

**Demonstration of the Cold Crucible Induction Melter Technology under the
US DOE EM Advanced Remediation Technologies (ART) Program - 9237**

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ABSTRACT

Cold Crucible Induction Melter (CCIM) technology is considered for industrial-scale implementation at nuclear facilities around the globe to extend the current limits of high-level waste (HLW) vitrification technologies. This paper provides a comprehensive summary of the results of the Phase II-A project awarded to AREVA Federal Services LLC (AREVA) by the US Department of Energy (DOE) and funded under the Advanced Remediation Technologies (ART) program. This contract followed Phase I of the ART program, during which AREVA assessed the feasibility and benefit of integrating a CCIM co-developed by AREVA and the Commissariat a l'Energie Atomique (CEA) into the Melter Cell at the Savannah River Site (SRS) Defense Waste Processing Facility (DWPF) in place of an existing joule-heated melter. The ART CCIM Phase II-A project is a 21-month effort that combines the resources of two US National Laboratories - Savannah River National Laboratory (SRNL) and Idaho National Laboratory (INL) - and two French nuclear engineering and process development organizations (CEA and SGN). The paper describes the results of laboratory work and pilot-scale demonstration runs, and the key findings of engineering studies that show: 1) increase in waste loading levels in the glass product which may allow processing SRS HLW faster than can be achieved with the existing DWPF melter, 2) production of a glass product that is more durable than the standard Environmental Assessment (EA) glass, and 3) feasibility of installing and maintaining a CCIM within the existing DWPF Melter Cell.

INTRODUCTION

CCIM technology is considered for industrial-scale implementation at nuclear facilities around the globe to extend the current limits of HLW vitrification technologies. The capabilities of CCIM technology answer challenges in HLW processing in the critical areas of immobilizing difficult effluent compositions (including corrosive effluents) and improving waste loading. Higher temperature operation, higher waste

throughput capacity, longer melter life, remotely replaceable key components, and lower equipment cost are the main advantages of that technology compared to existing joule-heated melter technology.

In September 2007, DOE awarded AREVA with the second phase of a project funded under the ART program of the Office of Environmental Management. This ART CCIM Phase II-A contract follows Phase I of the ART program (August 2006 through January 2007) during which the AREVA-led project team assessed the feasibility and benefit of integrating a CCIM into the Melter Cell at the SRS DWPF in place of an existing joule-heated melter.

Phase II-A combines the resources of US National Laboratories and French nuclear engineering and process development organizations who worked together successfully during Phase I of the project, assembling years of experience in development, design, deployment, and operation of HLW vitrification processes and unique knowledge of DWPF configuration and operations. Participants in Phase II-A include:

- CEA, co-developer with AREVA of the proposed CCIM technology and operator of several CCIM melters at their research facility in Marcoule, France,
- SRNL and Washington Savannah River Company (WSRC - URS), who provide R&D, analytical, and engineering support to DWPF operations,
- INL, who operates a pilot-scale CCIM test platform and provides expertise in characterization, monitoring and control of off-gas associated with HLW vitrification processes, and finally
- SGN, an AREVA group affiliate, who engineers industrial-scale HLW vitrification facilities and is currently executing a project to retrofit CCIM technology into an operating facility at AREVA's La Hague reprocessing plant.
- AREVA Federal Services LLC, the North American affiliate of AREVA who provides project management, technology integration, and project engineering services to many DOE offices and field sites.

The phased approach of the ART CCIM project provides DOE with a technically sound and cost effective means for making path-forward decisions regarding CCIM technology. The objectives of this stepped approach are directly aligned with the main objectives of the ART program through which DOE-EM funds demonstrations of new technologies to address significant cleanup challenges at DOE sites, including Hanford, Savannah River, and the INL. Applying CCIM technology co-developed by AREVA and CEA to immobilize DOE legacy waste streams requires laboratory work and large-scale demonstrations to verify the details of the process and ensure defined objectives can be met. From an engineering perspective, applying this technology by means of retrofit into an existing facility also requires an assessment of the feasibility that such retrofit can be accomplished – both technically and cost-effectively. Initial studies in the areas documented in the project's Phase I suggested an effective process could be developed and a successful retrofit design could be defined. The project's Phase II has been organized to validate these determinations. With respect to process development, Phase II-A was defined to build on previous demonstrations of CCIM technology and validate the effectiveness of the CCIM process for the most challenging waste streams considered for treatment at DWPF. Phase II-A relies on laboratory studies conducted by SRNL and CEA and on demonstration runs on existing pilot-scale facilities owned and operated by INL and CEA. This approach minimizes the costs incurred until strong evidence is assembled to support decision-making regarding eventual technology deployment. With respect to engineering, Phase II-A was planned to validate the conclusion that retrofit is technically feasible, and to perform the first steps towards identifying a design that is both cost-effective and offers the optimal configuration for operability and maintainability.

