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Start Here When Performing Radiochemical Reactions

Carla Daruich de Souza, Jin Joo Kim and Jin Tae Hong

Abstract

Radiation products are present in several fields of knowledge. From the energy field, with nuclear reactors and nuclear batteries, to the medical field, with nuclear medicine and radiation therapy (brachytherapy). Although chemistry works in the same way for radioactive and non-radioactive chemicals, an extra layer of problems is present in the radiochemical counter-part. Reactions can be unpredictable due to several factors. For example, iodine-125 is deposited in a silver wire to create the core of a medical radioactive seed. This core is the sealed forming a radioactive seed that are placed inside the cancer. Several aspects can be discussed in regards to radiation chemistry. For example: are there any competing ions? Each way my reaction is going? Each reaction is more likely to occur? Those are important questions, because, in the case of iodine, a volatile product can be formed causing contamination of laboratory, equipment, personal, and environment. This chapter attempts to create a guideline on how to safely proceed when a new radioactive chemical reaction. It discusses the steps by giving practical examples. The focus is in protecting the operator and the environment. The result can be achieved safely and be reliable contribution to science and society.

Keywords: Radiation chemistry, radioactive material manipulation, radiation sources fabrication

1. Introduction

Radiation products are present in several fields of knowledge. From the energy field, with nuclear reactors and nuclear batteries, to the medical field, with nuclear medicine and radiation therapy.

Although chemistry works in the same way for radioactive and non-radioactive chemicals, an extra layer of problems is present in the radiochemical counter-part. Reactions can be unpredictable due to several factors.

According with Neeb, radiation chemistry is a branch of chemistry, but is possible to identify in its context characteristics of an autonomous discipline. Usually, the incredibly high radiation solutions can be manufactured that actually correspond to a low concentration of chemicals. An example is several fission products with extremely high radioactivity with an actual concentration of 10^{-9} mol/L measured in nuclear spend fuel. With so small masses, is possible that expected reaction simply will not occur and a more “secondary” reaction becomes primary [1, 2].

This chapter attempts to create a guideline on how to safely proceed when a new radioactive chemical reaction is being investigated. It discusses the steps by giving practical examples.

2. Why is harder to predict radioactive chemical reactants

To answer the question, the manufacturing route for radioisotopes must be explained. Isotopes can basically be manufactured in 3 different ways (Figure 1).

In Figure 1, presented in pink, is the nuclear activation form. A thorough study of irradiation must be performed followed by purification essays. An example for promethium-147, used in pacemaker nuclear batteries, by Broderick et al. [3] is shown. Presented in green in the natural decay mode. Radioisotopes are obtained by purification of decay products or concentrated from natural radioactive isotopes. Examples are the Marie and Pierre Curie work in discovering Polonium and Radium and the Uranium-235 enrichment process. In yellow, the spent nuclear fuel reprocessing route is presented. If the isotope is a by-product of fission, then it can be recovered from the nuclear fuel that has already been used. Many isotopes are only found/fabricated through reprocessing. This process is known to be the most dangerous chemical process invented in human history [12]. The chemical process is relatively simple, but the byproducts are sometimes instable, highly radioactive, long lasting, even being able to reach criticality (nuclear chain reaction) [18]. For example, strontium-90 used in nuclear medicine and in nuclear batteries and plutonium-238 used in most RTG (Radioisotope Thermoelectric Generator) are

Figure 1. Modes of radioisotope production: Nuclear activation [3, 4], natural decay [5–11] and spend fuel reprocessing [12–17].

SHIPPER: Enterprise		QUALITY CERTIFICATE No 162			
Consignee:		Contract : CMR-02-2016 dated 29.01.2016			
By the order:					
Description and code of goods	Type of packages	Package No.	Unit	Quantity	Volume, in ml
Iodine-125 carrier free in the form of sodium iodide in water solution	Type A	1	mCi	1000 on 22.06.2018	0.90
Note: The preparation is dispensed in vial and placed into the container KT 1-5 No.332					
SPECIFICATIONS			Lot No. 106070618		
1. Appearance: Transparent, colourless liquid					
2. Radioactive concentration, mCi/ml (GBq/ml) 1360.0 (50.3) on 07.06.2018.					
3. pH 8-10 (measured 10)					
4. Content of Iodine-126 .% 5.6 · 10 ⁻⁶ on 22.06.2018.					
5. Concentration of NaOH, mol/l (mg/ml) 0.016 (0.64)					
6. Other gamma impurities, % 0 (The lack of Cs ¹³⁴ , Cs ¹³⁷ is guaranteed by the production technology)					
7. Radiochemical purity, % 99.0					
				Signature 08.06.2018.	

Figure 2.
Iodine-125 fact sheet.

produced by reprocessing. Besides that, many stable fission products are high cost and in high demand elements such as rubidium, palladium, and ruthenium.

Performing chemical analysis that would allow to identify contaminant most of the times are impossible. Isotopes with high half-life, may contaminate and permanently disable equipments. For example, Tritium, used in nuclear batteries, have 12.32-year half-life. It means that in 12.32 years the Tritium mass will emits half of its radioactive material. If an equipment such as an EDS would be used, even supposing that one half-life would yield background level radioactivity, the equipment would be contaminated and unusable for 12 years! In large productions centers, each isotope has its own production line containing exclusive equipment for analysis.

Besides that, a radiochemical fact sheet contains very little information. **Figure 2** shows an example of iodine-125, used in radiation therapy.

The issue of not having more information arises when the following comparison is done. For example, in a thyroid cancer treatment with iodine-131, the activity of 5.55–7.40 GBq (150–200 mCi) is administered. Converting:

$$\lambda = \frac{\ln 2}{T_{\frac{1}{2}}} = \frac{\ln 2}{8.02d \times 24h \times 3600} = 10^{-6}s^{-1} \quad (1)$$

$$A = \lambda \cdot N \rightarrow N = \frac{A}{\lambda} = \frac{7.40 \times 10^9}{10^{-6}} = 7.40 \times 10^{15} atoms \quad (2)$$

$$mass_{sample}(g) = \frac{MW \times N}{N_a} = \frac{131 \times 7.40 \times 10^{15}}{6.02 \times 10^{23}} = 1.61 \cdot 10^{-6} g \quad (3)$$

were: $T_{\frac{1}{2}}$ = Half-life (s), A = Activity in Bq (decays/second), λ = decay constant (s^{-1}), MW = atomic mass, N_a = Avogadro Number $\approx 6.02 \times 10^{23}$.

