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Particle Size and Fuming Rate of Radioactive Aerosols generated during the Heat Cutting of Activated Metals

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Abstract

The particle sizes and fuming rates of radioactive nuclides and matrix elements were extensively investigated for aerosols generated by the heat cutting of activated metals. The aerosols showed either lognormal activity or mass distributions with modes at $0.3\sim 0.5\ \mu\text{m}$ and/or $4\sim 6\ \mu\text{m}$. Some carrier-free radioactive nuclides were remarkably enriched in the aerosols, and showed different distribution patterns from matrix metal elements. The results are discussed on the basis of the thermal properties of the radioactive and matrix elements.

1 Introduction

At high-energy accelerator facilities, the beam-line components are exposed to high-energy primary and/or secondary particles during operation. As a result, a variety of radionuclides are produced in the accelerator hardware through nuclear reactions, including spallation reactions. Some of these nuclides are present in the carrier-free state. Such activated hardware comprise one of the major sources of radiation doses to maintenance workers. There are some possibilities for workers to receive internal radiation doses by inhaling radioactive aerosols as well as external doses in the machining of activated hardware, which is often carried out for repair work. When radionuclides are once incorporated in human bodies, they remain for a relatively long time, causing some extent of radiation exposure to workers. As Tesch (1991) and Donahue (1989) have pointed out, a large part of such radiation doses is due to external radiation

exposure during ordinary machining of activated hardware. On the other hand, in the machining of activated components containing mainly long-lived nuclides with no γ -ray emission, such as ^{55}Fe and ^{63}Ni , internal radiation doses become a major source. From the viewpoint of radiation safety, it is therefore very important to estimate the internal doses due to these radioactive aerosols in advance. The fuming rate and particle size of radioactive aerosols generated by machining are basic parameters for the evaluation of internal doses. There are, however, only scattered data available.

Thus far, studies concerning welding fumes have been extensively carried out from the viewpoint of industrial hygiene (Ogasawara and Kobayashi, 1981; Moreton *et al.*, 1985; Nishida *et al.*, 1977; Kogane, 1992; Suga and Kobayashi, 1984; Sakakibara *et al.*, 1988), since the inhalation of these fumes is one of the principal causes of lung disease (Morgan, 1989). Welding fumes are generated mainly by the evaporation of welding rods,

while fumes from cutting operations are formed from the workpieces, themselves. Thus, from the radiation safety viewpoint, more attention should be paid to cutting operations rather than welding, since respirable radioactive aerosols are generated in the cutting of activated hardware. Most of studies concerning cutting fumes have mainly concerned the aerosols of matrix elements formed from dismantling construction, including that of nuclear facilities (Windelberg *et al.*, 1987; Baston *et al.*, 1988; Waldie *et al.*, 1990; Newton, 1987). Studies concerning radioactive aerosols were thus limited to the aerosols bearing radionuclides produced in a reactor.

Some critical radionuclides for internal exposure due to inhalation, which have low ALI (annual limit on intake) values (ICRP, 1979), or large formation cross sections, are often formed in the carrier-free state in activated components. This is one of the most characteristic points concerning aerosols generated from hardware activated in high-energy accelerator facilities. However, little is known about the physico-chemical behavior of these carrier-free nuclides in the aerosol formation process during machining. Carrier-free nuclides such as ^{54}Mn and ^{60}Co , which are formed in accelerator materials, have some possibility to behave in a different manner from that of matrix metals. The fuming rates, enrichment factors and size distributions for these radioactive aerosols are therefore very important for a more quantitative estimation of the internal doses; furthermore, these are also interesting subjects for studying their physico-chemical behavior in the processes of aerosol formation.

In this paper, the size distributions, fuming rates and enrichments of radioactive nuclides for aerosols generated during cutting operations were extensively studied for activated accelerator materials (aluminum, iron, copper, stainless steel and brass), which are commonly used in accelerator hardware. Argon plasma-arc cutting and/or oxy-acetylene cutting were used as heat-cutting meth-

ods. The radioactive aerosols were analyzed by using a low-pressure cascade impactor and a high-volume air sampler. The results for individual nuclides were compared with those for matrix metal elements. Their formation mechanisms are discussed in terms of the thermal properties of the elements.