The main objectives of Phase II-A for the AREVA-led project team are to:

- Perform laboratory studies and testing activities at SRNL and at CEA Marcoule to design a glass matrix which allows waste loading of the order of 50wt% with a Sludge Batch 4 (SB4)-type waste composition (versus the current DWPF process capability for this feed at about 33wt%).
- Run pilot-scale demonstrations under representative conditions on existing CCIM research platforms at Marcoule and at INL, with analytical support from SRNL, to validate the promising waste processing rates expected when processing in the 1,250-1,300 deg C melt pool temperature range.
- Perform specific engineering studies of key technical issues identified in Phase I that validate the feasibility of retrofitting CCIM technology into the DWPF Melter Cell.
- Develop a comprehensive plan (including cost and schedule) for laboratory-testing, pilot- and large-scale demonstrations, and engineering activities to be performed during Phase II-B of the project.

The narrative which follows describes the execution of this project phase, summarizes the conclusions which have been identified, and looks forward to the tasks which are to be accomplished in order to complete CCIM deployment at DWPF.

PROJECT PLANNING

ART CCIM Phase II-A was designed as a stand-alone project under the management of AREVA Federal Service's Richland Office. A Project Management Plan (PMP) consistent with best management practices was prepared for this project phase, including a detailed working schedule and Work Breakdown Structure elements. Resource loading of the schedule was accomplished to provide basis for performance monitoring and reporting using Earned Value Management techniques. The final Project Management Plan and schedule were approved and submitted to DOE-EM per contract requirements in December 2007.

Each participating organization designated a lead to guide the performance of tasks assigned to them. These leads, along with the project manager, constituted a de facto project management team to coordinate and guide tasks performed at sites around the globe. Close communication by means of regular teleconferences were held over the term of the project to ensure effective coordination among participants. Also, several group meetings were held at SRS and other sites over the course of the project phase, to foster dialogue on technical issues and plans. These efforts were successful in ensuring all contributors could reach agreement on difficult technical topics.

Monthly reports consistent with the PMP have been prepared and circulated over the term of the project, to provide participants and DOE-EM representatives with a current summary of the project's status, accomplishments, current problem areas, planned actions, and Earned Value performance data.

Refinement of Phase II-A Objectives

In early project work, technical discussions were held among contributors regarding the simulated waste to be used for lab studies and demonstration runs. Work on defining the chemical composition of surrogate waste and the fabrication protocol for same was initiated by the circulation of a bibliographic study based on available data in December 2007. This study reviewed theoretical and actual waste compositions for HM-type waste (a waste form with a high aluminum content) stored at SRS and immobilized at DWPF, typical fabrication protocols, and the impact of the pretreatment steps actually performed at DWPF. Current DWPF processing requires the waste stream to be pretreated by means of acid addition and re-boiling to a final melter feed state, to establish target REDOX conditions in the melter and to control rheology of the melt feed.

A summary of technical topics and test objectives was circulated to contributors in December 2007, in order to focus subsequent team discussions and document reviews on the key elements to be considered in Phase II-A. This was followed by a project meeting held at SRS in January 2008 to refine specific details regarding the project's objectives and the approaches which were to be used by participants to achieve them. Work accomplished at this meeting included:

- Agreement on the Phase II-A waste composition;
- Initial discussion of fabrication protocol for simulated waste.
- Review of lab facilities used by SRNL to prepare and analyze glass samples;
- Agreement on path forward for collecting engineering design input data;
- Initial discussion of objectives for demonstration runs at CEA's Marcoule pilot-scale facility.

A Basic Data Summary report was prepared in January 2008 to provide the general technical framework and requirements used to develop the Phase II-A process validation (demonstrations) and preliminary engineering design work. Topics covered included waste forms to be vitrified at DWPF, waste loading for the current melter technology, qualified waste pre-treatment processes, melter feed preparation and melter feed rheology, frit compositions, pouring and canister handling, off-gas treatment processes, and the physical configuration of the existing melter cell.

The specific Phase II-A simulated waste composition to be used for lab-scale testing and pilot-scale demonstration activities was defined in the form of a project communication in February 2008. The selected composition simulates DWPF's Sludge Batch 4, an HM-type waste with relatively high alumina content that is difficult to process with the current technology and that had already been extensively studied (including for glass frit formulation). This selection allowed for subsequent project work to define laboratory tasks and plan demonstration runs.

