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■論 文■

Radiological Safety Assessment for KAERI Incineration Plant on the Basis of Trial Burn Results

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시험소각결과에 기준한 한국원자력연구소 소각시설의 방사학적 안전성 평가

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Abstract-Radiological safety for the conventional operation of Demonstration-Scale Incineration Plant (DSIP) was assessed on the basis of the results of trial burns using the simulated and real radioactive wastes. Radiation dose assessments for routine releases on an annual basis as well as several severe accidental releases on a short-term basis (2h) revealed that there would be no significant environmental impact when low-level waste is incinerated in DSIP. For semivolatile radioactive cesium species, expected emission concentrations slightly exceeded 10% of maximum permissible concentration. Removal characteristics of the bag filter for condensed-phase cesium species was investigated by the trial burns of simulated waste with inactive cesium tracer. In the off-gas before passing through bag filter, distributions of condensed cesium species in the transition size ranging between the diffusional and inertial region are less than 5%. The overall collection efficiency of the bag filter for cesium species was higher than 99.9%, showing enough decontamination capability as a primary filter for the low-temperature dry off-gas system in radwaste incineration plant.
Key words : radiological dose assessment, radwaste incineration, cesium, collection efficiency

요약 - 모의 및 실폐기물 시험소각 결과를 기준으로 한국원자력연구소 소각시설의 상용운전을 위한 방사학적 위해성을 평가하였다. 연간 정상운전을 통해 배출되는 방사성 물질로 인한 환경영향은 물론 가상된 사고시의 단기(2시간 기준) 배출로 인한 환경적 영향은 무시할 수 있을 것으로 평가되었으나 정상운전시에 배출되는 주배출원인 반휘발성 방사성 세슘의 농도는 공기중 허용농도의 10%를 약간 상회하는 것으로 평가되었다. 비방사능 세슘추적자를 포함하는 모의폐기물의 시험소각을 통하여 포대여과기의 응축상 세슘성분에 대한 제거특성을 고찰하였다. 포대여과장치를 통과하기전 배기체내에 확산과 관성의 전이영역에 분포하는 입자상 세슘성분은 5%에 불과하였다. 포대여과기의 세슘성분에 대한 총괄제거효율이 99.9% 이상이어서 방사성폐기물 소각설비의 저온 배기체처리계통의 일차 여과장치로서 충분한 제염성능을 가짐을 보였다.
중심단어 : 방사학적 위해성 평가, 방사성폐기물 소각, 세슘, 제거효율

BACKGROUND

In 1991, a demonstration-scale incineration plant (DSIP) was designed and installed at the Korea Atomic Energy Research Institute (KAERI) for the purpose of technology demonstration [1]. A step-by-step approach to demonstrate developed incineration technology to treat low-level burnable radioactive waste has been conducted since 1992. After the change in governmental policy regarding radwaste management in 1996, KAERI decided to utilize the DSIP as a conventional incineration plant to treat burnable dry active waste (DAW) which is generated at the site. After radiological risk assessments and a little modification, the DSIP has finally received a permit to treat DAW. In the absence of directly concerned regulations and technical guidelines on the radwaste thermal process in Korea, other applicable regulations and guidelines on domestic nuclear fuel cycle facilities and those in other nations were applied to get a permit[2].

In the first part of this paper, the results of radiological risk assessment on DSIP are described. Emission source terms were decided on the basis of trial burn results and analyzed distributions of nuclides in the waste. The expected emission concentrations of typical radionuclides under normal operation are compared with maximum permissible concentrations (MPCs) in air. Radiological risk assessments under abnormal operations with potential accidental scenarios are also described.

For cesium species, which were determined to be the dominant emission sources by several trial burns[3,4], additional investigations on their behavior in the plant were required to prove enough decontamination by means of the low-temperature dry off-gas system. Recent trial burns using inactive cesium tracers were focussed on the condensation of volatilized cesium species and the removal of particulate cesium by bag filter. These results are also discussed in the second part of this paper.

