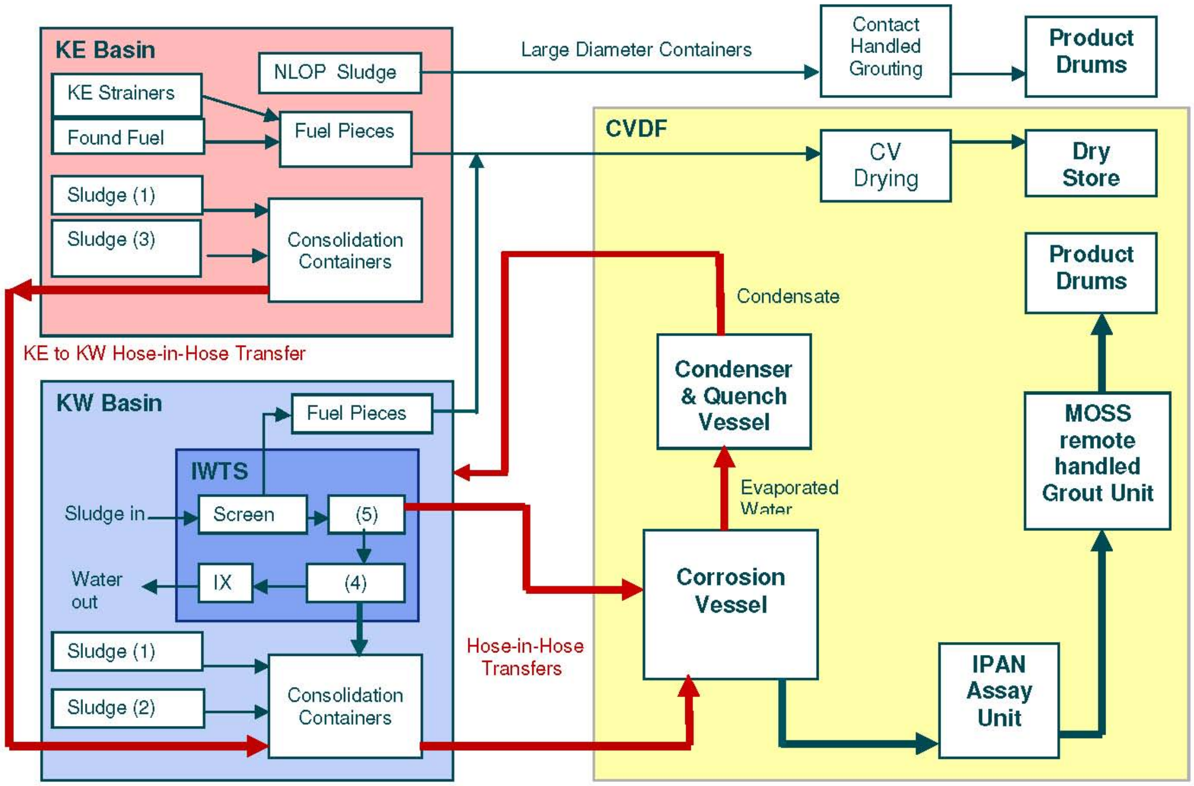

Fig. 1. Sludge recovery from KE and KW basins and the simplified stabilization & packaging processes

Fuel residence time was therefore low and this accounts for the relatively low activity of the sludge in the NLOP. It was thus possible to recover this sludge first, without further treatment, to road-transportable "Large Diameter Containers" (LDCs). The sludge was removed from the basins into the LDCs using the suction wand systems that are described later. It was then transported to an existing Hanford Site building (T Plant) where it is currently being grouted into standard 55 gallon (208 liter) drums using a Fluor Hanford-built grouting plant to produce contact-handleable packages.

Fuel pieces from the Basin floor and those removed by strainers have also been recovered and are treated in the same way as the bulk fuel, by vacuum drying in the Cold Vacuum Drying Facility (CVDF) sited adjacent to KW Basin. The remaining 36.3 m^3 of KE Basin sludge is currently being recovered using suction wands from the floor, and from the adjoining pits, into four Consolidation Containers that are immersed in the Basin water. The KE Basin Consolidation Containers are an initial design with a single hopper-type base equipped with an outlet for subsequent recovery of the sludge.

KE to KW Basin Sludge Transfers

It would be possible to move sludge direct from KE Basin Consolidation Containers to the new stabilization, assay and packaging processes that are being constructed in the Cold Vacuum Drying Facility (CVDF) that are described later. However, this would delay the movement of sludge from KE Basin until after these new treatment processes are constructed and commissioned. KE Basin is in poorer physical condition than KW Basin and it was considered urgent to empty it, and decommission it, as early as possible to remove a major threat to the Columbia River. Therefore it was decided as an interim measure to transfer the 36.3 m^3 of sludge from the KE Basin Consolidation Containers to new

Consolidation Containers constructed in KW Basin. This will allow draining of the KE Basin water on the earliest timescale. This transfer will be accomplished using transportable Hose-in-Hose (HIH) methods, a technology already used on the Hanford site. Liquid transfers between the highly level waste tanks at Hanford use this same technology. The Consolidation Containers in KW Basin are of an improved design developed following experience with the KE Consolidation Containers, and trials with inactive simulant sludges. They feature devices to improve the settling of sludges as they are fed to the containers, multiple compartments with hopper bottoms, and water and sludge recovery header connections to each hopper compartment.