The small mass calculated indicate that great chemical purity must exist in the entire course of a methodology/product development. For example, 1% impurity in 1 g of solution results in 0.01 g, an amount that is probably much greater than the total radioactive iodine. If the manufacturer changes significantly, for example, purification steps, new contaminants might be introduced and old expected results might not be achievable.

Ultimately, the best way to achieve the best results in radiation chemistry is to understand how reactions take place, and to recognize the various factors that influence their course.

3. Chemistry background

It is helpful to identify some general features of a reaction and then study the related topics. Some of the most important of these are [19]:

- **Energetics:** The potential energy of a reacting system changes as the reaction progresses. The reaction might release energy (exothermic) or need energy to occur (endothermic), plus the activation energy requirement. Always the reaction that needs less energy to occur will have preference;
- **Electronic Effects:** The distribution of electrons at the reaction sites is a particularly important factor. Electron deficient species or groups (electrophiles), which may or may not be positively charged, are attracted to electron rich species or groups (nucleophiles), which may or may not be negatively charged. The charge distribution in a molecule is usually discussed with respect to two interacting effects. The first is an inductive effect, that relates to electronegativity differences that exist between atoms (and groups). The second is a resonance effect, in which electrons move in a discontinuous fashion between parts of a molecule.
- **Steric Effects:** Atoms occupy space. When they are crowded together, van der Waals repulsions produce an unfavorable steric hindrance. Steric effects are nonbonding interactions that influence the shape (conformation) and reactivity of ions and molecules (destabilization of transition states) may be influenced by steric hindrance (the slowing of chemical reactions due to steric bulk).
- **Stereoelectronic Effects:** In many reactions atomic or molecular orbitals interact in a manner that has an optimal configurational or geometrical alignment. Departure from this alignment inhibits the reaction. It explains a particular molecular property or reactivity by invoking stabilizing or

destabilizing interactions that depend on the relative orientations of electrons (bonding or non-bonding) in space.

- Solvent Effects: Most reactions are conducted in solution, not in a gaseous state. The solvent selected for a given reaction may exert a strong influence on its course. Remember, solvents are chemicals, and most undergo chemical reaction under the right conditions.

Next, the basic concepts will be explained with radiochemistry examples.

3.1 Reactivity

Reactivity is a concept used for many things in chemistry [20, 21]. In this paper, the focus will be if a determined reaction can occur or not, or if a “secondary” reaction can take place instead of the expected one.

Reactivity encompasses both thermodynamic factors and kinetic factors. For example, it is commonly stated that the reactivity of alkali metals (group one metals) (Na, K, etc.) increases down the group in the periodic table [20, 21]. The behavior is shown in the periodic table in **Figure 3**.

Reactivity is related to the rate at which a chemical substance tends to undergo a chemical reaction in time. In pure compounds, reactivity is regulated by the physical properties of the sample. For instance, grinding a sample to a higher specific surface area increases its reactivity. In impure compounds, the reactivity is affected by the inclusion of contaminants [22].

In double-replacement reaction (most common in the fabrication of medical radioactive sources), if one of the products isn’t aqueous, by rule of thumb the reaction is possible [22].

Figure 3.
Reactivity shown in the periodic table.

In this reaction, A and C are positively-charged cations, while B and D are negatively-charged anions. Double-replacement reactions generally occur between substances in aqueous solution. In order for a reaction to occur, one of the products is usually a solid precipitate, a gas, or a molecular compound such as water [19].

For example, the 1982 patent (US Pat. n. 4.323.055), filed by the Minnesota Mining and Manufacturing Company [23], describes a method of impregnating Ag rods with iodine-125, forming the core of a brachytherapy seed. The silver rods previously reacted to for a layer of silver nitrate. That modified rod reacted with the radioactive NaI¹²⁵ solution. The reaction will be:

Accordingly with **Table 1** (explained ahead):

Because there is a solid product, theoretically the reaction will occur.

For example, if the silver rod wasn't pure silver and had contained potassium in high proportions, KI¹²⁵ will form more favorably than AgI¹²⁵ because potassium is more reactive than sodium.

3.2 Electronegativity

Electronegativity is a measure of the tendency of an atom to attract a bonding pair of electrons. Large electronegativity values indicate a stronger attraction for electrons than small values. Electronegativities increase from left to right across the periodic table (**Figure 4**). Elements on the left of the periodic table have low electronegativities and are frequently called electropositive elements [24].

If an atom B is more electron negative than A, the electron pair is dragged right over to B's end of the bond (Eq. (7)). A has lost control of its electron, and B has

Ions that form soluble compounds	Exceptions	Ions that form soluble compounds	Exceptions
Group 1 ions (Li ⁺ , Na ⁺ , K ⁺ , ...)	—	Carbonate (CO ₃ ²⁻)	When combined with group 1 ions or ammonium (NH ₄ ⁺)
Ammonium (NH ₄ ⁺)	—	Chromate (CrO ₄ ²⁻)	When combined with group 1 ions, Ca ²⁺ , Mg ²⁺ , or ammonium (NH ₄ ⁺)
Nitrate (NO ₃ ⁻)	—	Phosphate (PO ₄ ³⁻)	When combined with group 1 ions or ammonium (NH ₄ ⁺)
Acetate (C ₂ H ₃ O ₂ ⁻ or CH ₃ COO ⁻)	—	Sulfide (S ²⁻)	When combined with group 1 ions or ammonium (NH ₄ ⁺)
Hydrogen Carbonate (HCO ₃ ⁻)	—	Hydroxide (OH ⁻)	When combined with group 1 ions, Ca ²⁺ , Ba ²⁺ , Sr ²⁺ or ammonium (NH ₄ ⁺)
Chlorate (ClO ₃ ⁻)	—	Sulfates (SO ₄ ²⁻)	When combined with Ag ⁺ , Ca ²⁺ , Sr ²⁺ , Ba ²⁺ , and Pb ²⁺
Perchlorate (ClO ₄ ⁻)	—	Halides (Cl ⁻ , Br ⁻ , I ⁻)	When combined with Ag ⁺ , Pb ²⁺ , and Hg ₂ ²⁺

Table 1.
Solubility guidelines for Aqueous Solutions.

