UMo Solutions Processing in La Hague Cold Crucible Induction Melter: the Feedback From the First Years of Operation - 16376

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ABSTRACT

250 cubic meters of high-level liquid waste from reprocessed U-Mo-Sn-Al spent fuel, used in Gas Cooled Reactors (GCR), were produced during the mid-1960s at La Hague facility. These « UMo » solutions are less radioactive than the current fission product concentrates coming from ongoing reprocessing activities, but are very rich in molybdenum and phosphorus whose contents make the molten glass quite corrosive and require a high-temperature glass formulation to obtain sufficiently high waste loading factors (12% in molybdenum oxide). Hence the use of the Cold Crucible Induction Melter (CCIM) technology to process such solutions has been deemed a good opportunity for AREVA to meet its performance expectations.

In addition to being very corrosive, the UMo waste is quite challenging to process as the molybdenum has a strong tendency to stick in the calciner and causes clogging issues in off-gas treatment equipment. Therefore, the process and technological qualifications were deployed in order to address these specific issues.

UMo solutions processing in the La Hague CCIM has started in January 2013 and is currently ongoing. During this period (from 2013 to 2015), many data have been collected to confirm the process parameters that were defined during the qualification of this innovating process. Even if some difficulties occurred, operations teams experience along with engineering and R&D support allowed managing them.

This paper presents the start-up methodology and the feedback from the first years of UMo solutions processing with the CCIM technology at La Hague site. Lessons learned are presented with the difficulties encountered and the solutions implemented, emphasizing the benefits of a close integration between R&D, engineering and operations teams.

INTRODUCTION

Vitrification of high-level liquid waste is the internationally recognized standard to minimize the environmental impact resulting from radioactive waste disposal and the volume of conditioned waste. In France, high-level liquid waste arising from nuclear fuel reprocessing has been successfully vitrified for more than 35 years with three major objectives: durable containment of the long-lived fission products, minimization of the final waste volume and operational performance achieved in vitrification plants.

The CEA (French Alternative Energies and Atomic Energy Commission) and AREVA have acquired a unique experience in the field of high-level waste vitrification through continuous efforts to improve the technology (from hot to cold crucible melter) and the associated matrix formulations, with constant emphasis on quality and volume reduction, leading to the design and qualification of the Cold Crucible Induction Melter (CCIM) technology.

As a result, AREVA has replaced one existing Induction Heated Metal Melter (IHMM) in a production line in the R7 facility at La Hague plant by a cold crucible induction melter. Among others, this technology has three main advantages: vitrification of a broad spectrum of waste because of the upper reachable melt temperatures, increase of glass production capacity, and increase of melter lifetime because of the lower wall temperature (formation of a solid glass layer).

The CCIM started hot operation in April 2010 for the first time ever in a harsh environment at the La Hague R7 vitrification facility. The CCIM has now been in commercial operation for more than five years. The cold crucible deployment in La Hague facility was the culmination of several years of R&D led by the Joint Vitrification Laboratory (L.C.V), a common research laboratory between CEA and AREVA in charge of qualifying new processes and matrices for waste containment.

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CCIM VITRIFICATION PROCESS OPERATED IN R7 FACILITY

Industrial French Vitrification Design

In France, highly active liquid wastes are vitrified into a two-step vitrification process, shown schematically in Figure 1. In the two-step process, the feed solution coming from reprocessing operations is fed to a rotary calciner which performs the evaporating, drying and calcining functions. At the outlet of the calciner, the calcine falls directly into the melter along with the glass frit which is fed separately. The off-gas treatment unit recycles particulate material and purifies the gas streams, before stack release.