2 Experimental

2.1 Samples and Irradiation

Aluminum, iron, copper, SUS304 (Fe: 74%; Cr: 18%; Ni: 8%) and cartridge brass (Cu: 70%; Zn: 30%) were chosen as sample materials in this experiment. These materials are commonly used in accelerator components, *e.g.* vacuum pipes, magnets, collimators, beam stoppers and the pipes of cooling water. The samples used were discs of 10~11 cm in diameter and 1.2 cm in thickness.

The sample discs were placed near to the target, and were irradiated for 3 or 6 weeks in the slow extract beam line (EP-2) tunnel of the 12-GeV Proton Synchrotron (PS) of the Japanese National Laboratory for High Energy Physics (KEK). The cutting operation of these irradiated samples was started more than a week after the completion of irradiation. Most of the short-lived radioisotopes were, therefore, decayed out; the surface dose rates of the irradiated plates ranged from 10 to 50 $\mu\text{Sv/h}$.

Before the cutting operation, the uniformity of the radioactivity distribution in the disc was examined with a Ge-detector system using a lead collimator. Discs having a uniform radioactivity distribution were used in the following cutting operations.

2.2 Generation and Analysis of the Aerosols

The cutting method was plasma-arc cutting using argon gas, which is commonly employed in

the machining of accelerator components in beam-line rooms. For iron samples, oxyacetylene cutting was also carried out. To realistically simulate the cutting operations performed in the confined space of accelerator rooms, the sample discs were cut in a small sampling chamber of *ca.* 0.3 m³ (see Fig.1). The cutting was carried out by an experienced craftsman. Both the fuming rate and particle size distribution were examined for the aerosols generated by the cutting operation.

Particle Size Distribution: The chamber air was sampled with a low-pressure cascade impactor (Tokyo Dylec Co., model LP-20) at 24 ℓ /min for the particle-size analysis. The impactor comprised 11 impaction stages. Their 50% cut-off aerodynamic diameters were 11.3, 8.0, 5.1, 3.5, 3.1, 1.2, 0.69, 0.33, 0.22, 0.13 and 0.06 μ m when the sampling rate was adjusted to 24 ℓ /min (-550 mmHg). A teflon-coated glass-fiber filter (8 cm ϕ) with a high collection efficiency was used to collect the aerosols. Particles smaller than 0.06 μ m were trapped by the same filter (back-up filter). The filter papers were folded into a small square piece in order to measure their radioactivities at the same geometry and at high efficiency. The radioactivity of the filter was measured for at least one day with a high-resolution Ge semi-conductor detector (2 keV FWHM for 1.173-MeV ⁶⁰Co γ -ray) connected to a 4k-PHA.

The cutting duration was 5~15 sec for brass and 1~3 min for other materials. The fuming rate for brass was so large that clear distribution patterns were obtained only by short-duration cutting. Aerosol sampling was started simultaneously with the cutting; it was continued for an additional 1.5 min after the cutting was completed. During sampling, the chamber was slightly ventilated using a high-volume sampler in order to prevent the worker from inhaling any radioactive aerosols.

In order to determine the particle size distribution for matrix metallic elements, the deposit on each filter paper was dissolved in acid solutions, and the mass of the matrix elements in the solution

was determined by atomic emission or inductively coupled plasma emission spectrometry. The solution for the analysis was prepared as follows: nitric acid was used for copper, a mixture of hydrochloric acid and nitric acid for SUS, and hydrochloric acid for other samples.

Fuming Rate: Instead of the low-pressure impactor, a high-volume air sampler was used, and all of the generated aerosols were collected on a glass-fiber filter (Advantec Toyo Co., GB100R, 20cm $\times$ 25cm). The sampling was carried out at the maximum flow rate (1200 ℓ /min), and was continued for 1.5~2 min after the cutting for the complete collection of generated aerosols.

For each sample, all of the aerosols collected on the filter were completely dissolved in the acid solutions in the same way as described above. The weights of the matrix elements in the solution and the radioactive concentrations were determined by the same methods as those for the particle-size distribution. In a separate experiment, 2~5 g of each sample plate was dissolved in the same way, and the radioactivity was measured under the same counting conditions. From the weights of the matrix elements and the radioactivities of individual nuclides, the enrichment factors and fuming rates were calculated as described in the following section.

