APPLICATIONS OF CALIFORNIUM-252 NEUTRON SOURCES IN MEDICINE, RESEARCH, AND INDUSTRY

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SUMMARY

The ^{252}Cf radioisotope is an intense neutron emitter that is readily encapsulated in compact, portable, sealed sources. Californium-252 is used commercially as a reliable, cost-effective neutron source for prompt gamma neutron activation analysis (PGNAA) of coal, cement, and minerals, and for detection and identification of explosives, land mines, and unexploded military ordnance. Other uses include neutron radiography, materials characterization and nuclear assay, reactor start-up sources, and calibration standards. Also highlighted are the treatment of cancer using ^{252}Cf, experiments at the Californium User Facility for Neutron Science (CUF), and the ^{252}Cf distribution programs of the U.S. Department of Energy (DOE).

I. INTRODUCTION

Californium-252 neutron sources are used for many applications in which compact, portable, and reliable neutron sources are required.[1] A representative survey of applications was provided during recent American Nuclear Society conference sessions.[2] With 3.1% of ^{252}Cf decay via spontaneous fission, one microgram of ^{252}Cf emits 2.314×10^6 fast neutrons/s with a 2.645-year half-life (0.536 mCi/μg). The Maxwellian neutron energy distribution has an average energy of 2.1 MeV and most probable energy of ~0.7 MeV. A cylindrical source capsule the size of a person's little finger can emit a maximum of ~10^{11} neutrons/s.

Californium-252 is produced at only two sites: the High Flux Isotope Reactor at Oak Ridge National Laboratory (ORNL) and the Research Institute of Atomic Reactors in Dimitrovgrad, Russia. Californium-252 is produced, purified, and encapsulated at ORNL's Radiochemical Engineering Development Center (REDC) as a by-product of DOE’s heavy element program. The DOE inventory of sealed ^{252}Cf sources is stored at the REDC. These sources are used for a wide variety of applications, with some of the more common uses described below. The inherent safety of ^{252}Cf source encapsulations is well demonstrated by 30 years of experience, even under explosive impact.[3]

Research using ^{252}Cf can be facilitated by the CUF at ORNL which, as a user facility, alleviates regulatory burdens in source usage. DOE's Californium Industrial Loan Program can often provide intense neutron sources at significant discounts to qualified users as well as eliminate source disposal issues after task completion. DOE's University Loan Program is strongly supportive of academic research and training in experimentation with neutrons.

II. MATERIALS CHARACTERIZATION AND MONITORING FOR NON-NUCLEAR APPLICATIONS

A. PGNAA for On-line Process Monitoring

Prompt gamma neutron activation analysis is an elemental analysis technique in which an atom's nucleus captures a neutron, achieving an excited state with almost instantaneous de-excitation by emitting a high-energy (multi-MeV) "prompt" gamma ray. The energy of the gamma photon is characteristic of each element, and the gamma spectrum provides a finger print of the elements present in the sample. Because neutron capture is most efficient for thermal neutrons, PGNAA is sometimes called thermal neutron analysis (TNA). With rapid sample interrogation, no significant radioactivity is produced in the sample, and lower-intensity neutron sources are used (typically <100 μg of ^{252}Cf). However, this technique is less sensitive than conventional NAA and is typically used for the analysis of the principal components of a sample. Elemental sensitivities in the percent to sub-percent composition range are typical.

The most widespread commercial application of ^{252}Cf is in the PGNAA of commercial materials for process control or material management (blending, etc.). Gamma-Metrics, of San Diego, California, is a major manufacturer of on-line analyzers for the coal and cement industries. They market several systems for conveyor belt analyses of feed materials, slurry analyzers, and laboratory analyzers. For example, analysis of coal provides on-line information on ~12 elements including sulfur content (to meet smokestack release criteria), ash and moisture content, and indirect information on the calorific content of coal (Btu/lb). Over 200 analyzers have been placed in service worldwide.[2]