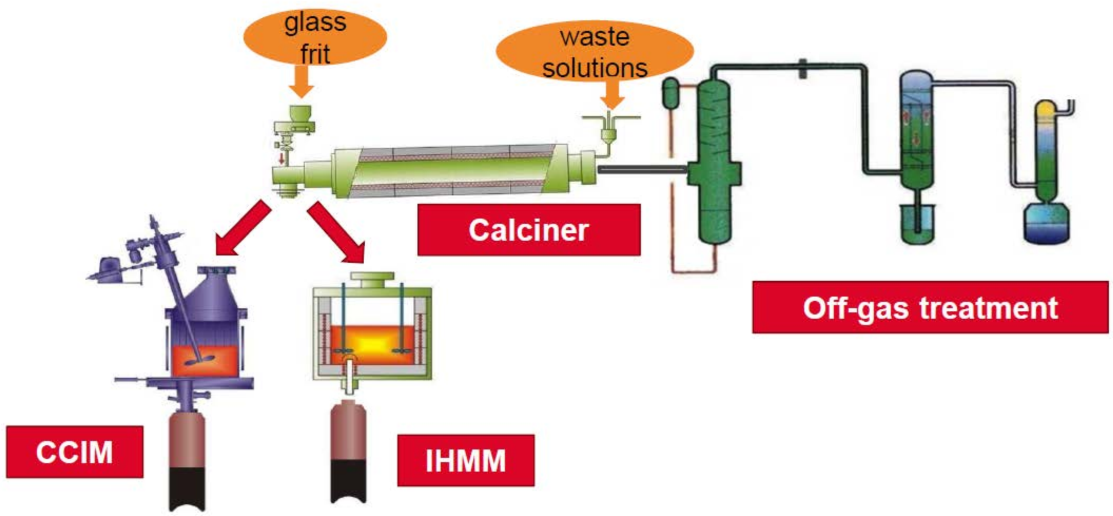

Fig. 1. Two-step vitrification process.

The calciner includes:

- a resistance furnace with four independent heating zones separated by interzone segments,
- a rotating tube,
- an upper end-fitting ensuring leak-tightness at the rotating upper end, with connections for exhausting the off-gas and for supplying the liquid feeds (vitrification feed solution, sugar and recycled solution),
- a lower end-fitting ensuring leak-tightness at the rotating lower end and guiding the calcine into the melter.

The calciner is controlled by assigning heating temperature setpoints to the electrical resistors. The calcining performance is observed by monitoring the heating power variations in each zone.

The off-gas treatment system is composed of a hot wet scrubber with weir plates (dust scrubber), a water and nitric acid vapor condenser, an absorption column, a washing column, a iodine filter, and three HEPA filters. The most active gas washing solutions are recycled from the wet scrubber to the calciner. The other solutions are concentrated in an evaporator before recycling into the vitrification facility. Off-gas treatment must be capable of ensuring a satisfactory decontamination factor in the gas exhausted from the calcining and glass production operations. Liquid samples can be taken from each of the four process devices to estimate the quantity of volatilized or entrained species. Each device is also supplied with level, temperature, and pressure measurements.

Direct Induction Vitrification Principles and Advantages

The direct induction process is characterized by currents directly induced inside the molten glass by a coil (Figure 2). These electromagnetic currents heat the glass inside the melter by the Joule effect. The segmented structure of the crucible enables penetration of electromagnetic field into its volume. Absorption of electromagnetic radiation allows the glass to be heated directly without heating the crucible.

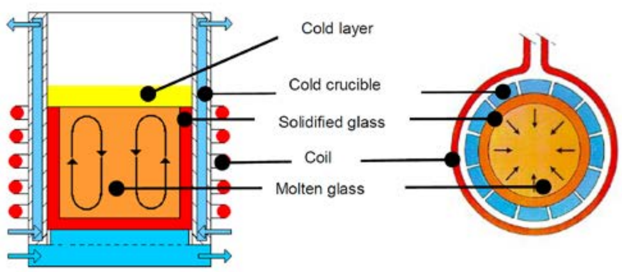

Fig. 2. Direct induction melting principle

The CCIM technology presents a number of major advantages.

First, cooling of the crucible forms a solidified layer of glass which coats the surface of the crucible in contact with the glass. This skull layer protects the crucible from the corrosive melt. The cooling of the crucible protects from corrosive vapours.

Second, the direct induction heating method allows the temperature to be increased (beyond 1300°C for some new matrix formulations still being tested) making it possible to obtain new waste containment matrices which would have been impossible to produce with the hot metallic melter.

Finally, when integrated into the two-step vitrification process (calcining and vitrification), as is the case in the R7 facility at La Hague, the CCIM technology allows the industrial vitrification throughput to be significantly increased. The higher temperature allows a faster calcine digestion by the glass, and consequently allows continuous feeding (no soaking period before pouring).

This technology can be used to vitrify various types of chemical waste. By allowing higher waste loading it also minimizes the volume of packaged waste. Furthermore, the presence of the cold layer minimizes the impact of the composition of the waste on the lifetime of the crucible.

