Treatment of nuclear mixed waste by induction heating and electromagnetic stirring of a metal/glass bath the PIVIC process.

P. Charvin, F. Lemont, A. Russello

Treatment of nuclear mixed waste by induction heating and electromagnetic stirring of a metal/glass bath: the PIVIC process

P. Charvin[1], F. Lemont[1], A. Russello[1]

[1] CEA, DEN,DE2D,SEVT,LPTI, 30207 Bagnols sur Cèze, France

patrice.charvin@cea.fr

Abstract

A fusion process based on low-frequency induction heating has been developed to treat mixed radioactive waste and produce biphasic glass/metal canisters compatible with a storage in a geological repository. The direct transfer of inductive power to the metal load ensures that fusion occurs directly in the final container and avoids a pouring stage. A thermal equilibrium develops during fusion between the power transmitted by induction and the power evacuated in the furnace's cooling circuits. The generator's electrical parameters are used to determine the amount of metal present in the canister.

Key words: nuclear waste, induction heating, electromagnetic stirring

Introduction

Several facilities are required to separate and recycle the valuable components of spent nuclear fuel [1]. These facilities, and notably those used to prepare new nuclear fuel, produce contaminated secondary waste. These surface-contaminated wastes come in various forms, a large proportion of which are organic (gloves and glovebox equipment, cable jackets, waste bags…), with also metals (hydraulic cylinders, tools, transfer boxes…) and ceramics (laboratory glassware, HEPA filter media).
Low-level wastes with activities less than 370 Bq/g of alpha radiation are sorted out by kind and treated at CENTRACO by incineration or fusion [2]. Weakly contaminated metals are treated by fusion in several countries (France, Sweden, Germany) [3] because this process offers several advantages:

- A reduction in waste volume (greater than can be achieved by compaction)
- A reduction in the surface/volume ratio (reduced corrosion)
- A partial decontamination of the metals, as the radionuclides migrate in the slag
- An homogenization of the remaining radionuclides.

Intermediate-level wastes are stored in 120 L metal drums. The treatment process being developed by the CEA (French Alternative Energies and Atomic Energy Commission) for these types of waste involves incinerating the organic fraction before fusing the residues (ash and metals) [4] into biphasic glass/metal waste packages that meet the requirements for a future geological storage. The work described in this article covers the design and development of the fusion module and the fusion tests carried out with simulated residues.

Description of the fusion process

Induction heating

Previous studies have shown that induction heating is well-suited for the fusion of ferrous metals with a supernatant oxide slag [5]. Indeed, electromagnetic stirring increases the exchanges between the metallic and the slag phase. A 500 kW Inductotherm VIP generator delivers low-frequency (50 Hz) alternating current (AC) to an induction coil 680 mm in diameter and 350 mm in height with 19 turns. At this frequency, the electromagnetic skin depth δ_B (Eq. 1) is about 80 mm in stainless steel. The very high value (several meters) obtained for liquid glass confirms its transparency to the magnetic field.

$$\delta_B = \sqrt{2/(\mu_0 \sigma \omega)} \qquad (1)$$

With μ_0 the permeability of free space, σ the electrical conductivity of the material, and ω the angular frequency.

In-can Setup

The fusion process is carried out in-can, meaning that the packet is prepared directly in the final canister. The canister is attached to the side of the furnace, forming part of the latter. The metal and glass phases are fused in the canister by power transfer into the metallic component. The multilayer design ensures that metal pieces are fused without degrading the metal canister itself. The inner walls of the metal canister are cladded with an insulator and the waste residues are placed in a smaller-diameter ceramic crucible. This crucible is heated to high temperatures by contact with the molten material. The canister is placed on a water-cooled plate inside a divided crucible, which is also cooled by circulating water. This setup allows the narrow external metallic shell to be cooled. A thermal gradient thus forms in the isolating cladding.

The in-can principle imposes batch production with a variable filling level. However, it avoids any pouring of molten metal and glass. Furthermore, the canister forms a barrier between the molten metal and the cooling water, thereby limiting the risk of water/metal interactions compared with cold crucibles. The insulator reduces the power required to achieve fusion in spite of the screening effect from the external metal shell.

