Hot Isostatic Pressing of Radioactive Nuclear Waste: The Calcine at INL. 16348

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ABSTRACT

Hot Isostatic Pressing (HIP) is a technology that has been around for 60+ years. By using high temperature and high gas pressure, dry metal and ceramic powders can be consolidated and a volume decrease can be achieved. This paper presents the efforts using the HIPing process at the Idaho National Laboratory to treat the calcine radioactive waste. Once loaded into collapsible canisters, the HIPing would be used to treat the waste before final disposal. The resulting volume reduction was shown to be 20-70% and the cost ratio vs vitrification is 1:1.74.

INTRODUCTION

Hot Isostatic Pressing (HIP)

Hot Isostatic Pressing has fundamentally two different designs when it comes to contain the high pressurized gas, typically Argon. The two methods are called mono-lithic, sometimes referred to as mono-block, and pre-stressed wire-wound technology. An example, can be seen below in Figure 1.

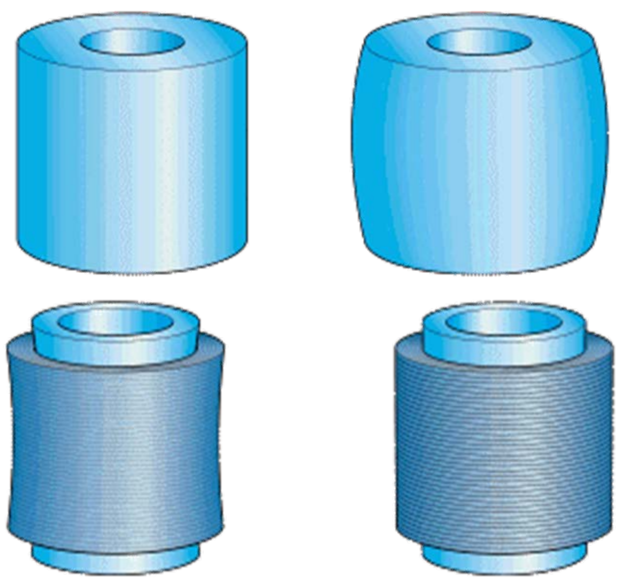

Figure 1. Mono-lithic vessel design (top) and pre-stressed wire-wound vessel design (below). Without pressure applied (left) and with pressure applied (right).

The mono-lithic design will always experience tensions stresses on the outside and inside of the pressure vessel making any material faults, and you will always have material faults, sensitive to fatal failures if the wall cracks. This failure mode is described as catastrophic. The consequence is a dramatic release of the gas pressure with serious damages to surrounding buildings. See figure 2 below.

Figure 2. Through wall crack in a mono-lithic pressure vessel.

The pre-stressed wire-wound HIP will always experience compressive stresses both on the inside and outside of the pressure vessel and the yoke frames during all phases of the HIPing process. This is the safest design and is approved by ASME according to ASME Boiler and Pressure vessel code, Section VIII, Division 3. This failure mode is described as “Leak-before-burst”. Meaning that if the pressure vessel will crack, the gas under high pressure will dissipate through the wire-wound package without any damages to the surrounding equipment and structures.

The combination of high temperature, 1050-1250 °C, and high gas pressure, 100 – 200 MPa, consolidates dry metal and ceramic powders by creep and diffusion, and heal internal voids, i.e. metal castings, to substantially improve the strength of any materials. The temperature depends on the material to be HIPed, e.g., Aluminum has lower melt temperature (650 °C) than steel (1550 °C). An example of the effect of HIPing of voids in a material can be seen in Figure 3.

Figure 3. Artificial pore before HIP (right) and after HIP (left).

The HIP cycle itself is strongly dependent, as mentioned before, on the parameters temperature and pressure. But, also time is of the essence in most applications. Therefore, much efforts has been done the last decades to optimize and minimize the total cycle time. The introduction of Uniform Rapid Cooling (URC®) greatly decreased the cycle time and also allows the HIP operators to optimize the cycle to be most suitable for them and their materials. An example of a HIP cycle without and with URC can be seen below in Figure 4.

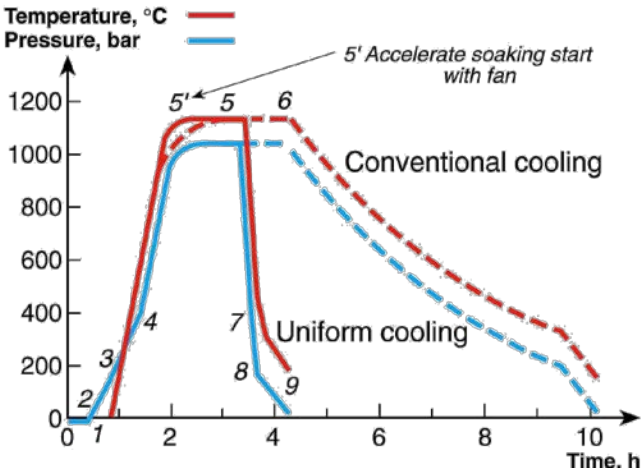

Figure 4. Typical HIP cycle times without and with rapid cooling.

