Full Scale Non-Radioactive Vitrification Development in Support of UK Highly Active Waste Vitrification

K. Bradshaw, N.R. Gribble, P.A. Mayhew
Nexia Solutions
Sellafield, Seascale, CA20 1PG
UK

M.C. Talford, A.D. Riley
British Nuclear Group
Sellafield, Seascale, CA20 1PG
UK

ABSTRACT

This paper describes the historic and current status of inactive research in support of UK Highly Active (HA) waste vitrification. The relationships between stakeholders involved in the reduction and management of Highly Active Liquor (HAL) stocks held at Sellafield in the UK are described. Experimental work performed to date on the UK's inactive vitrification research facility is summarised along with estimates of the potential impact of this research work on the reduction of HA Liquor stocks stored in the UK.

INTRODUCTION

There are three operating active vitrification lines in the UK's Waste Vitrification Plant (WVP) at Sellafield (WVP Lines 1, 2 and 3). The two original vitrification lines (Lines 1 & 2) have under-performed their original design intent since operations began in 1989-91 resulting in the requirement for the construction of a third, opened in 1998. The UK Government through the Nuclear Installations Inspectorate (NII) has set targets to reduce HAL volumes to buffer stock levels by 2015 and whilst significant progress has been achieved to date, it is recognised that more needs to be done to ensure that these targets will be met.

The Vitrification Test Rig (VTR) began operations in October 2004 and has been built to provide a development tool to optimise and improve the operation of the UK's High-Level Radioactive Waste Vitrification facilities (WVP) at Sellafield. The facility is a full-scale inactive replica of the core vitrification processes on the active plants, with additional instrumentation and sampling capabilities, processing an inactive simulant representative of the HAL processed in WVP. The VTR represents significant research and development investment and demonstrates the commitment of the BNFL Group to reducing HAL stock levels.

This paper describes the aims of the experimental program on the VTR, the progress against this program to December 2005 and the expected impact on HAL stocks achieved by applying the results obtained from the VTR onto the UK's operating active vitrification facilities.

VITRIFICATION TECHNOLOGY

The immobilisation or incorporation of HAL into glass is known as vitrification. HA liquor stored in the UK is generated from spent Oxide and Magnox fuel reprocessing operations. The origin of the liquor is an important consideration for the vitrification process, as the characteristics of the material vitrified will affect the product glass parameters. There are constraints on parameters associated with the glass product including heat generation, activity, fission product content and durability. A 75:25 blend of Oxide and Magnox liquors typically represents the feedstock for vitrification. By utilising a blended feed strategy the waste oxide loading efficiency in the product can be maximised whilst meeting commercial and technical restrictions on the vitrified waste form.

Prior to vitrification the HA liquor is in the form of slurry containing mainly metal nitrates in solution and comprising of fission products, activation products, process additives, some minor actinides and fuel cladding materials. The liquor contains around 10% by volume of insoluble solids including caesium phosphomolybdate and zirconium molybdate, and is typically fed into the vitrification process with a total solids concentration of 100-200 g/l.

The vitrification plants in the UK use a two-stage vitrification process to incorporate the HAL into glass. An overview of the key vitrification equipment is shown in

Fig, 1. The HAL, along with other calcination additives, is fed into a rotating kiln furnace known as a calciner to evaporate the liquor and de-nitrate the resulting solid thus producing an intermediate calcine product. The calcine product is a granular material consisting of mainly metal oxides with a residual nitrate content. The calcination process generates an off-gas stream and this requires abatement. The primary off gas system includes a dust scrubber to remove entrained calcine and to recycle this material back into the process. A condenser removes condensable gases such as water vapour, nitric acid vapour and absorbs some nitrous oxide from the process. The third main vessel for off gas abatement is the NOx absorber, present to remove NOx from the gaseous effluent by absorption of the soluble gas in water / nitric acid. Secondary off gas cleanup is achieved using electrostatic precipitators and HEPA filters.

