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Radiological Characterization Technical Report on Californium-252 Sealed Source Transuranic Debris Waste for the Off-Site Source Recovery Project at Los Alamos National Laboratory

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Cristy Abeyta: OSRP Team Leader

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ACRONYMS

AK	Acceptable Knowledge
DOE	Department of Energy
DOT	Department of Transportation
FGE	Fissile Gram Equivalent
HFIR	High Flux Isotope Reactor
ID	Identification
MCNP	Monte Carlo N-Particle (Code)
NMMSS	Nuclear Materials Management Safeguards System
NRC	Nuclear Regulatory Commission
ORNL	Oak Ridge National Laboratory
OSRP	Off-Site Source Recovery Program
REDC	Radiochemical Engineering Development Center
SFC	Special Form Capsule
SRS	Savannah River Site
TRU	Transuranic
US	United States
WAC	Waste Acceptance Criteria
WIPP	Waste Isolation Pilot Plant

ABSTRACT

This document describes the development and approach for the radiological characterization of Cf-252 sealed sources for shipment to the Waste Isolation Pilot Plant. The report combines information on the nuclear material content of each individual source (mass or activity and date of manufacture) with information and data on the radionuclide distributions within the originating nuclear material. This approach allows for complete and accurate characterization of the waste container without the need to take additional measurements.

The radionuclide uncertainties, developed from acceptable knowledge (AK) information regarding the source material, are applied to the summed activities in the drum. The AK information used in the characterization of Cf-252 sealed sources has been qualified by the peer review process, which has been reviewed and accepted by the Environmental Protection Agency.

1 INTRODUCTION

Sealed sources are manufactured for a variety of uses, including nuclear batteries, smoke detectors, neutron flux generators, and threshold detectors, and for numerous applications. Over the years, a significant number of these sealed sources that were manufactured for a wide range of applications have ceased to be used and have been declared to be excess. Under Public Law 99-240, titled the “Low-Level Waste Policy Amendments Act of 1985” (Reference 1), Congress assigned to the United States (US) Department of Energy (DOE) the responsibility for the management and disposal of “Greater-than-Class C” waste as defined in the Nuclear Regulatory Commission’s (NRC’s) 10 CFR Part 61 regulations (Reference 2), which includes actinide sealed sources. In response to Public Law 99-240, DOE established the Off-Site Source Recovery Project (OSRP) for the specific purposes of recovering, managing, and disposing of excess or unwanted actinide sealed sources. This report addresses the radiological characterization of Cf-252 sealed sources. In the early production period of Cf-252, small quantities of the source material were produced at both the Savannah River Site and Oak Ridge National Laboratory (ORNL). As the program matured, larger quantities were produced at ORNL in the High Flux Isotope Reactor (HFIR) and purified in the Radiochemical Engineering Development Center (REDC) at ORNL. This material was offered for sale to commercial entities or other DOE laboratories where the sealed sources were fabricated. The Cf-252 sealed sources were intended to be used as neutron sources for medical applications, activation analysis, and other neutron applications. The sealed sources addressed in this report were declared to be excess and are no longer useful. Further details on this waste stream are provided in Reference 3.

Because no facility other than the Waste Isolation Pilot Plant (WIPP) currently offers safe and secure permanent disposal capabilities, it is intended that the actinide-bearing sealed sources be disposed of as transuranic (TRU) waste at WIPP. As such, the sealed source waste packages must meet the WIPP waste acceptance criteria (WAC) (Reference 4). These criteria include the requirement for the radiological characterization of waste packages to identify the quantities and types of radionuclides in the package before they are disposed of. The effort described in this report provides the radiological characterization of actinide (Cf-252) sealed source waste packages needed to be in compliance with the WIPP WAC.

2 BACKGROUND

2.1 Californium-252 Production

In 1959, Savannah River Site (SRS) became involved in the production of transplutonium elements caused by the irradiation of Pu-239. A Cf-252 source fabrication was initiated in the 1960s at SRS as part of a market evaluation. The demand for Cf-252 sources resulted in the need to increase the production of the source material. Ultimately, the californium production program was transferred to the REDC at ORNL. The Cf-252 is produced from Pu-239 by 13 successive neutron captures, as shown in Figure 2-1.

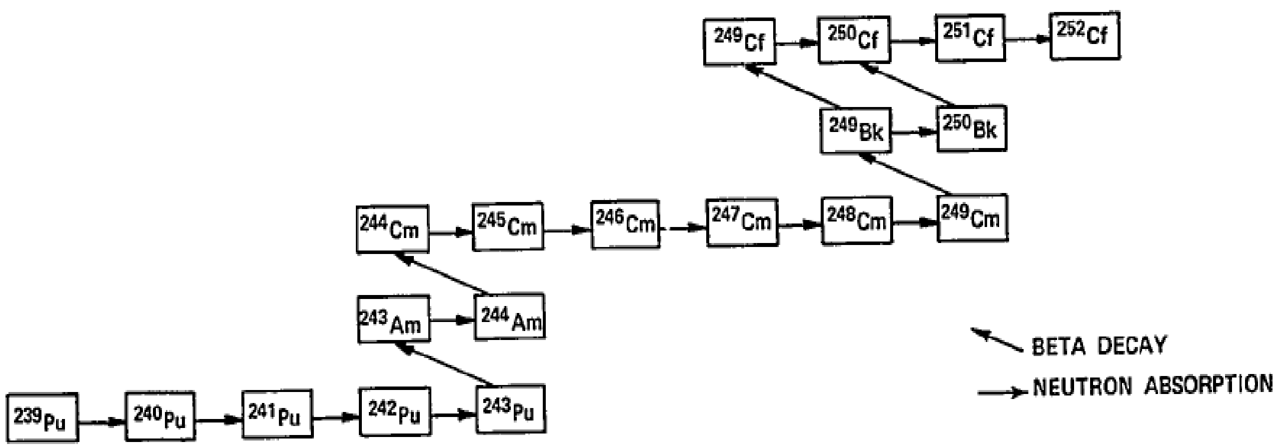


Figure 2-1. Californium-252 production scheme by neutron capture.

At ORNL, the Cf-252 is produced from the irradiation of heavier actinides (curium and americium), which are separated from the californium and recycled back to the reactor to produce more californium. The average isotopic mass continues to increase with the recycling. Curium-244 ultimately becomes the primary actinide, along with large quantities of Cm-246 and lesser quantities of americium. The heavier feed material reduces the irradiation times to less than a year. The irradiations are completed exclusively in the HFIR, with the final separations and purifications occurring in the REDC.

2.2 Californium-252 Source Descriptions

The sizes and configurations of the Cf-252 sources vary with the application or intended use of the source. Neutron sources are offered by ORNL and commercial suppliers in sizes ranging from 1 µCi up to 50 µCi in the form of fission foils. Some source designs are licensed to contain up to 50 mg of Cf-252 (27 Ci). A few sources have been fabricated with a single encapsulation, but the large majority is double encapsulated.

3 TECHNICAL APPROACH

The approach proposed for the radiological characterization of Cf-252 sealed source waste is to use the extensive documentation and information on the nuclear material content of each source (mass or activity of material used) and information and data on the radionuclide distributions within the nuclear material. This information allows for complete characterization without the need to take additional measurements.

