Radium Timepiece Dose Modeling

FINAL REPORT
REVISION 1

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Prepared for the
U.S. Nuclear Regulatory Commission

ORISE
Oak Ridge Institute for Science and Education

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RECORD OF REVISIONS

Revision	Issue Date	Description and Reason for Change
0	January 2007	Initial Issue
1	September 2007	Text in the Executive Summary, Introduction and Summary sections of the report was updated at the request of the Nuclear Regulatory Commission. The updates are intended to clarify the report, and do not change any results or conclusions. No changes were made to any section in the body of or appendices to the report.

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EXECUTIVE SUMMARY

1 Purpose

The Energy Policy Act of 2005 amended section 11e.(2) of the Atomic Energy Act of 1954 to place certain accelerator-produced radioactive material and discrete sources of radium-226 (Ra-226) under U.S. Nuclear Regulatory Commission (NRC) regulatory authority as byproduct material. Historically, each State had independent jurisdiction over Ra-226 and some States developed regulations for controlling this material. The model State standards provide an exemption for previously acquired timepieces with no more than 1 microcurie (μCi) of Ra-226. The Energy Policy Act of 2005 mandated that the NRC use model State standards, to the extent practicable, in developing its regulations for the expanded definition of byproduct material.

The primary purpose of this scoping report is to present an assessment of the potential radiological doses associated with Ra-226 timepieces. The results of this scoping study can provide the technical basis upon which the NRC can review, examine, and decide on an appropriate regulatory approach to ensure protection of the health and safety of the public.

2 General Approach to Dose Assessments

The objective of this scoping study is to calculate bounding estimates of potential radiological exposures to members of the public. This scoping study uses a simplified method for evaluating these potential exposures by incorporating existing models, parameters, assumptions, and available historical data into exposure scenarios in which an individual receives a dose from a radium-containing timepiece. In general, more sophisticated assessments will yield dose estimates that are significantly lower than those calculated in this scoping method. Therefore, if the doses calculated in this scoping study are considered acceptable, no additional analysis is necessary.

A series of nine exposure scenarios were developed to consider credible situations in which an individual may receive a dose from radium-containing timepieces. NUREG-1717, "Systematic Radiological Assessment of Exemptions for Source and Byproduct Materials," dated June 2001, had previously considered doses from tritium (H-3) and promethium-147 (Pm-147) containing timepieces, and provided general basis for many of the exposure scenarios in this scoping assessment. This includes adaptation of exposure scenarios, as well as mathematical equations used to calculate doses from the different exposure pathways in each scenario.

The radiological dose assessments were, in general, based on reasonable assumptions. This scoping assessment takes into consideration a potential exemption from licensing for Ra-226 timepieces for consistency with model State standards and limited existing data on the current uses of Ra-226 timepieces. For some of the scenarios, establishing exposure assumptions was difficult, mainly because the exemption is only for previously manufactured timepieces and the typical scenarios have likely changed from current routine use. For the scenarios involving accidents or non-routine conditions, the intent is to use prudently conservative parameter values.

Of the nine scenarios, scenarios 1 through 5 describe the use and repair of a single functional timepiece. Scenarios 6 through 9 describe collections of multiple timepieces, including collections of varying size. Of these, scenarios 7 through 9 describe accidents involving fires and accidental dispersion of Ra-226 from timepieces. Table 1 provides a summary of the scenarios, the assessed dosimetric quantity, and the exposure pathways considered.

Table 1) Summarized scenario descriptions

Scenario	Description	Assessed quantity	Exposure pathways
1	Dose to the skin from wearing a timepiece	Shallow-dose equivalent	External exposure
2	Dose to self from wearing a timepiece	Effective dose equivalent	External exposure
3	Dose to other individuals in the vicinity from wearing a timepiece	Effective dose equivalent	External exposure
4	Dose from a stationary timepiece	Effective dose equivalent	External exposure
5a	Dose due to professional repair activities	Total effective dose equivalent	External exposure Inhalation of paint Ingestion of paint Inhalation of radon
5b	Dose due to amateur repair activities	Total effective dose equivalent	External exposure Inhalation of paint Ingestion of paint Inhalation of radon
6	Dose due to collecting a large number of timepieces	Total effective dose equivalent	External exposure Inhalation of radon
7	Dose due to a catastrophic fire involving a collection of timepieces	Committed effective dose equivalent	Inhalation of smoke
8	Inhalation of resuspended activity during post-fire cleanup activities	Committed effective dose equivalent	Inhalation of resuspended activity
9	Ingestion of activity during handling or cleanup of non-intact timepieces	Committed effective dose equivalent	Ingestion of paint

Although the literature presents a range of activities for Ra-226 timepieces, the dose assessments in this scoping study are based on the exemption activity limit of 1 μCi of Ra-226 in model State standards. That is, all source terms were normalized to a 1 μCi average timepiece activity. Final dose estimates are presented to two significant figures.

3 Summary of Results

Scenario 1 estimates the shallow-dose equivalent to the skin of an individual who wears a Ra-226 wristwatch for 16 hours per day (hrs/day). The shallow-dose equivalent calculated to the skin is 1,600 millirem per year (mrem/yr).

Scenario 2 estimates the effective dose equivalent to a person who wears a radium-containing timepiece. In this scenario, a person is either being exposed to a Ra-226 wristwatch or a Ra-226 pocket watch worn in either a pants or vest pocket for 16 hrs/day. The effective dose equivalent calculated is: 61 mrem/yr for a person who wears a Ra-226 wristwatch, 110 mrem/yr for a person who wears a Ra-226 pocket watch in a pants pocket, and 480 mrem/yr for a person who wears a Ra-226 pocket watch in a vest pocket.

Scenario 3 estimates the effective dose equivalent to family members, office coworkers, and individuals in the vicinity of a person wearing a Ra-226 wristwatch or pocket watch. Family members are exposed for 12 hrs/day, office coworkers are exposed for 8 hrs/day, and individuals in the vicinity of a wearer are exposed for 100 hours per year (hrs/yr). For all three affected groups, the effective dose equivalent calculated is less than one millirem per year (< 1 mrem/yr).

Scenario 4 estimates the effective dose equivalent to individuals who are routinely in the vicinity of a stationary Ra-226 clock. This radium-containing device has the potential to expose family members, office occupants, office coworkers, and individuals who spend time in communal areas where this device is located. A Ra-226 clock in a communal area of a residence, such as a living room, exposes family members for 1,460 hrs/yr. When the clock is on a bedroom night stand, the exposure duration is 2,920 hrs/yr. The effective dose equivalent calculated is < 1 mrem/yr for family members exposed in a communal area of a residence, and 2.5 mrem/yr when the clock is located on a bedroom night stand. A Ra-226 clock exposes an office occupant for 2,000 hrs/yr, and office coworkers either passing by an office with a Ra-226 clock or in an employee lounge with a Ra-226 clock are exposed for 100 hrs/yr. An office occupant receives an effective dose equivalent of 1.7 mrem/yr, and office coworkers receives an effective dose equivalent of < 1 mrem/yr when exposed to a Ra-226 clock either passing by another coworker's office or while in an employee lounge.

Scenario 5a estimates the total effective dose equivalent to an individual who is employed as a jewelry and watch repair technician. A repair technician is exposed while repairing either a Ra-226 wristwatch, pocket watch, or clock and also to the inventory of radium-containing spare parts kept in the shop. A repair technician will work for 3 hrs repairing a device and will be exposed to the inventory of spare parts for 2,000 hrs/yr. The repair technician receives a total effective dose equivalent of 150 mrem/yr.

Scenario 5b estimates the total effective dose equivalent to an amateur who repairs a radium-containing timepiece in his or her timepiece collection. The amateur repairer is exposed while repairing a Ra-226 wristwatch, pocket watch, or clock and also to the inventory of radium-containing spare parts kept in their work area. The amateur will work for 25 hrs repairing a radium-containing timepiece and will be exposed for 5,840 hrs/yr to the inventory of radium-containing spare parts. The total effective dose equivalent calculated for the amateur repairer is 15 mrem/yr.

Scenario 6 estimates the total effective dose equivalent to an individual who collects radium-containing timepieces, and to family members, office occupants, and office coworkers routinely near the collection. A collection of radium-containing timepieces kept in a communal area of a residence, such as a living room, exposes family members for 4,380 hrs/yr. A collection of radium-containing timepieces kept in an office exposes the office occupant for 2,000 hrs/yr and exposes office coworkers for 100 hrs/yr. The total effective dose equivalent per microcurie of Ra-226 in the collection is calculated as: 2.1 mrem/yr for family members and an office occupant, and < 1 mrem/yr for office coworkers.

Scenario 7 estimates the committed effective dose equivalent to an individual who inhales smoke during a catastrophic fire involving a collection of Ra-226 timepieces assuming the individual is trapped in the fire for 30 minutes (mins). The committed effective dose equivalent depends on the collection size and building/room volume. The committed effective dose equivalent calculated for an individual who inhales smoke from a collection of 50 radium-containing timepieces is: 5.1 mrem in a room volume of 40 cubic meters (m^3), and < 1 mrem for building volumes of 450 m^3 and 1,000 m^3.

Scenario 8 estimates the committed effective dose equivalent to an individual who inhales Ra-226 particles as they perform post fire clean-up activities from the catastrophic fire of scenario 7 that destroyed a collection of radium-containing timepieces. The post fire clean-up process lasts for 30 mins. The committed effective dose equivalent depends on the collection size. The committed effective dose equivalent calculated for an individual who inhales Ra-226 particles during post fire clean-up activities from a collection of 50 radium-containing timepieces is 2.6 mrem.

Scenario 9 estimates the committed effective dose equivalent to an individual who ingests Ra-226 particles as they handle non-intact timepieces, either as they perform post fire clean-up activities from the catastrophic fire of scenario 7, or as they perform other activities with non-intact timepieces. Similar to scenario 8, the committed effective dose equivalent depends on collection size. The committed effective dose equivalent for an individual who ingests Ra-226 particles while handling a collection of 50 non-intact radium-containing timepieces is 6.6 mrem.

The normalized dose factors are summarized below. Figure 1 presents the dose factor per microcurie in a single functional timepiece for Scenarios 1-4. Figure 2 presents the dose factor per microcurie for Scenarios 5-9. Note that Figure 1 is presented with a logarithmic scale, while Figure 2 is presented on a linear scale.

While the dose factors per source unit for Scenarios 1-4 are generally higher than the dose factors per source unit for Scenarios 5-9, it is important to realize that the total source term will likely be much larger for Scenarios 5-9, yielding higher total doses.

Figure 1) Dose factors from a single functional timepiece

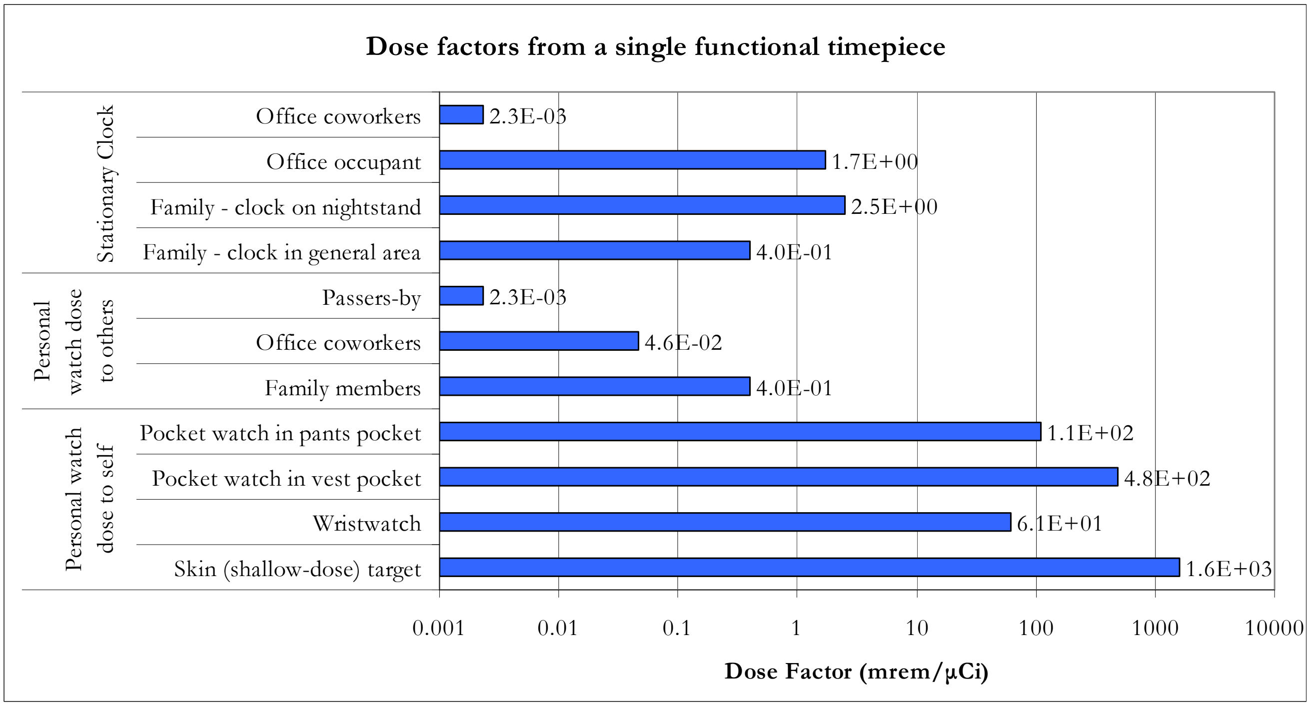
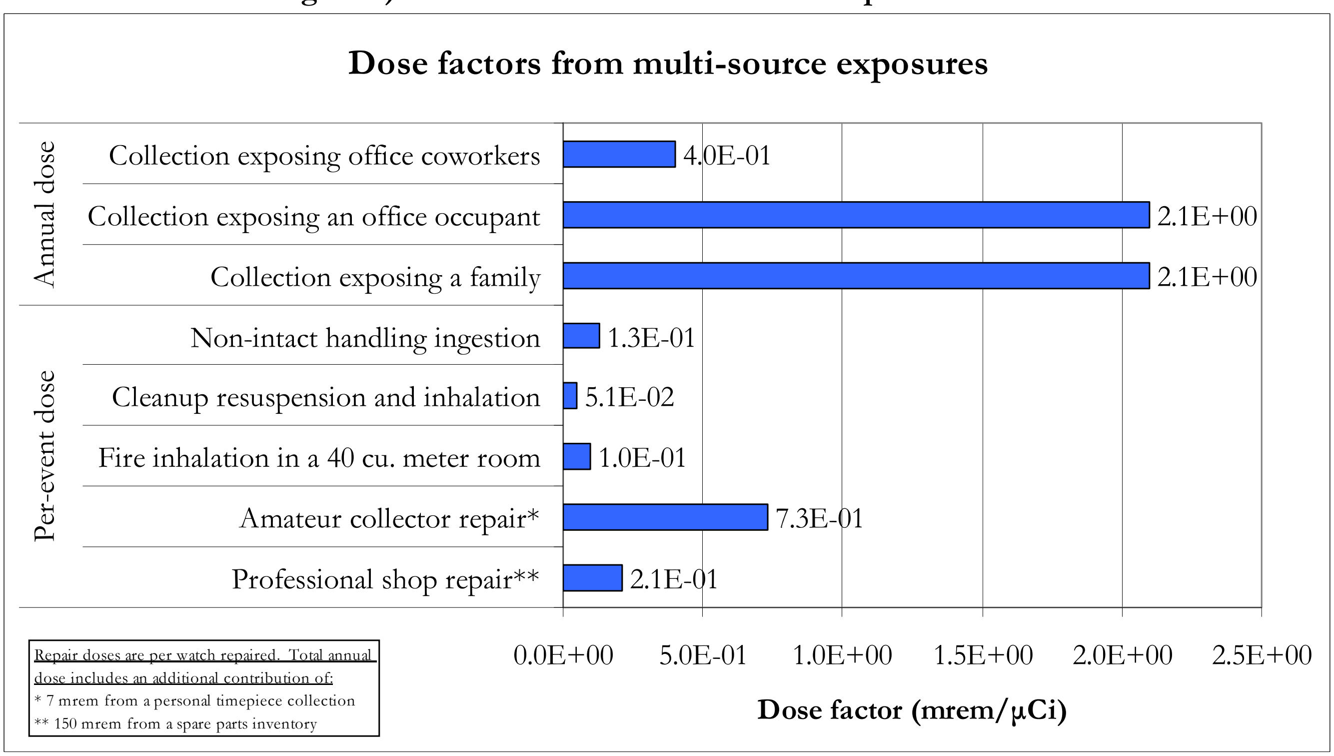


Figure 2) Dose factors from multi-source exposures



1.0 Introduction

In Title 10 of the Code of Federal Regulations, the U.S. Nuclear Regulatory Commission (NRC) and its predecessor agency, the U.S. Atomic Energy Commission, established regulations specifying products or materials containing source or byproduct material for which the possession, use, and transfer are exempted from requirements for domestic licensing. Many of the existing exemptions apply to consumer products containing radioactive material. In addition, some existing exemptions apply to other uses of radioactive material, or only to highly specialized uses of radioactive material not involving consumer products, e.g., uses in particular industries. However, the NRC did not have regulations for all radioactive material contained in consumer products, in particular, radium-226 (Ra-226), because certain material were previously not covered by the Atomic Energy Act of 1954.

The Energy Policy Act of 2005 amended section 11e.(2) of the Atomic Energy Act of 1954 to define certain accelerator-produced radioactive material and discrete sources of Ra-226 as byproduct material, thus placing them under NRC regulatory authority. Historically, each State had independent jurisdiction over Ra-226 and some States developed regulations for controlling this material. The model State standards provide an exemption for previously acquired timepieces with no more than 1 microcurie (μCi) of Ra-226. The Energy Policy Act of 2005 mandated that the NRC use model State standards, to the extent practicable, in developing its regulations for the expanded definition of byproduct material.

In response to this Congressional mandate, NRC staff with the assistance of Agreement State representatives developed a rulemaking entitled "Requirements for the Expanded Definition of Byproduct Material." This rulemaking provides the basic regulatory framework for regulating additional byproduct material as defined in the Energy Policy Act of 2005. One objective of this rulemaking was to establish exemptions and general license provisions for certain products and items containing Ra-226. For example, the NRC is exempting from licensing requirements previously manufactured intact timepieces containing no more than 1 μCi of Ra-226 per timepiece. The NRC also developed a general license to grant authority to any person to acquire, receive, possess, use, or transfer small amounts of Ra-226 incorporated in a number of categories, including intact timepieces containing greater than 1 μCi, non-intact timepieces, and timepiece hands and dials no longer installed in timepieces.

This scoping report provides radiological dose estimates for individuals exposed to radium-containing wristwatches, pocket watches, and clocks through various exposure scenarios. These dose estimates provide an assessment upon which the NRC can examine the potential radiological impact associated with the exemption activity limit of 1 μCi of Ra-226 and determine the appropriate regulatory approach for ensuring protection of public health and safety, with respect to radium-containing timepieces, without creating any undue regulatory burden.