Figure 4.
Electronegativity shown in the periodic table.

complete control over both electrons, forming an ion pair [25]. Electronegativity series follow **Figure 4**.

When a situation with two possible outcomes is present, it is interesting to evaluate electronegativity. For example, the paper by Lee et al. [26] mixes pre-treated silver rods with iodine-125, forming the core of a brachytherapy seed. Usually the radioactive iodine-125 solution is in the form of NaI¹²⁵. Let's suppose that there is excess of Cl⁻ as a contaminant in the mixture. **Figure 5** explain the possible outcome.

3.3 Gibbs free energy

In chemistry, a spontaneous process is one that occurs without the addition of external energy. A spontaneous process may take place rapidly or slowly, because spontaneity is not related to kinetics or reaction rate. According to the second law of thermodynamics, any spontaneous process must increase the entropy in the universe [27, 28]. This can be expressed mathematically as follows:

$$\Delta S_{universe} = \Delta S_{system} + \Delta S_{surroundings} > 0 \tag{8}$$

Figure 5.

Scheme of what happens when two anions, Cl^- and I^- , with two different electronegativities compete for the same cation, Ag^+ . AgCl will form in a higher rate than AgI . Since silver iodide is the desired product, the reaction yield is impaired.

Measuring the entropy change in the universe is not practical and the real interest is to observe the desired system (chemical reaction). When a process occurs at constant temperature T and pressure P , the second law of thermodynamics can be rearranged and define a new quantity known as Gibbs free energy (**Figure 6**). In other words, Gibbs free energy is a thermodynamic potential used to calculate the maximum reversible work that may be performed by a thermodynamic system at a constant temperature and pressure. The Gibbs energy, G , represents also the thermodynamic potential that is minimized when a system reaches chemical equilibrium [27, 28].

The Gibbs free energy of a system at any moment in time is defined as the enthalpy of the system minus the product of the temperature times the entropy of the system [27, 28].

$$\text{Gibbs free energy} \rightarrow G = H - TS \quad (9)$$

The change in the Gibbs free energy of the system that occurs during a chemical reaction is therefore equal to:

$$\Delta G = \Delta H - \Delta(TS) \quad (10)$$

If temperature is constant:

$$\Delta G = \Delta H - T\Delta S \quad (11)$$

The change in the free energy of a system that occurs during a reaction can be measured under any set of conditions. If the data are collected under standard conditions, the result is the standard-state free energy of reaction (ΔG°) [27, 28].

$$\Delta G^0 = \Delta H^0 - T\Delta S^0 \quad (12)$$

- Favorable or spontaneous reactions: $\Delta G^0 < 0$
- Unfavorable or non-spontaneous reactions: $\Delta G^0 > 0$
- equilibrium: $\Delta G^0 = 0$
- exothermic reactions: $\Delta H < 0$
- endothermic reactions: $\Delta H > 0$
- Favorable or spontaneous reactions: $\Delta H^0 < 0, \Delta S^0 > 0$
- Unfavorable or non-spontaneous reactions: $\Delta H^0 > 0, \Delta S^0 < 0$
- Unfavorable or non-spontaneous reactions at low temperatures: $\Delta H^0 < 0, \Delta S^0 < 0$
- Favorable, or spontaneous reactions at high temperatures: $\Delta H^0 > 0, \Delta S^0 > 0$

Reference [30] has a 25-page list of Gibbs Free Energy values.

Continuing to use the paper by Lee et al. [26] as an example, one of the methods is to pre-coat the silver rod with PO_4^{-3} forming Ag_3PO_4 following:

Figure 6.

Explanation of the Gibbs Free Energy equation indexes. *activation energy is the minimum amount of energy that must be provided to compounds to result in a chemical reaction [27–29].

Gibbs free energy for the equation is:

$Ag_3PO_4(s) + 3NaI^{125}(aq) \rightarrow 3AgI^{125}(s) + Na_3PO_4(s)$			
Reactants		Products	
$\Delta G^0 Ag_3PO_4$	$3 \times \Delta G^0 NaI^{125}$	$3 \times \Delta G^0 AgI^{125}$	$\Delta G^0 Na_3PO_4(s)$
87 kJ/mol	$3 \times (-284.512) \text{ kJ/mol}$	$3 \times (-66.19) \text{ kJ/mol}$	-1819 kJ/mol
-766.536 kJ/mol		-2017.57 kJ/mol	

$$\Delta G^0 = \Delta G^0_{products} - \Delta G^0_{reactants} \tag{14}$$

$$\Delta G^0 = -2017.57 + 766.536 = -1251.034 \text{ kJ/mol.}$$

$\Delta G^0 < 0$ = Favorable, or spontaneous reactions.

To correlate between 2 reactions, it is more practical to investigate activation energy. A reaction with lower activation energy will be preferable, thus preferable to occur. **Figure 7** explains it.

For example, for the AgI^{125} source fabrication, ions such as Cl^- and Br^- might be present. Activation energies are for AgBr 0.34 eV, AgI 0.48 eV, and 0.53 eV for AgCl. In a reaction when Br- and I- are present, is more likely that AgBr will form more easily than AgI. And, in a reaction when Cl^- and I^- are present, is more likely that AgI^{125} will form more easily than AgCl. This contradicts the previous electro-negativity statement. All of these influences are occurring at the same time, possibly influencing the final result [31–33].