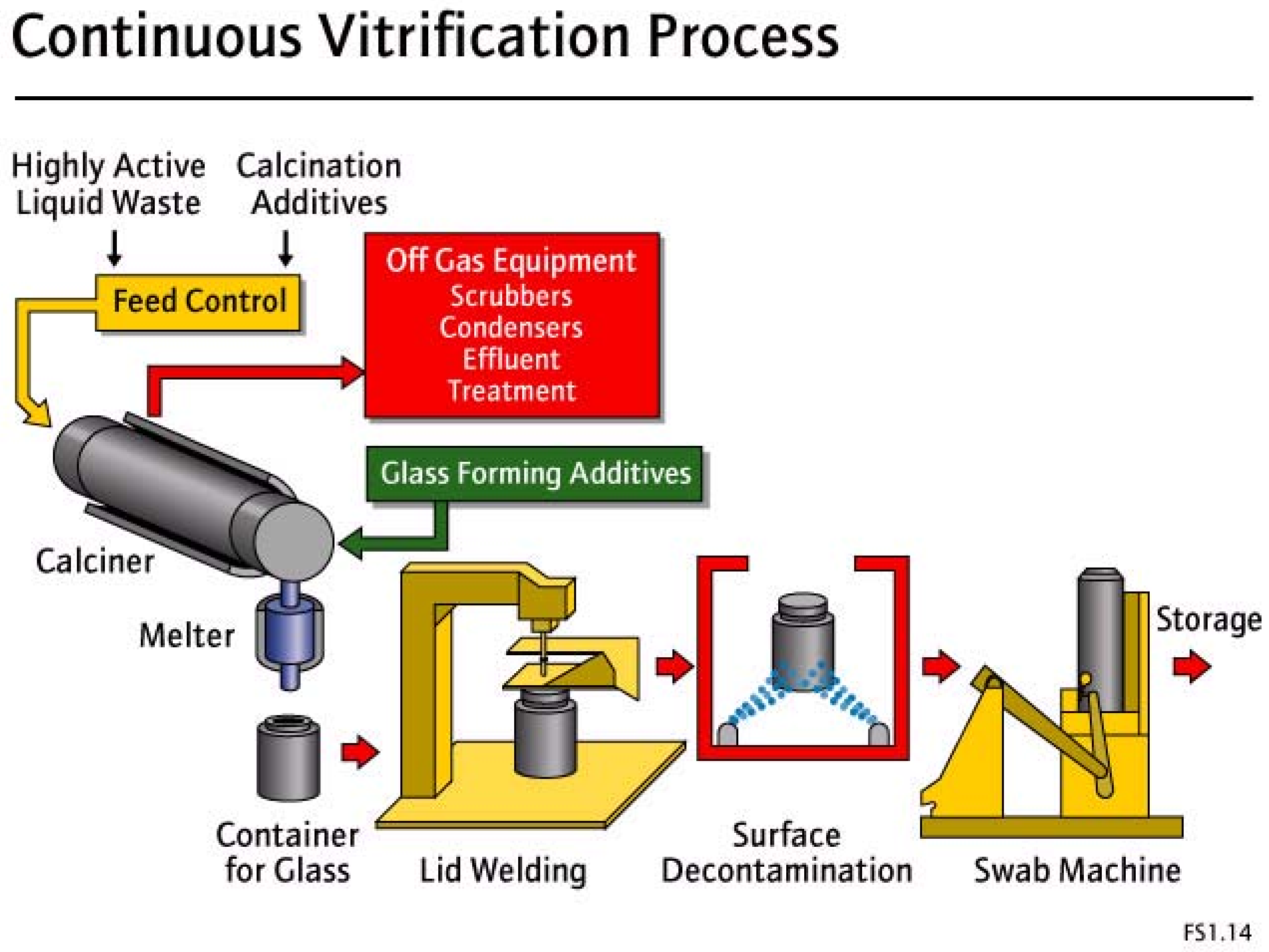

Fig. 2. Vitrification Process Overview

The BNFL Group comprises of a number of subsidiary companies including British Nuclear Group, Westinghouse Electric and Nexia Solutions. Although still a part of BNFL, British Nuclear Group is a stand-alone nuclear site Management Company and provider of nuclear clean up and decommissioning services. Nexia Solutions provides technology services and solutions across the nuclear fuel cycle and Westinghouse Electric Company provides fuel, services, technology, plant design and equipment to utility and industrial customers in the world wide commercial nuclear electric power industry.

British Nuclear Group is currently contracted by the Nuclear Decommissioning Authority to operate the UK's waste vitrification plants at Sellafield.

