PLASMA VITRIFICATION PROGRAM FOR RADIOACTIVE WASTE TREATMENT

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ABSTRACT

In order to treat radioactive wastes effectively and solve storage problems, INER has developed the plasma arc technology and plasma process for various waste forms for several years. The plasma vitrification program is commenced via different developing stages through nine years. It includes (a) development of non-transferred DC plasma torch, (b) establishment of a lab-scale plasma system with home-made 100kW non-transferred DC plasma torch, (c) testing of plasma vitrification of simulated radioactive wastes, (d) establishment of a transferred DC plasma torch delivering output power more than 800 kW, (e) study of NOx reduction process for the plasma furnace, (f) development of a pilot-scale plasma melting furnace to verify the vitrification process, and (g) constructing a plasma furnace facility in INER. The final goal of the program is to establish a plasma processing plant with capacity of 250 kg/hr to treat the low-level radioactive wastes generated from INER itself and domestic institutes due to isotope applications.

INTRODUCTION

Vast quantities of low-level radioactive waste (LLW) are generated from nuclear power plants due to normal operation and maintenance, and from hospitals and research institutes due to isotope applications. In order to dispose of these radioactive wastes safely and cost-effectively, they must be transformed into physically and chemically stable forms suitable to immobilize radionuclides with maximum volume reduction. Most of such techniques have to sort the wastes into combustibles, non-combustibles and metals at the pretreatment step. Combustibles are normally incinerated non-combustibles either compacted or directly converted into a solid matrix. Metals are melted and cast into ingots. All these conventional process technologies have the following disadvantages: (1) Different types of waste have to be separated, manipulated and treated with different equipment. (2) Volume reduction and vitrification are not achieved within one step. Fortunately, plasma technology is able to incinerate the combustibles of radioactive wastes for volume reduction and to vitrify the non-combustibles simultaneously into slags or metal ingots by using the same equipment and without pretreatment steps (Hoffelner et al., 1992, Geimer et al., 1993, Bogatov & Souris, 1995, Eschenbach, 1996).

Since 1978, the Institute of Nuclear Energy Research (INER) has been responsible for the treatment of all the domestic radioactive wastes except those from nuclear power stations. The combustible radioactive wastes are treated by a controlled air incinerator with capacity of 40 kg/hr, while the residual ash is temporarily stored in steel drum. The non-combustibles are either compacted or directly solidified into a cement matrix. In order to offer an effective alternative to the treatment and storage of these radioactive wastes, INER has been developing plasma arc technology and plasma processing for various waste forms since 1993. The plasma vitrification program involves development of several stages, including: (a) development of a non-transferred DC plasma torch, (b) establishment of a lab-scale plasma system with a home-made 100kW non-transferred DC plasma torch, (c) testing of plasma vitrification of simulated radioactive wastes, (d) establishment of a transferred DC plasma torch delivering an output power more than 800 kW, (e) development of a NOx reduction process for the plasma furnace, (f) development of a pilot-scale plasma melting furnace to verify the vitrification processes of simulated wastes, and

(g) establishing a plasma furnace facility in INER. The final goal of the program is to construct a plasma processing plant with capacity of 250 kg/hr to treat the low-level radioactive wastes generated from INER itself and domestic institutes due to isotope applications. The plasma processing plant is to be built in INER's waste treatment restricted area, located within the existing incineration facility. Especially, the new plasma furnace and the incinerator will utilize the same off gas treatment system which was upgraded in 1996.

In this paper, we describe the lab-scale plasma testing system, transferred and non-transferred DC plasma torches, the results of vitrification tests of simulated radioactive wastes and the layout of plasma pilot plant to be built in INER.

INER'S PLASMA PROGRAM

Generally speaking, the INER's plasma program is divided into four development stages covering more than nine years. Figure 1 summarizes the overall program. The first development stage commenced before 1993. After gaining much experience on the basic research of plasma technology for several years, INER's researchers transferred their focus on the development of plasma torch, as well as the innovative technique to treat radioactive waste. In 1994, the first non-transferred DC plasma torch delivering 100 kW thermal power was designed, fabricated and characterized in this institute.

