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1 **A comparative study using liquid scintillation counting**
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14 **A comparative study using liquid scintillation counting**
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23 **Abstract**

24 A comparative study using liquid scintillation counting was performed to measure ^{63}Ni in
25 low and intermediate level radioactive waste. Three dimethylglyoxime (DMG)-based
26 radiochemical procedures (solvent extraction, precipitation, extraction chromatography)
27 were investigated, the solvent extraction method being considered as the reference
28 method. Theoretical speciation calculations enabled to better understand the chemical
29 reactions involved in the three protocols and to optimize them. In comparison to the
30 method based on DMG precipitation, the method based on extraction chromatography
31 allowed to achieve the best results in one single step in term of recovery yield and
32 accuracy for various samples.

33 **Keywords**

34 ^{63}Ni , radiochemical analysis, liquid scintillation counting, decommissioning, radioactive
35 waste, dimethylglyoxime

36 **Introduction**

37 In France, the National Radioactive Waste Management Agency (ANDRA) is in
38 charge of the long-term management of all radioactive waste. Several repository sites
39 have been built in order to accommodate nuclear waste packages. One is dedicated to the
40 Low and Intermediate Level short-lived Waste. The specifications for 143 radionuclides
41 have been defined by ANDRA which guarantees the safety of the facility [1]. Among this
42 long list, ^{63}Ni has to be declared as soon as its activity concentration is over 1 Bq g^{-1} and
43 its maximum acceptance limit has been fixed to $3 \times 10^6 \text{ Bq g}^{-1}$ [1]. ^{63}Ni is produced by
44 neutron activation reactions of stable Ni and Cu which are components of various
45 materials used in the nuclear fuel cycle [2]. Consequently, ^{63}Ni can be present in many
46 radioactive materials and waste samples [2-17], such as graphites [6, 7], metals
47 (aluminium, lead, steel) [6-11], concretes [6, 7, 10, 12], ion-exchange resins and
48 charcoals [13], effluents [8, 14-17], sludges [14] and environmental samples [10, 18].

49 ^{63}Ni is a long-lived radionuclide with a half-life of 98.70 years (± 24) [19]. It is a pure
50 beta emitter with a maximum energy of 66.98 keV [19]. As liquid scintillation counting
51 (LSC) has a high counting efficiency for ^{63}Ni (around 70 %) [2], this detection technique
52 is widely used for ^{63}Ni determination [2-17]. As a pure beta emitting radionuclide, ^{63}Ni
53 must be isolated from the matrix and the interfering radionuclides (especially ^{60}Co a
54 major radionuclide which has a similar chemical behavior) through chemical separations
55 prior to any analysis by LSC [2-17]. Consequently, a selective radiochemical method is
56 needed to measure ^{63}Ni in low and intermediate level radioactive waste [2-18]. Most
57 procedures of ^{63}Ni purification rely on the complexing agent of dimethylglyoxime
58 (DMG) implemented in three different types of methods: solvent extraction, precipitation
59 and extraction chromatography [2-18]. In all cases, the $\text{Ni}(\text{DMG})_2$ complex is favourably
60 formed at basic pH, around 8-9 [2-18]. The recovery yield of the overall radiochemical
61 procedure is generally determined from the measurement of stable Ni by atomic
62 absorption spectroscopy (AAS) [12] or inductively coupled plasma - atomic emission
63 spectroscopy (ICP-AES) [5, 13, 15, 17].

64 Two or three decades ago, the reference radiochemical method to analyse ^{63}Ni was
65 based on a liquid-liquid extraction procedure. The $\text{Ni}(\text{DMG})_2$ complex is first extracted
66 in an organic solvent [20], commonly chloroform [8, 10, 11, 18, 20] which has a higher
67 Ni extraction capacity [20]. Ni is then back-extracted in aqueous solution, mostly with
68 hydrochloric acid [11, 16, 18]. In France, this extraction method has been standardized in
69 the standard NF M60-317 to determine ^{63}Ni in radioactive effluents and waste [21]. Ni
70 amount is generally less than 1 mg [8, 18, 20] whereas the DMG amount varies from 10
71 mg [20] to 250 mg [8]. By replicating several extractions, this type of separation
72 procedure enabled to achieve satisfactory decontamination factors of Co towards Ni (less
73 than 0.2% of Co was extracted) [8]. In spite of its efficiency, the implementation of this
74 solvent extraction procedure has tended to decrease in the last decades because of the
75 restrictions of chloroform use, notably through the European REACH regulation [22].

76 An alternative method to solvent extraction is the precipitation of the $\text{Ni}(\text{DMG})_2$
77 complex [4, 9, 12-14]. The French standard NF M60-317 also includes this alternative
78 option as a second ^{63}Ni purification method [21]. When the total activity concentrations
79 of the other radionuclides are 10 times higher in comparison to ^{63}Ni , this standard
80 indicates the necessity to perform a second precipitation step [21]. Higher Ni amount is
81 added (around 2 or 3 mg) [12-14] whereas the DMG amount varies from 50 mg [12, 13]
82 to 200 mg [21] to favour the precipitation of the $\text{Ni}(\text{DMG})_2$ complex, in comparison to
83 the solvent extraction method. Prior to LSC, the precipitate is destroyed to recover ^{63}Ni in
84 solution by using concentrated nitric acid [4, 9, 12, 13] or hydrogen peroxide [14]. The
85 procedure based on $\text{Ni}(\text{DMG})_2$ precipitation has been applied for the measurement of
86 ^{63}Ni in various radioactive matrices [4], such as metals [9], concretes [12], ion exchange
87 resins [13] and sludges [14]. However, the destruction of $\text{Ni}(\text{DMG})_2$ precipitate appears
88 to be a delicate and fastidious step before LSC analysis [21].

89 To overcome these above problems, the technique of extraction chromatography
90 based on the Eichrom $\text{Ni}^{\text{®}}$ resin has been developed to isolate Ni from the interfering
91 elements [23]. Some authors also prepared in-house Ni resins which relies on the same
92 principle [15, 27]. Indeed, over the past 20 decades, extraction chromatography has
93 become a leading technique for separation and preconcentration of radionuclides in the

94 environmental, biological and nuclear fields [24, 25]. The combination of an organic
95 extractant coated on an inert support delivers the selectivity of solvent extraction with the
96 ease of use of resin based methods. In the case of Ni resin, the DMG extractant is coated
97 on an inert support of acrylic ester based-resin [23]. As relatively high amounts of DMG
98 and Ni are involved (respectively 50 mg and 2 to 3 mg for a 2 mL pre-packed column
99 [23]), on-column precipitation of Ni with DMG occurs on Ni resin [23]. Elimination of
100 the interfering elements is mainly achieved with ammonium citrate during the rinsing
101 step. Then, Ni is generally stripped from the column using nitric acid [23, 26]. In recent
102 years, many radiochemical procedures based on Ni resin have been applied on many
103 nuclear materials [5, 6, 12, 13, 15, 17, 27].