LABORATORY STUDIES

With the simulated waste composition defined, a laboratory plan for glass formulation development and testing was defined by SRNL. Based on a review of previous glass formulation testing in support of demonstrations associated with CEA-Marcoule's pilot-scale CCIM and other CCIM test beds, the project team determined that glass composition development and testing associated with Phase II-A should be concentrated in a few specific areas. Specifically, the areas of liquidus temperature, REDOX conditions for processing acidified waste, and assessment of properties of the selected glass formulation were identified for laboratory study.

Laboratory Methods

Lab activities planned included:

- Analyzing glass samples from previous CCIM processing at CEA's Marcoule facility;
- Performing crucible-scale liquidus/crystallization studies to select a preferred frit;
- Evaluating the effect of melter temperature on REDOX conditions and resulting glass quality;
- Preparing a compositional analysis of the preferred glass formulation;
- Performing Product Consistency Testing;
- Conducting viscosity assessment; and determining electrical and thermal conductivity.

In addition, a program of variability testing was planned, where glasses were to be fabricated and characterized to provide insight into the impacts of variations in actual sludge composition - allowing the determination of what variations in as-produced simulated waste could be accepted for demonstrations.

Laboratory Results

SRNL characterization of melter glass samples received from CEA was completed in March 2008. These samples were poured during previous CCIM demonstrations conducted in 2007. Samples obtained from the final melter pour of an extended duration test (using an SRS Sludge Batch 3 simulant) were analyzed to evaluate the crystalline content within the glass. Analyses of these samples and comparison to pour stream samples that had been previously analyzed implied that no significant crystal settling occurs during CCIM processing.

SRNL identified three candidate glass frits for testing derived from the previously developed Frit 503 composition. Glasses were fabricated using these candidates at waste loadings (on a calcined oxide basis) of 45, 50, and 55wt %. The glasses were characterized as-quenched and after being subjected to the Modified Centerline Canister Cooling (MCCC) profile. Quenched glasses were completely amorphous at 45wt% waste loading and were primarily amorphous with some spinel crystals (minor) at 50 and 55wt% waste loading. The MCCC glasses at 45wt % waste loading contained some spinel crystals. The MCCC glasses at 50 and 55 wt % contained a few spinel crystals and nepheline was detected (the presence of nepheline in waste glasses is known to decrease the glass durability).

SRNL assessed candidate glasses for durability using the Product Consistency Test (PCT). The quenched glasses had normalized boron releases better than 1 order of magnitude lower than the Environmental Assessment (EA) reference glass used for repository qualification. The MCCC glasses had lower boron releases than the EA glass at all waste loadings. However, durability decreased with increasing waste loading, which is consistent with the detection of nepheline in the glasses. It is known that the MCCC treatment is not prototypical for the proposed CCIM operation and may be overly conservative.

Ensuring that the glass liquidus temperature remains below the glass melt temperature and that nepheline formation is avoided was the critical criteria in the selection of the final frit composition and the waste loading. As a result, SRNL recommended the project utilize Frit 503 Rev 6 at 46wt% waste loading. This waste loading level is somewhat below the initial target for this project phase (50wt%), but was selected to ensure a long-duration test representative of the DWPF process could be successfully performed with a high degree of confidence that glass quality would meet acceptance criteria. It was decided that this waste loading level reflected a significant improvement over the capabilities of current vitrification technology operated at DWPF and that “pushing the envelope” with respect to waste loading should be left for future demonstration efforts.

With the glass formulation defined, SRNL proceeded with lab testing to evaluate the effects of temperature on the glass REDOX using the current SB4 - Frit 510 composition and the reference DWPF REDOX control strategy reductant addition levels. Testing was conducted using both closed and open crucibles in an attempt to achieve both reducing and oxidizing environments. Results showed that melting temperature has a limited impact on the measured glass REDOX in the studied temperature range, in both sealed and open conditions. Based on this testing, it was initially recommended that the CCIM demonstrations should be conducted using the REDOX control strategy developed for DWPF operations at 1150° C. However, subsequent discussions identified that the CCIM process would tolerate a much wider range of REDOX conditions that the currently technology could accommodate. As a result, the team agreed that the target glass REDOX for CCIM demonstration runs would correspond to a Fe²⁺/total Fe ratio between 0.06 and 0.1 for the selected glass formulation, well below the range of 0.15 to 0.2 defined for processing with current technology. This agreement removed REDOX conditions as a driver for acid addition during simulant pre-treatment. However, it is important to note that acid addition for control of melt feed rheology (which constitutes the basis for the bulk of acid addition in SB4 pretreatment) was not impacted by this determination.