The WIPP WAC (Reference 4) requires that, as a minimum, the masses and activities of the following 10 radionuclides (if present) be reported:

Am-241	U-233
Pu-238	U-234
Pu-239	U-238
Pu-240	Sr-90
Pu-242	Cs-137

In addition to the above 10 radionuclides, other radionuclides are required to be reported that, in the aggregate, constitute not less than 95% of the total radiological hazard based on the A_2 values given in US Department of Transportation (DOT) packaging regulations, 49 CFR, *Transportation*, Part 173, *Shippers—General Requirements for Shipments and Packagings*, Section 435, Tables A1 and A2, Values for Radionuclides (Reference 5). Also, the "Contact-Handled Transuranic Waste Authorized Methods for Payload Control (CH-TRAMPAC)" (Reference 6) requires that 95% of the decay heat be accounted for in the report of the radionuclides in a package, plus any radionuclide that contributes >1% of the total.

The relative concentrations of the radionuclides in the source material were evaluated by the REDC at ORNL to determine the reporting requirement for parameters, such as fissile gram equivalent (FGE), decay heat, and radiological hazard (Reference 7). The californium isotopes undergo alpha decay, producing a curium isotope as a decay product. At the end of each production campaign at the REDC, all TRU isotopes of californium and curium were analyzed and reported before material was shipped. The evaluation showed that Cf-250 and Cf-252 are also required to be reported for WIPP disposal because of their contribution to the radiological hazard and decay heat. Californium-249 and Cf-251 are required to be reported because of their contribution to FGE. Table 3-1 lists the radionuclides required to be reported for material disposal at WIPP.

Table 3-1. Radionuclides Required to Be Reported for WIPP Disposal

Sr-90
Cs-137
Cm-245
Cm-246
Cm-247
Cm-248
Cf-249
Cf-251
Cf-250
Cf-252

The characterization approach involves four steps.

1. Determine the primary radionuclide and the quantity of the primary radionuclide in the source based on acceptable knowledge (AK) information and data specific to the individual sources.

2. Apply the specific radionuclide impurity distribution that has been developed from AK information for the identified primary radionuclide material in the source.

3. Perform the decay correction of the source material from the time of manufacture to the time of shipment for disposal.

4. Summarize the radionuclide content of all sources loaded into the special form capsule (SFC) and ultimately into a 55-gallon drum.

The AK information used in the characterization of Cf-252 sealed sources has been qualified by the peer review process (Reference 8), which has been reviewed and accepted by the Environmental Protection Agency (EPA). The uncertainties developed from AK information regarding the source materials are applied to the summed activities in the drum.

Three specific pieces of AK information are required as input for the radiological characterization of sealed source waste:

- the type of source (identification of the primary radionuclide),
- the radionuclide content of the source (in curies or grams), and
- the date of manufacture.

4 DEVELOPMENT OF REPRESENTATIVE RADIONUCLIDE DISTRIBUTIONS

This section presents the derivation and quantification of the WIPP-required radionuclide distributions that will be applied to the primary radionuclide. The Cf-252 source material is typically 71–89 wt% Cf-252, with the remainder of the material containing other californium isotopes. Trace impurities of other radionuclides fall below detectable limits because of the multiple separation and purification processes. Other impurity radionuclides in the recovered sources result from the decay of californium isotopes to their curium daughters. In addition, the fission products of Cs-137 and Sr-90 are produced from the spontaneous fissioning of both the californium isotopes and their curium daughters.

Specific information on the associated curium decay daughters of the californium isotopes are provided in Table 4-1, along with the identification of isotopes that are TRU radionuclides that spontaneously fission.

Table 4-1. Background Information on the Californium and Curium Decay Isotopes for the Cf-252 Source Material

Radionuclide	Half-Life, yrs	TRU Radionuclide	Spontaneous Fission	Daughter	Half-Life, yrs	TRU Radionuclide	Spontaneous Fission
Cf-249	350.6	Yes	Yes	Cm-245	8500	Yes	Yes
Cf-250	13.08	No	Yes	Cm-246	4750	Yes	Yes
Cf-251	900	Yes	No	Cm-247	1.56E+07	Yes	No
Cf-252	2.639	No	Yes	Cm-248	3.39E+05	Yes	Yes

The californium radionuclide distributions and associated uncertainties were developed from AK information on the radiological contents of the source materials used in the manufacture of the sources. Californium-252 source material initially was produced and purified at SRS. This production activity was transferred to the ORNL REDC in 1986; from there, materials are distributed to source manufacturers. The source material was sampled and analyzed for radionuclide content to meet source material purity requirements. Twenty-two batch analyses were retrieved from the REDC process records and were used to develop an average californium isotope distribution in the materials. The variability in the isotopic distributions was used to develop the uncertainties in the source content and radionuclide distribution. Figure 4-1 provides an example of the AK information on the Cf-252 product showing nondetectable quantities of curium impurities.

69CX -4 Material Balances

Material Balances (69CX-4)	Cm-244,g	% Feed	% output	09/12/94 Es-253,ug	% Feed	% output	Cf-252,mg	% Feed	% output	Bk-249,mg	% Feed	% output
69CX-4 Feed												
CXAF-056	0.043	100%		1213	100%		110	100%		38	100%	
69CX-4 Cut Balance												
Run Cuts												
Raffinate Cuts												
CXLR-308	8.9E-06			0.085			0.005					
CXLR-309	1.1E-04			14.0			0.751			0.241		
CXLR-310	2.3E-04			19.4			1.62			0.393		
CXER-272	9.5E-07			0.031			0.001					
CXER-273	3.7E-07			0.132			0.006					
CXER-274	1.7E-06			0.209			0.005					
Total	3.5E-04	0.8%	1.7%	33.9	2.8%	2.4%	2.39	2.2%	2.1%	0.635	1.7%	1.9%
Fm Product												
CXFM-092	5.2E-06	0.01%	0.03%	1.05	0.09%	0.07%	0.007	0.007%	0.007%			
Es Product												
CXES-208				4.48			0.004					
CXES-209				821.9			0.006					
CXES-210				521.6			0.013					
Total				1348	111%	93.9%	0.023	0.02%	0.02%			
Cf Product												
CXCF-524				50.8			3.94			0.008		
CXCF-525							75.6			0.041		
CXCF-526							20.4			0.357		
CXCF-527							8.56			2.53		
Total				50.8	4.2%	3.5%	109	98.8%	96.5%	2.94	7.9%	8.7%
Bk Cuts												
CXBK-216							1.21			29.3		
CXBK-217	4.5E-05			0.808			0.204			0.675		
CXBK-218	6.5E-04			0.208			0.034			0.133		
Total	6.9E-04	1.6%	3.3%	1.02	0.08%	0.07%	1.45	1.3%	1.3%	30.1	79.7%	89.4%
Cm Cut												
CXCM-186	0.020	45.5%	94.9%				0.039	0.04%	0.03%			
Pipette Leach												
CXSF-235	4.7E-06	0.01%	0.02%	0.726	0.06%	0.05%	0.015	0.01%	0.01%			
Total	**0.021**	**47.9%**	**100%**	**1435**	**118%**	**100%**	**112**	**102%**	**100%**	**33.6**	**89.2%**	**100%**
69CX-4 Run Balance												
Feed												
CXAF-056	0.043	100%		1213	100%		110	100%		37.7	100%	
Rework												
PVC-619	0.036			242			1.50					
PVC-620	0.020			2.44			0.124					
Total	0.056	128.7%	98.2%	244	20.1%	14.5%	1.63	1.5%	1.4%			
Fm Product												
CXFM-092	5.2E-06	0.01%	0.009%	1.05	0.09%	0.06%	0.007	0.007%	0.007%			
Es Product												
CXES-208				4.48			0.004					
CXES-209				822			0.006					
CXES-210				522			0.013					
Total				1348	111.1%	80.3%	0.023	0.02%	0.02%			
Bk Product												
CXBK-217	4.5E-05			0.808			0.204			0.675		
CXBK-218	6.5E-04			0.208			0.034			0.133		
Total	6.9E-04	1.6%	1.2%	1.02	0.08%	0.06%	0.238	0.2%	0.2%	0.808	2.1%	2.4%
Cf Product												
CXCF-524				50.8			3.94			0.008		
CXCF-525							75.6			0.041		
CXCF-526							20.4			0.357		
Total				50.8	4.2%	3.0%	100	91.0%	87.7%	0.406	1.1%	1.2%
Cub 4 Cleanup												
CXLR-309	1.1E-04			14.0			0.751			0.241		
CXLR-310	2.3E-04			19.4			1.62			0.393		
Total	3.4E-04	0.8%	0.6%	33.4	2.8%	2.0%	2.38	2.2%	2.1%	0.635	1.7%	1.9%
Recycle to 69CX-7(comp. w/ 69CX-6)												
CXCF-527							8.56			2.53		
CXBK-216							1.21			29.3		
Total							9.78	8.9%	8.6%	31.8	84.3%	94.5%
Total	**0.057**	**131%**	**100%**	**1678**	**138%**	**100%**	**114**	**104%**	**100%**	**33.6**	**89.2%**	**100%**

