Inadvertent Melting of Radioactive Sources in BOF or EAF: Distribution of Nuclides, Monitoring, Prevention

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This report lists the relevant nuclides presently or formerly in use as radiation sources and gives an account of their expected distribution between steel melt, slag, dust and off-gas upon inadvertent meltdown. Three groups of nuclides are identified, namely (a) strong $\gamma$-emitters (Co 60, Kr 85, Cs 137, Ir 192), (b) weak $\gamma$-emitters (Ra 226, Am 241), and (c) $\beta$- and $\alpha$-emitters (Ni 63, Sr 90, Pm 147, Pu 238/239, and Cm 244). Equilibrium distributions based on thermodynamic calculations and experimental investigations are presented.

Combining the equilibrium partition ratios with process-specific effects leads to realistic distribution ratios: The steel melt is expected to contain about 98% of the radioactive Co, Ni, and Ir, while the dust will contain practically all the Cs and about 1% of all the other nuclides except Kr which should completely pass to the off-gas. The slag is expected to contain about 99% of the nuclides Sr, Pm, Ra, Am, Pu and Cm, and about 1% of Co, Ni and Ir dissolved in the suspended metal granules.

The strongly $\gamma$-emitting nuclides can be, and are increasingly, monitored quasi on-line on steel samples taken in the meltshop and, with respect to Cs, in the baghouse. The respective equipment operates reliably and efficiently. An on-line detection of weak $\gamma$-emitters and of $\alpha$- and $\beta$-emitters is technically not possible at present. The steelworks can minimize the risks connected to the inadvertent melt-down of a radioactive $\gamma$-source by introducing three consecutive steps of measures: Prevention by inspection of incoming materials; Inhouse Scrap Monitoring by inspection during transport, and finally Product Control by monitoring of steel samples and in the bag-house.

KEY WORDS: radioactive sources; inadvertent melting in steelworks; nuclide distribution; radiation monitoring; preventive measures; risk assessment.

1. Introduction

For sealed radiation sources widely used in industry, medicine and research, many states have clear regulations concerning the management of disused sources. Once and again, however, disused sources get lost to regulatory control. Since most sealed sources have an outer containment made of steel (Fig. 1), a certain fraction of these “orphan” sources may eventually be discarded as plain steel scrap and be sold to the steel industry.

In a recent study, the number of $\gamma$-emitting sealed sources in use within the European Union has been estimated to be 110 000, while about 30 000 disused sources are held in storage at the users’ premises. According to a report published in 2002 by the (US) National Council on Radiation Protection and Measurements (NCRP), 71 inadvertent melting events had been confirmed from the early 1980s through the year 2000 in 23 countries, with 33 of these events occurring in the United States. Over 20 of the US events were encountered in the steel industry. The most frequently detected radionuclides after inadvertent melting were: Cs 137 (41%), Co 60 (18.5%), Ra 226 (7%) and Am 241 (6.5%).

The present paper lists the relevant nuclides presently or formerly in use as radiation sources and reports on their expected distribution between steel melt, slag, dust and off-gas upon accidental melt-down. The relevant nuclides are Co 60, Ni 63, Kr 85, Sr 90, Cs 137, Pm 147, Ir 192, Ra 226, Pu 238/239, Am 241, Cm 244. Equilibrium distributions based on thermodynamic calculations and experimental investigations are presented for Co, Ni, Sr, Cs, La (sub-
stituting Pm), and U (substituting Ra, Am, Pu and Cm).

2. List of Relevant Nuclides

All nuclides that are or have been used as sealed radiation sources in industry, research and medicine have been taken into account. The relevant nuclides are listed in Table 1.