CCIM Design Principles

The CCIM is composed of the following elements (Figure 3):

- The metallic crucible shell, which is a segmented structure, transparent to the electromagnetic field. The cooled sectors are separated by electrical insulators.
- The crucible bottom (slab), which includes the pouring valve. A cooled duct links the crucible to the container.
- The crucible is topped by a dome which supports a mechanical stirrer.
- Glass level and temperature are continuously measured by specific sensors.
- Bubblers are positioned on the crucible slab.

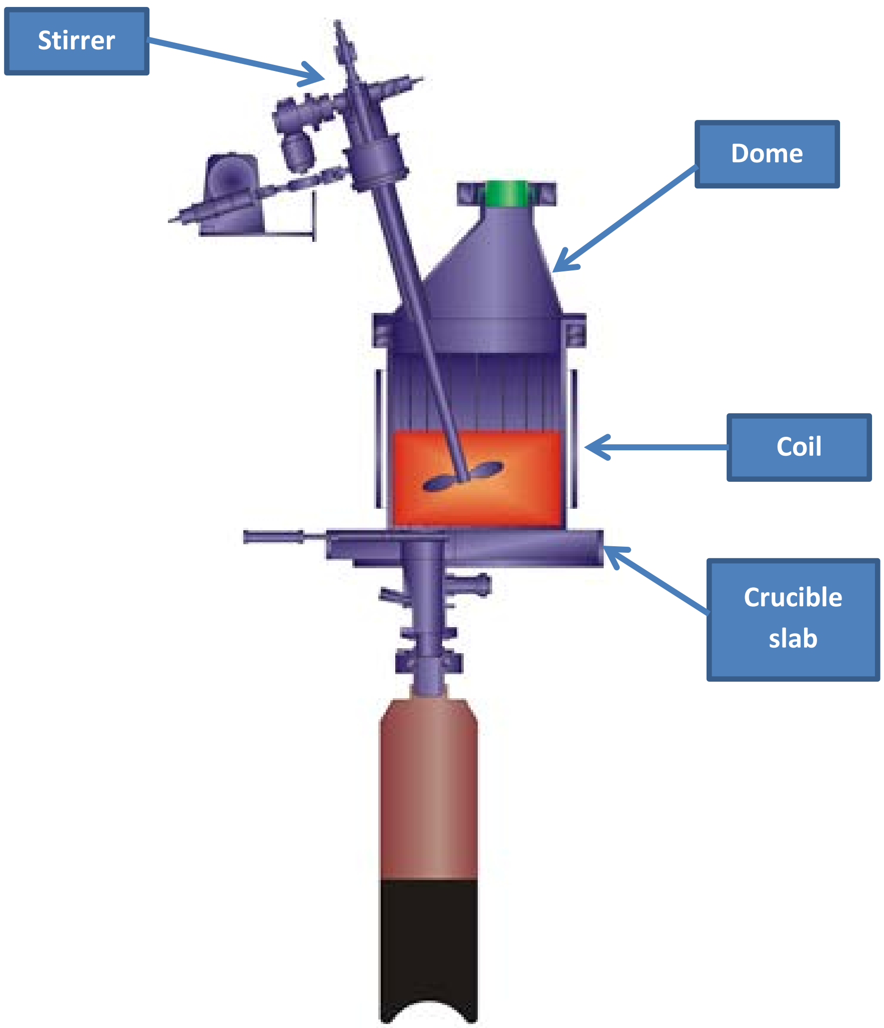

Fig. 3. Schematic drawing of a CCIM.

The crucible power supply comprises:

- A high-frequency generator with an output of around 400-600 kW.
- A high-frequency power line.
- A copper coil surrounding the crucible.

CCIM Deployment at La Hague

In April 2010, a CCIM started hot operation for the first time ever in an existing very high active facility (R7) at La Hague. This was the culmination of more than two decades of R&D involving progressive process and technological development. The design and implementation phases for the industrial deployment were described in a previous paper at WM [1]. The main stages are detailed hereafter.

1981 The first R&D CCIM prototype was put into service (350 mm in diameter).

1983 The feasibility of vitrification by electromagnetism was demonstrated. The reliability and endurance of the process were demonstrated by 800 hours of remelting inactive glass.

1985 **Industrialization phase 1**. A larger R&D CCIM was built (550 mm in diameter).

1987 The continuous two-step vitrification process of R7T7 glass was demonstrated with a reduced capacity mock-up in 175 hours of inactive melting.