B. Borehole Logging for Chlorinated Contaminants

A borehole geophysical logging tool developed by Waste Management Technical Services, Inc., used ~5 µg of ^{252}Cf for subsurface PGNAA investigation of waste Pit 9 in the Radioactive Waste Management Complex at the Idaho National Engineering and Environmental Laboratory.[4] PGNAA measurements of elemental chlorine (from chlorinated solvents, salts, and organic compounds) were made using a high-purity germanium gamma detector in a cylindrical borehole probe, with the detector shielded from ^{252}Cf source neutrons and gamma rays by tungsten metal. The ^{252}Cf source was stored in a small shielded container when not in use. Transfer of the source to the lower end of the logging tool was accomplished using a long source-handling tool to minimize personnel exposure. Twenty boreholes were drilled to a depth of ~4 m within Pit 9. Although PGNAA measurements of hydrogen, silicon, calcium, iron, aluminum, and chlorine were obtained, only the chlorine measurements were calibrated, providing a minimum detection limit of 300 ppm. Borehole concentrations of chlorine ranged from 1,000 to 30,000 ppm.

C. Explosives and Land Mine Detection and Munitions Identification

Ancore Corporation markets several explosives detection systems which employ ^{252}Cf sources for PGNAA detection of the nitrogen present in explosive compounds.[5] Examples of such systems are Ancore's Small Parcel Explosive Detection System and Vehicular Explosive and Drug Sensor (VEDS). The VEDS can either be mounted on a platform for use at checkpoints or mounted on a vehicle.

The Canadian Department of National Defence has developed a mobile multisensor system to detect buried land mines. For confirmation of the presence of explosives, a prototype system uses <100 µg of ^{252}Cf for PGNAA detection of nitrogen, and could confirm the presence of most antitank mines and many antipersonnel mines within minutes.[2]

The commercial Portable Isotopic Neutron-Spectroscopy (PINS) Chemical Assay System marketed by ORTEC is used for the nondestructive identification of the contents of munitions, chemical weapons, and general chemical-storage containers.[6] PINS systems typically use several micrograms of ^{252}Cf transported in a small shielded container. PINS can differentiate between high explosives, nerve agents, poison gases, and other common military compounds as well as inert contents in unidentified, unexploded munitions.

Low-intensity (~10^6 neutrons/s) ^{252}Cf electroplates within small ionization chambers[7] can time the release of neutrons with respect to the fission event. These low-intensity ^{252}Cf electroplates have recently been applied to the detection of landmines using a handheld unit and based on timed neutron backscattering from any plastic present.[8] Modern land mines use nonmetallic casing such as plastic to elude detection. Land mine detection based on conventional, steady-state neutron emission has also been demonstrated using ~3.5 µg of ^{252}Cf in a prototype handheld detector weighing ~8 kg.[9] This approach takes advantage of the higher hydrogen content in land mines than in most soil, with the backscattering signal increasing in the vicinity of a land mine. Radiological exposure to the operator during extended use is within acceptable levels.

D. Handheld Neutron Backscattering Detector for Contraband Detection

A handheld instrument containing a low-intensity ^{252}Cf source has been developed by Nova R&D, Inc., of Riverside, California, and deployed with the U.S. Coast Guard to detect contraband hidden in compartments behind metal and other structures.[2] Fast neutrons from the Compact Integrated Narcotics Detection Instrument (CINDI) penetrate the barrier material and are backscattered by any hydrogen-rich materials present. Unexpected detection of backscattered neutrons suggests the potential presence of contraband such as narcotics. Panels made of steel, wood, fiberglass, or lead-lined materials can be probed. An upgrade makes possible simultaneous detection of both neutron and gamma backscattering.