3.4 Solubility

Solubility is the capability of a solid, liquid, or gaseous substance (named solute) to dissolve in solvent (usually a liquid) and form a solution. The solubility of a chemical is dependent on the solvent used, temperature, and pressure. Solubility does not depend on particle size (even large particles will eventually dissolve given enough time). It is measured by the concentration of the saturated solution. A saturated solution is a solution that contains the maximum amount of solute that is capable of being dissolved. In other words, adding additional solute no longer

Figure 7.
Two reactions with different activation energies.

Figure 8. Solubility. The degree of solubility ranges broadly depending on the substances, from infinitely soluble to poorly soluble (insoluble). Under certain conditions, the equilibrium solubility can be exceeded, yielding a supersaturated solution.

increases the concentration of the solution. **Figure 8** explains solubility classifications.

To evaluate a desired reaction, **Table 1** can be used [22].

Solubility is important because it directly impacts the amount of radioisotope available for the reaction. It may affect distribution in the radiation source resulting in dosimetry issues. For example, in Benega et al. [34] a phosphorus-32 radioactive source for spinal cancer treatment was developed by mixing the radioisotope with a catalyst solution. This solution is then added to an epoxy resin. Both solutions need to result in a homogenous product. This won't be achievable if the isotope doesn't properly mix with the catalyst solution (water based).

The solubility product constant, K_{sp} , is the equilibrium constant for a solid substance dissolving in an aqueous solution. It represents the level at which a solute dissolves in solution. Eq. (16) shows the correlation.

$$K_{sp} = [C]^c [D]^d \tag{16}$$

If two competing ions are present, solubility and quantity play an important role in each reaction will be preferable. For example, in the iodine-125 seed manufacture, NaOH is used in pH control. NaOH is soluble in water, resulting in ionic completion for the silver binding sites. It maybe would be better to use $Fe(OH)_3$ that is insoluble. For instance, let's use the information in **Figure 2**. Iodine-125 solution has 50.3 GBq/mL and pH 10 (pOH 4). Calculating the amount of OH^- and I^- :

OH^-

pOH = 4 = 10^4 mol/L
MW_{OH-} = 17 g/mol

For 1 mL
 10^4 mol ----- 1000 mL
x ----- 1 mL
x = 10^1 mol/mL

17 g ----- 1 mol
y ----- 10^1 mol/mL
y = 170 g

170 g x 6.02×10^{23} atoms = **$1.02 \times 10^{26} OH^-$ ions**

I^-

50,3 GBq/mL

$$A = \lambda \cdot N \Rightarrow A = \frac{\ln 2}{T_{1/2}} N$$
$$\Rightarrow 50.3 \times 10^9 = \frac{\ln 2}{59.407 \times 24 \times 3600} N$$
$$\Rightarrow \mathbf{3.724 \times 10^{17} I^- \text{ atoms/mL}}$$

2.7×10^8 more OH^- ions than I^- atoms

3.5 Characteristic of the isotope and other problems (pH, reaction volume, vial type)

Characteristics of the isotope being used needs to be extensively investigated. Several problems may be present such as toxic decay atoms to a high possibility of contamination and volatilization. For example, Gold-198 used in colloid or nanoparticles for cancer treatment decays to the highly toxic mercury, demanding that a through toxicity study be done [35].

In another example, iodine salts and solutions are advised to be stored in dark bottles due to the fact that iodine reacts with light and undergo a photo decomposition reaction [36]. Even though performing a radioactive reaction in the absence of light is impractical, with this information the researcher can avoid light as much as possible.

In most cases, errors can be originated by unpredicted places. Eight different storage vials were tested by Kennedy et al. [37] in regards to its ability to contain iodine-131, used in thyroid cancer treatment, during 24 hours. Glass yielded the best results, with 10% loss and polyethylene the worse with >50% loss. He et al. [38] evaluate the iodine-125 activity intake on silver cores by varying the value of pH. They have found that the intake in the silver cores were higher at a low pH. The authors affirm that if pH is kept high, the Na¹²⁵I solution will remain stable not releasing the ¹²⁵I⁻ for silver binding. Both of these issues were confirmed by Daruich de Souza et al. [39].

Isotopes are being replaced for others or adapted in different fields all the time. For example, cobalt-60 teletherapy machines were the first developed. In the 1950's they were widely used, by producing a beam of gamma rays which was directed into the patient's body to kill tumor tissue. Cobalt-60 is produced by neutron irradiation of ordinary cobalt metal in a nuclear reactor. It is a high energy gamma ray emitter, 1.17 and 1.33 MeV, with specific activity of 44 TBq/g (≈ 1100 Ci/g). Because of its longer half-life, 5.27 years, cobalt-60 was widely used in radiation therapy. Nevertheless, this half-life still requires sources to be replaced every 5 years. As technology advanced, these machines were replaced by linear accelerators, that doesn't contain radiation sources [40, 41]. In recent years, the technology was revised, now in a new machine called gamma knife, were cobalt-60 sources are mounted [42]. Applications for Gamma Knife surgery include the treatment of cerebral vascular malformations, head tumors, certain pain conditions such as trigeminal neuralgia, along with the treatment of some movement and psychiatric disorders [42].

4. Mock trials and radiation safety

4.1 How to set up mock trials

The steps to set up mock trials are in **Figure 9**.

The first step is to analyze all possible reactions accordingly with item 3 of this chapter. After that, the reaction set up is investigated. Three important observations are:

1. Avoid heating: heating makes molecules more reactive and can cause secondary reactions, for example, the formation of a volatile product.
2. Add traps: the more enclosed the set-up is, the better it will retain possible radiation leakage;

Figure 9.
 Steps to set up mock trials [9, 43–45].

3. Simplify set-up: less material usage result in less radioactive waste.

The third step is to follow the 3 radiation principles: distance, shielding, and time.