DEMONSTRATION SCALE INCINERATION PLANT

The schematic diagram of the demonstration scale incineration system with a capacity of 20–25 kg/h (heat capacity: 470 MJ/h) is shown in Fig. 1. The plant consists of two combustion chambers and an off-gas treatment system. The controlled-air cylindrical incinerator having an outside diameter of 1.2 m and inside diameter of 0.8 m was 4 meters high, extending up to the second floor. The top of the incinerator cover is connected with a feeding device, which is composed of two interlocking sliding gate doors and was specially designed to handle radwaste without any release of incinerator off-gas. Negative pressure of about -30 mmH_2O is maintained in the incinerator during operation. The temperature of the incinerator furnace is controlled by waste feeding intervals and a gas burner according to the calorific value of burning waste.

An off-gas exhausting pipe, positioned directly underneath the incinerator cover, is connected with an after-burning chamber, which has a structure that functions as a cyclone to remove some coarse particles in the off-gas. The off-gas treatment system includes a heat exchanger, an air dilution cooler, a bag filter, a wet scrubber, and HEPA filters. Only when the release of some amount of HCl gas is anticipated due to PVC content in the wastes, a wet scrubber will

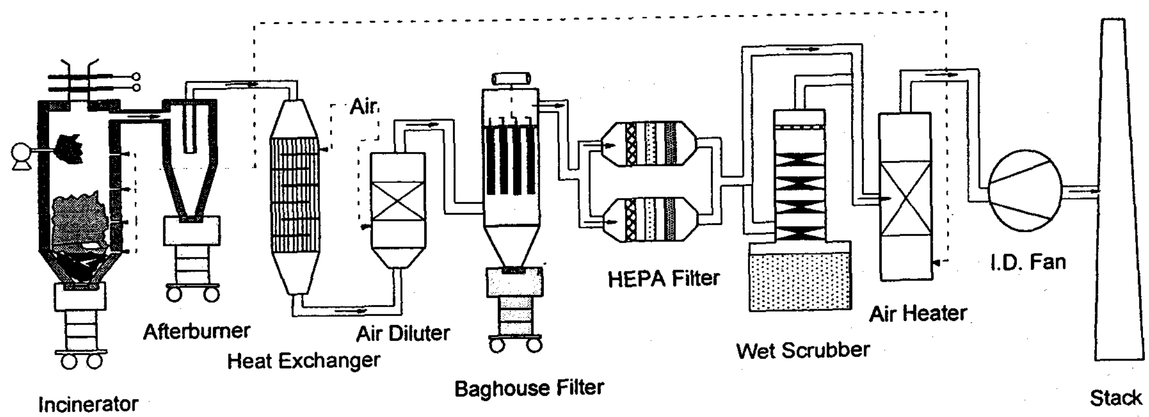

Fig. 1. The schematic diagram of demonstration-scale incineration plant.

Table 1. Estimated release concentrations of major nuclides and MSA for routine operation.

Nuclide	Fraction (%)	Average Specific Activity in DAW (mCi/kg)	Release Concentration (mCi/cc)	DF	MPC (mCi/cc)	Release Concentration per MPC (%)	MSA (mCi/kg)
Co-60	49.0	5.37	1.5×10^{-11}	4.7×10^{5}	3.0×10^{-10}	5.0	10.7
Cs-137	27.0	2.96	1.5×10^{-10}	2.6×10^{4}	5.0×10^{-10}	29.9	0.99
Cs-134	8.6	0.94	4.8×10^{-11}	2.6×10^{4}	4.0×10^{-10}	11.9	0.80
Co-58	9.8	1.07	3.8×10^{-12}	4.7×10^{5}	2.0×10^{-9}	0.15	7.16
Mn-54	0.72	0.08	1.7×10^{-13}	6.2×10^{5}	1.0×10^{-9}	0.02	4.72
Ru-106	2.4	0.26	1.3×10^{-11}	2.6×10^{4}	2.0×10^{-10}	6.64	0.40
Nb-95	2.4	0.26	1.3×10^{-11}	2.6×10^{4}	3.0×10^{-9}	0.44	5.94

be utilized. Dry and/or wet off-gas system is optionally utilized according to the acid gas concentration.