E. Trace Elemental Analysis of Environmental Samples

A significant thermal neutron flux is required for instrumental neutron activation analysis (INAA) and subsequent gamma spectroscopy. Typically this requires a nuclear reactor, although several ^{252}Cf-based INAA facilities have been demonstrated. A facility at the Savannah River Technology Center used ~5 mg of ^{252}Cf (neutron flux ~10^7 cm^{-2} s^{-1}) to provide INAA services for environmental and waste management customers, with analyses of organic compounds, metal alloys, sediments, and site process solutions.[10] Several dozen elements can be analyzed with parts-per-million sensitivity. The facility also produces short-lived radioactive tracers for radiochemical analyses and separation methods testing. Advantages of INAA for trace elemental analysis are that bulk samples require no dissolution, reducing analytical uncertainties, and that INAA is more cost-effective for bulk samples. This facility was recently upgraded for greater sensitivities.

F. Neutron Radiography

Unlike x-radiography, neutron radiograpy has the advantage of providing nondestructive examination and visual contrast between low-Z elements, in particular hydrogen and moisture. A major ^{252}Cf-based facility for neutron radiography of fighter aircraft was based at McClelland Air Force Base in California in the 1990s.[2] Overhead and ground-based mobile scanning units, each containing up to 50 mg of ^{252}Cf, were used to rapidly scan F-111 and F-15 aircraft without disassembly to detect debonding of composites and moisture, fuel leakage, or corrosion within the aluminum honeycomb structure. Although providing major cost savings in reduced aircraft maintenance and downtime, the facility was decommissioned during closure of the air force base.

More recently, a major ^{252}Cf radiography facility using up to 150 mg of ^{252}Cf was established at the Pantex Plant in Amarillo, Texas for the nondestructive examination of components. Up to 9 radiographs per day can be obtained with image quality comparable to reactor-based radiography, and up to 9 high-quality radiographs per week can be obtained.[11] Typical collimated neutron fluxes of ~2×10^4 cm^{-2} s^{-1} are delivered to the sample plane.

III. CHARACTERIZATION OF NUCLEAR MATERIALS

A. Characterization of Fissile Material

Researchers at ORNL have used low-intensity ^{252}Cf ionization chambers[7] to probe and characterize fissile material. This configuration uses the fission pulse as a trigger to time the release of the neutrons. The subsequent response of the material as measured by a detector array is analyzed using standard time-correlation and/or frequency-analysis techniques. For example, the spatial distribution, mass, and hydration of deposits of $UO_2F_2 \cdot nH_2O$ in process piping were determined to estimate subcriticality and plan for removal of the material.[2] Other applications include identification and inventory of nuclear weapons components and other uranium items for nuclear materials control and accountability, the determination of k_{eff} for optimization in storage and shipping of fuel elements, and measurement of mass flow rate of ^{235}U in a UF_6 gas stream for downblending of Russian weapons-grade uranium. Several of these cart-portable Nuclear Materials Identification Systems are reported in use at the Oak Ridge Y-12 Plant, including a battery-powered unit.[12]

B. Neutron Shufflers

Passive-active neutron shufflers employing ^{252}Cf have been used in national laboratories and industry for determination of fissile content of waste containers and drums, spent fuel assemblies, process materials, and to monitor vehicles.[1] The source can be placed near the sample, and the delayed neutrons from induced fissions counted after source removal. Detection of milligram masses of fissile isotopes has been demonstrated.

C. Trace Elemental Analysis of Vitrified Samples

Another major INAA system (thermal neutron flux ~10^9 cm^{-2} s^{-1}) has recently been established by Fluor Hanford in Richland, Washington for high-precision measurements of elemental sodium content within vitrified fuel reprocessing wastes.[2] This approach circumvents the problems of standard analytical measurements on high-dose-rate radioactive samples (i.e., sample preparation via dilution of highly radioactive waste with attendant radiological exposure and analytical uncertainties). This system can also quantify trace residues of fissionable isotopes (~0.1 ppm of uranium and plutonium) via delayed neutron counting.

IV. CALIFORNIUM USER FACILITY FOR NEUTRON SCIENCE

The CUF[13] is a unique facility that can provide moderate flux irradiations based on a fission fast neutron (FN) spectrum (average energy

~2.1 MeV). Although accelerator-based neutron sources can provide greater fluxes, they cannot reproduce a fission spectrum or provide the flexibility of the CUF for irradiating bulk samples in a variety of easily interchangeable irradiation configurations.