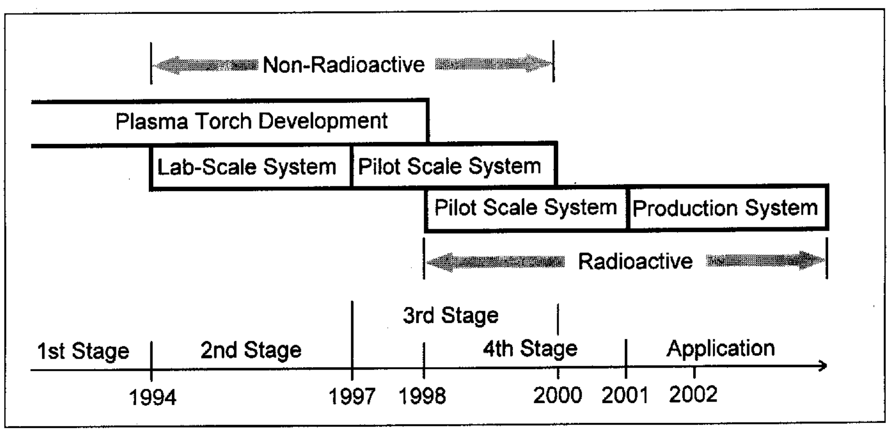

Figure 1 Scheme of INER's Plasma Vitrification Program

The second development stage, in 1995 and 1996, was to develop and to establish lab-scale plasma testing system for the demonstration of plasma vitrification technology. A crucible-type plasma melter and a lab-scale plasma furnace with capacity of 10 kg/hr (Tzeng et al., 1997, Chu et al., 1997) were set up for vitrification tests, using a 100kW DC plasma torch as a heat source. The maximum operation temperatures of the small plasma melter and the 10 kg/hr plasma furnace were 1700C and 1650C respectively. Several simulated radioactive wastes were processed by these plasma systems, producing high-quality slags. To improve the processing rate of plasma furnace, a 100 kW transferred plasma torch was also developed and tested. Since the demonstration of plasma vitrification test in the second stage was successful, the third stage of the program began in 1997. The objectives of the third stage are to develop an 800 kW transferred plasma torch and to establish plasma torch test utilities that can provide 1700V/1000A DC power. The non-radioactive pilot-scale plasma furnace will be set up in 1998, fired by an 800 kW plasma torch and operating at temperatures up to 1650C. The furnace with a 55-gallon drum feeder is designed to process the low-heat-value surrogate wastes with a rate greater than 250 kg/hr. The fourth stage will be executed from 1998 to 2001. Meanwhile, the third stage will keep progressing to support verification tests. The radioactive plasma pilot plant is planned to be established in the end of 2001. At that time, INER will be able to offer more efficient service for treating the low-level radioactive wastes generated from the domestic isotope applications. After the completion of the program, the developed plasma technologies could be extended to serve nuclear power plants and local industries.

PLASMA VITRIFICATION OF SURROGATE WASTES

The high power plasma torch is the heart of plasma waste-treatment technology. The 100 kW non-transferred plasma torch (INER-100 NT) developed by INER has the following characteristics :

1) Electric power range = 20~120 kW (600V/200A)
2) Maximum energy conversion efficiency = 87%
3) Average temperature of heated gas = 5000-6000C
4) Enthalpy of heated gas = 6-10 MJ/kg
5) Cathode/Anode lifetime > 150/500 hours

The INER-100NT plasma torches provide heat sources for the crucible-type plasma melter and the 10 kg/hr plasma furnace for the surrogate wastes vitrification tests. The small plasma melter can be heated up at a rate between 6 and 9 C/min, and the 40 kW plasma power is enough to maintain the highest temperature at 1700C. The average heating rate of the 10 kg/hr plasma furnace is about 0.62 C/min. To maintain the maximum temperatures of the primary chamber (PC) and the secondary combustion chamber (SCC) at 1670C and 1350C, the responsible plasma torches must deliver about 105 kW and 50 kW electric power respectively.

