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**Letter Report: Cold Crucible Melter
Assessment**

M.L. Elliott

March 1996

**Prepared for the U.S. Department of Energy
under Contract DE-AC06-76RLO 1830**

**Pacific Northwest National Laboratory
Operated for the U.S. Department of Energy
by Battelle Memorial Institute**

MASTER

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Pacific Northwest National Laboratory
Richland, Washington 99352

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INTRODUCTION

One of the activities of the PNL Vitrification Technology Development (PVTD) Project is to assist the Tank Waste Remediation Systems (TWRS) Program in determining which melter systems should be performance tested for potential implementation in the high-level waste (HLW) vitrification plant. The Richland Operations Office (RL) has recommended that the Cold Crucible Melter (CCM) be evaluated as a candidate "next generation" melter¹. As a result, the CCM System Evaluation cost account was established under the PVTD Project so that the CCM could be initially assessed on a high-priority basis. This letter report summarizes a brief initial review and assessment of the CCM. Using the recommendations made in this document, Westinghouse Hanford Company (WHC) and RL will make a decision regarding the urgency of performance testing the CCM. If the decision is favorable, a subcontract will be negotiated for performance testing of a CCM using Hanford HLW simulants in a pilot-scale facility.

Because of the aggressive nature of the schedule, the CCM evaluation was not rigorous. The evaluation consisted of a literature review and interviews with proponents of the technology during a recent trip to France. This letter report summarizes the evaluation and makes recommendations regarding further work in this area.

BACKGROUND

The CCM (also referred to as the Cold Wall Melter and the Two-Stage Vitrification System) is not a new concept. The technology stems from a 1925 German patent. Battelle Pacific Northwest Laboratories used this technique to melt reactive metals in the 1970s. In 1980 the Commissariat A L'Énergie Atomique (CEA) used direct induction heating to melt metal wastes from nuclear fuel reprocessing. This experience led to the development of a CCM for inductively heating glass in a water cooled crucible. Similar development was conducted in Russia in the 1970s.

Conventional induction glass melters rely on an inductively heated metal crucible that heats and melts glass by thermal conduction. By breaking the crucible up into isolated vertical sectors, cooling the sectors, and increasing the frequency of the induction signal, the glass can be directly heated by the induction field. Because the crucible is cooled on the exterior surface, a layer of cooled glass protects the crucible from corrosion. This

¹Letter from Leif Erickson, Director of Tank Waste Disposal Division to W.R. Wiley, Director of the Pacific Northwest Laboratory dated September 21, 1993. A copy of this letter is contained in Appendix A.

protective layer allows the bulk of the melter to be run at very high temperatures such that higher glass waste loadings, production rates and melting of refractory compounds can be achieved. The principles of the CCM are explained in the papers in Appendix B. The important parameters to be controlled are the frequency of the induction signal, the electrical resistivity of the material to be heated (glass in this case), and the penetration depth of the induced currents. The smaller the CCM, the higher the induction frequency that is required. There are size limits imposed on the CCM by these parameters. Small CCMs (< 15 cm) are difficult to heat because the required induction frequency is very high and an appropriate signal generator is required. Large CCMs are difficult to heat because the induction frequency is so low that it will not couple to the glass. The electrical resistivity of glass is strongly temperature-dependent. For this reason, the glass in a CCM must be preheated at the beginning of a run before induction heating can begin. This has been done using microwave heating or started paths.

REVIEW OF LITERATURE

The majority of the work with CCMs has been done in the area of metal melting, not glass melting. For the purposes of this report, only glass melting will be discussed. The literature on CCMs is very limited. The majority of the work done on CCMs was done by various government agencies in Russia and in France by the CEA. The CEA has published little in this area because the development has been considered proprietary. Most of the articles are either in French or Russian and contain little technical information.

FRENCH LITERATURE

The two French articles^{1,2} used for most of the information in this review are contained in Appendix B. The remainder of the information on the French CCM was gathered during a recent trip to France. A summary of the information acquired will be discussed in a later section of this report.

In the 1970s, development of a high-frequency (HF) induction melter for glass production was started in France at the CEA. The original design used direct induction heating of the glass inside a refractory chamber. This development was halted and later resumed in 1981. The design was changed and the refractory crucible was replaced by a water cooled, sectorized, steel crucible. The crucible was sectorized so that it is not

¹*Cold Crucible Techniques, Report on the State of the Art in France.* Prepared by CEA & SGN for NUMATEC, Inc. May 1991.

²Sombret, Claude G. *The Cold-Crucible Glass Melter.* Commissariat à l'Energie Atomique France. Paper presented to Savannah River Center. May 10-11, 1993.

heated by the HF field. Corrosion of the crucible was reduced or eliminated because the metal wall was kept below 200°C producing a frozen layer of glass that protected the metal. The bottom of the melter is also water cooled to prevent corrosion/melting of the crucible. The French CCM contains two bottom drains (freeze valves). One partially drains the melter during normal operation and one completely drains the melter at the end of a run. The flow of glass through the drain valves is controlled by induction heaters.

Most of the development work has been done with a 55-cm diameter (0.24 m² surface area) CCM. One of the papers indicates that a 1.5-m diameter CCM could be operated, but this has not been demonstrated. One of the papers states that the CCM design is optimized to ensure better than 80% electrical efficiency. This is misleading and will be clarified in a later section of this report. Actually, the CCM is very inefficient. The 55-cm diameter CCM has a 240 kW, 335 kHz power supply. For this reason, the CCM is dry fed, not slurry fed. Slurry feeding the CCM would require a prohibitively large power supply because of the additional energy required to evaporate the water. This is why both the French and the Russian designs have a calciner in series with the CCM.

Several thousand hours have been logged on the French CCMs. The CCM can be operated at very high temperatures because it is a skull-type melter. The French CCM has been used to melt refractories up to 2500°C. The maximum glass production capacity has been 25 kg/hr (260 kg/hr/m²) for the 35-cm diameter CCM and 50 kg/hr (210 kg/hr/m²) for the 55-cm diameter CCM. The La Hague vitrification plant (R-7) glass formulation has been processed at temperatures ranging from 1150°C to 1380°C.

A brief patent search was conducted with the key words "cold crucible" and "glass." The French patents that were found included a 1985 patent for a CCM drain spout, a 1987 patent for the basic CCM induction heater design, and a series of international patents (1984-1993) granted to the CEA for ceramic manufacturing using the CCM. Similar patents were found for the CCM developed in the former Soviet Union. This will be discussed in the following section.

