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Safety assessment methodology in management of spent sealed sources

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Abstract

Environmental hazards can be caused from radioactive waste after their disposal. It was therefore important that safety assessment methodologies be developed and established to study and estimate the possible hazards, and institute certain safety methodologies that lead and prevent the evolution of these hazards.

Spent sealed sources are specific type of radioactive waste. According to IAEA definition, spent sealed sources are unused sources because of activity decay, damage, misuse, loss, or theft. Accidental exposure of humans from spent sealed sources can occur at the moment they become spent and before their disposal. Because of that reason, safety assessment methodologies were tailored to suit the management of spent sealed sources. To provide understanding and confidence of this study, validation analysis was undertaken by considering the scenario of an accident that occurred in Egypt, June 2000 (the Meet-Halfa accident from an iridium-192 source).

The text of this work includes consideration related to the safety assessment approaches of spent sealed sources which constitutes assessment context, processes leading an active source to be spent, accident scenarios, mathematical models for dose calculations, and radiological consequences and regulatory criteria. The text also includes a validation study, which was carried out by evaluating a theoretical scenario compared to the real scenario of Meet-Halfa accident depending on the clinical assessment of affected individuals.

Keywords: Spent sealed sources; Safety assessment

1. Introduction

The general management process of radioactive waste material (liquid and solid) has been established to protect humans and the environment. This process starts with waste collection and ends by their disposal in suitable sites. Usually, environmental hazards from radioactive wastes appear after closure of the disposal site. The radionuclides can find their way to migrate from the burial design to reach the human environment. Due to that reason and according to international concepts [1] in the management of radioactive wastes, safety assessment procedures were established for the disposal processes [1–4]. These safety procedures are carried out to ensure compliance with the radiological protection and nuclear safety standards necessary for the disposal site. It is carried out by the estimation of the possible hazard of the radioactive waste disposed using mathematical models. The environmental pollution and possible individual exposures calculated help the decision-makers to take into consideration safety procedures and regulations to prevent impact occurrence.

Sealed sources are encapsulated radioactive materials of high specific activity ranging from 1 KBq to more than 1 PBq [5]. The capsule is strong enough to prevent dispersion of radioactive material. Several types of mobile and stationary sealed sources are used for various applications mainly, medicine, industry, research, agriculture, and other purposes under normal conditions. However, according to the IAEA definition [5], damaged, lost, and stolen sources are also considered spent sealed sources. This definition is derived from the fact that these sources are difficult to retrieve when

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lost or stolen. The number of spent sealed sources in developing countries is more than 100,000 sources according to the IAEA estimates [5]. Spent sealed sources are considered as radioactive waste of specific forms and nature. Health hazards, and sometimes environmental pollution, may result from sealed sources during the operational life of the source, mostly during transportation, operation, and storage steps (by damage, misuse, loss, and theft). On average, more than two accidents have been reported worldwide per year [5]. These accidents may cause uncontrolled radiation exposure to humans. Health hazards resulting from radiation exposure include acute deterministic effects and/or delayed stochastic effects [6,7]. The type and severity of effects depend on the absorbed dose and mode of exposure (external or internal) [1]. Therefore, the safety assessment methodology in management of spent sealed sources should be adopted to suit their purposes. The protocol proposed in this treatise is based on the lessons learned from previous accidents in order to provide certain degree of confidence and credibility. In addition, this treatise deals with the safety management of spent sealed sources during operation and storage before their permanent disposal.

2. Objective of the work

Management of spent sealed sources requires education and training for regulatory bodies, vendors and users as recommended in the "Code of Conduct on the Safety and Security of Radioactive Sources" [8–10]. This code was prepared by IAEA to overcome the unacceptable exposure incidents and to ensure the safety and security of radiation sources. The present study can be considered as fundamental training for users of sealed sources. The objective of this treatise is two-fold:

(1) The primary objective is to adapt the steps of the safety assessment methodologies of radioactive waste to suit the assessment methodologies for the safe management of spent sealed sources. This requires the proper understanding of accident causes and their possible consequences; aiming to improve the regulations and guidance related to the safety and security of spent sealed sources (Section 2.1).
(2) The second objective is to evaluate and assess the adapted safety methodology proposed for spent sealed sources (Fig. 1b). This was done through the performance of an evaluation and assessment study by consideration of a proposed scenario of a real accident, and comparing results to the actual events of the accident and its consequences; in particular the clinical manifestations of the exposed individuals. This can lead to the optimization of safety assessment procedures in the management of spent sealed sources (Section 2.2).