104 DMG is an effective and selective complexing agent of Ni but also of other metal
105 elements, such as Co, Cu, Cd and Pd [28], which can induce interferences for ^{63}Ni
106 purification. Indeed, the ^{60}Co activation product is often present in substantial amounts in
107 radioactive materials in comparison to ^{63}Ni . Correlation factors between ^{63}Ni and ^{60}Co
108 highly depend on the types of nuclear plants and samples [29]. In CEA France, the third
109 quartile of $^{63}\text{Ni}/^{60}\text{Co}$ ratio has been determined at 0.4 in solid radioactive waste.
110 Consequently, from the literature, it is frequently necessary to complete the purification
111 step based on DMG with other separation procedures so as to eliminate Co efficiently. In
112 the French standard NF M60-317, the elimination of Co is achieved with a preliminary
113 liquid-liquid extraction step based on the use of 2-nitroso-1-naphthol [21]. In this
114 standard, it is recommended to implement this Co solvent extraction when the total
115 activity concentrations of the other radionuclides are 10 times higher in comparison to
116 ^{63}Ni [21]. Furthermore, the presence of ^{55}Fe , another significant activation product, can
117 also hinder the formation of $\text{Ni}(\text{DMG})_2$ complex/precipitate because of its precipitation at
118 basic pH [23, 26]. Organic complexing agents, such as citric acid [6, 12, 21], tartaric acid
119 [9, 21] or oxalic acid [5] are generally introduced to prevent the precipitation of Fe and
120 the other metal elements at basic pH. However, their chelating properties may not be
121 sufficient in case of high Fe amounts, such as in steels [6, 28]. Consequently, it is also
122 highly recommended to remove Fe to achieve accurate ^{63}Ni measurements. Precipitation
123 with ammonia [12-16, 18] or hydroxide [6, 14] and anion exchange chromatography [4,
124 5, 9, 10, 11, 14, 15, 17] have been mainly applied in order to eliminate the interfering

125 elements such as Co and Fe. Decontamination factors of 10^5 or higher can be obtained
126 using a combination of these purification methods [2, 6]. In our group, the reference
127 radiochemical procedure to measure ^{63}Ni corresponds to the French standard NF M60-
128 317 [21]. It consists in combining systematically the Co solvent extraction (based on 2-
129 nitroso-1-naphthol) with the Ni solvent extraction (based on DMG). This method has
130 been applied to various radioactive waste samples and in particular to graphites [30, 31].
131 The works reported in the literature generally include several separation steps to analyse
132 ^{63}Ni [4-18] but do not compare different methods of ^{63}Ni determination. So, it is not
133 obvious to choose the most effective and simple procedure for the measurement of ^{63}Ni in
134 various low and intermediate level radioactive waste samples.

135 The aim of this work is to propose a reliable radiochemical method to measure ^{63}Ni in
136 various low and intermediate level radioactive waste with a large range of $^{63}\text{Ni}/^{60}\text{Co}$
137 ratios. For that purpose, the speciation of metal elements (Ni, Co and Fe) is first
138 discussed so as to achieve a better understanding of their behaviours in the chemical
139 reactions involved in the different separation steps. Subsequently, three radiochemical
140 procedures based on the use of DMG complexing agent were applied to different
141 radioactive samples (evaporate concentrates, steels, muds embedded in concretes,
142 effluents, ion exchange resins embedded or not in polymers and graphites). Solvent
143 extraction, precipitation and extraction chromatography based on DMG were compared
144 in terms of recovery yield and accuracy to determine the radiochemical method the most
145 selective in one single separation step.

146

147 **Experimental**

148 **Reagents and equipments**

149 All chemicals (nitric acid, hydrochloric acid, hydrofluoric acid, hydroiodic acid,
150 ammonium hydroxide, hydrogen peroxide, citrate ammonium, sodium citrate, tartaric
151 acid, 2-nitroso-1-naphthol, dimethylglyoxime) were of analytical grade. Ultra-pure water

152 (resistivity 18.2 M Ω cm) was obtained from a Milli-Q purification system (Millipore,
153 France). Anion-exchange resin AG1-X4 (50-100 mesh) was supplied by Bio-Rad
154 Laboratories (France). In-house 0.8 cm x 5 cm columns were prepared with 2 g of AG1-
155 X4 resin. Pre-packed Ni[®] cartridges of 2 mL (100-150 mesh) were purchased from
156 Triskem International (France).

157 All ⁶³Ni measurements were performed with a Tri-Carb liquid scintillation counter
158 (Perkin-Elmer, France). The instrument was calibrated using a certified ⁶³Ni standard
159 (NI63ELSB30 having a massic activity of 4 x 10⁴ Bq g⁻¹ \pm 3.5%) which was purchased
160 from CERCA LEA (France). After the radiochemical procedures, aliquots of 5 mL of the
161 ⁶³Ni purified samples were mixed with 15 mL Ultima Gold[™] LLT scintillation cocktail
162 (Perkin-Elmer, France) in 20 mL polyethylene vials (Perkin-Elmer, France). All
163 measurements of gamma emitting radionuclides were completed using a high purity
164 germanium detector (Canberra, France) which was calibrated with a multi gamma
165 standard (9ML01ELME20) supplied by CERCA LEA (France). Spectral analysis and
166 quantification were carried out with Genie 2000 software. The accuracy of our
167 radiological analyses was previously checked with proficiency tests, in particular with the
168 European Carbowaste project on irradiated graphites [30, 31]. The uncertainties of the
169 ⁶³Ni activities concentrations were calculated according to the standard NF M60-317 [21]
170 by combining the uncertainties associated with the quantities of digested samples, the
171 standards, the recovery yields and the LSC measurements. The overall expanded
172 uncertainties were calculated by using a coverage factor k of 2.

173 Stable Fe, Co and Ni concentrations were measured using an ICP-AES (Inductively
174 Coupled Plasma - Atomic Emission Spectroscopy) Activa M spectrometer (HORIBA
175 Jobin Yvon, Longjumeau, France). External calibration curves were established from ICP
176 standards (SPEX Certiprep, USA). The accuracy of our elemental analyses was
177 previously checked with proficiency tests, in particular those organized by the French
178 CETAMA and AGLAE committees.

179

180

181 Sample preparation and digestion

182 The different radioactive samples were collected in several French nuclear facilities
183 and laboratories. They consisted of the following types of materials: evaporate
184 concentrates, steels, muds embedded in concretes, effluents, ion exchange resins
185 embedded or not in polymers and graphites (denoted from S1 to S8 in this work). They
186 were chosen in order to cover a wide range of $^{63}\text{Ni}/^{60}\text{Co}$ ratios (from 0.3 to 16.4). All
187 samples were digested using a microwave acid digestion system (Speed Wave, Berghof,
188 Germany), except graphites. The digestion conditions were consistent with the French
189 guide NF M60-323 [32]. The evaporate concentrate sample (denoted as S1), the effluent
190 (denoted as S4) and the ion exchange resins embedded or not in polymers (denoted as S5,
191 S7 and S8) were digested with 15 mL of concentrated HNO_3 . The steel sample (denoted
192 as S2) was digested using aqua regia (5 mL of concentrated HNO_3 and 10 mL of
193 concentrated HCl). The muds embedded in concretes (denoted as S3) were digested using
194 a mixing of 10 mL of concentrated HNO_3 and 5 mL of concentrated HF . The graphite
195 samples were digested by using HI in excess and 5 mL of concentrated H_2SO_4 so as to
196 decompose graphite as CO_2 by heating. In all cases, 0.2 g up to 5 g of samples were
197 digested. The resulting solutions were transferred to 100 mL volumetric flasks and
198 diluted with ultra-pure water. Aliquots were prepared for the determination of stable
199 metal elements and gamma emitting radionuclides by ICP-AES and gamma
200 spectrometers respectively. As a function of the ^{63}Ni activity concentrations, 5 mL to 20
201 mL of the digested samples were used for ^{63}Ni purification. The amount of added Ni
202 carrier was then adapted depending on the studied radiochemical methods (from 0.1 mg
203 to 4 mg). As examples, the chemical and radiochemical compositions of two studied
204 samples (S1 and S2) are detailed in Table 1. For S2 steel, ^{55}Fe activity concentration was
205 determined at $7 \times 10^3 \text{ Bq g}^{-1}$ from the French standard NF M60-322 which relies on the
206 solvent extraction of the Fe complex formed with cupferron (N-nitroso-N-
207 phenylhydroxylamine) in chloroform [33].