Several surrogate wastes have been processed by these plasma systems. The volume reduction ratios (VRR) defined as the quotient of initial waste volume and slag volume ranged from 2 for cement solidified wastes to 100 for combustible wastes. The densities of slags are in between 2.4 and 3.2 g/cm^3. The compressive strength ranged from 400 to 3,000 kg/cm^2.

Table 1 presents plasma vitrification conditions and results of cement-solidified surrogate wastes. The waste forms were prepared according to the recipes and operational procedures of cement-solidified systems in nuclear power plants. The size of the waste form for testing is cylindrical with diameter of 5 cm and height of 10 cm. Boric acid waste surrogate, denoted by BA, is the simulated cement-solidified waste of PWR nuclear power plants. SS, SR and PR stand for sodium sulfate, spent resin and Powdex® resin cement-solidified waste surrogates respectively. The four different surrogate wastes are all processed at 1650C, and vitrified into ceramics with densities about 3.05 g/cm^3. The volume reduction ratios of these surrogates are between 2.6 and 4.6, and the weight reduction ratios (WRR) are from 1.6 to 2.2. The compressive strengths of these ceramics are between 432 and 1602 kg/cm^2. Table 2 shows the average leaching indices ranging between 8 and 15.

Table 1 Plasma vitrification conditions and results of tests in a crucible-type plasma melter

Waste ID	Processing Temp. (C)	VRR	WRR	Slag density (g/ cm^3)	Slag Strength (kg/cm^2)
BA	1650	2.8	1.6	3.05	1602
SS	1650	2.6	1.6	3.05	762
SR	1650	3.6	1.7	3.05	1077
PR	1650	4.6	2.2	3.06	432

Table 2 Average leaching indices of vitreous slags produced from a crucible-type plasma melter

Waste ID	Si	Na	Ca	K	Ti	Mg	Fe	Al
BA	12.6	8.2	11.5	10.6	12.7	10.2	14.5	14.2
SS	13.0	10.2	11.8	11.0	12.9	9.9	15.1	15.1
SR	13.4	8.0	12.1	11.1	13.2	8.2	15.2	14.9
PR	13.2	7.8	11.9	10.9	12.9	10.0	14.9	15.0

Instead of a small cemented waste form, a full scale 55-gallon drum of cemented surrogate waste was vitrified using PHP non-radioactive pilot-scale plasma system (Kuo et al., 1997). The PHP plasma furnace (Geimer, 1996) uses a 1.2 MW transferred arc torch as the heat source. The feed system can feed the 55-gallon waste drum with variable speed hydraulics. The vitrification testing was conducted under the cooperation contract between INER and SAIC (Science Applications International Corporation). The waste forms were four types of cemented surrogate waste mentioned above, two drums of each type. The total of eight drums were tested in a batch mode. The operating condition data were recorded and the vitrified products were characterized separately. The testing results show that the overall VRR is about 1.76. The VRR value is expected to be greater than 2 if the melter was operated continually without any additives (i.e. preheated steel) other than sand. The characteristics and leaching index of vitreous slags are shown in Table 3. The slags have densities ranging between 2.85 and 3.2 g/cm^3. Compressive strengths were variable within the slag block – from 700 to 3,000 kg/cm^2 – but everywhere much higher than that of cement-solidified form. Table 4 shows the leaching indices that are close to the results from the lab-scale tests shown in Table 2. In these vitrification tests, Co and Cs are purposely added in surrogate waste as tracers. Compared with other elements, the leaching index of Cs is significantly low. However, it is still beyond the limitation for disposal.