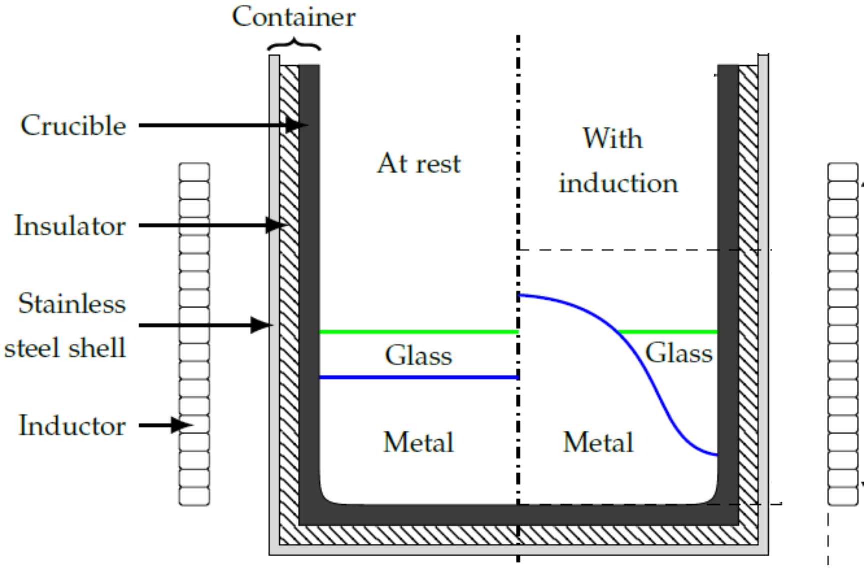

Fig. 1: Schematic cross-sectional view of the melting module.

Arrangement of the liquid phases

The different densities and chemical nature of the glass and metal phases ensure that they are well separated in the liquid state (Fig. 2), and after cooling (Fig. 3), with the vitrified phase on top. Nonetheless, the electromagnetic field from the inductor generates electromagnetic pressure that deforms the liquid metallic phase. This forms a dome [6,7] that can emerge in the center of the surface (Fig. 2) depending on the amount of glass present and the power used [8]. After the generator is turned off, the metal migrates to the bottom of the crucible and the glass forms a layer of even thickness on top. A relatively low cooling rate is used that avoid freezing the dome and let the liquid phases reorganize under the effect of gravity.

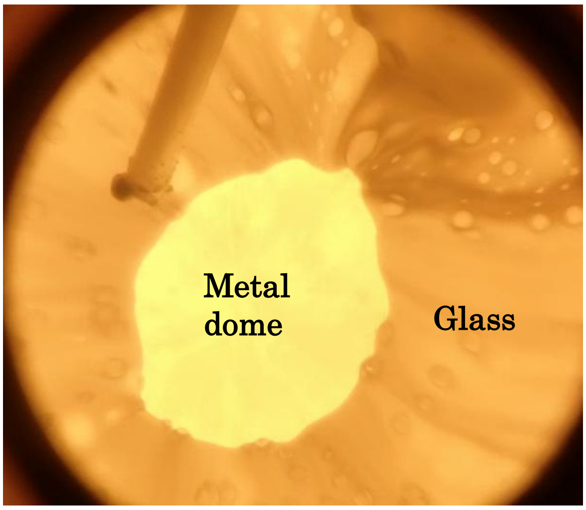

Fig. 2: Surface of the molten metal/glass bath.