208

209 Radiochemical separation

210 *Method 1 based on the organic extraction of the Ni(DMG)₂ complex*

211 Method 1 is based on the organic extraction of the Ni(DMG)₂ complex. It
212 corresponds to one of the separation protocols described in the standard NF M60-317
213 [21]. This is the reference radiochemical procedure of our group to measure ⁶³Ni in
214 radioactive waste and effluents [30]. Aliquots of the digested samples were first weighed
215 in a beaker. 0.1 mg of Ni carrier and 0.5 mg of Co carrier were then added. After the
216 addition of 5 mL concentrated HNO₃, the solutions were evaporated to dryness and the
217 residues were dissolved in a few mL of HNO₃. 10 mL of sodium citrate (100 g/L) was
218 then added and the pH of the solutions was adjusted between 3 and 4 with NH₄OH.
219 Afterwards, 1 mL of concentrated hydrogen peroxide was added to oxidize Co. Then, 4
220 mL of an acetic solution of 2-nitroso-1-naphthol (10 g/L) was introduced. As the reaction
221 between Co and 2-nitroso-1-naphthol proceeds rather slowly [34], the solutions were
222 allowed to stand for about 30 min. 3x10 mL of chloroform were then added to extract the
223 Co-nitrosonaphthol complex in the organic phases whereas Ni remained in the aqueous
224 phases. Thereafter, the pH of the solutions was adjusted to 9 with concentrated NH₄OH. 2
225 mL of DMG solution (10 g/L in ethanol) was then added. After a waiting period of 1
226 hour, 3x10 mL of chloroform were added to extract the Ni(DMG)₂ complex. Afterwards,
227 the organic phases were washed with 10 mL of 5 % NH₄OH. Ni was then back-extracted
228 using 3x10 mL of 0.5 M HCl. The obtained solutions were then evaporated to dryness
229 and the residues were dissolved in 10 mL of 0.5 M HCl. Finally, a 5 mL aliquot of the
230 ⁶³Ni purified samples was prepared for LSC as described above.

231 *Method 2 based on the precipitation of the Ni(DMG)₂ complex*

232 Method 2 is based on the precipitation of the Ni(DMG)₂ complex. It is also described
233 in the standard NF M60-317 [21]. As the total activity concentrations of the other
234 radionuclides are not 10 times higher in comparison to ⁶³Ni in the studied samples, only
235 one precipitation step was implemented from the specifications of this standard [21].

236 Aliquots of the digested samples were first weighed in a beaker. 10 mL of a saturated
237 tartaric solution and 4 mg of Ni carrier were then added. The pH of the solutions was
238 adjusted to 9 with concentrated NH_4OH . 5 mL of DMG solution (1% in ethanol) was then
239 added. The obtained solutions were heated at 50°C during 30 min so as to favour the
240 precipitation of the $\text{Ni}(\text{DMG})_2$ complex. The precipitates were collected by filtration and
241 washed with water. Thereafter, Ni was recovered by pouring gently 5 M HCl on the
242 precipitate. Afterwards, the solutions were evaporated near to dryness (otherwise
243 insoluble black residues were obtained as indicated in Ref. [26]). DMG was then
244 decomposed with hydrogen peroxide. Thereafter, the obtained solutions were evaporated
245 to dryness and the residues were dissolved in 10 mL of 0.5 M HCl. Finally, a 5 mL
246 aliquot of the ^{63}Ni purified samples was prepared for LSC as described above.

247 *Method 3 based on the precipitation of the $\text{Ni}(\text{DMG})_2$ complex on Ni resin*

248 Method 3 is based on the precipitation of the $\text{Ni}(\text{DMG})_2$ complex on Ni resin [23]. It
249 corresponds to the radiochemical method described by Eichrom Technologies [26] and
250 applied in many reported works [6, 12, 13, 15, 17, 27]. Aliquots of the digested samples
251 were first weighed in a beaker and 2 mg of Ni carrier were then added. After the addition
252 of 5 mL concentrated HCl, the solutions were evaporated to dryness and the residues
253 were dissolved in a few mL of 1 M HCl. 1 mL of 1 M ammonium citrate (that was
254 preliminary adjusted to pH 8-9 with NH_4OH) was then added. Afterwards, the pH of the
255 solutions was adjusted between 8 and 9 with NH_4OH . The samples were then loaded on
256 the prepared Ni columns. The pre-packed Ni columns were preliminary conditioned with
257 20 mL of 0.2 M ammonium citrate that was adjusted to pH 8-9 with NH_4OH . After the
258 loading of the samples, the Ni columns were rinsed with 20 mL of 0.2 M ammonium
259 citrate (that was adjusted to pH 8-9 with NH_4OH) to eliminate the interfering elements.
260 Thereafter, Ni was stripped with 5 mL of 3 M HNO_3 . Finally, a 5 mL aliquot of the ^{63}Ni
261 purified samples was prepared for LSC as described above. In those conditions, our
262 group checked that the presence of 3 M HNO_3 and DMG did not induce any quenching
263 effect in LSC by performing the protocol with a ^{63}Ni standard. Eichrom Technologies
264 recommend to eliminate Fe prior to the separation on Ni column [26] but no threshold of

265 Fe concentration is indicated. Given the Fe compositions of the studied samples, an
266 additional purification step was introduced only for the steel sample. From the works of
267 Hou et al. and Rajkovich et al. [6, 23], it was decided to implement a separation on the
268 anion exchange AG1-X4 resin before the purification step on the Ni resin. The AG1-X4
269 resin has indeed a higher loading capacity towards Fe (around 15 mg/g resin) in
270 comparison to TRU resin (5 mg/g resin). In concentrated HCl, Co and Fe are fixed on the
271 anion exchange resin whereas Ni is not retained [4, 5, 6, 13, 15-17]. In the case of steels,
272 2 mg of Ni carrier and 1 mg of Co carrier were added to the aliquots of the digested
273 samples. The solutions were evaporated to dryness and the residues were dissolved in 5
274 mL of 8 M HCl. The samples were then loaded on the AG1-X4 columns which were
275 preliminary conditioned with 25 mL of 8 M HCl. After the loading of the samples, Ni
276 was eluted with 5 mL of 8 M HCl. The resulting solutions were then evaporated to
277 dryness and the residues were treated as described above in the protocol dedicated to the
278 Ni columns.

279

280 **Results and discussion**

281 *Speciation studies*

282 A previous work of our group demonstrated the importance of speciation studies in
283 order to achieve a better understanding of the behaviours of the analytes during the
284 different separation steps and to optimize the radiochemical procedures [25]. This
285 approach was also investigated by Roskopfova et al. so as to determine the Ni species in
286 a method dedicated to ^{63}Ni purification in nuclear waste [12]. Nonetheless, Roskopfova
287 et al. did not take into account of all the chemical reagents (such as citrate) and the
288 interfering elements (such as Co and Fe) in their speciation calculations [12], which can
289 influence greatly the speciation results. Indeed, as a pure beta emitter, ^{63}Ni needs to be
290 isolated from the matrix and the interfering elements. Consequently, speciation studies
291 were performed by considering the main chemicals and metal elements involved in the

292 three ^{63}Ni radiochemical methods studied by our group. For that purpose, speciation
293 calculations were made with JChess software (Ecole des Mines ParisTech, France). The
294 database of the software (chess.tdb) was enriched with specific stability constants of Ni,
295 Co and Fe with ammonia, citrate, tartrate and DMG (the stability constants related to
296 hydroxide complexes and precipitates were already included). The relevant stability
297 constants were obtained from Smith and Martell [28]. As citric acid has three acidic
298 functions (the corresponding pKa values are: pKa1 = 3.1, pKa2 = 4.8, pKa3 = 6.4) [28], it
299 was denoted as H_3Cit . In the same way, tartaric acid was denoted as H_2Tart (the
300 corresponding pKa values are: pKa1 = 2.7, pKa2 = 3.7) [28]. Simple calculations were
301 first performed by investigating the behaviours of Ni, Co and Fe in NaOH and NH_4OH .
302 Whatever their quantities, Ni, Co and Fe are predicted to precipitate quantitatively with
303 hydroxide ions by using NaOH. Fe is foreseen to precipitate and can also co-precipitate
304 avec Co in NH_4OH medium, depending on their quantities. With regard to Ni, its
305 predominant species are $\text{Ni}(\text{NH}_3)_x^{2+}$ complexes by using NH_4OH : no significant Ni
306 precipitation is predicted at basic pH. Those results were in agreement with the
307 experimental studies of Hou et al. [6], which proves the reliability of our JChess
308 calculations.