RUSSIAN LITERATURE

The Russians have developed a cold crucible melter in parallel with the French. The Russian system is usually referred to as a two-stage vitrification process. For consistency, the term CCM will be used for the Russian two-stage vitrification process in this document. The Russian literature on the CCM was even more scarce than the French literature. The best source of information was a 1991 PNL report by Don Bradley

reviewing radioactive waste management in the USSR¹. The Russians began CCM development in the 1970s. The operating principle of the Russian CCM is similar to the French CCM but the approach is different. The Russian CCM is rectangular in cross section instead of round. The Russian design uses a spray calciner in series with the CCM instead of a rotary calciner. The most complete information is on a 30 kg/hr (170 kg/hr/m²) Russian CCM with a 0.18 m² melt pool. This unit operates at 1760 kHz, 160 kW and has an temperature range of 900°C to 2300°C. The Russians have tested their CCMs with several different minerals including glass.

Further information on the Russian CCM capabilities was gathered by Ben Johnson of PNL during a recent trip to Russia². The Russians are still pursuing the CCM technology. They have several units ranging from 1-2 kg/hr to "industrial scale." They operate their nonradioactive units at the All-Union Design-Construction Scientific-Research and Technological Conglomerate (VNIPIET) in St. Petersburg. They have recently installed a radioactive CCM system in the Mayak Plant. Original conversations with the Russians indicated that this system had a capacity of roughly 100 kg/hr. Subsequent conversations with Serge Merlin of SGN indicated that the Mayak Plant has three 30 kg/hr CCMs in parallel. It is not clear if the radioactive system has gone into active operation yet.

A brief patent search was conducted with the key words "cold crucible" and "glass." The patents from the former Soviet Union that were found included a 1984 patent for a fiberglass CCM crucible, a 1987 patent for a CCM refractory founding process, and a 1987 patent for the basic Russian CCM. During the literature search an article was found that briefly mentioned the use of mechanical stirring in one of their CCMs using a water-cooled agitator.

INFORMATION FROM RECENT TRIP TO FRANCE

Further information on the CCM was gathered during a recent trip to France. Mr. Antoine Jouan of CEA presented a review of the CCM on March 21, 1994. A tour of the CCM development facility at Marcoule followed the presentation. A copy of the presentation is contained in Appendix D. A basic overview of the CCM concept was presented along with a description of testing that has been completed at CEA. The amount of work in this area was impressive. They have run the CCM up to 2800°C in a batch mode. The limitations of the CCM were also discussed. As stated earlier, the diameter of the CCM is limited by the power supply frequencies and the electrical resistivity of the material to be melted. Several questions were asked relating to the ability

¹Bradley, D.J. 1991. *Radioactive Waste Management in the USSR: A Review of Unclassified Sources, Volume II*. PNL-7645. Pacific Northwest Laboratory, Richland, Washington.

²Trip report will be published by April 8, 1994.

to liquid feed the CCM. Mr. Jouan explained that the CCM is a very inefficient evaporator. One of his slides indicated that 70% of the power from the induction coil is transferred to the glass, but only 30-40% of this energy goes to heating the glass. The rest is lost to thermal inefficiencies. That is, the overall system is only 20-30% efficient. He indicated that the CCM is only 40-50% as efficient as a conventional refractory melter.

A later meeting was set up with Mr. Jouan of CEA and Mr. Serge Merlin of SGN to review questions that were not answered during the initial presentation. The first part of the discussion covered the maturity of the technology. Mr. Jouan provided most of the information since he did most of the CCM development. Most of the CCM testing has been done on a 55-cm diameter melter. This unit was observed under the Atelier de Vitrification Marcoule (AVM) calciner in Marcoule on the March 21 tour. This CCM is over ten years old, has processed phosphate glasses, lead glasses, and R-7 glasses, and is still in good shape. The 55-cm CCM produces 10-50 kg/hr depending on the glass. It can produce 30 kg/hr when running R-7 glass. At higher production rates the melter is dry fed without using the calciner because the production capacity of the calciner is limited. The maximum production rate using the calciner is 20 kg/hr of glass.

A 15-20-cm diameter CCM was tested for melting uranium oxide as part of a fast breeder reactor meltdown study. A 50-cm diameter CCM, a 20-25-cm diameter CCM, and a 35-cm diameter CCM have been developed and tested for non-nuclear uses. The 20-25-cm CCM has a new pour valve that can be turned on and off quickly. Mr. Jouan could not elaborate on this. They currently have a 65-cm diameter CCM and a 90-cm diameter CCM under construction for commercial glass production. The largest CCM that they have tested is a 1.2 m diameter unit. This was only tested for one day to see if it could heat glass at its low operating frequency, 10 kHz.

CEA has not developed a small CCM (< 15 cm) because the frequency of the induction signal would be too high. The most important parameter when operating the CCM is the resistivity of the material being melted. They are able to melt glasses with electrical resistivities between 1 Ω -cm and 10 Ω -cm. Above 10 Ω -cm the induction frequency must be increased. For this reason the glass must be preheated at the beginning of a run to get the electrical resistivity low enough to begin induction heating. Normally this is done using a microwave heater. During the UO_2 melting this was done using a tungsten heater under a vacuum.

They have not done calciner development in conjunction with the CCM development. They currently have 60 L/h, 40 L/h, and 20 L/h calciners. The Leahflash (also called Isoflash) is being developed by a private company for the denitration of uranium to produce salt cake.

CEA has recently licensed SGN to market the CCM. Serge Merlin of SGN has been working with the Russians to industrialize the CCM for nuclear waste in Russia. Evidently,

the Russians have designed and tested CCMs, but asked SGN to help industrialize the technology. They do not currently have a contract with the Russians, but plan on doing a nonradioactive test with a Russian melter later this year. The Russians currently have three CCMs installed in a radioactive facility at the Mayak plant. Each of the melters has a capacity of 30 kg/hr. Mr. Merlin did not know if the melters had gone into active operation yet. It was not clear why the Russians need SGN's help with the CCM if they have already installed melters in an active facility.

SGN is currently trying to get a contract with the Czech Republic to design a CCM for treating low-level liquid waste. The CCM would be coupled with a calciner. The negotiations are on-going but the outcome is still uncertain. CEA/SGN are currently constructing two CCMs for producing commercial glasses. They feel that they have a big future in this area.