2.0 Description of Items

2.1 Brief history of radioluminescent paint

Beginning in the early 1900s, various radioactive materials, including radium, were used to make self-luminescent paint. This self-luminescent paint was used to make a wide variety of items "glow" in the dark, such as watch and clock hands, airplane dials and gauges, and signs.

In the United States, the first company to produce radioluminescent paint was the Radium Luminous Material Corporation in Newark, New Jersey. It was founded in 1914 by Sabin von Sochocky and George Willis, both physicians. Their operations expanded tremendously when the United States entered World War I, and in 1917 they moved from Newark to Orange, New Jersey. They also expanded into the business of mining and producing radium. In 1921, they changed their name to the U.S. Radium Corporation. The brand name for the radioluminescent paint produced by U.S. Radium Corporation was "Undark." In addition, the Standard Chemical Company used the name "Luna" and the Cold Light Manufacturing Company, a subsidiary of the Radium Company of Colorado, made "Marvelite."

In the 1920s, "mesothorium" was sometimes added to radioluminescent paint. Mesothorium is the historical name given to radium-228 (Ra-228) which as a half-life of 5.8 years. Ra-228 is a beta emitter, but over time it decays into thorium-228 (Th-228), which is an alpha emitter with a half-life of 1.9 years. The result is that the intensity of the light from the paint will increase over the first five years or so due to the in-growth of the Th-228. The practice of adding mesothorium ended by 1930. Any mesothorium that might have been used will no longer be present, given that it has long since decayed away. (Frame 1999)

As time and science progressed, society began to realize that radioactive materials posed potential health risks. The most famous instance began in the 1920s with the plight of the radium-dial painters, who ingested radium as they "tipped" the paintbrushes with their mouths.

Despite the risks, radium continued to be used heavily in self-luminescent paint in the United States into the 1960s. Gradually, beginning in the 1950s, other nuclides began to replace radium in self-luminescent paint. Nuclides that were tried for a time, but never gained a strong market, include strontium-90 (Sr-90) and carbon-14 (C-14). The nuclides of choice today are tritium (H-3) and promethium-147 (Pm-147), which present a much lower radiological hazard.

According to the National Council on Radiation Protection and Measurements in Report 95, *Radiation Exposure of the U.S. Population from Consumer Products and Miscellaneous Sources* (NCRP 1987), radium has not been used in radioluminescent watches since approximately 1968, or in clocks since 1978.

Today, radium timepieces have become collectible antiques. Current commercial and personal sites on the internet convey the intense interest some individuals have in searching for and collecting old radium timepieces.

2.2 Physical and chemical properties of radioluminescent paint

Ra-226 is an alpha emitter with a 1600 year half-life. It emits a gamma ray at 186 keV. Radium decays into a number of short-lived decay products that can usually be expected to be present at, or close to, the same activity as the radium. These decay products emit alpha particles, beta particles and gamma rays. A brief summary of the decay chain is presented in Table 1.

Table 1) Radium-226 decay-chain data

Nuclide	Decay mode	Half life	MeV	Product of decay
Ra-226	α	1600 a	4.9	Rn-222
Rn-222	α	3.8235 d	5.6	Po-218
Po-218	α 99.98 % β^- 0.02 %	3.10 min	6.0 0.27	Pb-214 At-218
At-218	α 99.90 % β^- 0.10 %	1.5 s	6.7 2.9	Bi-214 Rn-218
Rn-218	α	35 ms	7.3	Po-214
Pb-214	β^-	26.8 min	1.0	Bi-214
Bi-214	β^- 99.98 % α 0.02 %	19.9 min	3.3 5.6	Po-214 Tl-210
Po-214	α	0.1643 ms	7.9	Pb-210
Tl-210	β^-	1.30 min	5.5	Pb-210
Pb-210	β^-	22.3 a	0.064	Bi-210
Bi-210	β^- 99.99987% α 0.00013%	5.013 d	1.4 6.0	Po-210 Tl-206
Po-210	α	138.376 d	5.4	Pb-206
Tl-206	β^-	4.199 min	1.5	Pb-206
Pb-206	.	stable	.	.

Data from the Chart of Nuclides hosted online by the U.S. Department of Energy's Brookhaven National Laboratory
a=Years, d=Days, min=Minutes, s=Seconds, ms=Milliseconds

Radioluminescent paint consists of a radioactive material mixed together with a luminescent crystalline powder. The radium is usually in the form of radium sulfate, which is less soluble than the other radium salts that were historically available (radium bromide and radium chloride). The most widely used luminescent powder is zinc sulfide (ZnS). The light emitted by the paint is due to the radiation energy deposited in the luminescent crystals by alpha and/or beta particles. The greater the number of alpha or beta particles striking the crystals, and the greater the energy deposited in them, the brighter the light.

More detailed information about the radioluminescent paint is reported an a 1987 article by Ed Landa (Landa 1987):

> "…zinc sulfide was mixed with a radium salt to yield products containing about 25 to 300 [micrograms] µg [one µg is essentially the same as one microcurie (µCi)] of radium element per gram. The more concentrated preparations (generally containing 215 µg of radium per gram to meet British Admiralty standards) were used on aircraft and ship instrument dials, while lower-grade materials containing about 50 to 100 µg of radium per gram of mixture were used on watches, switch markings, and other devices requiring less critical reading."

According to a Department of Commerce Information Circular from 1930, the paint might contain "…from 0.7 to 3 and even 4 milligrams of radium element to 100 grams of zinc sulfide. Impurities may be added to the zinc sulfide as follows: Cadmium, 0.05 per cent; copper, 0.001 per cent; manganese, 0.0002 per cent."

Over time, the intensity of the glow from the paint will decrease because of the damage caused to the ZnS crystals by the alpha particles. Since radium-226 has a 1600 year half life, its decay is not a significant factor.

Frame (Frame 1999) discussed statements from an early report about the reduction in the luminescence being due, at least in part, to a radiation-induced discoloration of the zinc sulfide crystals. The report also indicated that the damage could be reversed by heating the paint. One of the best kept trade secrets of the various manufacturers was how they minimized the inevitable decrease in the luminosity of their paint. A couple of the factors that affected this decrease in luminosity were the amount of the radium, and the size and concentration of the zinc sulfide crystals.

Citing NUREG/CP-0001, *Radioactivity in Consumer Products* (NRC 1978),

> "It is generally accepted that zinc sulfide is damaged by the action of ionizing radiation, the very radiation that produces light. Wallhausen (1956) suggested a half-life of 10 years for ZnS, a value which is also accepted by the IAEA (1967) expert group.
> […]
> Due to the long physical half-life of radium, the effective half-life of radium-activated paint will be about 10 years."

Due to the relatively insoluble chemical form of the radium sulfate paint, radium leakage from intact timepieces is considered to be minimal. However, as a noble gas, the radon decay product has the potential to escape into the surrounding environment.

2.3 Potential health hazards resulting from exposure to radium timepieces

Radium-226 emits principally alpha particles and gamma rays. Alpha particles are generally only harmful if emitted inside the body. However, both internal and external exposure to gamma radiation can present a hazard. Gamma rays can penetrate the body, so gamma emitters like radium can produce external exposures even when the source is located some distance away.

For intact timepieces, the primary health hazard is considered to be external exposure to the gamma rays. The other radiations are generally absorbed in the watch casing, although absorption of the beta particles emitted by the decay products may consequently produce varying amounts of bremsstrahlung radiation.

Significant dose rates have been measured through the back cover of timepieces containing Ra-226 (Haybittle 1958). Due to the close proximity, skin directly in contact with the back of a watch may receive a significantly higher dose than the rest of the body (NCRP 1987).

In situations involving large amounts of radium activity, such as the collection of many timepieces, emanation of radon into the surrounding air may present a hazard to the lungs, depending on ventilation rates in the area.

Internal exposures to radium are possible via inhalation following a fire or timepiece destruction, and via inadvertent ingestion of the radium paint. Once taken into the body, radium is metabolically treated similarly to calcium, and has been termed a "bone seeker" because of its selective uptake and long-term retention in bone. A thorough discussion of radium metabolism and internal exposure risks can be found in the BEIR IV report, *Health Risks of Radon and Other Internally Deposited Alpha-Emitters* (BEIR 1988).

3.0 Summary of Previous Assessments

3.1 U.S. Public Health Service 1968

The 1968 analysis conducted by the U.S. Public Health Service (PHS 1968) is perhaps the best existing consolidated discussion of radium timepieces and the estimated doses to wearers. Most of the assessments produced since then are based at least partly on the information in the Public Health Service report. The PHS assessment used information from a number of previous investigations to present typical radium activities in wristwatches from a variety of manufacturers. Additionally, dose estimates were provided for both the skin of the wrist and the gonads of a male watch-wearer. The estimated gonad dose rates ranged from 0.5 to 3.3 millirem per year for typical wristwatches with activity on the order of several tenths of a microcurie (μCi) of radium-226, and up to 310 mrem per year for a wristwatch with 4.5 μCi.

Based on the variety of sources available, the gonad doses are generally and fairly consistent in the range of 3-10 mrem from a wristwatch of typical activity on the order of several tenths of a microcurie, approximately 100 mrem from a wristwatch with 1 μCi, and approximately 300 mrem from a wristwatch with the highest reported activity, 4.5 μCi.

In a referenced study of pocket watches by the National Center for Radiological Health, measurements using dosimeters and a human phantom indicated that the annual dose to the gonads was 60 mrem (assuming that the watch was worn 16 hours per day).

However, the methodologies and terms used in the PHS report are dated, since the report was prepared in 1968. For example, rather than calculate a whole-body dose, the dose to the gonads is presented as the “genetically significant dose” and is compared to the limits in effect at the time. There is no calculation of or comparison to the current concept in 10 CFR Part 20 of total effective dose equivalent.

The report mentions that available information focuses on wristwatches, with almost no information existing for pocket watches or clocks. This lack of information is reiterated by Frame (Frame 1999). There was an apparent lack of information regarding the extent of radium paint use even at the end of the production era in the United States in the late 1960s.

3.2 NCRP 95

The National Council on Radiation Protection and Measurements, in Report 95, *Radiation Exposure of the U.S. Population from Consumer Products and Miscellaneous Sources* (NCRP 1987), summarized information from several previous studies, but provided little new information. The discussion of doses due to radium wristwatches is based almost entirely on the 1968 Public Health Service Report. The production rates of radium clocks in the mid to late 1970s are reported as ranging from a high of 1.5 million in 1974 to a low of 60,000 in 1978. However, the report notes that these values are greatly contradicted by a 1983 document that states 2.5 million radium clocks were manufactured and sold in Florida alone from 1976 to 1978.

3.3 NUREG-1717

Section 2.3 of NUREG-1717, *Systematic Radiological Assessment of Exemptions for Source and Byproduct Materials*, (NRC 2001), evaluated both individual doses and collective doses due to radioluminescent paint in watches and clocks containing H-3 and Pm-147. The evaluations were made by considering likely exposure scenarios and developing mathematical models to estimate doses under each scenario. These scenarios and calculation methodologies were adapted where appropriate for this report.

4.0 Timepiece Radiological Characterization

4.1 Typical timepieces activities

Wristwatch casings typically have a minimum density thickness of 50 mg/cm^2 of steel (NCRP 1987) with approximately 0.3 cm of glass covering the hands and dial (NRC 2001). Due to differences in construction, the amount of radium in individual watches and clocks varies greatly. The activity varies by watch size, manufacturer, model, and even from watch to watch.

Table 2 presents radium timepiece activities as reported in several documents (activity range in parentheses). While these documents present varying activity ranges, dose assessments in this scoping characterization are presented for a 1 μCi activity, such that the results are not limited to only one type of timepiece. The dose factors presented in this report need to be scaled up or down based on the actual activity in a particular timepiece or exposure scenario.

Table 2) Literature Reported Radium Activities (μCi)

Source Document	U.S. Public Health Service (PHS 1968)	Argonne National Laboratory (ANL 1975)	National Center for Radiological Health (reported in PHS 1968)	Paul Frame (Frame 1999)
Basis for reported values	Summary of previous investigations	Gamma spectroscopy of 32 timepieces	Measurement of 18 pocket watches	Reported average activity in the clock dials from one manufacturer. during the early 1970s
Wristwatches	0.15 (0.002-4.5)	0.15 (0.05-0.5)	----	----
Pocket watches	----	0.35 (0.16-0.6)	---- (0.6-1.39)	----
Clocks	----	0.6 (----)	----	0.5

While radium activities vary widely, there is general agreement for typical average and upper bound activities. As would be expected based on their relative sizes, wristwatches have the least activity, with pocket watches and clocks having activities several times higher. Wristwatch activities are generally on the order of several tenths of a microcurie, with a maximum value of 4.5 μCi reported by one manufacturer in the Public Health Service report. Note that no other reference estimates wristwatch activities nearly this high, and the data point may be an outlier. Pocket watches and clocks have activities generally around one half of a microcurie. Based on the variability seen in wristwatches, the upper bound of pocket watch and clock activities could also be expected to be several times higher than this average.

4.2 Component Activity

To date, no conclusive information has been found regarding activity levels in individual timepiece components. However, when an average component activity is required for calculations in this report, the value was based on the following:

- A typical timepiece is assumed to contain three painted pieces (e.g. two watch hands and a bezel).
- Each component is assumed to contain approximately one-third of the entire activity of the timepiece.
- Based on the information presented in Table 2, the average activity of clocks (the type of timepiece with the highest activity) is approximately 0.5 μCi. The average

activity in an individual component is therefore assumed to be approximately 0.5/3, rounded to 0.15 μCi per component.

In one survey of New York area watch shops, the state health agency found a shop that had two boxes of mixed pieces/components[1]. A survey with a microR meter indicated dose rates of 0.5 to 1.0 mR/hr on contact with each box. Also, in the general vicinity, the microR meter indicated 10-15 μR/hr, which is consistent with typical background radiation levels for this part of the United States.

5.0 Current Assessment Approach

5.1 Selection of scenarios

NUREG-1717 established a precedent for an NRC-acceptable approach for timepiece dose modeling. The NUREG-1717 methodology for predicting doses from exposure to H-3 and Pm-147 timepieces has been adapted for this assessment of Ra-226 timepieces. This includes adaptation of the scenarios by which an individual could reasonably be exposed, as well as the mathematical equations used to predict the dose from the exposure pathways for each scenario.

The exposure scenarios in NUREG-1717 fall into two general categories: chronic exposure under routine (non-accident) circumstances, and event-based exposure per non-routine event (e.g. accident). The NUREG-1717 scenarios and exposure pathways are slightly different between the H-3 and Pm-147 evaluations. For instance, the H-3 is assumed to spontaneously volatilize into the surrounding air via exchange with environmental hydrogen, and also absorbs directly through contact with the skin. Pm-147, conversely, does not spontaneously volatilize nor absorb through the skin. For the purpose of this report, these radionuclide behaviors are not applicable for Ra-226.

In adapting the NUREG-1717 approach to this assessment, scenarios and pathways from the H-3 and Pm-147 assessments were chosen that would be the most useful for evaluating radium-226 timepieces. Several scenarios were not deemed useful for this assessment, including dose due to transportation activities and calculations of collective population dose. Also, several additional scenarios and exposure pathways were added to adequately consider credible exposure conditions.

In general, parameter values are taken directly from NUREG-1717. Examples of adapted parameter values include the amount of time an individual wears a wristwatch, the distance from the wrist to other parts of the body, and the time spent in the vicinity of coworkers and family members.

For scenarios not directly based on NUREG-1717, prudently conservative parameter values were selected for the purpose of this scoping report which is to determine the adequacy of a proposed rule on byproduct material that includes radium-226. Calculation details, along

[1] Personal communication between W. Franklin (NYC Department of Health and Mental Hygiene) and A.J. Boerner (ORISE) by e-mail, September 12, 2006.

with a discussion of each parameter value for each calculation, are shown in Appendix A to this report.

Scenarios 1-5 describe the use and repair of a single functional timepiece. Scenarios 6-9 describe the collection of multiple timepieces, including number and activity combinations in support of the general license provision in the proposed rule. All values are presented to two significant figures.

5.2 Modeling of external contact exposures (skin dose)

Conceptual Model:

Due to the close proximity to the source, the skin of the wrist under a wristwatch or under a pocket containing a pocket watch has the potential to receive comparatively high radiation doses when a timepiece is worn for extended periods.

The skin dose (shallow-dose equivalent) is defined at a depth of 7 mg/cm^2 directly underlying the timepiece. The exposed area of skin is assumed to be roughly 10 square centimeters (cm^2) based on typical watch sizes, which is consistent with 10 CFR Part 20 for calculating the shallow-dose equivalent over the 10 cm^2 of skin receiving the highest exposure.

Beta radiation reduction by clothing and distance is ignored. For a pocket watch, the reduction by clothing and space between the watch and skin would reduce the dose. However, there are many uncertainties and variables in estimating this reduction. For example, the energy spectrum of beta particles penetrating the watch casing may vary significantly with minor variations in the casing design. The energy spectrum will determine the ability of the beta particles to penetrate the underlying clothing. The thickness of underlying clothing is dependent on the type of cloth. Cotton denim will provide significantly more shielding than silk or thin synthetic materials. Also, pocket watches may have a significant air gap between the clothing and the underlying skin, depending on the pocket location. Due to these variables, clothing and air gap reductions have been ignored to provide a prudently conservative estimate of the skin dose.

For comparison to the risk from a uniform dose, the dose equivalent to a preferentially exposed organ may be multiplied by the appropriate tissue weighting factor for that organ to yield the effective dose equivalent. However, current NRC regulations are based on the tissue weighting factors recommended in ICRP 26 (ICRP 1977), which does not include a tissue weighting factor for skin. Therefore no correlation of skin dose to effective dose equivalent is made.

Calculational model:

Since the source to target distance is constant, the absorbed dose is dependent only on the watch activity, the contact dose factor and the exposure time.

The dose to the skin of the wrist of an individual wearing a wristwatch is calculated as:

$$\text{Skin Dose} = A \times DCF_c \times T$$

Where

A	=	Total source activity (μCi)
DCF_c	=	Contact dose factor (mrem/hr per μCi).
T	=	Exposure time (hrs)

Dose Factor:
The dose factor, DCF_c, is based on the value of 0.275 mrem/μCi-hr presented on page 259 of NUREG/CP-0001. NUREG-1717 did not contain a dose factor for Ra-226, therefore the dose factor presented in NUREG/CP-0001 was the best available at the time of this report. There are other values presented in various documents, such as NCRP 95, that vary by up to several orders of magnitude from the NUREG/CP-0001 value. However, none of the other values found to date provide sufficient information on the technical basis, parameters or assumptions used to determine the factor, and are not considered to be adequately defensible or verifiable for use in this report.