1992 AREVA NC decided to study the implementation of the cold crucible.

1997 A 650 mm diameter R&D CCIM was built and tested (calcining-vitrification operation) with an industrial-range capacity for almost 3,000 hours (inactive tests).

2000 **Industrialization phase 2**. A specific CCIM prototype was designed and built for the specific purpose of the vitrification of highly corrosive UMo fission product solutions resulting from the recycling of legacy GCR fuels.

2004 AREVA NC decided to implement a CCIM in R7.

2005 Engineering (AREVA NP E&P) started the preliminary design phase of the R7 CCIM.

2006 **Industrialization phase 3**. A “nuclearized” R&D CCIM prototype was built, adapted to the La Hague vitrification process and environment. This CCIM was designed to vitrify a large variety of waste. It was used in Marcoule to qualify the process and glass quality. More than 6,000 hours of testing have been conducted on this platform.

Engineering (AREVA NP E&P) started the Detailed Design phase of the R7 CCIM.

2007 Construction in AREVA's Beaumont testing and development laboratory (HRB) of a full-scale test platform identical in every way to the hot cell environment of R7 facility. This platform was used to carry out tests outside the nuclear zone and train personnel in 2008 and 2009.

2008 **Industrialization phase 4**. A fully nuclearized industrial CCIM was built to be implemented in the R7 facility. This one was eventually used to qualify the equipment in the HRB.

Start of manufacturing and installation of the industrial CCIM in R7 facility.

2009 Start of commissioning and inactive tests of the CCIM implemented in the R7 vitrification facility (5 "inactive" canisters).

2010 First active operation of the CCIM implemented in R7 vitrification facility

Five D&D effluents vitrification campaigns (decontamination effluents from the La Hague UP2-400 facility D&D operations) conducted from 2010 to 2012.

2013 First industrial vitrification of legacy UMo waste (high-level liquid waste from reprocessed U-Mo-Sn-Al spent fuels) in La Hague cold crucible melter.

UMO GLASS CONTAINMENT FORMULATION AND LONG-TERM BEHAVIOR

The general qualification method for the UMo containment glass formulation was described in a previous paper at WM [2].

The main features of UMo legacy solutions are indicated in Table I.

Table I. Main characteristics of UMo solution

Composition (g/L)	MoO_3	137
	P_2O_5	42
	Na_2O	11
	Other	26
Volume		250 m^3
Activity		< 222 × 10^{10} Bq/L

Considering the elements present in the UMo high-level waste feed solutions, the molybdenum and phosphorus loading capacity of the glass has been critical for the waste loading capability of the containment matrix.

The reference UMo glass from the containment glass formulation qualification, SUMo2-10d, is a vitreous material fabricated at 1250°C. It is an opaque glass-ceramic. In the molten state the melt is homogeneous, but tailored phase separation and crystallization phenomena occur after cooling in the canister. The glass-ceramic is characterized by secondary phases dispersed in an encapsulating borosilicate glass matrix. The reference UMo glass composition is indicated in Table 2.

Table II. UMo reference glass composition (wt%)

SiO_2	38.7
Na_2O	9.4
B_2O_3	13.9
Al_2O_3	7.1
P_2O_5	3.1
MoO_3	10.0
ZnO	6.0
ZrO_2	3.3
CaO	6.1
Other	2.4

The molten glass properties are compatible with fabrication in a cold crucible melter: viscosity of around 40 dPa·s at 1250°C and electrical resistivity of about 7 Ω·cm at 1250°C. The maximum range of molybdenum and phosphorus content in the final glass determine the melting temperature range, which must be higher than the phase separation temperature in order to maintain a homogeneous melt in the crucible. The phase separation temperature depends on the molybdenum and phosphorous concentrations in the glass.

The physical and microstructural properties of the UMo glass in the solid and liquid states were determined over the full specified range of compositions and process operating parameters.

The long-term behavior of the matrix was also investigated, and particularly the matrix behavior under irradiation (UMo glass doped with americium and curium) and its leaching resistance.

The data from the leaching tests, carried out on glass samples synthesized in a cold crucible melter under conditions representative of the industrial process, confirm that the chemical durability of the glass-ceramic matrix is comparable to homogeneous borosilicate glasses for the alteration rate regimes investigated (initial rate and rate drop with time).

The result of the irradiation behavior study (doped glass) confirms its stability under irradiation.

The packages of the UMo vitrified fission products are known as CSD-U canisters.