CEA completed lab-scale work to determine material properties of glass samples, measuring viscosity, electrical resistivity and heat conductivity of molten SB4 reference glass. Results supported a conclusion that the candidate glass material properties were compatible with CCIM operation. Finally, the results of variability testing provided SRNL with information necessary to identify an acceptable envelope for actual sludge simulant and glass frit compositions.

DEMONSTRATION RUNS

Initial planning for Phase II-A demonstrations was to perform multiple discrete runs at CEA's 650 mm diameter pilot-scale CCIM in Marcoule, with each individual run having objectives related to determining waste loading limits and evaluating impact of increasing processing temperatures. Meanwhile, INL's demonstration at its 267 mm diameter engineering scale CCIM was to focus on characterizing the off-gas stream which results from processing at the higher temperatures employed by the CCIM process. After discussion and refinement of objectives, the project team decided that instead of multiple runs on the CEA platform, two runs - one initial run for system set-up and one extended-duration run at a single defined operating temperature of 1250 deg C - would be performed. This was determined to be the best approach to providing a direct comparison of CCIM performance with the current DWPF vitrification technology.

CEA and INL Demonstration Run Planning

Initial plans detailing CEA and INL activities in support of the demonstration runs were prepared and submitted to the Project Manager. Specific tasks included preparing demonstration run procedures and identifying and implementing changes in test platform configurations necessary to perform the Phase II-A demonstrations.

In preparation for their demonstration, CEA completed a draft plan in the form of a Technical Note consistent with their internal policies and procedures. The Note outlined the organization and contents of the Phase II-A CCIM pilot-scale demonstration activity to be performed on the existing 650 mm diameter CCIM demonstration platform at Marcoule, and the expected outcome of these demonstration runs, and was circulated to all project participants for review and comment. As envisioned during refinement of project objectives, the final plan issued to guide the Marcoule demonstrations included two specific runs - an initial "exploratory" run to demonstrate safe operation of the CCIM platform, and a "baseline" run to obtain steady-state, extended duration data for evaluating crystallization in the glass product and Cs volatility.

Planning at INL included completion of Quality Level Determination, preparation of a draft demonstration plan in the form of a Laboratory Instruction, and development of a work control checklist. Consistent with project objectives, the focus of INL planning was to evaluate CCIM performance with respect to off-gas. Process monitoring and sample collection and analysis were planned to characterize the off-gas composition and properties, and to show the fate of feed constituents, so as to provide data on how a retrofitted CCIM could operate with the existing DWPF off-gas control system. Participants provided comments on INL's draft plan. The focus of many comments was to ensure the highly flexible INL platform would be set up and operated in a manner that was representative of the CEA process at Marcoule. During comment, CEA provided specific recommendations for operating parameters to ensure this objective was met. Final recommendations for the INL demonstration plan were dispositioned, and INL then issued a final version of its plan.

As discussed previously, in order to ensure CCIM performance in this phase is directly comparable to current DWPF processing, it was agreed that simulated waste would be pretreated to a form equivalent to that which qualified for vitrification at DWPF. This includes addition of formic acid. It is important to

note that treating acidified waste imposes a safety consideration with respect to the generation of hazardous gases - the formic acid added in pretreatment is a source for the generation of hydrogen gas during processing, which may accumulate in off-gas systems to a concentration that poses an ignition hazard. As a consequence, the decision to replicate DWPF pretreatment of SB4 sludge by means of acid addition had several significant impacts on plans for preparing the simulant and the test platforms for the demonstration runs.

During early planning, CEA identified a safety limit on potential formation of flammable gases during melter operation in consultation with safety authorities at the Marcoule site. This limit was to be considered in identifying bounding values of acid addition for the planned demonstration campaign, and was based on a simple and highly conservative analysis that assumed all hydrogen introduced to the melter is liberated as hydrogen gas. Later, once the glass composition had been defined and REDOX strategy agreed to, it was found that the amount of acid needed to be added to the simulated SB4 sludge during simulant fabrication to ensure a representative feed caused this early limit on hydrogen in melter feed to be exceeded. In response, extensive technical discussions were held and supporting analytical work was performed in an attempt to refine the basis for safety limits at Marcoule. This included discussions among participants about the objectives for acid addition and SRNL preparation of an analysis of the flammable gas which may be actually generated by the process. This analysis was based on existing DWPF modeling, as modified for the technical details of the Marcoule platform. It was intended to account for the effects of combustion in the melter dome space in reducing the amount of flammable gas in the off-gas stream.