5.3 Modeling of external exposures, non-contact

Conceptual Model:
External dose from a timepiece that does not stay in direct contact with a single target area depends on several factors. The dose is a function of the source activity, a non-contact dose factor, and the combination of exposure time and target distance for each portion of the scenario. For instance, when an individual is wearing a watch, the distance from the watch to different parts of their body changes throughout the day. When the target is another individual not wearing a timepiece, that individual may spend a portion of the day in close proximity to the timepiece, and the rest of the day further away. The total dose to the target will be the sum of the doses from each of the configurations. Due to the small physical size of the source relative to the distance to the other individual, the timepiece can be treated as a point source, with the dose rate varying inversely with the square of the source to target distance.

Calculational Model:
The external dose to a target not in contact with the source is calculated as:

$$\text{Dose} = \frac{A \times DCF_e \times T}{d^2}$$

Where

A	=	Total source activity (μCi)
DCF_e	=	External dose factor (mrem/hr at 1 m/μCi).
T	=	Exposure time (hrs)
d	=	Source to target distance (m)

Dose Factor:
The DCF_c parameter is analogous to the traditional terms "gamma factor" or "gamma constant". Selection of an appropriate value for the DCF_c factor was based on consideration of the following:

- Ra-226 alone (no decay products) has a dose factor of 0.01 mrem/hr at 1 m/mCi (ORNL 1982).
- Ra-226 + decay products in secular equilibrium has a dose factor 0.825 mrem/hr at 1 m/mCi (ICRU 1979) (DHEW 1970).

There are several complicating factors that are not immediately apparent in the cited references. An important piece of information regarding the 0.825 mrem/hr at 1 m/mCi value that is often cited in a footnote in references, or omitted altogether, is that the value is based on experimental data from a radium source shielded by 0.5 millimeters of platinum. Available information indicates that the factor was originally used for medical applications of Ra-226, in which the source was contained inside a thin-walled metal container that would shield the majority of low energy x-rays, gamma rays and beta particles. The platinum shield used in the experiment simulated a medical-type container, and allowed measurement of the penetrating gamma radiation.

In applying this dose factor to radium timepieces, an important difference is that the timepiece case is potentially much thicker than the platinum shield used in the experiment. The thicker timepiece casing has several possible competing effects on the dose factor.

The thicker timepiece casing would potentially raise the dose factor above the reference value by shielding of a larger fraction of high energy beta particles than are shielded by the platinum, resulting in increased Bremsstrahlung radiation. Conversely, the thicker timepiece casing would potentially reduce the dose factor below the reference value by shielding more of the low energy gamma rays and x-rays than the platinum.

An additional consideration for adaptation of the dose factor to radium timepieces is that some fraction of the decay products will likely have escaped due to degraded timepiece seals, or components being removed from a timepiece entirely. Any reduction of decay product activities below secular equilibrium levels would reduce the dose factor below the reference value.

Based on this information, the reference value of 0.825 mrem/hr at 1 m/mCi was chosen as appropriately representative of the non-contact dose factor.

5.4 Modeling of smoke inhalation during a fire

Conceptual Model:
During a fire involving radioactive material, some fraction of the activity involved in the fire will be released into the air as respirable particles. The particles will be inhaled by an individual breathing in the smoke, and some fraction will be deposited in the lungs. The dose due to inhalation of these respirable particles depends on the average airborne radioactivity concentration during the event, how much air the individual breathes during the event, and the dose per unit activity inhaled.

Per NUREG-1717 methodology, the average airborne radioactivity concentration is based on an instantaneous release model, 30 minute fire duration and 1.0 hr^{-1} ventilation rate. The amount of radioactive material released at time zero is assumed to be 0.1% of the activity involved in the fire, based on the release fraction used in NUREG-1717. This release fraction does not take credit for a potentially lower release due to the physical protection afforded by the timepiece casing.

The amount of radioactivity inhaled is based on a breathing rate of 1.2 m^3/hr, with the exposed individual breathing the smoke for 30 minutes. This analysis does not consider the hazard associated with breathing any other household hazardous materials that may burn during the fire. The exposed individual is assumed to not wear a respiratory protection device. If the individual were a fireman, the dose would be a factor of 1000 lower due to firemen wearing NIOSH approved supplied-air respirators with a protection factor of 1000.

Calculational Model:

The average airborne radioactivity concentration (C_a) is calculated as:

$$C_a = \frac{Q}{Vkt} \times \left(1 - e^{-kt}\right)$$

Where

C_a	=	Average airborne radioactivity concentration (µCi/m^3)
Q	=	Amount of radioactive material released at t=0 (µCi)
k	=	Building ventilation rate (hr^{-1})
t	=	Time over which C_a is averaged (exposure time), beginning at t=0 (hrs)
V	=	Building volume (m^3)

The dose due to inhalation of airborne radioactivity is calculated as:

$$\text{Dose} = C_a \times T \times BR \times DCF_i$$

Where

C_a	=	Average airborne radioactivity concentration, dependent on building volume, ventilation rate, and averaging time
T	=	Exposure time (how long the individual breathes the smoke)
BR	=	Breathing rate, consistent with the physical exertion level
DCF_i	=	Inhalation dose factor; dose per unit radioactivity inhaled (mrem/µCi)

Dose Factor:

The inhalation dose factor (DCF_i) is based on the inhalation dose factors for Ra-226 and decay products presented in Federal Guidance Report No. 11 (EPA 1988). The decay products are assumed to be present in secular equilibrium with the Ra-226.

5.5 Modeling of resuspended contamination after a fire

Conceptual Model:

The airborne radioactivity concentration in the breathing zone of an individual disturbing a contaminated surface is typically calculated as the product of the contamination concentration (activity per area) and a resuspension factor.

NUREG-1717 Appendix A-1, Section A.1.3, states that 1 E-5 m^{-1} is an appropriate resuspension factor due to mechanical stresses on a contaminated surface. The traditional use of the resuspension factor is to multiply the factor (units of m^{-1}) by the areal activity concentration ($\mu Ci/m^2$) to estimate the airborne concentration ($\mu Ci/m^3$) in the air immediately above the surface being disturbed.

Resuspension factors such as this are normally applied to situations of uniform activity over a large area, such as fallout from a smoke plume downwind from a fire. Using NUREG-1717 methodology, 0.01% of the activity involved in a fire is assumed to be released as airborne respirable particulates (release fraction). Theoretically, this 0.01% would be the main contribution to fallout contamination on the floor available for resuspension.

However, in the case of cleanup of radium timepieces after a fire, the contaminated area of most concern is not due to fallout downwind, but rather cleanup of the destroyed timepieces themselves. In this case, the majority of activity is likely to be deposited very near the original timepiece location and non-uniformly distributed. Additionally, the contamination is likely to come directly from the destruction of the timepieces rather than fallout from airborne radioactivity in the smoke cloud.

This assessment is based on the NUREG-1717 resuspension concept, with minor modifications to estimate the activity areal concentration in the contaminated area. The contamination is no longer assumed to be solely due to deposition of the small fraction of activity liberated in a fire. The approach used in this report conservatively assumes that 100% of the activity involved in the fire is deposited in a loose/resuspendable form in a 1 m^2 area centered around the original timepiece location.

The airborne radioactivity concentration in the breathing zone is therefore estimated as the product of the total timepiece activity and the resuspension fraction, divided by the affected floor area. The inhalation dose is then based on a standard breathing rate of 1.2 m^3/hr and an inhalation dose factor.

Calculational Model:

The dose due to inhalation of activity resuspended by mechanically disturbing a contaminated surface following a fire is calculated as:

$$\text{Dose} = \left(\frac{A \times RF}{FA}\right) \times T \times BR \times DCF_i$$

Where

A	=	Total source activity (μCi)
RF	=	Resuspension Factor, 1 E-5 m^{-1}
FA	=	Affected floor area (m^2)
T	=	Exposure time (duration of disturbing the surface) (hrs)
BR	=	Breathing rate, consistent with the physical exertion level (m^3/hr)
DCF_i	=	Inhalation dose factor; dose per unit radioactivity inhaled (mrem/μCi)

<u>Dose Factor:</u>
The inhalation dose factor (DCF_i) is based on the inhalation dose factors for Ra-226 and decay products presented in Federal Guidance Report No. 11. The decay products are assumed for conservatism to be present in secular equilibrium with the Ra-226.

5.6 Modeling of ingestion during handling of non-intact timepieces

<u>Conceptual Model:</u>
The ingestion dose modeling in this report is in accordance with NUREG-1717, which in turn was based on IAEA SS No.7 (IAEA 1990). The following approach is adapted from NUREG 1717 Appendix A-1, Section A.1.6.

Radioactive materials would presumably not be deliberately ingested during normal use, but could be transferred to the hands during cleanup or other activities involving a non-intact timepiece. Once the material has been transferred to an individual's hands or skin, it can be ingested. It is assumed that 10% of the available material would be deposited somewhere on the skin of an individual, and that 0.1% of this deposited material would then be ingested before bathing removed the material from the body. Thus, the direct ingestion intake is estimated to be 1×10^{-4} times the available activity.

<u>Calculational Model:</u>
The ingestion dose is the product of the available activity, the fraction ingested and the ingestion dose factor.

$$\text{Dose} = A \times IF \times DCF_g$$

Where

A	=	Total source activity (μCi)
IF	=	Intake Fraction, 1 E-4
DCF_g	=	Ingestion dose factor, dose per unit radioactivity ingested, from Federal Guidance Report No. 11 (mrem/μCi).

<u>Dose Factor:</u>
The ingestion dose factor (DCF_i) is based on the ingestion dose factors for Ra-226 and decay products presented in Federal Guidance Report No. 11. The decay products are assumed to be present in secular equilibrium with the Ra-226.

5.7 Modeling of inhalation and ingestion of dust generated by sanding/scraping during repair activities

Conceptual Model:

During commercial or amateur repair activities, an individual may attempt to scrape or sand the radium paint off of the timepiece. In the process, paint dust would become airborne within the breathing zone of the individual and potentially be inhaled, as well as deposit on the individual's skin and potentially be ingested.

These exposure pathways present unique situations that do not yet have an industry standard method to model. Reasonably conservative parameter values and methods were used in those cases where there is no accepted industry standard. The modeling of inhalation and ingestion of dust generated by sanding and/or scraping of radium paint is based on NUREG-1717 and IAEA Safety Series No. 7 concepts, respectively.

For inhalation, the airborne radioactivity concentration for the duration of the repair process is calculated as the product of the total activity of the timepiece and a resuspension factor of 10^{-5}. This resuspension factor is adapted from the NUREG-1717 methodology used to estimate airborne radioactivity concentrations at any point in time during mechanical disturbance of a contaminated surface. The traditional use of the resuspension factor is to multiply the resuspension factor (units of m^{-1}) by the areal activity concentration ($\mu Ci/m^2$) to estimate the airborne concentration ($\mu Ci/m^3$) in the air immediately above the surface being disturbed.

For this scenario, the resuspension factor is assumed to be the unitless fraction of the available activity that, while being mechanically disturbed, is airborne as respirable particles in the work area. That is, at any given point in time during the repair process, 10^{-5} of the available activity is assumed to be present as respirable airborne particles in a 1.5 m radius volumetric hemisphere (7 m^3) around the work area. The 1.5 m hemisphere is based on the method used in NUREG-1717, Section 2.3.4.3. The employee is assumed to breathe the air from the 7 m^3 hemisphere at a rate of 1.2 m^3/hr.

For ingestion, the fraction being ingested is based on estimates for response to a transportation accident. The amount of activity ingested is estimated using the NUREG-1717 approach that 10% of the available activity deposits on the employee's skin, and 0.1% of this activity is then unintentionally ingested. These fractions are based on the transportation accident methodology established in IAEA Safety Series No. 7.

Neither the resuspension factor nor intake fraction factors are being applied in the manner for which they were originally developed. The inhalation and ingestion of dust generated by sanding and/or scraping is modeled by adapting these factors as a best estimate.

Calculational Model:

The dose due to inhalation of radium paint dust generated by sanding/scraping of a timepiece during repair is calculated as:

$$\text{Dose} = \left(\frac{A \times RF}{V}\right) \times T \times BR \times DCF_i$$

Where

A = Total source activity (µCi)
RF = Resuspension Factor, 1 E-5
V = Work area volume m^3
T = Exposure time (duration repair activity) (hrs)
BR = Breathing rate (m^3/hr)
DCF_i = Inhalation dose factor; dose per unit radioactivity inhaled (mrem/µCi)

The dose due to ingestion of radium paint dust generated by sanding/scraping of a timepiece during repair is calculated as:

$$\text{Dose} = A \times IF \times DCF_g$$

Where

A = Total source activity (µCi)
IF = Intake Fraction, 1 E-4
DCF_g = Ingestion dose factor, dose per unit radioactivity ingested, from Federal Guidance Report No. 11 (mrem/µCi).

Dose Factors:

The inhalation dose factor (DCF_i) is based on the inhalation dose factors for Ra-226 and decay products presented in Federal Guidance Report No. 11. The decay products are assumed to be present in secular equilibrium with the Ra-226.

The ingestion dose factor (DCF_g) is based on the ingestion dose factors for Ra-226 and decay products presented in Federal Guidance Report No. 11. The decay products are assumed to be present in secular equilibrium with the Ra-226.

5.8 Modeling of radon emanation and inhalation

Radon-222 is the first decay product in the radium-226 decay series. Being a noble gas, radon has the ability to escape the timepieces into the surrounding atmosphere. For radon emanation calculations, the entire inventory of decay products is assumed to be instantly and uniformly distributed into the surrounding building volume.

Note that the assumption that the entire activity of radon and decay products instantly escapes the timepiece is likely overly conservative. A mention is made of this issue in NUREG/CP-0001 on page 324, which states "… the radon emanating from the paint and its daughter products are almost totally trapped within the watch." If this trapping is assumed to occur, then the radon activity in the air outside of a timepiece would be much lower than predicted by this report. However, as these timepieces age, the seals on the watch face are likely to degrade, allowing more radon to escape the watch. Currently, there is no established method of quantifying this trapping behavior, therefore this report conservatively assumes that all radon activity escapes the timepiece.

If timepieces were located in an airtight room, the total radon activity will eventually approach the radium activity. The radon concentration will depend on the size of the room, but the total radon activity is independent of room size.

However, the assumption of an airtight room is not realistic, therefore a room with a non-zero ventilation rate must be used. With ventilation, the radon activity can no longer reach the full radium activity. The total radon activity will reach a maximum of some fraction of the radium activity. This equilibrium fraction is calculated as:

$$\text{E.F.} = \frac{\lambda_{\text{rad}}}{\lambda_{\text{rad}} + \lambda_{\text{vent}}}$$

Where

E.F.	=	Equilibrium fraction (total radon activity/total radium activity)
λ_{rad}	=	Radiological decay constant of Rn-222 expressed in units of hr^{-1}
λ_{vent}	=	Ventilation rate of the volume expressed in units of hr^{-1}

Development of this equation is provided as Appendix B to this report.

NUREG-1717 indicates that typical ventilation rates for offices, residences, and most other buildings are adequately approximated by a value of 1.0 hr^{-1}. Considerations are also made for volumes with non-typical ventilation rates, such as 0.25 hr^{-1} for a poorly ventilated volume. The maximum fraction of the total radium activity that the radon activity will reach for each of these ventilation rates are 0.75%, and 3%, respectively.

Calculational Model:

The maximum possible radon concentration is determined by three factors: the total radium activity, the volume of surrounding storage area, and the equilibrium fraction. The radon concentration for a scenario is calculated as:

$$C_{\text{Rn}} = \frac{\text{A} \times \text{E.F.}}{\text{V}}$$

Where

C_{Rn}	=	Radon concentration (pCi/l)
A	=	Total radium activity (pCi)
E.F.	=	The equilibrium fraction based on the ventilation rate
V	=	Building volume (l)

When calculating an individual's dose due to inhalation of the radon and decay products, the dose is calculated as:

$$\text{Dose} = C_{\text{Rn}} \times \text{DCF}_{\text{Rn}}$$

Where

C_{Rn} = Radon concentration (pCi/l)

DCF_{Rn} = Radon inhalation dose factor (mrem/yr per pCi/l)

Dose Factor:

The radon inhalation dose factor used in this report is based on adapting the traditional concepts of a Working Level (WL) and Working Level Month (WLM) assuming certain conditions. Radon dose factors are a widely studied topic, and have been shown to vary based on the surrounding environment, the attached fraction, and height in a building. The radon inhalation dose factor used in these calculations is based on nominal values from International Commission on Radiological Protection (ICRP) Report 65, *Protection Against Radon-222 at Home and at Work* (ICRP 1994), for a typical residential exposure situation.

The ICRP 65 value correlates to approximately 400 mrem (4 mSv) effective dose equivalent per working level month (WLM). Assuming a working level correlates to approximately 100 pCi/l each of radon and its decay products in secular equilibrium, and a working month is defined as 170 hrs, this inhalation dose factor equates to 0.0235 mrem/hr per pCi/l of radon.

The actual dose factor could vary from this approximation dependent on the attached fraction, height above ground level, and the equilibrium status of the decay products. However, the value used in this report provides a reasonable estimate of the radon inhalation doses under idealized circumstances.

Figure 1 presents potential radon concentrations from a home collection of 50, 1 µCi timepieces. For comparison, the EPA action level for radon in residences is 4 pCi/l (EPA 2002). Note that the radon concentrations are presented on a logarithmic scale.

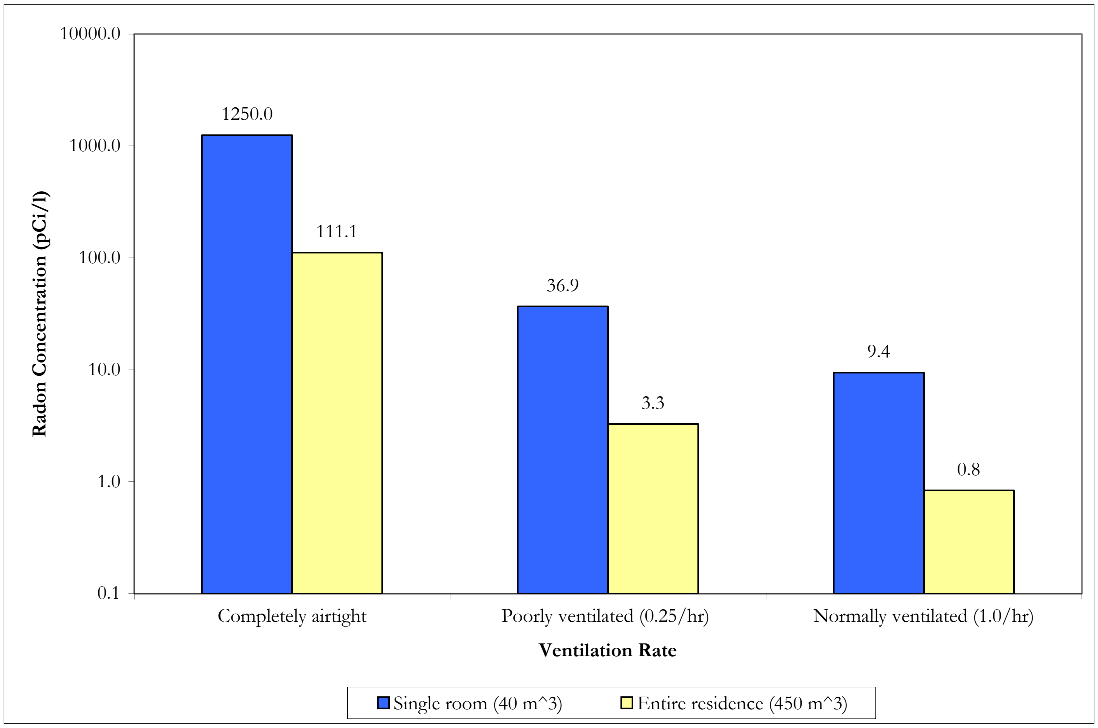


Figure 1) Radon concentration in a typical residence due to a collection of 50, 1 μCi timepieces

6.0 Scenario Results

Scenarios 1-5 describe the use and repair of a single functional timepiece.