Mr. Jouan is currently pushing to get the CCM installed in one of the La Hague vitrification plants (R-7 and/or T-7). He said that the CCM would be small (25 kg/hr) and would easily fit within the existing melter footprint. Mr. Jouan feels that the CCM would be easier to operate and would reduce the amount of solid waste produced in the plant because the melter lifetime would be much longer.

CEA has conducted volatility tests on the CCM. There was no difference between the CCM and the AVM melter when operated at the same temperature. Mr. Jouan feels that there would be a big difference at 1400°C. He also feels that it is better to work with the R-7 glass below 1200°C. The CCM can pour glass above 2000°C, but designing a canister suitable for receiving materials at 2000°C would be difficult. CEA has tested agitating the CCM using both gas sparging and mechanical agitation at 1200°C. Mr. Jouan would not say whether the agitator was metallic or ceramic. The mechanical agitation increased the production rate between 1.5X and 2X.

DISCUSSION AND RECOMMENDATIONS

It is safe to say that the CCM is a promising technology. Because of the lack of information, it is difficult to determine if the CCM is applicable to the Hanford HLW vitrification plant. Several uncertainties exist:

- Is a calciner compatible with the Hanford waste? Calciners were previously investigated for HLW vitrification in the U.S. Spray calciners have difficulties with particulate carryover and on-line efficiency. The Hanford tank waste is alkaline and has a high sodium content. This type of waste has conventionally been difficult to treat in rotary calciners. Low melting alkalis and mastic phases form in rotary calciners that can lead to clumping and clogging.

- Will operation of the calciner/CCM lead to unacceptable off gases that will adversely affect the rest of the off gas system? This includes both volatilization and particulate carryover.
- Can the CCM achieve high processing rates with Hanford feed? How many CCMs will need to be run in parallel to meet the processing requirements of the HLW vitrification plant?
- Is the CCM stable enough to be used in a remote environment?
- Is the residence time of the CCM sufficient to ensure proper dissolution and mixing of the glass? What is the quality of the glass produced by the CCM?
- Will glass spall off of the cold wall and "contaminate" the glass product?

Because of the demonstrated capabilities of the CCM, it is difficult if not impossible to discount its applicability to the Hanford HLW vitrification plant. It is the opinion of the author that a proof-of-principle test should be conducted using Hanford feed on a complete CCM system (feed system, calciner, CCM, dust scrubber, etc.). This could either be done at the Marcoule test facility in France or at the VNIPIET test facility in St. Petersburg, Russia. The current direction from RL favors doing the testing in France. The testing should entail, but not be limited to the following:

- The test system should be complete (feed system, calciner, CCM, and off gas system) and properly sized. The calciner should be slightly oversized such that the maximum production rate of the CCM can be determined (the current calciner on the 55-cm diameter CCM at Marcoule is undersized such that the CCM is normally dry fed). The CCM should be of sufficient size such that the people conducting the test can combine the test results with their previous experience to make a rough estimation of full-scale plant requirements.
- Hanford feed simulant (either NCAW or the current undefined blend composition) should be used for the test. This should include all of the problem compounds such as sulphate, chloride, nitrates, etc. The people conducting the test would be free to modify the simulant with additives (e.g., acidify or add sugar) provided that they also address the consequences (e.g., removing the NO_x from the off gas).
- The people conducting the test will be free to either use the Hanford glass composition or develop their own composition, as long as the waste composition is not altered and durability specifications are met. This will allow maximization of the waste loading.
- Testing should be conducted for a long enough time to allow the system operation

to be properly evaluated. This is estimated to be three to seven days.

- Product samples should be taken and analyzed for homogeneity, chemical durability, and undissolved phases.
- Decontamination factors for each major piece of equipment should be determined.
- Pre- and Post-test equipment examinations should be conducted to detect any corrosion or clogging problems.

It may be prudent to wait until the August/September time frame to sign a subcontract for CCM testing. This would allow verification by the independent technical review group working on the HLW melter selection effort that the recommendation made here (to go forward with an initial CCM performance test) is consistent with the overall TWRS HLW strategy. However, if testing of a CCM is going to go forward, the subcontract must be signed in FY 1994 so existing funds can be utilized since FY 1995 funds are limited.

APPENDIX A

LETTER FROM LEIF ERICKSON TO W.R. WILEY

Department of Energy

Richland Operations Office
P.O. Box 550
Richland, Washington 99352

SEP 21 1993

93-TRB-051

Contractors
Richland, Washington

President
Westinghouse Hanford Company

Director
Pacific Northwest Laboratory

Gentlemen:

TANK WASTE REMEDIATION SYSTEM (TWRS) FOREIGN TECHNOLOGY COLLABORATION FOR FISCAL YEAR 1994.

The following technological areas and activities should be considered for funding during FY 1994. The exact scope and nature of the testing programs need to be considered within the context of the TWRS New Technical Strategy. The objective is to identify potential areas of foreign collaboration for prioritization with other identified tasks.

HIGH-LEVEL WASTE IMMOBILIZATION

1. Consider the French "Cold Crucible" Melter (CCM) as a candidate "next generation" melter and evaluate with other likely technologies, such as the "stirred" and "high temperature" melters. If the CCM has merit then consider the following:
 - A) Conduct vitrification tests in the French "Cold Crucible" Melter (CCM) system using simulated Hanford Tank wastes. This includes calcining the waste prior to vitrification using the "LEAFSLASH" technology. This work will be conducted at Marcoule through Commissariat Energy Atomic (CEA).
 - B) Initiate dialogue with the French to purchase and install a CCM system within the 324 building (CEA).
2. Investigate implementing the CCM as the vitrification system for the Initial Pretreatment Module (IPM) hot pilot plant operation.
3. Evaluate the CCM system as a candidate technology for satisfying the HWVP "4X" scenario. This work will be conducted through collaboration with SGN.

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J. M. GREEN

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4. Continue discussions with the French concerning capabilities, acquisition, and licensing of the liquid transport system (LR-56).

PRETREATMENT

1. Continue collaboration with the French on the "Diamex" and "Calixarene" processes as well as other potentially beneficial processes for the separation of chemical species.

LOW-LEVEL WASTE IMMOBILIZATION

1. Initiate dialogue with the British (British Nuclear Fuels Limited-BNFL) regarding grout waste formulation, product and process control, and performance assessment modeling. The intent is to design an improved low-level waste form and evaluate performance for the regulators.