309 The results obtained from JChess software are presented for the S2 steel sample (its
310 chemical composition is given in Table 1) but similar conclusions can be drawn for the
311 other materials, such as the S1 evaporate concentrate. The theoretical distribution
312 diagrams of Ni(II), Co(II) and Fe(III) species are depicted respectively in Figures 1 to 3
313 for method 1. In the case of method 1, after the treatment of the sample in HNO_3 ,
314 sodium citrate was added and pH was adjusted to 3-4 with NH_4OH . From JChess
315 calculations, the predominant Ni(II) species are Ni^{2+} , $\text{Ni}(\text{NO}_3)^+$ and Ni-citrate complexes
316 (NiCit^- and NiH_2Cit^+) at pH 3-4. Those results are consistent with the work of Zelenin et
317 al. who investigated the interaction of the Ni(II) ion with citric acid in an aqueous
318 solution [35]. It is predicted that Co has the same behaviour as Ni at pH 3-4: the
319 predominant Co(II) species are Co^{2+} , $\text{Co}(\text{NO}_3)^+$ and Co-citrate complexes (CoCit^- and
320 CoH_2Cit^+). In those pH conditions, the predominant Fe(III) species are Fe-citrate
321 complexes (FeCit and FeOHCit^-). For method 1, no precipitation is predicted at pH 3-4.
322 Consequently, after the addition of hydrogen peroxide, Co can be complexed by 2-

323 nitroso-1-naphthol and further extracted by chloroform [34], which induces an efficient
324 elimination of Co. From literature [34], Fe can also be partly extracted. In this step, Ni
325 which was not complexed by 2-nitroso-1-naphthol remained in the aqueous phase. The
326 pH of the aqueous solution was then adjusted to 9 with ammonia. The speciation studies
327 indicate that the predominant Ni(II) species are $\text{Ni}(\text{NH}_3)_x^{2+}$ complexes at pH 9, which
328 prevents Ni from precipitating at basic pH. This is not the case for Fe which might start
329 precipitating as Fe_2O_3 hematite when the pH is higher than 6. After the pH adjustment at
330 9, DMG was added. It can be noted that no stability constant was found for Fe with
331 DMG: no stable complex might be formed [28]. On the contrary, the predominant Ni(II)
332 species is the $\text{Ni}(\text{DMG})_2$ complex at pH 9, which is in agreement with Dyrssen et al. [36].
333 Consequently, only Ni can be extracted in the organic phase after the addition of
334 chloroform, which enables a selective purification of Ni for method 1. However, the
335 presence of Fe precipitate might hinder the Ni extraction and induce a slight decrease of
336 Ni recovery yield. Finally, Ni can be back-extracted at low pH in HCl medium for LSC
337 analysis.

338 Concerning method 2, after the addition of tartaric acid and the pH adjustment with
339 ammonia, the same Ni(II) species as above might be observed: the $\text{Ni}(\text{NH}_3)_x^{2+}$ complexes
340 are predicted to be predominant at pH 8-9. In contrast, despite the use of tartaric acid, Co
341 and Fe are foreseen to precipitate as CoFe_2O_4 and Fe_2O_3 at basic pH. The complexing
342 properties of this chelating agent are not sufficient to prevent Co and Fe precipitation in
343 the case of steels (the formation constant of Fe_2O_3 hematite is much greater than the one
344 of FeTart^+ [28]). Afterwards, DMG was introduced in the aqueous solution. Since high
345 amounts of Ni and DMG were used for method 2, the $\text{Ni}(\text{DMG})_2$ precipitate is predicted
346 to be formed. As Co and Fe are present as precipitates in the former step, a co-
347 precipitation with $\text{Ni}(\text{DMG})_2$ might occur. From speciation calculations, the main
348 interfering elements, Co and Fe, are predicted to be not eliminated efficiently with
349 method 2 in the case of a steel sample. Similar results were obtained for the other
350 samples depending on Co and Fe quantities. It can be noticed that this point was not
351 precisely specified in the French standard [21]. After the DMG precipitation step, the
352 precipitate can be dissolved at low pH in concentrated HCl to recover Ni in solution.

353 The distribution diagrams of Ni(II), Co(II) and Fe(III) species related to method 3 are
354 very close to those obtained for method 1 (see Figures 1 to 3). After the addition of
355 ammonium citrate and the pH adjustment with ammonia, the predominant Ni(II) species
356 are $\text{Ni}(\text{NH}_3)_x^{2+}$ complexes at pH 8-9. As the used quantity of citrate is quite low in
357 method 3, at pH 8-9, Co and Fe exist as precipitate of CoFe_2O_4 and Fe_2O_3 in the case of
358 steel sample. Similar conclusions were obtained for the other samples. Consequently,
359 cautiousness has to be taken towards method 3 when Co or Fe are present in the analysed
360 aliquots, which is in agreement with Eichrom Technologies' recommendations [26].
361 After the pH adjustment, the sample was loaded on the Ni resin which was preliminary
362 conditioned with ammonium citrate at pH 8-9. Since high amounts of Ni and DMG are
363 used for method 3, the $\text{Ni}(\text{DMG})_2$ precipitate is predicted to be formed on the Ni column.
364 After the rinsing step of the Ni column, concentrated HNO_3 was introduced. At pH lower
365 than 1, the predominant Ni(II) species is predicted to be Ni^{2+} which allowed the Ni
366 stripping from the column and its further LSC measurement.

367 From the speciation studies, it can be inferred that the behaviours of Ni, Co and Fe
368 strongly depend on the considered purification methods. For method 1, no significant
369 reaction was predicted to hinder the selective isolation of Ni from Co and Fe. On the
370 contrary, Co and Fe might precipitate quantitatively during the different steps of method
371 2 and 3 as a function of their concentrations, but these interfering reactions are predicted
372 to be more pronounced for method 2. For a steel sample, according to JChess
373 calculations, the quantity of the complexing agent (citrate or tartrate) should be increased
374 by a 100 fold factor to prevent any Co and Fe precipitation, which is not convenient in
375 practice. As a consequence, it might be quite difficult to avoid the presence of
376 interferences for ^{63}Ni purification by applying only method 2, in case of high amounts of
377 Co and Fe in the samples.

378

379

380 *Applications of the three DMG-based radiochemical methods to real*
381 *nuclear waste samples*

382 From the literature, it is not obvious to choose the best selective radiochemical
383 procedure based on DMG (solvent extraction, precipitation and extraction
384 chromatography) and to determine if a single separation step can be implemented for
385 nuclear waste samples. For instance, for method 3 based on Ni column, Rajkovich et al.
386 [23] reported a decontamination factor of 100000 for Co. On the other hand, Hou et al.
387 [5] obtained a decontamination factor of 2000 for Co whereas Warwick et al. [15]
388 indicated the presence of 5 % of Co in the Ni purified fractions. To answer this question,
389 the three radiochemical methods based on the use of DMG complexing agent were
390 applied to different types of radioactive waste samples (evaporate concentrates, steels,
391 muds embedded in concretes, effluents, ion exchange resins embedded or not in polymers
392 and graphites). The samples denoted from S1 to S8 were chosen so as to cover a large
393 range of $^{63}\text{Ni}/^{60}\text{Co}$ ratios from 0.3 to 16.4. In those conditions, less than 2 % of Co must
394 be present in the Ni purified fractions so that Co does not induce any interference in LSC
395 analysis.

396 The results obtained for the three DMG-based radiochemical methods are given in
397 Table 2 in terms of ^{60}Co and ^{63}Ni activity concentrations. It can be noted that a wide
398 range of ^{63}Ni activity concentrations were measured from 1 to $2 \times 10^6 \text{ Bq g}^{-1}$ in the eight
399 samples. For all the studied radioactive waste, the ^{63}Ni values were lower than the
400 maximum acceptance limit fixed by ANDRA at $3 \times 10^6 \text{ Bq g}^{-1}$ [1].

401 The three DMG-based radiochemical procedures were compared in terms of Ni
402 recovery yields in Figure 4. The Ni recovery yields were satisfactory whatever the
403 analysed samples and the radiochemical methods. Those results are in agreement with the
404 values reported in the literature [4-18]. For method 1 based on solvent extraction, it can
405 be noticed that the Ni recovery yields varied from 69 % to 97 %. The lower value of Ni
406 recovery yield was obtained for the steel sample purified with method 1. This could be
407 explained by the Fe precipitation which might hinder slightly the extraction of $\text{Ni}(\text{DMG})_2$

408 complex in the organic phase at pH 9, in agreement with the theoretical speciation
409 calculations. Whatever the sample, the values of Ni recovery yields were higher than 95
410 % and 90 % respectively for methods 2 and 3.