6.1 Scenario 1) Dose to the skin from a single timepiece worn for 16 hrs/day (either a wristwatch or pocket watch)

Scenario 1 considers the dose to the skin of an individual who wears a timepiece each day.

Source Term:

- A single wristwatch worn on the wrist or pocket watch regardless of location.

Exposure Pathways:

- External dose, on-contact geometry.

Exposure Target:

- The shallow-dose equivalent at a shallow-dose depth (7 mg/cm^2) directly underlying the timepiece, averaged over a 10 cm^2 area.

Assumptions and Notes:

- The timepiece is worn for 16 hours per day, 365 days per year.

Table 3) Annual dose to the skin from wearing a 1 μCi timepiece

Activity (μCi)	Shallow-Dose Equivalent (mrem/yr)
1	1.6E+03

6.2 Scenario 2) Dose to self from a single timepiece worn 16 hrs/day (either a wristwatch or pocket watch)

Scenario 2 considers the dose to an individual who wears a timepiece each day, considered separately from the skin dose calculated in Scenario 1.

Source Term:

- A single wristwatch worn on the wrist, or a pocket watch kept in either a vest/blazer pocket or a pants pocket.

Exposure Pathways:

- External dose, non-contact geometry.

Exposure Target:

- The effective dose equivalent to the individual wearing the timepiece.

Assumptions and Notes:

- All organ doses are calculated assuming a point source and inverse square reduction for distance from the source, with no credit taken for intervening tissue.
- For a wristwatch, the distance between the watch and the various parts of the body changes throughout the day as the arm is moved. In order to allow an estimate of the dose, the arm position is summarized as three general locations, with the parameters as stated in NUREG-1717. The arm is assumed to be:
    - At the individual's side at a distance of 37 cm from the body for a total of 4330 hrs/yr
    - Near the head at a distance of 53 cm from the body for a total of 470 hrs/yr
    - Near the stomach at a distance of 16 cm from the body for a total of 1040 hrs/yr.
- For a pocket watch in a vest/blazer pocket, the exposure will be non-uniform across the various portions of the exposed individual's body. However, the dose at the center of the abdomen, 10 cm from the watch, is assumed to be representative of the average dose to most major organs, some being closer to the watch and some being further away. The remaining organs are considered to be exposed fairly uniformly with the center of the abdomen. The dose at the center of the abdomen is therefore assumed to represent the effective dose equivalent.
- A pocket watch in the pants pocket also exposes the individual's body non-uniformly. However, in this case, male gonads will receive a significantly higher dose than other radiosensitive organs, and must be given special consideration due to the close proximity of the gonads to a pocket watch in a pants pocket.

In this configuration, the ICRP tissue weighting factor for each radiosensitive organ must be used. These radiosensitive organs, along with their ICRP 26 tissue weighting factor are: breast (0.15), red bone marrow (0.12), lung (0.12), thyroid (0.03), bone surfaces (0.03), gonads (0.25), and remainder (0.30). The sum of these tissue weighting factors is 1.0.

The dose to the gonads is calculated assuming a source to target distance of 15 cm from the pocket watch to the gonads. The gonad dose contribution to the effective dose equivalent is calculated as the product of the gonad dose and the ICRP tissue weighting factor of 0.25.

The remaining radiosensitive organs are assumed to be exposed fairly uniformly, as was assumed for a pocket watch in a vest pocket. The source to target distance is assumed to be 25 cm from the pocket watch to the center of the abdomen and represents the average distance from the pocket watch in a pants pocket to the remaining radiosensitive organs. The contribution of the remaining radiosensitive organs to the effective dose equivalent is calculated as the dose to each organ times the ICRP tissue weighting factor for that organ, excluding the gonad tissue weighting factor. The sum of the remaining tissue weighting factors is 0.75.

The effective dose equivalent from a pocket watch in a pants pocket is then calculated as the sum of the gonad contribution and the contribution from the remaining radiosensitive organs.

Table 4) Annual dose to self from wearing a 1 μCi timepiece

Source Geometry	Effective Dose Equivalent (mrem/yr)
Wristwatch	6.1E+01
Pocket watch in vest pocket	4.8E+02
Pocket watch in pants pocket	1.1E+02

6.3 Scenario 3) Dose to others from a single timepiece worn by a person (either a wristwatch or pocket watch)

Scenario 3 considers the dose to individuals who are not wearing a radium timepiece themselves, but are exposed to the individual from Scenario 2 who wears a timepiece in their vicinity.

Source Term:

- A single wristwatch or a pocket watch, regardless of the location on the wearer's body.

Exposure Pathways:

- External dose, non-contact geometry.

Exposure Target:

- Family members sharing a residence with the wearer.
- Office coworkers who consistently work in the vicinity of the wearer.
- Passers-by, who occasionally come near or interact with the wearer.

Assumptions and Notes:

- Family members are 3 m away for 12 hrs/day (4380 hrs/yr).
- Office coworkers are 6 m away for 40 hours/week, 50 weeks/year (2000 hrs/yr).
- Passers-by are 6 m away for 100 hrs/yr.

Table 5) Annual dose to others from wearing a 1 μCi timepiece

Exposure Target Group	Effective Dose Equivalent (mrem/yr)
Family members	4.0E-01
Office Coworkers	4.6E-02
Passers-by	2.3E-03

6.4 Scenario 4) Dose from a single stationary timepiece (e.g. desk clock) used as a functioning timepiece

Scenario 4 considers the dose to an individual who is routinely in the presence of an in-use stationary timepiece, such as a desk clock or alarm clock.

Source Term:

- A clock kept as a functioning timepiece in the home or office.

Exposure Pathways:

- External dose, non-contact geometry.

Exposure Target:

- Family members in a residence with the clock in a communal location.
- Family members who sleep with the clock on their nightstand.
- An office occupant with the clock on their desk or nearby.
- Office coworkers and passers-by, who occasionally enter the office where the clock is located.

Assumptions and Notes:

- For a clock in a communal location, family members are 3 m away for 12 hrs/day (4380 hrs/yr).
- For a clock on a nightstand, family members are in the bed 1 m away for 8 hrs/day (2920 hrs/yr), and at other locations in the house at an average distance of 5 m for 4 hours per day (1460 hrs/yr).
- An office occupant is in the office at a distance of 1 m for 40 hours/week, 50 weeks/year (2000 hrs/yr).
- Passers-by are 6 m away for 100 hrs/yr.

Table 6) Annual dose from a stationary 1 μCi timepiece

Exposure Target Group	Effective Dose Equivalent (mrem/yr)
Family members - Clock on nightstand	2.5E+00
Family members - Clock in residence	4.0E-01
Office occupant	1.7E+00
Office coworkers and passers-by	2.3E-03

6.5 Scenario 5a) Commercial Repair activities

Scenario 5a considers the case of a typical small watch or jewelry shop that conducts repairs on radium timepieces. A customer is assumed to drop off and leave a timepiece with the shop for a time. The employee conducting the repairs handles the timepiece on a workbench during the actual repair process, and stores the timepiece in the shop for the remainder of the time until customer pickup. During the repair, the employee is assumed to sand or scrape the radium paint as part of refurbishing. The shop maintains a box of 50 spare parts to facilitate repairs. The shop conducts up to 10 repairs in a year.

Source Term:

- A single timepiece brought in to a commercial repair shop for repair.
- A box of spare parts kept in the repair shop.

Exposure Pathways:

- External dose, non-contact geometry.
- Inhalation of dust generated during sanding or scraping of the radioluminescent paint.
- Ingestion of dust generated during sanding or scraping of the radioluminescent paint.
- Inhalation of radon emanating from the spare parts.

Exposure Target:

- An employee of a small commercial repair shop.

Assumptions and Notes:

- Each timepiece dropped off for repair is left at the store for 1 week (40 hour employee exposure time) before it is picked up by the customer. During this time, the employee is at an average distance of 3 m. The only exposure pathway from the timepiece during this period is external non-contact exposure.
- The timepiece is handled during the repair process for 3 hours at a distance of 30 cm (0.3 m). Exposure pathways during this period are external non-contact exposure, inhalation of dust generated by scraping and sanding the paint, and ingestion of dust generated by scraping and sanding the paint.
- Skin doses incurred while handling pieces during repair are assumed to be insignificant. This assumption is based on the short duration of directly handling pieces and the likelihood of using tweezers or other tools during repair rather than direct skin contact.
- The repair shop is assumed to conduct 10 repairs each year.
- A box of spare parts is kept in the shop year-round. The box contains approximately 50 spare parts, with an average activity of 0.15 μCi per part. The employee is at an average distance of 3 m for 40 hours/week, 50 weeks/year (2000 hrs/yr). Exposure pathways from the spare parts include external non-contact exposure, and inhalation of radon emanating from the parts.
- Radon resulting from the decay of the radium in the spare parts is assumed to be in secular equilibrium with all decay products, and is assumed to instantaneously escape and be uniformly distributed in the shop volume of 18 m^3. The shop volume of 18 m^3 is based on the NUREG-1717 estimated volume of a small commercial watch repair shop. The shop is assumed to have a normal ventilation rate, established as 1.0 hr^{-1} in NUREG-1717. Based on this ventilation rate, the total radon activity in the shop reaches a maximum fraction of 0.75% of the total radium activity.

Table 7) Dose incurred during the repair of a 1 μCi timepiece (repair shop employee)

Exposure Pathway	Dose (mrem)
External exposure	3.1E-02
Inhalation during sanding/scraping	4.4E-02
Ingestion during sanding/scraping	1.3E-01
Total Effective Dose Equivalent	2.1E-01

Table 8) Annual dose from 50, 0.15 µCi spare parts kept in repair shop

Exposure Pathway	Dose (mrem/yr)
External exposure	1.4E+00
Inhalation of radon	1.5E+02
Total Effective Dose Equivalent	1.5E+02

Table 9) Annual dose to a repair shop employee assuming 10 repairs of 1 µCi timepieces and a spare parts inventory of 50, 0.15 µCi parts.

Exposure Source	Dose (mrem/yr)
From repairs, assuming 10 repairs per year	2.1E+00
From 50 spare parts kept in shop year-round	1.5E+02
Total Effective Dose Equivalent	1.5E+02

6.6 Scenario 5b) Amateur Repair activities

Scenario 5b considers the case of an amateur timepiece collector that attempts to repair one of their timepieces. The individual handles the timepiece on a workbench during the actual repair process, and stores the timepiece with the remainder of their collection the remainder of the time. The entire collection is assumed to contain 50 timepieces or components, with an average activity of 0.15 µCi each. The repair is assumed to take much longer than at a professional repair shop. During the repair, the individual is assumed to sand or scrape the radium paint in an attempt to refurbish the timepiece. The individual repairs up to 10 of their timepieces in a year.

Source Term:

- A single timepiece repaired by an amateur collector at home.
- A collection of timepieces or components kept in the home.

Exposure Pathways:

- External dose, non-contact geometry.
- Inhalation of dust generated during sanding or scraping of the radioluminescent paint.
- Ingestion of dust generated during sanding or scraping of the radioluminescent paint.
- Inhalation of radon emanating from the collection.

Exposure Target:

- An amateur collector who attempts to repair a radium timepiece.

Assumptions and Notes:

- The timepiece is handled during the repair process for 25 hours at a distance of 30 cm (0.3 m). Exposure pathways during this period are external non-contact exposure, inhalation of dust generated by scraping and sanding the paint, and ingestion of dust generated by scraping and sanding the paint.
- Skin doses incurred while handling pieces during repair are assumed to be insignificant. This assumption is based on the short duration of directly handling pieces and the likelihood of using tweezers or other tools during repair rather than direct skin contact.
- The collection of timepiece components, including the particular piece being repaired, is kept in the residence year-round. The collection contains approximately 50 components, with an average activity of 0.15 μCi per component. The individual and family members are at an average distance of 3 m for 16 hours/day, 365 days/year (5840 hrs/yr). Exposure pathways from the collection include external non-contact exposure during the entire 5840 hour duration, and inhalation of radon emanating from the parts for the 25 hours spent in the room conducting repairs.
- Radon resulting from the decay of the radium in the spare parts is assumed to be in secular equilibrium with all decay products, and is assumed to instantaneously escape and be uniformly distributed in the volume of a typical room, 40 m^3. The volume of 40 m^3 is based on a room with dimensions of 9 ft by 9 ft with an 8 foot ceiling. The room is assumed to have a poor ventilation rate, established as 0.25 hr^{-1} in NUREG-1717. Based on this ventilation rate, the total radon activity in the room reaches a maximum fraction of 3% of the total radium activity.

Table 10) Dose incurred during the repair of a 1 μCi timepiece (amateur collector)

Exposure Pathway	Dose (mrem/yr)
External exposure	2.3E-01
Inhalation during sanding/scraping	3.7E-01
Ingestion during sanding/scraping	1.3E-01
Total Effective Dose Equivalent	7.3E-01

Table 11) Annual dose from a collection of 50, 0.15 μCi timepieces or components kept in residence

Exposure Pathway	Dose (mrem/yr)
External exposure	4.0E+00
Inhalation of radon	3.3E+00
Total Effective Dose Equivalent	7.3E+00

Table 12) Annual dose to an amateur collector assuming 10 repairs of 1 μCi timepieces and a collection of 50, 0.15 μCi timepieces or components

Exposure Source	Dose (mrem/yr)
From repairs, assuming 10 repairs per year	7.3E+00
From 50 spare parts kept in shop year-round	7.3E+00
Total Effective Dose Equivalent	1.5E+01

Scenarios 6-9 describe the collection of a varying number of timepieces, including number and activity combinations in support of the general license provision.

6.7 Scenario 6) Dose from a collection of timepieces or components

Scenario 6 considers the dose to an individual who collects a large number of radium timepieces and their components, or an individual who is routinely around such a collection. The dose factor is normalized per microcurie in the collection. To determine the dose from a collection of a particular size, the dose factor should be scaled by the total activity in the collection.

Source Term:
- A collection of timepieces or components kept in a residence or office.

Exposure Pathways:
- External dose, non-contact geometry.
- Inhalation of radon emanated from the collection.

Exposure Target:
- Family members in a residence with the collection in a communal location.
- An office occupant with the collection in their office.
- Office coworkers and passers-by, who occasionally enter the office where the collection is located.

Assumptions and Notes:
- For a collection in a communal location, family members are 3 m away for 12 hrs/day (4380 hrs/yr).
- An office occupant is in the office at a distance of 1 m for 40 hours/week, 50 weeks/year (2000 hrs/yr).
- Passers-by are 6 m away for 100 hrs/yr.
- Radon resulting from the decay of the radium in the spare parts is assumed to be in secular equilibrium with all decay products, and is assumed to instantaneously escape and be uniformly distributed in the surrounding volume. The residence has a volume of 450 m^3, based on the typical residence volume presented in NUREG-1717, and the office has a volume of 1000 m^3. The office space volume was scaled

from the warehouse volume in NUREG-1717. Both locations are assumed to have a normal ventilation rate of 1.0 hr^{-1}.

Table 13) Dose from a collection, per microcurie in the collection

Target Group	External exposure (mrem)	Radon inhalation (mrem)	Total Effective Dose Equivalent (mrem/yr)
Family Members	4.0E-01	1.7E+00	2.1E+00
Office occupant	1.7E+00	3.5E-01	2.1E+00
Office co-workers	4.6E-02	3.5E-01	4.0E-01

Figure 2 provides a graphical representation of the data from Table 13 to illustrate the difference in the relative contributions of the external and radon pathways to the total effective dose equivalent for each target group.

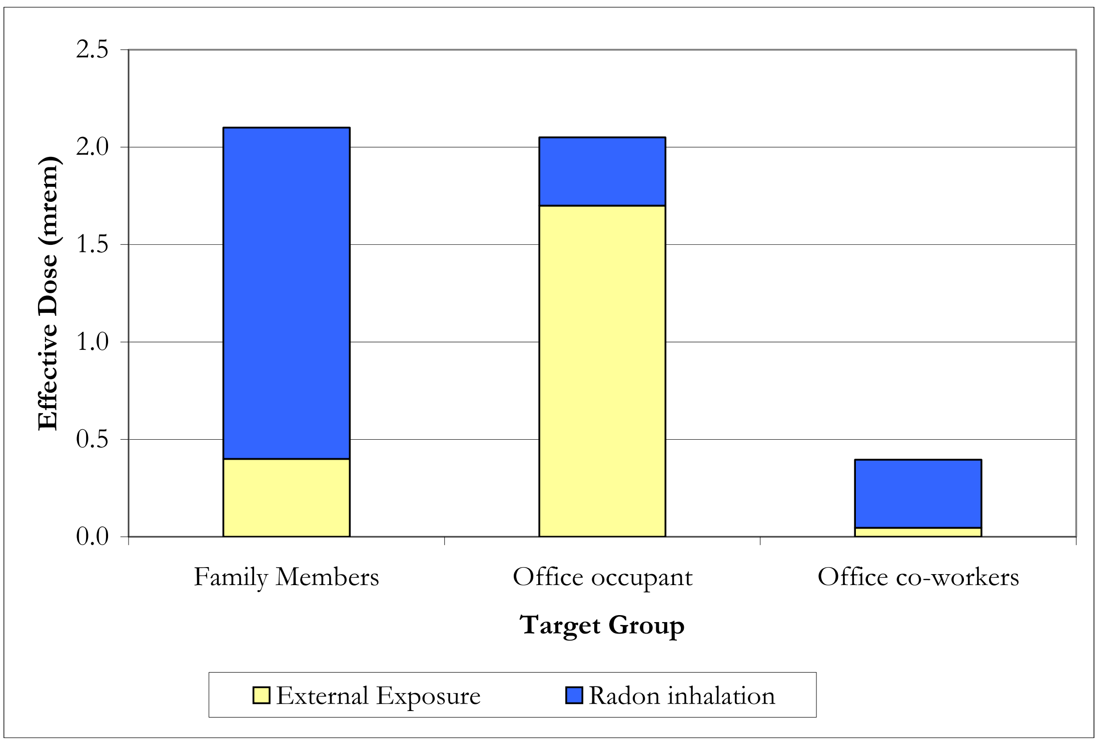


Figure 2) Dose from a collection (per microcurie in the collection)

6.8 Scenario 7) Inhalation during a catastrophic fire involving a collection of timepieces or components

Scenario 7 considers the dose to an individual who inhales the smoke during a catastrophic fire involving the collection from Scenario 6. Doses are calculated for collection sizes varying from 1 to 500 timepieces or components, with the average per-unit activity of 1 µCi.