KW Basin Sludge Recovery

Of the total of approximately 7.4 m^3 of sludge in KW Basin, some 4.3 m^3 is located on the basin floor and in the Loadout Pit and will be recovered by vacuum wands, in the same way as KE Basin floor sludge, into another improved design Consolidation Container. The remaining 3.1 m^3 of sludge is already in containment as a result of the operation of the IWTS within K Basins, described previously. Operation of IWTS resulted in the accumulation of 0.5m^3 sludge in the Knockout Pots, and 2.6m^3 of sludge in the Settler tanks.

KW to CVDF Sludge Transfers

The current reference design for the transfer of KE and KW sludge from the Consolidation Containers in KW Basin to the stabilization and packaging processes in the CVDF is to use a HIH system similar to that being used for the KE to KW transfers.

SLUDGE RECOVERY AND TRANSFER EQUIPMENT

A range of new equipment has been designed from scratch or adapted from existing equipment to enable sludge to be recovered from the basin floors and KW settlers, to transfer the sludge from basin to basin and to transfer it from the basins to the treatment plant.

Vacuum Wands

Sludge recovery is achieved by use of submersible pumps attached to vacuum wands, which in turn, are attached to a range of specially designed suction heads that provide simultaneous dilution with drawn-in basin water, and thus mobilization of the sludge. A typical arrangement is shown in Fig. 2 where a standard suction head is used. The standard suction head has a nozzle surrounded by a shroud that provides the basin water inlet. The setting of appropriate nozzle and shroud diameters and clearances is crucial to efficient sludge mobilization and was achieved by a program of development work using test rigs. Smaller variations of this suction head have also been developed to provide “crevice tools” to allow sludge to be retrieved where access is restricted. These tools have been developed by BNG America, drawing on British Nuclear Group’s experience, and the experience of its predecessor company, British Nuclear Fuels (BNFL), with sludge recovery at its Sellafield, UK site. At Sellafield some 650m^3 of sludge has been recovered and packaged over the last 10 yrs from fuel storage basins that contained uranium metal fuel in magnesium-aluminum alloy cans, and which had corroded in a similar way to the K Basins sludge.

The vacuum wand and suction head are connected by flexible piping to the submersible pump which is suspended from an overhead monorail. The wand is suspended via a ballast tank from the same monorail and the operator maneuvers it by use of a handwheel into the required position to suck up sludge, while standing on a grating above the basin water. The water provides radiation shielding to the operator but also makes it more difficult for him to observe the operation of the suction head. During the sludge recovery processes a number of difficulties are being encountered and these closely parallel Sellafield experience:

- Sweeping the suction head across the floor of the basin disturbs the sludge and the lighter fractions of it then cloud the water, exacerbating the operator’s visibility difficulties.
- Debris on the floor of the basin (for example fuel rack components, broken fuel pieces, general accumulated trash) make it difficult for the operator to sweep the wand and suction head and pick up the sludge. It is usually necessary to pre-clear the basin floor of such debris before operating the wands. However, it is impossible to assess the extent of this pre-clearance before sludge recovery operations commence because of the restricted visibility within the basin water.
- Disturbing the sludge contributes to an increase in airborne radioactivity, limiting operator working time and/or requiring the use of respirators, thus further inhibiting the operator’s ease of working.
- Difficulties are being experienced in achieving re-settling of the sludge within the Consolidation Containers, leading to loss of newly recovered sludge back into the basin water. The design provides flocculent injection systems that can be used when required to mitigate this difficulty.