A. Facility Infrastructure and Experimental Capabilities

The CUF was established at ORNL to make ^{252}Cf sources available to researchers for experiments inside contamination-free hot cells.[13] The CUF stores the DOE inventory of prefabricated ^{252}Cf sources. After hands-on experimental setup inside a hot cell, ^{252}Cf sources are pneumatically transferred into the cell for irradiation with up to ~50 mg of ^{252}Cf (~10^{11} neutrons/s). These medium-flux irradiations can provide fast and thermal neutron fluxes up to ~10^9 cm^{-2} s^{-1}, with extended irradiations possible within the ^{252}Cf storage pool.

The Canadian Department of National Defence's multisensor land mine detection system uses a moderate-intensity ^{252}Cf source for PGNAA of nitrogen to confirm land mine presence. The high-count-rate gamma detection system was optimized at the CUF with a range of ^{252}Cf source intensities, and acceptable performance was demonstrated up to 1.5×10^6 counts/s with a 300-μg ^{252}Cf source.[14] These results represented a four-fold increase in system performance.

Experimental boron-containing compounds are developed for potential use in boron neutron capture therapy (BNCT) of cancer. One criterion for boronated pharmaceuticals is their relative effectiveness in killing cancer cells in a neutron field. Living lung cancer cells were exposed to four boron compounds developed at the University of Tennessee, Knoxville, and then irradiated in the CUF with 28 mg of ^{252}Cf (thermal neutron flux ~2×10^8 cm^{-2} s^{-1}).[13] Comparison of cell killing to that of nonboronated cells provided a ranking of their relative cell-killing effectiveness.

The CUF has ideal infrastructure for ^{252}Cf-based INAA. In-house gamma spectroscopy capabilities were recently established, and a polyethylene irradiator was fabricated with nearly cubic dimensions of ~26 cm on a side.[15] An internal source holder can contain up to twelve ^{252}Cf sources around a cylindrical sample void of ~4-cm diameter × ~6-cm height. Fifty milligrams of ^{252}Cf provides fast and thermal fluxes at the sample of ~10^9 cm^{-2} s^{-1}. A cadmium shield has been designed which can filter out the thermal neutrons to evaluate FN activation. Several irradiations to quantify FN-induced threshold reactions were recently performed for spectral characterization of the irradiator. Future analysis of soil and environmental samples is planned. Advantages of ^{252}Cf-based INAA relative to reactor-based INAA are the ability to activate larger samples, insignificant gamma heating (important for liquid and biological samples), and significant FN flux for more versatile applications.

B. Radiation Damage Studies

1. Irradiation Testing of Semiconductor Detectors. A consortium between Northeastern University and the University of Minnesota used up to 59 mg of ^{252}Cf at the CUF in a series of irradiations to test the neutron hardness of avalanche photodiode detectors. These photodetectors were chosen as an integral part of the electromagnetic crystal calorimeter in the Compact Muon Solenoid Detector at the Large Hadron Collider, constructed at the CERN accelerator in Geneva, Switzerland.[16] Real-time data acquisition and computer control were provided by cables connecting the experiment to out-of-cell hardware. The experiments simulated the expected in-service FN flux of 2×10^5 cm^{-2} s^{-1}, and accelerated irradiations provided the expected lifetime fast fluence of 1.2×10^{13} cm^{-2} in 335 h of irradiation. Following these irradiations, a specialized ^{252}Cf irradiator was designed and built at the University of Minnesota and charged with ~10 mg of ^{252}Cf. This irradiator provides quality control testing of devices manufactured for installation at CERN.