This list is neither comprehensive nor complete, but is intended to highlight potential areas of collaboration identified by the TWRS technology team during their visit to French and British facilities during July 1993. Please contact Steve Burnum of my staff, on 376-8409, for additional details.

Sincerely,

Laif Erickson, Director
Tank Waste Disposal Division

TRB:STB

cc: D. Wynne, EM-36
J. Creer, WHC
T. Weber, WHC
D. Wodrich, WHC
S. Schaus, WHC
W. Miller, WHC
J. Voogd, WHC
R. Murkowski, WHC
R. Kirkbride, WHC
S. Barker, WHC
J. Appel, WHC
G. Hansrote, WHC
W. Apley, PNL
J. Westik, PNL
G. Lumetta, PNL
G. Beeman, PNL

APPENDIX B

FRENCH LITERATURE EXPLAINING COLD CRUCIBLE CONCEPT

The Cold-Crucible Glass Melter

Claude G. Sombret

*Commissariat à l'Energie Atomique
France*

Savannah River Center
May 10-11, 1993

INTRODUCTION

The vitrification process currently implemented in France to solidify concentrated fission product solutions uses melters in which the heat source is an induction-heated metal chamber. This process meets the requirements of the French and English reprocessing plants, but does not allow melting at temperatures above 1200°C.

In the 1970s, advantages were perceived in developing a facility with a larger throughput capacity, capable of achieving higher melting temperatures. A heating process was developed implementing direct induction in the glass inside a refractory chamber. The development of this process was interrupted in the late 1970s to meet the workload arising from commissioning of the Marcoule Vitrification Facility (AVM) and from the UP3 and UP2/800 reprocessing plant projects with their two vitrification units, R7 and T7.

A direct induction process using a water-cooled metal crucible was developed in 1980 to melt metal waste. The experience acquired made it possible to consider renewed development of the direct induction glass melting process beginning in 1981, but with a water-cooled sectorized metal crucible instead of the initial hot refractory crucible. The new process not only allows fabrication of high-silica glass and eliminates crucible corrosion problems, but also considerably increases the melter capacity without increasing the overall dimensions of the facility.

OPERATING PRINCIPLE

The glass is fabricated and melted in a generally cylindrical, water-cooled metal crucible. The glass in contact with the cooled wall solidifies to a depth of a few millimeters, as the wall temperature does not exceed 200°C. The bottom of the crucible is also a water-cooled metal plate, so the glass is fully contained in a solid glass "crust", hence the term "skull melting".

The crucible is surrounded by the coils of an inductor supplied with a high-frequency alternating current, which induces currents in the molten glass that dissipate heat by Joule effect (the resistivity of molten glass is a few $\Omega\cdot\text{cm}$). In order to ensure suitable electrical efficiency when transferring power from the inductor to the melt, the frequency must be determined so the penetration depth of the induced currents in the glass is less than the crucible radius. The penetration is given by the following relation:

$$p = \sqrt{\frac{\rho}{\pi\mu_0\mu_r F}}$$

where p is the penetration depth in meters, ρ the glass resistivity in $\Omega\cdot\text{m}$, μ_0 the magnetic permeability of empty space ($4\pi \times 10^{-7} \text{ H}\cdot\text{m}^{-1}$), μ_r the relative magnetic permeability of the glass and F the inductor frequency in Hz. The following simplified formula is generally used:

$$p = 503 \sqrt{\frac{\rho}{F}}$$

The metal crucible containing the glass must be sectorized to ensure relative transparency to the electromagnetic field generated by the inductor; otherwise, it would constitute a Faraday cage, preventing the formation of induction currents to heat the glass. The power density transmitted to the glass decreases to zero from the wall to the center of the melt. This gradient provides for convective stirring within the molten glass. The glass level rises along the wall and diminishes in the center of the crucible. There is no electromagnetic stirring effect, since the electromagnetic forces are one or two orders of magnitude lower than those generated by the thermal gradient.

DESCRIPTION

A direct-induction glass melting facility comprises four subsystems:

- a water-cooled sectorized cold crucible;
- a crucible bottom structure supporting the glass casting nozzle;
- a high-frequency generator, inductor and trimming capacitors;
- a glass preheating system required on startup, since cold glass is a poor conductor and must be preheated until the energy transmitted by induction exceeds the thermal losses.

Cold Crucible

The crucible (Figure 1) is an assembly of stainless steel sectors forming a cylindrical structure. Typical crucibles are 0.55 m in diameter and 0.70 m high, although the actual dimensions may be smaller or larger (e.g. 1.50 m diameter). A three-dimensional computer model is used to optimize the dimensions and ensure better than 80% electrical efficiency. Each sector has a rectangular cross section, and includes water ports mating with the inlet and outlet manifolds. The sectors are separated from one another by electrically insulating material. The structure is maintained externally by strapping with refractory fabric.

Crucible Bottom Structure

The cold crucible is supported by a bottom structure comprising a water-cooled stainless steel center plate and a refractory cement outer ring. The refractory assembly is molded to allow handling. Water cooling of the center plate and crucible walls is sufficient to solidify the glass in contact with the refractory ring, forming a continuous layer around the melt. The center plate supports the following elements:

- a casting nozzle extending into the melt, designed to retain a sufficient glass heel to allow continued induction after casting; it comprises either a glass freeze valve controlled by a medium-frequency inductor, or a separate mechanical shutter;
- a drain nozzle with an induction-heated freeze valve at the bottom of the crucible to empty the glass heel;
- air or argon injectors extending into the melt to ensure thermal and chemical homogeneity by stirring if necessary.

Figure 1. French Cold-Crucible Melter

High-Frequency Generator

A vacuum tube generator with three shunted triodes supplies 240 kW at 12 000 V at a frequency of 335 kHz for a crucible 0.55 m in diameter. A high-frequency line consisting of two water-cooled copper sections connects the generator to a multiple-winding inductor placed around the cold crucible. The geometry of the oscillating circuit and the distribution of the trimming capacitors ensure a null potential between the cold crucible — containing the molten glass — and earth, making additional insulation unnecessary between the crucible and its supporting structure.

Preheating System

Various methods were considered, including expendable or recoverable susceptors, a heated arch, gas burner, plasma torch, graphite additive, etc. Finally, a microwave system was adopted

because it allows energy to be transmitted to the cold glass without contact, and without requiring placement of the generator in the shielded cell containing the melter: no mechanical or electronic components of unproven reliability are therefore located inside the cell.