Figure 4-1. Example of AK information on impurity levels in the Cf-252 product.

Figures 4-2 and 4-3 provide examples of the AK information on the Cf-252 isotope distributions in the source product. Figure 4-2 is an isotope analysis report based on a mass spectrometry measurement of a sample taken from the dissolved target solutions for Campaign 69.

ISOTOPE ANALYSIS REPORT

REQUISITION NUMBER 7091		CHARGE NUMBER 3370-6001
SUBMITTED BY Chris Parks	BUILDING NUMBER 720 6384	DATE 4/27/95
REPORT TO	BUILDING NUMBER	PHONE 4-7064

PROBABLE COMPOSITION OF SAMPLES

CUSTOMER NUMBER	DSOP-249	CXOF-537		
LOG NUMBER	12-8-94-0182	12-894-0184		
RUN NUMBER				
249	4.29 ± .04	4.72 ± .03		
250	9.97 ± .08	10.19 ± .04		
251	2.93 ± .03	3.04 ± .01		
252	82.72 ± .07	82.04 ± .05		
253	0.07 ± .02	0.01 ± .01		
254	0.02 ± .01	<0.01		

*Isotopic abundance is expressed in atom percent unless otherwise specified.

Figure 4-2. Example of mass spectrometry measurements taken to determine isotopic distribution in the Cf-252 product.

Figure 4-3 shows the projected Cf-252 product composition for Campaign 69 based on the physics calculations for the targets and rework material.

Rework from Camp 68 0.0207 g Cf252 09/06/94 CLCP-725A&B

Mass analysis, 02/04/93 Adjusted to, 12/31/94

Isotopes	At %	Wt %	Decay Factor	Corrected	Normalized	Weight
249	20.080	19.908	0.996	19.833	27.128	0.0095
250	10.760	10.711	0.905	9.692	13.257	0.0046
251	3.700	3.698	0.999	3.692	5.050	0.0018
252	65.460	65.682	0.607	39.892	54.564	0.0190
253	0.001	0.001	0.000	0.000	0.000	0.0000
254	0.001	0.001	0.000	0.000	0.000	0.0000
Avg MW	251.230	100.000		73.109	100.000	0.0349

Targets 0.485658 g Cf252 09/15/94 DSDP-250 Mass(DSDP-249)

Mass Analysis 01/04/95 Adjusted to, 12/31/94

Isotopes	At %	Wt %	Decay Factor	Corrected	Normalized	Weight
249	4.900	4.849	1.000	4.849	4.837	0.0263
250	9.750	9.687	1.001	9.692	9.668	0.0526
251	2.830	2.823	1.000	2.823	2.816	0.0153
252	82.470	82.591	1.003	82.829	82.622	0.449768
253	0.040	0.040	1.168	0.047	0.047	0.0003
254	0.010	0.010	1.046	0.011	0.011	0.0001
Avg MW	251.711	100.000		100.250	100.000	0.5444

Figure 4-3. Projected Cf-252 compositions for Campaign 69 based on REDC physics calculations.

The process data were retrieved from REDC processing records from 1972 to 2003. The californium isotopic data retrieved are given in Table 4-2 in units of weight percent.

Table 4-2. Californium Isotopic Data from Processing Campaigns

Data Source	Date	Cf-249	Cf-250	Cf-251	Cf-252
Campaign 37	1/10/1972	0.21%	11.43%	3.72%	84.64%
Campaign 35 Rework	5/1/1972	7.72%	10.88%	3.31%	78.09%
Campaign 37 Rework	11/11/1972	12.26%	12.28%	3.92%	71.55%
Campaign 38	11/28/1972	6.01%	12.14%	3.45%	78.40%
Campaign 39 Targets + Rework	2/6/1973	1.81%	8.55%	2.41%	86.62%
Campaign 51 Rework	9/2/1976	11.92%	9.75%	2.99%	75.35%
Campaign 51 + Rework	9/19/1976	0.65%	7.93%	2.13%	88.79%
Campaign 51 + Turf Rework	1/5/1977	7.00%	11.28%	3.63%	78.06%
Campaign 52 Targets	1/10/1977	0.03%	7.85%	2.09%	88.62%
Campaign 53 Rework	8/14/1977	11.17%	8.99%	2.65%	77.18%
Campaign 53	8/31/1977	0.34%	7.70%	2.15%	88.86%
Campaign 53	9/21/1977	0.79%	7.67%	2.10%	88.94%
Campaign 54	1/10/1978	1.46%	8.25%	2.31%	87.86%
Campaigns 56 and 57 Rework	1/14/1980	10.97%	8.41%	2.55%	78.07%
Camp 63 Targets and Rework	10/8/1982	1.65%	7.92%	2.19%	87.33%
Campaign 65 Rework	10/15/1985	2.92%	7.38%	2.14%	87.41%
Campaign 67 Targets	2/2/1987	1.93%	7.21%	2.09%	88.40%
Campaign 69 Targets	12/31/1994	4.83%	9.67%	2.81%	82.68%
Campaign 70	4/22/1996	1.77%	8.71%	2.46%	87.05%
Campaign 71	10/12/1998	0.32%	10.18%	2.84%	86.67%
Campaign 72	9/11/2000	0.75%	8.68%	2.44%	87.59%
Campaign 73	2/6/2003	0.79%	8.21%	2.40%	88.61%
Shilton email	6/9/2003	3.37%	8.64%	2.59%	85.39%

The average concentrations of the isotopes' activities relative to Cf-252 were determined from these analytical results and the specific activities of the isotopes, as given in Table 4-3.

Table 4-3. Average Activity Distribution of the Californium Isotopes in Cf-252 Source Material

	Ci/Ci Cf-252			
Average Activity	Cf-249	Cf-250	Cf-251	Cf-252
	3.82E-04	2.24E-02	9.48E-05	1.00E+00

The contributions of Cs-137 (and Sr-90) to the impurity levels from spontaneous fission of Cf-249, Cf-250, Cf-252, Cm-245, Cm-246, and Cm-248 were also considered. The ultimate concentration of the fission products depends on the fission time due to buildup; consequently, different fission times were considered. Table 4-4 shows the results of the calculations for the buildup of Cs-137 as a function of the fission time.