After much consideration, and to ensure commitments to Marcoule safety officials were met in a clear, reliable manner, it was decided that the effects of combustion in the CCIM dome space would be neglected, and that the simple, conservative method which formed the basis for early planning would be retained. As a consequence, in order to accommodate the planned volume of acid addition, it was decided that CEA would modify their melter off-gas system so as to introduce dilution air to the extent necessary such that any potential ignition hazard was eliminated.

Simulant Preparation

The initial plan for this project phase included CEA preparation of the simulated waste form for the Marcoule runs under subcontract agreement with a pre-qualified chemical fabricator in France, and SRNL preparation of a lesser amount of simulated waste for the INL demonstration (due to the smaller scale of the INL platform). To ensure simulant prepared by both participants was consistent with project objectives and essentially identical, the project prepared guidance documents intended to form the basis for chemical fabrication procedures at both CEA's subcontractor and at SRNL. Two documents were prepared, one to guide the fabrication of simulated SB4 sludge, and one to define the pretreatment steps, including acid addition, that would result in melter feed consistent with project objectives.

However, once the waste form and pretreatment requirements were agreed to, it was determined that the chemical fabricator pre-qualified by CEA and selected for simulant preparation in this project phase did not have the necessary equipment and processes for the acid addition step which was to be required, and establishing the capability for acid addition at this facility would incur costs not planned for in project cost estimating. As a consequence, sub-tasks were incorporated in the project working schedule to identify an alternative domestic source for the simulant required for demonstrations at Marcoule and at INL, and to prepare and circulate Requests for Expression of Interest and then a Request For Proposal (RFP). This RFP included work scope to prepare simulant for both CEA-Marcoule and INL demonstrations, as this would ensure consistency in feed and eliminate redundant tasks that had been assigned to SRNL.

Proposals were received and evaluated, with two being deemed responsive to RFP requirements. These proposals were then compared to a cost estimate provided by CEA's pre-qualified vendor identifying costs to establish a capability for acid addition at their facility in France. As a result of this evaluation, one of the two domestic fabricator proposals was recommended as the best approach to sourcing simulant for Phase II-A. A compliance package was then submitted to DOE-EMCBC, and after its acceptance, a subcontract was placed with the recommended supplier in August 2008.

A kick-off meeting was held with the subcontractor, initial submittals under the contract were received and approved, and fabrication of simulated SB4 sludge was performed per the contract's Statement of Work. SRNL provided close support to the vendor to ensure work stayed on track and complied with fabrication guidance documents prepared to direct the work. Under the terms of the subcontract, simulated sludge representative of SB4 waste was prepared, analyzed, and accepted. Later, once agreement was reached by project participants on the final volume of acid addition, simulant fabrication was completed, analyzed, and accepted for use in planned demonstration runs. Following acceptance of the final waste form, shipments of simulated waste were made to the demonstration sites in France and Idaho.

In parallel with simulant fabrication, SRNL executed tasks to specify and procure frit and start-up glass for both CEA and INL demonstration runs. During preparation for this procurement, an approved frit specification was developed, a simplified composition for start-up glass was defined, and the required quantities of frit and start-up glass were confirmed. Following fabrication the as-fabricated glass frit and start-up glass were analyzed, accepted for use, and shipped to CEA's and INL's demonstration sites.

CCIM Demonstration Facility Preparation

Once objectives for demonstration runs were defined within agreed-on run plans, CEA and INL planned and implemented facility modifications so that the runs could be executed in accordance with them. At CEA, plans for facility modifications included addition of dilution air to the off-gas stream, as discussed previously. Verification of a safety interlock related to dilution air flow was included in the objectives for CEA's initial demonstration run. At INL, a "start-up punch-list" was prepared to track facility preparation items required preparatory to the test. Items worked included installation of calibrated voltage meters to simplify the system and reduce the cost of power generator operation and maintenance during testing, installing a liquid feed system, modify the crucible tapping system, crucible lid, and off-gas sampling systems, and installing a bubbler in the CCIM. These modifications were followed by subsystem tests on the crucible (including determination of the power frequency to be used during the runs) and the glass tapping mechanism, and tests to evaluate the impact of a titanium startup ring.

