Determination of Radionuclides Induced by Fast Neutrons from the JCO Criticality Accident in Tokai-mura, Japan for Estimating Neutron Doses

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JCO criticality accident/Fast neutron/(n, p) reaction/Cobalt-58/ Manganese-54.

A criticality accident occurred at a uranium conversion facility in Tokai-mura, Japan on September 30, 1999, and fission neutrons were continuously emitted for about 20 hours. Materials of stainless steel or iron, and chemical reagents were collected at places between 2 m and 270 m from the criticality accident site on October 25 and 26, 1999, November 27, 1999 and February 11, 2000. Neutron-induced radionuclides, such as $^{54}$Mn and $^{58}$Co, in the materials exposed to fast neutrons from the accident were measured to estimate the neutron fluences and energy distributions. Highly sensitive γ-ray spectrometry with a well-type Ge detector was performed after radiochemical separation of Mn and Co from the materials. An instrumental neutron activation analysis was mainly applied for determinations of the target elements and chemical yields. The concentrations of $^{54}$Mn and $^{58}$Co in a mesh screen of stainless steel collected at a location 2.0 m from the accident site were determined. The total number of fission events was evaluated to be $2.5 \times 10^{18}$ by Monte-Carlo calculations of neutron transfer by considering the observed values of $^{54}$Mn and $^{58}$Co. The results presented here are fundamental to estimate the neutron doses at various distances.

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INTRODUCTION

A criticality accident occurred at the Uranium Conversion Building (UCB) of JCO Company Limited in Tokai-mura, Ibaraki Prefecture, Japan on September 30, 1999, and fission neutrons were continuously emitted from the uranium solution in the precipitation vessel (PV) for about 20 hours. The neutron-induced radionuclides such as $^{24}$Na, $^{32}$P, $^{46}$Sc, $^{51}$Cr, $^{54}$Mn, $^{59}$Fe, $^{58}$Co, $^{60}$Co, $^{65}$Zn and $^{198}$Au were detected in soil, pine needle, table salt, stainless steel, coins and gold products at and around the JCO site 1–7). Most of the detected radionuclides were induced by thermal neutrons, but $^{32}$P, $^{54}$Mn and $^{58}$Co were produced by fast neutrons. Cobalt-58, $^{54}$Mn and $^{57}$Co were produced by fast neutrons from Chinese atmospheric nuclear weapons tests, and the concentrations of the nuclides in the air have been determined 8), 9). Such radionuclides have not been detected in the air after the end of 1981.

Residual neutron-induced radionuclides, such as $^{152}$Eu, $^{154}$Eu and $^{60}$Co, in materials exposed to atomic-bomb radiation at Hiroshima and Nagasaki were measured to estimate the neutron fluences 10,11). However, a new approach to evaluate neutron fluences by (n, p) reactions with fast neutrons is more useful than by (n, $\gamma$) reactions with thermal neutrons because of less influence by shielding effects 12).

Kofuji et al. 2) performed the detection of $\beta$–rays from $^{32}$P induced by the $^{35}$Cl(n, $\alpha$) reaction using a low-background $\beta$-counting system with a passively implanted silicon detector after chemical separation to estimate the fluences of fast neutrons at various distances from the JCO criticality accident site. We independently attempted to measure $^{54}$Mn and $^{58}$Co, $\gamma$–ray emitters with longer half-lives than $^{32}$P, formed by the (n, p) reaction with fast neutrons from the accident in materials of iron and nickel. The determination of radioactivity induced by fast neutrons is important for both a precise estimation of the neutron spectrum, and an accurate evaluation of a more biological effective dose given by fast neutrons than thermal neutrons.

The (n, $\gamma$) reaction products with thermal neutrons were also determined. Shielding effects could be estimated by comparing the fast-neutron fluences with the thermal-neutron fluences.