TECHNOLOGICAL AND PROCESS QUALIFICATIONS

CCIM Qualification

Qualification of the CCIM process, for UMo glass production, has consisted of different types of full-scale pilot tests with inactive surrogate solutions. These tests, carried out by the LCV's R&D team at Marcoule in a full-scale pilot of the industrial process including the CCIM, are described below.

- The nominal tests have defined the nominal parameter values which guarantee that the industrial-scale glass has the same characteristics as the laboratory reference glass.
- The sensitivity tests have validated an operating range for operating parameters over the entire composition domain, to maintain the nominal throughput.
- The transient mode tests have defined the operating parameters adjustments necessary to guarantee the chemical composition and microstructure of the final glass and to avoid strong volatility during transient phases.
- The degraded mode tests have defined the operating parameters to preserve the process equipment and the material properties. Detection means have been determined and management procedures have been defined.
- Finally, a 21 day endurance test has demonstrated that the process is reliable, and that the material properties of the product remain constant over time.

The cold crucible melter control modes were defined by the LCV process licensor. They are specified in the process data book, which includes three levels of information, in accordance with the scope of LCV responsibilities:

- The requirements from the LCV process licensor.
- The operating recommendations based on LCV experience and on the limits of the test program.
- The lessons learned from operating experience.

Another full-scale pilot of the CCIM is installed in AREVA's Beaumont testing and development laboratory (HRB). This pilot-plant is a full-scale replica of R7 vitrification cell and process without calciner and with a simplified off-gas treatment system. It is specifically devoted to technological development for the CCIM nuclearization and to defining some additional operating parameters and procedures as well as maintenance procedures for application to the industrial facility. This pilot is operated by AREVA NP E&P Fuel Cycle Engineering teams.

Specific Qualifications

UMo solutions have a strong tendency to stick in the calciner due to the high molybdenum content. The calcining parameters (heating power of each zone and rotation speed) have therefore been defined by specific tests without vitrification, and optimized during the qualification process for various throughputs. The feed solution composition adjustment has also been defined during the inactive qualification. Compliance with calcining and composition adjustment parameters ensures that a proper calcine is obtained and prevents sticking issues.

Qualification of the cold crucible melter for vitrification of UMo solutions also required changes in the process: specific devices, at the outlet of the calciner, were defined and qualified to limit the sticking of molybdenum from calcining and vitrification exhaust stream in off-gas treatment equipment.

FIRST UMO VITRIFICATION CAMPAIGN

On January 3, 2013, a “witness” campaign of UMo waste vitrification was carried out in the R7 facility CCIM. This “witness” vitrification campaign lasted 5 days with the following objectives:

- Validate the calcining and adjustment parameters defined during inactive tests.
- Validate the efficiency of the devices implemented at the calciner outlet with respect to molybdenum sticking behavior.
- Check that the process parameter values are consistent with those obtained during inactive tests.
- Check the stability of the process parameters in nominal operation.
- Check that the operation of the off-gas treatment system is consistent with the results obtained during inactive qualification.
- Check that the energy balance is consistent with the results obtained in the inactive pilot facility under similar operating conditions.
- Check for satisfactory equipment operation and endurance.

A specific organization was set up for the first UMo solution vitrification (CSD-U) campaign, with the following participants:

- The industrial operator of the vitrification units: AREVA NC.
- The Joint Vitrification Laboratory (LCV) as process licensor.
- AREVA NP E&P (Engineering & Projects).

The feedback obtained with the two inactive prototypes (at Marcoule and Beaumont) was used to verify that the operation of the equipment, during the “witness” run, was consistent with the inactive tests.

During this “witness” campaign, the operating parameters were monitored by support teams from the LCV (R&D) and AREVA NP E&P (engineering). The operation of the main equipment on the vitrification line was analyzed in real-time and advices and recommendations were provided during the daily debriefing meetings. When necessary, control adjustments were implemented to improve process performance.

Process parameters were monitored and analyzed in the following areas:

- Energy balance; Thermal parameters
- Electrotechnical parameters

- Technological operation of the melter (stirring, bubbling, glass pouring, etc.)
- Calciner operation
- Off-gas treatment process operation
- Material feeds; Material balance.

The organization set up between the industrial operator, the process licensor, and the engineering teams ensured a detailed analysis of process operation with precise diagnostics of process performance. Some process control adjustments were applied during this “witness” run, they allowed improving performance of the process.