Most of the cold crucibles implemented to date have used a 25 kW microwave generator operating at a frequency of 915 MHz, transmitting energy to the melter via a rectangular waveguide with inside dimensions of 124×248 mm. The waveguide is connected to the tapered upper junction between the melter and the calciner; a quartz window on the melter end ensures a leaktight seal.

ADVANTAGES

The process avoids any contact between molten glass and the cold metal wall, thereby preventing crucible wear regardless of the glass temperature or the melt composition. This type of crucible has successfully been used to melt UO_2 at 2500°C .

Not only is corrosion eliminated, but the energy input to the glass is unlimited, allowing high production rates. The glass melting temperature may easily be raised above 1200°C if necessary.

PERFORMANCE

Several thousand hours of tests have been conducted to date with melters 0.35, 0.55 and 1.20 m in diameter, supplied with ground glass, or with glass and calcinate (either premixed or with the melter coupled to a calciner of the same type used in the R7 vitrification facility), and at temperatures ranging from 1150 to 1380°C . The maximum capacity has been about $25 \text{ kg}\cdot\text{h}^{-1}$ for the 0.35 m diameter melter, and $50 \text{ kg}\cdot\text{h}^{-1}$ for the 0.55 m diameter melter. The actual throughput depends not only on the melter diameter, but also on the temperature. At 1300°C , a melter 1 meter in diameter can produce 200 kg of glass per hour when supplied with dry material. Testing with liquid feed resulted in a lower capacity, and raised some technological problems.

APPLICATIONS

In addition to melting metal waste, the high capacity and high temperature capability of the cold crucible melter are compatible with many applications in the area of radioactive waste vitrification: concentrated fission product solutions, low- and intermediate-level solutions with vitrifiable compositions, and solid inorganic waste that is either unfit for incineration or for which incineration would produce a heterogeneous ash/oxide mixture and a low volume reduction ratio (e.g. restoration of contaminated soils).

Among other projects, the French are now building a vitrification facility for low-level radioactive liquid waste from the Temelin power station in the Czech Republic. A full-scale prototype unit with a cold crucible 0.60 m in diameter will begin operating at the site in 1994.

XC: Jensen
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Prepared by CEA & SGN
for NUMATEC, Inc.

May 1991

THE COLD CRUCIBLE TECHNIQUE

GENERAL

Several operations for the treatment of radioactive wastes involved high temperature thermal processing, for instance in view of embedding HLW in a glass matrix or fusing metallic wastes for reducing their volume or even high temperature cracking of organic compounds. These operations are traditionally carried out in conventional ovens or furnaces, but difficulties in operation may arise in account of the temperatures required and the nature of the materials in contact. These difficulties cannot always be overcome in a satisfactory manner, the more so when operating conditions which would reduce these difficulties are conflicting with process requirements: in some instances, it would be desirable to decrease the temperature to reduce the corrosion of the crucible and increase its MTBF, but a lower temperature would not yield the desired product characteristics.

- PRINCIPLES OF THE COLD CRUCIBLE

The temperature level between the material to be heated and the crucible may be significantly reduced if the heat flux does not have to be transmitted through the wall of the crucible and if the wall of the crucible is cooled.

This may be accomplished by an appropriate heating of the material in the bulk by means of an electromagnetic field produced by an external coil. The frequency of the electromagnetic wave must be adapted to the material to be heated for an efficient energy coupling. Quite low, from 1 to 10 kHz, when metals are concerned, much higher, 100 to 500 kHz in the case of glass or dielectric materials. If the crucible is made in a non-conductive material or made of narrow and insulated metallic strips, it is transparent to the electromagnetic field and should remain cool.

However, the heated mass in the center will conduct and radiate heat towards the outside, and to prevent the temperature of the crucible from increasing too much, the metallic strips constituting it are cooled (Fig 1), generally by water running through channels within the strips or through copper tubes welded outside (Fig 2).

Under these circumstances, the material directly in contact with the cooled crucible solidifies. As a result, the molten material comes only in contact with solid material of the same composition, and risks of corrosion of the crucible as well as the subsequent contamination of the facility and environment are greatly reduced. Also, when producing materials with exacting specifications, the desired product does not come in contact with foreign compounds and maintains a high degree of purity.

The choice of the frequency of the electromagnetic wave is very important as it bears directly on the power efficiency of the process.

The depth of penetration (p , in meters) of the induced currents depends on the resistivity (ρ , in Ωm) of the material and on the frequency (F , in Hz) of the current in the inductor, as well as of a few parameters which may be lumped together in a constant. In the case of glass, the depth of penetration is given by the formula:

$$p = 503 \frac{\sqrt{\rho}}{\sqrt{F}}$$

For a good efficiency, the penetration depth must be well under the radius of the crucible, and the operating frequency set accordingly.

COLD CRUCIBLE EXPERIENCE AT CEA

The cold crucible technique is under development and testing at Marcoule since 1981. Since that time, it has been applied successfully at various scales, up to the industrial scale, to quite diverse problems.

The first development concerned the melting of hulls from reprocessing. The process has been qualified both at the industrial level and on the radioactive standpoint through the operation of two facilities:

- firstly, an industrial size facility built in Marcoule and commissioned in 1983. Twenty tons of stainless steel and zircaloy have been processed successfully into one meter long ingots in this facility.

- secondly, radioactive stainless steel hulls from the reprocessing of breeder fuels have been cold crucible melted in a smaller facility housed in a hot cell. A high α -decontamination factor has been noted, enabling the ingots to comply very likely with sub-surface storage specifications. The α -contamination is essentially dissolved in the flux, and may be subsequently vitrified.

Another application concerns a large capacity glass melting furnace based on the cold crucible technique which has been built and operated. In account of the heat transfer limitations met with the Joule or direct induction heated crucible techniques, the cold crucible will enable the throughput to be increased, the temperature of the glass to be raised for a greater homogeneity, a faster processing and an increased flexibility in the choice of glass compositions. Moreover, the crucible life expectancy will be considerably extended.

- Finally, the cold crucible concept has also been applied to an induction plasma torch. This overcomes the power limitations of the inductors surrounding a quartz tube while producing a plasma with a lower velocity, a valuable asset.