3 Results and Discussion

The accelerator components activated in high-energy proton accelerators contain many kinds of radionuclides produced through various nuclear processes, such as spallation, (n, γ), (n, 2n), (n, p) and (p, n) reactions. The principal radionuclides formed in steels are listed in Table 1. Some of these nuclides are present in a carrier-free state. In the machining of activated hardware, they are incorporated into the aerosols. The present experiment is therefore especially considered to provide useful information concerning the physico-chemical behav-

ior of carrier-free nuclides in their aerosol generation.

In the following sections, the particle-size distributions and fuming rates are given for both individual radionuclides and matrix elements. The radionuclides analyzed for each metal sample are listed in Table 2.

3.1 Particle-Size Distribution

Table 3 gives the activity and mass distributions of aerosols collected in the following four diameter ranges: < 0.06 , $0.06\sim 1.2$, $1.2\sim 11.3$, and $> 11.3\mu\text{m}$. More than 80 % of the mass and radioactivities were found to be present in the size range of 0.06 to $11.3\mu\text{m}$ for both matrix elements and carrier-free nuclides. The distributions in the range of 0.06 to $11.3\mu\text{m}$ are illustrated in Fig.2-5 for the individual radionuclides and in Fig.6 for the matrix elements. $\Delta A/A$ in the ordinate of Fig.2-5 represents the ratio of the activity of individual radionuclides collected on each impaction stage to the total activity collected; d_p is the aerodynamic diameter of the aerosol particles. $\Delta M/M$ in Fig.6 represents the ratio of the mass of the matrix elements for each stage to the total mass collected.

At least three separate cutting operations were carried out for each sample, and a good reproducibility was observed in their distribution patterns. Figures 2-5 show the distribution patterns for individual radionuclides along with the counting statistics error. All of the figures shown are those obtained by measuring the samples made by bundling three filters together for each stage to obtain good counting statistics. They, all have a lognormal distribution.

Iron and Stainless Steel: The distributions for radionuclides, except for those of ^{46}Sc and ^{22}Na , ranged widely from 0.06 to $11.3\mu\text{m}$ (Fig.2-3), having an AMAD (activity mean aerodynamic diameter) of *ca.* $0.5\mu\text{m}$. This is almost the same as the MMAD (mass median aerodynamic diameter) of the matrix elements (Fig.6).

The ^{59}Fe pattern (Fig.2e) was almost the same as that of matrix iron, as shown in Fig.6b. ^{48}V in iron cutting had a somewhat bimodal pattern (Fig.2b). As shown in Fig.3e-3i, no significant isotopic effects were observed for manganese and cobalt isotopes. A large difference was observed between the distributions for ^{46}Sc and ^{22}Na (Fig.2a, 3a and 3b); ^{46}Sc aerosols were mainly distributed above $1\mu\text{m}$, while no ^{22}Na activity was observed above $1\mu\text{m}$ (Table 3). It is particularly noteworthy that the ^{46}Sc pattern was quite different from those of the matrix elements.

Oxyacetylene cutting was performed for iron samples in addition to plasma cutting. Only the distribution of ^{54}Mn was analyzed, because of the low radioactivities of the samples (Fig.2f). The ^{54}Mn aerosols showed a narrower distribution with a peak at *ca.* $0.5\mu\text{m}$, compared to that for plasma cutting (Fig.2d).

Copper and Brass: The distributions of radionuclides for copper showed an AMAD of *ca.* $0.5\mu\text{m}$ (Fig.4), which was the same as the MMAD of matrix copper (Fig.6g). ^{46}Sc (Fig.4a) and cobalt isotopes (Fig.4f-4h) had somewhat of a bimodal distribution. There was also no isotopic effect among the cobalt isotopes.

Figures 5b-5e show the size distributions of radionuclides for brass; ^{57}Co and ^{58}Co showed the same distribution, which was mainly distributed in size above $1\mu\text{m}$. As Fig.5b shows, most of the ^{54}Mn was also distributed above $1\mu\text{m}$. Contrary to the situation for manganese and cobalt, ^{65}Zn was dominantly distributed below $1\mu\text{m}$. Figures 6h and 6i show the size distributions for the matrix elements of copper and zinc. Copper showed to some extent a bimodal distribution, with peaks at *ca.* 5 and $0.3\mu\text{m}$, while the distribution for Zn was monomodal with an MMAD of *ca.* $0.2\sim 0.3\mu\text{m}$.