2.1. Appraisal of safety assessment methodology of spent sealed sources

Essentially, safety assessment methodologies of radioactive wastes are based on basic sequential components [1] namely: (1) identification of phenomena that could lead to human exposure, (2) estimation of the probability of exposure occurrence, (3) quantification of the effects of these phenomena, (4) calculation of the radiological consequences of exposure and (5) estimation of subsequent health effects to individuals. The improvement of these methodologies is performed through additional analysis; namely sensitivity analysis, uncertainty analysis and validation processes which offer a realistic image of a particular situation and reduces the uncertainty parameters. The safety assessment studies are the responsibility of the assessor.

The safety assessment methodologies for radioactive waste are tailored to accommodate the procedures required for the safe assessment in management of spent sealed sources. Each item of safety methodology should be conditioned to suit the purpose of this objective. Fig. 1a describes the sequential steps for the safety assessment methodology for radioactive waste and Fig. 1b describes the proposed safety assessment methodology for spent sealed sources.

2.1.1. Assessment context of sealed source

The assessment context of spent sealed sources should constitute of two previously documented reports namely (a) the design evaluation report and (b) security evaluation report.

(a) Design evaluation report

This report should be prepared by a qualified person on behalf of the supplier and should include the following:

- Type and form of source encasement (shield).
- Source type, form (powder or solid state), activity and specific activity (in Bq and Bq/g), half-life, and type of radiation emitted and energy spectrum.
- Form of encapsulation (inner shield), dimensions, thickness and type of metal used.
- Design and dimensions of equipment.
- Dose levels at surface of outer shield (at time of source production).
- Exit and entry of source from equipment.
- Mechanism of operation and estimated operational life.
- Precaution information during the different phases of equipment operation.
- Safety items in equipment design, and probability of damage.
- Corrective actions during the malfunction or damage of equipment.
- Type of equipment and field of application.
- Recommendation for proper transportation.
- Recommendation for proper storage.

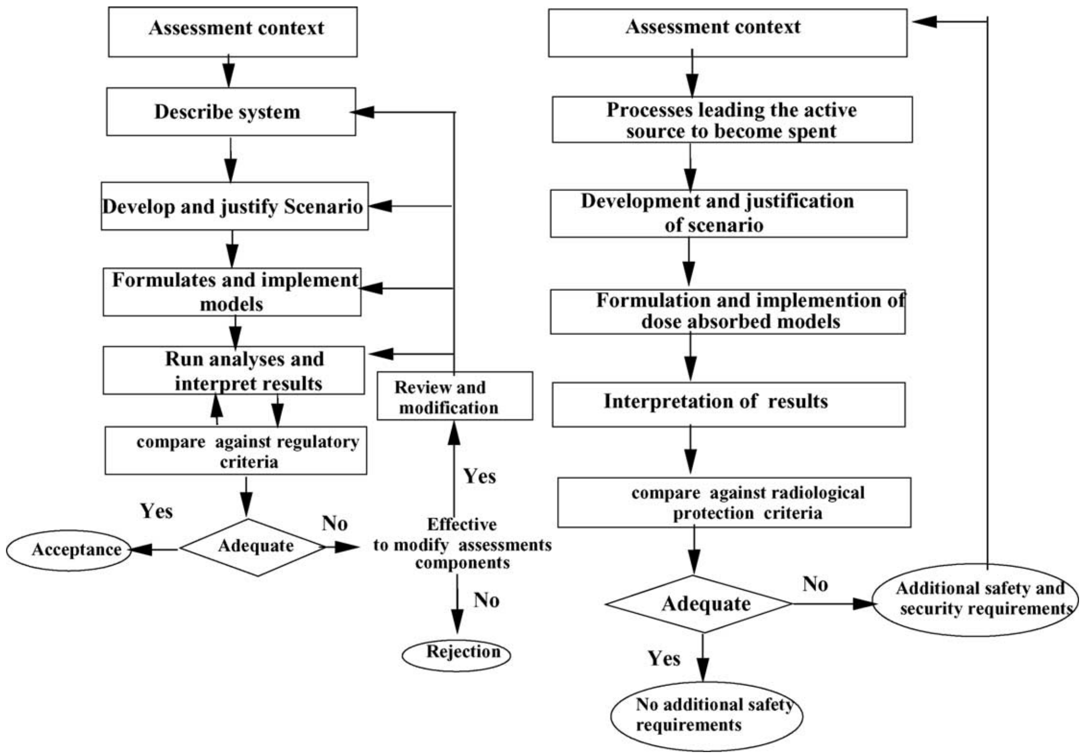

Fig. 1. (a) Safety assessment methodology of methodologies radioactive wastes; (b) proposed safety assessment of spent sealed sources.