This “witness” campaign demonstrated the feasibility of vitrifying UMo fission product solutions in a cold crucible melter at industrial scale. The operation of the vitrification line was satisfactory and confirmed the results obtained in the R&D and technological development facilities.

This “witness” UMo vitrification campaign was described in a previous paper at WM [3].

FEEDBACK FROM THE FIRST YEARS OF OPERATION

As of June 30, 2015, four UMo solutions vitrification campaigns have been performed; it represents 96 CSD-U canisters produced.

UMo solutions are very hard to process because of the high molybdenum and phosphorus contents. The main features of the waste behavior in the process are detailed hereafter.

- The melting glass is very corrosive.
- The solutions have a strong tendency to stick in the calciner.
- Vitrification and calcining exhaust stream may cause strong clogging issues in off-gas treatment equipment.

The feedback from the first UMo campaigns is presented with regard to these specific issues.

CCIM Operation

Analysis of the process parameters showed satisfactory overall operation of the CCIM during UMo campaigns. For each UMo vitrification campaign, the following elements are noteworthy:

- Analysis of cross-checking parameters (energy balance) revealed no process drift. The electrotechnical parameters obtained during the campaigns were stable and comparable to those obtained during inactive qualification tests. The electrotechnical operation of the process was satisfactory and matched the expected performance.
- The operation of the stirrer was satisfactory. The various descent cycles were suitable and did not create any significant heterogeneity in the molten glass.

Operating feedback from the prototypes permitted satisfactory management of transient modes associated with the stirrer.

- The bubblers and glass level specific sensor allowed monitoring the mass of glass in the melter. The bubblers process parameter values were consistent with the material balance, and confirmed the absence of variations in the feed and in the composition of the poured glass. The glass level specific sensor values confirmed the feed stability. The bubblers and glass level specific sensor operated as expected.
- The melter draining pours were performed satisfactorily. The process control parameters applied ensured that the melter was emptied in satisfactory conditions. The residual amount of glass remaining in the melter is low, it corresponds to the glass skull present during its operation and to a small fraction of the melt that remained in the crucible after draining.
- Special attention was paid to the CCIM integrity after each UMo campaign owing to the very corrosive characteristic of the UMo glass and observations were always the same: The remaining glass was easily detachable and did not adhere to the melter structures. Inspections of the melter after removal of the remaining glass showed that its structure was clean and corrosion-free.
- Expected throughputs for each UMo campaign were achieved. Continuous feeding was operated during each campaign and did not cause any particular difficulties.

The melter operation, during the UMo campaigns, was satisfactory and confirmed the results obtained in the R&D facilities. The expected performances of the CCIM, in terms of protection of the equipment, are validated on an industrial scale. The expected performances in terms of production capacity are also validated on an industrial scale.

Calciner Operation

Special attention was paid to calciner operation in relation to the sticking issues in this part of the process.

UMo solution composition was adjusted in compliance with the recommendations of the CEA process licensor. Calciner parameters — feed rates, heating power values, and rotation speed — were also applied in compliance with the recommendations of the process licensor (during the calciner start-up phase and in nominal operation). The heating power values in the four zones of the calciner were stable throughout the campaigns. This satisfactory result shows that there was no drift in the liquid feed streams — and in particular no clogging.

Compliance with UMo solution adjustment parameters and calcining parameters, defined during the R&D phase, allowed producing a satisfactory calcine and prevented sticking issues in the tube. Analysis of the calciner process parameters revealed satisfactory calciner operation and validated the qualification obtained under inactive conditions. The interior of the calciner was inspected after each campaign and the tube was found to be clean, confirming that no sticking occurred in operation (Figure 5).