2. Advanced Photon Source Magnet Irradiations. The Advanced Photon Source (APS) at Argonne National Laboratory uses neodymium-iron-boron (Nd-Fe-B) permanent magnets inside the insertion devices (for beam tailoring) to produce high-intensity x-rays for scientific research. These magnets are exposed to high-energy radiation including bremsstrahlung-produced photoneutrons inside the 7-GeV APS storage ring. The potential for radiation-induced demagnetization could impact the long-term stability of the APS insertion devices as well as those for next-generation light sources (e.g., Free Electron Lasers) with more intense radiation fields.

This concern prompted a series of systematic irradiations of sample magnets.[17] Handling precautions must be taken because of their intense magnetic field strength (~1 tesla). The magnets proved impervious to very high radiation doses from a ^{60}Co γ-ray source and from x-rays. The APS Operations Division and the CUF then collaborated to irradiate sample magnets with ^{252}Cf FNs. Maximum FN fluence (energies >0.1 MeV) was delivered from ~48 mg of ^{252}Cf placed ~6 cm from the magnets. After 24 hours of irradiation (fluence ~10^{13} cm^{-2}), measurements of the magnets showed an average degradation in magnetic field strength of 0.6%. At a fluence of ~2×10^{13}, the cumulative degradation averaged 1.3%. After 7-day irradiation to a fluence of ~10^{14} cm^{-2}, the magnetic field strength of the magnets had degraded by 16%. Neutron flux estimates were based on MCNP-4B computer code estimates[18] and confirmed with dosimetric measurements.

To elucidate neutron damage mechanisms, polyethylene blocks were then placed between and around the ^{252}Cf sources and new magnets to thermalize the neutron spectrum. Irradiation with >48 mg for 25 days produced no magnet damage from a thermal fluence well above 10^{12} cm^{-2}. We initially expected a significantly lower threshold thermal fluence for magnet damage than that for FNs because of thermal neutron capture within the magnets (~8 atom % of boron) and the resulting emission of energetic helium and lithium nuclei. However, the data suggests that, neutron for neutron, FNs are more destructive to the magnetic domains of Nd-Fe-B permanent magnets than are thermal neutrons.

C. Fast-neutron-induced Mutation of Seeds

In the early decades of the nuclear era, radiation-induced genetic damage of seeds was pursued as a versatile tool in plant breeding.[19] Renewed interest in seed irradiations for inducing mutations has focused on FNs because of their ability to induce extensive genetic damage within plant chromosomes. FNs are characterized by greater linear energy transfer (LET) within matter than are other common radiation sources. While the LET spectrum for ^{60}Co photons peaks at <1 keV/μm, the LET of ^{252}Cf FNs peaks near 100 keV/μm and produces much greater localized genetic damage. FNs were previously available for mutation studies from FN beam lines at nuclear research reactors. Attrition of these reactors has severely limited this option. One of the few remaining sources of fission neutrons for research studies (other than an inhospitable reactor core) is the ^{252}Cf radioisotope.

One reason for renewed interest in FN-induced mutations is the development of modern tools of DNA sequencing.[3] By noting the physical abnormalities in the germinated plant, followed by its DNA sequencing and comparison to normal DNA, one might conclude that any missing base sequences correspond to specific DNA components which correlate to the physical abnormalities. Subsequently, judicious cloning of genes corresponding to desirable plant properties could improve, for example, crop yields, nutritional value, or disease resistance.

Syngenta, formally known as Novartis, has sequenced the rice genome. To understand the functions of rice genes, a preliminary test was conducted to generate rice deletion lines with FNs at the CUF. Several rice samples were irradiated to FN doses ranging from 12 to 37 Gy, based on an MCNP-4B calculation[18] for a standardized irradiation geometry. The irradiation configuration is designed around a 2.5-cm-thick packet of rice, sandwiched between two lead bricks each 5-cm thick, and ten compact ^{252}Cf neutron sources on the outside of the bricks positioned so as to reduce neutron flux variations across the rice sample. Assuming a simplified geometry and a typical elemental distribution for rice, an average neutron dose to the rice sample was calculated to be 7.5 Gy/h from 50 mg of ^{252}Cf. The lead bricks reduced gamma dose to the sample to an estimated 5% that of neutron dose. A parametric study of dose effects for the U.S. Department of Agriculture irradiated rice samples from ~8 to ~163 Gy. Increasing dose, to ~50 Gy, increasingly stunted growth.[20] Above 50 Gy, the embryos germinate but none survive as seedlings.