1. Distance: A greater distance from the radiation source can reduce radiation exposure. The amount of radiation exposure is inversely proportional to the square of the distance. Using extension tweezers and moving away stock radioactive solutions will diminish radiation exposure;
2. Shielding: There are many shielding devices such as caps, lead glasses (**Figure 10**), thyroid protectors, aprons, even radiation reducing gloves. Shielding follows the attenuation rule being:
3. Radiation exposure can be accumulated over the time of exposure. The longer the exposure time, the more radiation exposure to the operator. For reducing laboratory time, the operator has to improve his skill by practicing thus acquiring more experience.

The fourth step is about setting up cold mock trials, meaning, the test of expected reaction and set-up with no radioactive material. Pay special attention to:

- optimizing results;
- simplifying set-ups;
- having easy access to necessary solutions;
- check for availability of all materials and equipment that will be use;
- having easy access to protective equipment;

Figure 10.

Attenuation Law and examples of shielding materials (apron and gloves from [46]).

- installing protection were needed;
- make sure all detectors used in contamination assessment are working properly;
- perform the reaction several times to gain speed and experience;
- determined individuals' tasks: person that will perform the experiment, radiation protection team member that will give support, and person that will write in the lab book during the experiment. Make certain that a support person that can take over in case of an emergency are informed of the experiments schedule;
- use multiple pairs of gloves and change them numerous times during experiment to diminish radiation contamination on the experiment location;
- verify that exhaustion in the experiment location is working properly;
- and select the place that radioactive waste will go.

In Daruich de Souza PhD thesis [2] the set-up in **Figure 11** was used to handle iodine-125.

In Silva et al. [47] the cold fabrication of a phosphorous-32 radioactive source to be used in CNS cancer using epoxy resin was described. MCNP simulation was used to evaluate the radiation dose. Special attention was given to factors that can impact dose distribution such as source thickness and thickness variance. Two molds, Teflon and Silicon were used. The epoxy plaque fabricated with Teflon mold presented better agreement. MCNP for this plaque resulted in an average dose of $8.54 \pm 0.01\%$ cGy/s. It was also found that, differences of less than 0.01 cm in thickness within the plaque lead to alterations of up to 25% in the dose rate. This work now set up the foundation to the hot tests.

It is also possible to access possible yields by using different equipment and procedure. In Uhm et al. [48] a nickel-63 betavoltaic battery using a three-dimensional single trenched p-n transduction was designed. The optimum thickness

Figure 11.
Set-up was used to handle iodine-125 [2].

of the nickel-63 layer was determined to be approximately $2\ \mu\text{m}$, considering the minimum self-shielding effect of beta particles. The experiments to evaluate the P-N junction were first carried out by electron beam induced current technique employed to experimentally simulate beta emission from nickel-63 and to estimate the total device current. The open-circuit voltage was found to be $0.29\ \text{V}$ and the short-circuit current was $3.3\ \text{A}$. The power output was found to be $66.5\ \text{W}/\text{cm}^2$. From the e-beam test, the good operation of the P-N absorber was confirmed before a radioactive source was fabricated.

The fifth step is to use less radioactive material or a different radioisotope to practice. This will ensure that the expected reaction is working and that the radiation protection measuring methods are efficient. For example, the AgI^{125} reaction can be performed by using AgI^{131} initially. Iodine-131 has a half-life of 8.04 days (59.43 for iodine-125) with energy $364.49\ \text{keV}$ gamma and $191.58\ \text{keV}$ beta ($29\ \text{keV}$ average gamma for iodine-125). This has the advantage of:

- the lower half-life allows contaminations to end faster. As a rule of thumb, 10 half-lives are counted to consider a material not contaminated (except for living animals – the biological half-life is also considered in this case). For iodine-125 that would be roughly 2 years and for iodine-131, less than 2 months;
- since iodine-131 has a much higher gamma emission, it can be easily detected by radiation detectors. This is convenient to access each reaction step is more contaminant, when to change gloves, and the overall radiation exposure;
- being easy to detect also makes it useful to access experiment yields. If $0.5\ \text{mCi}$ ($18.4\ \text{MBq}$) is used and 0.4 (14.8) is measured, that is equal to an 80% fixation efficiency.

But it has the disadvantages of:

- a higher gamma emission results in higher radiation exposure to the operator;

- one mCi (370 MBq) of each isotope result in a different number of atoms. The results obtained might not be representative of the real reaction:

To iodine-131: Half-life: 8.04 days $A = \lambda \cdot N$ $10^{-3} \cdot 3.7 \cdot 10^{10} = \frac{\ln 2}{8.04 \cdot 24 \cdot 60 \cdot 60} \cdot N$ $N = 3.70 \cdot 10^{13} \text{ atoms in 1 mCi}$ $m = 8.06 \cdot 10^{-9} \text{ g in 1 mCi}$	To iodine-125: Half-life: 59.43 days $A = \lambda \cdot N$ $10^{-3} \cdot 3.7 \cdot 10^{10} = \frac{\ln 2}{59.43 \cdot 24 \cdot 60 \cdot 60} \cdot N$ $N = 2.70 \cdot 10^{14} \text{ atoms in 1 mCi}$ $m = 5.75 \cdot 10^{-8} \text{ g in 1 mCi}$
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4.2 Radiation safety

The guiding principle of radiation safety is “ALARA”. ALARA stands for “as low as reasonably achievable”. This principle means that even if it is a small dose, if receiving that dose has no direct benefit, it should be avoided. To achieve this:

- the three basic protective measures in radiation safety already discussed can be used: time, distance, and shielding;
- use the three basic principles of radiation protection: justification, optimization, and dose limitation [49].