411 The three DMG-based radiochemical methods were then compared in terms of
412 normalized errors in Figure 5, the method 1 based on solvent extraction being considered
413 as the reference method. The formula used for calculating the normalized error E-normal
414 (denoted as E_n) is shown in Equation 1 [37]. When E_n is lower than 1, the performances
415 of the studied method are judged as satisfactory.

$$416 \quad E_n = \frac{|x_i - X_{\text{method 1}}|}{\sqrt{(U_i^2 + U_{\text{method 1}}^2)}} \quad \text{Eq. (1)}$$

417 Where

418 x_i is the ^{63}Ni measurement result obtained with method i ($i=2$ to 3)

419 $X_{\text{method 1}}$ is the ^{63}Ni reference measurement result obtained with method 1

420 U_i is the expanded uncertainty of x_i

421 $U_{\text{method 1}}$ is the expanded uncertainty of $X_{\text{method 1}}$.

422 For method 2 based on DMG precipitation, the E_n values were higher than 1 for the
423 majority of the studied samples (up to 17), which indicated that the performances of
424 method 2 were unsatisfactory. For instance, the E_n value related to the S2 steel was
425 around 2. In agreement with the theoretical speciation calculations, those unacceptable
426 results might be related to the presence of Fe and Co in the Ni purified fractions due to
427 their precipitations at basic pH. This hypothesis was confirmed by gamma and ICP-AES
428 measurements. Around 2 % of Fe (thus ^{55}Fe) and 2 % of ^{60}Co were respectively
429 determined in the Ni fractions, which induced interferences for ^{63}Ni characterization by
430 LSC, given the $^{63}\text{Ni}/(^{60}\text{Co}+^{55}\text{Fe})$ ratio of 0.2 and $^{63}\text{Ni}/^{60}\text{Co}$ ratio of 0.4 in the S2 steel. As
431 a conclusion, method 2 implemented with a single precipitation step was not selective
432 enough to ensure accurate ^{63}Ni measurements in nuclear waste having a large range of
433 activity concentrations of interfering elements. Besides, the French standard NF M60-317
434 prescribes that one DMG-based precipitation step should be sufficient when the total

435 activity concentrations of the other radionuclides are not 10 times higher in comparison
436 in comparison to ^{63}Ni [21], which is not in agreement with our experimental results. This
437 standard published in 2001 [21] might be no more adapted to the nuclear waste produced
438 in the past decade from decommissioning operations of various radioactive facilities.
439 Consequently, the French standard NF M60-317 might be revised to take into account of
440 the variety of the present nuclear waste samples. Co and Fe elimination should be
441 specified by performing a second systematic purification step which can be a second
442 DMG-precipitation or a preliminary separation on an anion exchange resin in HCl
443 medium.

444 For method 3 based on Ni column, the E_n values were lower than 1 whatever the
445 studied samples, which demonstrated that the performances of method 3 were
446 satisfactory. Method 3 proved to be very efficient towards a large variety of radioactive
447 waste. In conclusion, method 3 implemented in only one single Ni column step was
448 selective enough to obtain accurate ^{63}Ni analyses in nuclear waste with various $^{63}\text{Ni}/^{60}\text{Co}$
449 ratios, except samples with high Fe contents such as steels. In the case of steels, a
450 preliminary separation on an anion exchange resin was implemented prior to the Ni resin,
451 which provided reliable ^{63}Ni measurements (the E_n value was 0.6). Indeed, less than 2 %
452 of Fe (thus ^{55}Fe) and 2 % of ^{60}Co were respectively measured in the Ni fractions.
453 Consequently, from these studies, method 3 was deduced to be more selective than
454 method 2 in the case of a single separation step.

455 A systematic separation on an anion exchange resin might be proposed prior to the Ni
456 resin in order to obtain a simple and reliable radiochemical method that can be applied to
457 all nuclear matrices whatever their $^{63}\text{Ni}/^{60}\text{Co}$ ratios and their Fe amounts. To check this
458 assumption, the S3 sample (corresponding to muds embedded in concrete) was analysed
459 with and without performing the AG1-X4 separation before the purification of the Ni
460 column. The difference between the two ^{63}Ni values was less than 1 % and the values of
461 Ni recovery yields were very similar (higher than 90 %). Furthermore, a blank separation
462 was implemented so as to determine the ^{63}Ni detection limit of the overall method 3. The
463 ^{63}Ni detection limit was found to be 0.2 Bq g^{-1} for an effluent sample, which is
464 compatible with the ^{63}Ni declaration threshold fixed by ANDRA at 1 Bq g^{-1} . As a

465 conclusion, method 3 based on the AG1-X4 and Ni resins was selected to determine ^{63}Ni
466 accurately in low and intermediate radioactive waste whatever their chemical and
467 radiological compositions. In the future, this method which prevents the use of
468 chloroform might be included in the revised version of the French standard NF M60-317.

469

470 **Conclusions**

471 ^{63}Ni is a major activation product which has to be characterized in low and
472 intermediate level radioactive waste. As a pure beta emitter, this radionuclide must be
473 isolated from the matrix and the interfering elements (mainly ^{60}Co and ^{55}Fe) through
474 separation procedures prior to LSC measurement. A comparative study using LSC was
475 performed to measure ^{63}Ni in various radioactive waste samples with a large range of
476 $^{63}\text{Ni}/^{60}\text{Co}$ ratios. Three dimethylglyoxime (DMG)-based radiochemical procedures
477 (solvent extraction, precipitation, extraction chromatography) were investigated, the
478 solvent extraction method being considered as the reference method. Theoretical
479 speciation calculations enabled to better understand the chemical reactions involved in
480 the different steps of the three protocols and to optimize them. The presence of
481 significant cobalt and iron quantities was predicted to generate interferences for the
482 method based on DMG precipitation, in agreement with the experimental results. The
483 three DMG-based methods were compared in terms of recovery yield and accuracy. In
484 comparison to the method based on DMG precipitation, the method based on nickel
485 extraction chromatography resin allowed to achieve the most reliable results in one single
486 step for the majority of radioactive waste. For the characterization of ^{63}Ni in all nuclear
487 waste samples, the combination of a separation on an anion exchange resin and a
488 purification on a Ni resin was proved to be selective enough to ensure accurate results.
489 The methodology implemented in this work (based on speciation calculations and
490 experimental results) can be applied to future developments of radiochemical procedures,
491 such as ^{55}Fe determination in nuclear waste.

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495 **References**

496 1. ANDRA, National Radioactive Waste Management Agency (2014)
497 ACO.SP.ASRE.99.0002D ANDRA specifications. Accessed 5 June 2015

498 2. Hou X, Roos P (2008) Critical comparison of radiometric and mass spectrometric
499 methods for the determination of radionuclides in environmental, biological and nuclear
500 waste samples. *Anal Chim Acta* 608:105-139

501 3. Hoepfener-Kramar U, Pimpl M, Willmann F (1997) Application of procedures for low
502 level radionuclide analysis in environmental monitoring for the purpose of clearance
503 measurements of materials from decommissioning of nuclear facilities. *J Radioanal Nucl*
504 *Chem* 226:99-103

505 4. Lee CH, Lee MH, Ha YK, Song KS (2011) Systematic radiochemical separation for
506 the determination of ⁹⁹Tc, ⁹⁰Sr, ⁹⁴Nb, ⁵⁵Fe and ^{59,63}Ni in low and intermediate radioactive
507 waste samples. *J Radioanal Nucl Chem* 288:319-325

508 5. Lee CH, Choi KS, Song BC, Ha YK, Song K (2013) Rapid separation of nickel for
509 ⁵⁹Ni and ⁶³Ni activity measurement in radioactive waste samples. *J Radioanal Nucl Chem*
510 298:1221-1226

511 6. Hou X, Østergaard LF, Nielsen SP (2005) Determination of ⁶³Ni and ⁵⁵Fe in nuclear
512 waste samples using radiochemical separation and liquid scintillation counting. *Anal*
513 *Chim Acta* 535:297-307