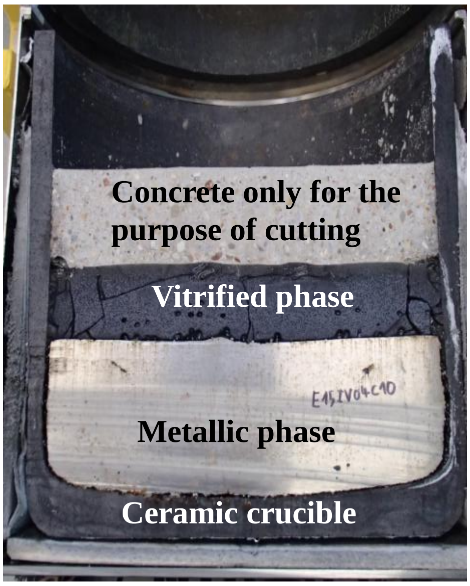

Fig. 3: Cross-section of a canister at the end of a test

Thermal transfers

Power delivered by the inductor

The inductor transfers power to all metallic elements inside the coil. The divided crucible and the divided plate absorb only a very small amount of this power. The magnetic field then reaches the metal canister. Despite the thinness of the outer walls, this shields the magnetic field and receives a substantial proportion of the transferred power. It contributes to the inductive load inside the coil.

The residual magnetic field that passes through the metal canister transfers power to the massive metal pieces in the ceramic crucible, which along with the insulating cladding are transparent to the electromagnetic field at this frequency. The more metal is present in the crucible, the higher the transferred power is.

Power evacuated in the cooling circuits

The power delivered to the metal canister and the metallic contents of the ceramic crucible heat these two elements. A set of springs keeps the metal canister in contact with the water-cooled divided crucible. Power is dissipated via the thermal gradient between the two according to Equation (2).

$$P_{released} = h \,.\, S \,.\, \Delta T = h \,.\, S \,.\, (T_{canister} - T_{water}) \qquad (2)$$

Where h is the heat-transfer coefficient between the canister and the divided crucible and S is the exchange surface area.

When the temperature difference (ΔT) is large enough for all the induced power ($P_{transfered}$) to be transferred by conduction ($P_{released}$) according to Equation (3), the metal canister ceases to heat up and its temperature stabilizes.

$$P_{released} = P_{transfered} \qquad (3)$$

The same thermal transfer occurs between the bottom of the canister and the cooled plate.

The thermal power transferred to the metallic pieces in the ceramic crucible leads to the same heating phenomenon. The metallic pieces need to be massive given the electromagnetic skin depth at this frequency. However, an insulator has been placed around the ceramic crucible to avoid thermal losses. The glass frit placed on top of the metal load acts similarly as an insulator for the upper surface. The temperature of the metal in the ceramic crucible thus increases until the melting point of the metal is reached. The dome that forms once the metal becomes liquid pushes the glass frit to the sides. This drastically increases the thermal losses from the surface because of the hot surface of the metal dome. In contact with the metallic phase, the glass frit also heats up until it melts, but at a lower temperature than the metal does.

Thermal equilibrium

The surface of the liquid baths is much hotter than the rest of the furnace, which leads to substantial heat loss. The temperature of the liquid baths increases until the thermal equilibrium defined by Equation (3) is reached. The released power is the sum of the power lost through all the edges of the bath (sides, bottom and top). A substantial portion of the power lost through the upper surface is radiative because of the surface's temperature. The T^4 dependence of the Stephan-Boltzmann law (Equation 4) means that the power lost through the surface increases rapidly with the temperature.

$$P_{radiation} = \sigma \,.\, \varepsilon \,.\, S \,.\, (T^4_{surface} - T^4_{water}) \qquad (4\ )$$

Where σ is the Stefan-Boltzmann constant, ε, the emissivity of the material, and S, the surface area.

Thermal equilibrium thus occurs at a temperature close to the melting point of the metal. If the power transferred is too low, more power is lost as soon as the metal dome forms. Surface cooling freezes the dome to maintain thermal equilibrium between the received and emitted power. To avoid this, the canister has to be loaded with at least 70-80 kg of metal to ensure that the amount of power it receives is sufficient to maintain fusion after the dome forms.

Electrical parameters

The charge in the induction coil can be monitored using the generator's electrical parameters. However, no significant variation is observed during the fusion of the metal pieces.