Source Term:

- A collection of timepieces or components kept in a residence, office or warehouse that is destroyed in a catastrophic fire.

Exposure Pathways:

- Inhalation of airborne radioactivity.

Exposure Target:

- An individual who is present/trapped in the building for the entire 30 minute fire duration.

Table 14) Dose via inhalation from a fire in a volume of 40 m^3 (typical room), per number of 1 µCi timepieces involved in the fire

# of Timepieces / Components	Committed Effective Dose Equivalent (mrem)
1	1.0E-01
10	1.0E+00
50	5.1E+00
100	1.0E+01
500	5.1E+01

Table 15) Dose via inhalation from a fire in a volume of 450 m^3 (typical residence), per number of 1 µCi timpieces involved in the fire

# of Timepieces / Components	Committed Effective Dose Equivalent (mrem)
1	9.0E-03
10	9.0E-02
50	4.5E-01
100	9.0E-01
500	4.5E+00

Table 16) Dose via inhalation from a fire in a volume of 1000 m^3 (office space), per number of 1 μCi timepieces involved in the fire

# of Timepieces / Components	Committed Effective Dose Equivalent (mrem)
1	4.1E-03
10	4.1E-02
50	2.0E-01
100	4.1E-01
500	2.0E+00

6.9 Scenario 8) Inhalation of resuspended activity during post-fire cleanup activities

Scenario 8 considers the effective dose to an individual who attempts to clean up the timepieces destroyed in the fire of Scenario 7, and inhales radioactive particles resuspended by the cleanup process. Doses are calculated for collection sizes varying from 1 to 500 timepieces or components, with the average per-unit activity of 1 μCi.

Source Term:

- A collection of timepieces or components that was destroyed in a catastrophic fire, and is now being cleaned up in the post-fire cleanup activities.

Exposure Pathways:

- Inhalation of resuspended airborne radioactivity.

Exposure Target:

- An individual who is kneeling in and mechanically disturbing the 1 m^2 area contaminated by the entire activity of the destroyed timepieces.

Assumptions and Notes:

- The time spent performing cleanup activities is 30 minutes.

Table 17) Dose due to inhalation of resuspended activity during post-fire cleanup activities, per number of 1 µCi timepieces involved in the fire

# of Timepieces / Components	Committed Effective Dose Equivalent (mrem)
1	5.1E-02
10	5.1E-01
50	2.6E+00
100	5.1E+00
500	2.6E+01

6.10 Scenario 9) Ingestion of activity during handling or cleanup of non-intact timepieces

Scenario 9 considers the effective dose to an individual who ingests radioactivity, either as they perform the cleanup activities of Scenario 8, or during other instances of handling non-intact timepieces. Doses are calculated for collection sizes varying from 1 to 500 timepieces or components.

Source Term:

- A collection of non-intact timepieces or components that are handled by an individual who inadvertently ingests some of the activity.

Exposure Pathways:

- Ingestion of radioactivity deposited on the skin.

Exposure Target:

- An individual handling the timepieces or components.

Table 18) Dose due to ingestion of activity during handling or cleanup of non-intact pieces, per number of 1 µCi timepieces involved

# of Timepieces / Components	Committed Effective Dose Equivalent (mrem)
1	1.3E-01
10	1.3E+00
50	6.6E+00
100	1.3E+01
500	6.6E+01

7.0 Summary

The Public Health Service 1968 assessment provided dose estimates for individuals wearing radium wristwatches. This publication indicates annual gonad doses from typical wristwatches range from less than 1 millirem (mrem) to over 300 mrem depending on the amount of Ra-226 in the timepiece. Skin doses to the wrist are potentially on the order of many rem. However, these estimates were based on the methodology and standards in use at the time of publication. For example, the dose to the gonads is presented as the "genetically significant dose." In current dose limit terms, "genetically significant dose" is no longer applicable and instead the total effective dose equivalent (TEDE) would be calculated.

The NUREG-1717 methodology differed from the Public Health Service 1968 report in several ways. NUREG-1717 provided a systematic method for estimating doses to wearers of tritium (H-3) and promethium-147 (Pm-147) watches, as well as individuals in their vicinity. The scenarios in NUREG-1717 incorporated normal daily activities, such as dynamic body positions, and the doses calculated considered both internal and external exposure pathways including calculations for TEDE rather than for specific target organs, such as the gonads. The NUREG-1717 approach was adapted for use in this scoping assessment by applying its general scenario configurations and calculation methodologies to Ra-226 timepieces.

For the analysis in this scoping report, all source terms were normalized to a 1 microcurie (μCi) average timepiece activity. This normalized activity represents the maximum allowable exemption activity in model State standards and was used in the proposed rule to comply with the requirement in the Energy Policy Act of 2005. It should be noted that activities greater than 1 μCi would fall into the general license provision of the proposed rule.

The radiological dose estimates obtained are, in general, based on reasonable assumptions and incorporated limited existing data on the current uses of Ra-226 timepieces. For some of the scenarios, establishing exposure assumptions was difficult, mainly because the exemption is only for previously manufactured timepieces and the typical scenarios have likely changed from current routine use. The radiological doses estimated in this scoping study can provide an assessment upon which the NRC can examine the potential radiological impact associated with radium-containing timepieces and determine the appropriate regulatory approach for ensuring protection of public health and safety.

Scenarios 1 through 5 describe the use and repair of a single functional timepiece. Scenario 1 estimates the shallow-dose equivalent to the skin of an individual who wears a Ra-226 wristwatch. Scenario 2 estimates the effective dose equivalent to a person who wears a radium-containing wristwatch or pocket watch, in either a pants or vest pocket. Scenario 3 estimates the effective dose equivalent to family members, office coworkers, and individuals in the vicinity of a person wearing a Ra-226 wristwatch or pocket watch. Scenario 4 estimates the effective dose equivalent to individuals who are routinely in the vicinity of a stationary Ra-226 clock. Scenario 5a estimates the total effective dose equivalent to a jewelry and watch repair technician who is exposed while repairing a radium-containing timepiece and also to the inventory of radium-containing spare parts kept in the shop. Scenario 5b estimates the total effective dose equivalent to an amateur who repairs a radium-containing timepiece in his or her timepiece collection.

Scenarios 6 through 9 describe collections of multiple timepieces, including collections of varying size. Of these, scenarios 7 through 9 describe accidents involving fires and accidental dispersion of Ra-226 from timepieces. Scenario 6 estimates the total effective dose equivalent to an individual who collects radium-containing timepieces, or to individuals who are routinely in the vicinity of a collection of radium-containing timepieces. Scenario 7 estimates the committed effective dose equivalent to an individual who inhales smoke during a catastrophic fire involving a collection of radium-containing timepieces. Scenario 8 estimates the committed effective dose equivalent to an individual who inhales Ra-226 particles as they perform post fire clean-up activities from the catastrophic fire of scenario 7 that destroyed a collection of radium-containing timepieces. Scenario 9 estimates the committed effective dose equivalent to an individual who ingests Ra-226 particles as they handle non-intact timepieces, either as they perform post fire clean-up activities from the catastrophic fire of scenario 7, or as they perform other activities with non-intact timepieces.

The normalized dose factors are summarized below. Table 19 provides a summary of the scenarios, the assessed dosimetric quantity, the exposure pathways considered, and the calculated dose. Figure 3 presents the dose factor per microcurie in a single functional timepiece for Scenarios 1-4. Figure 4 presents the dose factor per microcurie for Scenarios 5-9. Note that Figure 3 is presented with a logarithmic scale, while Figure 4 is presented on a linear scale.

While the dose factors per source unit for Scenarios 1-4 are generally higher than the dose factors per source unit for Scenarios 5-9, it is important to recall that the total source term will likely be much larger for Scenarios 5-9, yielding higher total doses.

Table 19) Summarized scenario results

Scenario	Description	Exposure pathways	Assessed quantity	Calculated Dose	
1	Dose to the skin from wearing a timepiece	External exposure	Shallow-dose equivalent	1,600 mrem/yr	
2	Dose to self from wearing a timepiece	External exposure	Effective dose equivalent	Wristwatch	61 mrem/yr
				Pocketwatch in pants	110 mrem/yr
				Pocketwatch in vest	480 mrem/yr
3	Dose to other individuals in the vicinity from wearing a timepiece	External exposure	Effective dose equivalent	< 1 mrem/yr for all affected groups	
4	Dose from a stationary timepiece	External exposure	Effective dose equivalent	Family with clock in communal area	< 1 mrem/yr
				Family with clock in bedroom	2.5 mrem/yr
				Office occupant	1.7 mrem/yr
				Office coworker	< 1 mrem/yr
5a	Dose due to professional repair activities	External exposure Inhalation of paint Ingestion of paint Inhalation of radon	Total effective dose equivalent	150 mrem/yr	
5b	Dose due to amateur repair activities	External exposure Inhalation of paint Ingestion of paint Inhalation of radon	Total effective dose equivalent	15 mrem/yr	
6	Dose due to collecting a large number of timepieces	External exposure Inhalation of radon	Total effective dose equivalent	Family members	2.1 mrem/yr per µCi
				Office occupant	2.1 mrem/yr per µCi
				Office coworkers	< 1 mrem/yr per µCi
7	Dose due to a catastrophic fire involving a collection of timepieces	Inhalation of smoke	Committed effective dose equivalent	40 m^3 room volume	5.1 mrem for a 50 piece collection
				450 m^3 and larger room volumes	< 1 mrem for a 50 piece collection
8	Inhalation of resuspended activity during post-fire cleanup activities	Inhalation of resuspended activity	Committed effective dose equivalent	2.6 mrem for a 50 piece collection	
9	Ingestion of activity during handling or cleanup of non-intact timepieces	Ingestion of paint	Committed effective dose equivalent	6.6 mrem for a 50 piece collection	

Figure 3) Dose factors from a single functional timepiece

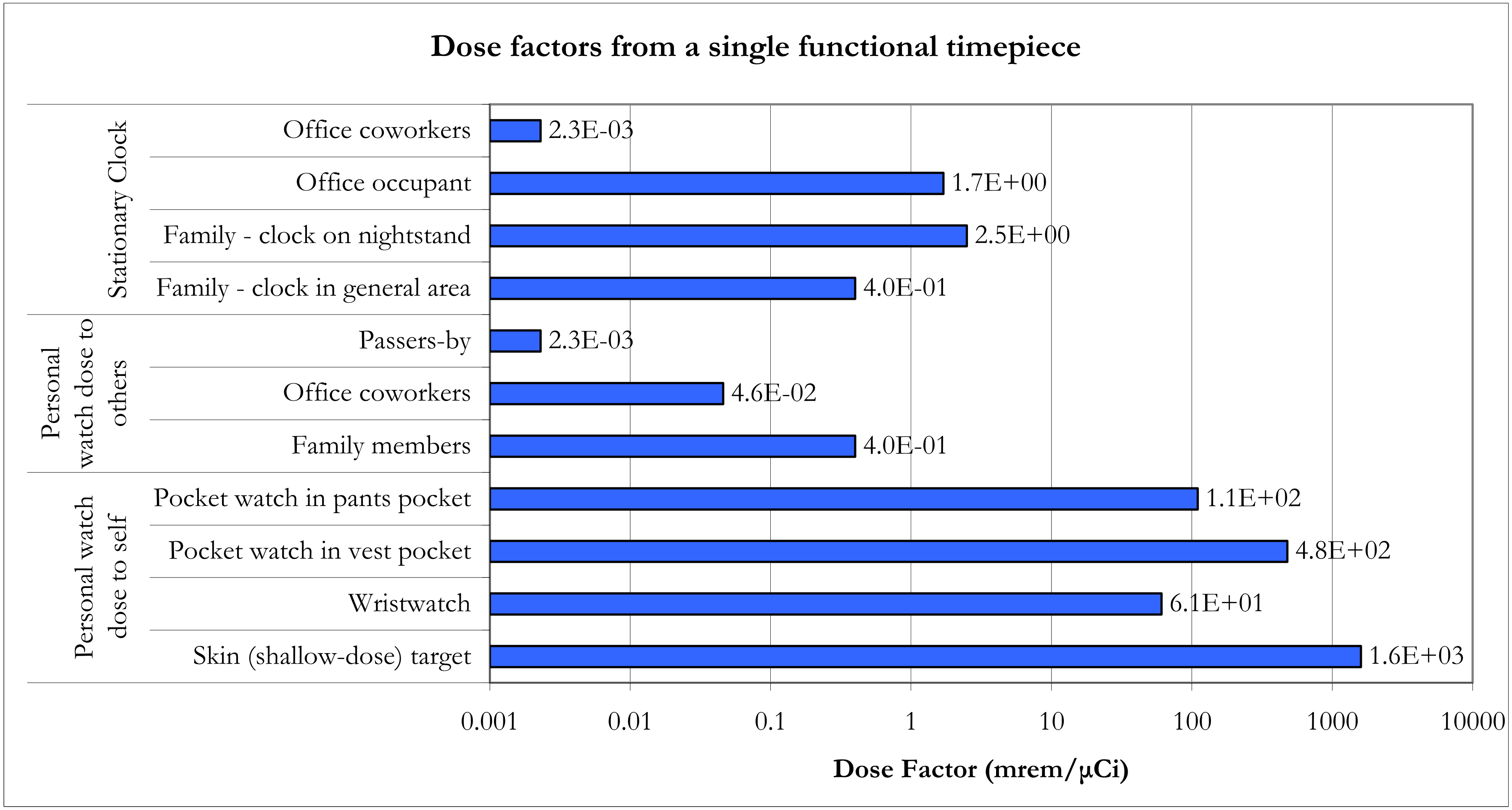
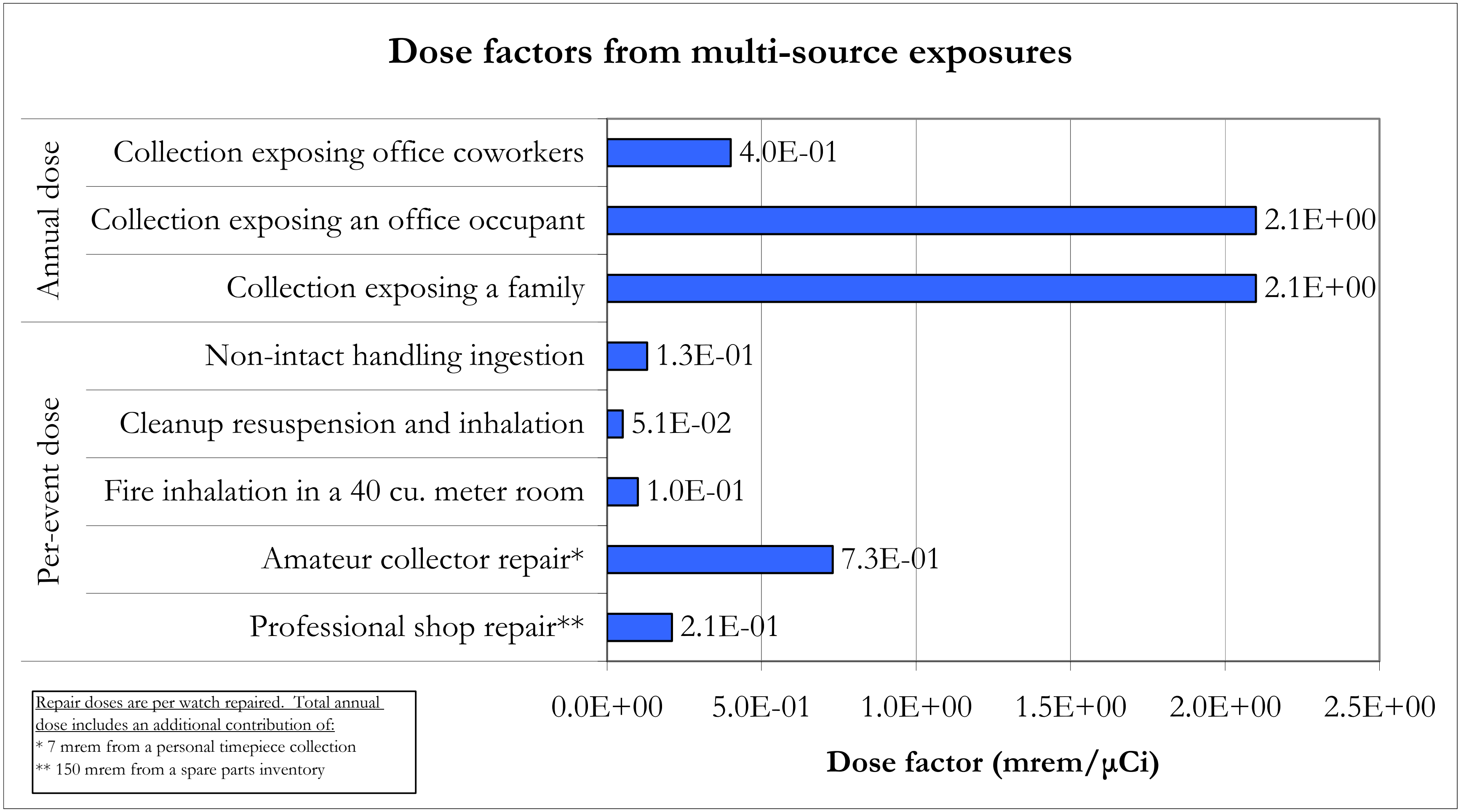


Figure 4) Dose factors from multi-source exposures



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Appendix A

Calculation Details in Support of Reported Values

Appendix A – Calculation Details in Support of Reported Values

This appendix provides the calculation details in support of the values presented in the assessment. These details are intended primarily for readers interested in the mechanics and step-by-step results of the calculations. This appendix provides no new conclusions or final results beyond those presented in the body of the report.

The following information is presented for each scenario:

- The scenario description, repeated from Section 6 of the report.
- The appropriate equations from Section 5 for each exposure pathway considered.
- A spreadsheet for each exposure pathway showing the step-by-step calculation of the reported results, prior to rounding to two significant figures.
- A step-by-step walkthrough of each value in the spreadsheet, giving a definition and justification for the parameter values.

Scenario 1) Dose to the skin from a single timepiece worn for 16 hrs/day (either a wristwatch or pocket watch)

Scenario 1 considers the dose to the skin of an individual who wears a timepiece each day.