Aluminum: The ^{22}Na (Fig.5a) showed a distribution with an AMAD at *ca.* $0.5\mu\text{m}$; a similar distribution pattern was observed for matrix aluminum (Fig.6a).

Although there are several reports (Newton *et al.*, 1987; Tarroni *et al.*, 1986; Steiner *et al.*, 1988) concerning the aerosol size distribution of the cutting fume from steels, most of them were concerned with aerosols of the matrix element, itself. The present results for steel agreed with the reported MMAD values of *ca.* 0.2~0.5 μm (Newton *et al.*, 1987; Tarroni *et al.*, 1986; Steiner *et al.*, 1988).

The above-mentioned results show that the particle-size distribution in heat-cutting techniques depends on various factors, such as the kind of materials cut, the radioactive nuclides which are dispersed during the operation, and the cutting method. These features are very different from those of the mechanical cutting techniques, where the radionuclides are expected to behave in the same manner as the matrix elements.

The heat-cutting mechanism of metals is due to a removal of molten metal by a plasma jet (Ar gas plasma in this experiment) in plasma cutting or by an oxygen jet in oxyacetylene cutting, in addition to the evaporation of metals from a molten site of metals. The following three mechanisms (Morris *et al.*, 1966; Bates, 1963; Sargent, 1964) have been proposed for the generation of aerosols (fume). One is vaporization of the metal and/or metallic oxide at the impact site of the plasma or the oxygen jet, which is followed by oxidation of metallic vapor. The second is vaporization of more volatile chemical species, such as iron carbonyl and nickel carbonyl (Wiseman, 1989), which are formed at the gaseous boundary layer. The last one is due to the explosion of metallic droplets or a burst of gas bubbles, such as carbon monoxide, which are formed in molten metals.

These mechanisms are closely related to the thermal properties of metals, such as the vapor pressure. Table 4 shows the thermal properties of the elements involved in this experiment. The two peaks observed at 0.3~0.5 μm and 4~5 μm in the distribution patterns were considered to be due to different mechanisms.

Large aerosols with a peak at 4~5 μm are con-

sidered to be mainly formed due to the explosion of molten metallic droplets. The formation of these large aerosols is considered to be less influenced by the vapor pressure of their concerned elements. On the other hand, smaller aerosols of 0.3~0.5 μm are likely to be formed by the first mechanism, *i.e.*, vapor condensation. The amount of these aerosols is therefore considered to be largely dependent on the vapor pressure of the elements. Accordingly, the proportion of radioactivities for the aerosols of 0.3~0.5 μm is likely to be more dominant for an element with a higher vapor pressure.

This was confirmed for the radionuclides, except for ^{46}Sc in iron, SUS and copper. The elements having a low vapor pressure, such as vanadium and cobalt (see Table 4), showed somewhat bimodal patterns (Fig.2b, 3c for ^{48}V , Fig.3g-3i, 4f-4h for cobalt isotopes). As the vapor pressure of the element increases, its activity proportion in the larger aerosols with peaks at 4~5 μm decreases in order of their vapor pressures, and finally becomes negligibly small, as shown for sodium (Fig.3a, 5a) and zinc (Fig.5e), which have very high vapor pressures at the plasma temperature.

In a brass sample, ^{54}Mn and cobalt isotopes were mainly observed at above 1 μm , unlike SUS and copper. Their distribution patterns were similar to that for matrix copper. The distribution pattern of matrix copper was largely different from that for matrix copper in the copper sample (see Fig.6). As stated in the experimental section, only several seconds of plasma cutting for brass samples were sufficient to obtain the above-mentioned distribution patterns. This suggests that the decomposition of the alloy takes place explosively at the site heated by the plasma. Thus, these results may be explained by an explosion of the matrix metal due to vigorous vaporization and/or bumping of matrix zinc, due to its extremely high vapor pressure. However, the distribution pattern for zinc aerosols (see Fig.6) implies that evaporation of matrix zinc proceeds at the same time.

^{46}Sc showed a very different pattern from the matrix elements in iron and SUS. This result cannot be explained by the difference in their thermal properties, which are almost the same as that shown in Table 4. The differences in the physico-chemical properties between scandium and iron in molten iron or iron oxide might be responsible for their distribution patterns. In general, the physico-chemical properties of elements in molten metals, *e.g.*, the solubility and diffusivity, are known to influence their concentration at the molten sites (Goldberg, 1971). However, no data concerning the solubility or diffusivity of scandium in molten iron are available at present. Details concerning their mechanism must be awaited until further experiments can be carried out.