Table 4-4. Cesium-137 Contribution from Spontaneous Fission

Years	Cs-137 from SF of Cf-249	Cs-137 from SF of Cf-250	Cs-137 from SF of Cf-252	Cs-137 from SF of Cm-245	Cs-137 from SF of Cm-246	Cs-137 from SF of Cm-248	Total Cs-137	% from Cf-252
	Ci/Ci Cf-252	Ci/Ci Cf-252	Ci/Ci Cf-252	Ci/Ci Cf-252	Ci/Ci Cf-252	Ci/Ci Cf-252	Ci/Ci Cf-252	
1	2.14E-13	2.08E-08	3.10E-05	1.35E-19	7.23E-13	9.75E-15	3.10E-05	99.9%
2	4.24E-13	4.01E-08	5.42E-05	5.34E-19	2.68E-12	3.61E-14	5.42E-05	99.9%
3	6.28E-13	5.79E-08	7.13E-05	1.19E-18	5.79E-12	7.48E-14	7.13E-05	99.9%
38	5.27E-12	2.05E-07	6.22E-05	1.45E-16	4.02E-10	1.97E-12	6.24E-05	99.7%
39	5.35E-12	2.03E-07	6.07E-05	1.52E-16	4.15E-10	2.01E-12	6.09E-05	99.7%
40	5.43E-12	2.01E-07	5.94E-05	1.59E-16	4.27E-10	2.04E-12	5.96E-05	99.7%

The results presented in Table 4-4 show that the contribution of Cs-137 from the spontaneous fission from Cf-252 is >99.7%, with decays of up to 40 years. Accordingly, because the contribution from the spontaneous fission of other isotopes is so small, only the contribution of Cs-137 (and Sr-90) to the impurity level from the spontaneous fission of the Cf-252 will be considered in the characterization spreadsheet.

Another source of fission products is fast neutron fission induced by neutrons emitted during spontaneous fission. This source was assessed (Reference 9) by the use of the Monte Carlo N-Particle code (MCNP) 5. From these analyses it was concluded that fission products from neutron-induced fission are negligible compared with the fission products from spontaneous fission.

5 DETERMINATION OF THE QUANTITY OF NUCLEAR MATERIAL IN SEALED SOURCES

In general, significant documentation and information (including the original production, transportation, and source control documents) exist on sealed sources manufactured in the US. However, for individual sealed sources, variability exists in the quantity and extent of the documentation available for use in the characterization of the sealed source. Because sealed sources are manufactured to meet user specifications, strict adherence to procedures under the oversight of quality assurance programs of the day ensured that these sources and their associated production documents were prepared with a high degree of care and accuracy. The nature of the source production and the historically successful functioning of these sources to meet their intended purposes support this observation. The nuclear material contents of the sources were carefully controlled to meet the specifications imposed by the end user on the power output, neutron flux, impurity levels, etc.

After a source is declared excess, but before it is recovered, all available information and documentation on the source is retrieved, reviewed, and evaluated to determine if the information is adequate relative to the identity of the primary radionuclide in the source and the quantity of the radioactive material in the source. This information may be derived from a set of documents that are considered *primary* information sources in that they contain all of the information necessary to establish the source type (primary radionuclide) and the quantity of radionuclide material in the source.

Generally, only one piece of documentation is required from the list of primary AK information to identify the radionuclide and quantity in a sealed source. The following list provides primary AK information:

- the Nuclear Materials Management Safeguards System (NMMSS),
- shipping records,
- source certificates, and
- fabrication documents.

This primary AK information is unique to a specific sealed source, as identified by a unique serial number. The NMMSS database is available in the public domain and includes information on the

- source manufacturer,
- serial number,
- material type (primary radionuclide),
- weight of the element,
- weight of the isotope,
- date of manufacture,

- ownership,
- possession, and
- NRC license number.

The remaining three primary AK information sources typically show the primary radionuclide, the quantity of the material, and the serial and model number of a specific sealed source. Examples of a source certificate and a licensing document are shown in Figures 5-1 and 5-2.

If these information sources are not available, then reliance is placed on the secondary AK information. One document from the secondary AK information may identify the primary radionuclide in the sealed source, and a second may identify the quantity of material in the source. The secondary AK information includes the

- source markings,
- NRC registry,
- manufacturers' sales catalogues,
- sealed source drawings,
- unique physical descriptions, and
- miscellaneous other documents.

Many sources will have etched markings on the source itself. Often these markings will indicate the primary radionuclide and the quantity of the material in the source. The source markings may identify the model number of the sealed source to allow it to be traced to the NRC registry or to fabrication information for that model of sealed sources. The NRC Registry of Radioactive Sealed Sources is an NRC-controlled web site (http://nrc-stp.ornl.gov/ssdr.html) that typically identifies the

- source manufacturer,
- manufacturer model numbers,
- primary radionuclide, and
- maximum quantity of radioactive material in the different source models.

Manufacturers' sales catalogues will generally include information on the sealed source models that have been manufactured, such as the

- model number,
- primary radionuclide,
- quantity of radioactive material in the source, and
- physical dimensions of the sealed source.

In many cases, the availability of the physical dimensions on a particular source model will allow measurements to be made in the field at the time of recovery to confirm the source manufacturer, model, and source content.

If further information is needed for the source, photographs may be taken if the source has a unique physical shape that allows the source model number to be identified. Once the model number is identified, secondary AK documents can be used to identify the primary radionuclide and content of the sealed source. Figures 5-1 through 5-8 provide examples of various primary and secondary AK information (e.g., source certificate of calibration report, source quality control certificate, manufacturer's sales catalogue information, and source shipping papers).

CERTIFICATE OF CALIBRATION
ALPHA STANDARD SOURCE

Radionuclide:	Cf-252	Customer:	UCLANL
Half Life:	2.645 ± 0.008 years	P.O.No.:	2-2F2-Y5226-1
Catalog No.:	AF-252	Reference Date:	September 1 1991
Source No.:	R-380	Contained Radioactivity:	1.438

Description of Source

a. Capsule type:	A-2
b. Nature of active deposit:	Electrodeposited and diffusion bonded oxide
c. Active diameter/volume:	5 mm
d. Backing:	0.254 mm platinum clad nickel
e. Cover:	50 μgram/cm² gold

Radioimpurities

None detected

Method of Calibration

The source was assayed by alpha spectrometry using a surface barrier detector.

Uncertainty of Measurement

CAUTION
DELICATE SU
DO NOT W
ACTIVE AF

a. Systematic uncertainty in instrument calibration:	±2.2%
b. Random uncertainty in assay:	±1.2%
c. Random uncertainty in weighing(s):	±0.0%
d. Total uncertainty at the 99% confidence level:	±3.4%

NIST Traceability

This calibration is implicitly traceable to the National Institute of Standards and Technolog

Notes

1. Nuclear data were taken from "Table of Isotopes", Seventh Edition, edited by Virginia
2. IPL participates in an NIST measurement assurance program to establish and maintain i traceability for a number of nuclides, based on the blind assay (and later NIST certific Standard Reference Materials. (As in NRC Regulatory Guide 4.15)

QUALITY CONT

ISOTOPE PRODUCTS LABORATORIES
1800 No. Keystone Street.,
Burbank, California 91504
(818) 843 - 7000

IPL Ref. No.: 386-3

Figure 5-1. Example of certificate of a calibration document.