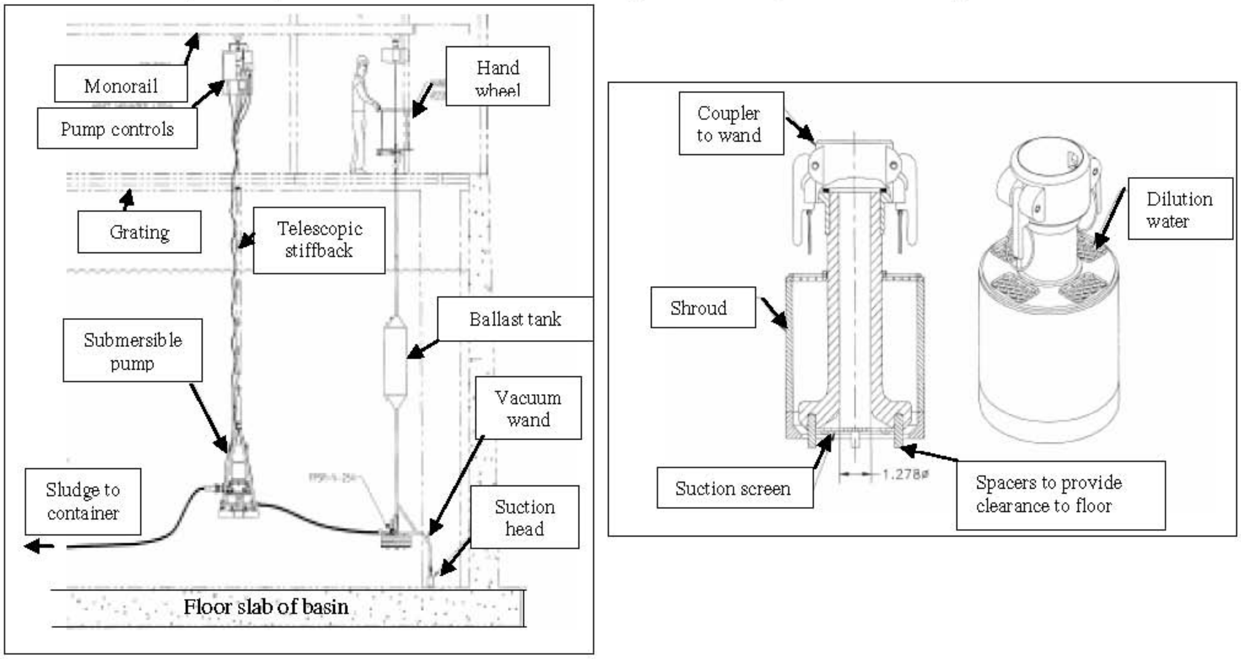

Fig. 2. Arrangement of submersible pump, vacuum wand & suction head for sludge recovery

KW Basin Consolidation Containers

The KW Basin Consolidation Containers are approximately 1.7m (5.6ft) by 3.8m (12.5ft) by 4.1m (13.5ft) high and weigh 590kg (1300lbs) and are submerged in the KW Basin water. They are fabricated from five stainless steel sections, each with lifting lugs, and assembled and bolted together within the basins. During the sludge consolidation process, the level of sludge may be monitored by visual observation of depth markings inside the container, and by level instruments installed to actuate indication at a specific height.

These containers are of an improved design and have the following features, developed from KE Basin experience and a series of development tests:

- Feed header pipe divided into two slurry distributors to disperse the flow and reduce upward fluid flux, so as to aid sludge settling.
- Clear rigid plastic cover with apertures to allow water and evolved gas to escape, while minimizing sludge loss from the container.
- A top skimmer nozzle, pipe and pump system to remove turbid water and send it to a secondary settling container.
- Compartmentalized, “hopper” bottom sections to aid sludge remobilization and removal when required.
- Separate dilution and discharge manifolds to facilitate future sludge re-mobilization and removal.

Hose in Hose Sludge Transfers

The flexible, transportable Hose-in-Hose (HIH) and booster pump system is used to transport sludge the 760m (2500ft) from KE to KW Basins, Similar HIH systems have been used for a number of years at Hanford to transfer high level radioactive waste between the underground storage tanks, and this design has been adapted to suit the sludge transfer requirements. The system consists of a coaxial hose arrangement with an annular gap (Fig. 3). Trace heating and an outside insulation layer can be added if required. The inner/primary hose is used to transfer the dilute sludge and flush water. The outer hose provides secondary containment for the primary hose and, in the unlikely event of leakage from the primary hose, routes this leakage to the leak detector elements located at the pump booster stations and leak detection boxes located at the basins.

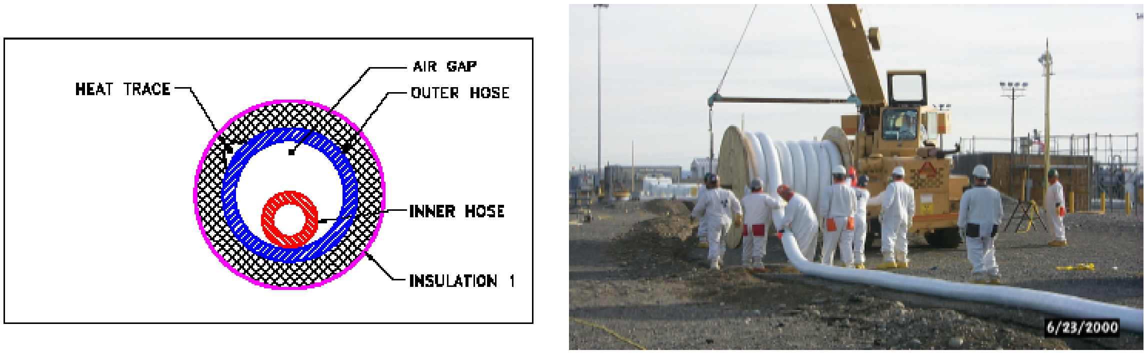

Fig. 3. The hose in hose sludge transfer system, cross section and installation

The hose is constructed of Ethylene Propylene Diene Monomer (EPDM), with double spiral wound wire reinforcement. The outer hose is normally covered with 3.8cm (1½ inch) thick Armaflex1 insulation. Hose couplings are fully engineered stainless steel devices. The hoses are factory tested to burst pressures for the inner (1.38E7 Pa, 2000 psig) and outer (6.89E6 Pa, 1000 psig,) hoses. The hose assemblies will be pressure tested to 5.17E6 Pa (750 psig), in order to qualify a 3.45E6 Pa (500psig) working pressure of the inner hose after site installation. The integrity of the hose will be maintained through the use of rupture disks located at the pump booster stations. Installation of the HIH simply requires it to be unrolled and placed into position (Fig. 3) either on the ground surface or in a shallow trench. Although the hose route will be a traffic exclusion area, extensive testing has shown that the hose keeps its integrity even when run over by trucks and other heavy vehicles.