VITRIFICATION DEVELOPMENT IN THE UK

The Waste Vitrification Plants at Sellafield are based on the French AVH (Atelier de Vitrification de La Hague) Vitrification Process. The original BNFL development programme on vitrification was aimed at supporting the HARVEST (Highly Active Residue Vitrification Experimental Studies) single stage batch process, but in 1979 BNFL decided to purchase the two stage AVM (Atelier de Vitrification de Marcoule) process. The AVM process had a higher design throughput than HARVEST, which was desirable given the need to reduce HAL stocks and the process used a calciner and a cylindrical melter. A Full Scale Inactive Facility (FSIF) replica of the AVM plant was installed at Sellafield, with the installation process starting in 1981 and completed in 1983. During that time, however, in 1982, a decision was taken that the UK's vitrification plants would be based on the second-generation French AVH vitrification process design. This decisions was based on the belief that only two AVH vitrification lines would be needed instead of the projected four AVM plants to meet the throughput requirements. The AVH is a larger plant than AVM with a larger calciner and an elliptical melter system. The operational differences due to scale and melter design between the AVM development rig (the FSIF) and the operational AVH plants were determined during WVP commissioning. Due, however, to programme and production pressures during the commissioning of WVP Lines 1 & 2, only a limited envelope of conditions was studied at full scale.

The vast majority of the development work, both laboratory and FSIF, was done on Magnox wastes. There were 30 FSIF Magnox campaigns including 15 full vitrification campaigns of around 20 - 30 pours each. By contrast there were only 2 full vitrification campaigns with Oxide wastes, and 2 campaigns of various blends of Oxide and Magnox waste. WVP Lines 1&2 were commissioned exclusively on Magnox simulants, whereas the majority of the waste processed through WVP during its lifetime will be blended waste.

Three trials were done at Marcoule with Magnox simulants. The third trial was done using an AVH type melter. In effect the third trial at Marcoule provided a bridge from the in-house development work on an AVM type plant to WVP operations with the AVH type plant.

In addition to the differences between AVM and AVH described above, the AVH process was installed in WVP with a different dust re-cycle system to that used on the FSIF, which is one reason why dust scrubber recycle problems encountered during WVP operations were not detected during the development work. The other reason is the fact that the FSIF campaigns were generally short and the dust scrubber was cleaned between campaigns which is why the long term effects such as blockages were not detected.

The Requirement for a New Vitrification Research Facility

It became clear that the design and operational differences between the AVM-FSIF and WVP led to a number of long term operability issues being missed during the development programme. The FSIF development work could be characterised as mostly a case study approach, which was adopted because the objective was to prove flowsheets with BNFL wastes and to confirm the glass product quality over a range of variations around those flowsheets. Operation and product quality for blended feeds has now been underpinned under a limited envelope of operating conditions. Changes outside of this envelope, for example increases in throughput and incorporation rate, require new technical work to provide the product quality case.

The UK government requires the HAL volumes stored at Sellafield to be reduced to buffer stock levels by 2015. The two original vitrification lines had under-performed their original design intent since operations began in 1991 and although a third line was opened in 1998 there remains a requirement to improve vitrification throughput rates in WVP lines 1, 2 and 3 to attain the UK Government's target.

Considering the ongoing requirement to further optimise the active vitrification lines, the significant benefits of a new research facility were recognised. A decision was taken to construct and operate a full-scale vitrification research facility, the Vitrification Test Rig.

THE VITRIFICATION TEST RIG (VTR)

The Vitrification Test Rig (VTR) has been built to provide a development tool to optimise and improve the operation of WVP. The facility is a full-scale inactive replica of the core vitrification processes on the active plants, with additional instrumentation and sampling capabilities, processing an inactive simulant representative of the HAL processed in WVP. The facility contains identical feed systems, calciner, melter and primary off gas systems to those on the active facilities, and was designed to be as representative as possible with similar detail down to length and angles of pipework.

The VTR represents significant research and development investment and demonstrates the commitment of the BNFL Group to reducing HAL stock levels. Following a year of commissioning the VTR was handed over to Nexia Solutions (BNFL Group’s research and development subsidiary) in October 2004.

Operating the VTR

In total around 30 people form the core VTR project delivery team, composed of an Experimental Team charged with planning, overseeing and reporting the experimental work, and the Operations Team responsible for the safe and accurate operation of the test rig. Nexia Solutions expert groups in the fields of Materials, Glass Technology, Waste Chemistry, Modelling and Operational Research support this core membership.