MATERIALS AND METHODS

Chemical reagents were collected at the JCO site on October 26, 1999, and on November 27, 1999. Also, a piece of stainless-steel mesh screen of a cooling tower and a few iron bolts were sampled on February 11, 2000. This sampling program was a part of the activity of the Japanese University Research Group for the Environmental Impact of the JCO Criticality Accident '99 Tokai (abbreviated to JUniRGEnI-JCO-CAT)13). The sampling locations are shown in Fig. 1. The distance between the sampling places and PV ranged from 2.0 m to 65 m. The mesh screen of stainless steel was collected at the closest place (Site-A) 2.0 m from the center of PV and the iron bolts were collected on the ground 7.8 m from PV (Site-B). Raney nickel and Co(NO$_3$)$_2$.6H$_2$O were collected at the Wet Chemistry Testing Laboratory (WCTL), which is located 65 m southeast from the Uranium Conversion Building (UCB). Nickel chloride, NiSO$_4$.6H$_2$O and CsCl were
collected at the Third Uranium Testing Building (TUTB), which lies 63 m northwest from PV. Non-destructive $\gamma$-ray spectrometry by the use of a well-type Ge detector was performed for all samples. A stainless-steel plate was collected at a material-storing place (Site-C), 270 m east from UCB, in the vicinity of the JCO Company on October 25, 1999. When the stainless-steel plate was set up on the $\gamma$-ray detector, only $^{51}$Cr was detected. After radiochemical separation, the radioactive cobalt in the samples containing nickel was measured with a well-type Ge detector under the condition of high detection efficiency.

Each stainless-steel sample was dissolved in 6M HCl, and iron was removed by solvent extraction. Cobalt was then separated from other elements with an anion-exchange resin. The Raney nickel and the nickel salts were dissolved in 8M HCl, and cobalt carriers were added to the nickel solutions other than the solution of the Raney nickel. Cobalt in the nickel reagents was also purified by an anion-exchange technique. The chemical yields of cobalt were more than 85% for all samples. The contents of Mn, Fe, Co and Ni in the stainless-steel samples and those of Co and Ni in the nickel reagents were determined by an instrumental neutron activation analysis (INAA) at Kyoto University Reactor (KUR). One of the iron bolts was partly dissolved in 6M HCl; the solution was neutralized with Na(OH) to recover Fe and Mn as hydroxides.

Table 1 lists the concentrations of Cr, Fe, Co, Ni and Cs in the samples.

The detection efficiency of the $\gamma$-ray spectrometer was measured using mock-up samples. The radionuclides used to prepare the mock-up samples were produced at KUR and calibrated
Table 1. Chemical composition of samples.

| Samples                          | Distance and direction from PV | Cr/% | Fe/% | Co/% | Ni/% | Cs/% | Method          |
|----------------------------------|-------------------------------|------|------|------|------|------|----------------|
| Stainless-steel mesh (SS-1)      | 2.0 m NW (Site-A)             | 16.3 | 65.9 | 0.245 | 8.88 | –    | INAA.          |
| Iron bolt                        | 7.8 m W (Site-B)              | –    | 56.5 | –    | –    | –    | Colorimetry.   |
| NiSO₄·6H₂O                       | 63 m NW (TUTB)                | –    | –    | –    | 25.4 | –    | Stoichiometry. |
| NiCl₂                            | 63 m NW (TUTB)                | –    | –    | –    | 45.3 | –    | Stoichiometry. |
| CsCl                             | 63 m NW (TUTB)                | –    | –    | –    | –    | 78.9 | Stoichiometry. |
| Raney Ni                         | 65 m SE (WCTL)                | –    | –    | 0.061 | 49.6 | –    | INAA.          |
| Co(NO₃)₂·6H₂O                    | 65 m SE (WCTL)                | –    | –    | 20.3 | –    | –    | Stoichiometry. |
| Stainless-steel plate (SS-2)     | 270 m E (Site-C)              | 16.9 | 71.7 | 0.200 | 7.95 | –    | INAA.          |

Table 2. Ratios of radioactivity to unit weight of target element

| Samples         | Distance and direction | ⁵¹Cr/Cr (Bq·g⁻¹) | ⁵⁴Mn/Fe (Bq·g⁻¹) | ⁵⁹Fe/Fe (Bq·g⁻¹) | ⁵⁷Co/Ni (Bq·g⁻¹) |
|-----------------|------------------------|------------------|------------------|------------------|-----------------|
| SS-1            | 2.0 m NW (Site-A)      | 2620±6           | 2.691±0.008      | 8.89±0.08        | 0.121±0.005     |
| Iron Bolt       | 7.8 m W (Site-B)       | 0.040±0.001      | 0.49±0.03        | –                | –               |
| NiSO₄·6H₂O      | 63 m NW (TUTB)         | –                | –                | –                | –               |
| NiCl₂           | 63 m NW (TUTB)         | –                | –                | –                | –               |
| CsCl            | 63 m NW (TUTB)         | –                | –                | –                | –               |
| Raney Ni        | 65 m SE (WCTL)         | –                | –                | –                | –               |
| Co(NO₃)₂·6H₂O   | 65 m SE (WCTL)         | –                | –                | –                | –               |
| SS-2            | 270 m E (Site-C)       | 0.057±0.004      | –                | –                | –               |