Booster pump stations are necessary at 120-150m (400-500ft) intervals along the HIH pipe to provide the required motive force to transfer the dense sludge slurry. The booster stations comprise a stainless steel radiation-shielded enclosure measuring approximately 183cm (6ft) wide by 366cm (12 ft) long by 152cm (5ft) tall, containing the centrifugal booster pumps, an over-pressure rupture disk and a catch tank with leak detection. The booster station enclosures provide four functions: (1) to provide radiation shielding, (2) to detect and contain releases in the event of a primary line failure or rupture disk actuation, (3) to direct leakage from the outer hose to the leak detector sumps for detection, and (4) to provide a pathway for hydrogen to escape.

It was recognized that the K Basin sludge is more abrasive than high level tank waste because it contains pieces of uranium metal up to 0.25 inch (0.635cm), zircaloy fuel cladding shards and sand particles. A test program was therefore designed and carried out to demonstrate the suitability and resistance to wear of hose, fittings, and pumps. A test circuit of inner hose and a scaled-down pump was set up and a sludge simulant slurry of equal or greater abrasiveness to the KE Basin sludge was circulated through it for the equivalent of twice the required volume of sludge to be pumped. It was found that the HIH was unaffected by this but that significant wear occurred within the pump impeller housings. Although the projected erosion was still just within the allowable wear limit for the impeller housing thickness, a duplicate pump is included in each booster station as a standby unit to provide operational margin. The pump impeller housings are equipped with ultrasonic wear monitors and changeover of the pumps can be achieved from outside the radiation shielding.

The current reference design intention is to use the same, relocated, HIH system to transport the consolidated KE and KW sludges the 460m (1500ft) from KW Basin to the Cold Vacuum Drying Facility (CVDF) for stabilization and packaging by grouting. However, the KW sludge is known to be even more abrasive than the KE sludge so further hose and pump wear tests are in progress and alternative systems are being studied as fallback options.

Recovery of Sludge from the Settlers and Knockout Pots

The 3.1 m^3 of sludge within the Settlers and Knockout Pots (KOPs) in KW Basin requires special treatment to remobilize it for subsequent stabilization and packaging in the CVDF.

There are ten Settler tanks, each 51cm (20 inches) in diameter by 610cm (20 feet) long in a rigid assembly in KW Basin (Fig. 4). For sludge removal, basin water is pumped into each Settler via a high-pressure rotating spray nozzle to sluice and mobilize the sludge while it is simultaneously removed via the suction hose. The sluicing hose is manually manipulated within each Settler using long-reach tools.

A fiber-optic endoscope system is inserted into each Settler to verify that all the sludge has been removed. Because of criticality concerns, sludge from only one Settler at a time is recovered into a Consolidation Container, where samples can be removed for analysis. This system was developed and proven using a full-scale inactive test rig to demonstrate the methods of inserting the sluicing and suction hoses and their remote manipulation.

The KOP units contain substantial amounts of uranium fragments making it necessary to restrict retrieval batch size to avoid unacceptable decay heat output and the possibility of criticality. Retrieved sludges are therefore weighed using an existing load cell and the contents selectively combined to ensure that the recovered batches remain acceptable. The selected KOPs are dismantled under water using long reach tools, and submersible pump -vacuum wand systems similar to those previously described are used to remove the sludge. The sludge is pumped to a single critically safe 56cm (22inch) diameter Accumulation Container within KW Basin. This container has a hopper base with dilution water inlet for easy mobilization and subsequent removal of the sludge.

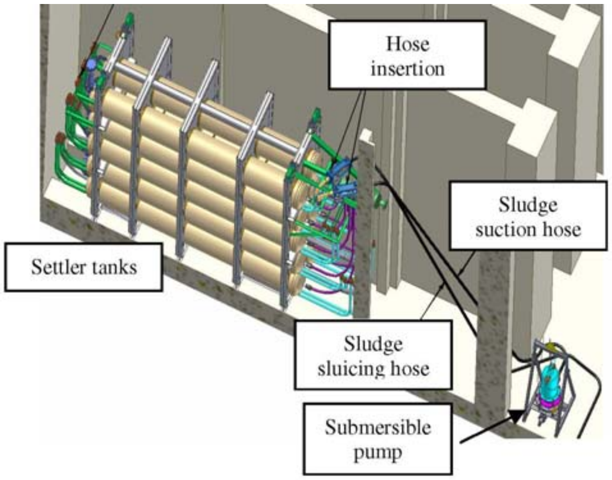

Fig. 4. Recovery of sludge from the KW basin settler tanks

SLUDGE STABILIZATION AND PACKAGING IN GROUT

Overview and Selection of Processes

The goal is to recover all the sludge consolidated within KW Basin, stabilize it and package it so that it will be suitable for transport off the Hanford Site for eventual long-term storage.