The facility is controlled via a Distributed Control System (DCS). The DCS allows the operations team to perform the majority of control procedures via computer screens, and plant monitoring is also possible using this system. In accordance with the requirements of an experimental facility the VTR is equipped with a wealth of additional instrumentation compared to the active vitrification plants. To assist the analysis of the significant amount of data generated by the equipment state of the art process monitoring software is installed allowing online and archived monitoring and trending of any captured process parameter(s). The system used is identical to that installed on WVP and allows easy comparison of inactive and active plant performance.

The VTR operates on a continuous 24-hour shift cycle for around 60% of the year, with the operations team returning to day support for the remainder of the time and this represents the most cost-effective way of operating the facility. Experimental work is based around 8 to 12-week operational blocks known as Campaigns, each with an overall aim but split into smaller sub-experiments as necessary.

It is important to perform extensive sampling on an experimental facility of this nature and numerous gas, liquid and solids sampling points are available covering all of the key process streams and unit operations. Sampling is regularly carried out on the feed systems, off gas effluent, calcine and the glass product and these are summarised in Table I. Nexia Solutions analytical teams perform analysis of the VTR samples, although outside contractors are utilised for some routine analytical work.

Table I. Summary of Sampling Performed on the Vitrification Test Rig.

Sample Type	Routine Analysis
HA Simulant	Acidity Density Elemental Composition Solids Content
Off-Gas Liquor	Acidity Elemental Composition Solids Content
Calcine	Bulk Density Elemental Composition Particle Size Distribution Residual Nitrate Content
Glass Product	Bulk Density Durability Elemental Composition Optical Analysis

Why Full Scale?

Due to significant radiological and cost constraints sampling of the highly active product glass is not performed as a matter of course. It is however essential to ensure confidence that the glass product meets requirements on physical properties, chemical resistance, radiation stability appearance and consistently represents a waste type that is suitable for storage, transport and ultimate disposal.

Without regularly analysing the glass produced the approach to product quality is based around defining the limits of product acceptability initially through laboratory testing then defining the process envelope by operating at full scale. The inactive glass product is comprehensively analysed to confirm that an acceptable waste form is generated throughout the innovative operations tested on the VTR. The analysis performed includes assessment of durability, bulk density, elemental composition, homogeneity and transition temperatures. New methods of digital glass analysis have been developed by Nexia Solutions to reduce time required to perform measurements such as percentage crystalline phase content in glass, and these developments also help move towards more quantitative methods of glass assessment than those used in the past.

THE VTR EXPERIMENTAL PROGRAM

British Nuclear Group currently funds Nexia Solutions to perform research on the VTR, with contracts between the two companies overseen by the NDA. This arrangement represents an industrial team dedicated to realising the UK Government's goal of HAL stock reduction, and ensures that the VTR experimental program is very focused towards satisfying the NDA's requirements of British Nuclear Group i.e. optimised management and operation of the UK's vitrification facilities. Detailed cost-benefit analyses are always performed prior to progressing an experimental Campaign to ensure that maximum benefit is derived from the planned experimental work. The short-term focus is on immediate improvement in throughput utilising existing equipment. Longer term there are other potential benefits, for example next generation equipment development.

Nexia Solutions, supported by British Nuclear Group, developed an experimental programme covering the first 2 years of operation on the VTR. This initial program was developed to target significant benefits in many areas of vitrification process technology including plant throughput, waste oxide incorporation, plant availability, glass formulation, expanded operational envelopes and product quality underpinning. The programme aims to help improve the vitrification plants by addressing the following three main areas.

- **Throughput** - Increase the glass production rate usually through optimisation of plant operating methodology. Throughput improvements of around 20% are being attempted by experimental Campaigns addressing this issue
- **Incorporation** - Increase the amount of waste that can be vitrified per product container. Incorporation improvement Campaigns are targeting a 12% increase in the amount of waste vitrified per product container in the short term, rising to 40% further on in the program.
- **Availability** - Potential availability improvements are usually included as part of Campaigns with one of the above wider aims, such as calciner heater failure recovery.

