

**Technical Basis Document:  
Irradiated Gemstones and their  
Characterization  
Using Handheld Instruments**

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**Introduction:** The jewelry industry imports large numbers of gemstones that have been irradiated in nuclear reactors, in particle accelerators, and with gamma radiation. Because some forms of irradiation can produce activation products, irradiated gemstones may be considered byproduct material. In particular:

1. Neutron irradiation with neutrons of any energy can cause activation via neutron absorption or via various neutron reactions (e.g. neutron absorption followed by proton ejection). Thus, neutron-irradiated gemstones are byproduct materials.
2. PAJ purchases neutron-irradiated gemstones **only** from neutron-irradiation facilities that are either licensed for exempt distribution of byproduct materials. Once released for exempt distribution by a licensed facility, this form of byproduct material is exempt from regulation. **Thus, neutron-irradiated gemstones produced by licensed neutron treatment facilities and released for exempt distribution are exempt from regulation and their possession and sale by PAJ does not require licensure by the NRC.**
3. Irradiation with gamma rays with energies in excess of the activation threshold energy can cause activation via neutron ejection, and also via subsequent neutron absorption. **Thus, gamma-irradiated gemstones are not byproduct materials unless the gamma energy exceeds the threshold energy for activation.**
4. Irradiation with electrons with energies in excess of the activation threshold energy can cause activation via neutron ejection, and also via subsequent neutron absorption. **Thus, electron-irradiated gemstones are not byproduct materials unless the electron energy exceeds the threshold energy for activation.**
5. The Food and Drug Administration (FDA) has declared that foods irradiated with electron or gamma radiation is suitable for human consumption provided the energy of the incident gamma ray or electron radiation does not exceed 7.5 MeV, because food materials do not become activated when irradiated with lower-energy radiation.
  - a. Although the chemical composition of foods differs somewhat from that of gemstones, it is worth noting that virtually every element found in gemstones is also present in foods (including iron, calcium, magnesium, sodium, sulfur, chlorine, chromium, cobalt, uranium, boron, selenium, zinc, and many others). In fact, food that lacks these “impurities” lacks nutrition because these “impurities” are vital nutrients – it is not the presence of these atoms that makes food nutritious and gemstones the opposite but, rather, the chemistry that makes these elements biologically available in foods and unavailable in minerals. As such, it is reasonable to

assume that food materials offer the same activation targets as do gemstones.

- b. It is also worth noting that gemstones are exposed to substantially higher radiation dose than are foods. However, if the energy of the incident radiation is below the activation threshold, the total dose to which materials are exposed is irrelevant because, below the threshold energy level, *no* number of incident electrons or photons is capable of inducing radioactivity. The total dose is relevant *only* when the energy of the incident radiation exceeds this activation threshold.
6. According to Auditore et al. (2004), Cossairt (1996, and personal communication in 2007), Weeks and O'Shea (1998) and documents published by the IAEA, high-energy electrons striking a target generate high-energy photons via bremsstrahlung, and these bremsstrahlung photons can then produce neutrons via the photo-neutron effect. In particular, Weeks and O'Shea state that "Electrons can produce radioactivity via conversion of their kinetic energy into electromagnetic energy (photons) followed by the subsequent absorption of those photons by nuclei." Further in this paper, the authors state that electrons can also directly cause activation via direct excitation of the nucleus, but that "The cross section for activation of materials (by this process) was observed to be roughly 100 times less than the photon activation cross sections." As such, the forms of interaction are virtually identical in both foods and gemstones, with the exception of the outermost layer of the gemstones (where the radioactivity is easiest to detect). In addition, the previous comment regarding exposure to radiation below threshold energies remains relevant.

This activation threshold is well-documented, including in the references cited elsewhere in this TBD and in IAEA 2000. This last document is of particular interest in that it summarizes the threshold energies and interaction cross-sections for gamma-neutron ( $\gamma$ -n) interactions for 164 isotopes, including most naturally-occurring stable isotopes. A summary table is attached that lists the threshold energies for these interactions for a large number of these natural isotopes; this include those isotopes that are present in an abundance of 5% or greater (for example, U-235, with an abundance of 0.72% is not included) and in which the elemental abundance in the earth's crust exceeds 10 ppm.

Using these criteria, there are 4 elements with nuclides that have the potential to become activated at photon energies of less than 7.5 MeV; Mg, Zr, Pb, and Th and that are present in the earth's crust at concentrations in excess of 100 ppm,

and none of these form anything other than impurities in the gemstones that are commonly irradiated. In fact, with the exception of the mineral zircon, Pb, Zr, and Th are not seen in gemstones, and I was unable to find any examples of Mg being found in gemstones in any measurable concentrations. To these elements, Be should be added because of its abundance in beryl-group gemstones. Of the elements noted, the activation cross-section is less than 10 mb (0.01 barns) for all except Pb and Th (for which the highest cross-section is about 30 mb).