The transport requirements limit hydrogen generation from the waste, and also limit the amount of fissile material within each waste package. Much of the sludge generates significant amounts of hydrogen from the corrosion reactions with water of the uranium particles entrained within it, to form uranium oxides. The water also undergoes radiolysis and releases hydrogen, though this is a relatively minor contributor to the overall hydrogen release. It was determined that the extent of hydrogen generation exceeded that allowable for transport of the waste, even though it was within limits for storage.

To reduce and manage the release of hydrogen from the sludge there are two main options:

- Dry the sludge completely and develop systems to ensure it remains dry during interim storage and transport to the final repository,
- Accelerate the oxidation of the uranium so that all of it is converted to oxide prior to interim storage.

In addition, it was determined that some of the sludge would exceed the Fissile Gram Equivalent (FGE) for typical long-term storage Waste Acceptance Criteria (WAC) and/or the dose rate limit for handling and transport if the 208 liter (55 gallon) storage drums to be used were filled to capacity. Therefore an inert filler must be mixed with the sludge in accordance with its measured FGE and dose rate. This filler also provides dimensional stability to the sludge and drum so that it resists mechanical deformation during storage.

A total of 15 candidate processes were identified that could potentially treat the sludge to meet the above requirements and these are summarized in Table II. Each candidate process was rated against a range of criteria including the following:

- Previous experience with the technology at pilot, full scale, and with modular equipment.
- Hydrogen generation from the resultant waste form by uranium corrosion and by radiolysis.
- Compatibility of the waste form with standard 55 gallon drums.
- Total volume of final waste form.

- Stability of final waste form.
- Compliance of final waste form with likely WAC of ultimate repository.
- Secondary wastes, if produced.
- Ease of producing satisfactory safety and permitting cases.
- Extent of any development work required.
- Likely ability of the process to meet the sludge-processing schedule.
- Overall estimated cost of implementing the process.

The difficulty of ensuring that dried sludge in storage remained dry, and could be demonstrated to do so, was recognized early in the selection process. Therefore processes that pre-oxidized the uranium were favored because the sludge could then become damp during storage with no adverse effects on hydrogen generation.

Table II. Candidate Processes for Sludge Treatment

Process	Notes
Steam Reforming.	Will oxidize uranium. Development required and may need specific permitting action.
Heated Drying.	Will oxidize uranium metal but development work needed to quantify extent. Safety issues with uranium ignition.
Vitrification.	Isolates uranium from water. Needs development work. Likely high cost.
Grouting with cement.	Ample previous experience but does not eliminate uranium metal and does not dry the sludge.
Grouting with polymer cement.	Development work needed to quantify hydrogen generation.
Sorption with polymeric materials.	Development work needed to quantify hydrogen generation.
Cold Vacuum Drying.	Will not oxidize uranium, so will need to keep product dry throughout storage period.
Freeze Drying.	Removes water efficiently but need to keep product dry.
Vacuum Thermal Desorption with U-metal oxidation.	Will oxidize uranium and remove water. May be regulated as an incinerator.
Calcination.	Will oxidize all uranium efficiently but off-gases and incinerator licensing are disadvantages. Uranium metal ignition of concern.
"Wetox" process.	Use of organic reagents and temperature to oxidize the uranium. Secondary waste streams may be an issue.
Incorporation in high temp ceramic.	Converts uranium to oxide. Ignition of uranium of concern. Needs development.
Incorporation in cold ceramic.	Does not dry or oxidize the uranium.
In-drum pyrolysis.	Thermal process that may need permitting as an incinerator.
U-metal corrosion plus cement grouting.	Moderate pressure and temperature used to accelerate the oxidation the uranium. Grout used to provide final de-water.

This assessment resulted in the selection of accelerated uranium corrosion with water at moderate temperature and pressure, together with cement grouting of the corroded sludge to produce the final waste form. There was already significant data available at Hanford on uranium metal corrosion rates in water [3] so that this allowed the design of the corrosion reaction system without needing new development work. For the grout process, BNG America was able to draw on over 20 years of development and operational experience at Sellafield in the UK in the use of cement grouts to immobilize radioactive waste. British Nuclear Group, as part of British Nuclear Fuels group, operates three large grout plants at the Sellafield site and has produced over 25,000 drums of cement-encapsulated waste containing 350m of uranium metal-bearing sludge [4]. A transportable "MOSS" grouting unit, developed from this experience, was selected for this application, and targeted development work was carried out by the R&D Department at Sellafield to determine the optimum grout formulation for this application [5].

Use of these simple and compact processes enables the sludge treatment to be carried out in the existing CVDF building, thus obviating the need to build a new facility, and shortening the schedule for treatment of the sludge.

Sludge Stabilization and Packaging Processes

Sludge stabilization and packaging is carried out in the existing CVDF, previously used for the treatment and stabilization of the fuel elements recovered from KE and KW Basins. The processes used are:

- Recovery of the sludge into a tank within the CVDF.
- Dewatering of the sludge to a solids concentration suitable for uranium corrosion.
- Accelerated uranium corrosion at temperatures and pressures up to 365ºF (185ºC) and 1.65E6 Pa (240psig) respectively.
- Fissile content monitoring of the corroded sludge to determine its FGE.
- Encapsulation of calculated amounts of sludge within a grout matrix so that the 55 gallon (208 liter) drums meet Waste Acceptance Criteria.