CERTIFICATE OF ALPHA STANDARD SOURCE

Radionuclide: Cf-252 Half-life: 2.645 ± 0.(
Customer: UNIVERSITY OF CALIFORNIA (LANL) P.O. No.: 2-2N1-V7444
Catalog No.: AF-252 Source No.: N-746 Reference Date: 3 –
Contained Radioactivity: 0.00543 µCi

Description of Source

a. Capsule type: A2
b. Nature of active deposit: ELECTRODEPOSITED & DIFFUSI
c. Active diameter: 5 mm.
d. Backing: Pt CLAD Ni
e. Cover: N/A

Radioimpurities

Method of Calibration

The source was assayed using

(✓) Alpha spectrometry with a surface barrier detector.
( ) An internal gas flow proportional counter.
( ) Large area low alpha background counter.
( ) Gamma Spectrometry, integrating under the ______ Mev. peak(s). The branching ratio(s) used was/were ______ gamma rays per decay.
( ) The source was prepared from a weight aliquot of solution activity in uCi/gram was determined by the method above.

Uncertainty of Measurement

a. Systematic uncertainty of standard/efficiency: ± 1.8
b. Random uncertainty
1. In assay: ± 0.7 %
2. In weighing(s): ± ______ %
c. Total Uncertainty: ± 2.5 % at the 99% confidence level.

NBS Traceability

This calibration is implicitly traceable to the National Bureau of Stan

Notes

1. Nuclear data were taken from "Table of Isotopes", Seventh Edition, edi C. Michael Lederer et al.
2. IPL participates in an NBS measurement assurance program to establi maintain implicit traceability for a number of nuclides, based on the blind (and later NBS certification) of Standard Reference Materials. (As ir Regulatory Guide 4.15)

Quality Control

ISOTOPE PRODUCTS LABORATORIES
1800 No. Keystone St., Burbank, California 91504
(818) 843-7000

3

Figure 5-2. Example of a sealed source certificate.

INFORMATION SHEET

-1671

^{252}Cf NEUTRON SOURCE
SPECIAL FORM RADIOACTIVE MATERIALS
CERTIFICATE NO. USA/0065/S, Rev. 7

Source Identification Number: SR-Cf-1347

Shipped To: Frontier Technology Corp., 1641 Burnett Drive, Xenia, OH 45385

Shipping Capsule Dwg. No.: M-12541-CP-099 E-1, Items 1a, 1b, 1c, and 1d

Closure Date: 9/5/2001

Decontamination and Closure Tests

Method: After closure, capsule surfaces were decontaminated until all exterior surfaces were free of contamination (≤9 d/m alpha and <100 d/m beta-gamma) as determined by a wipe test. The assembly was immersed in a helium atmosphere at a pressure of 300 pounds per square inch for a period of 30 minutes, then transferred to a helium leak detector. The leak detector has a minimum sensitivity of 1.0×10^{-8} standard cubic centimeters of helium per second.

Tests: The finished capsule was found free of detectable leakage and free of transferrable contamination on 9/5/2001.

Californium Content

Isotopic Composition: The californium stock material used to prepare the Pd-Cf_2O_3 composite wires in the special form shipping capsule SR-Cf-1347 is identified by Batch Code CXCF-579. The isotopic mass distribution of this lot of material is listed in Table 1. The date for the last separation of ^{248}Cm decay product from this material was 12/27/2000.

Wire Form: The californium, in the form of Pd-Cf_2O_3 composite, has been heated to 1600°C for 60 minutes to melt the palladium and homogenize the mixture. The resulting melted pellet was rolled to a wire having a nearly oval cross section. The resulting wire, Pd-Cf-161, was measured to be ≤0.054 inches across the long width of the oval.

Source Strength: The neutron emission rate of the finished assembly SR-Cf-1347 was determined by comparing its strength to that of SR-Cf-3022, a reference ^{252}Cf source traceable to the national reference radium-beryllium source, NS-1, at the National Institute of Standards and Technology. The comparison was made by inserting the capsule assembly into a moderator containing an array of fission counters and measuring the subsequent induced electric current by a picoammeter. The total neutron emission rate of this assembly was found to be 1.0260×10^{10} neutrons per second with a relative standard error of ±0.25 % as of 9/6/2001.

Cf-252 Content: The ^{252}Cf content of this assembly has been inferred from the measured neutron emission rate by correcting the gross emission rate by a factor of 0.99839, the fraction of the spontaneous fission neutrons emanating from the isotope ^{252}Cf, and by dividing by 2.31434×10^{6} neutrons per second per microgram. These values may be calculated from the isotopic compositions listed in Table 1, the relative quantities listed in the accompanying letter, and from the nuclear data listed in Table 2. The

Figure 5-3. Example of an information sheet for a source certificate (Page 1).

equivalent ^{252}Cf content on the assay date, 9/6/2001, was computed to be 4,426.2 µg with a relative standard error of ±0.25 %. Due to propagation of errors along the chain of traceability and also to non-random errors, including variations in source geometry, the overall accuracy of the assay is estimated to be ±3% limit of error.

The radiation intensity one meter from a ^{252}Cf source in air at standard atmospheric conditions and without contributions from scattering media is nominally 2210 mrem/h fast neutrons plus 190 mR/h gamma for each milligram of ^{252}Cf in the capsule.

Table 1. Isotopic Mass Analyses

Cf Batch Code	CXCF-579
Mass Analysis Date	9/23/96
Nuclide	**Isotopic Composition (atom %)**
^{249}Cf	6.70
^{250}Cf	9.63
^{251}Cf	2.97
^{252}Cf	80.63
^{253}Cf	0.03
^{254}Cf	0.04

Table 2. Assumed Nuclear Parameters

Nuclide	Half-Life	Alpha branching ratio	Spont. fission branching ratio	ν
^{249}Cf	351 y	~1.0	5.2×10^{-9}	3.4
^{250}Cf	13.20 y	0.99921	0.00079	3.53
^{251}Cf	898 y	~1.0	9.0×10^{-6}	3.7
^{252}Cf	2.645 y	0.96904	0.03096	3.768
^{253}Cf	17.81 d	0.0031		
^{254}Cf	61.9 d	0.00299	0.99701	3.93

Attested [signature] Date 9/7/01

Figure 5-4. Example of an information sheet for a source certificate (Page 2).

Call: 937-376-5691 | Fax: 937-376-5692 | Email: treva@frontier-cf252.com

FRONTIER TECHNOLOGY CORPORATION
WORLD'S EXPERT IN NEUTRON SOURCES

Home | About Us | Contact Us | Product Ordering

PRODUCTS / CAPABILITIES

Californium - 252 Neutron Sources
- Standard Californium - 252 Sources: Model 10 Series
- Standard Californium - 252 Sources: Model 100 Series
- Semi-Custom Neutron Sources
- Custom Neutron Sources
- Antimony-Beryllium Neutron Sources

Custom and Semi-Custom Packaging of Radioactive Materials
- Custom and Semi-Custom Type A Containers

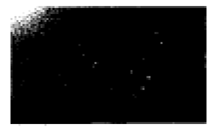
U.S.D.O.T. Special Form Certificate

Californium - 252 Neutron Sources

Standard Californium - 252 Sources: Model 10 Series

Single-encapsulated neutron source generally used as inner capsules of multi-encapsulated sources.

The capsule material used is either 304L stainless steel or Zircaloy-2, and the closure is TIG welded.



The Model 10 series of neutron sources are singly-encapsulated sources generally used as the inner capsules of multiply-encapsulated sources. The Model 10 sources have an outside diameter of 0.217/0.218 inches and are available in two lengths, the longer of which is equivalent to the Savannah River SR-CF-1X capsule. Capsule material may be either Type 304L stainless steel or Zircaloy-2. Closure is by tungsten-inert-gas (TIG) welding. The sources are designed to meet Special Form requirements even after infinite decay of the Cf-252 contents.