(b) Security evaluation report

The security report should be presented on official standard forms by the responsible health physicist and approved by the utility owner. This report should describe all details concerning the following:

- Type of source.
- Description of equipment design.
- Field of application.
- Site of operation (mobile or stationary).
- Design and shielding of storage site (room or pit).
- Operational procedures of source.
- Regulatory control procedures adopted.
- Security measures against loss, theft, and damage.
- Emergency plans and remedial actions, according to consultations with official radiation protection and health physics offices.
- Disposal procedures of decayed sources.
- Name, qualification and license of user/s.

2.1.2. Processes leading the active source to become spent

The probable processes leading an active source to be spent should be considered in the light of the safety measures presented in the design evaluation and security reports. Consideration should concentrate on causes whose occurrence is more probable in spite of the restrictions made by the two reports. These should be carefully described and studied by the assessor. Screening of these processes should be performed to select the most probable processes that may lead the active source to be spent.

2.1.3. Development and justification of scenarios

An accident scenario is a sequential process of events considered for the purpose of illustrating the range and ramification of these events and the involvement of human behavior. The scenario selected should provide adequate overall picture of the exposure situation and should provide justification for the different situations of the scenario. In some situations, an accident from spent sealed sources may involve environmental pollution. A scenario describing such accident will require consideration dealing with the various pathways leading to human exposure both internal and external. The scenario dealing with spent sealed sources depends mainly on human behavior, which makes estimation of the sequence of events hard to follow. Therefore, the choice of appropriate scenarios and the justification of their events should be based on causes described by IAEA publications [11,12]. These causes are based on knowledge of the several accidents that have occurred [13–18]. Accurate knowledge of the events of previous accidents provides suitable logistic information to help formulate intelligent justified scenarios. The development of suitable scenarios and its consequences are considered of major importance in safety assessment methodology of spent sealed sources.

2.1.4. Formulation and implementation of dose absorbed models

The conceptual models are based on scenarios proposed and are used to describe all different processes causing the different exposure modalities to individuals. These conceptual models are further formulated into mathematical equations. There are various mathematical models that treat the external and/or internal exposure dose to individuals such as Popular Model [19], Energy Deposition Model [14], and the French Approach [20]. The Popular Model is popular due to its low uncertainty and low error factor compared to other models. This method utilizes the criteria of the gamma constant. This model was adopted in the evaluation and assessment study considered in this treatise. However, Energy Deposition Model is utilizing the energy deposition in the whole body with the association of high degree of uncertainty due to the assumptions involved the same as for the French approach, which is complicated model using specific multifactorial organ dose scenarios.

Conservatism/and or simplification should be carefully used to overcome the uncertainty of the prediction of human behavior. Uncertainty may be reduced by the performance of evaluation and assessment processes.

2.1.5. Interpretation of results

The results obtained from the mathematical calculations provide an estimate of the radiological consequences in terms of radiation dose. A radiological event is quantified by the overall consequences of human exposure. On the other hand, human exposures should compare with the dose limit provided by the Safety Series on radiological protection of the IAEA [21], and the ICRP [22] publications. It is important to realize that human impacts due to release of radioactive waste after disposal may occur with various probabilities mostly from low dose exposure [23,24]. On the other hand, human impacts due to exposure from spent sealed sources usually occur mostly from high dose exposure resulting in acute deterministic effects and possibly death [25]; however, probabilistic delayed effects after low dose exposures are possible.

2.1.6. Adequacy of safety assessment implemented

The final stage of the safety assessment methodology of spent sealed sources is the judgment of the adequacy of the considerations undertaken. This adequacy is judged by comparing the regulatory limit, which based on the "ALARA" principle and established by the national authority, with the dose exposures obtained. If the exposures calculated are less than the regulatory limit, the safety provisions of the equipment under consideration are sufficient and the safety assessment methodology undertaken is adequate. If not, this indicates that the equipment requires more additional safety design and more security provisions.