Among them, plutonium and radium are not any more or only rarely used, and nickel and promethium have only limited applications. The others are frequently used in medicine, as thickness and level gauges, for weld tests and crack inspection, as smoke detectors or as radionuclide batteries. Their half-lives vary between 0.2 (Ir 192) and 24,110 (Pu 239) years. According to the type of radiation, the nuclides under consideration can be classified into three groups, namely

– strong γ-emitters (Co 60, Kr 85, Cs 137, Ir 192),
– weak γ-emitters (Ra 226, Am 241),
– β- and α-emitters (Ni 63, Sr 90, Pm 147, Pu 238/239, Cm 244).

3. Equilibrium Calculations

Partition ratios were determined by thermodynamic calculations taking into account the steel melt, the slag phase and the vapour phase. For Kr and Ir, no calculations were made because Kr as a noble gas can be expected to completely pass to the gas phase and finally to the cleaned off-gas, and Ir as a noble metal with a very low vapour pressure to totally be dissolved in the steel melt.

For several nuclides, thermodynamic data were not available to the extent required to describe their partition ratios. They have therefore been substituted by chemically related elements with better known thermodynamic data. Promethium as a lanthanide was replaced by lanthanum, and the actinides americium, plutonium and curium as well as radium were substituted by the more thoroughly investigated actinide uranium.

As a common basis for the calculations, a steel melt with 0.07 wt% C, balance Fe, and a slag with 49 wt% CaO, 43 wt% Al2O3 and 8 wt% SiO2 plus variable FeO contents up to 10 wt% with a slag to metal ratio of 133 : 1 000 were assumed. The partition ratios of the nuclides or of their respective substitutes were calculated for a content of 3 wt% of these nuclides in the scrap.

At RWTH Aachen, the equilibrium calculations were carried out with the program package ChemSage which is based on the SOLGASMIX Gibbs energy minimizer and is designed to take into account complex systems involving phases with nonideal mixing properties.5) The thermodynamic models used were the Wagner unified interaction parameter formalism for dilute solutions (for the steel melt), the Blander-Pelton quasichemical formalism for ionic liquids (for the slag), and the ideal mixing model for the gas phase.

To predict the partition ratios of the elements under consideration (Co, Ni, Sr, Cs, La and U), a thermodynamic database was set up making use of the SGTE Pure Substances database6) and the FACT database7) which covers the regular steelmaking components in the gas, the liquid metal and the liquid slag phases.

For the present purpose, additional thermodynamic information had to be collected or assessed to calculate the partition ratios in question with appropriate accuracy:

The Metal Phase: Data for the elements Sr and Cs in the liquid iron phase have been added taking them as pure liquids and estimating the interactions using the Miedema method8) for $\Delta H^\infty$ together with Kubaschewski’s $\Delta H = 3 \cdot 400 \cdot \Delta S$ rule. These estimates result in strong positive interactions which is in accordance with the phase diagrams Fe–Sr and Fe–Cs. U has been added to the metal phase using information on the Fe–U system available from the thermodynamic database for nuclear chemistry at Thermodata, Grenoble.9) The data for the substitutional model used there have been adjusted to fit the requirements of the dilute solution approach in the present database.

The Slag Phase: CoO, SrO and Cs2O have been added to the slag phase for the present work using the data for the respective pure liquid oxides from the SGTE Pure Substance database. Interaction data for CoO have been included according to the availability of phase diagrams. Mainly CoO–
MeO systems (–SiO\(_2\), –Al\(_2\)O\(_3\), –Fe\(_x\)O, –CaO) were available.\(^{10,11}\) SrO interactions had to be estimated since no phase diagram information was available for the derivation of appropriate data. It was assumed that because of the chemical similarity between Sr and Ca using interactions from the relevant CaO–Me\(_x\)O\(_y\) systems would be a reasonable starting point. On similar grounds Cs\(_2\)O interactions have been taken to be equal to equivalent data for K\(_2\)O stored in the FACT database. La\(_2\)O\(_3\) could be moved from a separate dataset available within the FACT database which covers interactions with Al\(_2\)O\(_3\), SiO\(_2\), and CaO. All other interactions of La\(_2\)O\(_3\) in the slag were taken to be ideal. Information on UO\(_2\) in the liquid oxide phase was available in the thermodynamic database for nuclear chemistry (Thermodata). Again only the phase diagrams calculated with the database could be used as information since the quasi-chemical model for the liquid slag used in the present work is not directly compatible with the associated solution model used by Thermodata. CsCl has been added to the slag phase using the dilute solution feature that is available for the quasi-chemical interaction model.