ASSESSMENT OF RADIOLOGICAL SAFETY

On the basis of determined decontamination factors (DFs) of the plant and maximum permissible concentrations (MPCs) of major radionuclides in the waste, the acceptable limit of nuclide contents per unit mass of DAW, which can be referred to as maximum specific activity (MSA), were determined by the following equation[5]:

$$MSA = \frac{Q_n \cdot MPC}{W \cdot SF} \cdot \prod_i DF_i \qquad (1)$$

where *MSA* is the maximum specific waste of a nuclide in mCi/kg, Q_n is the volumetric flow rate of total off-gas in Nm^3/h, *MPC* is the maximum permissible concentration of a nuclide in air in mCi/Nm^3, *W* is the feeding rate of the waste in kg/h, *SF*, which is regarded as 10, is the safety factor of the process, and DF_i is the decontamination factor of the process unit.

The estimated MSAs for major radionuclides are shown in Table 1. Applied specific activity was based on the average values for DAW generated from the Korea Nuclear Power Station (KNPS) at Kori site. Nuclide distributions were the measured values of the sample of DAW transported from the same power reactor. Assuming that Ru and Nb have the same DF that for semivolatile cesium, their MSAs were estimated. The MSAs for all nuclides except for cesium species are lower than the average concentrations in the DAW. However, the estimated emission concentrations of Cs-137 and Cs-134 range between 10% and 30% of the MPCs. Estimated MSAs for Cs-137 and Cs-134 slightly exceed average concentrations of those in DAW from KNPS if the safety factor of 10 is considered. Considering that the estimated emission concentrations of Cs-137 and Cs-134 are in conflict with 10% of the MPCs, extensive investigations on the removal characteristics of volatilized cesium species by the off-gas system were required. The results of these investigations are discussed in the second part of this study.

On the basis of the estimated release concentrations in Table 2, which can be accepted as emission source term, radiological impacts from the routine operational release of radionuclides were estimated. The exclusion area boundary (EAB) was established as 25-m distance from the stack. Computer program XOQDOQ, which implements the model in Regulatory Guide 1.111 by U.S. NRC [6, 7], was used to determine relative atmospheric dispersion factors and deposition factors. Input meteorological data (wind speed, wind direction and atmospheric stability) was the measured values at the 10-m height meteorological tower from Jan. 1. to Dec. 31. 1995. The used release mode was ground release, considering the low height of the stack (15 m). Estimated radiological dose for individual at EAB was 8.49 Sv/yr, corresponding to about 0.17% of dose limit for whole body under regulation (5 mSv/yr) and about 17% of dose limit under design basis (0.05 mSv/yr).

Like other conventional incineration facilities, some considerations to prevent or mitigate accidents and abnormal operations, such as alarming systems, pressure relief valves, an automatic power generator and stand-by draft fans, etc. were included in the DSIP. It can therefore be understood that potential radiological hazards will not be associated with severe accidents such as explosion, fire and loss of power failure but rather with operational mistakes which occur in sorting and handling of waste and incinerator ash. However, considering the lack of design considerations against earthquakes, risk assessments for several kinds of severe accidents were required in the licensing stage. On the assumption that earthquakes can cause severe accidents like explosion, fire, filter failure and rupture of the off-gas pipe, radiological risks were assessed.

The probabilistic tool used to determine the relative atmospheric dispersion factors was PAVAN, which was a developed computer program based on the model in Regulatory Guides 1.145 by U. S. NRC[8] which also has a regulatory compliance in Korea. Input meteorological data were the same data used for routine operational dose assessment. The ground release mode was applied as in the case for the assessment of routine operational dose. In Table 2, the results of radiological dose assessments when considering four cases of accidents are shown. Estimated individual whole body dose in case of incinerator explosion, the most severe accident among four considered typical accidents, was 3.2 mSv for 2-hr short-term period, corresponding to 1.3 % of the whole body dose limit (0.25 Sv) notified by the Ministry of Science and Technology [9].

