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Volume Reduction Ratio and Decontamination Factor of the Bench Scale Radwaste Incineration Process

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실험용 방사성 폐기물 소각로의 감용비와 제염계수

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Abstract

A bench scale incineration process for the burnable radwaste has been constructed and operated at KAERI as a self-surpported development of incineration technology. The purposes of operating the process are to get experience in incineration, to analyze the characteristics of combustion and to test the performance of off-gas treatment units. Simulated paper and polyethylene wastes were incinerated. Volume reduction ratio and decontamination factor of the process have been determined to observe the economical efficiency and operational capability of the process. A methodology to estimate the acceptance limit of specific activity to an incineration facility by using a decontamination factor and to calculate the volume reduction ratio of the facility is introduced. The acceptance criteria for different radionuclides in the combustible waste at the bench scale incineration process are suggested using this methodology.

요 약

방사성 폐기물 소각기술 개발 자립의 일환으로 한국에너지연구소에서는 실험용 방사성폐기물 소각공정을 설치하여 운전중에 있다. 이 공정은 소각경험의 습득 및 소각 특성 시험, 여과기의 성능시험 등을 위하여 설치되었다. 종이와 폴리에틸렌 모의폐기물을 소각하여 공정의 경제성과 운전성을 나타내는 감용비과 제염계수를 결정하였다. 제염계수로부터 소각설비의 허용비방사능치를 얻어내고 설비의 감용비를 산출하는 방법을 기술하였다. 실험용 소각공정에서의 가연성 폐기물에 함유된 핵종에 대한 인수기준치를 상기방법을 이용하여 제시하여 보았다.

1. Introduction

Considering the severe limitations on volumes which can be disposed at low-level radiocative waste disposal facilities, incineration of low-level radioactive waste becomes relatively important as a voluem reduction technique. Therefore, a long-term plan to utilize incineration technoloy incinerating the burnable radwastes generated from power plants was established with a maximum localized portion[1].

As the first step of the introduced schedule, a bench scale incineration process was designed and constructed. This process consists of an incinerator with a capacity of 5 kg plastic wastes per hour and various off-gas filtering units.

For most incineration facilities, a performance test is required to demonstrate the system ability to meet the applicable regulatory performance standard and to achieve the better volume reduction. In other words, successful implementation of the performance test is essential for obtaining a permit that controls incinerator operation consistent with regulatory requirements and appropriate guidelines. The test must also contain enough flexibility to allow the incinerator to be operated in an efficient and cost-effective manner. Some of the most important parameters to be estimated during performance test are the volume reduction for cost efficiency and the decontamination factor for safety requirement. During a performance test or operational test the decontamintion degree of the facility is determined, so that the results can be used to establish the acceptable limits for different nuclides in the combustible waste to be incinerated.

Several incineration experiments using the simulated polyethylene(PE) and paper waste have been conducted to test the performance of the process. In this paper, a methodology to estimate the performance of a facility and the test results of the bench scale incineration process at KAERI with application of the suggested method are discussed. The volume reduction ratio is also observed in the event that the compacted burnable waste now stored at a nuclear power plant is incinerated using the KAERI bench scale process.

2. Methodology to Analyze an Incineration Process

1) Estimation of Volume Reduction Ratio

The volume reduction ratio of an incineration process is defined as the following equation,

$$VR = V_i / V_f \text{ ------------------------- (1)}$$

where VR is the volume reduction ratio, V_i is the initial volume of waste to be incinerated and V_f is the final volume of waste to be disposed.

In the case of the combustible waste at Korean nuclear power plants, V_i cannot be directly obtained since most of the wastes are now packed in a drum by compaction. However, their original volume can be calculated from the density of the compated waste and the VR of a drum compactor which is now in use at nuclear power plants. Therefore, the initial volume of the waste, V_i is given by

$$V_i = VR_c \; V_{cw} = VR_c \; (W_w / \rho_{cw}) \text{ ------- (2)}$$

where VR_c is the volume reduction ratio of a drum compactor and V_{cw} is the volume of the compacted waste, ρ_{cw} and W_w are the density and the weight of the waste, respectively.