All Model 10 sources are certified by the U.S. Department of Transportation (USDOT) as Special Form, and all have been approved for licensing purposes by the U.S. Nuclear Regulatory Commission (USNRC) for general uses other than well logging.

The Model 10 sources offer great flexibility in meeting customer outer capsule configuration and material requirements because Model 10 sources may be further encapsulated in capsules of arbitrary design, and still be licensed and transported as Model 10 sources.

Nominal dimensions for the Frontier Technology Corporation Model 10 and 10S sources are shown below:

Dimensions	Model 10	Model 10S
Outside diameter	0.217/0.218 inch	0.217/0.218 inch
	5.51/5.54mm	5.51/5.54mm
Outside length	0.975 inch	0.470 inch
	24.77mm	11.94mm
Inside diameter	0.154 inch	0.154 inch
	3.91mm	3.91mm
Inside length	0.75 inch	0.24 inch
	19.05mm	6.10mm
Maximum content Californium-252	10 milligrams	4 milligrams

Standard Neutron Source Model 10S per Dwg. No. A10010-AA01

Figure 5-5. Example of a manufacturer's sales catalogue (Page 1).

Standard Californium - 252 Sources: Model 100 Series

Double encapsulated, employing a Model 10 series source as the primary encapsulation.

The outer capsule material is either 304L stainless steel or Zircaloy-2.

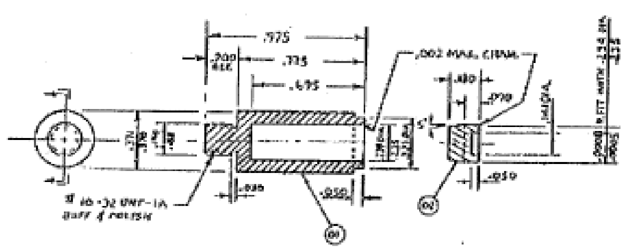
The Model 100 series of neutron sources are doubly-encapsulated sources which employ a Model 10 series source as the primary encapsulation. Model 100 series sources have an outside diameter of 0.370/0.371 inches and are available in two lengths, both of which are available with or without a 10-32 threaded stud on one end. The longer length version with the stud is equivalent to the Savannah River SR-CF-100 series capsules. Outer capsule material may be either type 304L stainless steel or Zircalloy-2. Closure is by TIG welding.

Thirty-two versions of the standard length source and thirty-two versions of the shortened source are possible as the result of various combinations of inner and outer capsule materials and orientations, and the presence of or lack of the threaded stud. All sixty-four versions of the Model 100 series are certified by the USDOT as Special Form, and all have been approved for licensing purposes by the USNRC for general uses.

Nominal dimensions for the Frontier Technology Corporation Model 100 and Model 100S sources are shown below:

Dimensions	Model 100	Model 100s
Outside diameter	0.370/0.371 inch	0.370/0.371 inch
	9.398/9.423mm	9.398/9.423mm
Outside length w/stud	1.48 inches	0.97 inch
	37.59mm	24.6mm
Outside length w/o stud	1.28 inches	0.77 inch
	32.5mm	19.55mm
Inside diameter	0.234/0.235 inch	0.234/0.235 inch
	5.953/5.982mm	5.953/5.982mm
Inside length	1.02 inches	0.52 inch
	30.6mm	13.2mm
Maximum content: Californium-252	10 milligrams	4 milligrams

Standard Neutron Source Model 100S per Dwg. No. A10010-PA02



Standard Neutron Source Model 100 per Dwg. No. A10100-PA01

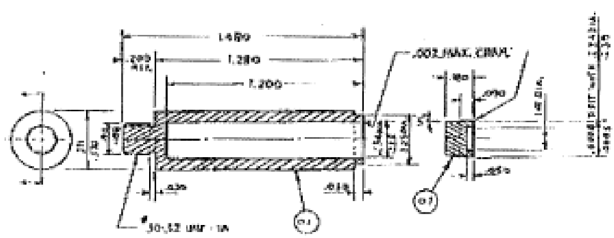


Figure 5-6. Example of a manufacturer's sales catalogue (Page 2).

AEA TECHNOLOGY
NUCLEAR SCIENCE

92

EA02

AEA Technology
Nuclear Science

220 Harwell, Didcot
Oxfordshire OX11 0RA
United Kingdom
Telephone 01235 821111
Facsimile 01235 432916
www.aeat.co.uk

Radioactive source test report

product code: CVNK 8015 FIS no: NS/AM/923 source model no: CVN.CY2	description: Californium-252 Neutron Source (Spontaneous Fission) Capsule Type X1 nominal content activity: 2.22 MBq	customer order no: 58077 customer: AEAT QSA Inc Burlington USA Item No NA 9682	*BS/ISO classification: E66545 special form certificate no: GB/007/S-85 recommended working life: 15 Years

serial no batch no	measurement 1	date	measurement 2	date	test A	test D	test L
9590 NC	2.6 MBq	05/02/01	$3.01x10^{5}$ n/sec	05/02/01	05/02/01	05/02/01	06/02/01

Notes: Export Control Applicable ; DUEC(exempt)

signature: [signature] position: PRODUCTION MANAGER date: 6/2/01

*this classification complies with BS5288:1976, which is in agreement with ISO.2919

(see overleaf for definition and description of tests)

Figure 5-7. Example of a source test report.

AEA Technology QSA Inc.

AEA TECHNOLOGY
QSA

40 North Avenue
Burlington, MA 01803
(781) 272-2000
(800) 815-1383

6765 Langley Drive
Baton Rouge, LA 70809
(225) 751-5893
(800) 225-1383

Packing list number 19996

Page 1
2/13/01 17:40:13

Shipped from:
Company . . . : 1 AEA TECHNOLOGY
Warehouse . . : IS

Ship Date . . . : 2/13/01
Shipment number : 98322

Ship to . :
TROXLER ELECTRONICS
3008 CORNWALLIS ROAD
RESEARCH TRIANGLE PARK NC 27709
UNITED STATES

Order information
CO 106555 1/02/01
TROXLER ELECTRONICS
P.O. Information
PO61723-00
Date . . . : 0/00/00

Shipping instructions . . : FEDEX STD COLLECT #0276 0020 4

Carrier/pro number: Federal Express Corporati
412757228950
Truck/trailer number:
Gross weight 4.000 U/M LB

Shipping instructions : FEDEX STD COLLECT #0276 0020 4

Approved by:
Comments:

License number: 032-0182-1(NC)
-

Items not assigned to containers

Item number	Rel	Item description	Packed qty/ Backorder qty	U/M U/M
CVNK8015	1	"A" CF252 NEUTRON SOURCE	1.000 .000	EA EA

TROXLER ITEM #105779

RAS DATE 2/7/01

Serial numbers: 9590NC

** End of Packing List **

Surface 6 mr/hr
One Meter 0.8 mr/hr
Yellow II Labels
Ext. Contamination <0.001 uCi

Figure 5-8. Example of a source shipping record.

6 CHARACTERIZATION OF Cf-252 SOURCES IN WASTE DRUMS

After the Cf-252 sealed sources are recovered, they are placed into a special form capsule (SFC) or into another approved consolidation container that, in turn, is loaded into a 55-gallon drum. For the characterization of the drum, an Excel spreadsheet is used for the information input and the subsequent calculations for the characterization of the drum, including the quantities of reportable radionuclides in the drum. Also determined are the derived parameters, such as TRU concentration, decay heat, and the uncertainties in these values. All of the documentation on each source is reviewed, and the required information for the characterization of the source is input to the "*Source Inputs*" Sheet of the Excel workbook (Reference 10). The required information is the source identification (ID), the manufacture date, the curies or grams of Cf-252, and the estimated total weight of the SFC and sources. Figure 6-1 shows an example of the *Source Inputs* datasheet for the Cf-252 characterization workbook.