Table 2. Results of risk assessment in case of typical severe accidents.

Types of Accident	Total Release (Ci)	Individual Whole Body Dose (mSv)	% Dose Limit
Fire	1.1×10^{-2}	1.2	0.6
Explosion	5.5×10^{-2}	3.2	12.8
Rupture of off-gas pipe before bag filter	1.1×10^{-3}	0.12	0.048
Failure of filters	2.6×10^{-5}	0.031	0.013

INVESTIGATIONS ON THE BEHAVIOR OF CESIUM

As described in the previous part of this study, the dominant emission source when DAW is burnt in DSIP was determined to be Cs-137 and Cs-134, due to their high volatility and relatively high concentration in the waste. The removal efficiency of volatilized cesium species by means of the low-temperature dry off-gas system are investigated by trial burns of simulated waste containing inactive cesium.

The off-gas treatment system utilized in this study was a dry off-gas system. The gas flow pattern of the dry off-gas system is shown in Fig. 2. The off-gas leaving the afterburner is cooled down to about 450~500 °C by vertical air-to-gas heat exchanger. About 35% of the heated cooling air at 250 °C is used as combustion air for the incinerator. About 65% of the heated air is used to heat the off-gas leaving the HEPA filter in order to prevent water vapor from condensing in the stack. Off-gas leaving the heat exchanger is further cooled down to about 200 °C for the safe operation of PTFE bag filter, by mixing with 35% of the heated air. Relatively clean gas leaving the bag filter is filtered by a HEPA filter before emitting from the stack.

Ten packages of plastic waste (PE) were prepared for cesium-containing simulated waste. The 10 grams of inactive CsCl powder was contained in each waste package. The incinerator was initially heated up to 450 °C by a gas burner. Some waste packages without tracer

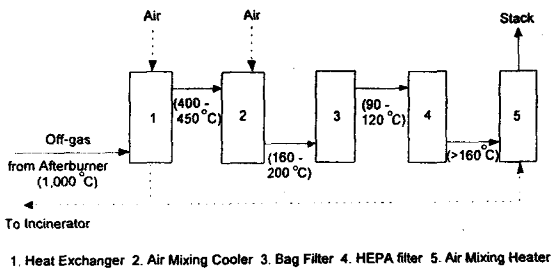

Fig. 2. Gas flow patterns in low-temperature dry off-gas system.

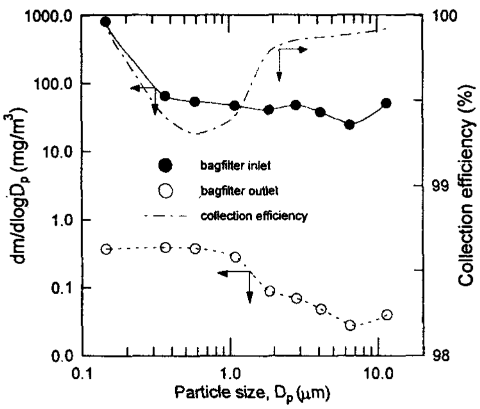

Fig. 3. Distribution of particulate matters before and after passing bagfilter, as a function of˜ particle size.

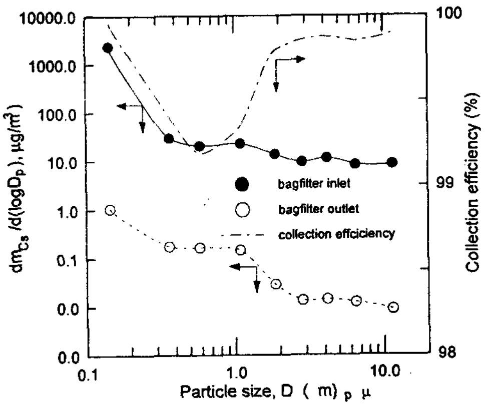

Fig. 4. Distribution of particulate cesium before and after passing bagfilter, as a function of particle size.

metals were fed into the incinerator until it reached 900 °C. The first simulated waste package with tracers was then fed and the desired temperature was maintained with fluctuations of 30~80 °C during the burning of each tracer-containing waste package.