514 7. Hou X (2007) Radiochemical analysis of radionuclides difficult to measure for waste
515 characterization in decommissioning of nuclear facilities. *J Radioanal Nucl Chem*
516 273:43-48

- 517 8. Poletiko C (1988) Determination of nickel-63. *Environ Int* 14:387-390
- 518 9. Numajiri M, Oki Y, Suzuki T, Miura T, Taira M, Kanda Y, Kondo K (1994)
519 Estimation of nickel-63 in steel and copper activated at high-energy accelerator facilities.
520 *Appl Radiat Isot* 45:509-514
- 521 10. Scheuerer C, Schupfner R, Schottelkopf H (1995) A very sensitive LSC procedure to
522 determine Ni-63 in environmental samples, steel and concrete. *J Radioanal Nucl Chem*
523 193:127-131
- 524 11. Shizuma K, Iwatani K, Hasai H, Oka T, Hoshi M, Shibata S, Imamura M, Shibata T
525 (1997) Identification of ^{63}Ni and ^{60}Co produced in a steel sample by thermal neutrons
526 from the Hiroshima atomic bomb. *Nucl Instrum Methods Phys Res Sect A* 384:375-379
- 527 12. Roskopfova O, Galambo M, Rajec P (2011) Determination of ^{63}Ni in low level solid
528 radioactive waste. *J Radioanal Nucl Chem* 289:251-256
- 529 13. Taddei MHT, Macacini JF, Vicente R, Marumo JT, Sakata SK, Terremoto LAA
530 (2013) Determination of ^{63}Ni and ^{59}Ni in spent ion-exchange resin and activated charcoal
531 from the IEA-R1 nuclear research reactor. *Appl Radiat Isot* 77:50-55
- 532 14. Kaye JH, Strebin RS, Nevissi AE (1994) Measurement of ^{63}Ni in highly radioactive
533 Hanford waste by liquid scintillation counting. *J Radioanal Nucl Chem* 180:197-200
- 534 15. Warwick PE, Croudace IW (2006) Isolation and quantification of ^{55}Fe and ^{63}Ni in
535 reactor effluents using extraction chromatography and liquid scintillation analysis. *Anal*
536 *Chim Acta* 567:277-285
- 537 16. Jordan N, Michel H, Barci-Funel G, Barci V (2008) Radiochemical procedure and
538 quantitative determination of the activation product, ^{63}Ni , in environmental soft water
539 samples with high Ca and Mg phosphate concentration. *J Radioanal Nucl Chem* 275:253-
540 256

- 541 17. Remenec B, Dulanska S, Matel L (2013) Determination of difficult to measure
542 radionuclides in primary circuit facilities of NPP V1 Jaslovske Bohunice. *J Radioanal*
543 *Nucl Chem* 298:1879-1884
- 544 18. Holm E, Rots P, Skwarzec B (1992) Radioanalytical Studies of Fallout ^{63}Ni . *Appl*
545 *Radiat Isot* 43:371-376
- 546 19. Laboratoire National Henri Becquerel (2005) Table de radionucléides - ^{63}Ni .
- 547 20. Yonezawa C, Sagawa T, Hoshi M, Tachikama (1983) Rapid determination of specific
548 activity of nickel-63. *J Radioanal Nucl Chem* 78:7-14
- 549 21. AFNOR Standard NF M60-317 (2001) Nuclear energy - Nuclear fuel technology -
550 Waste - Determination of nickel 63 in effluents and waste by liquid scintillation after a
551 preliminary chemical extraction. Association Française de Normalisation, Paris, France
- 552 22. European Chemicals Agency (2012) Guidance for the implementation of REACH
553 (Registration, Evaluation, Authorisation and Restriction of Chemicals). Accessed 5 June
554 2015
- 555 23. Rajkovich S, Cahill D, Peedin L, Wheland S, Lardy M (1996) 2 case studies using
556 Eichrom's Nickel resin: a nuclear power plant and a commercial laboratory. Eichrom
557 Cincinnati Users' Seminar, USA. Accessed 5 June 2015
- 558 24. Horwitz EP, Dietz ML, Chiarizia R, Diamond H, Maxwell SL, Nelson MR (1995)
559 Separation and preconcentration of actinides by extraction chromatography using a
560 supported liquid anion exchanger: application to the characterization of high-level
561 nuclear waste solutions. *Anal Chim Acta* 310:63-78
- 562 25. Gautier C, Coppo M, Caussignac C, Fichet P, Goutelard F (2013) Zr and U
563 determination at trace level in simulated deep groundwater by Q ICP-MS using extraction
564 chromatography. *Talanta* 106:1-7
- 565 26. Eichrom Technologies, Inc. (2003) Analytical procedures NIW01, nickel 63/59 in
566 water, Feb 25

- 567 27. Fisera O, Sebesta F (2010) Determination of ^{59}Ni in radioactive waste. *J Radioanal*
568 *Nucl Chem* 286:713-717
- 569 28. Smith RM, Martell AE (1973) In *Critical Stability Constants*, Plenum Press
- 570 29. International Atomic Energy Agency (2009) Determination and Use of Scaling
571 Factors for Waste Characterization in Nuclear Power Plants. AIEA, Nuclear Energy
572 Series NW-T-1.18
- 573 30. Fréchet C, Degros JP (2006) Radiological inventory of irradiated graphite samples. *J*
574 *Radioanal Nucl Chem* 273:677-681
- 575 31. Banford AW, Eccles H, Graves MJ, von Lensa W, Norris S (2008) Carbowaste - An
576 integrated approach to irradiated graphite. *Nucl Future* 4:1-5
- 577 32. AFNOR Standard NF M60-323 (2011) Nuclear energy - Nuclear fuel cycle
578 technology - Waste - Guide for pre-analysis dissolution of effluents, waste and
579 embedding matrices. Association Française de Normalisation, Paris, France
- 580 33. AFNOR Standard NF M60-322 (2005) Nuclear energy — Nuclear fuel cycle
581 technology — Waste — Determination of iron 55 activity in effluents and waste by liquid
582 scintillation after prior chemical separation
- 583 34. Marczenko Z, Balcerzak M (2000) In: *Separation, Preconcentration and*
584 *Spectrophotometry in Inorganic Analysis*, Elsevier, Amsterdam, Netherlands
- 585 35. Zelenin O.Y (2007) Interaction of the Ni^{2+} Ion with Citric Acid in an Aqueous
586 Solution. *Russ. J. Coord. Chem.* 33:346-350
- 587 36. Dyrssen D, Krašovek F, Sillén LG (1959) On the Complex Formation of Nickel with
588 Dimethylglyoxime. *Acta Chem Scand* 13:50-59
- 589 37. Standard NF EN ISO/CEI 17043 (2010) General requirements for proficiency testing.
590 Association Française de Normalisation, Paris, France
- 591

592 **Table 1** Chemical and radiochemical compositions of studied nuclear waste samples

	Activity concentration (^{60}Co) (Bq g^{-1})	Activity concentration (^{137}Cs) (Bq g^{-1})	Fe (mg g^{-1})	Co (mg g^{-1})	Ni (mg g^{-1})
Evaporate concentrate S1	$8.64 \times 10^2 \pm 10\%$	$1.66 \times 10^3 \pm 6\%$	$0.4 \pm 10\%$	< 0.05	$0.4 \pm 10\%$
Steel S2	$1.10 \times 10^4 \pm 4\%$	$9.88 \times 10^2 \pm 10\%$	$970 \pm 5\%$	$0.2 \pm 10\%$	$6 \pm 10\%$

593

594 **Table 2** Comparison of the three studied DMG-based radiochemical methods in terms of
 595 ^{60}Co and ^{63}Ni activity concentrations (n/a*: not available, ** an anion exchange resin is
 596 implemented prior to Ni column)