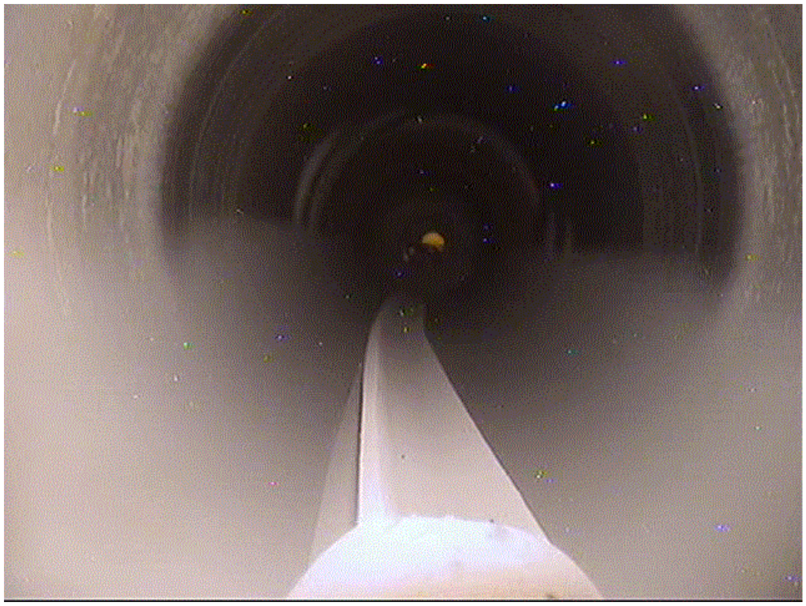

Fig. 5. Interior of the calciner after the first UMo campaign

Off-gas Treatment Operation

Special attention was paid to the off-gas treatment operation in relation to the clogging issues in this part of the process.

The duct from the calciner to the scrubber can be critical with respect to clogging by molybdenum compounds. Specific devices, at the outlet of the calciner, were therefore defined and qualified to limit the sticking of molybdenum from calcining and vitrification exhaust stream. The process parameters in this part of the process were also specifically monitored during the UMo campaigns. In particular, the pressure drop variation in this duct was monitored as a good indicator of the degree of clogging. During operation the increase in the pressure drop over time was consistent with what is generally observed in the inactive prototype in similar configuration. The process control recommendations defined by the LCV and applied by the operators ensured satisfactory operation of this functional unit.

Specific process control parameters for the dust scrubber were applied (with respect to molybdenum clogging behavior) in accordance with the ones defined during the process qualification (inactive tests). The liquid density at the bottom of the scrubber, indicative of acidity, was consistent with what is generally observed in the inactive prototype at the same feed rate.

The implementation of specific devices at the outlet of the calciner and the recommendations defined by the LCV and applied by the operators ensured satisfactory operation and allowed reducing clogging occurrence. During these UMo campaigns, the off-gas treatment operation was satisfactory, remained stable and matched the expected performance. The downtime arising from clogging issues is low.

Improvements Implemented

Different optimizations have been deployed on the CCIM since its industrial commissioning. These optimizations are technological evolutions of the process in adequacy with its maturity. These improvements are mainly related to compliance with high glass throughputs and decrease of downtime arising from maintenance operations. Some are detailed hereafter.

Temperature Sensors

The CCIM allows the temperature to be increased compared to the other vitrification processes. This makes it possible to obtain new waste containment matrices which would have been impossible to produce with other vitrification processes. Glass melt temperature is therefore an important operating parameter and its control is a key component for glass quality (in terms of long term behavior) and production throughput. The achievable temperatures are usually above the temperatures that can be withstood by conventional thermocouples.

Temperature measurement in the R7 cold crucible is performed via two partially cooled rods immersed in the melt. This technology was developed by the LCV in collaboration with AREVA NP engineering teams and is subject to protection of intellectual property (patents) [4].

The feedback from R&D on the CCIM temperature specific sensor operating highlighted the need to enhance reliability of this functional unit. Thus technological developments have been continuously implemented on this device to enhance its industrial performance. The technological developments have been led by the R&D teams in collaboration with engineering teams. They cover the following items:

- Improvement of mechanical properties of some elements of the equipment.
- Optimization of materials used.
- Optimization of the design of the equipment, especially to improve the cooling.

The long-term operating of these optimized rods, in the inactive prototypes, allowed validating the optimizations implemented and the equipment qualification. Lessons learned from active campaigns in R7 facility with these optimized rods demonstrated a reliability improvement.

The optimizations developed by the R&D teams in collaboration with the engineering teams allowed significantly increasing the lifetime of the cooled rods temperature sensors. Reliability of this equipment is now compatible with long term production vitrification campaigns.

Bubblers

Bubblers are important devices of the CCIM, in particular they contribute to the proper reactivity of the glass (proper digestion of cold products arriving on the surface of the molten glass). The feedback from the various R&D tests carried out on the inactive prototypes highlighted that a degradation of the bubblers, in the first design developed, could occur for certain operating modes.

Thus a phase of R&D aimed at increasing lifetime of bubblers was deployed over the period 2013 – 2014. This phase of R&D led to several optimizations of the bubblers. These optimizations were validated and qualified on the R&D prototypes and then implemented on the industrial CCIM (in R7 facility) in 2014.