It is important to note that, among the nuclides listed that have a threshold activation energy of less than 7.5 MeV, all share one or more of the following characteristics:

- Low abundance in the Earth's crust (< 10 ppm)
- Low abundance for the nuclide of interest (< 5%)
- Low abundance in gemstones (not reported in the scientific literature)
- Low activation cross-section (< 1 mb)

In fact, only Zr-91 Pb-207 and 208, and Th-232 do not meet all of these criteria, and none of these are reported as impurities in any gemstones other than zircons. As noted earlier, Be-9 is present in beryl-group gemstones in high concentrations. *Accordingly, it seems appropriate to consider that gemstones (with the exception of beryl-group gemstones and zircons) irradiated with accelerator energies of less than 7.5 MeV cannot be made radioactive and, therefore, are not byproduct materials.*

7. According to these same documents, only beryllium and deuterium are capable of activation at energies less than 10 MeV. Beryllium has an activation energy threshold of 1.66 meV and deuterium has an activation energy threshold of 2.2 MeV. The ( $\gamma$ ,n) cross-section at these energies is on the order of a few mbarns.
  - a. Beryllium minerals used in the jewelry industry include beryl, emerald, aquamarine, and morganite.
  - b. Hydrogen is not a major constituent of any gemstones
8. Based on the above, we can conclude that:
  - a. *Neutron-treated gemstones* do not require licensure by PAJ because they are produced by facilities that are licensed for exempt distribution.
  - b. *Gamma- and electron-treated gemstones that do not contain beryllium* need not be regulated because they cannot become radioactive (and are, therefore

not byproduct material) unless the photon or electron energy exceeds the activation threshold of 7.5 MeV.

- c. *Gamma- or electron-treated gemstones containing beryllium* need not be regulated unless the electron or gamma energy exceeds the activation threshold of 1.66 MeV because they cannot become radioactive (and are, therefore, not byproduct material). This is greater than the gamma energy of commercial irradiation sources such as Co-60 and Cs-137.
- d. *Gamma- and electron-treated gemstones* that are subsequently exposed to neutron irradiation are exempt from regulation as a result of being released for exempt distribution by the neutron-treatment facility
- e. **Thus, a radioactive materials license is *only* required for gemstones in which the *final* treatment step consists of:**
  - i. **Beryllium-containing gemstones exposed to electron or gamma radiation with an energy in excess of 1.66 MeV.**
  - ii. **Any other gemstones exposed to electron or gamma radiation with an energy in excess of 7.5 MeV.**

9. Irradiated gemstones include both major and minor radionuclides. The presence of these radionuclides depends on the impurities present in the gemstone-bearing rocks and the type and energy of the radiation(s) used in gemstone treatment.

Nuclide		Production	Half-life	Exempt concentration	
				( $\mu$ Ci/gm)	dpm/gm)
a. Na-24		minor	15 hrs	N/A	
b. P-32	$\beta$	minor	14 days	$2 \times 10^{-4}$	444
c. S-35	$\beta$	minor	89 days	$6 \times 10^{-4}$	1332
d. Sc-46	$\beta\gamma$	major	84 days	$4 \times 10^{-4}$	888
e. Cr-49		minor	42 min	N/A	
f. Cr-51	$\gamma$	minor	28 days	$2 \times 10^{-2}$	44,400
g. Mn-54	$\gamma$	major	312 days	$3 \times 10^{-4}$	666
h. Fe-59	$\beta\gamma$	minor	44 days	$6 \times 10^{-4}$	1332
i. Cu-64		minor	13 hrs	N/A	
j. Zn-65	$\gamma$	major	244 days	$1 \times 10^{-3}$	2220
k. Ga-72		minor	14 hrs	N/A	
l. As-77		minor	39 hrs	N/A	
m. Ge-77		minor	11 hrs	N/A	
n. Sb-124	$\beta\gamma$	minor	60 days	$2 \times 10^{-4}$	444
o. Cs-134	$\beta\gamma$	major	2.1 yrs	$9 \times 10^{-5}$	200
p. Ta-182	$\beta\gamma$	major	114 days	$4 \times 10^{-4}$	888

In the above table, "major" radioactivities are those that have been noted in the scientific literature (the papers by Ashbaugh, for example, as well as in NUREG/CR 5883) as being found in a large fraction of irradiated gemstones and, usually, in higher concentrations compared to the minor radioactivities. "Minor" radionuclides are those found in a lesser fraction of irradiated gemstones, typically in less concentrations.