Table 3 Characteristic of vitreous slags produced from pilot-scale furnace, comparing with initial cemented waste forms. Strengths of three slag specimens were measured for each type of waste

Waste ID	Slag Density g/cm^3	Slag Strength (kg/cm^2)			Cemented Form Strength (kg/cm^2)
BA	3.2	3104(#1)	740(#2)	1077(#3)	25
SS	2.85	1324(#1)	1587(#2)	1460(#3)	152
SR	2.9	1240(#1)	940(#2)	722(#3)	189
PR	2.9	3081(#1)	1462(#2)	1765(#3)	129

Table 4 Average leaching indices of vitreous slags produced from pilot-scale furnace

Waste ID	Al	Ca	Co	Cs	Fe	Si
BA	12.9	12.1	11.6	8.5	17.0	12.8
SS	14.6	12.4	11.5	8.5	16.9	12.2
SR	15.2	13.5	11.5	8.5	16.9	13.6
PR	14.6	12.9	11.0	8.7	17.7	13.7

PLASMA PROCESSING PLANT

The low-level waste plasma processing plant is to be built in INER's waste treatment restricted area, within the existing 40 kg/hr incinerator facility. The new plasma furnace and the incinerator will utilize the same off gas treatment system. The facility will be partially reconstructed and enlarged to approximately 800 square meters of floor space. The construction will be completed in mid 1998. Figure 2 illustrates the facility floor plan, and Table 5 depicts the key features of the plasma vitrification facility.

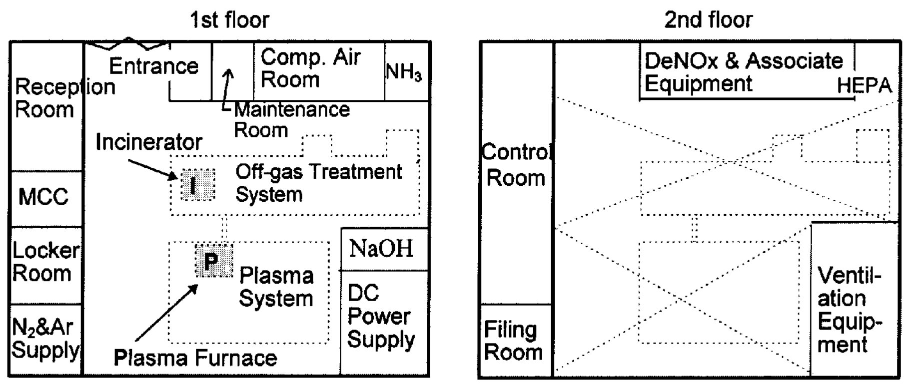

Figure 2 The layout drawing of a plasma processing facility

The heat source of this radioactive pilot-scale plasma furnace is a 800 kW transferred plasma torch by using nitrogen as major working gas. The processing rate is specified as 250 kg/hr for non-combustible waste and up to 40 kg/hr for combustible waste. The maximum operation temperature of the PC is 1650C, while the normal operation temperature of the SCC is about 1100C. The feed system can manipulate 55-gallon waste drum with hydraulics in a semi-continuous operation mode. Molten slag is discharged into a 45-gallon carbon steel drum which is cooled by a water jacket. The vitreous slag contained in the 45-gallon drum will pass through a cooling tunnel until the temperature is below 60C. Finally, the 45-gallon drums will be overpacked in 55-gallon drums.

Table 5 Key features of the plasma processing facility

Furnace	Fixed hearth with internal diameter of 150 cm and depth of 75 cm
Plasma Torch	800 kW transferred arc plasma torch
Capacity	250 kg/hr for non-combustible, miscellaneous LLW radioactive wastes
Feed System	55-gallon drum fed with hydraulics
Discharge System	Water jacket cooling and convey cooling tunnel
Furnace Pressure	-20 ~ -50 mm WG
Building Pressure	@-10 mm WG

The flow diagram of the LLW plasma processing plant is shown in Figure 3. The existing offgas treatment system of the incinerator is modified by adding a spray dryer to remove salt generated in the scrubber (Ju and Hung, 1997). It aims to eliminate the secondary liquid waste from the process. Additionally, an electric heater and a DeNOx unit are equipped behind HEPA filters to remove the thermal nitrogen oxides from high temperature plasma processes. The salt powders from spray dryer and fly ashes from the baghouse are collected in 55-gallon drums, and could be recycled back into the plasma furnace for vitrification.