	Activity concentration (^{60}Co) (Bq g^{-1})	Activity concentration (^{63}Ni) (Bq g^{-1})			Ratio $^{63}\text{Ni}/^{60}\text{Co}$ for method 1
		Method 1 based on DMG solvent extraction	Method 2 based on DMG precipitation	Method 3 based on Ni column	
Evaporate concentrate S1	$8.64 \times 10^2 \pm 10\%$	$2.76 \times 10^2 \pm 5\%$	$2.50 \times 10^2 \pm 5\%$	$2.88 \times 10^2 \pm 5\%$	0.3
Steel S2	$1.10 \times 10^4 \pm 4\%$	$3.99 \times 10^3 \pm 5\%$	$3.37 \times 10^3 \pm 5\%$	$3.82 \times 10^3 \pm 5\%$ **	0.4
Muds embedded in concrete S3	$1.38 \times 10^4 \pm 4\%$	$8.94 \times 10^3 \pm 5\%$	n/a*	$9.35 \times 10^3 \pm 5\%$	0.7
Effluent S4	$2.10 \pm 10\%$	$1.39 \pm 9\%$	$1.18 \times 10^1 \pm 5\%$	$1.45 \pm 9\%$	0.7
Ion exchange resins S5	$6.65 \times 10^5 \pm 4\%$	$1.81 \times 10^6 \pm 4\%$	$1.76 \times 10^6 \pm 4\%$	$1.73 \times 10^6 \pm 4\%$	2.7
Graphite S6	$4.05 \times 10^3 \pm 4\%$	$2.78 \times 10^4 \pm 4\%$	n/a*	$2.90 \times 10^4 \pm 4\%$	6.9
Ion exchange resins embedded in polymer S7	$2.85 \times 10^4 \pm 4\%$	$3.48 \times 10^5 \pm 4\%$	$3.26 \times 10^5 \pm 4\%$	$3.50 \times 10^5 \pm 4\%$	12.3
Ion exchange resins S8	$4.67 \times 10^3 \pm 4\%$	$7.66 \times 10^4 \pm 4\%$	$6.57 \times 10^4 \pm 4\%$	$7.95 \times 10^4 \pm 4\%$	16.4

597

598

599 **Fig. 1** Theoretical distribution diagram of Ni(II) species for a steel (using JChess
600 software)

601 **Fig. 2** Theoretical distribution diagram of Co(II) species for a steel (using JChess
602 software)

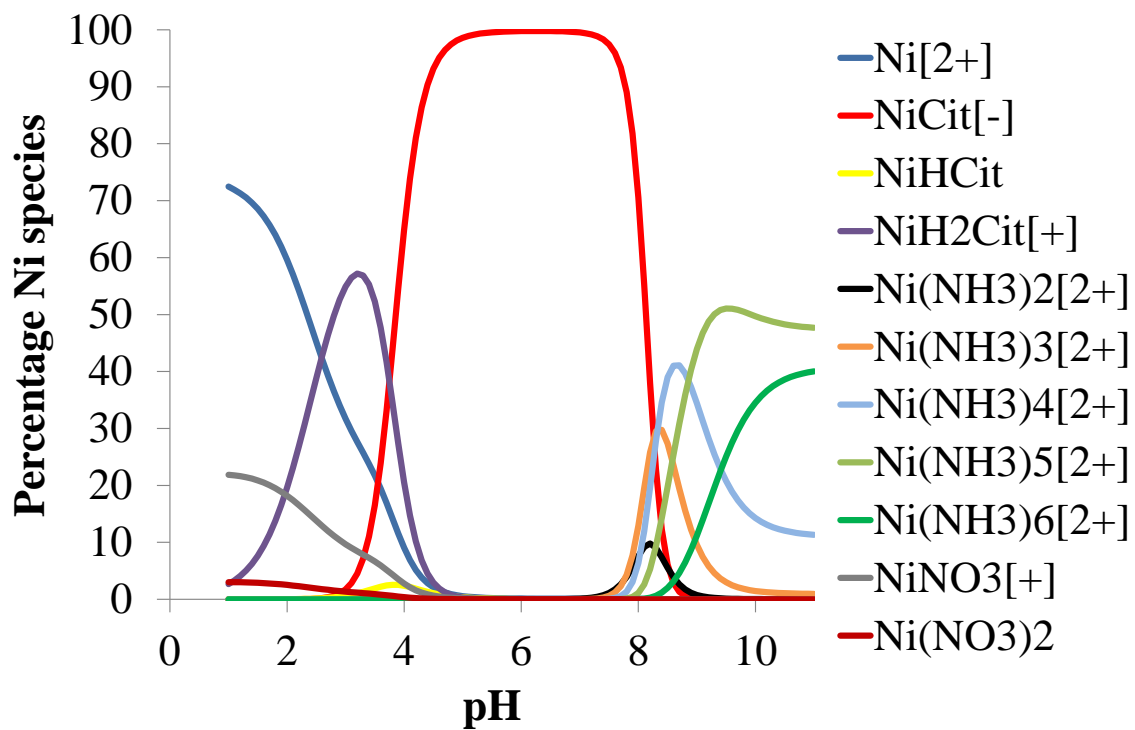
603 **Fig. 3** Theoretical distribution diagram of Fe(III) species for a steel (using JChess
604 software)

605 **Fig. 4** Ni recovery yields (%) obtained for the three studied DMG-based radiochemical
606 methods

607 **Fig. 5** Comparison of the studied DMG-based radiochemical methods in terms of
608 normalized errors E_n

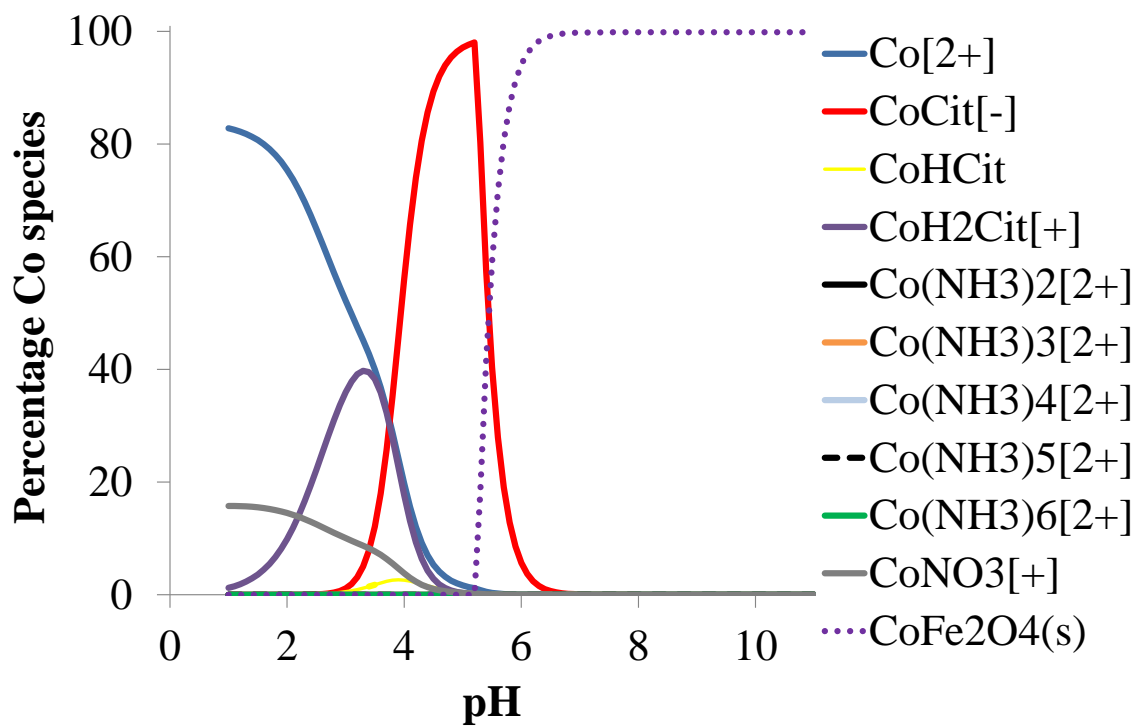
609

610 **Fig. 1** Theoretical distribution diagram of Ni(II) species for a steel (using JChess
611 software)