2.2. Evaluation and assessment

In order to gain confidence in the assessment methodology adapted, evaluation analysis was performed by consideration of a real accident, which occurred in Egypt during May–July 2000 (Meet-Halfa accident). The evaluation analysis through the proposed scenario will help the modeler to consider various other scenarios of human behavior in similar accidents involving spent sealed sources. It will also improve and integrate the mathematical formulations [26] involved in the calculation of the radiation exposure to exposed individuals.

The assessment context that deals with the safety design and security evaluation reports is not available for this case. Therefore, the available information about the source and some known facts are used as the content of the assessment context to predict a suitable scenario of the accident. The source involved was Ir-192 industrial radiological source used to test pipe welding. The source is a long bar of 18 cm with 8 mm × 4 mm active volume at one end as shown in Fig. 2. The activity of the source was 31.5 Ci when it was found on May 5, 2000 [27].

The known facts about Meet-Halfa accident are as follows [27]: the number of the family involved in the accident was seven including the father (60 years old), sister (55 years old), wife (50 years old), elder son (22 years old, an army recruit), two daughters (17 and 13 years old) and young son (9 years old). The seven members of the family lived in a small house of two rooms and hallway; one utility room which is not frequently used by the family. The upper floor of the house is incomplete and was used at night for sleeping during summer days (Fig. 3).

The loss of the source by the radiographer in the field is the process *leading the active source to be spent*.

Since the exact facts concerning the details of the exposure patterns of the different individuals of the family are unknown; *Scenario Proposed and Dose Calculations* portray the human behavior, which influences the various types of the exposure patterns. The scenario proposed will deal separately with each individual member of the family as related human behavior and exposure

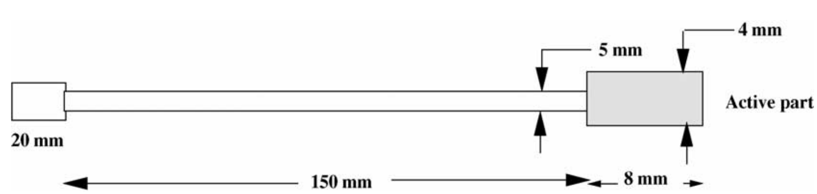

Fig. 2. Schematic design of the iridium source.

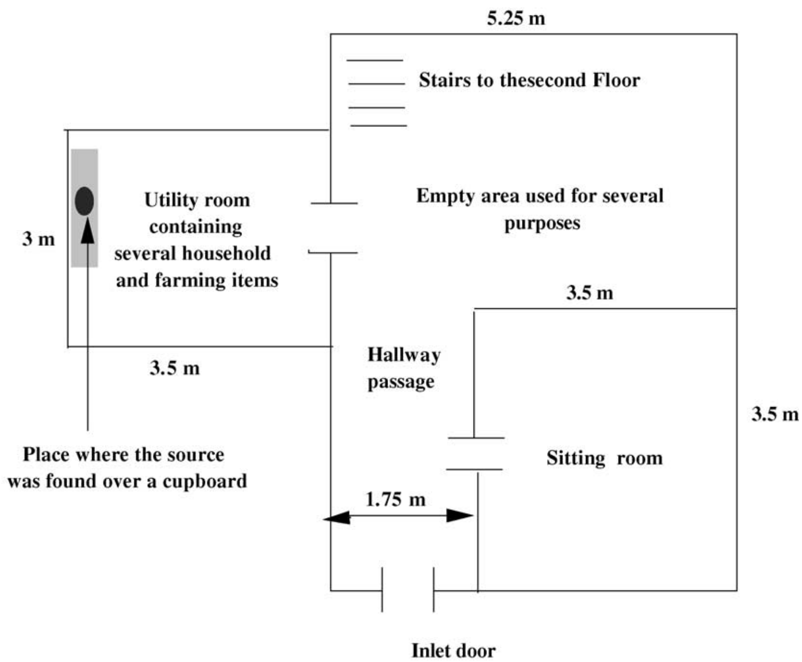

Fig. 3. Plan of the ground floor of the house.

patterns during the period from finding the source to its final retrieval.