In an incineration process, most of the combustibles react with oxygen to convert into gases which are finally released to the environment through a stack. Noncombustibles and the unreacted materials are left as ashes at the bottom of an incinerator and off-gas cleaning units. The amount of ashes generated during incineration varies by a combustion efficiency even if the amount of noncombustibles in the waste is fixed. If the combustion efficiency is constant, the amount of ash generated is given by

$$W_{ash} = W_w\{F_{nonc} + F_c(1-\eta)\} = W_w\{1-\eta(1-F_{nonc})\} \quad (3)$$

where W_{ash} is the weight of ashes after incineration, η is the combustion efficiency in fraction, F_{nonc} is the weight fraction of the noncombustibles, and F_c is the weight fraction of combustibles in the waste. And the sum of F_c and F_{nonc} is unity. The ashes generated from the incinerator have to be stabilized for the disposal. If a cementation process, recommended up to now to be proper for stabilization of ashes, is used, the final weight of waste, W_f, will be as follows.

$$W_f = W_{ash}(1+MR) = W_w[1-\eta(1-F_{nonc})](1+MR) \quad (4)$$

where MR is the mixing ratio of cement and water to ash in weight for cementation. Using the density of the solidified ash product, ρ_f, the final volume of waste is given by

$$V_f = W_f/\rho_f \quad (5)$$

Consequently, in the event that the compacted combustible waste in drums is incinerated, the volume reduction ratio by an incineration process can be estimted by using the following equation; a combiantion of all the above equations, (1),(2),(3),(4) and (5).

$$VR = \frac{VRc.(W_w/\rho_{cw}).\rho_f}{W_w[1-\eta(1-F_{nonc})](1+MR)} = \frac{VRc.\rho_f}{[1-\eta(1-F_{nonc})](1+MR)\rho_{cw}} \quad (6)$$

2) Determination of DF and Maximal Specific Activity

The decontamination factor of a radionuclide in the waste at an incineration process depends upon the volatility of each nuclide and the particle collection efficiency of off-gas treatment units. Some volatile nuclides such as C-14, H-3, I-135, and I-131, so called permanent gases, are released in gas state and resulted in passing through all the dust collection equipments without any decontamintion. There decontamination factors of these volatile nuclides at any incineration process are almost 1.

$$DF_v = 1 \quad (7)$$

However, most metallic nuclides are nonvolatile, in which case decontamination effect through an incineration process is determined from the fly ash amount leaving the incinerator and the particle collection efficiency of the off-gas treatment system. DF of a nonvolatile nuclide is determined by the following equation.[2]

$$DF_{nv} = \prod_i \frac{1}{1-\phi i} \quad (8)$$

Where, Øi is the particle collection efficiency of the ith off-gas treatment system. For incinerator, Øi is better called the ratio of ashes at the bottom of the incinerator to the total amount of ashes generated.

On the basis of DF and allowable release concentrations of radioactive nuclide in air, the acceptable activity limit per unit mass of waste to an incinerator, which is called the maximal specific activity(MSA), could be estimated. The maximal specific activity of each nuclide in the combustible waste is given by

$$MSA = (Q_n/W)(R)(DF) \quad (mCi/kg) \quad (9)$$

and for nonvolatile nuclides,

$$MSA = \frac{Q_n \cdot R}{W} \cdot \prod_i \frac{1}{1-\phi i} \ (mCi/kg) \quad (10)$$

where, MSA is the maximal specific activity of a nuclide in mCi/kg, Q_n is the volumetric flow rate of total off-gas from the incineration process in Nm^3/hr, W is the feeding rate of the waste in kg/hr and R is the maximum permissible concentration of a nuclide at stack, in mCi/Nm^3. R for each nuclide is listed on the regulatory.

3. Process and Experiment

1) Process Description

The bench scale incineration process consists of a waste pretreatment system, an incinerator, an off-gas treatment system, and a measurement and control system. The waste pretreatment system includes shredding and preparing simulated wastes using a paper bag or box. A schematic diagram of the process is shown in Figure 1. The waste is fed through the top fo the incinerator and burnt at 750-950°C, some ashes are removed downward by a rotary valve, and the off-gas with fly ash passes through a high-temperature and/or low-temperature filter system and a HEPA filter section. It then leaves through the stack.