RESULTS

Figure 2 shows the g-ray spectrum of the mesh screen of stainless steel (collected at Site-A) before chemical separation. The photo-peaks of five radioisotopes, i.e. ⁵¹Cr, ⁵⁴Mn, ⁵⁹Fe, ⁵⁸Co and ⁶⁰Co, were clearly detected. A weak photo-peak of 122 keV, attributed to ⁵⁷Co, was also recognized by non-destructive γ-ray spectrometry, and the peak of ⁵⁷Co became clear after the chemical separation of Co from the stainless-steel mesh. The data for concentrations of radionuclides in all of the samples are given in Table 2. The values represent the ratios of the radioactivity, decay-corrected to the end of the criticality accident, to the unit weight of the target element. The associated errors of the concentration data were evaluated by considering only counting statistics.

The half-lives, the production reactions, the cross sections with fission neutrons or thermal neutrons, and the threshold energies for all of the reactions are given in Table 3. Chromium-51, ⁵⁹Fe and ⁶⁰Co were induced by (n, γ) reactions. Manganese-54 and ⁵⁸Co were induced by (n, p)
reactions. Based on the assumption that the cross section of the $^{60}\text{Ni}(n, p)^{60}\text{Co}$ reaction is equal to that of the $^{58}\text{Ni}(n, p)^{58}\text{Co}$ reaction, the activity ratio of $^{60}\text{Co}$ to $^{58}\text{Co}$ should be 0.014. The threshold energy of the $^{60}\text{Ni}(n, p)$ reaction is about 2 MeV, while the $^{58}\text{Ni}(n, p)$ reaction has no threshold energy, and hence the activity ratio of $^{60}\text{Co}/^{58}\text{Co}$ should be less than 0.014. In contrast to the expectation, the measured concentrations of $^{60}\text{Co}$ and $^{58}\text{Co}$ in the sample were 5.7 Bq/g and 15.5 Bq/g, respectively, and the activity ratio of $^{60}\text{Co}/^{58}\text{Co}$ became 0.37, viz., the measured activity ratio was much higher than the estimated one. Since the concentration of Co in the sample was

![Non-destructive $\gamma$-ray spectrum for the mesh screen of stainless steel collected at Site-A.](https://academic.oup.com/jrr/article-abstract/42/Suppl/S45/932176)

(Sample weight: 9.855 g, counting date: March 2, 2000, counting time: 150 ks.)

| ($^{58}\text{Co}/\text{Ni}$ (Bq$^{-1}$), decay corrected to October 1, 1999)) | ($^{60}\text{Co}/\text{Co}$ (Bq$^{-1}$)) | ($^{134}\text{Cs}/\text{Cs}$ (Bq$^{-1}$)) |
|---|---|---|
| 175.0 ±0.3 | 2334 ±5 | - |
| 0.00068 ±0.00011 | - | - |
| 0.00064 ±0.00018 | - | - |
| - | - | 0.290 ±0.007 |
| 0.0029 ±0.0004 | 0.87 ±0.10 | - |
| - | 0.634 ±0.015 | - |
| 0.00037 ±0.00017 | 0.053 ±0.007 | - |
Table 3. Production reactions and half-lives of neutron-induced radionuclides, threshold energies of the reactions and cross sections.

| Radionuclides | Half-lives | Production reactions | Threshold energies | Cross sections |
|--------------|------------|----------------------|--------------------|---------------|
|              | (natural isotopic abundance) | / MeV | Fission/ m barn | Thermal/ barn. |
| $^{54}$Mn    | 312 d      | $^{54}$Fe(n, p) (5.8%) | – | 81 – |
| $^{59}$Fe    | 44.6 d     | $^{58}$Fe(n, $\gamma$) (0.29%) | – | – 1.30 |
| $^{57}$Co    | 271 d      | $^{58}$Ni(n, np) (68.3%) | 8.32 | 0.22 – |
| $^{57}$Co    | 271 d      | $^{58}$Ni(n, 2n) $^{57}$Ni $^{57}$Co (68.3%) | 12.42 | 0.0030 – |
| $^{58}$Co    | 70.8 d     | $^{58}$Ni(n, p) (68.3%) | – | 107 – |
| $^{60}$Co    | 5.27 y     | $^{59}$Ni(n, np) (26.1%) | 2.07 | 2.6 – |
| $^{60}$Co    | 5.27 y     | $^{59}$Co(n, $\gamma$) (100%) | – | – 37.2 |
| $^{134}$Cs   | 2.06 y     | $^{133}$Cs(n, $\gamma$) (100%) | – | – 29.0 |