Compared to conventional furnaces or ovens, the cold crucible technique has also the tremendous advantage of having most of the maintainable equipment removed from the active area. The crucible, instead of acting as the hot source, is maintained at a rather low temperature and is protected from corrosion by a layer of solid material; the risk of its cracking or piercing becomes very small, and its very structure makes it easily amenable to remote dismantling with minimal waste generation. Moreover, the energy source, the RF-generator, is located in the non-nuclear area, a simple coil surrounding the crucible being located in the hot cell area.

FROM REPROCESSING HULLS TO INGOTS

Several schemes have been conceived in the past for the processing of the hulls issued from the dissolution step of spent fuel reprocessing. Hulls are "empty shells" but still contain a residual, essentially alpha plus high level beta-gamma contamination, with traces of tritium and $Kr35$ when originating from light water reactors. Fuel cladding material is stainless steel in the case of breeder reactors, and zircaloy, with a small percentage of stainless and inconel, in the case of LWRs.

The most straightforward packaging method is embedding the hulls in a concrete matrix, but the gain in volume is nil, a disadvantage whenever deep underground disposal is contemplated. A reduction in volume may be obtained by first compacting the hulls, then embedding them in a metallic matrix such as lead.

However, the greatest reduction in volume is obtained by fusion of the hulls. Conventional metallurgical techniques seem inappropriate in account of the radioactivity of the processed material. On the contrary, the cold crucible technique exhibits many advantages: there is no transfer of material in the melt, the ingot is continuously fed with scrap material until it reaches its final size, and the use of a flux prevents the oxidation of the metal, removes surface oxides and contamination. The process is also easily amenable to remote operation and maintenance. These reasons led CEA to the design and construction of several facilities to test and qualify this process at the industrial scale:

Firstly, an industrial scale facility, fully nuclearized, enabling ingots 200 mm in diameter and 1000 mm in length to be cast semi-continuously has been built in Marcoule. A run enables some 200 to 250 kg of wastes to be processed, with a power requirement of 4 to 6 kWh per kilogram of metal cast. The top of the crucible is closed with a cover fitted with an inlet port through which a metered flow of hulls is introduced, an inlet tube for supplying an argon atmosphere and an outlet for off-gases. These include trapped radioactive gases released during the melting of the hulls. At the bottom, the crucible (Fig 3) is closed by a water cooled moving plate.

At the beginning of a run, the moving plate is brought flush with the bottom of the inductor, hulls are fed into the crucible and the inductor is energized. Flux introduction is apportioned to the hull feed rate. More hulls are fed into the crucible until the metal reaches a preset level where pulling down of the ingot is initiated. More hulls are metered into the crucible, maintaining the level at the required value until the desired length is reached. After cooling down, the ingot, still surrounded by an external layer of slag, is entirely drawn down

from the crucible. The slag does not form a hard crust and may, therefore, be easily separated from the ingot. A general view of the process together a fresh ingot is given in Fig 4.

The initial melting capability of 40 kg per hour may be easily boosted to 100 kg per hour. Tests were carried out on stainless steel hulls and 17 tons have been processed so far. Some 3 tons of Zircalloy hulls have also been cast. Based on the initial volume of the hulls, the compaction factor is sizeable, and the surface area reduction of the order of 200, lowering significantly the risks to the environment associated with leaching, not to mention the decrease in the amount of radioactivity contained through the combined action of fusion and fluxing.

Secondly, a small size hot facility located in Marcoule and housed in a heavy concrete cell has been commissioned in 1988 (Fig 5 and 6). Stainless steel hulls, originating from the reprocessing of the Phénix fast breeder reactor fuel, have been processed very successfully yielding small ingots (Fig 7). These weigh around 2.5 to 3 kg, with a nominal diameter of 60 mm and a length of 130 to 180 mm.

Data show that most of the α -activity has concentrated in the slag originating from the flux used in the operation. The resulting slag may be very easily separated from the ingot and furthermore, be embedded by vitrification. Tests carried out on Zircalloy hulls show a lesser degree of decontamination. This is little surprising on account of the reducing power of zirconium: some oxides from the hulls, once they have been reduced, are prevented from migrating into the flux. Flux formulation (oxides and fluorides) is being optimized so as to achieve the highest decontamination factor.

Table 1

FLUX PERFORMANCES			
Cladding	Flux formula	Decontamination Factor for	
		α	beta-gamma
Stainless	75/25-CaF ₂ /MgF ₂	≥ 99,5%	≈ 11%
Zircalloy	50/50-CaF ₂ /BaF ₂	N.A.	N.A.
N.A. :Not Available			

VITRIFICATION

The vitrification process developed by CEA and operated by COGEMA in La Hague and by BNFL in the UK includes two successive operations: to start with, the nitrate solution issued from reprocessing is sent to a rotary kiln in which it is dried and calcined. The resulting calcinate is then transferred to the vitrification process where it is mixed with a glass frit, a primary glass with a formulation adapted to the elements contained in the calcinate, designed to obtain adequate performances with respect to lixiviation of the finished product. In the past, vitrification has been carried out satisfactorily in induction heated inconel crucibles.

A cold crucible has been designed and is currently under inactive tests in view of future vitrification units (Fig 8). Compared to the present induction heated inconel crucible, the cold crucible under test would have many assets. It will enable much larger capacity to be attained and higher glass temperatures (1400°C and over) to be reached, broadening the formulation range, and yielding a more homogeneous product with improved characteristics. In account of the lower operating temperature of the crucible, the corrosion prone component in the process, the MTBF should be significantly increased.

Operating conditions differ widely whether it is metal or glass that is processed in a cold crucible, as the depth of penetration depends on resistivity (cf. supra). But, the resistivity of glass has a negative temperature coefficient. Therefore, it is necessary to raise the glass temperature for an efficient coupling with the induction field. This is accomplished by first heating locally a small volume of glass at sufficiently high a temperature. This is best accomplished by creating a hot spot by means of a microwave beam (25 kW), a technique well suited to a nuclear environment, then energizing the inductor.

Thanks to a 3-D model developed jointly by the MADYLAM laboratory of the National Polytechnic Institute in Grenoble and CEA, it is possible to optimize the dimensions and design of the cold crucibles for glass melting. Thus, power efficiencies in excess of 80% can be achieved.