The industrial CCIM in R7 facility is now equipped with the latest design of bubblers. Their lifetime has been significantly increased.

Operating an efficient and sustainable bubbling in corrosive glasses, at very high temperature is a challenge that was met by the R&D and engineering teams. These optimizations allowed increasing the reliability of the cold crucible and limiting the downtime arising from maintenance operations.

Maintenance Operations

The CCIM has been developed with a modular and removable design. In this way, majority of the CCIM devices are remotely-dismountable and can be separately replaced (dome, measuring rods, bubblers, pouring valve, stirrer, …).

The stirrer was in particular designed to be dismantled in hot cell and thus to allow replacing some mechanical parts of the equipment if necessary. In 2013, a replacement operation for a bearing was programmed and successfully performed. This operation is a major demonstration of the high level of maintainability of the CCIM.

The remotely-removable design, augmented by both the high knowledge and experience of the operators and the support of a full-scale pilot enabling qualification of remote maintenance procedures, allows some high level maintenance operations and thus increasing the overall efficiency of the vitrification line.

It should also be noted, that so far, the low level of contamination of the CCIM, due to the solid glass layer which protects the surface of the melter, allowed the operators to carry out hands-on maintenance operations for certain devices of the CCIM. The reason is that the glass does not adhere to the melter structures thereby significantly reducing the final CCIM level of contamination once the solid glass layer is removed prior to maintenance hands-on tasks.

CONCLUSION

UMo solutions processing in the La Hague CCIM has started in January 2013 and is currently ongoing. These UMo solutions are very hard to process because of the high molybdenum and phosphorus contents which make the molten glass very corrosive and also cause severe sticking issues in the calciner and clogging issues in the off-gas treatment equipment.

Analysis of the process parameters showed satisfactory overall operation of the CCIM. The electrotechnical parameters obtained during the campaigns were stable and comparable to those obtained during inactive qualification tests. The bubblers, glass level specific sensor and stirrer operated as expected. The melter operation, during the UMo campaigns, was satisfactory and confirmed the results obtained in the R&D facilities.

Expected throughputs for each UMo campaign were obtained and continuous feeding was operated without difficulties. The expected performances of the CCIM, in terms of production capacity, are validated on an industrial scale.

Special attention was paid to the CCIM integrity after each UMo campaign owing to the very corrosive characteristic of the UMo glass and observations were always the same: The remaining glass was easily detachable and did not adhere to the melter structures. Inspections of the melter after removal of the remaining glass showed that its structure was clean and corrosion-free. The expected performances of the CCIM, in terms of protection of the equipment, are validated on an industrial scale.

Special attention was paid to calciner operation in relation to the sticking issues in this part of the process. Analysis of the calciner process parameters revealed satisfactory operation and validated the qualification obtained under inactive conditions. Compliance with solution adjustment parameters and calcining parameters produced a satisfactory calcine and prevented sticking issues.

Special attention was paid to the off-gas treatment operation in relation to the clogging issues in this part of the process. The implementation of specific devices at the outlet of the calciner and the recommendations defined by the LCV and applied by the operators ensured satisfactory operation and allowed reducing downtime from clogging. During these UMo campaigns, the off-gas treatment operation was satisfactory, remained stable and matched the expected performance.

Several optimizations have been implemented on temperature sensors and on bubblers. Their lifetime has been significantly increased. Reliability of these devices is now compatible with long term production vitrification campaigns. These optimizations allowed increasing the reliability of the cold crucible and limiting the downtime arising from maintenance operations.

The modular and remotely-dismountable design of the CCIM, augmented by both the high knowledge and experience of the operators and the support of a full-scale pilot enabling qualification of remote maintenance procedures, allows some high level maintenance operations and thus increasing the overall efficiency of the vitrification line. Major demonstrations of the high level of maintainability of the CCIM have been performed.

The feasibility of vitrifying highly corrosive UMo fission product solutions in a cold crucible melter at industrial scale has been demonstrated. The operation of the vitrification line was satisfactory throughout the UMo campaigns and confirmed the results obtained in the R&D and technological development facilities.

Vitrifying UMo fission product solutions in a cold crucible melter is a world premiere; it is the outcome of more than 20 years of R&D and close collaboration between R&D teams, engineering teams and the industrial operator.

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