Although there were some exceptions, most of the carrier-free nuclides had a similar particle size distribution to that of the matrix elements. This is indicative that the aerosols of radionuclides, as well as those of matrix elements, are not formed independently, and that most of the carrier-free radionuclides become incorporated into the aerosols of the matrix elements and form radioactive aerosols during the process of aerosol formation of the matrix elements.

3.2 Fuming Rate

The enrichment factor of the radionuclides and the fuming rate were defined as follows:

$$R_M = \frac{M_F}{M_P} \times 100, \quad (1)$$

$$E_i = \frac{A_{i,F}/M_F}{A_{i,P}/M_P} \quad (2)$$

and

$$R_{A,i} = \frac{A_{i,F}}{A_{i,P}} \times 100 = R_M \times E_i, \quad (3)$$

where, R_M is the fuming rate of the matrix element (%), $R_{A,i}$ the fuming rate of the radionuclide i (%), E_i the enrichment factor of the radionuclide i , M_F the total mass of matrix elements collected on the filter, M_P the total mass removed

from the sample disc by the cutting, $A_{i,F}$ the activity of the radionuclide i collected on the filter, and $A_{i,P}$ the activity of the radionuclide i removed from the sample disc by the cutting. Here, M_F and M_P for alloy samples are replaced by the sum of the weights of individual matrix elements, *i.e.*, Cr+Fe+Ni for SUS and Cu+Zn for brass.

In other studies concerning fume generation, the fuming rate of the matrix elements is often expressed in terms of the mass of fumes collected per unit time of welding or cutting operation, *e.g.*, in g/min. However, this expression is known to be greatly influenced by the cutting conditions, such as the thickness of the workpiece, speed of welding or cutting, and gas pressure (Fume, 1985). In this work, the definition in % and the enrichment factor (eq.(2)) are used, which are more suitable for an intercomparison between the fuming rates obtained in separate experiments, since these are less affected by the conditions.

The enrichment factors and the fuming rate were obtained from at least four separate experiments. Table 5 gives the fuming rates of matrix elements; for a comparison with the other reported values, the results are also expressed in g/min in parentheses. The fuming rates for oxyacetylene cutting of iron agree with those values given in the literatures (Newton *et al.*, 1987; Fume, 1985); that for the plasma-cutting of SUS304, however, was about one third to half that obtained by Newton *et al.* (1987). This may be attributed to the differences in the experimental conditions, such as the thickness of the workpiece and/or cutting speed.

The experimentally obtained enrichment factors are illustrated by the bars in Fig.7, in which they are depicted in the order of the boiling points of the elements. The bars in the figure simply show the minimum and maximum values of the enrichment factors. Table 6 shows their mean and maximum values as well as the fuming rate for individual radionuclides calculated using eq.(3). An enrichment factor greater than unity indicates that

the nuclide is enriched in the aerosols generated by the cutting operation. On the contrary, a depletion of the nuclides gives an enrichment factor of less than unity. The factors widely ranged from 0.2 to 63. Non-carrier-free nuclides (^{59}Fe in iron, ^{59}Fe and ^{51}Cr in SUS) showed factors of around unity, while enrichment or depletion was observed in other radionuclides. No significant isotopic effect was observed in cobalt isotopes. Those elements having a high vapor pressure, such as ^{22}Na and ^{65}Zn , showed a very high enrichment.

In iron and SUS, ^{22}Na was highly enriched in the aerosols. Its maximum enrichment factors reached 21 for the plasma cutting of iron, 48 for that of SUS304 and 63 for oxyacetylene cutting of iron. Cobalt isotopes were also enriched in iron (Fig.7a-7b), while they were depleted in other materials (Fig.7c-7e). The factor for ^{54}Mn , however, was 1.3~6 for iron and SUS (Fig.7a-7c). The enrichment of manganese in fume has also been reported by several authors (Waldie *et al.*, 1990; Morris *et al.*, 1966), and is also attributed to its higher vapor pressure compared to other transition metal elements.

In copper, all of the nuclides, except for cobalt isotopes, were enriched. A high enrichment factor of over 10 was observed for ^{48}V (Fig.7d), while ^{48}V for all other materials were found to be depleted (Fig.7a-7c, 7e). Whereas most of radionuclides were depleted in brass (Fig.7e), only ^{65}Zn was slightly enriched.