Source Term:

- A single wristwatch worn on the wrist or pocket regardless of location.

Exposure Pathways:

- External dose, on-contact geometry.

Exposure Target:

- The shallow-dose equivalent at a shallow-dose depth (7 mg/cm^2) directly underlying the timepiece, averaged over a 10 cm^2 area.

Assumptions and Notes:

- The timepiece is worn for 16 hours per day, 365 days per year.

Calculations:

The dose to the skin of the wrist of an individual wearing a wristwatch is calculated as:

$$\text{Skin Dose} = A \times DCF_c \times T$$

Where

A	=	Total source activity (μCi)
DCF_c	=	Contact dose factor (mrem/hr per μCi).
T	=	Exposure time (hrs)

Annual skin dose per µCi in a timepiece worn on one's person

Source type	Source location	Target	Source Activity (µCi)	Contact Dose Factor (mrem/hr per µCi)	Exposure Time (hrs)	Shallow-Dose Equivalent (mrem)
Timepiece	Carried on self	Skin at 7 mg/cm^2	1	0.275	5840	1.61E+03
			a	b	c	d

Column	Description
a	Total activity in the wristwatch. As discussed in Section 4.1, doses in this report are calculated for a 1 µCi activity such that the end-result can be easily scaled.
b	Contact dose factor for direct contact with the back of a watch. Section 5.2 discusses that this contact dose factor (0.275 mrem/hr per µCi) is based on the value on page 259 of NUREG/CP-0001.
c	Exposure time. Per the scenario description, the watch is worn for 16 hours per day, 365 days per year. This gives a total annual exposure time of 5840 hours.
d	Shallow-dose equivalent to the skin. Calculated as: $d = a \times b \times c$

Scenario 2) Dose to self from a single timepiece worn 16 hrs/day (either a wristwatch or pocket watch)

Scenario 2 considers the dose to an individual who wears a timepiece each day, considered separately from the skin dose calculated in Scenario 1.

Source Term:

- A single wristwatch worn on the wrist, or a pocket watch kept in either a vest/blazer pocket or a pants pocket.

Exposure Pathways:

- External dose, non-contact geometry.

Exposure Target:

- The effective dose equivalent to the individual wearing the timepiece.

Assumptions and Notes:

- All organ doses are calculated assuming a point source and inverse square reduction for distance from the source, with no credit taken for intervening tissue.
- For a wristwatch, the distance between the watch and the various parts of the body changes throughout the day as the arm is moved. In order to allow an estimate of the dose, the arm position is summarized as three general locations, with the parameters as stated in NUREG-1717. The arm is assumed to be:
    - At the individual's side at a distance of 37 cm from the body for a total of 4330 hrs/yr
    - Near the head at a distance of 53 cm from the body for a total of 470 hrs/yr
    - Near the stomach at a distance of 16 cm from the body for a total of 1040 hrs/yr.

- For a pocket watch in a vest/blazer pocket, the exposure will be non-uniform across the various portions of the exposed individual's body. However, the dose at the center of the abdomen, 10 cm from the watch, is assumed to be representative of the average dose to most major organs, some being closer to the watch and some being further away. The remaining organs are considered to be exposed fairly uniformly with the center of the abdomen. The dose at the center of the abdomen is therefore assumed to represent the effective dose equivalent.
- A pocket watch in the pants pocket also exposes the individual's body non-uniformly. However, in this case, male gonads will receive a significantly higher dose than other radiosensitive organs, and must be given special consideration due to the close proximity of the gonads to a pocket watch in a pants pocket.

  In this configuration, the ICRP tissue weighting factor for each radiosensitive organ must be used. These radiosensitive organs, along with their ICRP 26 tissue weighting factor are: breast (0.15), red bone marrow (0.12), lung (0.12), thyroid (0.03), bone surfaces (0.03), gonads (0.25), and remainder (0.30). The sum of these tissue weighting factors is 1.0.

  The dose to the gonads is calculated assuming a source to target distance of 15 cm from the pocket watch to the gonads. The gonad dose contribution to the effective dose equivalent is calculated as the product of the gonad dose and the ICRP tissue weighting factor of 0.25.

  The remaining radiosensitive organs are assumed to be exposed fairly uniformly, as was assumed for a pocket watch in a vest pocket. The source to target distance is assumed to be 25 cm from the pocket watch to the center of the abdomen and represents the average distance from the pocket watch in a pants pocket to the remaining radiosensitive organs. The contribution of the remaining radiosensitive organs to the effective dose equivalent is calculated as the dose to each organ times the ICRP tissue weighting factor for that organ, excluding the gonad tissue weighting factor. The sum of the remaining tissue weighting factors is 0.75.

  The effective dose equivalent from a pocket watch in a pants pocket is then calculated as the sum of the gonad contribution and the contribution from the remaining radiosensitive organs.

Calculations:

The external dose to a target not in contact with the source is calculated as:

$$\text{Dose} = \frac{A \times DCF_e \times T}{d^2}$$

Where

A = Total source activity (μCi)
DCF_e = External dose factor (mrem/hr at 1 m/μCi).
T = Exposure time (hrs)
d = Source to target distance (m)

Exposure pathway	External, non-contact	
Source activity	1	μCi
Dose factor	8.25E-04	(mrem/hr at 1 m/μCi)

External exposure to self per microcurie in a timepiece worn on one's person

Source type	Source location	Target	Distance (m)	Exposure Time (hrs)	Organ Dose (mrem)	Tissue Weighting Factor	Deep-Dose Equivalent (mrem/yr)
Wristwatch	Arm at side	Whole body	0.37	4330			26.09
Wristwatch	Arm near head	Whole body	0.53	470			1.38
Wristwatch	Arm near stomach	Whole body	0.16	1040			33.52
						Total:	60.99
Pocketwatch	Vest/blazer pocket	Whole Body	0.1	5840			481.80
Pocketwatch	Pants pocket	Gonads	0.15	5840	214.13	0.25	53.53
Pocketwatch	Pants pocket	Rest of body	0.25	5840	77.09	0.75	57.82
						Total:	111.35
	a	b	c	d	e	f	g

Column	Description
a	Source location. As discussed in the scenario description, a wristwatch source will be in various locations throughout the day. The total dose contribution will be the sum of the doses incurred from the source at each of these locations. The generalization of wristwatch-bearing arm into the 3 categories listed (at side, near head, near stomach) is directly taken from NUREG-1717.
b	Target location.
c	Distance between the source location and the target location. For consideration of a uniformly irradiated "whole body" target, the distance to the center of the abdomen was taken as adequately representative of the average distance to radiosensitive organs. For non-uniform irradiations (e.g. gonads), an approximate distance to the target organ is used. Discussion of the uniform versus non-uniform irradiation considerations is provided in the scenario "Assumptions and Notes" section. The values for the distance between a wristwatch on the arm and the whole body were taken directly from NUREG-1717.
d	Exposure time. The duration of the exposure in the particular source-target configuration being considered. The total annual exposure time (5840 hrs) is based on wearing the timepiece for 16 hours per day, 365 days per year. For a wristwatch worn on the arm, the fraction of the total time spent in each position relative to the whole body was taken directly from NUREG-1717.

e	Organ dose. For consideration of non-uniform irradiations, calculation of the dose to each preferentially exposed organ is an interim step in calculating the overall deep-dose equivalent. The dose to a preferentially exposed organ is calculated as the product of the source activity (normalized to 1 μCi), the dose factor (8.25E-4 mrem/hr at 1 m/μCi as discussed in Section 5.3) and the exposure time, divided by the square of the source to target distance. e=(1 μCi) x (8.25 E-4 mrem-m^2/μCi-hr) x d / c^2 For uniform whole body irradiations, the interim calculation of an organ dose is not necessary, since all organs are exposed equally.
f	Tissue weighting factor. In order to convert an organ-specific equivalent dose into a corresponding effective dose equivalent, the organ dose is multiplied by a tissue weighting factor for the exposed organ. The gonad tissue weighting factor of 0.25 is taken directly from ICRP 26/30. Explanation of using a summed weighting factor of 0.75 for the remaining radiosensitive organs is discussed in the scenario "Assumptions and Notes" section.
g	Effective dose equivalent. For uniform whole body irradiations, the effective dose equivalent is calculated identical to the organ dose in Column E: The effective dose equivalent is calculated as the product of the source activity (normalized to 1 μCi), the dose factor (8.25E-4 mrem/hr at 1 m/μCi as discussed in Section 5.3) and the exposure time, divided by the square of the source to target distance. g=(1 μCi) x (8.25 E-4 mrem-m^2/μCi-hr) x d / c^2 For non-uniform irradiations, the dose contribution from each exposed organ is calculated as the product of the dose for the organ from Column E and the tissue weighting factor from Column F. g=e x f

Scenario 3) Dose to others from a single timepiece worn by a person (either a wristwatch or pocket watch)

Scenario 3 considers the dose to individuals who are not wearing a radium timepiece themselves, but are exposed to the individual from Scenario 2 who wears a timepiece in their vicinity.

<u>Source Term:</u>

- A single wristwatch or a pocket watch, regardless of the location on the wearer's body.

Exposure Pathways:

- External dose, non-contact geometry.

Exposure Target:

- Family members sharing a residence with the wearer.
- Office coworkers who consistently work in the vicinity of the wearer.
- Passers-by, who occasionally come near or interact with the wearer.

Assumptions and Notes:

- Family members are 3 m away for 12 hrs/day (4380 hrs/yr).
- Office coworkers are 6 m away for 40 hours/week, 50 weeks/year (2000 hrs/yr).
- Passers-by are 6 m away for 100 hrs/yr.

Calculations:

The external dose to a target not in contact with the source is calculated as:

$$\text{Dose} = \frac{A \times DCF_e \times T}{d^2}$$

Where

A	=	Total source activity (μCi)
DCF_e	=	External dose factor (mrem/hr at 1 m/μCi).
T	=	Exposure time (hrs)
d	=	Source to target distance (m)

Source activity	1	μCi
Dose factor	8.25E-04	(mrem/hr at 1 m/μCi)

External exposure per microcurie in a timepiece worn on one's person

Source type	Source location	Target	Distance (m)	Exposure Time (hrs)	Effective Dose Equivalent (mrem/yr)
Timepiece	Carried on self	Family members	3	4380	4.02E-01
Timepiece	Carried on self	Office coworkers	6	2000	4.58E-02
Timepiece	Carried on self	Passers-by	6	100	2.29E-03
		a	b	c	d

Column	Description
a	Exposure target group.
b	Distance between the person wearing the timepiece and the target group being considered.
c	Exposure time. Duration of the target group's exposure.
d	Effective dose equivalent. The dose is calculated as the product of the source activity (normalized to 1 μCi), the dose factor (8.25E-4 mrem/hr at 1 m/μCi as discussed in Section 5.3) and the exposure time, divided by the square of the

	source to target distance. d=(1 μCi) x (8.25 E-4 mrem-m^2/μCi-hr) x c / b^2

Scenario 4) Dose from a single stationary timepiece (e.g. desk clock) used as a functioning timepiece

Scenario 4 considers the dose to an individual who is routinely in the presence of an in-use stationary timepiece, such as a desk clock or alarm clock.

<u>Source Term:</u>
- A clock kept as a functioning timepiece in the home or office.

<u>Exposure Pathways:</u>
- External dose, non-contact geometry.

<u>Exposure Target:</u>
- Family members in a residence with the clock in a communal location.
- Family members who sleep with the clock on their nightstand.
- An office occupant with the clock on their desk or nearby.
- Office coworkers and passers-by, who occasionally enter the office where the clock is located.

<u>Assumptions and Notes:</u>
- For a clock in a communal location, family members are 3 m away for 12 hrs/day (4380 hrs/yr).
- For a clock on a nightstand, family members are in the bed 1 m away for 8 hrs/day (2920 hrs/yr), and at other locations in the house at an average distance of 5 m for 4 hours per day (1460 hrs/yr).
- An office occupant is in the office at a distance of 1 m for 40 hours/week, 50 weeks/year (2000 hrs/yr).
- Passers-by are 6 m away for 100 hrs/yr.

<u>Calculations:</u>
The external dose to a target not in contact with the source is calculated as:

$$\text{Dose} = \frac{A \times DCF_e \times T}{d^2}$$

Where

A	=	Total source activity (μCi)
DCF_e	=	External dose factor (mrem/hr at 1 m/μCi).
T	=	Exposure time (hrs)
d	=	Source to target distance (m)

External exposure per microcurie in a stationary timepiece

Source type	Source location	Target	Distance (m)	Exposure Time (hrs)	Effective Dose Equivalent (mrem/yr)
Timepiece	Residence, not otherwise specified	Family members	3	4380	4.02E-01
Timepiece	Bedroom nightstand	Family members on bed while sleeping	1	2920	2.41E+00
Timepiece	Bedroom nightstand	Family members at other times	5	1460	4.82E-02
				Total:	2.46E+00
Timepiece	Office	Office occupant	1	2000	1.65E+00
Timepiece	Office	Coworkers and Passers-by	6	100	2.29E-03
	a	b	c	d	e

Column	Description
a	Source location. Location of the stationary timepiece in the particular configuration being considered.
b	Exposure target group.
c	Distance between the person wearing the timepiece and the target group being considered.
d	Exposure time. Duration of the target group's exposure.
e	Effective dose equivalent. The dose is calculated as the product of the source activity (normalized to 1 μCi), the dose factor (8.25E-4 mrem/hr at 1 m/μCi as discussed in Section 5.3) and the exposure time, divided by the square of the source to target distance. $d=(1\ \mu Ci) \times (8.25\ E\text{-}4\ mrem\text{-}m^2/\mu Ci\text{-}hr) \times c\ /\ b^2$

Scenario 5a) Commercial Repair activities

Scenario 5a considers the case of a typical small watch or jewelry shop that conducts repairs on radium timepieces. A customer is assumed to drop off and leave a timepiece with the shop for a time. The employee conducting the repairs handles the timepiece on a workbench during the actual repair process, and stores the timepiece in the shop for the remainder of the time until customer pickup. During the repair, the employee is assumed to sand or scrape the radium paint as part of refurbishing. The shop maintains a box of 50 spare parts to facilitate repairs. The shop conducts up to 10 repairs in a year.

<u>**Source Term:**</u>

- A single timepiece brought in to a commercial repair shop for repair.
- A box of spare parts kept in the repair shop.

Exposure Pathways:

- External dose, non-contact geometry.
- Inhalation of dust generated during sanding or scraping of the radioluminescent paint.
- Ingestion of dust generated during sanding or scraping of the radioluminescent paint.
- Inhalation of radon emanating from the spare parts.

Exposure Target:

- An employee of a small commercial repair shop.

Assumptions and Notes:

- Each timepiece dropped off for repair is left at the store for 1 week (40 hour employee exposure time) before it is picked up by the customer. During this time, the employee is at an average distance of 3 m. The only exposure pathway from the timepiece during this period is external non-contact exposure.
- The timepiece is handled during the repair process for 3 hours at a distance of 30 cm (0.3 m). Exposure pathways during this period are external non-contact exposure, inhalation of dust generated by scraping and sanding the paint, and ingestion of dust generated by scraping and sanding the paint.
- Skin doses incurred while handling pieces during repair are assumed to be insignificant. This assumption is based on the short duration of directly handling pieces and the likelihood of using tweezers or other tools during repair rather than direct skin contact.
- The repair shop is assumed to conduct 10 repairs each year.
- A box of spare parts is kept in the shop year-round. The box contains approximately 50 spare parts, with an average activity of 0.15 μCi per part. The employee is at an average distance of 3 m for 40 hours/week, 50 weeks/year (2000 hrs/yr). Exposure pathways from the spare parts include external non-contact exposure, and inhalation of radon emanating from the parts.
- Radon resulting from the decay of the radium in the spare parts is assumed to be in secular equilibrium with all decay products, and is assumed to instantaneously escape and be uniformly distributed in the shop volume of 18 m^3. The shop volume of 18 m^3 is based on the NUREG-1717 estimated volume of a small commercial watch repair shop. The shop is assumed to have a normal ventilation rate, established as 1.0 hr^{-1} in NUREG-1717. Based on this ventilation rate, the total radon activity in the shop reaches a maximum fraction of 0.75% of the total radium activity.

Calculations:

<u>Calculation of doses from the timepiece being repaired, incurred during the repair process:</u>
The external dose to a target not in contact with the source is calculated as:

$$\text{Dose} = \frac{A \times DCF_e \times T}{d^2}$$

Where

A = Total source activity (µCi)
DCF_e = External dose factor (mrem/hr at 1 m/µCi).
T = Exposure time (hrs)
d = Source to target distance (m)

External Exposure from a 1.0 µCi timepiece during repair

Source Activity (µCi)	Dose Factor (mrem/hr at 1 m/µCi)	Source location	Target	Distance (m)	Exposure Time (hrs)	Effective Dose Equivalent (mrem)
1	8.25E-04	Stored in shop before/after repair	Employee	3	40	3.67E-03
1	8.25E-04	On workbench during repair	Employee	0.3	3	2.75E-02
					Total:	3.12E-02
a	b	c	d	e	f	g

Column	Description
a	Total activity in the timepiece being repair. As discussed in Section 4.1, doses in this report are calculated for a 1 µCi activity such that the end-result can be easily scaled.
b	Dose factor. The non-contact dose factor, 8.25 E-4 mrem/hr at 1 m/µCi as discussed in Section 5.3.
c	Source location. Location of the timepiece in the particular configuration being considered.
d	Exposure target. The exposure target is the repair shop employee conducting the repairs.
e	Distance between the source location and the target individual.
f	Exposure time. The duration of the exposure in the particular source-target configuration being considered.
g	Effective dose equivalent. The dose is calculated as the product of the source activity, the dose factor and the exposure time, divided by the square of the source to target distance. $g = a \times b \times f / e^2$

The dose due to inhalation of radium paint dust generated by sanding/scraping of a timepiece during repair is calculated as:

$$\text{Dose} = \left(\frac{A \times RF}{V}\right) \times T \times BR \times DCF_i$$

Where

A = Total source activity (µCi)
RF = Resuspension Factor, 1 E-5
V = Work area volume m^3
T = Exposure time (duration repair activity) (hrs)
BR = Breathing rate (m^3/hr)

DCF_i = Inhalation dose factor; dose per unit radioactivity inhaled (mrem/μCi)

Inhalation dose from a 1.0 μCi timepiece via suspended activity during scraping/sanding during repair

Source Activity (μCi)	Work Volume (m^3)	Resuspension Factor	Average Concentration (μCi/m3)	Exposure Time (hrs)	Breathing Rate (m^3/hr)	Inhalation Dose Factor (mrem/μCi)	Committed Effective Dose Equivalent (mrem)
1	7	1.00E-05	1.43E-06	3	1.2	8.58E+03	4.41E-02
a	b	c	d	e	f	g	h

Column	Description
a	Total activity in the timepiece being repair. As discussed in Section 4.1, doses in this report are calculated for a 1 μCi activity such that the end-result can be easily scaled.
b	Work volume. The volume of the localized work area into which airborne radioactivity is generated. As discussed in Section 5.7, the volume of 7 m^3 is based on a localized work area of radius 1.5 m around the work location.
c	Resuspension factor. The fraction of the total available activity that is present as respirable airborne particles within the work volume at any point in time.
d	Average concentration. The average airborne radioactivity concentration in the localized work volume. The average concentration is calculated as the product of the total activity and the resuspension factor, divided by the work volume. d=a x c / b
e	Exposure time. The time the employee spends on the actual repair process.
f	Breathing rate. The rate at which the exposed individual breathes. In accordance with NUREG-1717 methodology, the ICRP 23 Reference Man (ICRP 1975) light exercise breathing rate of 1.2 m^3/hr is used.
g	Inhalation dose factor. The effective dose per unit activity inhaled. The value of 8.58 E+3 mrem/μCi is taken from Federal Guidance Report No. 11 (EPA 1988).
h	Committed effective dose equivalent. The dose is calculated as the product of the average airborne concentration, the exposure time, the breathing rate, and the inhalation dose factor. h=d x e x f x g

The dose due to ingestion of radium paint dust generated by sanding/scraping of a timepiece during repair is calculated as:

$$\text{Dose} = A \times IF \times DCF_g$$

Where

A = Total source activity (μCi)
IF = Intake Fraction, 1 E-4
DCF_g = Ingestion dose factor, dose per unit radioactivity ingested, from Federal Guidance Report No. 11 (mrem/μCi).