- Following irradiation, gemstones are transported to the factory, cleaned, set, and transported into the US. This process typically takes no less than 3 weeks. Thus, induced radioactivities with a half-life of 2 days or less need not be considered. Among the nuclides listed above, only those with half-lives in excess of 2 days are considered in the following analysis.

### Detecting induced radioactivities

Radionuclide detection efficiency depends on the type and energy of the radiation(s) emitted by the nuclide in question and on the type of radiation detector used. The detection efficiencies for some of the nuclides noted above are summarized in the following table.

Using the values provided in the previous table in addition to the emission probability for each of the radiations, we can determine the counts per minute for each of the nuclides of concern in one gram of irradiated gemstone. These are provided in the following table. The gamma detection efficiencies were taken from information provided in Knoll (2000) with the source at a distance of 1 cm from the detector face.

Nuclide	Emission	Max Energy (MeV)	Detection efficiency (GM for $\beta$ and 1"x1" NaI for $\gamma$ )	Emission fraction (%)	At exempt concentrations (Summing all decays and intensities)			Instrument reading (CPM per gram)	
					$\mu\text{Ci/gm}$	DPM/gm	cpm/gm	GM	1"x1" NaI
P-32	$\beta$	1.71	8%	100%	2.00E-04	444	35	35	
S-35	$\beta$	0.168	5%	100%	6.00E-04	1332	66	66	
	$\beta$	0.357	15%	100%	4.00E-04	888	133	133	
Sc-46	$\gamma$	0.889	5%	100%	4.00E-04	888	44.4		89
	$\gamma$	1.121	5%	100%	4.00E-04	888	44		
Cr-51	$\gamma$	0.32	10%	10%	2.00E-02	44,400	444		444

Nuclide	Emission	Max Energy (MeV)	Detection efficiency (GM for $\beta$ and 1"x1" NaI for $\gamma$ )	Emission fraction (%)	At exempt concentrations (Summing all decays and intensities)			Instrument reading (CPM per gram)	
					$\mu$ Ci/gm	DPM/gm	cpm/gm	GM	1"x1" NaI
<b>Mn-54</b>	$\gamma$	0.835	5%	100%	1.00E-03	2220	111		111
	$\beta$	0.273	15%	46%	6.00E-04	613	92		
<b>Fe-59</b>	$\beta$	0.466	20%	53%	6.00E-04	706	141.192	233	
	$\gamma$	1.099	5%	56%	6.00E-04	746	37		
	$\gamma$	1.292	5%	44%	6.00E-04	586	29		67
	$\gamma$	1.292	5%	44%	6.00E-04	586	29		
<b>Zn-65</b>	$\gamma$	1.116	5%	51%	1.00E-03	2220	57		57
	$\beta$	0.611	25%	51%	2.00E-04	226	57		
<b>Sb-124</b>	$\beta$	2.302	40%	24%	2.00E-04	106	43	99	
	$\gamma$	0.603	5%	98%	2.00E-04	435	22		
	$\gamma$	1.691	5%	48%	2.00E-04	213	11		32
	$\beta$	0.658	5%	70%	9.00E-05	140	7	7	
<b>Cs-134</b>	$\gamma$	0.605	5%	98%	9.00E-05	196	10		
	$\gamma$	0.796	5%	86%	9.00E-05	172	8		18
	$\beta$	0.26	15%	29%	4.00E-04	258	39		
<b>Ta-182</b>	$\beta$	0.44	20%	21%	4.00E-04	186	37	147	
	$\beta$	0.524	20%	40%	4.00E-04	355	71		
	$\gamma$	0.1	10%	14%	4.00E-04	124	12		
	$\gamma$	1.121	5%	35%	4.00E-04	311	15		
	$\gamma$	1.189	5%	16%	4.00E-04	142	7		52
	$\gamma$	1.221	5%	27%	4.00E-04	240	12		
	$\gamma$	1.231	5%	11%	4.00E-04	97.68	4.884		

\*The detection efficiencies listed are the gamma detection efficiencies, according to information provided in Knoll (2000). The counting efficiency for a nuclide is a function of the emission probability for the gamma and the detection efficiency for that gamma ray. For example, a 1"x1" NaI(Tl) detector has a total

counting efficiency of 10% for the 320 keV Cr-51 gamma, which is emitted in 10% of all Cr-51 decays. Thus, the absolute Cr-51 counting efficiency using a 1"x1" NaI(Tl) detector would be 10% x 10% = 1%.