V. CALIFORNIUM-252 CANCER THERAPY

Brachytherapy is a method of treating cancer in which a small radioactive source is inserted into a patient through a catheter to the tumor site. Today accelerator-based FN therapy is the most common neutron-based method of cancer treatment, with ~1000 to 2000 patients treated annually around the world. Californium-252 neutron brachytherapy (NBT) follows, with a few hundred patients a year, but is expected to increase rapidly. Reactor-based neutron capture therapy treats a smaller number of patients. At a recent workshop, the rapid expansion of NBT was highlighted by the Linden Neutron Knife Company, which installed the first NBT treatment unit in China in 1999, and now has 10 treatment centers in operation (>350 patients treated to date) and up to 30 centers planned. The Masaryk Memorial Cancer Institute in Brno, Czech Republic routinely treats ~80 patients annually.

The effectiveness of ^{252}Cf NBT has been demonstrated for 30 years in over 6000 patients. NBT limits dose to healthy tissue by placing the ^{252}Cf source at the tumor site, with maximum dose to the cancerous cells. NBT is more effective than conventional photon and gamma brachytherapy in treating radioresistant tumors such as bulky and late-stage tumors, melanomas, and glioblastomas. NBT is extremely effective in causing rapid regression of bulky, localized, radioresistant (hypoxic) tumors. A recent study[21] demonstrated a 14% improvement in 5-year survival statistics of cervical carcinoma when ^{252}Cf NBT was included in a gamma irradiation regimen, and even greater improvement for late stage tumors.

Iridium-192 photon brachytherapy is the current standard for clinical high-dose-rate (HDR) brachytherapy. Small (~1-mm outer diameter) ^{192}Ir HDR sources with activities up to 10 Ci can provide treatments in as few as 5 to 10 minutes. Californium-252 HDR treatments require $\geq$500 μg of ^{252}Cf (0.27 Ci, with FN emission $>10^9$ s^{-1}).[22] HDR ^{252}Cf sources with an outer diameter of ~3 mm have been fabricated in Russia. Such sources are appropriate for intracavitary brachytherapy (e.g., gynecological, rectal, head, neck, and oral cavity treatments), but are too large for interstitial brachytherapy (inside organs, such as the brain and prostate). Californium-252 NBT has not achieved widespread use because optimal treatments require miniature HDR sources coupled to a remote afterloader system for automated source delivery and positioning. To date, ^{252}Cf interstitial brachytherapy has been limited to low-dose-rate treatments with lengthy treatment times[22] because of the operational difficulty in miniaturizing high-activity ^{252}Cf source forms, comparable to ^{192}Ir source geometries.

Beginning in 1995, an ORNL project pursued fabrication of thinner, higher-intensity ^{252}Cf source forms based on a cermet wire containing Cf_2O_3 within a metallic palladium matrix.[23] Fabrication of cermet wire with ~1-mm diameter was demonstrated. In 1999, ORNL and Isotron, Inc., entered into a Cooperative Research and Development Agreement to further reduce the wire diameter and design a new family of medical sources. The ^{252}Cf-containing cermet wire was reduced to diameters smaller than any previously available.

A new generation of these ^{252}Cf sources suitable for interstitial and intracavitary HDR NBT are under development. The first prototype sources have been designed for use with existing gamma-source applicators, achieving the desired miniaturization goal. Using a comparative figure of merit of encapsulated ^{252}Cf mass per total source volume, the first prototype sources are an order of magnitude more intense than existing interstitial sources. Successful application of such sources will provide interstitial Cf-252 treatments in reasonable times (a few hours to less than an hour), permitting optimized treatments and application to glioblastomas and other tumors not previously accessible.