Metal pieces are added to the crucible during the waste treatment process. These increase the height of the metallic phase. The charge in the induction coil therefore increases, which affects the generator's electrical parameters. The current intensity in the coil decreases each time metal is added (by 2 A/kg, Fig. 4). These changes in the electrical parameters are used to determine the amount of metal in the ceramic crucible (Fig. 5). In parallel, power transfer into the metal phase is improved, which increases the temperature at the surface before thermal equilibrium is reestablished.

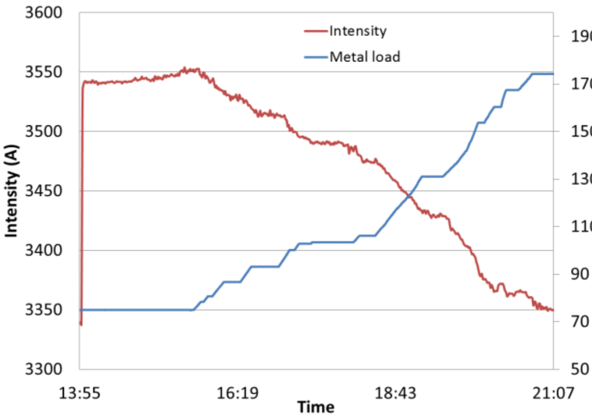

Fig. 4: Intensity variations during the feeding step

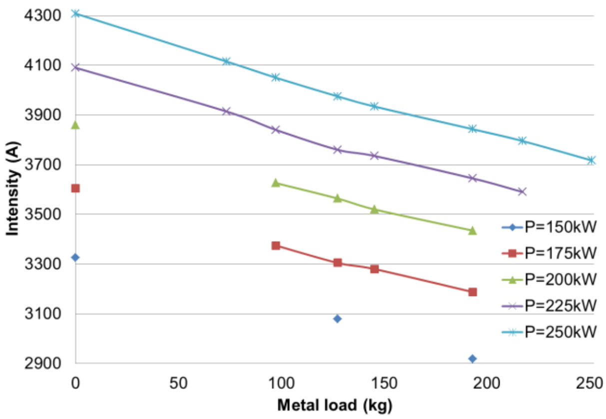

Fig. 5: Intensity vs metal load at several powers

Conclusion

A fusion process based on low-frequency induction heating has been developed to treat mixed radioactive waste and produce biphasic glass/metal canisters compatible with a storage in a geological repository. Preliminary tests have validated the method of direct induction heating inside the final container (in-can principle). The two phases are heated and stirred by the electromagnetic field, directly for the metallic phase and indirectly for the glass phase via exchanges at the glass-metal interface. The transfers of heat and momentum through this interface are sufficient to keep the glass molten. An analysis of the heat transfers shows that an equilibrium is established close to the metal's melting temperature between the power transferred by induction and the power evacuated by the cooling circuits. The generator's electrical parameters are used to determine the amount of metal present in the canister and thus monitor the filling process.

Acknowledgment

The PIVIC project is a partnership between CEA, ORANO and ANDRA. It is supported by the French government program "Programme d'Investissements d'Avenir" whose management has been entrusted to ANDRA.

References

1. P. Bernard, Progress in Nuclear Energy, 49 (2007), 583-588
2. J.M. Ducoulombier, B. Lantes, M. Bordier, Nuclear Engineering and Design, 176, (1997), 27-34
3. H-W. Seo, D-H. Lee, D.S.Kessel, C-L. Kim, Annals of Nuclear Energy, 110 (2017), 633-647
4. R. Boen, P. Charvin, F. Lemont, A. Russello, Patent EP 3031054, (2016)
5. B. Heshmatpour, G..L. Copeland, Nuclear and chemical waste management, 2 (1981) 25-31
6. K. Pericleous, V. Bojarevics, G. Djambazov, R.A. Harding, M. Wickins, Applied Mathematical modelling, 30 (2006), 1262-1280
7. G. Sugilal, J.J. Shashikumar, M.H. Rao, K. Banerjee, G.K. Dey, Materials Today : Proceedings, 3 (2016), 2942-2950
8. R. Bourrou, A. Gagnoud, O. Budenkova, P. Charvin, C. Lafon, F. Lemont, EPM 2018 Conference