With a crucible 55cm in diameter, it is possible to melt 50 kg of glass per hour. Increasing the diameter up to 100 cm will increase the capacity up to 200 kg per hour at the least, a value coherent with the current throughput of reprocessing plants. Today, only refractory furnaces with electrode heating attain such capacities. But they are very bulky, their MTBF rather low and very costly to dispose of once contaminated. On the contrary, cold crucibles can be readily dismantled and decontaminated: solid glass does not adhere to stainless steel, and the decontamination of stainless is routine. A one meter diameter cold crucible has been built and tested at CEA. Its larger dimensions enable the inductor to operate at 10 to 50 kHz, opening the way to solid state high power supplies.

With process optimization in view, the benefits of processing a nitric solution straight from reprocessing versus a calcinate feed is under study. With a cold crucible, the power increase resulting from such a change in the process flowsheet would not have any detrimental effect on the nuclear side of the facility. A change in the energy requirements would only concern the water cooled coils located just outside the crucible, and, of course, the power supply located outside the nuclear area.

Vitrification would then become a preferred packaging process, not only for HLW, but for MLW and LLW as well.

PLASMA TORCH

Very high temperatures may be attained with a plasma torch. Two types are currently in use: the arc induced plasma, and the inductively coupled plasma. Higher power levels may be attained by the arc induced plasma. However, this technique presents some difficulties when the plasma is used to crack corrosive gases and vapors: failure of the electrodes, general corrosion.

The inductively coupled plasma overcomes these drawbacks, has a plasma velocity ten times slower, but, with a quartz nozzle, seems limited to around 50 kW. From the experience acquired on the cold crucible, a nozzle based on this technique has been designed and built. A "flame" temperature of 2000°C is easily obtained at this power level. This technique

circumvents the power limitations of the quartz nozzle, and much higher temperatures are achievable at greater power inputs. The cold crucible plasma torch technique should find applications in many areas, and in particular to the burning of the off-gases produced during the calcination of organic bearing materials even when highly corrosive.

MISCELLANEOUS APPLICATIONS

The cold crucible technique, the more it is known, the more versatile it proves. Its characteristics have opened many areas in the nuclear field, in the processing of wastes in particular. It should find many applications for the processing of difficult or noxious or highly corrosive compounds. This technique being well mastered by CEA for a nuclear environment, it is available for solving pending questions.

For instance, asbestos which has been widely used in lagging and fire protection until recent years, presents an unacceptable health hazard and should be disposed of properly. Its melting into solid, non fibrous blocks, vitrified just like nuclear wastes would solve this problem once and forever.

Needless to say, the cold crucible technique will find applications in many areas in the nuclear field. In particular, it should become a preferred process for the fusion, with a proper additive, of ashes originating from any type incinerator. The higher temperatures accessible with the cold crucible technique opens a gamut of new formulations.

Special glass manufacturers show great interest in the cold crucible technique -- in account of its non-polluting characteristics: optical glasses, flint glass, crystal, enamels. Many of them may become partners in the construction and operation of a 200 kg/h capacity "vitrification" facility in a near future.

FUTURE DEVELOPMENTS

The cold crucible technique shows significant advantages over conventional techniques insofar as no wear occurs in the vicinity of the materials to be processed as it is the case with joule heated or other conventional hot crucible techniques. This represents a tremendous asset in the nuclear field where maintenance is a very heavy and costly operation. There is no crucible to corrode, there is no resistor to fail, there is no bulky equipment to dispose of in the end.

The experience gained by scientists and technicians in Marcoule suggests a bright future for the whole of this technology held by the DCC, (Direction du Cycle du Combustible) the Fuel Cycle Direction of CEA and developed in close cooperation with French industry.

In particular, a cold crucible hot facility for the melting of radioactive hulls from reprocessing is presently under construction in the APM at Marcoule. It should come on stream in 1992 and process hulls issued from the reprocessing of the fuel from the Phénix breeder as well as from LWR spent fuel from the La Hague plant.

A TGF, Très Grand Four (a very large furnace), for glass melting with a rating of 200 kg per hour and a hold up reaching 500 kg is presently under study. Plans call for its commissioning in 1993, long term testing in 1994, and its coming in support of glass industries in 1995.

...ooOoo...

TECHNIQUE

FIG. 1

FIG. 2

WATER COOLED HEADERS
AND SECTORS

HULL MELTING IN A COLD CRUCIBLE

FIG. 3

NON RADIOACTIVE INDUSTRIAL-SCALE PROTOTYPE

OUTSIDE VIEW OF THE HOT CELL
FOR HULL MELTING

FIG 5

HULL MELTING FACILITY INSIDE
THE HOT CELL

Fig 6

SMALL INGOT FROM HOT HULLS

Fig 7

COLD CRUCIBLE WITH A COATING
OF GLASS

Fig 3

APPENDIX C

INFORMATION ON RUSSIAN COLD CRUCIBLE MELTER DEVELOPMENT

RADIOACTIVE WASTE MANAGEMENT IN THE USSR:
A REVIEW OF UNCLASSIFIED SOURCES

Volume II

D. J. Bradley

March 1991

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Pacific Northwest Laboratory
Richland, Washington 99352

- 1 - Shipping Cask
- 2 - Crane
- 3 - Reinforced Concrete Shaft for Cans
- 4 - Air Duct
- 5 - Storage Bays

FIGURE 8.5. Natural-Circulation-Cooled Storage Facility for Vitrified Wastes (Nikipelov et al. 1990a)

Further details on the two-stage vitrification process were given in a recent paper by B. V. Nikiforov. The process revolves around a method to dry the liquid waste and then melt the waste in a second stage using a high-frequency induction melter with a so-called "cold wall" or "cold crucible" design to help contain the melt and decrease corrosion of the melter materials. The expected design capacity of the system is 100 L/h of feed solution and 25-35 kg/h of solidified product. For the first stage, fluidized bed, spray and rotating horizontal calciners as well as a once-through evaporator have been studied. It appears that only the once through "tube in tube" evaporator meets their engineering and capacity requirements. Experiments with the once-through evaporator have showed satisfactory operation with up to 100 L/h feed rate of solutions with salt contents up to 350 g/L (Nikiforov et al. 1990).

→ The performance of the inductive melting process has been experimentally demonstrated in the cold crucible at temperatures from 1200°C to 2300°C. This

process may be used to produce glassy-crystalline and "mineral-like" materials such as pyroxene and pyrosilicates, titanates and titano-silicates, ferrogarnets and ferrosilicates, and Synrock-C.

