DEVELOPMENT OF HIGH-ACTIVITY ^{252}Cf SOURCES FOR NEUTRON BRACHYTHERAPY

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R. C. Martin, R. R. Laxson, and J. H. Miller
Chemical Technology Division
Oak Ridge National Laboratory*
P.O. Box 2008
Oak Ridge, TN 37831-6385

J. G. Wierzbicki and M. J. Rivard
Department of Radiation Oncology
Harper Hospital
Wayne State University
Detroit, MI 48201

D. L. Marsh
Nuclear Engineering Department
The University of Tennessee
Knoxville, TN 37996

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DISCLAIMER

DEVELOPMENT OF HIGH-ACTIVITY ^{252}Cf SOURCES FOR NEUTRON BRACHYTHERAPY

R.C. Martin,[1] R.R. Laxson,[1] J. H. Miller,[1] J.G. Wierzbicki,[2] M. J. Rivard,[2] and D. L. Marsh[3]

The Gershenson Radiation Oncology Center of Wayne State University (WSU), Detroit, Michigan, is using ^{252}Cf medical sources for neutron brachytherapy. These sources are based on a 20-year-old design containing ≤30 μg ^{252}Cf in the form of a cermet wire of Cf_2O_3 in a palladium matrix. The Radiochemical Engineering Development Center (REDC) of Oak Ridge National Laboratory has been asked to develop tiny high-activity ^{252}Cf neutron sources for use with remote afterloading equipment to reduce treatment times and dose to clinical personnel and to expedite treatment of brain and other tumors. To date, the REDC has demonstrated that ^{252}Cf loadings can be greatly increased in cermet wires much smaller than before. Equipment designed for hot cell fabrication of these wires is being tested. A parallel program is under way to relicense the existing source design for fabrication at the REDC.

[1] Oak Ridge National Laboratory, Oak Ridge, TN 37831-6385, USA.

[2] Wayne State University, Detroit, MI 48201, USA.

[3]University of Tennessee, Knoxville, TN 37996, USA.

Introduction

The heavy element ^{252}Cf is an intense neutron emitter that is readily encapsulated in compact, portable neutron sources and used in a variety of industrial and research applications. Californium-252 has a half-life of 2.645 years and decays by alpha emission (96.9%) and spontaneous fission (3.1%). One milligram of ^{252}Cf (0.536 Ci) emits 2.314×10^9 neutrons/s, with average energy of 2.1 MeV.

The Gershenson Radiation Oncology Center of Wayne State University (WSU), Detroit, Michigan, is the only medical institute in the United States currently using ^{252}Cf sources for tumor therapy. Neutron brachytherapy (i.e., inserting the neutron source directly into the tumor) is more effective than conventional photon radiotherapy in treating certain tumors, specifically bulky tumors and hypoxic (oxygen-deficient) tumors. Dr. Y. Maruyama and collaborators at the University of Kentucky obtained impressive results using ^{252}Cf brachytherapy for advanced bulky gynecological tumors (Maruyama, et al., 1991). A recent workshop organized by Dr. Maruyama's collaborators at WSU presented data on improved survivability for several types of bulky and recurrent tumors (head and neck, gynecological, rectal) from ^{252}Cf brachytherapy followed by photon therapy, compared with photon therapy alone (Wierzbicki, 1996). The clinicians at WSU are using a 20-year-old brachytherapy source design called the Applicator Tube (AT), which was developed at Savannah River Laboratory (SRL). The physical dimensions and maximum licensed strengths of the AT sources used at WSU and the other medical source forms developed at SRL are listed in Table 1. Clinicians manually load the sources into the patient, followed by treatment times of several hours. The clinicians would like stronger sources to reduce treatment times, remotely afterloaded sources to reduce dose to clinical personnel, and smaller sources which are more amenable to restricted

treatment geometries such as brain tumors. Until these are available, the WSU clinicians would like full-strength replacement AT sources.

The Radiochemical Engineering Development Center (REDC) at Oak Ridge National Laboratory processes the national supply of ^{252}Cf after production in the neighboring High Flux Isotope Reactor and encapsulates the ^{252}Cf in sealed sources upon request (Martin, et al., 1996). The REDC has been asked to develop tiny high-activity ^{252}Cf neutron sources for use with remote afterloading equipment and to relicense the AT source design for manufacture at the REDC. The REDC is now working on relicensing the AT source and developing new ^{252}Cf brachytherapy sources tailored to an existing gamma-source afterloader design. This collaborative effort between WSU, Varian Oncology Systems, and the REDC will develop ^{252}Cf afterloader sources that have high dose rates but are small enough for treatment of glioblastoma multiforme (a virulent brain tumor). The challenge laid out by WSU staff is to fabricate an afterloader source containing 1 mg of ^{252}Cf.