Of the nuclides listed above, only P-32 is a pure beta emitter and its counting efficiency may be degraded by self-shielding by the gemstone itself. The range of a high-energy beta (such as the P-32 beta) is sufficiently great (about 2-3 mm in a gemstone with a specific gravity of about 3.3) that at least 80% of the volume of a large (10 mm sphere) is within this distance of the surface of the gemstone. If we assume that the lower energy of the escaping beta particles also detracts from counting efficiency by a further factor of 4, then the effective counting efficiency for this nuclide is about 8%, producing about 35 cpm/gm when counted with a "pancake" Geiger probe. Making similar assumptions, we can expect that the presence of Cs-134 in a gemstone at exemption limits will produce a GM count rate of about 7 cpm per gram of gemstone counted. In addition, it must be noted that many of the P-32 and Cs-134 betas that do not escape from the crystal produce bremsstrahlung x-rays that are detectable via NaI counting. Thus, while these betas will not be detected using a GM probe, they will nevertheless evidence themselves (along with the gamma emissions) during NaI counting. Detecting these nuclides at exempt concentration limits, then, is a matter of increasing the sample size, increasing the counting time, and using shielding (if necessary) to reduce background count rates. This is described in greater detail below.

The other pure beta emitter that has been reported in the scientific literature, S-35, is formed by neutron activation of S-34 (present in an atomic abundance of about 4.21%). The presence of S-35 has been observed in *neutron*-irradiated gemstones, but its presence in accelerator-irradiated gems has not been reported in the scientific literature. This is presumably due to a combination of the low natural abundance of S-34 (4.21%), the relatively low abundance of sulfur in the earth's crust (260 ppm), and the even lower abundance of sulfur in gemstones. Another possible mechanism is S-36 ( $\gamma, n$ ), but the high threshold energy for this reaction (9.89 MeV) mitigates against this formation mechanism. We also note that very few minerals contain sulfur, and those that do are almost universally ugly and soft – characteristics that do not make for good gemstones. Thus, this combination of factors (the low abundance of target atoms, the absence of sulfur in gemstones, and the lack of scientific mention of S-35 in accelerator-irradiated gemstones) mitigate against the presence of S-35 in accelerator-irradiated gems.

We also note that neutron-irradiated gemstones will have been released for exempt distribution by an NRC licensee and do not require further characterization by PAJ. Every other nuclide noted in the preceding table emits gamma radiation, and is detectable using the methodology outlined in this document.

### Counting statistics, detection limits, and minimum detectable activity

We are immersed in a natural radiation environment. Every time we turn on a radiation detector, we will, at the very least, detect counts from this background. There is variability in the background radiation fields, and we must account for this variability when counting potentially radioactive samples. Before we can reliably claim to have detected radioactivity, the net count rate must be sufficiently above background radiation levels that there is reasonable assurance that the "excess" counts detected represent radioactivity and not simply a random fluctuation in the background radiation count rate. Using counting statistics, we can determine the minimum count rate that represents the probable detection of "excess" radioactivity. At the 95% confidence interval, this critical level ( $L_c$ ) can be calculated as follows:  $L_c = 2.326\sigma_b$  where  $\sigma_b$  is the square root of the total number of counts registered during the counting interval. So, for example, for a 1-minute count using a Geiger-Mueller "pancake" probe in a background radiation field of 50 cpm,  $L_c = 16$  counts in excess of background.

If we wish to determine the lowest level of radioactivity that has a 95% chance of not producing a false negative, we may use the relationship  $N_D = 4.635\sigma_{NB} + 2.706$  (where  $N_B$  is the total number of background counts). To continue the example above, the minimum number of counts above background (i.e. sample counts) that can be quantified is 35.5 counts above background, or a total of 86 counts in a one-minute counting interval (assuming that background count rate is 50 cpm). Using the meter detection efficiency, we can then determine the minimum detectable activity for a given radionuclide. The following tables summarize values of  $L_c$ ,  $N_D$ , and MDA under a variety of circumstances.

**Note:** At the  $L_c$ , there is a 95% chance of avoiding a false positive if *no* activity is present. At  $N_D$  there is a 95% chance of avoiding a false negative if activity *is* present. Combining the results from the preceding two tables, we can compare the exemption limit for each nuclide with the MDA for that nuclide using a particular detector.

If the probes are shielded to reduce background count rates to 20 cpm (for GM) and 500 cpm (for NaI), and if we assume a counting efficiency of 5% for both these types of detectors, these levels change as shown in the second table.