The International Commission on Radiological Protection (ICRP) system of radiological protection is a fundamental outline for dealing with any exposure situation in a systematic and coherent manner. At its core, the system relies on the three principles of justification, optimization and dose limitation. The principle of justification ensures that any decision that alters the radiation exposure should do better than harm. The outcome needs to be beneficial to society and the environment. The principle of optimization is for application in situations for which the implementation of protection strategies has been justified. Optimization of the protection strategy ensures that the likelihood of incurring exposures, the numbers of people exposed and the magnitude of their individual doses should be kept as low as reasonably achievable, taking into account societal and economic factors. This means that the level of protection should be the best under the prevailing circumstances, maximizing benefit over harm. Reference levels are adopted as an indicator of the level of exposure considered tolerable. This guideline help liming the dose for workers and public (Table 2) [51–53]. Specific environmental discharge of radioisotopes can be found in Ref. [54].

The basic requirements for achieving the highest standard in radiation safety are:

- Dose limits for radiation workers and members of the public;
- Monitoring and labeling radioactive materials;
- Using personal dosimeter and accurate monitoring detectors;
- Posting signs in and around radiation areas;
- Reporting the theft or loss of radioactive material;
- Having a trained radiation protection team available;
- Managing radioactive waste correctly.

4.3 Leakage tests

Radioactive sources that are used for medical treatments, industrial radiography, and nuclear batteries are routinely leak tested at the time of manufacture and, in some cases, during the lifetime of the sources. The various leak test procedures are designed to detect the presence of leak paths in the containment walls of sources through which radioactive material might escape to the surroundings. Shielding harboring liquid radioisotopes, such as Mo⁹⁹/Tc^{99m} generators are also leak tested. There are several requirements for the tests and they are presented in the ISO 2919 [55] and ISO 9978 [56].

A series of classification steps must be performed so a classification code can be emitted. Each of the tests (temperature, pressure, impact, vibration, and punching) corresponds to a specific digit in the product classification code, and can assume different values (1 to 6), according to the required performance level. The classification result will be an alphanumeric code that characterizes the product according

Categories of exposure (Publications)	1990 Recommendations and subsequent publications	Present Recommendations
Occupational exposure including recovery operations	20 mSv/year average over defined periods of 5 years*	20 mSv/year average over defined periods of 5 years
Eye lens	150 mSv/year	150 mSv/year
Skin	500 mSv/year	500 mSv/year
Hands and feet	500 mSv/year	500 mSv/year
Pregnant women, remainder of pregnancy	2 mSv to the surface of abdomen or 1 mSv from intake of radionuclides	1 mSv to the embryo/fetus
Public exposure	1 mSv in a year	1 mSv in a year
eye lens	15 mSv/year	15 mSv/year
skin	50 mSv/year	50 mSv/year

*With the further provision that the effective dose should not exceed 50 mSv in any one year.

Table 2.
Acceptable dose limits separated by ICRP's publications [50].

Figure 12.
Sealed source classification accordingly with the ISO 2919 standard. The numbers are the classification obtained.

Source type		Tests for production sources		Tests to establish classification of source	
A	Sealed sources containing radioactive material	Immersion (5.1)	Wipe (5.3)	Immersion (5.1)	Wipe (5.3)
A1	Thin single integral window, e.g. smoke detectors				
A2	Low-activity reference sources, e.g. encapsulated in plastic				
A3	Single or double encapsulated sources (excluding H ³ , Ra ²²⁶) for gauging, radiography and brachytherapy	Immersion (5.1) Helium (6.1)	Bubble (6.2)	Immersion (5.1) Helium (6.1)	Bubble (6.2)
A4	Single or double encapsulated Ra ²²⁶ and other gaseous sources	Gaseous emanation (5.2)	Immersion (5.1)	Gaseous emanation (5.2)	Immersion (5.1)
A5	Double encapsulated sources for teletherapy and high activity irradiation sources	Helium (6.1)	Wipe (5.3.2)	Immersion (5.1) Helium (6.1)	Bubble (6.2)
B	Simulated sealed sources of Types A3, A4 and A5			Immersion (5.1) Helium (6.1)	Bubble (6.2)
C	Dummy sealed sources			Helium (6.1)	Bubble (6.2)

Table 3.
All recommended leakage tests. Numbers in () refers to the standard subtitles where the test description can be found.

to the ISO 2919 standard. **Figure 12** shows an example of a sealed source classification.

The ISO 9978 standard establishes the conditions and procedures for carrying out leakage tests on sealed radioactive sources, presenting various methods for inspecting these sources. Appendix A presents a guide for choosing the type of test, depending on the type of source to be controlled. Basically, they are (**Table 3**).

The test choice and performance level depend on the source being evaluated and its use. A source is considered leak thigh if less than 185 Bq (5nCi) is detected.

5. Conclusion and future perspective

The future perspective is that research in the different fields will increase. In the medical field new forms of treatment are being developed. Two new of interest are the lutetium-177 radiopharmaceuticals and nanobrachytherapy. Accordingly with Banerjee et al. [57] research with ¹⁷⁷Lu-based radiopharmaceuticals has demonstrated spectacular growth in recent years. ¹⁷⁷Lu Radiolabeling was performed with monoclonal antibodies, peptides, phosphonate ligands, particulates, steroids, and other small molecules. High success was achieved on treating neuroendocrine tumors with ¹⁷⁷Lu-labeled DOTA-Tyr³-octreotate (DOTA-TATE). Nanobrachytherapy is a new form of brachytherapy that uses radioactive nanoparticles. The major advance is the small size makes it possible to penetrate tumor vascularity and cell barrier, delivering the treatment directly into the target

[35]. Works with gold-198, palladium-103, indium-111, and lutetium-177 are currently being investigated. In industrial applications, one major area that can be highlighted is nuclear power systems, more specifically, nuclear batteries. Withing this, Radioisotope Thermoelectric Generator and betavoltaic batteries. The first mode converts the decay heat to power by using the seebeck effect. Efforts are being made in several countries such as South Korea using strontium-90 for space exploration, Brazil using strontium-90 for oil extraction, and Europe using ameri-cium-241 for space exploration. The second mode uses beta decay (electron) to generate power directly. They are used in micro sensors and random number generators. Betavoltaic batteries using diamond are being developed in Russia and the UK. In South Korea, a p-i-n diode Nickel-63 beta battery is under development.