A comparison of the originally designed sludge stabilization process [1] and the process after a series of optimization studies had been completed is shown in Fig. 5.

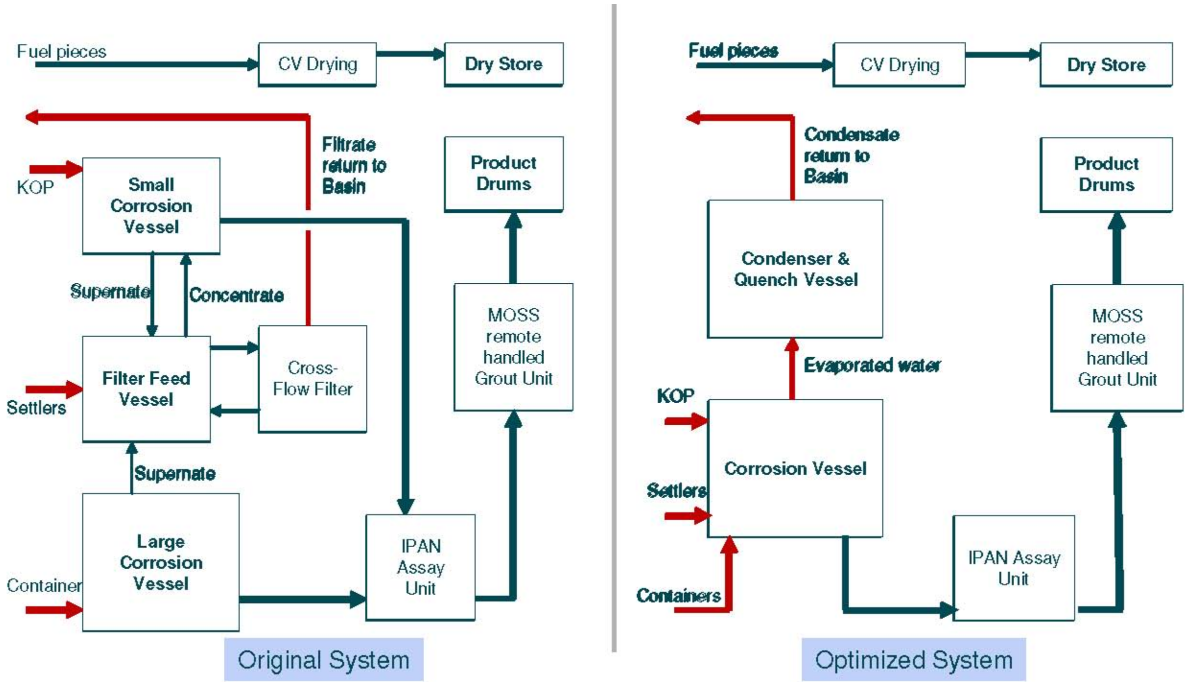

Fig. 5. Comparison of original and optimized sludge treatment

Original Dewatering and Corrosion Processes

The original design processed the contents of the Consolidation Containers by pumping the slurry via the HIH system to a 229cm (90 inches) diameter Large Corrosion Vessel (LCV). The sludge is about 12% by volume solids as received; settling and decantation is used to increase this to 22%. The decanted supernate is sent to the Filter Feed Vessel (FFV) for concentration to 25% by volume solids using cross-flow filtration, with the filtrate returned to KW Basin via another HIH system. The LCV has mechanical agitation and nitrogen sparging and these are used, in combination with temperatures and pressures of approximately 185ºC (365ºF) and 1.65E6 Pa (240psig) respectively, to corrode the uranium present in the sludge. The progress of the reaction is followed by measuring the hydrogen content of the off-gas stream and, when the hydrogen has dropped to near zero, the reaction is shown to be complete. During the reaction, a reflux condenser in the off-gas stream returns all evaporated water to the LCV. The heat of the corrosion reaction plus decay heat from the irradiated uranium is thus removed from the LCV via vaporization of the water and taken out of the system via the condenser cooling water.

The supernate that was concentrated via the FFV and cross-flow filter is combined with concentrated supernates from subsequent batches of container sludge, and is sent to the Small Corrosion Vessel (SCV) for accelerated corrosion in a similar way to that described for the LCV.

KOP sludge is dealt with in a similar way to Container sludge, except that the SCV is used for settling, decantation and subsequent corrosion of the concentrated slurry at 160ºC (320ºF) and 9.31E5 Pa (135psig). In the same way as for the LCV, the decanted liquid is concentrated via the FFV and cross-flow filter, combined with subsequent batches of concentrated KOP supernate, and corroded in the SCV. The SCV is a critically eversafe vessel and so can accommodate safely any amount of KOP sludge.

Settler sludge requires more water to re-mobilize it from the KW settlers and this produces a slurry of about 2.4% by volume solids that is received in the CVDF. It is therefore sent direct to the FFV for concentration to about 14% solids by volume and then corroded in the SCV at temperatures and pressures of 160ºC (320ºF) and 9.31E5 Pa (135psig).