Simultaneous particulate samplings of both inlet and outlet off-gas of the bag filter were made as soon as the first waste package including tracer metals was fed into incinerator. Sampling trains were arranged in a series of sampling probes, 8-stage particle-sizing cascade impactors, rotameters, moisture removal systems and flow control systems. Sample flow rates were set before the sampling operations according to the isokinetic rates determined by the off-gas linear flow rates. When the flow rates were lowered to 90% of the isokinetic rates by increasing the pressure drop across the impactor stages, sampling operations were finished. After weighing, quantitative analyses of each size group of particles on metal substrates and bag-up filters were obtained by Neutron Activation Analysis (NAA).

Based on the weight of particulate matters (PMs) on metal substrates and the results of their NAA, the distributions of particulate matters (PMs) and cesium species in a discrete size interval between D_{p1} and D_{p2} were determined at two sampling position over sampling time. The variations of distribution functions for particulate matters (PMs) and cesium species are plotted in the form $\Delta m/\Delta logD_p$ versus $logD_p$, and are shown in Figs. 3 and 4. Collection efficiencies are also plotted as a function of particle size. The overall particle collection efficiency for the bag filter was determined to be 99.96%. For inlet cooled off-gas at about 200 ℃, particulate cesium species in a particle size range of 0.29~1.45 μm were somewhat more distributed than those by the series of laboratory experiments[3] but relatively evenly distributed with particle size. The effect of existing soot particles, which are up to 99% by mass in the size range, are found. However, the distributions of the condensed particulate cesium species in the transition range from diffusional to the inertial collection, which generally corresponds to the size between 0.3 and 1.0 μm[10], are relatively small. Less than around 5% of the particulate cesium species is distributed in this transition size range of particulate matters. For this reason, the collection efficiencies of the bag filter for condensed cesium species are not much less than those for total particulate matters. The collection efficiency of the bag filter is determined to be 99.93% for condensed particulate cesium, showing enough decontamination efficiency as a primary filter for major emission sources.

CONCLUSIONS

Radiological risk assessments to utilize the DSIP as a conventional plant reveal that its routine operation to treat DAW would have little impact on the environment. Also even in the case of potential severe accidents like explosion, fire and failure of power or filters, the expected radiological risks are so low that can be ignored. For the purpose of regulation, the estimated emission concentrations from the stack were required to meet maximum permissible concentrations, ignoring dispersion or dilution effect in the atmosphere, but rather considering safety factor of 10. However, the compared results based on the trial burns reveal that emission concentrations of most radionuclides meet the MPCs, except for semivolatile cesium species. The expected emission concentrations of Cs-137 and Cs-134 slightly exceed the 10% of MPCs if the DAW from KNPS is treated.

An extensive investigation using inactive tracer cesium shows that most vapor-phase cesium volatilized in an incinerator furnace condenses during dry off-gas cooling to 200 °C. Cesium species are present as particulate in the off-gas before passing through low-temperature filtering devices. Distributions of condensed metal species in the transition size ranging between the diffusional and inertial region are less than 5%. It can, therefore, be said positively that a low-temperature dry off-gas system, which is composed of a dry off-gas cooling and low-temperature filtering with a minimization of secondary waste, is able to effectively control vapor-phase cesium, which is volatilized from an incinerator furnace.

SYMBOLS

DAW : dry active waste
D_p : particle size, μm
DSIP : demonstration-scale incineration plant
KAERI : Korea Atomic Energy Research Institute
KINS : Korean Institute of Nuclear Safety
KNPS : Korea Nuclear Power Station
NAA : neutron activation analysis
PMs : particulate matters

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