With research increasing at a fast pace, new students are starting in radiation chemistry, more collaborations are being signed, and the field is becoming more multidisciplinary in nature. This chapter created a guide by summarizing the basic chemistry, concepts, and steps to be consider to achieved the expected results when performing a radioactive reaction. The focus is, through knowledge and practical examples, in achieving high degree of success, protecting the operator, and the environment.

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References

- [1] Neeb KH. The Radiochemistry of Nuclear Power Plants with Light Water Reactors. Berlin: Walter de Gruyter; 1997.
- [2] Daruich de Souza C. Parâmetros para produção de fontes de iodo-125 utilizadas em Braquiterapia [Doctorate, PhD] . IPEN-CNEN/SP, São Paulo: Instituto de Pesquisas Energéticas e Nucleares; 2016.
- [3] Broderick K, Lusk R, Hinderer J, Griswold J, Boll R, Garland M, et al. Reactor production of promethium-147. Applied Radiation and Isotopes. 2019; 144:54-63.
- [4] Meyerhof WE. Elements of Nuclear Physics. New York: McGraw-Hill Book Company; 1989.
- [5] Marie Curie Charity. Marie Curie the scientist [2021] . Available from: <https://www.mariecurie.org.uk/who/our-history/marie-curie-the-scientist>. Access in: 2021, May 17.
- [6] Nobel. Nobel Lectures: Marie Curie Biographical. , Amsterdam. <https://www.nobelprize.org/prizes/physics/1903/marie-curie/biographical/>: Elsevier Publishing Company; 1967.
- [7] Macrovector. Gold vector created by macrovector [2021] . Available from: <https://www.freepik.com/vectors/gold>. Access in: 2021, May 17.
- [8] Macrovector. Buildings factory vector created by macrovector [2021] . Available from: <https://www.freepik.com/vectors/design>. Access in: 2021, May 17.
- [9] Macrovector. Nuclear Energy Icons Vector Created by Macrovector [2021] . Available from: <https://www.freepik.com/vectors/background>. Access in: 2021, May 17.
- [10] Macrovector. Technology vector created by macrovector [2021]. Available from: <https://www.freepik.com/vectors/technology>. Access in: 2021, May 17.
- [11] PCH.VECTOR. Circle vector created by pch.vector [2021] . Available from: <https://www.freepik.com/vectors/circle>. Access in: 2021, May 17.
- [12] Centro de Tecnologia das Radiações - IPEN, Daruich de Souza C. Reprocessamento. Instituto de Pesquisas Energéticas e Nucleares; 2020.
- [13] brgfx. Car vector created by brgfx [2021]. Available from: <https://www.freepik.com/vectors/car>. Access in: 2021, May 10.
- [14] Sul UFdRGd. Usina Nuclear [2021] . Available from: http://www.if.ufrgs.br/tex/fis01043/20041/Moacir/usina_arquivos/usinanuclear.html. Access in: 2021, May 10.
- [15] Laboratory AN. The Alpha-Gamma Hot Cell Facility: used to perform nuclear materials experiments and examinations for over 40 years [2019] . Available from: https://www1.anl.gov/images/ARRA_AGHCF-200.JPG. Access in: 2020, 24 abr.
- [16] Fomin VV, Shevchenko VB, Zemlyanukhin VI, Chugreev NS, Shmidt VS, Kondrat'ev AN, et al. Fundamental Problems of The Reprocessing of Spent Fuel Elements. At Energ [Sov J At Energy]. 1977;43(6): 481-6.
- [17] Maher CJ. Reprocessing and Recycling of Spent Nuclear Fuel (Woodhead Publishing Series in Energy Book 79): Current headend technologies and future developments in the reprocessing of spent nuclear fuels Taylor R, editor: Woodhead Publishing, Elsevier; 2015.
- [18] NAYLOR A, BAXTER W, DUNCAN A, SCOTT AFD. A Miniature Pilot Plant

For The Reprocessing Of Nuclear Fuels Part I-Description And Operation. Journal of Nuclear Energy Parts 1964;18:14.

[19] Reusch W. Virtual Textbook of Organic Chemistry: Chemical Reactivity [2020]. Available from: Michigan State University, <http://www.cem.msu.edu/~reusch/VirtualText/intro1.htm>. Access in: 2021, May 18.

[20] Foltz RD. CRC Handbook of Chemistry and Physics: A Ready-Reference Book of Chemical and Physical Data. 4 ed: CRC Press Inc; 2000. 133 p.

[21] Mellor JW. A comprehensive treatise on inorganic and theoretical chemistry. Londres: Longmans, Green and CO; 1965.

[22] Miessler GL, Fischer PJ, Tarr DA. Inorganic Chemistry. EUA: Prentice Hall; 2013.

[23] Kubiawicz DO, inventor; Minnesota Mining and Manufacturing Company, assignee. Radioactive iodine seed1982.

[24] Ouellette RJ, Rawn JD. 1 - Structure of Organic Compounds. In: Ouellette RJ, Rawn JD, editors. Principles of Organic Chemistry. Boston: Elsevier; 2015. p. 1-32.

[25] Clark J. <https://www.chemguide.co.uk/atoms/bonding/electroneg.html> [2013] . Available from: <https://www.chemguide.co.uk/atoms/bonding/electroneg.html>. Access in: 2021, May 20.

[26] Lee J-B, Park U, Son K, Choi K, Yu K. Mass Production of Source Core for Iodine-125 Seed. Bull Korean Chem Soc. 2014;35:2172-4.

[27] Morowitz HJ. CHAPTER XIII - Applications of the Gibbs Free Energy and the Gibbs Chemical Potential. In: Morowitz HJ, editor. Entropy for Biologists: Academic Press; 1970. p. 145-56.

[28] Schmitz KS. Chapter 3 - Gibbs Free Energy, Work, and Equilibrium. In: Schmitz KS, editor. Physical Chemistry. Boston: Elsevier; 2017. p. 99-157.