	Background (cpm)	Count time (minutes)	Total background (counts)	Counting efficiency	Lc (counts)	Lc (cpm)	ND (counts)	ND (cpm)	MDA ( $\mu$ Ci)
GM	50	1	50	20%	16	16	36	36	8.02E-05
	50	2	100	20%	23	12	49	25	5.54E-05
	50	5	250	20%	37	7	76	15	3.44E-05
	50	10	500	20%	52	5	107	11	2.40E-05
	50	20	1000	20%	74	4	150	7	1.69E-05
1"x1" NaI	1200	1	1200	5%	81	81	164	164	1.48E-03
	1200	2	2400	5%	114	57	231	115	1.04E-03
	1200	5	6000	5%	180	36	363	73	6.54E-04
	1200	10	12000	5%	255	25	512	51	4.62E-04
	1200	20	24000	5%	360	18	724	36	3.26E-04
GM	20	1	20	5%	10	10	24	24	2.12E-04
	20	2	40	5%	15	7	32	16	1.45E-04
	20	5	100	5%	23	5	49	10	8.87E-05
	20	10	200	5%	33	3	69	7	6.17E-05
	20	20	400	5%	47	2	96	5	4.31E-05
1"x1" NaI	500	1	500	5%	52	52	107	107	9.62E-04
	500	2	1000	5%	74	37	150	75	6.75E-04
	500	5	2500	5%	116	23	235	47	4.24E-04
	500	10	5000	5%	164	16	332	33	2.99E-04
	500	20	10000	5%	233	12	468	23	2.11E-04

Nuclide	At Exempt concentrations, for a 1-gram sample		For a 1-minute counting time			
	CPM (GM)	CPM (1"x1"NaI)	L <sub>c</sub> (CPM)		N <sub>D</sub> (CPM)	
			GM	NaI	GM	NaI
P-32	36	N/A	16	81	36	164
Sc-46	N/A	89	16	81	36	164
Cr-51	N/A	444	16	81	36	164
Mn-54	N/A	111	16	81	36	164
Fe-59	N/A	67	16	81	36	164
Zn-65	N/A	57	16	81	36	164
Sb-124	N/A	32	16	81	36	164
Cs-134	7	18	16	81	36	164
Ta-182	N/A	52	16	81	36	164

Nuclide	At exempt concentrations, for a 5-gram sample		For a 5-minute counting time			
	CPM (GM)	CPM (1"x1"NaI)	L <sub>c</sub> (CPM)		N <sub>D</sub> (CPM)	
			GM	NaI	GM	NaI
P-32	175	N/A	7	36	15	73
Sc-46	N/A	445	7	36	15	73
Cr-51	N/A	2220	7	36	15	73
Mn-54	N/A	555	7	36	15	73
Fe-59	N/A	335	7	36	15	73
Zn-65	N/A	285	7	36	15	73
Sb-124	N/A	160	7	36	15	73
Cs-134	35	90	7	36	15	73
Ta-182	N/A	260	7	36	15	73

These calculations show us that counting a 1-gram sample for 1 minute will produce a count rate that exceeds the L<sub>c</sub> for any single radionuclide except Cs-134, and that such a count will allow identification of any single nuclide at or above the N<sub>D</sub>.

Using a more sensitive detector (e.g. a 2"x2" NaI detector), a larger sample (e.g. 5 grams), reducing background, or utilizing a longer counting time (e.g. 5 minutes) produces a count rate in excess of both L<sub>c</sub> and N<sub>D</sub> for all radionuclides noted to occur in irradiated blue topaz. The exempt concentration for Cs-134 is lower than for virtually

any of the nuclides listed in Schedule A (Exempt Concentrations) of 10 CFR 30.70, and the nuclides with lower exempt concentrations are nuclides of iodine, which has not been identified in any irradiated gemstone.

To summarize, we can see that reducing background count rates and using a 5-minute counting time per sample produces a count rate that is adequate to detect both P-32 and Cs-134 in a 1-gram sample using a GM detector. Increasing the sample size to 5 grams reduces the counting time needed to identify the presence of these nuclides at exempt concentrations to about 2 minutes.

**For the reasons outlined above, to minimize the potential for a false negative reading even further, the PAJ counting procedure will call for:**

1. Using a shielded probe to reduce count rates to 20 cpm or lower with a GM probe and to 500 cpm or lower with a NaI(Tl) probe.
2. Obtaining integrated counts for 5 minutes on all samples and all detectors
3. Utilizing a sample size of at least 5 grams
4. Arranging the sampled gemstones in a single layer to minimize self-absorption of beta radiation
5. For all samples that produce count rates less than the limit for Cs-134 (35 cpm, or 175 net counts above background when counting with a GM detector and 80 cpm, or 400 net counts above background when counting with an NaI detector) the radionuclide concentrations will be recorded as "<MDA".