Optimized Dewatering and Corrosion Processes

It was recognized that the original sludge dewatering and corrosion processes were somewhat complex and would benefit from simplification. An optimization study was initiated which identified the possibilities, advantages and constraints shown in Table III.

Table III. Optimization Advantages and Constraints

Optimization Possibility	Advantages	Constraints
Use evaporation rather than crossflow filtration to dewater the sludge.	•Evaporation already takes place because of nitrogen purge to LCV/SCV and elevated temperatures •Eliminates reflux condensers on LCV and SCV. •Eliminates cross-flow filtration system, FFV and associated equipment.	•Must be able to achieve desired corroded sludge solids content within time required for corrosion. •Need ability to add water to system in case corrosion reaction is longer than expected •Need a Quench Vessel to condense evaporated water.
Use only a single Corrosion Vessel.	•Eliminates another vessel. •Eliminates associated equipment. •Simplifies operation of process.	•Corrosion Vessel will not be eversafe for KOP sludge. •Need to adjust batch sizes and final solids concentrations of Settler and KOP sludge so that batch volumes are not too small with respect to heel in Corrosion Vessel.

A series of calculations showed that by adjusting the final corroded sludge solids content for Container, Settler and KOP sludge to 20%, 4.1% and 8% by volume respectively, corrosion and evaporation times could be approximately equalized. A water feed is provided to the Corrosion Vessel in case corrosion times are longer than expected; if they are shorter it is merely necessary to maintain the Corrosion Vessel at temperature and pressure for a little longer. The low Settler corroded sludge solids content was found to be acceptable in the context of all the sludge to be grouted and the extra water that had to be added to ensure proper cure of the grout.

A series of criticality assessments were carried out for the KOP sludge. These showed that weighing the sludge within KW Basins prior to transfer from the Accumulation Container so as to produce single batches of < 510 kg (1125 lb) each was possible. The safe-by-mass limit for the KOP sludge was shown to be 1100kg (2430 lb) so that an off-normal operation that recovered a double batch would remain critically safe. On this basis, the SCV could be eliminated, while still being able to produce a satisfactory safety case for the process.

These optimizations resulted in the elimination of some 7 process vessels, 2 heat exchangers, a cross-flow filter unit, 13 valves, and associated instrumentation. This resulted in a series of gains:

- Capital cost of equipment reduced.
- Design and construction time reduced.
- Plant operating complexity significantly reduced.

Uranium Corrosion Process

The accelerated uranium corrosion process using water at moderate temperatures and pressures is a "tempered" system. This means that, so long as water is present with the sludge, any amount of uranium water reaction heat, and radioactive decay heat, will be removed via the latent heat of vaporization of the water. As water is continuously vaporized from the system, the heat removed by this vaporization plus any other heat losses from the system will always equal or exceed the heat generated by the uranium water corrosion reaction plus the decay heat and any heater input. This gives the system two features for any sludge with its particular uranium surface area and reactivity:

- There is a pressure below which heat losses by vaporization of the water and by conduction through the vessel walls will always exceed heat inputs from the uranium-water reaction heat and the sludge decay heat. The corrosion reaction will thus not proceed to any significant extent
- For pressures above this minimum, the corrosion reaction will proceed at a significant rate and there will be a Stable Operating Point (SOP) to which the system will always return following any temperature perturbation.

When combined with the ability to measure hydrogen evolution to indicate reaction rate and endpoint, this means that, by initially ramping up the temperature and pressure for each new batch of sludge, the reactivity of the system can be gauged and a SOP readily identified. Should the sludge reactivity differ from that expected (because for example the uranium particle size differs) this is of no consequence because the operator will readily locate an appropriate SOP. The only process constraint is that the sludge is kept wet throughout. Development trials were carried out with sludge simulant to find the optimum combination of nitrogen sparging and mechanical agitation to achieve this and prevent "dry spot" formation.

The corrosion system is thus flexible and the operator does not need to know precisely the reactivity of a particular sludge in advance. This is a valuable attribute for K Basin sludge where, despite the characterization work, it is impossible to be certain about the particle size and hence reactivity of all uranium present in every batch of sludge recovered.

Fissile Content Monitoring

Once corroded, the sludge is transferred to the Image Passive Active Neutron (IPAN) system for fissile content measurement. This system is based on well-proven technology used in a number of radioactive waste packing systems at US nuclear sites [6]. It uses a combination of active neutron interrogation and passive neutron counting to determine FGE for the sludge batch. In this application gross gamma monitoring and shielding is added to deal with the gamma-emitting sludge. The system outputs data on the mass of sludge that can be placed in each product drum while staying within both FGE and gamma dose rate limits. A confirmatory gamma measurement is made on each drum of grouted waste.

MOSS Transportable Grouting Unit

The sludge is pumped from the IPAN unit to the transportable MOSS grouting system, where the calculated amount of sludge is metered into each 208-liter (55 gallon) drum. The appropriate amount of cement is added and, by suitable specification of this cement, the remaining water with the sludge is reacted, thus reducing free water to below the required limit in the drum. The MOSS unit is skid mounted within a shielded transportable container and allows remote lidding and monitoring of each drum before it is transported to a temporary store.