The off-gas treatment system could be divided into two sections by temperature as follows; high-temperature filter units are a sintered metal filter and a SiC filter, and low-temperature filter units are a bag filter and a wet scrubber. The performance test for each unit can be done selectively

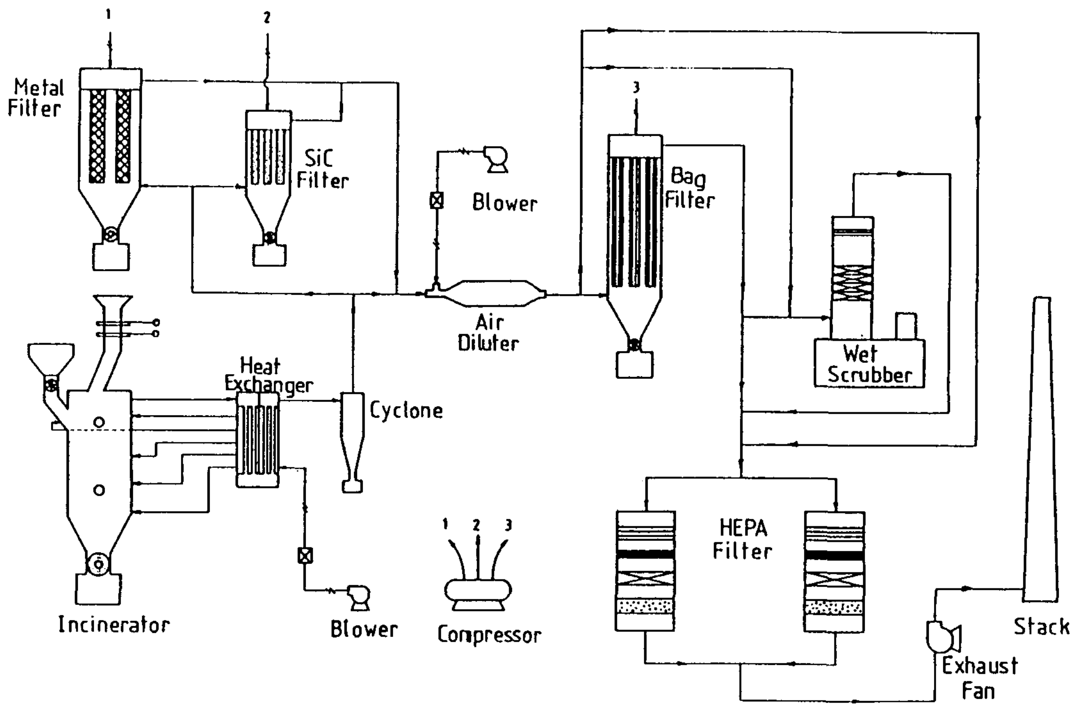

Fig. 1. A Schmatic Diagram of the Bench Scale Incineration Process

Table 1. Results of Proximate Analysis and Calorific Value of the Simulated Wastes

Waste	Proximate Analysis, wt%				Calorific Value, cal/g
	moisture	volatile matter	fixed carbon	noncombustibles	
paper	8.50	77.80	1.69	12.01	3,224
PE	1.78	96.38	0.65	1.19	10,874

by controlling valves. The measurement and control system functions to indicate and control temperatures and pressures at different locations in the process.

2) Experiment

The simulated wastes are paper and PE film and their proximate analysis results and calorific values are shown in Table 1. The paper used in the experiment is that which is used for printing at a computer center. It has a significantly high amount of noncombustible content than cleaning paper used at power plants which has around 1% of noncombustibles. Paper and PE film were shredded to be packed in a paper bag. Three different simulated wastes; paper, PE, and a mixture of paper and PE were incinerated. The weights of a single package were about 250 g, 125 g, and 150 g, respectively. The mixed waste consisted of paper and PE with 50% of each in weight. Table 2 shows the summary of the experimental conditions. One of these simulated wastes was fed as soon as the temperature of the incinerator was heated up to a certain temperature by a preheating burner. The following feeding intervals were every 60 s for paper and 60~90 s for PE. In the case of burning the mixed waste the feeding interval was controlled by a fixed temperature of 850°C, thus, the interval was kept changing with the average of 76