4. Calculated Partition Ratios

The results of the equilibrium calculations have been plotted as partition ratios of the respective components between liquid metal, liquid slag, and gas phase for 1500, 1600 and 1700°C as a function of the FeO content in the slag, thus pointing at possible differences between reducing and oxidizing conditions. As typical examples, results for Co, Sr, Cs and U are given in Figs. 2 to 5. The diagrams for Ni and for La may be found in a previous paper.\(^{12}\)

Cobalt clearly concentrates in the steel melt, Fig. 2. The Co content in the slag may reach up to 0.1% in strongly oxidizing conditions. Co is not transferred to the gas phase.

The behaviour of nickel\(^{12}\) is very similar to that of cobalt. The maximum Ni content in the slag is by a factor of 10 lower than that of Co.

Strontium, Fig. 3, is exclusively found in the slag, as expected because of its similarity to calcium. The maximum partition ratio in the metal is 0.001%, in the gas phase 0.008%.

Caesium (Fig. 4) is the only nuclide of Table 1 (apart from krypton) to pass almost completely to the gas phase assuming CsCl as the source compound. Since in fact the chloride is mostly used in Cs sources, this case appears to be the most realistic one. The vapour pressure of CsCl reaches 1 bar at 1314°C. On cooling of the off-gas, CsCl reports to the dust, because at 100°C, its vapour pressure is only 10\(^{-11}\) bar. With other (less volatile) Cs compounds (like sulphates or hydroxides) the partition ratio between slag and vapour phase is closer to 1. The steel melt is always free of Cs.

The partition calculations for lanthanum (which substitutes Pm) show that La is completely absorbed by the slag.\(^{12}\) The amounts expected to be transferred to metal and gas phase are in the range of a few ppm.
The results obtained for uranium (Fig. 5) are very similar to those for La: Again, this element is predicted to concentrate completely in the slag, only traces to be found in the metal and the vapour phases. The U results are taken as representative for the nuclides Ra, Pu, Am and Cm.

With respect to the partitioning of the nuclides under consideration, the thermodynamic calculations carried out by RWTH have led to the result that the respective nuclide should definitely concentrate in one phase only and not dissipate among the phases to any noticeable degree. Co and Ni should pass to the metal phase, Cs (when present as chloride) to the vapour phase (and after cooling to the dust), while all other nuclides (Sr, Pm, Ra, Am, Pu, Cm) should exclusively pass to the slag phase.

5. Additional Thermodynamic Calculations

At HUT Finland, thermodynamic data have been searched from the literature and from relevant databases and used in addition to the RWTH database made for this project. In some cases, assessments were carried out to predict phase equilibria relevant to nuclide distribution calculations. The software used were HSC Chemistry 4.0, a thermodynamic calculation program developed at Outokumpu Research Oy, and the FactSage package by GTT.

Equilibrium distributions of selected radioactive elements between steel melt, slag and gas phase were calculated. Ni, Co and Cs were most thoroughly investigated. For several nuclides of the lanthanide and actinide groups where the thermodynamic data are still not completely known, substitutes have been selected for the calculations: Pm, Am and Cm were replaced by La, and Pu by Zr.