***Accordingly, hand-held instruments are able to detect exempt concentrations of any single nuclide whose presence has been noted in irradiated gemstones.***

In reality, it is exceptionally unlikely that any gemstone will contain only a single nuclide; irradiation will generate multiple radionuclides. Because of this, the most limiting nuclides (Cs-134 and Mn-54) will be present in combination with other nuclides. In fact, the existing literature (e.g. Table 2.2.1 of NUREG 1717, Table 6 of NUREG 5883, and papers by Ashbaugh) suggests that Mn-54 is typically present in activity concentrations that are comparable to those of most other of the induced radioactivities – with the exception of Ta-182, which is usually present in significantly higher concentrations. Accordingly, it is very probable that the concentrations of Mn-54 will not exceed exempt concentrations in the absence of regulated quantities of other induced radioactivities. **Interpreting these data under the assumption that the only radioactivities present are those of the most limiting nuclides is a conservative approach that will result in an over-estimate of the amount of radioactivity present in the sample.**

Documents by Ashbaugh and the NRC list a large number of radioactivities that can be induced by irradiation with neutrons and electrons. While not all of these nuclides are listed in the tables provided in this document, it is worth noting that all of the nuclides noted in these documents are detectable using the techniques described in this document because of the combination of radiation emission energies and exempt concentration limits.

### False negative probability

Appendix G of NUREG/CR 1556, Vol. 8 asks that radiological survey techniques be such that there is less than 1 chance in 1000 that an outlier gemstone containing twice the exempt concentration of radionuclides will accidentally be not be detected.

Using a GM detector, the net count rate for a 5-gram sample of gemstones that contain radionuclides at the exempt concentration limits is 35 cpm. Twice this value is 70 cpm, so we need to calculate the probability that a sample with a net count rate of 70 cpm will not be detected, when all counts are performed to the 95% confidence interval.

Using Poisson statistics, this probability is calculated using the formula  $P_{(m,N,p)} = \frac{e^{-\mu} \mu^m}{m!}$

In this equation,  $P$  is the probability of an event occurring (in this case, that a gemstone will not be detected),  $m$  is the number expected counts,  $N$  is the number of counts that, if not detected, would represent twice the exempt concentration limits, and  $\mu = Np$  where  $p$  is the probability of non-detection in each trial (5%).

Using these values, the probability of not detecting this concentration of radionuclides in a sample is  $P_{(m,N,p)} = \frac{e^{-0.05 \times 70} \times (0.05 \times 70)^{35}}{35!} = \frac{e^{-3.5} \times (3.5)^{35}}{35!} = \frac{0.0302 \times (1.06 \times 10^{34})}{1.033 \times 10^{40}} = 3.1 \times 10^{-8}$

Thus, using the survey methodology outlined in this TBD is sufficient to meet the criteria specified in Appendix G of NUREG/CR 1556, Vol. 8. Given the higher values for  $m$  and  $N$  (80 and 160, respectively) it is obvious that the probability of non-detection using a sodium iodide detector is even lower.

### Other nuclides

According to 10 CFR 32.23, safety criteria (including exempt concentration and exempt activity limits) are designed so that:

“In normal use and disposal of a single exempt unit, it is unlikely that the external radiation dose in any one year, or the dose commitment resulting from the intake of radioactive material in any one year, to a suitable sample of the group of individuals expected to be most highly exposed to radiation or radioactive material from the product will exceed the dose to the appropriate organ as specified in Column I of the table in § 32.24 of this part.”

These limits are 1 mrem to the whole body, 15 mrem to the extremities and to localized parts of the skin (not exceeding 1 square cm), and 3 mrem to any other organ. These criteria are discussed in greater detail as follows.