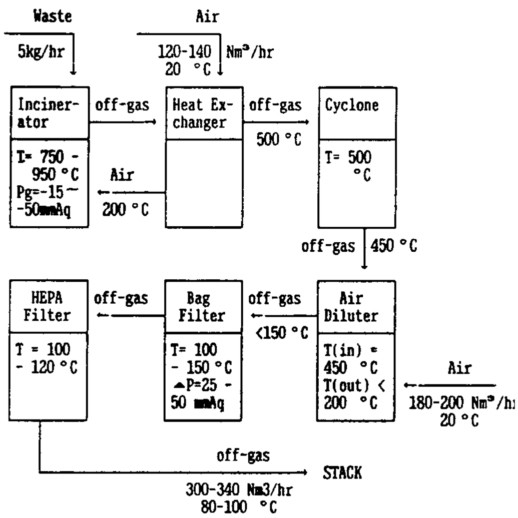

Fig. 2. Experimental Conditions of the Bench Scale Incineration Process

Table 2. Experimental Conditions for Incinerating the Simulated Wastes

waste	feeding amount, kg	weight of package, kg	density of package, g/cc	feeding interval, s
paper	13.9	.250	.185	60
PE	4.9	.125	.144	60 → 90
mixed	5.4	.155	.243	76

waste	prepheated temperature, °C	temperature in incinerator, °C	pressure in incinerator, mmAq
paper	660	750 ~ 850	−28 ~ −50
PE	660	850 ~ 910	−15 ~ −25
mixed	718	845 ~ 880	−20 ~ −30

s. In these conditions, the average temperature of the incinerator were 800°C for paper, 900°C for PE, and 860°C for the mixed waste. Off-gas from the incinerator, which was cooled down to its temperature of about 500°C through a heat exchanger, passed through a cyclone and low-temperature off-gas filtering units. Variables at a typical incineration such as pressure, temperature and flowrate of gas are shown in Figure 2.

During incineration, a certain amount of off-gas was sampled at the outlet of the air diluter and the outlet of the bag filter to measure the particle collection efficiency of off-gas treatment system. Figure 3 shows a setup of particulate sampling train in the process. Before each sampling run, velocity distributions across the cross sections of the sampling positions were measured to identify fully developed flows and to determine isokinetic sampling velocity. During sampling, thimble type sampling HEPA filters were heated to about 150°C to prevent water vapor in the sample gas from condensing. There was little increase of pressure drop, so that isokinetic sampling conditions could be maintained without problem.