The basic slag system for equilibrium calculations for CoO was CaO-CoO-SiO$_2$, which was evaluated and calculated in this project. Figure 6 shows the calculated ternary system based on evaluated parameters at 1600°C. The distribution calculations showed that both Ni and Co pass almost entirely to the metal phase. Only fractions of $10^{-4}$ (Ni) and $10^{-3}$ (Co) may be found in the slag, and evaporation is negligible. On the other hand, Cs is not found in the metal phase at all. In the HUT calculations, 80% of the Cs partition to the vapour phase, and 20% to the slag phase. This result applies to slightly oxidizing conditions and to Cs$_2$O as starting compound (or CsOH, Cs$_2$CO$_3$ or Cs$_2$SO$_4$). It should be noted that with CsCl as additive, the volatility of Cs is much higher, and practically 100% of the incoming Cs partition to the vapour (and to the dust upon cooling).

Calculations with Sr, Zr and La have shown that these elements tend to form very stable oxides which pass entirely to the slag phase.

6. Laboratory Tests on Nuclide Distribution

At ACERINOX, non-radioactive isotopes of Co, Sr and Cs have been used to determine the distribution ratios in the different phases in laboratory induction furnaces. The base material was austenitic stainless steel 18Cr8Ni, the slag contained (in wt%) 39.2 CaO; 31.2 SiO$_2$, 7.5 MgO; 6.8 Al$_2$O$_3$; 6.8 Cr$_2$O$_3$; 2.4 MnO; 2.0 TiO$_2$. The isotopes were added as Co metal powder, as SrCO$_3$, and as CsCl, respectively.

In a 50 g furnace, 40 g of stainless steel, 5 g of slag and
0.1 g of Co were melted in crucibles made of 68% SiO₂; 17% SiC and 14% Al₂O₃. Analyses of the metal phase, the slag and the crucible and a thorough mass balance led to the conclusion that Co passed completely to the metal phase. Any Co found in the crucible and in the slag could be identified as adhering or suspended metal droplets. Figure 9 shows metal droplets trapped in stainless steel slag both in laboratory and in production scale.

The Sr distribution was tested in a 50 g and a 1 kg induction furnace. In the latter furnace, 225 g of stainless steel, 25 g of slag, and 1 g of Sr as SrCO₃ were melted. During these tests, the fumes were also collected, weighed and analyzed. While in a SiC-containing crucible a chemical reaction between SrO and the crucible appeared to take place, there was no reaction between SrO and another, SiC-free crucible. Then, the Sr added passed completely to the slag phase. There were no traces of Sr neither in the metal nor in the fumes.

Caesium was added to the metal–slag mixture as CsCl, and both the 50 g and the 1 kg furnace were used. Again, the fumes were collected for analysis. The tests confirmed that Cs does not alloy with steel and does not appear in the slag. Cs was observed to partition to the fumes (64%) and to the crucible (36%), no matter which crucible was used. Further analyses showed that Cs was present in the fumes and the crucibles as CsCl, again.

The relatively high content of CsCl in the crucible has not yet been fully understood. The other laboratory results obtained at ACERINOS are in full agreement with the respective thermodynamic calculations carried out by RWTH Aachen and HUT Finland.

7. Realistic Distribution Ratios

Due to incomplete phase separation, a small amount of liquid metal typically remains suspended in the slag when the slag is removed from the furnace, see Fig. 9. Although this amount varies with the slag to metal ratio, with the slag viscosity and its temperature during deslagging, an average of 1% appears to be a realistic value for the metal to be found as granules in the slag. A greater part of this metal is often recovered during subsequent slag beneficiation.

Another cause for deviations of the realistic element distribution from the equilibrium partition ratios is the interaction of gas bubbles rising to the surface of a melt. The effect called bubble bursting produces extremely small droplets which are easily carried up with the gas flow forming very fine off-gas dust both in BOF and in EAF steelmaking. Again, about 1% of the metal and the slag are typically transferred from the steel and slag melt to the dust.

Combining the equilibrium partition ratios with these process-specific effects leads to realistic distribution ratios as they are expected to be observed in operating steelworks, in case that one of the nuclides under consideration happens to be melted down in an EAF or a BOF, Table 2.