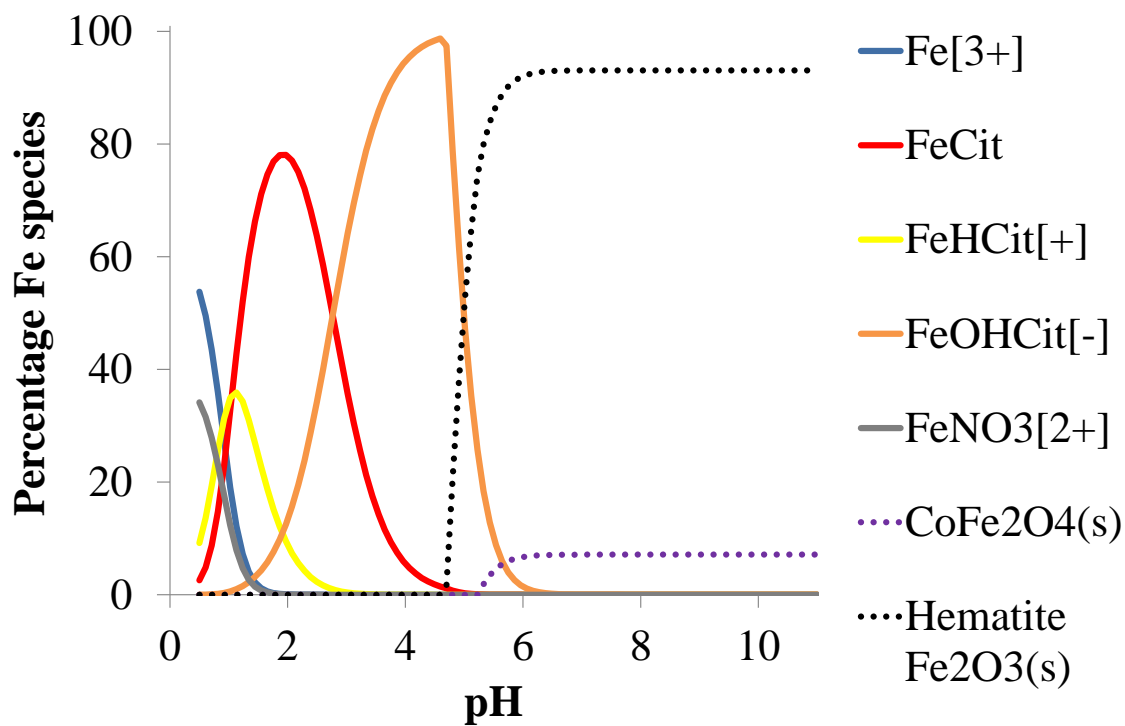
612

613 **Fig. 2** Theoretical distribution diagram of Co(II) species for a steel (using JChess
614 software)



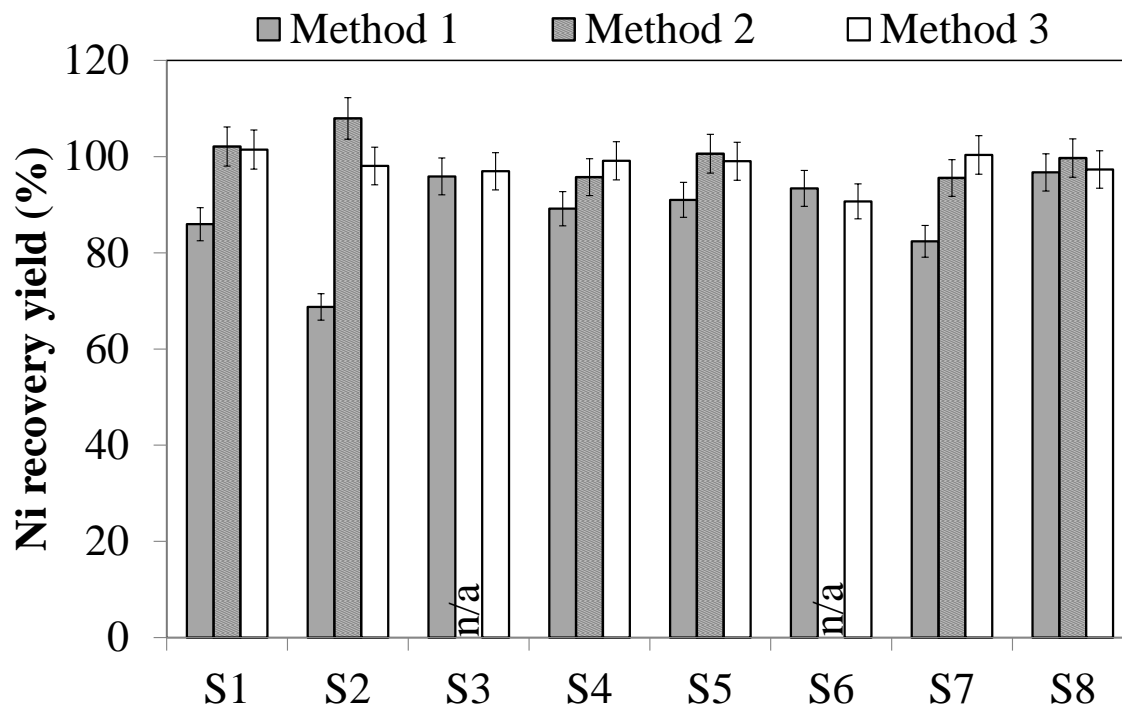
615

616 **Fig. 3** Theoretical distribution diagram of Fe(III) species for a steel (using JChess
617 software)



618

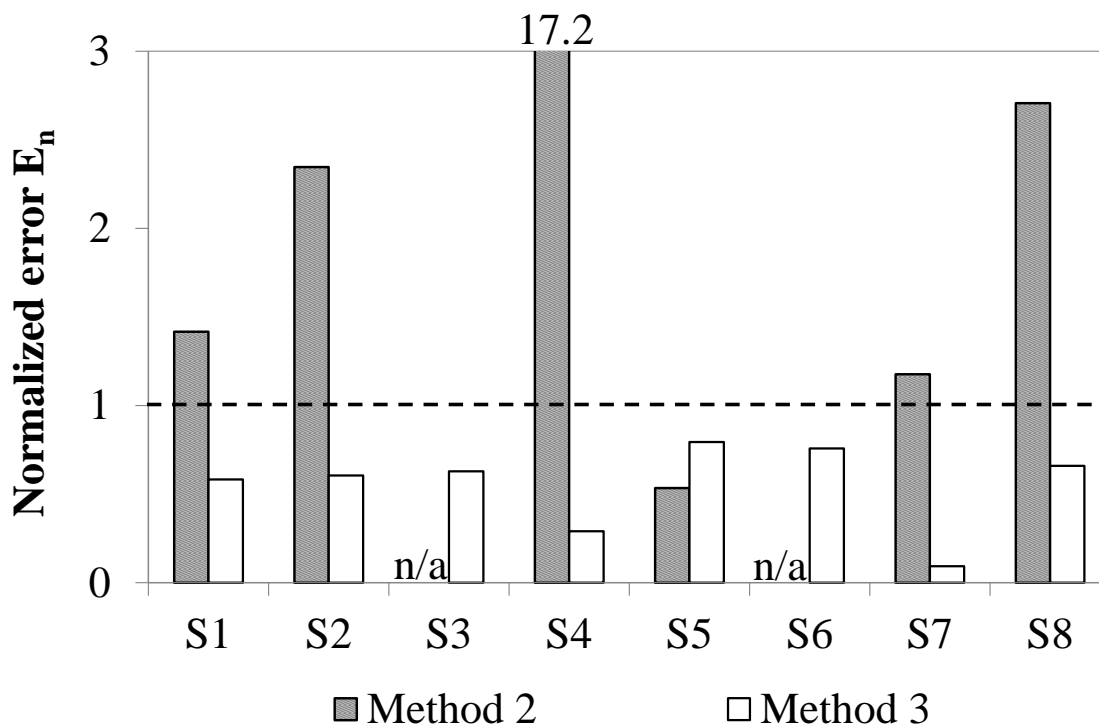
619 **Fig. 4** Ni recovery yields (%) obtained for the three studied DMG-based radiochemical
620 methods (n/a: not available)



621

622

623 **Fig. 5** Comparison of the studied DMG-based radiochemical methods in terms of
624 normalized errors E_n (n/a: not available)



625

626