*External radiation dose* – according to NUREG 5883 (Table 46) radiation dose to the individual wearing a 30-carat blue topaz pendant is less than 1 mrem to the whole body, making it unlikely that any internal organ can receive a radiation dose of 3 mrem in one year. Table 48 of NUREG 5883 summarizes the beta dose rate (in units of mrem/cm<sup>2</sup>) from a 30-carat blue topaz that contains a number of radionuclides present at the exemption limits (which vary from 0.09 – 20 nCi/gm). The sum of all calculated doses is 2967.8 mrem for a 30-carat gemstone. For a 1-carat gemstone (which is larger than the size of an average individual gemstone) that has a size of ½ cm x ¼ cm, the calculated radiation dose is about 12 mrem for all of these nuclides that are present at the exempt concentration limit. It is implausible that radionuclides other than those listed in Schedule A will result in a skin dose in excess of 15 mrem/yr under realistic gemstone “aging” and wearing scenarios – particularly given that such radioactivities will be detected using the techniques described in this document. Accordingly, the potential presence of unlisted nuclides does not preclude declaring these gemstones exempt from regulation.

*Radiation from a radionuclide intake* – One aim of these exemption requirements is to preclude exceeding a radiation dose limit following ingestion or inhalation of radioactive materials. Irradiated gemstones are not intended to be eaten or inhaled, and this happens only very rarely. In those instances in which gemstones or articles of jewelry are ingested, the chemical form of the gemstone limits the uptake of radionuclides, while the normal movement of materials through the digestive tract precludes the retention of these gemstones for an extended time. In addition, gemstones are not highly soluble, so the radioactivity contained within a swallowed gemstone will not enter the body.

From the above, we can conclude that radionuclides that may be present in an irradiated gemstone that are not listed in Schedule A to 10 CFR 30.70 are very unlikely to produce radiation doses in excess of those listed in 10 CFR 32.23 and the table in 10

CFR 32.24. In addition, such nuclides (if present) are detectable and will be present in conjunction with other radioactivities. Accordingly, irradiated gemstones may be exempted from regulation following the survey procedures noted in this document, even given the possible presence of radionuclides not listed in the Schedule A.

## Conclusions

1. Of the several categories of irradiated gemstones, the only gemstones requiring licensure are those containing beryllium that are exposed to electron or gamma radiation in excess of 1.66 MeV, or those that do not contain beryllium that are exposed to energies in excess of 7.5 MeV.
2. Of the radioactivities that have been noted to be induced in irradiated gemstones, handheld instruments are sufficiently sensitive to detect any individual radionuclide that is present at the exempt concentration limit.
3. For those induced radioactivities that are not listed in Schedule A of 10 CFR 30.70, none are likely to produce a radiation dose in excess of the limits noted in 10 CFR 32.24.
4. Accordingly, radiological surveys with handheld radiation detectors (GM "pancake" probes and 1"x1" NaI detectors) are sufficient to declare that irradiated gemstones contain only radionuclides in concentrations that meet exempt concentration criteria.
5. Gemstones that do not meet the screening criteria outlined in this document will be returned to the vendor, held until screening criteria are met, or sent to a licensed facility for quantitative analysis.

## References

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**Appended materials: Chemical composition of irradiated gemstones and photon activation cross-sections for many natural nuclides**

Gemstone	Chemical composition
Topaz	$\text{Al}_2\text{SiO}_4(\text{F},\text{OH})_2$
Beryl	$\text{Be}_3\text{Al}_2\text{Si}_6\text{O}_{18}$
Diamond	C
Rubellite	$(\text{Na}, \text{Ca}) (\text{Al}, \text{Fe}, \text{Li}, \text{Mg})_3\text{B}_3\text{Al}_3(\text{Al}_3\text{Si}_6\text{O}_{27})(\text{O}, \text{OH}, \text{F})_4$
Kunzite	$\text{LiAlSi}_2\text{O}_6$

Nuclide	Element abundance (ppm)	Nuclide abundance (%)	Gamma activation threshold (MeV) (IAEA 2000)	Approximate $\gamma$ activation cross-section (mb) at 7.5 MeV
			$\gamma - n$	$\gamma - n$
Be-9	2.6	100	1.67	1.5
C-12	480	98.93	18.72	
N-14	25	99.632	10.55	
O-16	474,000	99.757	15.66	
Na-23	23,000	100	12.42	
Mg-24	23,000	78.99	16.53	
Mg-25		10	7.33	< 1
Mg-26		11.01	11.09	
Al-27	82,000	100	13.06	
Si-28	277,000	92.23	17.18	
S-32	260	95.02	15.04	
Cl-35	130	75.77	12.65	
Cl-37		24.23	10.31	
Ar-40	1.2	99.6	9.87	
K-39	21,000	93.26	13.08	
K-41		6.73	10.10	
Ca-40	41,000	96.94	15.64	