The HIP system itself consists of the wire-wound yoke frames and a thin-walled cylinder, which can be considered as the back-bone of the pressure vessel since they take up the forces coming from the compressed gas. See Figure 5 below.

The furnace, which is the heart of the HIP machine, has an elaborate design to ensure good insulation, temperature accuracy, rapid cooling and reliable and safe requirements. HIP furnaces can be supplied in steel, Molybdenum or Graphite, depending on the operating temperature. See below Figure 6.

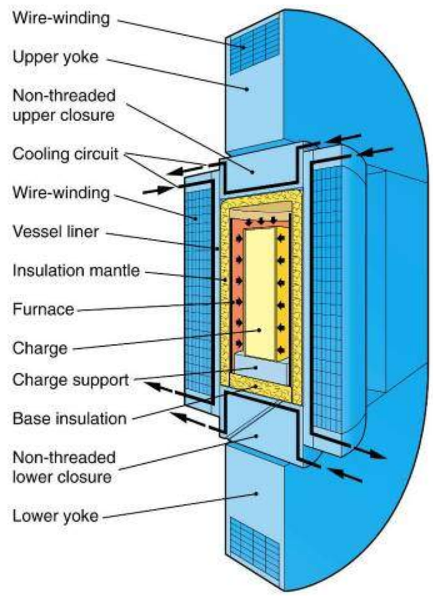

Figure 5. Pre-stressed Wire-wound HIP vessel.

The charge, which can be canisters of powder or cast/forged parts, is placed on an insulated support structure. The gas flows freely around the charge for utmost temperature accuracy. The best temperature accuracy is achieved with a multi-zone radiation furnace. See below Figure 6.

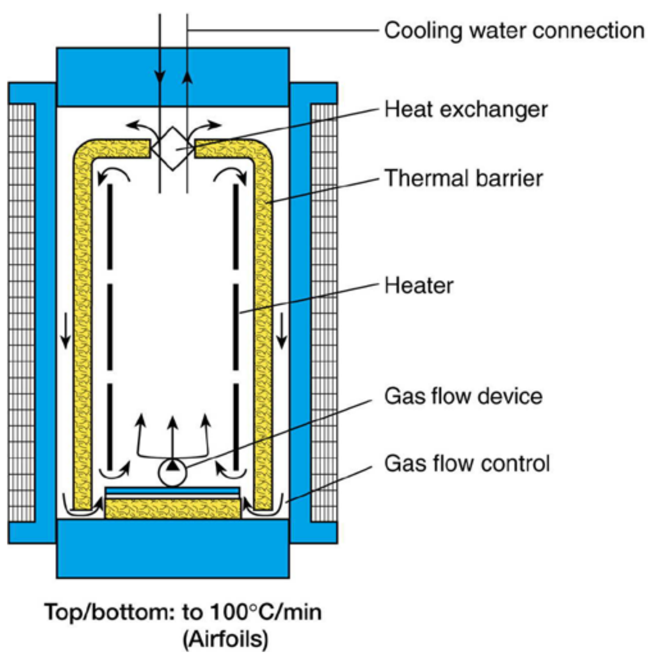

Figure 6. Closer Look on the Furnace.

The Radioactive Waste.

Calcine is by definition a high level waste. It is the first raffinate from the reprocessing of the spent nuclear fuel. The un-treated calcine is also classified as hazardous waste as it exhibits hazardous waste characteristics for toxicity of metals.

Today roughly 4400 m^3 of granular solid is stored in bins at the Idaho National Laboratory (INL) Site. It has been shown by several studies that a calcine can be HIPed directly or it can be treated with an additive and then HIPed in a collapsible canister [1], [2]. In both cases the result is a glassy ceramic waste form that can be packaged and disposed of in a final repository.

DESCRIPTION

Hot Isostatic Pressing of Calcine.

To make the test mixture, additives will be combined with surrogate calcine to make a glass-ceramic final waste form in the HIP. The mixture will be placed into a HIP can for bakeout and sealed for HIP testing. Quintus Technologies, LLC assisted in development of the bakeout and can sealing approach.

After HIP testing, the canisters were sectioned so that samples could be collected from the HIP material. The temperature was varied to test the volumetric reduction for different pressures and temperatures. See Figure 7 [3].