Isotron's NBT system will treat adult and pediatric cancer in eighteen sites throughout the body, including tumors of the brain, breast, colon and rectum, esophagus, eye, lung and bronchus, prostate, gynecological tumors and melanomas, among others. After initial clinical trials, coupling with boronated pharmaceuticals (BNCT) will be tested. Boron introduction into the treatment site via a direct intratumoral drug delivery technique will enhance dose within the tumor volume with corresponding reduction of dose to more distant healthy tissue.

VI. CALIFORNIUM-252 SOURCE AVAILABILITY AND DISTRIBUTION PROGRAMS

DOE's Californium Industrial Sales Program sells ^{252}Cf source material to commercial reencapsulators for resale. DOE also has a loan program to provide sources to government agencies and qualified subcontractors of the U.S. government and to universities for educational, research, and medical applications **without charge for the radioisotope**. To promote academic research and educational uses, DOE also **waives loan fees** on lower-intensity sources under the Californium University Loan Program, with only transportation costs incurred by the user.[3] Some international loans have also been made on a case-by-case basis.

A. Californium Industrial Sales Program

Californium-252 sources for commercial applications typically must be obtained from one of several commercial ^{252}Cf vendors rather than directly from ORNL. An exception is when a custom source request cannot be supplied by a commercial vendor. Because the cost of the radioisotope is not a significant factor for sources under several tens of micrograms, low-intensity sources can often be purchased from a commercial vendor at lower cost than a loaned source. However, end-of-useful-life disposal of a source becomes the user's responsibility unless a return agreement exists with the vendor.

B. Californium Industrial/University Loan Program

A source containing up to 50 mg of ^{252}Cf (neutron intensity ~10^{11} s^{-1}) can be obtained for ~$50,000, including fabrication costs, under the Californium Industrial Loan Program.[3] A source containing a few milligrams or less of ^{252}Cf can often be obtained from the REDC's prefabricated inventory of sources, in which case the loanee is not charged for fabrication but pays only the technical service charges incurred for source preparation, shipment, and return. Loan costs for lower-intensity sources (≤7 µg) are additionally reduced due to reduced shielding mass requirements during transportation. All loan costs are waived for university loans of lower-intensity sources, and costs for moderate-intensity sources can sometimes be waived with adequate justification. Transportation charges to the customer are handled separately from the loan. As part of the loan agreement, DOE requires source return to ORNL after use, eliminating source disposal concerns for the user (a potentially unwelcome surprise for those wishing to dispose of, e.g., Am-Be sources).

Loan costs for high-intensity sources compare very favorably with procurement costs for electronic neutron generators and accelerators with comparable intensities. The choice of radioisotopic vs electronic neutron sources is dependent on the application and other practical factors. The standard for pulsed applications is the neutron generator, but 14-MeV neutrons require more moderation and shielding for thermal neutron applications compared with ^{252}Cf (2.1-MeV average energy). In industrial and commercial systems, this increase in design requirements can increase the total cost of the system.

VII. CONCLUSIONS

The DOE Californium Loan Program eliminates neutron source disposal concerns by providing compact, portable ^{252}Cf sources to governmental organizations, subcontractors, and universities. Loan costs compare favorably with alternate sources of neutrons, especially for high-intensity sources. Experimental use of ^{252}Cf sources at the CUF further reduces the regulatory burden. A sampling of ^{252}Cf-based technologies relevant to commercial, inspection and characterization, and research applications is presented. Further information and contacts are available from *http://www.ornl.gov/nstd/cuf.* New miniature ^{252}Cf sources designed for HDR interstitial and intracavitary brachytherapy will provide unprecedented treatments of glioblastomas and a variety of other radioresistant tumors. Fabrication of prototype sources has been demonstrated. Boron-enhanced NBT will be evaluated for tailoring dose to the tumor and reducing necrosis of healthy tissue. Continuing expansion of international treatments and collaboration is expected.

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