Nuclide	Element abundance (ppm)	Nuclide abundance (%)	Gamma activation threshold (MeV) (IAEA 2000)	Approximate $\gamma$ activation cross-section (mb) at 7.5 MeV
			$\gamma$ - n	$\gamma$ - n
Ti-46	5600	8.0	13.19	
Ti-47		7.30	8.88	
Ti-48		73.80	11.63	
Ti-49		5.5	8.14	
Ti-50		5.4	10.94	
V-51	160	99.75	11.05	
Cr-52	100	83.79	12.04	
Cr-53		9.50	7.94	
Mn-54	950	100	10.23	
Fe-54	41,000	5.90	13.38	
Fe-56		91.72	11.20	
Co-59	20	100	10.45	
Ni-68	80	68.08	12.22	
Ni-60		26.22	11.39	
Cu-63	50	69.17	10.85	
Cu-65		30.83	9.91	
Zn-64	75	48.60	11.86	
Zn-66		27.90	11.06	
Zn-68		18.80	10.20	
Ge-71	1.8	21.23	11.54	
Ge-72		27.66	10.75	
Ge-73	1.8	7.73	6.78	< 1
Ge-74		35.94	10.20	
Ge-76		7.44	9.43	
Sr-86	370	9.86	11.49	
Sr-87	370	7.00	8.43	

Nuclide	Element abundance (ppm)	Nuclide abundance (%)	Gamma activation threshold (MeV) (IAEA 2000)	Approximate $\gamma$ activation cross-section (mb) at 7.5 MeV
			$\gamma$ - n	$\gamma$ - n
Sr-88		82.58	11.11	
Zr-90	190	51.45	11.97	
<b>Zr-91</b>		11.22	<b>7.19</b>	5
Zr-92		17.15	8.64	
Zr-94		17.38	8.22	
Nb-93		20	100	8.83
Mo-92	1.5	14.84	12.67	
Mo-94		9.25	9.68	
<b>Mo-95</b>		15.92	<b>7.37</b>	5
Mo-96		16.68	9.15	
<b>Mo-97</b>		9.55	<b>6.82</b>	5
Mo-98		24.13	8.64	
Mo-100		9.63	8.29	
Pd-104		6x10 <sup>-4</sup>	11.14	9.99
<b>Pd-105</b>	22.33		<b>7.09</b>	6
Pd-106	27.33		9.56	
Pd-108	6x10 <sup>-4</sup>	26.46	9.22	
Pd-110		11.72	8.81	
Ag-107	0.07	51.84	9.54	
Ag-109		48.16	9.19	
Cd-110	0.11	12.49	9.92	
<b>Cd-111</b>		12.80	<b>6.97</b>	5
Cd-112		24.13	9.40	
<b>Cd-113</b>		12.22	<b>6.54</b>	5
Cd-114	0.11	28.73	9.04	
Cd-116		7.49	8.70	

Nuclide	Element abundance (ppm)	Nuclide abundance (%)	Gamma activation threshold (MeV) (IAEA 2000)	Approximate $\gamma$ activation cross-section (mb) at 7.5 MeV
			$\gamma$ - n	$\gamma$ - n
Sn-116	2.2	14.53	9.56	
Sn-117		7.68	6.94	10
Sn-118		24.22	9.33	
Sn-118		8.58	6.49	
Sn-120		32.59	9.11	
Sn-124		5.79	8.49	
Sb-121	0.2	57.36	9.24	
Sb-123		42.64	8.97	
Te-125	0.005	7.12	6.57	
Te-126		18.93	9.11	
Te-128		31.70	8.78	
Te-130		33.87	8.41	
I-127	0.14	100	9.14	
Cs-133	3	100	8.99	
Pr-141	9.5	100	9.40	
Sm-147	7.9	15.00	6.35	8
Sm-148		11.30	8.14	
Sm-149		13.80	5.87	10
Sm-150		7.40	7.99	
Sm-152	7.9	26.70	8.26	
Sm-154		22.70	7.97	
Tb-159	1.1	100	8.13	
Ho-165	1.4	100	7.99	
Ta-181	2	99.99	7.58	
W-182	1	26.30	8.07	
W-183		14.28	6.19	30

Nuclide	Element abundance (ppm)	Nuclide abundance (%)	Gamma activation threshold (MeV) (IAEA 2000)	Approximate $\gamma$ activation cross-section (mb) at 7.5 MeV
			$\gamma$ - n	$\gamma$ - n
W-184		30.70	7.41	20
W-186		28.60	7.19	30
Au-197		0.0011	100	8.07
Pb-206	14	24.10	8.09	
Pb-207		22.10	6.74	20
Pb-208		52.40	7.37	20
Bi-209	0.048	100	7.46	10
Th-232	12	100	6.44	20
U-238	2.4	99.27	6.15	30