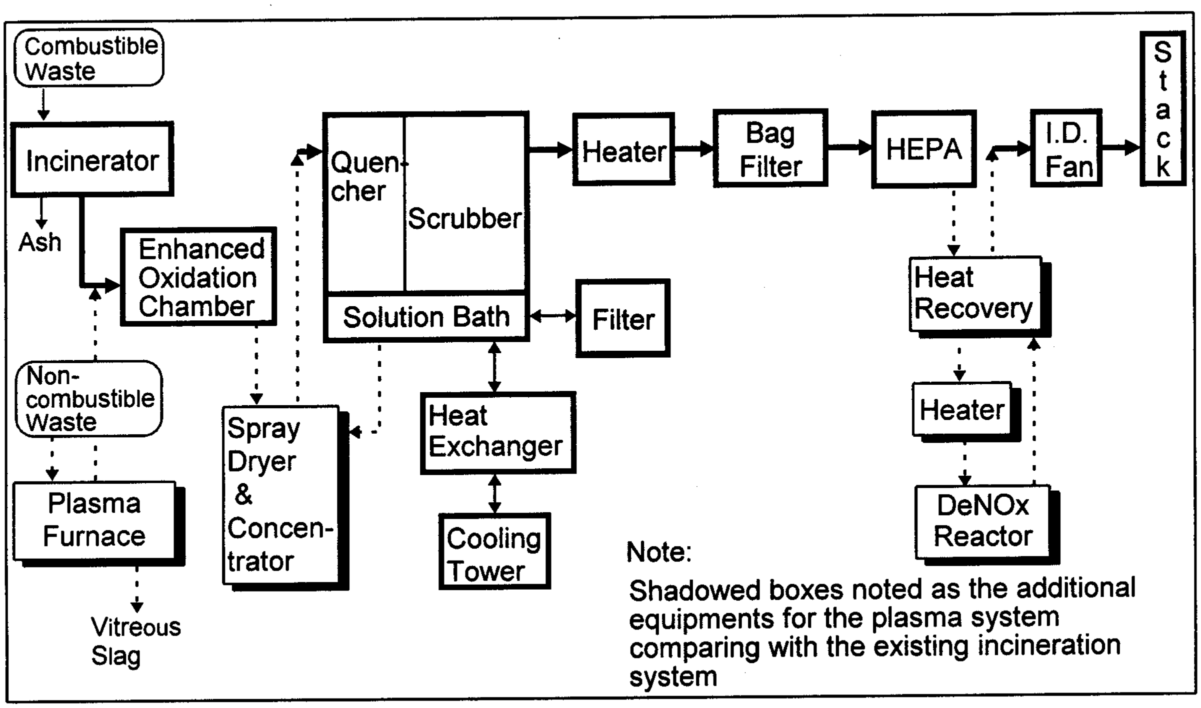

Figure 3 Flow diagram of a plasma processing system

CONCLUSION

The Institute of Nuclear Energy Research has commenced a plasma vitrification program to develop plasma technology for radioactive waste treatment. Vitrification tests of surrogate wastes shows that thermal plasma processing is an innovative technology for the treatment of low-level wastes. Surrogate wastes, even cement-solidified wastes, can be vitrified easily by plasma torch and converted into high quality slags. The compressive strength of the vitreous slag ranged from 400 to 3000 kg/cm^2, and their leaching indices for eight elements are between 8 and 15, which are all beyond the ROC regulation of waste forms for final disposal (i.e., 15 kg/cm^2 and 6). An LLW plasma processing plant will be established in mid 2001 in INER, and the various low-level radioactive wastes generated from domestic isotope applications will be treated safely and effectively in the near future.

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KEY WORDS

plasma vitrification, plasma arc torch, vitreous slag, low-level radioactive waste, cemented waste form, leaching index, compressive strength.