All these materials have been prepared using the induction melting process at a temperature of 1250°C to 1550°C, and then treated at 650°C for two hours to simulate annealing, and irradiated to 10^{10} rad to determine their radiation resistance. Chemical stability was determined by an "express" [rapid] method under "contact with distilled water fraction 0.16-0.25mm" at a temperature of 60°C during 1 hour (Nikiforov et al. 1990). Tentative results showed that sphene, ferrogarnet, and a complex type of glassy-crystalline pyroxene have high chemical stability, jadeite, aegirine-augite and andradite were the most stable, and synroc "type" materials were "intermediate" in durability.

The Soviets have developed "cold crucibles," made of stainless steel and "sealed" by refractory materials, with a tank area of 0.05-0.12 m². At a mean temperature of 1500°C, operating in the "continuous mode," they have demonstrated production of silicate materials at 12-18 kg/h. Details of their design are given in Table 8.1. Figures 8.6 and 8.7 show a general hot cell arrangement for the two-stage vitrification process and concept of the induction-heated cold crucible melter, respectively (Nikiforov et al. 1990). It should be noted that two-stage vitrification processes have been under development since the 1970s in the Soviet Union. A diagram of the KS-KT-100 two-stage vitrification process is shown in Figure 8.3 (Nikiforov et al. 1985).

The principle of transmutation, as stated by the Soviet scientists, is to separate actinides, fission products, and/or isotopes of long half-life and subject these isotopes to high fluxes of thermal neutrons, protons, or lasers. It was indicated that heavy water reactors will be used to produce neutrons which will bombard a mixture of Lithium and waste (with an approximate composition of: ²³⁷Np - 35%, ²⁴³Am - 27% and Cm - 44%). Approximately 500 to 1000 kg per year of actinides will be "burnt" (National Academy of Sciences 1990). Work along these lines has recently been reported by the Ukrainian Academy of Sciences Institute of Physics and Technology in Kharkov. Scientists have installed "several new 100 MeV accelerators" at an unspecified

TABLE 8.1. Specifications of the Two-Stage Vitrification Process Using a Spray Calciner and Induction Melter with a Cold Crucible

Spray Dryer-Calciner (RS-100)

1. Diameter, m	0.7
2. Height, m	3.5
3. Material,	Ch18NIOT (Stainless Steel)
4. Furnace Power, kW	240
5. Electrical Consumption, kWh/L	0.9
6. Working Temperature, °C	750
7. Production Based on Feed Solution, L/h	100

Induction Melter with Cold Crucible (IPChT)

1. Inductor Power, kW	160
2. Operating Frequency, MegaHz	1.76
3. Crucible Material	12Ch18NIOT (Stainless Steel)
4. Dimensions of "Cold" Crucible, mm	600x300x600
5. Operating Temperatures, °C	900-2300
6. Production Based on End Product (Glass or Mineral-Like), kg/h	30

nuclear station to bombard isotope targets with electrons. Full-scale "experiments" are scheduled to begin later in 1990 (Nuclear Waste News May 10, 1990).

The Khlopin Radium Institute is conducting research on partitioning of HLW using the organic compound cobalt dicarbonyl anion in HNO_3 acid solutions. This reagent is especially effective for large ions, and the process separates Sr, Cs, REE and TRU with efficiencies up to 99%. Cs and Sr were reported to

FIGURE 8.5. General Hot Cell Arrangement for the Two-Stage Vitriification Process (Nikiforov et al. 1990)

FIGURE 8.7. Drawing of the Induction-Heated Cold Crucible Melter Concept
(Nikiforov et al. 1990)

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APPENDIX D

PRESENTATION FROM TRIP TO FRANCE

Ce circuit fermé fait écran
et le champ est nul

Les courants se referment
sur chaque secteur et le
champ n'est pas nul

PRINCIPE ELECTRIQUE DE LA FUSION EN CREUSET FROID

PRINCIPE DE LA FUSION EN CREUSET FROID

Couche de produit
de base en cours
de fusion

Verre fondu

Creuset Froid

Verre figé :
autocreuset

Inducteur

Eau

Eau

Buse de coulée

Inducteur

Creuset Froid

COLD CRUCIBLE TECHNIQUE

■ Using electric induction

- High frequency magnetic electric field coming from a coil
 - » electric current directly into the product to be heated
 - » power coming from the Joule effect

$$P = RI^2$$

■ Advantages

- power directly in the product
- high temperatures possible
- high specific power possible

GLASS MELTING IN COLD CRUCIBLE

■ No contact between crucible and melting glass

■ No wear of the crucible.
Life time : 10, 20, 30 years ?

■ No contamination of the cold crucible (or very low)

■ No limit of temperature

ZrO₂ 2750°C

UO₂ 2800°C

GLASS MELTING IN COLD CRUCIBLE

- When cold, glass is an electric isolating material

---> no possibility to introduce power in the glass !

- It's necessary to preheat a little "part of the glass using an other mean

---> for nuclear purposes, microwaves are proposed

- It's necessary to keep, continiously a part of melted glass, in the bottom of the crucible

COLD CRUCIBLE EQUIPMENT

The depth of the electric current penetration "d" is reciprocally proportional to the current frequency

$$D = \frac{K}{F}$$

50 cm
1 m

200 000 Hz
50 000 Hz

COLD CRUCIBLE TECHNIQUE

■ Power balance

- electric losses in the coil 10 %
- electric losses in the cold crucible 20 %
- power into the glass 70 %

to melt 30 to 40 %

thermic losses 60 to 70 %

---> high electric power consumption
but...glass is a thermic isolating material

Conventional melting
(refractory furnace)

1 kWh/kg of glass

Melting in cold
crucible

2 to 2.5 kWh/kg

COLD CRUCIBLE EQUIPMENT

Tests have been made with this equipment
connected to AVM calciner

30 kg.h⁻¹ is a possible capacity with R7 glass type

POSSIBLE CAPACITY OF A COLD CRUCIBLE MELTER

■ We have today demonstrated

ϕ 55 cm

R7 type glass

1200°C

-----> 30 kg.h⁻¹

It's probably not the upper limit

“

■ Flowrate is proportional :

to surface ϕ^2

to temperature T^4

and increases with stirring means

Example : ϕ 80 cm $\rightarrow$ 63.5 kg.h⁻¹

ϕ 90 cm $\rightarrow$ 80 kg.h⁻¹

(same temperature of 1200°C)

f 55 cm $\rightarrow$ 55.6 kg.h⁻¹

f 80 cm $\rightarrow$ 80 kg.h⁻¹

(at 1400°C)