Container Characterization Report
Cf-252 Sources

Data Input Sheet

NDA/Radiological Characterization BDR#	LA11-OSR-CH-00X
Run Date	11/15/2011
Container Number	1234
Estimate Waste Weight, kg	7.7

Source ID	Manufacture Date	Source Contents, Curies	Source Contents, Grams
91-191	1/1/1991		0.01
91-192	1/1/1991	3.00E-02	
91-193	1/1/1991	3.00E-02	
91-194	1/1/1991	3.00E-02	
91-195	1/1/1991	3.00E-02	
91-196	1/1/1991	3.00E-02	
91-197	1/1/1991	3.00E-02	
91-198	1/1/1991	3.00E-02	
91-199	1/1/1991	3.00E-02	
91-200	1/1/1991	3.00E-02	

Figure 6-1. Example of the Source Inputs Datasheet.

Each source is decay corrected from the input manufacture date to the run date entered into the input sheet. The californium isotopes are decayed to account for the ingrowth of their respective curium daughters. The production of Cs-137 and Sr-90 is accounted for by the spontaneous fission of Cf-252 from the date of manufacture to the run date.

The spreadsheet calculates both the activity and mass for all of the radionuclides in the drum and the associated uncertainties in these values (Reference 11). The derived parameters of TRU, FGE, Plutonium Equivalent (**PE**-Ci), decay heat, and total activity are also calculated.

Figure 6-2 provides an example of the characterization summary report for a drum of Cf-252 sources.

Californium-249 through Cf-252 undergo alpha decay to Cm-245, Cm-246, Cm-247, and Cm-248, respectively. Further decays along the decay chain produce very small quantities of the WIPP-reportable actinides U-233, U-234, U-238, Pu-238, Pu-239, Pu-240, Pu-242, and Am-241 as a function of total decay time. To determine the upper-bound drum inventories of these radionuclides, the 50-year decay of a 1-curie Cf-252 source was calculated using the RadDecay code. In the calculation, a limiting drum is assumed to contain 10 curies of Cf-252 sources, so the RadDecay results are multiplied by a factor of 10. The total Cf-252 activity of the sources within any single drum is assumed to be <10 Ci. This amount is the approximate total of the 50 largest Cf-252 sources in Los Alamos National Laboratory's OSRP database. It therefore provides a conservative limit for the potential ingrowth of secondary and tertiary daughters of californium isotopes that could be found in a single drum. These values are thus used as the maximum values (upper bound) of a single drum's daughter inventory (Reference 12).

The "less than" values shown in Table 6-1 will be reported for each drum containing Cf-252 sources. Note that Pu-238 is not a decay product of any of the californium isotopes and is therefore reported as zero.

Table 6-1. Reported "Less Than" Values for the Upper-Bound Activities of Decay Products of Cf-252 in a Drum of Sources

Radionuclide	Total (Ci)
U-233	< 5.97E-17
U-234	< 4.36E-21
U-238	< 1.12E-16
Pu-238	0.00E+00
Pu-239	< 2.34E-15
Pu-240	< 6.56E-14
Pu-242	< 3.68E-08
Am-241	< 2.87E-07

Container Characterization Report

Cf-252 Sources **Version 1.0**

NDA/Radiological Characterization BDR#	LA11-OSR-CH-00X	
Run Date	11/15/2011	
Container Number	1234	
Net Waste Weight	7.7	kg

Nuclide	% Type A Limit	Activity (Ci)	Grams	FGE	PECi	Watts	Uncertainty in Curies	Uncertainty in Grams
Cm-245	1.51E-06	3.63E-06	2.09E-05	3.13E-04	3.87E-06	1.21E-07	1.74E-06	9.98E-06
Cm-246	9.82E-05	2.36E-04	7.58E-04	0.00E+00	2.51E-04	7.73E-06	2.00E-05	6.43E-05
Cm-247	6.15E-10	4.98E-10	5.31E-06	2.65E-06	4.79E-10	1.58E-11	5.38E-11	5.74E-07
Cm-248	8.20E-03	4.43E-05	1.03E-02	0.00E+00	1.64E-04	5.69E-06	3.13E-07	7.28E-05
Cf-249	2.58E-03	2.09E-03	5.05E-04	2.27E-02	2.25E-03	7.78E-05	9.94E-04	2.40E-04
Cf-250	7.84E-03	4.23E-02	3.81E-04	0.00E+00	1.83E-02	1.57E-03	3.40E-03	3.07E-05
Cf-251	2.80E-04	5.33E-04	3.33E-04	3.00E-02	5.85E-04	1.96E-05	5.11E-05	3.20E-05
Cf-252	1.70E+00	2.38E-02	4.37E-05	0.00E+00	6.09E-03	1.77E-03	1.68E-04	3.09E-07
Sr-90	6.93E-04	5.61E-05	4.07E-07	0.00E+00	0.00E+00	6.50E-08	3.97E-07	2.87E-09
Cs-137	9.67E-04	5.22E-04	5.94E-06	0.00E+00	0.00E+00	5.78E-07	3.69E-06	4.20E-08
U-233	0.00E+00	<5.97E-17	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
U-234	0.00E+00	<4.36E-21	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
U-238	0.00E+00	<1.12E-16	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Pu-238	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Pu-239	0.00E+00	<2.34E-15	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Pu-240	0.00E+00	<6.56E-14	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Pu-242	0.00E+00	<3.68E-08	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Am-241	0.00E+00	<2.87E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Totals	1.72	6.96E-02	1.23E-02	5.30E-02	2.76E-02	3.46E-03		

	Value	(one Sigma)	Units
TRU Alpha Activity Concentration	3.78E+02	4.16E+01	nCi/g
TRU Alpha Activity	2.91E-03	3.20E-04	Ci
Total Pu-239 Equiv Activity	2.76E-02	2.11E-04	Ci
Total Pu-239 Fissile Gram Equiv	5.30E-02	1.62E-02	g
Total Decay Heat	3.46E-03	2.46E-05	W

	(Print Name)	Signature	Date
RC Operator Review	____________	____________	______
2nd RC Operator Review	____________	____________	______

Figure 6-2. Example of the Characterization Spreadsheet Report.

7 UNCERTAINTY ANALYSIS

This section discusses the uncertainty in the reported values of the radionuclides in the drums containing the Cf-252 sources. The radionuclide inventory of each sealed source is calculated based on the manufacturer's reported Cf-252 activity and the radionuclide distributions derived from REDC process data, as described in Section 4.0. Sources of uncertainty are summarized in Table 7-1.

Table 7-1. Summary of Uncertainty Elements for Cf-252 Sources

Source of Uncertainty	Treatment
Manufacturer's uncertainty in mass or activity of source	±5% per source, with 50 sources per drum
Uncertainty in californium isotopics	Based on variability among REDC campaigns
Uncertainty in other radionuclide impurities	Derived from californium decay
Instrument uncertainty	Included as one source of variability in the REDC data
Uncertainty in decay time from REDC campaign measurement to source calibration date	±6 months

7.1 Manufacturer's Source Material Uncertainty

The Cf-252 sources were manufactured by a number of different manufacturers. Figures 5-5 and 5-6 are reproduced from a product catalog for one manufacturer. This catalog specifies that, for various sources (including Cf-252), the source material will be determined to within 2%–5%. A value of 5% is assumed for each source. Each drum is assumed to contain at least 50 sources of approximately equal size. Therefore, the drum uncertainty due to the manufacturer's uncertainty is ~$5/\sqrt{50}$ % = 0.71%. It is assumed that sources from other manufacturers, including ORNL, have a similar level of uncertainty.