According to Table 2, the steel melt is expected to contain about 98% of the radioactive Co, Ni, and Ir, while the dust will contain practically all the Cs and about 1% of all the other nuclides expect Kr which should completely pass to the off-gas. The slag is expected to contain about 99% of the nuclides Sr, Pm, Ra, Am, Pu and Cm, and about 1% of Co, Ni and Ir dissolved in the suspended metal granules.

| Nuclide | Radiation | Melt | Slag *) | Dust **) |
|---------|-----------|------|---------|---------|
| Co 60   | γ (β)     | 98   | 1       | 1       |
| Ni 63   | β         | 98   | 1       | 1       |
| Kr 85   | γ (β)     | -    | - 100 gas | 99       |
| Sr 90   | β         | -    | 99       | 1       |
| Cs 137  | γ (β)     | -    | < 1 > 99 *** | 1       |
| Pm 147  | β         | -    | 99       | 1       |
| Ir 192  | γ         | 98   | 1       | 1       |
| Ra 226  | α (γ)     | -    | 99       | 1       |
| Pu 238, 239 | α | -    | 99       | 1       |
| Am 241  | α (γ)     | -    | 99       | 1       |
| Cm 244  | α         | -    | 99       | 1       |

*) about 1% of the metal is lost to the slag as suspended granules.
**) about 1% of metal + slag ends up in the dust as fine droplets via bubble bursting.
***) when in the source as CsCl

Table 2. Realistic distribution ratios expected for the nuclides listed in Table 1 upon inadvertent meltdown in the EAF or BOF.
8. Operational Observations on Nuclide Distribution

A recent US-EPA report contains a literature survey on observed distributions of a number of nuclides including Co, Ni, Cs, Am, Ra and U. In most cases, the results support the predictions of thermodynamics or—when plant measurements were made—those of the "realistic distributions."

For Cs, the report contains several references that reflect the different behaviour of CsCl as compared to CsOH and Cs$_2$SO$_4$. The chloride was found to volatilise completely and to pass to the dust, while the other Cs compounds tend to partition between slag and dust depending on the specific compound and on the slag basicity. Most investigations confirmed that no Cs was ever found in the steel phase.

As the oxides of the heavy nuclides, (Am$_2$O$_3$, PuO$_2$, Cm$_2$O$_3$, Ra$_2$O$_5$) have very high densities of 11 to 12 g/cm$^3$, they may fall to the furnace bottom before having dissolved in the slag. However, no practical evidence has been reported in the literature to this point.

Siempelkamp Nukleartechnik has gained experience concerning the distribution of nuclides from melting radioactively contaminated steel scrap in their 3.2 t medium frequency induction furnace (“CARLA”) designed to melt and handle slightly radioactive scrap with a specific activity up to 200 Bq/g. Since the mid-1980s, about 16 000 t of scrap have been melted in the CARLA facility up to now. The distribution of nuclides was regularly measured by means of γ-spectroscopic methods. α- and β-emitting nuclides are analyzed in external laboratories, or their distribution is calculated based on experimental data.

A recent evaluation of these distributions with respect to nuclides that are also used as radiation sources is summarised in Table 3. As expected, Am, Pu, and Sr partitioned to the slag. Co and Ni were mainly transferred to the steel melt, but about 10% found in the slag. This fraction is interpreted as high content of metal granules in the slag. The Cs distribution is typical for non-chloride Cs compounds.

The nuclide distributions for uranium and radium contained in Table 3 have recently been measured at Siempelkamp on the occasion of two special melting campaigns: (1) 28 t of scrap from pipelines for gas extraction contaminated with Ra 226, and (2) more than 2 000 t of uranium- and MOX-contaminated steel scrap from dismantled fuel fabrication plants. Both oxides, UO$_2$ and Ra$_2$O$_5$, reported to the slag with small amounts found in the dust as expected, and small fractions attributed to the steel melt which can be interpreted as slag particles contained in the steel samples. A mass balance made for uranium showed that the UO$_2$ added as a powder did not collect at the furnace bottom but dissolved in the slag. The results summarised in Table 3 are exclusively based on spectroscopic radioactivity measurements.