determined to be 0.25% by INAA, we can conclude that $^{60}$Co was entirely formed from the $^{59}$Co(n, $\gamma$) reaction. Although the possible reactions to produce $^{57}$Co are $^{58}$Ni(n, np) $^{57}$Co and $^{58}$Ni(n, 2n) $^{57}$Ni $\text{□}^{57}$Co with fast neutrons, the (n, np) reaction was considered to be the main reaction of the detected $^{57}$Co because of a higher threshold energy of the (n, 2n) reaction than the (n, np) reaction.

The concentrations of $^{51}$Cr, $^{54}$Mn, $^{59}$Fe, $^{57}$Co, $^{58}$Co and $^{60}$Co in the mesh screen of stainless steel collected at Site-A (2.0 m from PV) were 2620(±6) Bq/g-Cr, 2.691(±0.008) Bq/g-Fe, 8.89(±0.08) Bq/g-Fe, 0.121(±0.005) Bq/g-Ni, 175.0(±0.3) Bq/g-Ni and 2334(±5) Bq/g-Co, respectively. The radioactivities of the nuclides in another part of the mesh screen of stainless steel collected by Japan Atomic Energy Research Institute (JAERI) at the same site were reported by the Japanese Nuclear Safety Commission15). The JAERI group reported that the concentrations of $^{51}$Cr, $^{54}$Mn, $^{59}$Fe, $^{58}$Co and $^{60}$Co were 469 Bq/g-sample, 1.82 Bq/g-sample, 6.57 Bq/g-sample, and 15.4 Bq/g-sample and 5.49 Bq/g-sample, respectively, and that the contents of Cr, Fe, Co and Ni in the sample were 19%, 71%, 0.24% and 9.6%, respectively by ICP-AES. Consequently, our results agree well with those by JAERI.

The concentrations of $^{54}$Mn and $^{59}$Fe in the iron bolt collected at Site-B (7.8 m from PV) were 0.040(±0.001) Bq/g-Fe and 0.49(±0.03) Bq/g-Fe, respectively. The values of $^{54}$Mn and $^{59}$Fe decrease to 1.5% and 5.5%, respectively, as the distance from PV becomes long from 2.0 m (Site-A) to 7.8 m (Site-B). The neutron fluences would decrease to 6.6% between Site-A and Site-B when released neutrons diffused toward the 4$\pi$-geometry. Since the decreasing tendency of measured $^{54}$Mn /Fe between Site-A and Site-B was steeper than that estimated by a simple assumption of neutron diffusion, the energy of the released neutrons would have thermalized...
between Site-A and Site-B by scattering with air

The concentrations of $^{60}$Co in the Raney nickel and in Co(NO$_3$)$_2$.6H$_2$O collected at WCTL (65 m from PV) were 0.87(±0.10) Bq/g-Co and 0.634(±0.015) Bq/g-Co, respectively. Other members of JUniRGEN-JCO-CAT determined independently the radioactivities of the nuclides induced by (n, $\gamma$) reactions in other parts of the chemical reagents. Our values agree well with the data reported for the shared samples with Muroyama et al.\textsuperscript{16} and Murata et al.\textsuperscript{17} The concentration of $^{58}$Co in the Raney nickel was 0.0029(±0.0004) Bq/g-Ni. The values of $^{58}$Co and $^{60}$Co decrease to $1.7 \times 10^{-5}$ and $3.2 \times 10^{-4}$, respectively, as the distance becomes long from 2.0 m (Site-A) to 65 m (WCTL), although the neutron fluences would decrease to $9.4 \times 10^{-4}$ between the distances by assuming the geometric effect.

For the two nickel reagents collected at TUTB (63 m from PV), the ratio of $^{58}$Co to Ni in NiSO$_4$.6H$_2$O (0.00068(±0.00011) Bq/g-Ni) agreed well with that in NiCl$_2$ (0.00064(±0.00018) Bq/g-Ni). The $^{58}$Co/Ni values obtained at WCTL (65 m from PV) are four times as high as those values at TUTB (63 m from PV), though the distances from both sites to UCB are nearly equal. There is a building (the Second Uranium Testing Building, SUTB) between TUTB and UCB, and the reason for the difference in $^{58}$Co/Ni between TUTB (63 m from PV) and WCTL (65 m from PV) is that the fission neutrons were shielded by SUTB. On the other hand, there is no building between UCB and WCTL, but trees of about 10 m high are planted between them. T. Matsuzawa et al.\textsuperscript{18} and J. Takada et al.\textsuperscript{19} reported that the non-uniform spatial distribution of the neutron radiation might result from the complex internal and external structures of the buildings surrounding PV.