In general, the cutting of copper is more difficult than that of other materials, because of its high thermoconductivity (Lide, 1990). Therefore, a longer cutting time is required compared to that for other materials; an entire copper plate, as well as the site of impact of the plasma, is heated until it shines red during cutting. The enrichment in copper is, therefore, considered to be due to the evaporation of radionuclides from the entire plate, as well as the impact site of the plasma. On the other hand, the cutting operation for brass was extremely short because of its high fuming

rate of matrix metals. The aerosol generation in brass takes place only at the impact site of the plasma. Thus, the above-mentioned difference between copper and brass may be explained in terms of these thermal properties of the sample materials.

The enrichment of transition-metal elements seems to be rather complicated and cannot be explained simply in terms of their thermal properties. It is considered to be closely related to their behavior in molten matrix elements. Such factors as the chemical reactions and diffusivities of radionuclides in the molten site may play an important role concerning their enrichment. At present, little is known about the physico-chemical behavior of carrier-free radionuclides in cutting operations. Although the mechanism of radionuclide enrichment and/or depletion in aerosol formation is an attractive theme, its details must be awaited until further systematic and well-defined experiments are carried out.

In summary, the particle size and fuming rate of aerosols generated during plasma and oxyacetylene cutting operations, were investigated for iron, copper, brass, aluminum and SUS discs, in which a variety of radionuclides, including carrier-free nuclides, were contained. The aerosol size distribution and the fuming rate were experimentally obtained for both matrix elements and radionuclides.

The particle sizes are distributed widely with peaks of *ca.* 0.3~0.5 μm and/or 4~5 μm in diameter, and the fuming rates are very dependent on the matrix elements and radionuclides. Since enrichment of radionuclides directly influences the estimation of the internal doses, attention should be paid to the enrichment factors of radionuclides, especially concerning those of nuclides having low ALI values (ICRP, 1979). These nuclides were ^{22}Na , ^{60}Co , ^{65}Zn in iron cutting, ^{22}Na in SUS, and ^{46}Sc , and ^{48}V in copper cutting. For example, when a worker inhales ^{22}Na during iron cut-

ting, the internal dose without any correction by the enrichment factors can be underestimated by a factor of *ca.* 1/100 as maximum. The present results are considered to be very useful for a quantitative evaluation of internal radiation doses to workers during these cutting operations.

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Table 1: Principal Radionuclides ($T_{1/2} > 25d$) formed in Steels

Nuclide	Half Life	Decay Mode	ALI* (Bq)
^3H	12y	β^-	3×10^9
^7Be	53.28d	EC	7×10^8
^{22}Na	2.602y	β^+ , EC	2×10^7
^{46}Sc	83.8d	β^-	9×10^6
^{44}Ti	48.2y	EC	2×10^5
^{48}V	15.97d	β^+ , EC	2×10^7
^{51}Cr	27.70d	EC	7×10^8
^{54}Mn	312.5d	EC	3×10^7
^{55}Fe	2.7y	EC	7×10^7
^{59}Fe	44.6d	β^-	1×10^7
^{56}Co	78.76d	EC, β^+	7×10^6
^{57}Co	271d	EC	2×10^7
^{58}Co	70.8d	EC, β^+	3×10^7
^{60}Co	5.271y	β^-	1×10^6
^{59}Ni	$7.5 \times 10^4\text{y}$	EC	1×10^8
^{63}Ni	100.1y	β^-	6×10^7