INL Demonstration Runs

In preparation for planned demonstrations, INL assembled melter feed by mixing the 75 gallons of SB4 simulant supplied by the chemical fabricator with rinse water and 99.5 kg of glass frit (the amount targeted as necessary for a waste loading in the glass of 46wt%). This resulted in a total of 98 gallons of melter feed with a final total solids loading of 45.5wt%. The resulting melter feed was then accepted for subsequent demonstrations.

INL demonstrations were performed using the engineering-scale CCIM test platform in two discrete sessions. The initial session was performed during the week of December 15, 2008, with CEA representatives in attendance. This demonstration consisted of a parametric evaluation of operating conditions within ranges defined by process and test objectives. This initial demonstration was intended to confirm the melter was ready for sustained operations. It also enabled the operators to determine how to operate each related CCIM subsystem within target ranges.

During the initial demonstration, INL operated the CCIM with the generator energized for a total of about 30 hours. During this time the melter was fed about 7 gallons of waste feed surrogate, for an average melter feed rate of 0.7 gal/hr (3.6 kg/hr). Generator power levels generally ranged between 25 and 35 kW. Operators were able to observe the temperature of the melt, cold cap behavior, and power level changes while varying the feed rate from a minimum of about 1 kg/hr to a maximum of about 6 kg/hr. As a result of this initial demonstration, operators expressed satisfaction with their ability to control the process and concluded they could establish and maintain the steady operating conditions necessary to generate test samples considered representative of CCIM performance.

The second session of demonstration testing at INL consisted of the Off-gas System Evaluation itself. This test session was successfully completed during the week of January 19, 2009, with an SRNL representative in attendance. The test system was operated at selected conditions while data was recorded both electronically and manually. Testing activities also included collection and analysis of samples from process input and output streams for selected test conditions, and post-test cleanout, inspection, and sampling.

During the Off-gas System Evaluation run, the CCIM was operated with power on for a total of about 58 hours, and total feed time amounted to over 50 hours. During the run, simulant feed-rate was varied from 1.0 kg/hr to 4.5 kg/hr. Over the course of the run, INL established the three test conditions defined in the test plan, obtained CEMS melter off-gas composition data (O₂, CO₂, H₂, CO, CH₄, THC, NO, NO_x), measured off-gas flow rates, collected samples for metals and particulate analysis using an EPA method 29 metals sample train (%H₂O, particulate matter, and metals including Cs), and took grab samples in “Summa” canisters for assessment of H₂, CH₄, and volatile organic compound (VOC) concentrations. The three test conditions are summarized as follows:

- CCIM operating with an essentially complete cold cap at a nominal 1,250 deg C melt temperature to establish a clear baseline test. Maintaining the cold cap under these conditions required a melter feed-rate of 3.8 kg/hr. A few hours after start-up, the 1st tap of glass from the melter was started. After 4-5 hrs of operating time, almost one complete melter volume had been discharged. Three other pours were executed while running at this baseline condition.
- CCIM operating with less complete cold cap at a nominal 1,250 deg C melt temperature, to assess the impact of reduced cold cap on volatility of off-gas constituents. To establish this condition, melter feed-rate was reduced to 2.3 kg/hr for a period of 6 to 10 hours, and a glass pour was made.
- CCIM operating with an essentially complete cold cap at a nominal 1,300 deg C melt temperature, to assess the impact of increased melt temperature on volatility of off-gas constituents. To establish this condition, it was necessary to increase melter feed-rate to 4.1 kg/hr. This condition was sustained for a period of 6 to 10 hours, and a glass pour was made.

The 6 to 10 hour periods over which off-baseline tests were conducted were considered long enough to establish stable operating conditions, while not too long to bias material balance results from the overall test.

Following completion of the Off-gas System Evaluation demonstration, a clean-out of the crucible was performed. Glass samples were collected from all pours, and solids accumulated in the scrubber were retrieved for analysis. Preliminary analysis of results indicates the following:

- Measurements of CO₂, CO, H₂, and methane were made during the Off-gas System Evaluation run. Preliminary results showed about 85% of hydrogen in the feed was converted to water vapor, about 5% associated with carbon in the feed to form methane, and only about 10% was

converted to molecular H₂. These results were consistent with prior experience with similar processes at INL,

- Preliminary evaluation of concentrations in off-gas showed methane was about 1% of CO₂ level. CO was about 5% of CO₂, and H₂ was about 10% of CO₂ level,
- On a dry basis, CO₂ in off-gas was 2%, H₂ was 0.1%, CO was about 0.05%, methane was about 100 ppm, and NO_x was in the range of 3,000 to 4,000 ppm (which, considering the dilution rate used during the Off-gas System Evaluation run, was consistent with parametric testing in December). Normalizing the off-gas and subtracting the effects of dilution increases CO₂ concentration to 12%, H₂ to 0.6%, while CO and methane remain low at <0.5%.