When a proposal for a specific period of work is completed by Nexia Solutions this information is presented to a Steering Group comprise of vitrification process experts and plant operations specialist from British Nuclear Group for peer review and acceptance. The Nuclear Decommissioning Authority also reviews the proposal. At this stage clear, well-defined deliverables and success criteria are agreed, which helps to ensure scope creep is avoided.

The experiments are then planned in detail and operated on the VTR. Results are reported back to the Steering Group when available, who review, accept and endorse the final reports. The reported information is the then available for implementation onto the active facility, and this is realised by an implementation group charged with prioritising and addressing improvements from the VTR and other initiatives.

The involvement of Nexia vitrification scientists is not limited to operating the VTR facility; they offer support and a consultancy service to the active facilities and interact regularly with the

Technical and Manufacturing Support teams on WVP. This close involvement with WVP ensures that the experimental proposals for work on the VTR take into account detailed understanding of the difficulties and requirements of the active plants, and keep the VTR process team informed of the issues faced by WVP.

OPERATIONAL CAMPAIGNS COMPLETED

As of November 2005, the first three operational Campaigns had been performed on the VTR facility. These campaigns involved baselining the equipment against the active vitrification facilities, operating at a 20% plant throughput increase and increasing the amount of waste oxide incorporated into the glass by 12% by weight.

VTR Campaign 1: The Calcination Baseline

The first operational Campaign on the facility commenced in November 2004 and involved benchmarking and optimisation of the calciner and off gas equipment. The behaviour of the inactive test rig was compared to that of the active vitrification facilities to provide confidence that future results would be relevant and transferable. This work was performed and compared to active operations at an identical throughput.

The next stage of the campaign involved operating the calciner system at an increased glass production rate equivalent whilst performing some optimisation of calcine properties, specifically to optimise particle size distribution and residual nitrate composition, and also to measure dust carry-over into the off-gas system. The aim of this work was to provide calciner setpoints for the following campaign involving the fully integrated VTR with the melter in place and ultimately to recommend operating parameters to the active plant to allow a similar throughput increase.

VTR Campaign 2: The Vitrification Baseline

The second operational campaign on the VTR was performed between February and July 2005. The main aims of this campaign were to baseline the integrated VTR (Calciner, off-gas and Melter system) against the WVP, and to derive an operational configuration to allow the throughput of these facilities to be increased by 20%.

The first VTR Campaign had demonstrated that the off-gas system and the calciner were able to comfortably operate at increased throughput levels. However, experience on the active vitrification facilities had demonstrated that the melter system had at times been unable to make the pour temperature criteria by the end of the calcine and glass feed period even during operations at the current WVP throughput. If this occurred feeds were stopped and temperatures allowed to rise until the glass melt was hot enough to meet the pour criteria. These periods in the absence of feeds, known as 'soaks', essentially represent plant unavailability and could therefore negate any time benefits in increasing the plant throughput if not addressed.

As throughputs, and hence the challenge on the equipment are increased it can be even more difficult to obtain the required melt temperatures at the end of the feed period. Therefore in order to enable the vitrification equipment to be operated at increased throughput a number of innovative operating regimes were tested during Campaign 2 with the goal of raising melter temperatures at the end of the feed cycle. These included new methods of controlling and operating the melter heating inductors, increased melt air sparge rates and duration of use, completing the glass charge into the melter faster than the calcine feed cycle and pouring from the melter system at lower temperatures than normal.

On completion of these trials a plant configuration was derived for a 20% throughput increase and a forty feed cycle baseline at this throughput was subsequently performed successfully on the VTR. From this work, operating parameters were recommended to WVP and phased implementation is planned for completion early 2006.

In addition to work relating to increasing vitrification plant throughput, the second Campaign also carried out trials to broaden the melter process envelope demonstrated to give acceptable product quality, leading to more operational flexibility.

VTR Campaign 3: Increased Incorporation

The third operational Campaign on the VTR was completed in September 2005. This Campaign was used to try to increase the amount of waste oxide incorporated into the product glass.

Operating envelopes for the calciner and melter were established at the new level of plant challenge. The calcination system was optimised for higher waste loading due to the required increased incorporation levels by varying zone temperatures to provide ideal calcine properties and minimised levels of dust entrainment in the off gas system. Aspects of the operation of the melter system were adjusted to provide the best possible internal melt temperatures at the completion of feeds. The methods implemented at this stage involved increased levels of sparging and variation of the method of batching glass and calcine into the crucible. An extended trial at increased waste oxide incorporation was successfully completed and from this work a recommended operating configuration for the active vitrification facilities is being compiled. This work is likely to be completed to implemented on WVP in summer 2006.