* The lowest values for inhalation

Table 2: Radioactive Nuclides analyzed in This Experiment

Material	Cutting Method	Particle Size Distribution	Fuming Rate
Iron	Plasma-arc	^{46}Sc , ^{48}V , ^{51}Cr , ^{54}Mn , ^{59}Fe	^{22}Na , ^{46}Sc , ^{48}V , ^{51}Cr , ^{54}Mn , ^{59}Fe , ^{56}Co , ^{57}Co , ^{58}Co , ^{60}Co
Iron	Oxyacetylene	^{54}Mn	^{22}Na , ^{46}Sc , ^{48}V , ^{51}Cr , ^{54}Mn , ^{59}Fe , ^{56}Co , ^{57}Co , ^{58}Co , ^{60}Co ^{65}Zn
SUS304	Plasma-arc	^{22}Na , ^{46}Sc , ^{48}V , ^{51}Cr , ^{52}Mn , ^{54}Mn , ^{57}Co , ^{58}Co , ^{60}Co	^7Be , ^{22}Na , ^{46}Sc , ^{48}V , ^{51}Cr , ^{54}Mn , ^{59}Fe , ^{56}Co , ^{57}Co , ^{58}Co , ^{60}Co
Copper	Plasma-arc	^{46}Sc , ^{48}V , ^{51}Cr , ^{54}Mn , ^{59}Fe , ^{57}Co , ^{58}Co , ^{60}Co	^{46}Sc , ^{48}V , ^{51}Cr , ^{54}Mn , ^{59}Fe , ^{56}Co , ^{57}Co , ^{58}Co , ^{60}Co , ^{65}Zn
Brass	Plasma-arc	^{54}Mn , ^{57}Co , ^{58}Co , ^{65}Zn	^{46}Sc , ^{48}V , ^{51}Cr , ^{54}Mn , ^{59}Fe , ^{56}Co , ^{57}Co , ^{58}Co , ^{60}Co ^{65}Zn
Aluminum	Plasma-arc	^{22}Na	^7Be , ^{22}Na

Table 3: Particle Size Distributions of the Aerosols

Nuclide or Element	Proportion (%)			
	< 0.06	0.06 ~ 1.2	1.2 ~ 11.3	> 11.3 μm
<i>Iron in plasma cutting</i>				
⁴⁶ Sc	0	11	89	0
⁴⁸ V	4	48	48	0
⁵¹ Cr	2	66	32	0
⁵⁴ Mn	3	77	19	1
⁵⁹ Fe	3	71	24	2
Matrix Fe	3	70	25	2
<i>Iron in oxyacetylene cutting</i>				
⁵⁴ Mn	4	69	22	5
Matrix Fe	3	61	31	5

<i>SUS304 in plasma cutting</i>				
²² Na	11	89	0	0
⁴⁶ Sc	0	0	82	18
⁴⁸ V	7	65	25	3
⁵¹ Cr	6	75	17	2
⁵² Mn	6	84	9	1
⁵⁴ Mn	6	83	10	1
⁵⁷ Co	5	69	23	3
⁵⁸ Co	5	69	23	3
⁶⁰ Co	4	72	21	3
Matrix Cr	8	86	6	0
Matrix Fe	7	78	13	2
Matrix Ni	7	77	14	2

<i>Copper in plasma cutting</i>				
⁴⁶ Sc	0	61	38	1
⁴⁸ V	0	80	19	1
⁵¹ Cr	1	89	10	0
⁵⁴ Mn	1	73	25	1
⁵⁹ Fe	0	69	31	0
⁵⁷ Co	0	67	31	2
⁵⁸ Co	1	67	31	1
⁶⁰ Co	0	65	35	0
Matrix Cu	1	79	18	2

<i>Brass in plasma cutting</i>				
⁵⁴ Mn	15	28	51	6
⁵⁷ Co	0	20	75	5
⁵⁸ Co	2	19	74	5
⁶⁵ Zn	1	88	11	0
Matrix Cu	2	30	62	6
Matrix Zn	2	83	14	1

<i>Aluminum in plasma cutting</i>				
²² Na	4	89	7	0
Matrix Al	9	80	10	1

Table 4: Thermal Properties of Elements

Element	Melting Point ($^{\circ}\text{C}$)	Boiling Point ($^{\circ}\text{C}$)	Vapor Pressure* (Torr)
Be	1289	2472	9.6×10^{-4}
Na	97.81	882.9	—
Al	660.37	2467	6.9×10^{-4}
Sc	1541	2836	7.8×10^{-5}
V	1890 ± 10	3380	7.9×10^{-10}
Cr	1857 ± 20	2672	5.9×10^{-5}
Mn	1244 ± 3	1962	8.9×10^{-2}
Fe	1538	2862	2.4×10^{-5}
Co	1495	2870	9.8×10^{-7}
Ni	1455	2730	1.1×10^{-6}
Cu	1083.4 ± 0.2	2567	4.2×10^{-4}
Zn	419.58	907	—