- *The father*, after finding the source, he placed it in his pocket for 20–30 min until he arrived home at a distance about 3 km. Therefore, the exposure was localized to an area of his trunk. It is important to recognize that the highest quantity of the bone marrow is in the trunk [28], which was certainly affected by the absorbed dose. This is resulted in acute exposure to skin. At home, he examined the source for about 1 h at a distance of about 50 cm causing exposures to whole body and hands after showing the source to the family members, and he returned handling the source for another 1 h. During these 2 h, he contacted the active part for 30 min. Afraid to lose the source, he hid the source in a safe place.
  During the following 14 days at home, the father trying to discover the nature of the source over interrupted periods by handling the source by different ways and distances; he was exposed to protracted doses over different time periods taken as an average of approximately 1.5–2 h at distances of 0.5–1 m. During the following period until his death, the father gradually became aware of several skin burns on his hands and complained of body weakness resulted from chronic whole body exposure. Therefore, he became concerned with his condition, and also the health condition of his son who showed similar medical complaints. The medical condition of the father imposed him to remain at home with few occasionally period of handling the source. These accumulated doses are known to cause death of the exposed individuals. The calculated exposure doses are presented in Table 1.

Table 1
Calculated dose received by the father

Organ	Absorbed dose (Gy)
Trunk dose	1.5
Whole body dose	7.1–8.4
Hands fingers	5

- *The younger son* during the first 2 weeks, the young son was the most attracted member of the family to the source. He was always close while his father handled the source. He also received direct protracted exposure when he personally handled the source for approximate half-hour daily. During that time, he touched the active part of the source on several occasions for at least 5 min on each occasions. After the first 7–10 days, his hands showed signs of skin burns of various degrees; a condition which prevented him from handling the source with his hands. During the following 10 days, the young boy set close to the source observing without handling it with his hands at a distance about half a meter. Besides receiving a dose to his hands, the boy received a total protracted body dose during all the period. These accumulated doses are known to cause death of the exposed individuals (Table 2).

Table 2
Calculated dose received by the younger son

Organ	Absorbed dose (Gy)
Exposure dose of hands	4.2
Whole body dose	6–7.5

Table 3
Calculated dose received by the younger daughter

Organ	Absorbed dose (Gy)
Whole body dose	3.4–4
Hands	3

Table 4
Calculated dose received by the elder son

Organ	Absorbed dose (Gy)
Whole body dose	4.4–5
Skin dose	4.4

- *The younger daughter* had very limited chance to handle the source during the first 10 days. She handled the source more frequently during the second-week when her brother was not able to handle the source because of the burns of his hands. She only succeeded to handle the source in that period during which she received maximal dose to the hands and smaller dose to her body. Depending on the dose calculated in Table 3, the girl had suffered severe hands burns but not severe condition of bone marrow depression.
- *The elder son*, who is an army recruits, came to the house over the weekends. During the weekends, he handled the source more than any member of the family (being the eldest son of the family). For two successive weekends, the elder son was fascinated by the nature of the metallic source and wished to exhibit the source by putting it in his belt for about 4–5 h during the whole weekend. This gave a substantial dose to the area of the abdomen behind the source (right lower quadrant of the abdomen). This dose mostly received during the period before the severe illness of his brother and father. Table 4 shows the local dose calculated for the elder son. Clinically, he suffered from bone marrow depression in addition to his abdomen burns.
- *The mother, sister, and elder daughter* those three members of family, depending on the scenario, received similar doses. The three are more wises and more occupied in different work to do. Based on that, the three members are exposed to the source 4–5 h daily at 3 m far during the 5 weeks until the retrieval of the source. They suffered from bone marrow depression with lately appearance than the other members. Clinically, the three are recovered from bone marrow depression after hospitalization. The protracted dose calculated for each is represented in Table 5.

The exposure dose of the family members calculated depending on the scenario proposed and presented in Tables 1–5

Table 5
Calculated dose received by the three members (mother, sister, and elder daughter)

Organ	Absorbed dose (Gy)
Whole body dose in 14 days	3.3–4.3

had crossed the limit of exposure dose defined in IAEA [21], and the ICRP [22] publications. According to *the safety assessment methodology adopted, the safety management system of the iridium source is not adequate*. The reasons led to this accident:

- the mal function of the equipment (mechanical defect),
- weak security,
- leak in the qualification of radiographer,
- leak in the surveillance program of the responsible of physical protection in the utility,
- ignorance of people about the sealed sources.

Consequently, *additional safety design and security requirements* should provided to improve the safety management system of similar source.

2.2.1. Clinical manifestations of the real accident

Three weeks after May 5 (time when the source was found by the father), the young son and the father developed marked skin burns and complained of marked weakness. Seeking medical advice, the young boy was hospitalized and died 1 week later. The diagnosis was severe infected skin burns and bone marrow depression without indication of the cause. About 1 week later, the father died complaining of the same clinical manifestations.