Ingestion dose from a 1.0 μCi timepiece via ingestion via scraping/sanding during repair

Source Activity (μCi)	Fraction onto skin	Fraction on skin then ingested	Total Activity Ingested (μCi)	Ingestion Dose Factor (mrem/μCi)	Committed Effective Dose Equivalent (mrem)
1	10%	0.10%	1.00E-04	1.32E+03	1.32E-01
a	b	c	d	e	f

Column	Description
a	Total activity of the timepiece being repaired.
b	Fraction of activity getting onto the skin. As discussed in Section 5.7, the value adapted from NUREG-1717 is 10%.
c	Fraction on skin then ingested. The fraction of the activity getting onto an individual's skin that is then also inadvertently ingested. As discussed in Section 5.7, the value adapted from NUREG-1717 is 0.1%.
d	Total activity ingested. The activity that gets onto the skin and is then inadvertently ingested. This parameter is the product of the available activity and both of the transfer fractions. d = a x b x c
e	Ingestion dose factor. The effective dose per unit activity ingested. The value of 1.32 E+3 mrem/μCi is taken from Federal Guidance Report No. 11 (EPA 1988).
f	Committed effective dose equivalent. Calculated as the product of the total activity ingested and the ingestion dose factor. f = d x e

<u>Calculation of annual doses from other radioactive items in the area (spare parts)</u>

The external dose to a target not in contact with the source is calculated as:

$$\text{Dose} = \frac{A \times DCF_e \times T}{d^2}$$

Where

A = Total source activity (μCi)
DCF_e = External dose factor (mrem/hr at 1 m/μCi).
T = Exposure time (hrs)
d = Source to target distance (m)

External Exposure from spare parts kept in the shop

Number of sources	Source unit Activity (µCi)	Total Activity (µCi)	Dose Factor (mrem/hr at 1 m/µCi)	Source location	Target	Distance (m)	Exposure Time (hrs)	Effective Dose Equivalent (mrem/yr)
50	0.15	7.5	8.25E-04	Stored in repair shop	Employee	3	2000	1.38E+00
a	b	c	d	e	f	g	h	i

Column	Description
a	Number of sources in the spare parts inventory.
b	Average activity per source in the spare parts inventory.
c	Total activity in the spare parts inventory. This is calculated as the product of the total number of sources, and the average activity per source. c=a x b
d	Dose factor. The non-contact dose factor, 8.25 E-4 mrem/hr at 1 m/µCi as discussed in Section 5.3.
e	Source location. Location of the timepiece in the particular configuration being considered.
f	Exposure target. The exposure target is the repair shop employee conducting the repairs.
g	Distance between the source location and the target individual.
h	Exposure time. The duration of the exposure in the particular source-target configuration being considered.
i	Effective dose equivalent. The dose is calculated as the product of the total source activity, the dose factor and the exposure time, divided by the square of the source to target distance. i=c x d x h / g^2

The radon concentration due to emanation from the spare parts is calculated as:

$$C_{Rn} = \frac{A \times E.F.}{V}$$

Where

C_{Rn}	=	Radon concentration (pCi/l)
A	=	Total radium activity (pCi)
E.F.	=	The equilibrium fraction based on the ventilation rate
V	=	Building volume (l)

The effective dose due to inhalation of the radon and decay products is calculated as:

$$\text{Dose} = C_{Rn} \times DCF_{Rn}$$

Where

C_{Rn} = Radon concentration (pCi/l)
DCF_{Rn} = Radon inhalation dose factor (mrem/yr per pCi/l)

Inhalation of radon emanating from spare parts, assuming a shop volume of 18 m^3 and a normal ventilation rate (1 hr^{-1})

Number of sources	Source unit Activity (µCi)	Total Activity (µCi)	Equilibrium Fraction	Shop Volume m^3	Radon Concentration (pCi/l)	Dose Factor (mrem/hr per pCi/l)	Exposure Time hrs	Committed Effective Dose Equivalent (mrem)
50	0.15	7.5	0.75%	18	3.14	2.35E-02	2000	1.48E+02
a	b	c	d	e	f	g	h	i

Column	Description
a	Number of sources in the spare parts inventory.
b	Average activity per source in the spare parts inventory.
c	Total activity in the spare parts inventory. This is calculated as the product of the total number of sources, and the average activity per source. $c=a \times b$
d	Equilibrium Fraction. The maximum activity the radon can reach expressed as a fraction of the radium activity. As discussed in Section 5.8, the equilibrium fraction for a ventilation rate of 1.0 hr^{-1} is 0.75%.
e	Shop volume. The volume of the repair shop. Adapted from the NUREG-1717 value for a small jewelry shop.
f	Radon concentration. The equilibrium radon concentration in the shop. The radon concentration is calculated as: $f=c \times (10^6\ pCi/\mu Ci) \times d \times / [e \times (1000\ l/m^3)]$
g	Dose factor. The radon inhalation dose factor (mrem/hr per pCi/l). As discussed in Section 5.8, this value is adapted from ICRP 65.
h	Exposure time. The total amount of time the employee spends in the shop breathing the air with elevated radon due to the spare parts inventory. The value used is 2000 hours based on a standard work year.
i	Committed effective dose equivalent. The dose is calculated as the product of the radon concentration, the dose factor and the exposure time. $i=f \times g \times h$

Scenario 5b) Amateur Repair activities

Scenario 5b considers the case of an amateur timepiece collector that attempts to repair one of their timepieces. The individual handles the timepiece on a workbench during the actual repair process, and stores the timepiece with the remainder of their collection the remainder of the time. The entire collection is assumed to contain 50 timepieces or components, with an average activity of 0.15 μCi each. The repair is assumed to take much longer than at a professional repair shop. During the repair, the individual is assumed to sand or scrape the radium paint in an attempt to refurbish the timepiece. The individual repairs up to 10 of their timepieces in a year.

Source Term:

- A single timepiece repaired by an amateur collector at home.
- A collection of timepieces or components kept in the home.

Exposure Pathways:

- External dose, non-contact geometry.
- Inhalation of dust generated during sanding or scraping of the radioluminescent paint.
- Ingestion of dust generated during sanding or scraping of the radioluminescent paint.
- Inhalation of radon emanating from the collection.

Exposure Target:

- An amateur collector who attempts to repair a radium timepiece.

Assumptions and Notes:

- The timepiece is handled during the repair process for 25 hours at a distance of 30 cm (0.3 m). Exposure pathways during this period are external non-contact exposure, inhalation of dust generated by scraping and sanding the paint, and ingestion of dust generated by scraping and sanding the paint.
- Skin doses incurred while handling pieces during repair are assumed to be insignificant. This assumption is based on the short duration of directly handling pieces and the likelihood of using tweezers or other tools during repair rather than direct skin contact.
- The collection of timepiece components, including the particular piece being repaired, is kept in the residence year-round. The collection contains approximately 50 components, with an average activity of 0.15 μCi per component. The individual and family members are at an average distance of 3 m for 16 hours/day, 365 days/year (5840 hrs/yr). Exposure pathways from the collection include external non-contact exposure for the entire 5840 hour duration, and inhalation of radon emanating from the parts for the 25 hours spent in the room conducting repairs.
- Radon resulting from the decay of the radium in the spare parts is assumed to be in secular equilibrium with all decay products, and is assumed to instantaneously escape and be uniformly distributed in the volume of a typical room, 40 m^3. The volume of 40 m^3 is based on a room with dimensions of 9 ft by 9 ft with an 8 foot ceiling.

The room is assumed to have a poor ventilation rate, established as 0.25 hr^{-1} in NUREG-1717. Based on this ventilation rate, the total radon activity in the room reaches a maximum fraction of 3% of the total radium activity.

Calculations:

Calculation of doses from the timepiece being repaired, incurred during the repair process:
The external dose to a target not in contact with the source is calculated as:

$$\text{Dose} = \frac{A \times DCF_e \times T}{d^2}$$

Where

A = Total source activity (μCi)
DCF_e = External dose factor (mrem/hr at 1 m/μCi).
T = Exposure time (hrs)
d = Source to target distance (m)

External Exposure from a 1.0 μCi timepiece during repair

Source unit Activity (μCi)	Dose Factor (mrem/hr at 1 m/μCi)	Source location	Target	Distance (m)	Exposure Time (hrs)	Effective Dose Equivalent (mrem)
1	8.25E-04	On workbench during repair	Individual	0.3	25	2.29E-01
a	b	c	d	e	f	g

Column	Description
a	Total activity in the timepiece being repaired. As discussed in Section 4.1, doses in this report are calculated for a 1 μCi activity such that the end-result can be easily scaled.
b	Dose factor. The non-contact dose factor, 8.25 E-4 mrem/hr at 1 m/μCi as discussed in Section 5.3.
c	Source location. Location of the timepiece in the particular configuration being considered.
d	Exposure target. The exposure target is the individual conducting the repairs.
e	Distance between the source location and the target individual.
f	Exposure time. The duration of the exposure in the particular source-target configuration being considered.
g	Effective dose equivalent. The dose is calculated as the product of the source activity, the dose factor and the exposure time, divided by the square of the source to target distance. $g = a \times b \times f / e^2$

The dose due to inhalation of radium paint dust generated by sanding/scraping of a timepiece during repair is calculated as:

$$\text{Dose} = \left(\frac{A \times RF}{V} \right) \times T \times BR \times DCF_i$$

Where

A	=	Total source activity (μCi)
RF	=	Resuspension Factor, 1 E-5
V	=	Work area volume m^3
T	=	Exposure time (duration repair activity) (hrs)
BR	=	Breathing rate (m^3/hr)
DCF_i	=	Inhalation dose factor; dose per unit radioactivity inhaled (mrem/μCi)

Inhalation dose from a 1.0 μCi timepiece via suspended activity during scraping/sanding during repair

Source Activity (μCi)	Work Volume (m^3)	Resuspension Factor	Average Concentration (μCi/m3)	Exposure Time (hrs)	Breathing Rate (m3/hr)	Inhalation Dose Factor (mrem/μCi)	Committed Effective Dose Equivalent (mrem)
1	7	1.00E-05	1.43E-06	25	1.2	8.58E+03	3.68E-01
a	b	c	d	e	f	g	h

Column	Description
a	Total activity in the timepiece being repaired. As discussed in Section 4.1, doses in this report are calculated for a 1 μCi activity such that the end-result can be easily scaled.
b	Work volume. The volume of the localized work area into which airborne radioactivity is generated. As discussed in Section 5.7, the volume of 7 m^3 is based on a localized work area of radius 1.5 m around the work location.
c	Resuspension factor. The fraction of the total available activity that is present as respirable airborne particles within the work volume at any point in time.
d	Average concentration. The average airborne radioactivity concentration in the localized work volume. The average concentration is calculated as the product of the total activity and the resuspension factor, divided by the work volume. d=a x c / b
e	Exposure time. The time the individual spends on the actual repair process.
f	Breathing rate. The rate at which the exposed individual breathes. In accordance with NUREG-1717 methodology, the ICRP 23 Reference Man light exercise breathing rate of 1.2 m^3/hr is used.
g	Inhalation dose factor. The effective dose per unit activity inhaled. The value of 8.58 E+3 mrem/μCi is taken from Federal Guidance Report No. 11 (EPA 1988).
h	Committed effective dose equivalent. The dose is calculated as the product of the average airborne concentration, the exposure time, the breathing rate, and the inhalation dose factor. h=d x e x f x g

The dose due to ingestion of radium paint dust generated by sanding/scraping of a timepiece during repair is calculated as:

$$\text{Dose} = A \times IF \times DCF_g$$

Where

A = Total source activity (µCi)
IF = Intake Fraction, 1 E-4
DCF_g = Ingestion dose factor, dose per unit radioactivity ingested, from Federal Guidance Report No. 11 (mrem/µCi).

Ingestion dose from a 1.0 µCi timepiece via ingestion via scraping/sanding during repair

Source Activity (µCi)	Fraction onto skin	Fraction on skin then ingested	Total Activity Ingested (µCi)	Ingestion Dose Factor (mrem/µCi)	Committed Effective Dose Equivalent (mrem)
1	10%	0.10%	1.00E-04	1.32E+03	1.32E-01
a	b	c	d	e	f

Column	Description
a	Total activity of the timepiece being repaired.
b	Fraction of activity getting onto the skin. As discussed in Section 5.7, the value adapted from NUREG-1717 is 10%.
c	Fraction on skin then ingested. The fraction of the activity getting onto an individual's skin that is then also inadvertently ingested. As discussed in Section 5.7, the value adapted from NUREG-1717 is 0.1%.
d	Total activity ingested. The activity that gets onto the skin and is then inadvertently ingested. This parameter is the product of the available activity and both of the transfer fractions. d = a x b x c
e	Ingestion dose factor. The effective dose per unit activity ingested. The value of 1.32 E+3 mrem/µCi is taken from Federal Guidance Report No. 11 (EPA 1988).
f	Committed effective dose equivalent. Calculated as the product of the total activity ingested and the ingestion dose factor. f = d x e

Calculation of annual doses from other radioactive items in the area (home collection)

The external dose to a target not in contact with the source is calculated as:

$$\text{Dose} = \frac{A \times DCF_e \times T}{d^2}$$

Where

A = Total source activity (µCi)
DCF_e = External dose factor (mrem/hr at 1 m/µCi).
T = Exposure time (hrs)
d = Source to target distance (m)

External Exposure from a collection of timepieces

Number of sources	Source unit Activity (µCi)	Total Activity (µCi)	Dose Factor (mrem/hr at 1 m/µCi)	Source location	Target	Distance (m)	Exposure Time (hrs)	Effective Dose Equivalent (mrem/yr)
50	0.15	7.5	8.25E-04	Stored	Individual	3	5840	4.02E+00
a	b	c	d	e	f	g	h	i

Column	Description
a	Number of sources in the home collection.
b	Average activity per source in the home collection.
c	Total activity in the spare parts inventory. This is calculated as the product of the total number of sources, and the average activity per source. c=a x b
d	Dose factor. The non-contact dose factor, 8.25 E-4 mrem/hr at 1 m/µCi as discussed in Section 5.3.
e	Source location. Location of the timepiece in the particular configuration being considered.
f	Exposure target. The exposure target is the individual conducting the repairs.
g	Distance between the source location and the target individual.
h	Exposure time. The duration of the exposure in the particular source-target configuration being considered.
i	Effective dose equivalent. The dose is calculated as the product of the total source activity, the dose factor and the exposure time, divided by the square of the source to target distance. $i=c \times d \times h / g^2$

The radon concentration due to emanation from the home collection is calculated as:

$$C_{Rn} = \frac{A \times E.F.}{V}$$

Where

C_{Rn} = Radon concentration (pCi/l)
A = Total radium activity (pCi)
E.F. = The equilibrium fraction based on the ventilation rate
V = Building volume (l)

The effective dose due to inhalation of the radon and decay products is calculated as:

$$\text{Dose} = C_{Rn} \times DCF_{Rn}$$

Where

C_{Rn} = Radon concentration (pCi/l)
DCF_{Rn} = Radon inhalation dose factor (mrem/yr per pCi/l)

Inhalation of radon emanating from a collection of timepieces, assuming a residence volume of 40 m^3 and a poor ventilation rate (0.25 hr^{-1})

Number of sources	Source unit Activity (µCi)	Total Activity (µCi)	Equilibrium Fraction	Room Volume m^3	Radon Concentration (pCi/l)	Dose Factor (mrem/hr per pCi/l)	Exposure Time hrs	Committed Effective Dose Equivalent (mrem)
50	0.15	7.5	3.00%	40	5.63	2.35E-02	25	3.31E+00
a	b	c	d	e	f	g	h	i

Column	Description
a	Number of sources in the home collection.
b	Average activity per source in the home collection.
c	Total activity in the home collection. This is calculated as the product of the total number of sources, and the average activity per source. c=a x b
d	Equilibrium Fraction. The maximum activity the radon can reach expressed as a fraction of the radium activity. As discussed in Section 5.8, the equilibrium fraction for a ventilation rate of 0.25 hr^{-1} is 3%.
e	Room volume. The volume of the room in which the individual conducts the repairs. 40 m^3 is assumed as representative of an average "hobby" room. Room size is discussed in Section 6.6.
f	Radon concentration. The equilibrium radon concentration in the room. The radon concentration is calculated as: f=c x (10^6 pCi/µCi) x d x / [e x (1000 l/m^3)]
g	Dose factor. The radon inhalation dose factor (mrem/hr per pCi/l). As discussed in Section 5.8, this value is adapted from ICRP 65.
h	Exposure time. The total amount of time the individual spends in the room breathing the air with elevated radon due to the home collection
i	Committed effective dose equivalent. The dose is calculated as the product of the radon concentration, the dose factor and the exposure time. i=f x g x h

Scenario 6) Dose from a collection of timepieces or components

Scenario 6 considers the dose to an individual who collects a large number of radium timepieces and their components, or an individual who is routinely around such a collection. The dose factor is normalized per microcurie in the collection. To determine the dose from a collection of a particular size, the dose factor should be scaled by the total activity in the collection.

Source Term:

- A collection of timepieces or components kept in a residence or office.

Exposure Pathways:

- External dose, non-contact geometry.
- Inhalation of radon emanated from the collection.

Exposure Target:

- Family members in a residence with the collection in a communal location.
- An office occupant with the collection in their office.
- Office coworkers and passers-by, who occasionally enter the office where the collection is located.