* Calculated vapor pressures at 1083 $^{\circ}\text{C}$

Table 5: Fuming Rates of Matrix Elements

Material	Cutting Method	Fuming Rate*	
		%	(g/min)
Iron	Plasma-arc	2.6 ± 0.2	(0.8 ± 0.2)
Iron	Oxyacetylene	0.3 ± 0.1	(0.2 ± 0.1)
SUS304	Plasma-arc	0.6 ± 0.2	(0.3 ± 0.1)
Copper	Plasma-arc	1.0 ± 0.7	(0.13 ± 0.07)
Brass	Plasma-arc	28 ± 2	(5.9 ± 0.3)
Aluminum	Plasma-arc	2 ± 1	(0.15 ± 0.02)

* listed are the average values of at least four separate experiments and their standard deviations (1σ).

Table 6: Enrichment Factors and Fuming Rates of Radionuclides

Material Method	Iron		Oxyacetylene		SUS304		Copper		Brass		Aluminum	
	Plasma-arc Mean	Max.	Plasma-arc Mean	Max.	Plasma-arc Mean	Max.	Plasma-arc Mean	Max.	Plasma-arc Mean	Max.	Plasma-arc Mean	Max.
⁷ Be	10 (2.6)*	21 (55)	44 (13)	63 (19)	10 (6)	39 (23)					1.3 (2.6)	2.1 (4.2)
²² Na	0.52 (1.4)	0.54 (1.4)	0.98 (0.3)	1.9 (0.6)	30 (18)	48 (29)					3.6 (7.2)	5.6 (11)
⁴⁶ Sc					0.7 (0.4)	1.1 (0.7)	8.6(8.6)	13 (13)				
⁴⁸ V	0.53 (1.4)	0.56 (1.5)	0.8 (0.2)	1 (0.3)	0.5 (0.3)	0.8 (0.5)	18 (18)	21 (21)	0.29 (8.1)	0.4 (11)		
⁵¹ Cr	0.94 (2.4)	0.95 (2.5)	0.76 (0.2)	0.86 (0.3)	0.9 (0.5)	1.3 (0.8)	8.5 (8.5)	14 (14)	0.52 (15)	0.79 (22)		
⁵⁴ Mn	1.7 (4.4)	2.0 (5.2)	2.4 (0.7)	3.4 (1.0)	4.7 (2.8)	6 (3.6)	4.5 (4.5)	5.7 (5.7)	0.48 (13)	0.65 (18)		
⁵⁹ Fe	1.1 (2.9)	1.1 (2.9)	1.1 (0.3)	1.1 (0.3)	1.0 (0.6)	1.4 (0.8)	3.6 (3.6)	4.8 (4.8)	0.31 (8.7)	0.49 (14)		
⁵⁶ Co	2.3 (6.0)	3.0 (7.8)	2.3 (0.7)	4.9 (1.5)	0.7 (0.4)	0.9 (0.5)	0.54 (0.54)	0.79 (0.79)	0.36 (10)	0.66 (18)		
⁵⁷ Co	5.2 (14)	7.5 (20)	3.7 (1.1)	10 (3.0)	0.9 (0.5)	1.4 (0.8)	0.52 (0.52)	0.83 (0.83)	0.39 (11)	0.51 (14)		
⁵⁸ Co	4.5 (12)	6.0 (16)	3.6 (1.1)	8.8 (2.6)	0.7 (0.4)	1 (0.6)	0.49 (0.49)	0.82 (0.82)	0.38 (11)	0.59 (17)		
⁶⁰ Co	2.0 (5.2)	3.4 (8.8)	2.7 (0.8)	6.4 (1.9)	0.7 (0.4)	1 (0.6)	0.56 (0.56)	0.89 (0.89)	0.44 (12)	0.44 (12)		
⁶⁵ Zn			23 (6.9)	28 (8.4)			4.1 (4.1)	4.1 (4.1)	1.5 (42)	1.9 (53)		

* Fuming rates in % are shown in parentheses.

Fig.1 Sampling chamber

Fig.2 Particle size distributions of radionuclides in iron cutting

Fig.3 Particle size distributions of radionuclides for plasma cutting of SUS304

Fig.4 Particle size distributions of radionuclides for plasma cutting of copper

Fig.5 Particle size distributions of radionuclides for plasma cutting of aluminum and brass

Fig.6 Particle size distributions of matrix elements

Fig.7 Enrichment factors of radionuclides