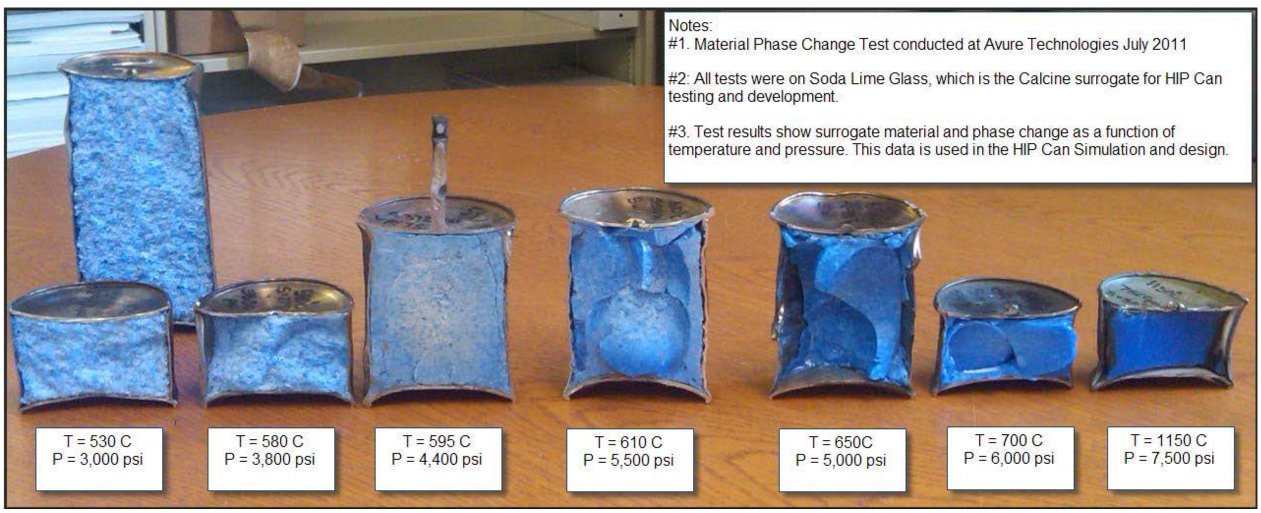

Figure 7. Vertical cuts of all cans showing various volumetric reductions.

DISCUSSIONS

Results of HIPing

From the trials mentioned above, some important conclusions could be made. First of all, that HIPing works to consolidate a ceramic like calcine. Also, that it is a versatile method for many different applications and can be used for many different possible treatment routes. See Table I.

TABLE I. HIP Technology Advantages over Vitrification [4].

Consolidation:	HIP	Vitrification (JHM)
Matrix:	Glass-ceramic	Borosilicate glass
Waste Loading:	60-90%	20-35%
Durability:	10-100 x EA-glass	10 x EA-glass
Final Volume: (relative to untreated calcine	20-70% reduction (treat=low, non-treat=high)	+100% increase
Temperature:	1050-1200 °C	1150 °C
Pressure:	35-50 MPa	Atmosphere
Off-gas/By-Product waste:	Minimal	Medium-High
Flexibility:		
- Calcine:	Treat or super-compact	Treat only
- Future mission:	Diverse/Flexible	Limited/Less flexible.

Secondly, that HIPing proves to be a very cost effective method with the lowest life-cycle cost for the consolidation of the calcine. Today's generally established route of vitrification is shown to cost about 75% more than HIPing. See Table II.

TABLE II. Cost Comparison HIP vs Vitrification [4].

Parameters	HIP without RCRA Treatment		HIP with RCRA Treatment		Direct Disposal		Vitrification with Separations		Vitrification without Separations	
Canisters	2 900	3 300	3 700	4 600	6 700	7 300	750	2 200	11 100	13 300
Total Life Cycle Cost (MUSD)	5 503	6 228	6 052	7 119	7 661	8 408	9 556	12 769	11 054	13 074
Cost ratio	1.00	1.13	1.10	1.29	1.39	1.53	1.74	2.32	2.01	2.38

CONCLUSIONS

Several advantages can be seen by using pre-stressed wire-wound Hot Isostatic Presses (HIP) for consolidating the calcine at INL site. HIP is a proven technology since 60+ years with world-wide safe operations. HIP systems are built according to ASME Boiler and Pressure vessel code, Section VIII, Division 3, "Leak-before-burst". Technical advantages are that the waste is isolated from other process equipment, the process is scalable, it has the highest safety, there are no emissions from the consolidating process, it is flexibility to produce a range of waste forms, volume reduction of 20-70%, and it is a batch process for easy operation and diversity and reduces risk for heterogeneous waste feeds. Economically the HIP process shows the lowest life-cycle cost compared with direct disposal and vitrification.

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