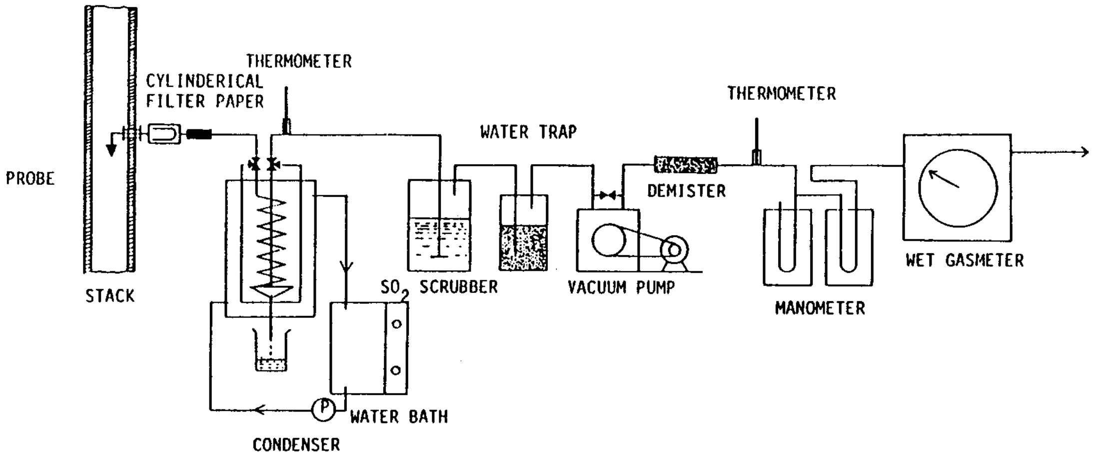

Fig. 3. A Setup of Particulate Sampling Train

4. Results and Discussion

1) Experimental Results

Figure 4 shows the temperature profiles in the incinerator in the case of incinerating PE. When the interval of waste feeding is fixed at 60 s, the temperature goes up to 950°C, however, it becomes stable at around 900°C after changing the interval to 90 s.

The amount of ashes collected from each equipment and the concentrations of dust in the off gas stream are shown in Table 3. The values in parentheses are the amounts of ashes on the basis of an hour, which are calculated by dividing the ash amounts by the total incineration time for the collected ashes and by multiplying them with the total off gas generation per hour for dust concentrations. These values are useful to analyze the collection efficiency because fo the same basis of unit.

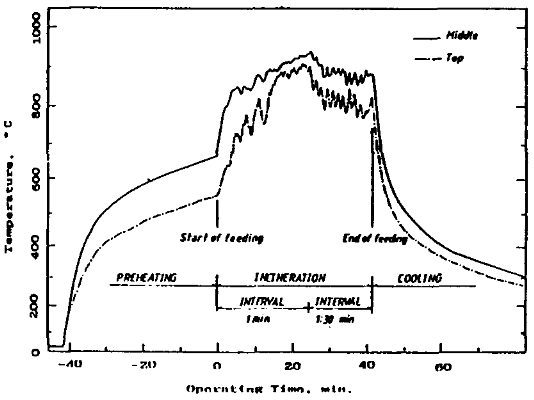

Fig. 4. Temperature Profiles in the Incinerator for PE Incineration

From the results, the weight reduction ratios are found to be around 15 to 17, however, the volume reduction ratios are quite different for each waste since it is a function of the initial density of waste and the ash density. The volume reduction ratios were 38, 51 and 17 for paper, PE, and the mixture, respectively. The reason of less volume reduction for the mixed waste is mainly because of the high density of the initial package as shown in Table 2.

To estimate the VR (Volume reduction Ratio) of the process when the combustible waste of power plants is incinerated, the combustion efficiency of the process must be determined. The combustion efficiency could be obtained by using the following definition.

$$\eta = 1 - \frac{\text{Weight of Combustibles in Ashes}}{\text{Weight of Total Combustibles in Waste}}$$

The weight of combustibles in ashes was measured by analysing the carbon content. The combustion efficiency is calculated from the carbon content in ashes and the amount of combustibles in waste, and Table 4 shows the results for paper and PE. The efficiency over 0.997 is found even when some amounts of carbon soots are found in the ashes of the bag filter in the case of PE incineration.

The next parameter for observing the performance of an incineration process is the dust collection efficiency for incinerator and filtering equipment, which could be estimated from the amount of ashes collected at each equipment and the concentrations of dust in the lines. The results of incinerating the mixed waste were used to find out the collection efficiency using the following equation.

$$\varnothing i = 1 - \frac{\text{Dust Concentration of Outlet}}{\text{Dust Concentration of Inlet}}$$

$$= 1 - \frac{\text{Ashes Passed through the Equipment}}{\text{Ashes Collected in the Equipment + Ashes Passed through the Equipment}}$$

The dust collection efficiency was calculated using the data in parentheses in Table 3. Figure 5 shows the dust collection efficiency with the accumulation of ashes collected by a series of equipments and the amount of dust remaining in the equipment. The dust collection efficiency of HEPA filter was assumed to be 99.97%.

2) Volume Reduction

Using the combustion efficiency estimated from the experimental results, the volume reduction ratio fot he combustible waste which is compacted and stored at Korean nuclear power plants could be deduced using Eq.(6) with consideration for the use of the bench scale incineration process.