[29] Daněk V. Chapter 4 - Enthalpy. In: Daněk V, editor. Physico-Chemical Analysis of Molten Electrolytes. Amsterdam: Elsevier Science; 2006. p. 221-53.

[30] University of Central Oklahoma, Jezercak M. Standard Thermodynamic Values [2021] . Available from: <https://www.drjez.com/uco/ChemTools/Standard%20Thermodynamic%20Values.pdf>. Access in: 2021, May 21.

[31] Mudrak I. Ionic conductivity and interfacial interaction in penton/AgI composites. Ionics. 2014;20(1):83-8.

[32] Tani T, Mifune H, Yamashita S, Aiba S, Ohzeki T, Yamane K. Ionic and Electronic Properties of Silver Iodide Grains. Journal of Imaging Science and Technology - J IMAGING SCI TECHNOL. 2007;51(3).

[33] Shukla AK, Ramdas S, Rao CNR. Mechanism of ion movement in AgCl and AgBr. J Solid State Chem. 1973;8(2): 120-5.

[34] Benega MG, Nagatomi H, Rostelato MECM, Peleias Junior FDS, Tiezzi R, Souza CD, et al., editors. Development of radioactive sources fixated in epoxy matrix to verificate nuclear medicine equipments. ENC; 2014; Marselha.

[35] Daruich de Souza C, Zeituni CA, Arcos Rosero WA, Nogueira BR, Rostelato MECM. New gold-198 nanoparticle synthesis to be used in cancer treatment. Brazilian Journal of Radiation Sciences. 2021;09(01-A):18.

[36] Royal Chemical Society. Iodine [2015] . Available from: Access in: 2015, 30 out.

- [37] Kennedy JA, Besses GS. Comparison of Adsorption of Iodine-131-Thyroxine to Glass and Plastic Containers. *J Nucl Med.* 1967;8:226-228
- [38] He JH, Jiang L, Xingliang L, Wenbin Z, Jing W, Zongping M, et al. Preparation of the radioactive source core of iodine-125 seed. *Nucl Sci Tech.* 2009;20(4):231-234
- [39] Daruich de Souza C, Alberto Zeituni C, Feher A, Augusto Moura J, Luiz da Costa O, Angelocci LV, et al. New core configuration for the fabrication of 125I radioactive sources for cancer treatment. *Applied Radiation and Isotopes.* 2020;165:109307.
- [40] Podgorsak EB. *Radiation Oncology Physics: A Handbook For Teachers And Students.* Viena2005.
- [41] Weinberg RAW, Robert A. *The Biology of Cancer.* 1st edition ed: Taylor & Francis; 2006.
- [42] Lindquist C. *gamma* knife radiosurgery. *Semin Radiat Oncol.* 1995; 5(3):197-202.
- [43] Katemangostar. Business vector created by katemangostar [2021] . Available from: <https://www.freepik.com/vectors/business>. Access in: 2021, May 25.
- [44] Macrovector. Online medicine elements vector created by macrovector [2021] . Available from: <https://www.freepik.com/vectors/design>. Access in: 2021, May 25.
- [45] Macrovector. Fast customer support technical assistance vector created by macrovector_official [2021] . Available from: <https://www.freepik.com/vectors/business>. Access in: 2021, May 27.
- [46] Nuclead. Lead Safety Products, Lead Safety Clothing & Garments [2021]. Available from: <https://www.nuclead.com/safety-2/>. Access in: 2021, May 25.
- [47] Silva JT. Distribuição da atividade de Fósforo-32 e o revestimento com silicone em placas poliméricas para tratamento de câncer paraespinal e intracranial.: Instituto de Pesquisas Energéticas e Nucleares; 2020. Contract No.: Seminário de Área- 02/2020.
- [48] Uhm YR, Choi BG, Kim JB, Jeong D-H, Son KJ. Study of a Betavoltaic Battery Using Electroplated Nickel-63 on Nickel Foil as a Power Source. *Nuclear Engineering and Technology.* 2016;48 (3):773-7.
- [49] Shapiro J. *Radiation protection.* United States: Harvard University Press; 1990.
- [50] International Commission on Radiological Protection. The 2007 Recommendations of the International Commission on Radiological Protection. <https://www.icrp.org/publication.asp?id=ICRP%20Publication%20103>: International Commission on Radiological Protection,; 2207. Contract No.: ICRP Publication 103.
- [51] Protection ICoR. ICRP 60: Occupational radiological protection in interventional procedures. <https://www.icrp.org/publication.asp?id=icrp%20publication%2060>: International Commission on Radiological Protection. ICRP Publication 21; 1991.
- [52] Lopez PO, Dauer LT, Loose R, Martin CJ, Miller DL, Vaño E, et al. Occupational radiological protection in interventional procedures. <https://www.icrp.org/publication.asp?id=ICRP%20Publication%20139>: International Commission on Radiological Protection. ICRP Publication 139; 2018.
- [53] Nisbet A. Justification, Optimisation and Dose Limitation Following Nuclear Accidents – An ICRP Perspective.

European ALARA Network Workshop
n°17; Lisbon; 2017.

[54] International Atomic Energy Agency. Clearance Levels for Radionuclides in Solid Materials: Application of Exemption Principles. https://www-pub.iaea.org/MTCD/Publications/PDF/te_855_web.pdf, Vienna: International Atomic Energy Agency,; 1996. Report No.: IAEA-TECDOC-8S5 Contract No.: IAEA-TECDOC-8S5.

[55] International Standard Organization. Radiological protection - Sealed radioactive sources - General requirements and classification. <https://www.iso.org/standard/54441.html>: International Standard Organization; 2012. p. 19.

[56] International Standard Organization. Radiation protection - Sealed radioactive sources - Leakage test methods. <https://www.iso.org/standard/70598.html>: International Standard Organization; 2020.

[57] Banerjee S, Pillai MRA, Knapp FF. Lutetium-177 Therapeutic Radiopharmaceuticals: Linking Chemistry, Radiochemistry, and Practical Applications. *Chem Rev.* 2015; 115(8):2934-74.