EARLY SIGNIFICANT SUCCESSES

Data from work performed on the VTR has already provided significant benefits to the UK's vitrification facilities. The glass product quality has been confirmed when pouring at relatively low temperatures from the melter system. If at the completion of feeds melt temperatures are lower than target, previously feeds were stopped to allow melt temperatures to rise to meet existing pour temperature criteria. The plant now has the option to initiate a pour provided the reduced pour temperature criteria are met thus avoiding lost production time whilst waiting for glass temperatures to increase.

Increased throughput and incorporation operations have been successfully operated on the VTR and from this work a number of plant configurations to enable a similar throughput increases have been or will be recommended to WVP. The phased implementation of this work onto the active plant has begun.

A number of new sensors relating to plant parameter measurement offering improved resolution and / or reliability have been tested during operational campaigns, some of which are now being installed on the active vitrification lines.

The potential HA liquor work off increases per hour of plant availability derived from the first three VTR campaigns is more than 30% if successfully applied to WVP. In addition, assuming a successful outcome of the work planned on the facility to April 2006, this figure could reach 50%. These increases would greatly assist British Nuclear Group in achieving the UK Government target of the reduction of HAL stocks to buffer levels by 2015. In addition, the potential cost savings of increased HAL work off and the value of risk reduction achievable by these successes are expected to run into £10M's and are likely to greatly exceed the capital costs of building and operating the VTR facility. These potential cost savings result from the reduced lifetime of the active facilities through the ability to vitrify the HA liquor volumes over reduced time periods.

Catalysts to Success

When considering the success of the facility to date a number of key areas are thought to contribute to the positive results obtained from the facility. British Nuclear Group as an intelligent customer can clearly describe their requirements of the VTR facility, and these requirements can then be translated into contract deliverables, which helps to focus the experimental work, reduce the possibility of scope creep and ensure Nexia Solutions delivery satisfies requirements exactly.

The level of investment in technical training for all staff levels has assisted the success of the project to date. Personnel on the project undergo detailed technical written and verbal assessments before being assessed as suitably qualified for the position they occupy. The operations team are highly motivated, and are trained to monitor the facility and experiments from a technical perspective in the absence of the experimental team, such as during night shifts.

The safe operation of the VTR facility is of maximum importance, and the commitment to safety has been demonstrated by the investment in the fail-safe design of the equipment along with significant time investment into job planning. Considered as important as the technical training investment, VTR staff undergo relevant safety training courses and actively participate in behavioural safety monitoring.

A policy of shared learning is adopted, the whole team including Operations, Experimental and support teams regularly meet to discuss the outcome of work and to generate ideas on how to overcome difficulties. This encourages contribution from individuals of numerous disciplines and backgrounds and tends to enrich the work performed on the VTR. This along with the significant investment in training and safety helps to encourage motivation and commitment from the staff.

FUTURE WORK

The majority of work during the first two years of operation (through to 2006) on the VTR facility is likely to be for British Nuclear Group in support of UK vitrification facilities considering throughput, incorporation and availability issues. Though not finalised, Nexia Solutions along with British Nuclear Group are developing a continued programme of work beyond 2006 including:

- The investigation of more dilute feed stocks, which would represent a change in emphasis from increasing the glass production rate of WVP to dealing with an increased liquor throughput of low concentration.
- Very high incorporation product for UK wastes to maximise the waste oxide loading per storage container.
- Processing of historic wastes on the Sellafield site with unusually high components of species such as chromium.
- Decontamination and decommissioning waste streams or wastes without a current management route.
- Design changes to vitrification process equipment such as mechanical stirrers within the melter

Even when considering these options, beyond 2006 there may be some spare experimental time on the facility not utilised by British Nuclear Group or the NDA. In that scenario it would be conceivable that the VTR could be applied to the requirements of alternative customers.

Whilst the facility currently represents a full-scale replica of WVP, the VTR is an excellent platform for the development of vitrification technology. Systems such as the calciner or melter could potentially be replaced or upgraded should a requirement for development of new vitrification systems, such as Cold Crucibles or new off-gas systems, arise.