Table 3. Amounts of Ashes Collected at the Bottom of Each Equipment and Concentrations of Dust in the Lines

waste	amount of ashes collected g (g/hr)			concentration of dust mg/Nm (g/hr)		total weight of ashes g (g/hr)
	incinerator	cyclone	bag filter	outlet of cyclone	outlet of bag filter	
paper	598.0 (652.4)	247.9 (270.4)	12.4 (13.5)	47.05 (15.42)	5.78 (1.89)	860.0 (938.2)
PE	19.6 (25.5)	246.7 (321.8)	14.4 (18.8)	67.64 (20.99)	—	288.9 (365.2)
mixed	310.8 (416.9)	69.2 (92.8)	14.6 (19.6)	—	9.67 (3.28)	397.0 (532.5)

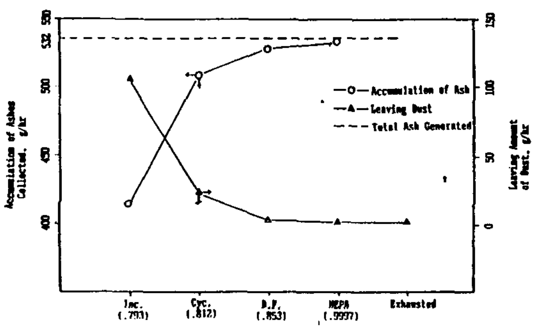

Fig. 5. Dust Collection Efficiency (in Parenthesis) with the Accumulation of Ashes Collected and the Leaving Amount of Dust

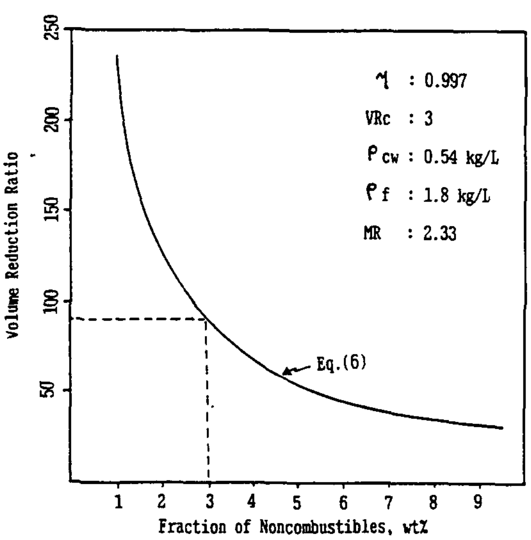

Fig. 6. Variance of Volume Reduction Ratio with the Fraction of Noncombustibles

The density of the compacted waste at power plants is known to be 0.54 kg/L and the VR of a drum compactor is about 3[3]. It is found that the proper mixing ratio of cement and water to ash is 7:3 and the density of a final solidified form is 1.8 kg/L[4]. When one drum of the compacted waste is incinerated using the bench scale incineration process which has the combustion efficiency of 0.997, the VR with varying the noncombustibles fraction in waste is shown in Figure 6. The change of the noncombustibles fraction in waste at lower range will make a big difference in volume reduction. Therefore, a power plant must use the materials which contains less noncombustibles. It is known that the combustible waste from the power plants has noncombustibles of less than 3% (PVC: 2.86%, PE: 1.19%, paper: 0.69%, and wool: 2.05%, from[5]). It is concluded that a VR of over 90 could be acheivable, however, PVC waste needs to be burnt with the operation of a scrubber to remove the acid gas, thus, the secondary waste which has to be solidified will result in less volume reduction.

3) Determination of DF and Maximal Specific Activity

The decontamination factor could be determined from the results of dust collection efficiency of the process. Decontamination factors of the bench scale incineration process for volatile nuclides and nonvolatile nuclides were determined to be 1 and 7.3 E 5 by the equations of (7) and (8), respectively. These results are shown in Table 5.

On the basis of DF of the process and the allowable release concentrations in air by the regulation, the maximal specific activity (MSA) of each nuclide in the combustible waste was calculated from the equations of (9) and (10), in the following examples.