In order to get final data, off-gas samples collected during testing will be assessed by both INL and a specialized laboratory equipped with the tools and procedures for necessary for a detailed evaluation of sample characteristics. Also, samples of glass from each pour, material scraped from the upper melter walls and lid, and solids retrieved from the scrubber will be analyzed by SRNL, along with a sample of the melter feed. These analyses should be sufficient to achieve complete closure of the material balance resulting from the demonstration. All test and analytical results are to be included in a specific paper to be presented by INL project representatives.

CEA Demonstration Results

Results of CEA's demonstration run and evaluation of the CCIM technology's performance with respect to waste loading and glass quality are pending performance of the planned demonstration. Preliminary testing, consisting of parametric runs to verify the operability of the process over the range of targeted test conditions, is planned for February 2009. This is followed by the extended duration run which accomplishes the pilot-scale demonstration objectives established for this project phase. All demonstration runs are planned to be complete by April 2009. Results of these project activities are to be presented during the oral presentation of this paper.

ENGINEERING STUDIES

Studies carried out in 2006 provided a preliminary assessment of the feasibility of implementing CCIM technology within the existing Melter Cell of DWPF. These studies were performed by SGN as a part of the ART CCIM Phase I scope of work in the form of a pre-conceptual feasibility study. Key technical topics were identified at that time which were to be the subject of more detailed evaluations in later phases. For ART CCIM Phase II-A, the engineering scope of work was to conduct mechanical engineering studies regarding the feasibility to install and maintain a CCIM in the Melter Cell, and process studies to define the Process Data Flow Sheet for such a CCIM retrofit.

Under the topic of mechanical engineering studies, Phase II-A tasks included:

- defining the CCIM layout configuration within the Melter Cell,
- designing the CCIM frame, and
- selecting the preferred maintenance strategy among the three approaches defined in ART CCIM Phase I studies:
 - Strategy S1: Robot mounted on a mast,
 - Strategy S2: Robot(s) mounted on the CCIM frame
 - Strategy S3: Re-use of the existing means inside the Melter Cell

Other engineering studies and modeling were planned for Phase II-A to directly supplement these mechanical engineering studies: CEA assessment of the preferred configuration of mechanical stirrer(s)

to be fitted to the CCIM envisioned for retrofit at DWPF; and, CEA identification of electromagnetic parameters for an eventual full-scale production CCIM. Assessment of the CCIM performance during demonstration runs and updating sizing information for a production-scale melter were also planned, in order to validate assumptions made for melter sizing in the mechanical studies.

Design Inputs

A Technical Note was prepared by SGN to define the design inputs necessary to develop its Phase II-A engineering design activities. Several packages of DWPF technical documents and design media were transmitted by DWPF engineering staff in response, which consisted primarily of scanned documents depicting the as-built conditions of the Melter Cell. Later, a project engineering meeting was held at SRS including SGN design team members and representatives from DWPF to review input data and the design assumptions on which engineering work would be based. On the basis of this design input data, the Basic Data Summary defined at the start of the project, and studies conducted in Phase I, SGN assembled a Design Basis document summarizing inputs, enabling assumptions and basic design parameters related to the CCIM design. This document then guided the mechanical engineering studies which followed.

DWPF Modeling and CCIM Layout

In order to create a design environment with sufficient detail to allow conduct of planned engineering studies, SGN created a three-dimensional model of the existing DWPF Melter Cell with the joule-heated melter removed. Drawings of the Melter Cell extracted from this model were then reviewed by SRNL and DWPF Engineering staff to ensure that the interfaces which would be relied on for CCIM installation were captured accurately.

With respect to the CCIM configuration envisioned for retrofit into the Melter Cell, design assumptions were made to enable performance of the planned mechanical engineering studies. The main characteristics of the CCIM were defined with the support of CEA experts, and the design assumptions were defined and justified in the Design Basis document. With these two elements in hand, SGN was able to consider alternative locations for the CCIM within the Melter Cell and, in conjunction with assessing maintenance alternatives, identify the optimal position for the CCIM and resulting design requirements for a support frame. This positioning included considerations for interfacing with the current glass canister management system. Functional requirements for the frame and interfaces with Melter Cell wall penetrations were defined and current penetrations were assessed for their ability to deliver cooling water, electrical power, and control signals. In conjunction with CCIM positioning and frame design, a jumper schedule was prepared to verify sufficient penetrations would be available for all required functions, and the most effective means of interconnecting the CCIM and appurtenant elements to these interface points was identified.