The ratios of $^{51}$Cr/Cr and $^{60}$Co/Co in the stainless-steel plate collected at Site-C (270 m east from PV) were 0.057(±0.004) Bq/g-Cr and 0.053(±0.007) Bq/g-Co, respectively. The stainless-steel plate was shared by us and Endo et al., who independently reported that the ratio of $^{51}$Cr/Cr was obtained to be 0.064(±0.011) Bq/g-Cr\textsuperscript{3}. Our result agrees well with the value reported by Endo et al. Cobalt-58 in the stainless-steel plate was barely detected after a long counting time (about 9 days), and the low ratio of $^{58}$Co to Ni was obtained to be 0.00037(±0.00017) Bq/g-Ni. There is no shielding other than trees between UCB and Site-C. The ratio of ($^{58}$Co/Ni)/($^{60}$Co/Co) at Site-A shows a high value of 0.075, but the ratio decreases down to 0.004 and 0.007 at WCTL or at Site-C.

**DISCUSSION**

The relation between the radioactivity of an induced long-life radionuclide and the number of target atoms is

$$D = \int_0^\infty \ln(2) \cdot \frac{T}{T} \cdot N \cdot \Phi(E) \cdot \sigma(E) \, dE,$$

where \(D\) is the radioactivity produced by a reaction (Bq), \(T\): the half-life of the radionuclide (s), \(N\): the number of target atoms, \(\Phi(E)\): the neutron fluence (cm$^{-2}$), and \(\sigma(E)\): the neutron cross section (cm$^2$). Although the cross sections are available in the literature, the neutron fluence and...
the energy distribution depend on the shielding and the distance between the neutron source and the target material. Neutron-transfer calculations were performed for the JCO criticality accident using a Monte-Carlo code by T. Imanaka\textsuperscript{20} and S. Endo et al.\textsuperscript{21}; they estimated the neutron doses for various places by reference to the radioactivity of induced radionuclides. Imanaka\textsuperscript{20} calculated the neutron energy distribution for the closest site, 2.0 m from the center of PV, where the mesh screen of stainless steel was collected; the total number of fission events was calculated to be $2.5 \times 10^{18}$ by referring to our data of the induced radioactivity. This result is in good agreement with that in the final report of the Japanese Nuclear Safety Committee\textsuperscript{22}. The neutron fluence at Site-A was concurrently evaluated to be $4.8 \times 10^{12}$ cm$^{-2}$ by the above-mentioned calculation methodology. The neutron FIA KERMA at Site-A is estimated to be 57 Gy on the basis of the calculated neutron fluence, the calculated neutron energy distribution and the neutron fluence-to-KERMA factors in the literature\textsuperscript{23}. The observed concentrations of $^{51}$Cr, $^{54}$Mn, $^{59}$Fe, $^{58}$Co and $^{60}$Co are well reproduced by this calculation\textsuperscript{20}. We can conclude that the Monte-Carlo calculation by Imanaka is entirely successful, because both the (n, p) reaction and (n, $\gamma$) reaction products were fully reproduced by the calculation\textsuperscript{20}. This calculation will be applicable to an estimation of the neutron doses for the exposed employees who worked around the precipitation vessel.

As described above, satisfactory results for estimating the neutron dose have been obtained in the vicinity of the precipitation vessel. An attempt by Imanaka has been made to simulate the behavior of neutrons up to 20 m around the Uranium Conversion Building\textsuperscript{20}. Although those calculations are considered to be successful in reproducing the radioactivities of the (n, $\gamma$) reaction products, the calculated results were larger than our observed values for the iron bolt collected 7.8 m from PV by a factor of about three. A more refined calculation may be needed, which includes appropriate shielding conditions between UCB and the sampling places. The neutron doses were estimated for further distances from 130 m to 450 m on the basis of the measurement of $^{51}$Cr and the Monte-Carlo calculation\textsuperscript{21}. An accurate and precise determination of $^{58}$Co in the stainless-steel plate collected at Site-C (270 m east from the criticality accident site) is essential for a proper extension of the calculation methodology to distal places.