9. Limits of Detection

Of the nuclides under consideration, strong γ-emitters are Co 60, Kr 85, Cs 137 and Ir 192, while Ra 226 and Am 241 are weak γ-emitters. The group of α- and β-emitters without any noticeable γ-component comprises Ni 63, Sr 90, Pm 147, Pu 238/239, and Cm 244.

With presently available technology, the on-line radiation detection is restricted to strong γ-emitters. They are Co 60 and Ir 192 concentrating in the steel melt, Kr 85 passing to the off-gas, and Cs 137 that partitions to the vapour phase and after cooling to the dust. The respective monitoring equipment operates reliably and efficiently.

The weak γ-emitters considered here pass to the slag phase. They are Ra 226 and Am 241. Their monitoring is not state-of-the-art because of the difficulties and uncertainties connected to identifying weak γ-radiation from continuously taken slag samples.

β- and α-emitters without any noticeable γ-component cannot be detected on-line, because their spectroscopic analysis requires lengthy sample preparation and measuring procedure. The most important nuclides in this group are Sr 90 and Cm 244 both concentrating in the slag.

To summarize, an on-line detection of weak γ-emitters and of α- and β-emitters is technically not possible at present.

10. Risk Assessment for the Relevant α- and β-Emitters

For the β-emitting Sr 90 and the α-emitter Cm 244, a risk assessment has been carried out on the basis of specific data presented in a recent US-EPA report. For these short-range emitters the most critical contamination path for humans is their incorporation into the human body. A conceivable pathway starts with the use of BOF slag as limiting agent of the soil in agriculture. This widely applied practice consumes about 20% of the European BOF slag.

The pathway of the nuclides consists of the steps slag→soil→crop→food→human body.

The specific radioactivity dose $D_{pec}$ that becomes effective in the human body according to this pathway has been estimated to be:

| Nuclide | Distribution ratio, % | Comments |
|---------|-----------------------|----------|
| Co 60   | 88 11 1              | suspended metal in slag |
| Ni 63   | 90 10  -             | suspended metal in slag |
| Sr 90   | <1 97 2              |          |
| Cs 137  | <1 60 40             | Cs not present as chloride |
| Ra 226  | 3.2 95.7 1.1        |          |
| U 235, U 238 | 1.3 94.9 3.8 | depleted U added as oxide powder* |
| Am 241  | 1 99  -              | no dust samples taken |
| Pu 242  | 1 99  -              | no dust samples taken |

*) to fulfill the requirements of the German Atomic Act.
\[ D_{\text{spec}}(\text{Sr 90}) = 1.16 \cdot 10^{-3} \text{ mSv/a per Bq/g} \]
\[ D_{\text{spec}}(\text{Cm 244}) = 4.89 \cdot 10^{-3} \text{ mSv/a per Bq/g} \]

The unit Sv (Sievert) is the energy released in the human body per kg of tissue ("dose") with 1 Sv = 1 J/kg. The unit Bq (Becquerel) is the activity of the nuclide with 1 Bq = 1 transition/s (the former activity unit was Ci (Curie) with 1 Ci = 3.7 \cdot 10^{10} \text{ Bq}).