MODELING AND DEVELOPMENT WORK

The K Basin sludge retrieval and treatment processes are based on well-established technology and previous experience so that the need for new development work is minimized. Nevertheless, a combination of some development work with the use of three mathematical models was used to provide confirmed design data and indicate how the systems should be operated for maximum efficiency. The development work is summarized in Table IV, while the mathematical models are shown in Table V.

Table IV. Development Work for Sludge Retrieval and Treatment

Development Topic	Comments
Settler tank sludge retrieval methods.	Special nozzles developed.
HIH and transfer pump erosion testing.	Needed because of abrasiveness of the K Basins sludge. KW sludge recognized as more abrasive than KE sludge.
Small scale grout trials.	Principles of grout formulation well understood from Sellafield work. Small scale trials conducted to develop specific formulations to suit K Basin sludge.
G Value estimation for grouted K Basin sludge.	Theoretical and experimental determination of G values in grouted sludge to produce estimate of residual hydrogen production by water radiolysis.
Cement formulations for grout.	May improve waste to grout ratios for sludge that is not FGE limited.
Lidding system for MOSS grout drums.	New mechanism developed for this application for removal and re-insertion. of the lid plug
"Lost Paddle" agitator for MOSS system.	General principles of grout agitation well understood from previous work. These trials carried out to confirm performance with K Basin sludge.
Corrosion vessel agitation tests.	Tests to confirm agitation efficiencies of nitrogen sparging and mechanical stirring.
IPAN System.	Confirmation testing.
Sludge treatment modules slurry pump testing.	Confirmation testing to prove the capability of mobilizing and pumping the higher concentration slurries produced by dewatering prior to corrosion.

The Operational Research Model

Operational Research (OR) modeling has been adapted and extended by British Nuclear Group for nuclear plant applications and is now extensively used to optimize the design and operation of its plants. For the present application it is used both to evaluate initial designs for the sludge retrieval and treatment processes and to investigate changes that could improve the design, by reducing equipment sizes and requirements, shortening processing times, improving operator interfaces and optimizing operating team sizes.

The model utilizes a stochastic simulation routine that provides a visual and dynamic representation of the various processing stages including sludge retrieval, treatment and packaging. The model integrates the process flow diagrams (that is process and mechanical handling equipment, size, capacity and operational requirements), mass and material balance calculations, control and instrumentation requirements, operator interfaces, equipment reliability and maintenance requirements, and shift and labor requirements. It can effectively "run" the plant in accelerated real time.

BNG America has developed this model by taking proprietary OR software and adapting it to the simulation of process plant. Once set up with reliability and maintenance data taken from British Nuclear Group's existing nuclear site experience, the model is used to determine mean throughput, total operating efficiency and sludge packaging timescales. It is used to study a range of "what if" questions to find and eliminate bottlenecks in the process. It is also used to study off-normal and fault conditions to provide inputs to safety case production and to allow operating procedures for both normal operation and off normal recovery to be developed.

Table V. Mathematical Models for Sludge Retrieval and Treatment Model

	Comments
Operational Research Model.	Confirms process throughput and availability of the plant and processes by studying vessel and equipment utilization, reliability of equipment, maintenance times, workshift patterns, operator utilization.
Process (ACM) Model for Waste Drum Loading calculations.	Used to calculate and predict the combinations of sludge and cement grout needed for each type of sludge so as to minimize drum numbers while keeping within FGE and gamma activity limits. Produces algorithms that are used with the IPAN output to calculate exact amounts of sludge to place in a drum.
Uranium corrosion dynamic model.	Uses U-water reaction rates and heats, sludge volume, heat capacity, decay heat, U particle size, operating pressures and temperatures, input heat applied and certain physical properties of the materials to predict temperature-and pressure-time profiles for the corrosion reaction. These will act as a guide to the operator who will nevertheless operate the corrosion vessel in accordance with the reactivity indicated by hydrogen rate of release.

CONCLUSIONS

Removing the sludge from K basins and stabilizing it for long term storage is a vital step in the cleanup of K Basins and the protection of the Columbia River. As with many older plants on nuclear sites, the cleanup requirements can seem to be intractable, with the need to handle old equipment, minimally characterized materials, high radiation levels, criticality potential and difficult working conditions.

This paper has shown that by utilizing, adapting and extending existing methods and technologies, and combining skills and experience from US and UK nuclear sites, successful cleanup can be achieved. The problem of minimally characterized sludge can be overcome by designing robust and flexible processes such as the tempered uranium corrosion process, and by the use of well-understood, widely used waste encapsulation methods such a cement grout.

The optimization of the sludge corrosion step and the elimination of process equipment show what can be achieved by systematic review of an initial design. The project continues to emphasize the re-use of existing cleanup equipment and the modularization of process plant so that it is transportable. This speeds up installation, and allows subsequent re-positioning and re-use. It also, and very importantly, avoids the build of new monolithic plants that have to be decommissioned. The processes and techniques discussed in this paper therefore potentially have wide applicability to a range of cleanup task on nuclear sites worldwide.

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