**ACKNOWLEDGEMENT**

The authors express thanks to members of the Japanese Research Group for the Environmental Impact of the JCO Criticality Accident '99 Tokai for their encouragement throughout the work. This study was carried out in part under the Visiting Researcher’s Program of Research Reactor Institute, Kyoto University. This work was partly supported by a Grant-in-Aid for Scientific Research from the Ministry of Education, Science, Sports and Culture, Japan (No. 10480024).

**REFERENCES**

1. Koide, H., Imanaka, T., Kobayashi, K. and Ogino, K. (2000) Radioactive contamination from the JCO criticality accident. J. Environ. Radioactivity 50: 123–130.
2. Kofuji, H., Komura, K., Yamada, Y. and Yamamoto, M. (2000) An estimation of fast neutron flux by $^{35}$Cl(n, α)$^{32}$P reaction. ibid., 50: 49–54.
3. Endo, S., Tosaki, N., Shizuma, K., Ishikawa, M., Takada, J., Suga, S., Kitagawa, K. and Hoshi, M. (2000) Radioactivity of $^{51}$Cr in stainless steel collected from residence in the JCO neighborhood. ibid., 50: 83–88.
4. Murata, Y., Muroyama, T., Kofuji, H., Yamamoto, M. and Komura, K. (2000) Neutron-induced radionuclides in soil from the JCO campus by non-destructive γ-ray spectrometry. ibid., 50: 69–76.
5. Nakaniishi, T., Hosotani, R., Komura, K., Muroyama, T., Kofuji, H., Murata, Y., Kimura, S., Sahoo, S. K., Yonehara, H., Watanabe, Y. and Ban-nai, T. (2000) Residual neutron-induced radionuclides in a soil sample collected in the vicinity of the criticality accident site in Tokai-mura, Japan: A progress report. ibid., 50: 61–68.
6. Komura, K., Yousef, A. M., Murata, Y., Mitsugashira, T., Seki, R. and Imanaka, T. (2000) Activation of gold by the neutrons from the JCO accident. ibid., 50: 77–82.
7. Kohno, M. and Koizumi, Y. (2000) Neutron dose estimates from 5-yen coins. Nature 406: 693.
8. Kojima, S. and Furukawa, M., (1986) The measurement of neutron-induced radionuclides from Chinese nuclear weapons tests. J. Radioanal. Nucl. Chem. Articles 100: 231–240.
9. Furukawa, M and Kojima, S. (1991) Time variations of artificial radionuclides concentrations in the air over Japan since 1974. Radiochim. Acta. 62: 163–173.
10. Nakanishi, T., Imura, T., Komura, K. and Sakanoue, M. (1983) $^{152}$Eu in samples exposed to the nuclear explosions at Hiroshima and Nagasaki. Nature 302: 132–134.
11. Nakanishi, T., Miwa, K. and Ohki, R. (1998) Specific radioactivity of europium-152 in roof tiles exposed to atomic bomb radiation in Nagasaki. J. Radiat. Res. 39: 243–250.
12. Shizuma, K., Hoshi, M. and Hasai, H. (1999) Uncertainties of DS86 and prospects for residual radioactivity measurement. ibid., 40: Suppl., 138–144.
13. Komura, K., Yamamoto, M., Muroyama, T., Murata, Y., Nakaniishi, T., Hoshi, M., Takada, J., Ishikawa, M., Takeoka, S., Kitagawa, K., Suga, S., Endo, S., Tosaki, N., Mitsugashira, T., Hara, M., Hashimoto, T., Takano, M., Yanagawa, Y., Tsuboi, T., Ichimasa, M., Ichimasa, Y., Imura, H., Sasajima, E., Seki, R., Saito, Y., Kondo, M., Kojima, S., Muramatsu, Y., Yoshida, S., Shibata, S., Yonehara, H., Watanabe, Y., Kimura, S., Shiraishi, K., Ban-nai, T., Sahoo, S. K., Igarashi, Y., Aoyama, M., Hirose, K., Uehiro, T., Doi, T., Tanaka, A. and Matsuzawa, T., (2000) The JCO criticality accident at Tokai-mura, Japan: an overview of the sampling campaign and preliminary results. J. Environment. Radioactivity 50: 3–14.
14. JENDL-3.2 (1994) Nuclear Data Center at Japan Atomic Energy Research Institute.
15. Nuclear Safety Commission, Investigation Committee for Criticality Accident at Uranium Processing Plant (1999) Appendix report of Urgent recommendations - Interim report (Nov. 5, 1999) (in Japanese).