In case of a volatile nuclide,
MSA for I-131 =
330 (Nm^3/hr) $\times$ 1E-7 (mCi/Nm^3) $\times$ 1
5 (kg/hr)
= 6.6 E-6 (mCi/kg)

In case of a nonvolitile nuclide,
MSA for Co-60 =
330 (Nm^3/hr) $\times$ 3E-7 (mCi/Nm^3) $\times$ 7.3E5
= 14.5 (mCi/kg)

The results for careful nuclides at power plants[6] are shown in Table 6. In case of nonvolatile nuclides, the acceptable MSAs in waste for the incineration process are high enough that most of the power plant waste could be accepted for incineration. However, care must be given for volatile nuclides by installing a kind of capturing system of such nuclides.

Table 4. Analysis of Carbon Content in Ashes Collected and Combustion Efficiency Calculated

	combustibles in waste, g	combustibles in ash, g	combustion efficiency, %
paper	11,049	15.1	99.88
PE	4,754	12.5	99.74

Table 5. Dust Collection Efficiencies and Decontamination Factors

	Incinerator	Cyclone	Bag Filter	HEPA Filter	Total
Particle Collection Efficiency	0.793	0.812	0.853	0.997	
DF for a nonvolatile nuclide	4.83	5.32	8.55	3.3 E3	7.3E5
DF for a volatile nuclide	1	1	1	1	1

Table 6. Calculated Maximal Specific Activities for Accepting at the Incineration Process and Allowable Release Concentrations in Air

Nuclide	Allowable Release Concentration in Air (mCi/Nm^3)	Maximal Specific Activity (mCi/kg)
Co-60	3E -7	1.4E 1
Co-58	3E -6	1.4E 2
Cs-137	5E -7	2.5E 1
Cs-134	4E -7	1.9E 1
Ni-63	1E -5	4.8E 2
Sr-90	2E -7	9.6E 0
Nb-95	3E -6	1.4E 2
Tc-99	2E -6	9.6E 1
Pu-239	1E -9	4.8E -2
Am-241	4E -9	1.9E -1
H-3	8E -2	5.3E -0
C-14	1E -6	6.6E -5
I-131	1E -7	6.6E -6
I-135	1E -5	6.6E -4

Conclusions

The bench scale incineration process at KAERI has been operated for giving practical experience in incineration. The operational test and the primary experiment of the process was performed successfully. A methodology to estimate volume reduction ratio, decontamination factor and maximal specific activity of nuclides was introduced. From the results of experiments and the implementation of the methodology to them, the following conclusions could be made.

1) The incineration process has shown a reasonable volume reduction ratio with the combustion efficiency of over 99.7%.
2) When the process is utilized to incinerate the power plant waste, the volume reduction ratio could be made over 90 considering cementation of ashes and exclusion of PVC.
3) The incineration process has the decontamination factor of 7.3E5 so that most combustible wastes at power plants could be acceptable with a special care only for volatile nuclide content.
4) The suggested methodology to analyze the performance of an incineration process, such as VR and DF, was useful, and MSA for accepting the waste to the facility can also be calculated by using it.

Acknowledgement

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Nomenclatures

DF : decontamination factor [−]
DF_{nv} : decontamination factor for nonvolatile nuclide [−]
DF_v : decontamination factor for volatile nuclide [−]
F_c : weight fraction of combustibles [−]
F_{nonc} : weight fraction of noncombustibles [−
MR : mixing ratio of cement and water to ashes [−]
MSA : maximal specific activity [mCi/kg]
Q_n : volumetric flow rate of off-gas [Nm^3/hr]
R : maximum permissible concentration of a nuclide for emission to air [mCi/Nm^3]
V_{cw} : volume of the compacted waste [m^3]
V_f : final volume of waste [m^3]
V_i : initial volume of waste [m^3]
VR : volume reduction ratio [−]
VR_c : volume reduction ratio of a drum compactor [−]
W : feeding rate of waste [kg/hr]
W_{ash} : weight of ashes [kg]
W_f : final weight of waste [kg]

W_w : weight of the compacted waste [kg]
η : combustion efficiency [–]
ρ_{cw} : density of the compacted waste [kg/m^3]
ρ_f : density of the final solidified product [kg/m^3]
ϕi : collection efficiency of the ith collector [–]

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