Assumptions and Notes:

- For a collection in a communal location, family members are 3 m away for 12 hrs/day (4380 hrs/yr).
- An office occupant is in the office at a distance of 1 m for 40 hours/week, 50 weeks/year (2000 hrs/yr).
- Passers-by are 6 m away for 100 hrs/yr.
- Radon resulting from the decay of the radium in the spare parts is assumed to be in secular equilibrium with all decay products, and is assumed to instantaneously escape and be uniformly distributed in the surrounding volume. The residence has a volume of 450 m^3, based on the typical residence volume presented in NUREG-1717, and the office has a volume of 1000 m^3. The office space volume was scaled from the warehouse volume in NUREG-1717. Both locations are assumed to have a normal ventilation rate of 1.0 hr^{-1}.

Calculations:

The external dose to a target not in contact with the source is calculated as:

$$\text{Dose} = \frac{A \times DCF_e \times T}{d^2}$$

Where

A	=	Total source activity (µCi)
DCF_e	=	External dose factor (mrem/hr at 1 m/µCi).
T	=	Exposure time (hrs)
d	=	Source to target distance (m)

External Exposure per microcurie in a collection of timepieces or components

Exposure pathway	External, non-contact	
Source activity	1	µCi
Dose factor	8.25E-04	(mrem/hr at 1 m/µCi)

Source type	Source Location	Target	Distance (m)	Exposure Time (hrs)	Effective Dose Equivalent (mrem/yr)
Timepieces / Components	Residence	Family members	3	4380	4.02E-01
Timepieces / Components	Office	Office occupant	1	2000	1.65E+00
Timepieces / Components	Office	Office coworkers	6	2000	4.58E-02
	a	b	c	d	e

Column	Description
a	Source location. The source location, whether in an unspecified area of a residence, or in an office.
b	Exposure target group.
c	Distance between the person wearing the timepiece and the target group being considered.
d	Exposure time. Duration of the target group's exposure.
e	Effective dose equivalent. The dose is calculated as the product of the source activity (normalized to 1 µCi), the dose factor (8.25E-4 mrem/hr at 1 m/µCi as discussed in Section 5.3) and the exposure time, divided by the square of the source to target distance. $e=(1\ \mu Ci) \times (8.25\ E\text{-}4\ mrem\text{-}m^2/\mu Ci\text{-}hr) \times d / c^2$

The radon concentration due to emanation from the collection is calculated as:

$$C_{Rn} = \frac{A \times E.F.}{V}$$

Where

C_{Rn}	=	Radon concentration (pCi/l)
A	=	Total radium activity (pCi)
E.F.	=	The equilibrium fraction based on the ventilation rate
V	=	Building volume (l)

The effective dose due to inhalation of the radon and decay products is calculated as:

$$\text{Dose} = C_{Rn} \times DCF_{Rn}$$

Where

C_{Rn} = Radon concentration (pCi/l)
DCF_{Rn} = Radon inhalation dose factor (mrem/yr per pCi/l)

Radon inhalation from per microcurie timepiece in a normally ventilated volume (1.0 hr^{-1})

Source Location	Total Activity (µCi)	Equilibrium Fraction	Air Volume m^3	Radon Concentration (pCi/l)	Dose Factor (mrem/hr per pCi/l)	Exposure Time hrs	Committed Effective Dose Equivalent (mrem/yr)
Residence	1	0.75%	450	1.68E-02	2.35E-02	4380	1.73E+00
Office	1	0.75%	1000	7.54E-03	2.35E-02	2000	3.55E-01
a	b	c	d	e	f	g	h

Column	Description
a	Source location. The source location, whether in an unspecified area of a residence, or in an office.
b	Total activity in the collection. The value is set to 1 µCi so that the results can be easily scaled.
c	Equilibrium Fraction. The maximum activity the radon can reach expressed as a fraction of the radium activity. As discussed in Section 5.8, the equilibrium fraction for a ventilation rate of 1.0 hr^{-1} is 0.75%.
d	Air volume. The volume of the building into which the radon is emanating. The residence volume of 450 m^3 is taken directly from NUREG-1717. The office volume is scaled from the warehouse volume presented in NUREG-1717.
e	Radon concentration. The equilibrium radon concentration in the shop. The radon concentration is calculated as: $f = b \times (10^6 \text{ pCi}/\mu\text{Ci}) \times c / [d \times (1000 \text{ l}/m^3)]$
f	Dose factor. The radon inhalation dose factor (mrem/hr per pCi/l). As discussed in Section 5.8, this value is adapted from ICRP 65.
g	Exposure time. The total amount of time the individual spends breathing the air with elevated radon due to the collection.
h	Committed effective dose equivalent. The dose is calculated as the product of the radon concentration, the dose factor and the exposure time. $h = e \times f \times g$

Scenario 7) Inhalation during a catastrophic fire involving a collection of timepieces or components

Scenario 7 considers the dose to an individual who inhales the smoke during a catastrophic fire involving the collection from Scenario 6. Doses are calculated for collection sizes varying from 1 to 500 timepieces or components, with the average per-unit activity of 1 μCi.

Source Term:

- A collection of timepieces or components kept in a residence, office or warehouse that is destroyed in a catastrophic fire.

Exposure Pathways:

- Inhalation of airborne radioactivity.

Exposure Target:

- An individual who is present/trapped in the building for the entire 30 minute fire duration.

Calculations:

The average airborne radioactivity concentration (C_a) is calculated as:

$$C_a = \frac{Q}{Vkt} \times \left(1 - e^{-kt}\right)$$

Where

C_a	=	Average airborne radioactivity concentration (μCi/m^3)
Q	=	Amount of radioactive material released at t=0 (μCi)
k	=	Building ventilation rate (hr^{-1})
t	=	Time over which C_a is averaged (exposure time), beginning at t=0 (hrs)
V	=	Building volume (m^3)

The dose due to inhalation of airborne radioactivity is calculated as:

$$\text{Dose} = C_a \times T \times BR \times DCF_i$$

Where

C_a	=	Average airborne radioactivity concentration, dependent on building volume, ventilation rate, and averaging time
T	=	Exposure time (how long the individual breathes the smoke)
BR	=	Breathing rate, consistent with the physical exertion level
DCF_i	=	Inhalation dose factor; dose per unit radioactivity inhaled (mrem/μCi)

Inhalation dose per microcurie involved in a catastrophic fire (normalized to a building volume of 1 m^3)

Source Activity (µCi)	Release Fraction	Available Activity (µCi)	Building Volume m^3	Ventilation Rate (hr^{-1})	Fire Duration (hrs)	Average Concentration (µCi/m^3)	Breathing Rate (m^3/hr)	Inhalation Dose Factor (mrem/µCi)	Committed Effective Dose Equivalent (mrem)
1	0.001	0.001	1	1	0.5	7.87E-04	1.2	8.58E+03	4.05E+00
a	b	c	d	e	f	g	h	i	j

Column	Description
a	Source activity. Total activity of the sources involved in the fire.
b	Release fraction. The fraction of radioactive material released as respirable size particles. This parameter is discussed in detail in NUREG-1717, Appendix A-1, page A.1-2. A release fraction of 0.1% is assumed for most materials. For solid materials in protective devices, a value of 0.01% would potentially be justified. However, this assessment does not take advantage of this allowance, and uses the generic release fraction of 0.1%.
c	Available activity. The amount of radioactivity going airborne at t=0. $c = a \times b$
d	Building volume. The volume of the building into which the airborne radioactivity is released. The calculation in this table is normalized to a 1 m^3 volume. To scale the results of this calculation for the various types of buildings discussed in the scenario, the final result of this normalized calculation is then divided by the volume of the building of interest.
e	Ventilation rate. The number of total volume changes per hour due to building ventilation. This is mathematically equal to the volumetric ventilation rate (m^3/hr), divided by the total building volume (m^3). Ventilation rates are discussed in NUREG-1717 Appendix A-1, Section A.1.5, with typical values presented in NUREG-1717 Table A.1.2. As discussed in Section 5.4, a typical ventilation rate of 1.0 hr^{-1} is used.
f	Fire duration. The fire duration and individual exposure time are assumed to be 0.5 hrs, in accordance with NUREG-1717.
g	Average concentration. The airborne radioactivity concentration averaged over the duration of the fire. $g= [c/(d \times e \times f)] \times (1-\exp(-e \times f))$
h	Breathing rate. The rate at which the exposed individual breathes. In accordance with NUREG-1717 methodology, the ICRP 23 Reference Man light exercise breathing rate of 1.2 m^3/hr is used.
i	Inhalation dose factor. The effective dose per unit activity inhaled. The value of 8.58E+3 mrem/µCi is taken from Federal Guidance Report No. 11 (EPA 1988).
j	Committed effective dose equivalent. The dose is calculated as the product of the average concentration, breathing rate, inhalation dose factor and fire duration. $j = f \times g \times h \times i$

Scenario 8) Inhalation of resuspended activity during post-fire cleanup activities

Scenario 8 considers the effective dose to an individual who attempts to clean up the timepieces destroyed in the fire of Scenario 7, and inhales radioactive particles resuspended by the cleanup process. Doses are calculated for collection sizes varying from 1 to 500 timepieces or components, with the average per-unit activity of 1 µCi.

Source Term:

- A collection of timepieces or components that was destroyed in a catastrophic fire, and is now being cleaned up in the post-fire cleanup activities.

Exposure Pathways:

- Inhalation of resuspended airborne radioactivity.

Exposure Target:

- An individual who is kneeling in and mechanically disturbing the 1 m^2 area contaminated by the entire activity of the destroyed timepieces.

Assumptions and Notes:

- The time spent performing cleanup activities is 30 minutes.

Calculations:

The dose due to inhalation of activity resuspended by mechanically disturbing a contaminated surface following a fire is calculated as:

$$\text{Dose} = \left(\frac{A \times RF}{FA}\right) \times T \times BR \times DCF_i$$

Where

A	=	Total source activity (µCi)
RF	=	Resuspension Factor, 1 E-5 m^{-1}
FA	=	Affected floor area (m^2)
T	=	Exposure time (duration of disturbing the surface) (hrs)
BR	=	Breathing rate, consistent with the physical exertion level (m^3/hr)
DCF_i	=	Inhalation dose factor; dose per unit radioactivity inhaled (mrem/µCi)

Inhalation dose per µCi via resuspended activity during post-fire cleanup activities

Source Activity (µCi)	Release Fraction	Available Activity (µCi)	Floor Area (m^2)	Resuspension Factor (m^{-1})	Average Concentration (µCi/m^3)	Exposure Time (hrs)	Breathing Rate (m^3/hr)	Inhalation Dose Factor (mrem/µCi)	Committed Effective Dose Equivalent (mrem)
1	1	1	1	1.00E-05	1.00E-05	0.5	1.2	8.58E+03	5.15E-02
a	b	c	d	e	f	g	h	i	j

Column	Description
a	Source activity. The total activity of the sources involved in the fire, intentionally normalized to 1 μCi in these calculations.
b	Release fraction. The fraction of radioactive material distributed into the affected floor area. As described in report Section 5.5, this value is assumed to be 100%.
c	Available activity. The amount of radioactivity on the floor available to be disturbed and resuspended. c = a x b
d	Affected floor area. The size of the floor area in which the activity is spread, and which is mechanically disturbed by an individual's cleanup activities. As described in the report Section 5.5, this value is assumed to be 1 m^2.
e	Resuspension factor. The fraction of activity in an area that, upon mechanical disturbance, becomes airborne in the breathing zone directly above that area. In accordance with NUREG-1717, this value is assumed to be 1 E-5 m^{-1}.
f	Average concentration. The average airborne radioactivity concentration in the breathing zone of the individual disturbing the contaminated area. The airborne radioactivity concentration is calculated as the product of the available activity and the resuspension factor. g = d x f
g	Exposure time. The time that the individual spends disturbing the contaminated surface and breathing the resultant resuspended activity, assumed to be 0.5 hrs.
h	Breathing rate. The rate at which the exposed individual breathes. In accordance with NUREG-1717 methodology, the ICRP 23 Reference Man light exercise breathing rate of 1.2 m^3/hr is used.
i	Inhalation dose factor. The dose per unit activity inhaled. The value of 8.58 E+3 mrem/μCi is taken from Federal Guidance Report No. 11 (EPA 1988).
j	Committed effective dose equivalent. The dose to the individual is calculated as the product of the average airborne radioactivity concentration, the breathing rate, the exposure time, an the inhalation dose factor. j = f x g x h x i

Scenario 9) Ingestion of activity during handling or cleanup of non-intact timepieces

Scenario 9 considers the effective dose to an individual who ingests radioactivity, either as they perform the cleanup activities of Scenario 8, or during other instances of handling non-intact timepieces. Doses are calculated for collection sizes varying from 1 to 500 timepieces.

Source Term:

- A collection of non-intact timepieces or components that are handled by an individual who inadvertently ingests some of the activity.

Exposure Pathways:

- Ingestion of radioactivity deposited on the skin.

Exposure Target:

- An individual handling the timepieces or components.

Calculations:

The ingestion dose is the product of the available activity, the fraction ingested and the ingestion dose factor.

$$\text{Dose} = A \times IF \times DCF_g$$

Where

A	=	Total source activity (µCi)
IF	=	Intake Fraction, 1 E-4
DCF_g	=	Ingestion dose factor, dose per unit radioactivity ingested, from Federal Guidance Report No. 11 (mrem/µCi).

Ingestion dose per µCi via handling or cleanup of non-intact timepieces

Source Activity (µCi)	Fraction onto skin	Fraction on skin then ingested	Total Activity Ingested (µCi)	Ingestion Dose Factor (mrem/µCi)	Committed Effective Dose Equivalent (mrem)
1	10%	0.10%	1.00E-04	1.32E+03	1.32E-01
a	b	c	d	e	f

Column	Description
a	Total activity of the sources involved.
b	Fraction of activity getting onto the skin. In accordance with NUREG-1717, this value is assumed to be 10% of the available activity. b = 0.1

c	Fraction on skin then ingested. The fraction of the activity getting onto an individuals skin that is then also inadvertently ingested. In accordance with NUREG-1717, this value is assumed to be 0.1%. c = 0.001
d	Total activity ingested. The activity that gets onto the skin and is then inadvertently ingested. This parameter is the product of the available activity and both of the transfer fractions. d = a x b x c
e	Ingestion dose factor. The effective dose per unit activity ingested. The value of 1.32 E+3 mrem/µCi is taken from Federal Guidance Report No. 11 (EPA 1988).
f	Committed effective dose equivalent. Calculated as the product of the total activity ingested and the ingestion dose factor. f = d x e

Appendix B

Development of the Radon Equilibrium Fraction (E.F.)

Appendix B – Development of the Radon Equilibrium Fraction (E.F.)

When a radionuclide decays into a decay product that is also radioactive, such as the case of radium-226 decaying to radon-222, the quantity of the decay product can be calculated from the equation:

$$N_2 = \frac{N_1^{t=0}\lambda_1}{\lambda_2 - \lambda_1}\left(e^{-\lambda_1 t} - e^{-\lambda_2 t}\right)$$

Where:

N_1 = Number of atoms of the parent nuclide (Ra - 226)
N_2 = Number of atoms of the decay product (Rn - 222)
λ_1 = Rate at which the parent nuclide decays (decay rate) (hr^{-1})
λ_2 = Rate at which the decay product is lost (hr^{-1})
t = Time period over which the decay occurs (hrs)

Normally in situations of radioactive decay, the only mechanism through which the decay product is lost (λ_2) is by radiological decay. However, in this case, λ_2 has two components: a radiological decay rate ($\lambda_{2,rad}$), and a ventilation removal rate ($\lambda_{2,vent}$). The total removal rate is the sum of these two components, and is denoted as $\lambda_{2,T}$.

$$\lambda_{2,T} = \lambda_{2,rad} + \lambda_{2,vent}$$

Restating the original equation in terms of the total decay product loss rate:

$$N_2 = \frac{N_1^{t=0}\lambda_1}{\lambda_{2,T} - \lambda_1}\left(e^{-\lambda_1 t} - e^{-\lambda_{2,T} t}\right)$$

Given that the activity of a nuclide is the product of the number of atoms (N) and the radiological decay rate (λ) for that nuclide, $A = \lambda N$, the equation can be multiplied on both sides by $\lambda_{2,rad}$ to express the activity of the decay product in terms of the original activity of the parent nuclide, rather than in terms of numbers of atoms.

$$N_2\lambda_{2,rad} = \frac{\left(N_1^{t=0}\lambda_1\right)\lambda_{2,rad}}{\lambda_{2,T} - \lambda_1}\left(e^{-\lambda_1 t} - e^{-\lambda_{2,T} t}\right)$$

$$A_2 = \frac{A_1^{t=0}\lambda_{2,rad}}{\lambda_{2,T} - \lambda_1}\left(e^{-\lambda_1 t} - e^{-\lambda_{2,T} t}\right)$$

The equation can be further simplified in this case by knowing that the decay rate of the parent nuclide (λ_1) is five orders of magnitude lower than the loss rate of the decay product ($\lambda_{2,T}$) (λ_1=5E-8 hr^{-1} for Ra-226 , $\lambda_{2,rad}$=7.6E-3 hr^{-1} for Rn-222). The $(-\lambda_1)$ term in the denominator is insignificant in this context, and can ignored.

$$A_2 = \frac{A_1^{t=0}\lambda_{2,rad}}{\lambda_{2,T}}\left(e^{-\lambda_1 t} - e^{-\lambda_{2,T} t}\right)$$

Additionally, the first exponential term, $e^{-\lambda_1 t}$, is essentially equal to 1 for any modeling timeframe of interest; it takes over 23 years for the value to change by 1%.

$$A_2 = \frac{A_1^{t=0}\lambda_{2,rad}}{\lambda_{2,T}}\left(1 - e^{-\lambda_{2,T} t}\right)$$

The second exponential term, $e^{-\lambda_{2,T} t}$, is essentially equal to 0 for any time beyond several weeks; the value is reduced to 0.01 in 18 days. The exponential multiplier in parentheses therefore reduces to a multiplier of 1, and is eliminated.

$$A_2 = \frac{A_1^{t=0}\lambda_{2,rad}}{\lambda_{2,T}}$$

The equilibrium fraction (E.F.) is the maximum fraction of the original parent activity that the decay product will reach given enough time, and is expressed as

$$E.F. = \frac{A_2}{A_1^{t=0}} = \frac{\lambda_{2,rad}}{\lambda_{2,T}}$$

$$E.F. = \frac{\lambda_{2,rad}}{\lambda_{2,rad} + \lambda_{2,vent}}$$

For this case, the decay product is Rn-222; $\lambda_{2,rad}$=0.0076 hr^{-1}. Based on NUREG-1717 ventilation rates, the equilibrium fraction is

100% for an airtight room with no ventilation.
~ 3% for a poorly ventilated room, with a ventilation rate of 0.25 hr^{-1}.
~ 0. 75% for a normally ventilated room, with a ventilation rate of 1.0 hr^{-1}.