7.2 Californium Isotopic Distribution Uncertainty

The isotopic composition of californium produced at ORNL's REDC was measured for each production campaign. "Development of Radionuclide Distributions for Cf-252 Sealed Sources" (Reference 13) provides a summary of these compositions for over 20 campaigns. The standard deviation among the campaigns is calculated based the reported isotopic distributions in the batches of Cf-252 source materials, as shown in Table 7-2.

Table 7-2. Uncertainties in the Isotopic Distribution for Cf-252 Source Material

	Cf-249	Cf-250	Cf-251	Cf-252
Average	3.94%	9.12%	2.67%	84.01%
Standard Deviation	4.18%	1.54%	0.57%	5.33%
Relative Standard Deviation	106.2%	16.9%	21.4%	6.3%

Note that for Cf-252, the campaign-to-campaign variability in the Cf-252 fraction is accounted for when the source is calibrated. Therefore, only the manufacturer's uncertainty applies to Cf-252.

It is assumed that 10 sources in each drum are derived from the same batch of californium and that each drum contains at least 50 sources of approximately equal size. As a result, each drum has material from at least five batches of californium. The uncertainty is therefore estimated to be the above relative standard deviation values divided by the square root of five.

7.3 Uncertainty in Other Radionuclide Impurity Levels

The impurity levels for other radionuclides are derived from the decay of the californium isotopes. Table 7-3 shows each radionuclide and its parent. The uncertainty in the radionuclide's impurity level is the same as the relative uncertainty of the parent. Note that the fission products Cs-137 and Sr-90 are formed from the spontaneous fission of several californium and curium isotopes. The contribution of Cs-137 and Sr-90 is overwhelmingly driven by the spontaneous fission of Cf-252; accordingly, only the uncertainty in the Cf-252 is applied. Table 7-3 summarizes the treatment of the uncertainties in the impurity levels in the source material.

Table 7-3. Summary of the Treatment of Uncertainties in the Impurity Levels

Radionuclide	Parent	Uncertainty in Impurity Level
Cm-245	Cf-249	Same as Cf-249
Cm-246	Cf-250	Same as Cf-250
Cm-247	Cf-251	Same as Cf-251
Cm-248	Cf-252	Only manufacturer's uncertainty applies
Cs-137	Cf-252 via spontaneous fission	Only manufacturer's uncertainty applies
Sr-90	Cf-252 via spontaneous fission	Only manufacturer's uncertainty applies

7.4 Uncertainty in the Decay Time from the REDC Production Date to the Shipping Date

The californium isotopics are taken from REDC campaign measurements when the californium targets are processed. It is assumed that the sources are fabricated and calibrated within a relatively short time after processing because the principal source material (Cf-252) has a relatively short half-life. This decay is accounted for when calibrating the Cf-252 source; therefore, this element of uncertainty does not apply to Cf-252 or its decay products. However, the levels of the other californium isotopes will be affected by decay and the uncertainty in the decay time. The uncertainty in the decay time is assumed to be 6 months. The uncertainty in the decaying radionuclide is

$$\frac{\Delta A}{A} \cong \lambda \Delta t \, .$$

The uncertainty in the decay product is

$$\frac{\Delta A}{A} \cong \frac{\lambda \Delta t e^{-\lambda t}}{\left(1 - e^{-\lambda t}\right)} \, .$$

Table 7-4 shows the uncertainty in each radionuclide due to uncertainty in the decay time as a function of decay time.

Table 7-4. Uncertainty in Each Radionuclide as a Function of the Uncertainty in the Decay Time

Radionuclide	10-Year Decay	15-Year Decay	20-Year Decay
Cf-249	0.1%	0.1%	0.1%
Cf-250	2.6%	2.6%	2.6%
Cf-251	0.0%	0.0%	0.0%
Cf-252	-	-	-
Cm-245	5.0%	3.3%	2.5%
Cm-246	3.8%	2.2%	1.4%
Cm-247	5.0%	3.3%	2.5%
Cm-248	-	-	-
Cs-137	-	-	-

It is assumed that the sources are, on average, >10 years old. Therefore, as an upper bound, the uncertainty values for a 10-year decay period are applied.

7.5 Total Uncertainty

The total uncertainty is calculated by combining all of the uncertainties as discussed below.

Because the manufacturer's uncertainty is common to all of the radionuclides, it is treated separately. Therefore, the combination in quadrature is performed in two steps:

1. all uncertainties other than manufacturer's uncertainty are combined in quadrature, and

2. the manufacturer's uncertainty is added to determine the total uncertainty.

Table 7-5 summarizes the contributions of the uncertainties for each radionuclide.

Table 7-5. Summary of the Total Uncertainty Derivation

Radionuclide	Uncertainty in Manufacturer's Stated Source Size	Uncertainty in Californium Isotopics	Uncertainty in Decay Time	Total Uncertainty Excluding Mfg. Uncertainty	Total Uncertainty
Cm-245	0.71%	47.5%	5.0%	47.8%	47.8%
Cm-246	0.71%	7.6%	3.8%	8.5%	8.5%
Cm-247	0.71%	9.6%	5.0%	10.8%	10.8%
Cm-248	0.71%	-	-	0.0%	0.7%
Cf-249	0.71%	47.5%	0.1%	47.5%	47.5%
Cf-250	0.71%	7.6%	2.6%	8.0%	8.0%
Cf-251	0.71%	9.6%	0.0%	9.6%	9.6%
Cf-252	0.71%	-	-	0.0%	0.7%
Sr-90	0.71%	-	-	0.0%	0.7%
Cs-137	0.71%	-	-	0.0%	0.7%

7.6 Uncertainty for Derived Parameters

The derived parameters TRU, FGE, PE-Ci, decay heat, and total activity are summations made over the individual radionuclides multiplied by the appropriate weighting factors. The manufacturer's uncertainty applies to all radionuclides and therefore introduces a statistical dependency when the uncertainty in the derived parameters is being determined. Other parameters also introduce potential statistical dependences. The decay time introduces a dependency among the decaying radionuclides (either too much or too little decay) and the opposite dependency among the decay products (i.e., too little or too much production). These dependencies tend to be offsetting. The uncertainty in the californium isotopics affects both the californium isotope and its curium daughter. However, the activities of the curium isotopes are very small, so this dependency is negligible. Therefore, the only dependency explicitly considered is the manufacturer's uncertainty.

The uncertainty in the derived parameters is therefore calculated by combining in quadrature the independent sources of uncertainty for each radionuclide, again multiplied by the appropriate weighting factors. The manufacturer's uncertainty is then combined in quadrature with the independent sources of uncertainty, resulting in the total derived parameter uncertainties, as shown in Table 7-6.

Table 7-6. Total Uncertainties for Derived Parameters

Derived Parameter	Source Total Uncertainty
TRU	7.7%
FGE	8.0%
PE-Ci	2.2%
Decay Heat	2.2%
Total Activity	2.2%

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3. CCP-AK-LANL-008, "Central Characterization Project Acceptable Knowledge Summary Report for Los Alamos National Laboratory Off-Site Source Recovery Project Sealed Sources, Waste Stream: LA-OS-00-01.001, LA-OS-00-03 and LA-OS-00-04," Revision 8 (February 22, 2010).

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