The Melter Cell, frame, and interface design configurations prepared by SGN were at a level of detail sufficient for assessing maintenance alternatives as planned for this project phase. Other areas of study included penetration requirements for the CCIM power supply and interfaces with the current Melter Cell off-gas sub-system and melter feed sub-system, but final recommendations for configuration of these interfaces is pending more detailed work planned for future phases.

CCIM Maintenance Alternatives

In parallel with work to optimize CCIM positioning and develop a support frame configuration, SGN performed the assessment of maintenance alternatives which was assigned to the work scope for this phase. The ability to operate and maintain the CCIM over its operating life is a key consideration in validating the feasibility of installation, and selecting a preferred approach to maintenance tasks is the

first element in refining a conceptual design to the point where firm cost and schedule for retrofiting can be identified.

Assessment of maintenance alternatives began with defining the specific operating and maintenance tasks needed to be performed over the service life of the melter. Operating tasks so defined included insertion of a metallothermic ring for start-up, spreading glass frit in the melter vessel, inserting a temporary plug in canister throats, and glass sampling during pouring. Maintenance tasks included preventive and corrective maintenance activities, such as replacement of components or sub-systems mounted to the CCIM itself, feed tube unclogging, replacement of the melter dome or pouring shell, operation on the high-frequency power supply lines, and CCIM decommissioning.

For each of the three basic maintenance strategies considered, a specific layout and frame design were developed, considering both the requirements discussed above and the capabilities of the tooling adopted by each strategy. Impacts on CCIM and frame design, the feasibility of performing defined tasks, and the benefits and drawbacks posed by each solution were identified. The maintenance assessment then compared the results for each of the three strategies considered, and, by weighting the impacts, benefits, and drawbacks in accordance with their importance, identified the preferred alternative. A project engineering meeting was held at SRS including SRNL, DWPF Engineering and SGN design team members to refine weighting and scoring of each element in the final assessment. This final review session ensured the resulting recommendation on preferred strategy reflected the thinking of the staff that would be responsible for actually operating the system, once installed, as well as the design agent and process development leaders.

The results of this assessment found that maintenance of the CCIM within the melt cell is achievable by all three strategies considered, but that Strategy S2, which relies on robot(s) mounted on the CCIM frame, is the preferred alternative. This approach offers the most flexibility for CCIM operations and minimizes the duration of operating and maintenance tasks, when compared to the other approaches studied. This approach does not require any significant modification to the Melter Cell, and is recommended as the reference strategy for future design and engineering work on retrofit of a CCIM into DWPF.

Results of Other Studies and Modeling

Results of other studies planned for Phase II-A have been obtained and have provided additional details supporting the results and conclusions of the mechanical engineering study. CEA modeling of the stirring configuration for a DWPF retrofit application suggest three mechanical stirrers positioned around the melter center line represents the optimal solution for maximizing waste loading. This configuration mitigates the settling of dense particles, if any are present in the melt, and ensures glass quality meets acceptance criteria. This configuration is identical to the configuration assumed for design purposes in mechanical engineering studies. Similarly, CEA studies on electromagnetic parameters required for optimal processing of DWPF waste streams showed system start-up could be achieved (a key consideration for feasibility) and verified the attributes considered by SGN in its mechanical engineering studies accurately reflected the configuration required for DWPF retrofit. .

With respect to updating CCIM sizing based on results of the Phase II-A demonstrations, CEA's demonstration run and evaluation of the technology's performance with respect to waste loading and throughput are pending performance of the demonstration, which will be completed in early April 2009.

Process Flow Sheet Development

At the time of this paper, process flow sheet development has not been completed. This work is pending evaluation of the CCIM technology's performance with respect to waste loading and throughput and

potential volatilization of chemical species in off-gas. Evaluation of the data which were recorded during the Off-gas System Evaluation run at INL in early 2009 and which will be recorded during the extended duration run at CEA Marcoule, and integration of the analytical results for all the samples taken during those tests, provides basis for completing the planned process flow sheet.

PHASE II-A CONCLUSIONS

At the time of this paper's publication, development of Phase II-A conclusions is not complete. Project conclusions are pending completion of demonstration runs and process flow sheet development, which are expected to be complete in April 2009. Preliminary conclusions drawn from project activities completed after publication are to be included in the oral presentation of this paper.