Assuming a BOF shop that produces 300 t heats of steel with 30 t of slag, we consider an inadvertent melting event of a radioactive source that may have the maximum commercially available activity, namely

\begin{itemize}
  \item Sr 90 with 3.7 GBq and
  \item Cm 244 with 110 GBq, respectively.
\end{itemize}

One such source passing to 30 t of slag yields an activity, specified per g of slag, of

\begin{itemize}
  \item 123 Bq/g for Sr 90, and
  \item 3 667 Bq/g for Cm 244.
\end{itemize}

If we assume one such melting event per year, we obtain the annual dose on the individual by multiplying the specific dose with the specific activity in the slag:

\[ D(\text{Sr 90}) = 143 \mu \text{Sv/a}, \text{ and} \]
\[ D(\text{Cm 244}) = 179 \mu \text{Sv/a}, \text{ respectively.} \]

The general limit for the population has been set by the European Basic Safety Standard for Radiation Protection to be 1 000 \mu \text{Sv/a.}

As long as such melting events of Sr or Cm sources remain rare (in the order of one event per year and location) the radiation risk caused by the incorporation of these nuclides via the food chain can be classified as negligible.

11. Three-step Concept for Radiation Monitoring

Steelworks can minimize the risks connected to the inadvertent melt-down of a radioactive source by introducing three consecutive steps of measures as shown in Fig. 10:

- Prevention (Inspection of incoming materials, training and information of workforce),
- In-house Scrap Monitoring (Inspection during transport), and
- Product Control (Monitoring of steel samples and of the dust).

Preventive measures are of paramount importance to detect any potential radioactive contaminant in the incoming scrap before melting. The first step is now being applied in most steelworks in the EU. The second step increases the chance of detecting hidden sources because the scrap is moved and less closely packed. It is already applied in a number of steelworks and is recommended as an efficient additional measure to detect nuclides before melting, see Fig. 11.

As an example, ACERINOX has installed radiation detectors
- at the weigh bridge of their main entrance,
- at the weigh bridges and at the grab crane of their harbour, and
- at the scrap load pits of their three EAFs.

Step no. 3, on-line product monitoring, is needed for immediate response to any inadvertent melting event in order to be able to react quickly and competently and to minimize the potential risk of contamination of individuals and of the plant.

Steel samples taken from each heat for chemical analyses can regularly be subjected to radiation monitoring in the meltshop lab. Dust monitoring can either be done in the off-gas duct or with freshly collected dust during transport. As an example, ACERINOX carries out radiation monitoring

\[ \text{Prevention (Incoming Materials Inspection, Education / Information)} \]
\[ \text{In House Scrap Handling (Inspection of Transport Sequences)} \]
\[ \text{Product Control (Sample Measurement, Dust Inspection)} \]

Fig. 10. Three-Step concept for radiation monitoring in steelworks.

Fig. 11. Examples for in-house monitoring: Wireless grapple/magnet detection (left) and charge bucket detection systems (right).
of all steel samples in their meltshop lab and off-gas monitoring at their EAF no. 3.

12. Conclusions

With presently available technology, the on-line radiation detection is restricted to strong γ-emitters.

The relevant strong γ-emitters are:
- Co 60 and Ir 192 concentrating in the steel phase,
- Kr 85 passing to the gas phase, and
- Cs 137 concentrating in to the dust.

With regard to these γ-emitters a three-step inspection should become standard throughout the steel industry:
1. Inspection of incoming materials,
2. Scrap inspection during in-house handling,
3. On-line product monitoring of steel samples and of off-gas or dust.

The weak γ-emitters are Ra 226 and Am 241. Both partition to the slag phase. Their monitoring is not state-of-the-art because of the difficulties and uncertainties connected to identifying weak γ-radiation from continuously taken slag samples.

The α- and β-emitters are Ni 63, Sr 90, Pm 147, Pu 238/239, and Cm 244. Of these, strontium 90 and curium 244 are widely used. Such nuclides without any noticeable γ-component in their radiation can not be detected on-line, because their spectroscopic analysis requires lengthy sample preparation and measuring procedure.

In this context, it should be kept in mind that the primary responsibility for the safe handling of radioactive sources throughout their complete life cycle is not with the steelmakers but with the producers and the users of these sources. Global regulations and control managements1,2) must become sufficiently strict and efficient that “lost” sources cannot find their way into steel meltshops anymore.

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