The source was retrieved on the 26 June, and the rest of the family members were hospitalized in a specialized hospital. The clinical manifestations reported was marked bone marrow depression with severe skin burns to both hands and fingers of the younger girl and severe localized skin burn of the elder son appearing on the right lower quadrant of the abdomen. All the five members were given the necessary medical treatment and discharged from the hospital after 1 month. The burn of the elder son was attended by skin graft on three occasions. However, the three grafts failed due to underlying infection. The rest of the family members recovered from the bone marrow depression and discharged. Table 6 presents the comparison of radiation dose estimated to the exposed groups as recorded by the medical investigations [27] and the radiation dose calculated in the proposed scenario. This data was provided by a competent attending physician closely related to the accident event [28].

Table 6
Comparison of radiation dose clinically recorded and calculated depending on scenario proposed

Members	Dose (Gy) recorded by the clinical investigations [27]	Dose (Gy) calculated through the scenario proposed
Father	7.5–8 total body	7.1–8.4 total body
Younger son	5–6 total body	6–7.5 total body
Younger daughter	3.5–4 localized	3 localized
Elder son	3.5–4 localized	4.4 localized
Sister	3.5–4 total body	3.3–4.3 total body
Wife	3.5–4 total body	3.3–4.3 total body
Elder daughter	3.5–4 total body	3.3–4.3 total body

The radiological dose tabulated for the two cases clinically and theoretically depending on the scenario, as is presented in Table 6, show nearest dose that lead to the same radiological effects. Except for the localized dose of the younger daughter, the theoretical value represents higher value than the recorded clinical dose. However, this slight difference does not contribute to different radiological effect. That is resulting convenient proposed scenario with the real situation of the accident. This concludes the relevance of the adopted safety assessment methodology for the management of spent sealed sources.

3. Summary and conclusions

A safety assessment methodology was adopted for the safe management of spent sealed sources from the safety assessment methodology of radioactive waste disposal. The structure of the adopted methodology consists of assessment context, processes leading an active source to be spent, development of scenarios, mathematical models for dose calculations and radiological consequences, and comparison with regulatory criteria.

The assessment context of the adopted methodology is represented by the design evaluation and the security evaluation reports. The first is prepared by the supplier and the second by the utility owner. These two reports will provide the assessor all information and details about the sealed source under consideration. Based on these reports, the assessor will expect the probable processes that lead the active source to become spent and suitable scenarios will be built based on these processes. The scenario proposed is formulated into suitable mathematical dose exposure models. The exposure doses calculated are compared with the radiological national regulatory criteria to assess the safety measures and security provisions, which are applicable.

In order to gain confidence in the assessment methodology adopted, evaluation analysis was performed by consideration of a real accident, which occurred in Egypt during May–July 2000 (Meet-Halfa accident). The various items of the methodology were demonstrated and analyzed by the discussing the features of the accident. A scenario of the accident was assumed. The results of individual dose exposures obtained from the scenario proposed were evaluated by comparison with the clinical manifestations of the exposed individuals and their consequences. The comparison showed the same radiological effects.

From the present treatise the following conclusions are reached:

- The spent sealed sources are specific type of radioactive waste that requires distinctive management because the majority of accidental exposures of humans from spent sealed sources occur at the moment they become spent and before their disposal.
- The safety assessment methodology of radioactive waste disposal is a flexible methodology, which can be adapted to suit the safe management of spent sealed sources.
- The design and the safety provisions of sealed sources are the key components for the safe management of the source at the moment it becomes spent.
- The prediction of human behavior during the development of scenarios is considered the most complicated aspect in the methodology. Therefore, this prediction should be based on suitable logistic information to help create intelligent justified scenarios.
- The choice of appropriate scenarios and the justification of their events should be based on causes described by IAEA publications. These causes are based on knowledge of the several accidents that have occurred.
- On the same time, the scenario developed should be general, flexible and reflects a common behavior depending on the following factors:
  (a) source type, form, and dimension,
  (b) sex, age, social state and conditions of persons handling the source,
  (c) place of scenario and its dimension.
- The assessor should be aware of the radiological effect of the calculated dose to individual to develop the most realistic scenario.
- The adopted safety methodology will help assess the safety and security of the management of spent sealed sources and provide an understanding of what is needed to assure and improve safety for present and future management.
- Additionally, this methodology helps to improve the safety of the management system provided for the source during its operational life.

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