Medical Source Design Goals

Table 1 lists the primary and secondary capsule dimensions for the AT source design. AT sources from SRL contain an active core of sintered Pd-Cf_2O_3 cermet material with <0.1 wt % ^{252}Cf, surrounded by a Pt-Ir sheath in a wire ~0.4 mm in diameter. The REDC will fabricate the new AT based on a melted Pd-Cf_2O_3 cermet material, probably sheathed in an outer layer of palladium tubing, with all other dimensions and capsule materials unchanged. The REDC plans to relicense the AT to contain up to 100 μg ^{252}Cf to permit more flexibility, but much more ^{252}Cf is feasible.

The ^{252}Cf remote afterloader source design will be modeled on the existing geometry for ^{192}Ir gamma sources which are used in a remote afterloader marketed by Varian Oncology Systems. The new ^{252}Cf source will be limited to dimensions of 10 mm in length and 0.34 mm in diameter and will be sealed inside a flexible nickel-titanium afterloader wire (Varian, 1994). Fabrication of AT sources at the REDC will require a limited extension of existing fabrication techniques, but fabrication of the afterloader sources will be very challenging because of the severe limitations on maximum source dimensions. Also, containment and licensing issues for ^{252}Cf sources are more complex than for gamma sources because of potential pressurization via the alpha-decay branch of ^{252}Cf.

Experimental

The SRL medical source fabrication techniques are documented by Mosley et al. (1972). In general, operations must be conducted remotely in a heavily shielded hot cell. Palladium is deposited onto a fine precipitate of californium oxalate, $Cf_2(C_2O_4)_3$, in an aqueous solution. The Pd-coated particles are then dried, calcined to Pd-coated Cf_2O_3, pressed into a "green" pellet of approximately 50% theoretical density, sintered to 1300°C, repressed to approximately 90% theoretical density, then pressed into a capsule of platinum-10% iridium alloy, and sealed as a billet. At SRL, draw dies were used to reduce the diameter of this billet until a long, thin Pt-alloy-sheathed cermet wire remained, as small as 0.30 mm in diameter.

The REDC fabrication process diverges at the sintering step. Instead of sintering at 1300°C, the pellet is heated to 1600°C, which melts the Pd-Cf_2O_3 mixture. After cooling, the melted pellet material is sufficiently strong to roll into a thin wire on a jeweller's rolling mill. For commercial

sales, 1.1-mm square cermet wires are routinely fabricated with nominal loading of 500 μg ^{252}Cf per inch (~0.6 wt % ^{252}Cf). For medical source wires, the REDC will continue to swage 1.1-mm wires that contain more ^{252}Cf into thinner wires by sequentially feeding them through smaller dies. (The SRL drawing process basically pulls the wires through a die of fixed size, while the REDC swaging process feeds the wires into a swager whose dies hammer the wire into a smaller diameter.)

A nonradioactive surrogate is substituted for californium in development laboratory scoping studies. The chemical properties of the rare earth elements parallel those of the actinides, and terbium was used to estimate the maximum practical ^{252}Cf loading in machineable wires. From experience, the higher the weight percent of ^{252}Cf, the harder it is to swage tiny wires without splintering. Periodic annealing of the wire at high temperatures improves the workability and reduces the limiting diameter.

Although the standard REDC process is to melt the cermet pellet at 1600°C followed by rolling and swaging, most of the work discussed below used sintered pellets of varying Cf-analog content. These pellets were rolled and swaged down to the point of structural instability, then sheathed in stainless steel or platinum tubing, and swaged down to the smallest practical diameters. These results must be confirmed in cell by the use of ^{252}Cf rather than terbium.

Results and Discussion

The maximum loading demonstrated for ^{252}Cf cermet material in the hot cell is 1.8 wt % ^{252}Cf (12.9 mg ^{252}Cf in 700 mg Pd) in a green pressed pellet, but this material was not rolled into a wire. No data exist on the workability of heavily loaded ^{252}Cf cermet material. A problem encountered with greater ^{252}Cf and Cf-analog loadings was the capillary-like migration of the melted cermet

material out of the small-diameter glassy carbon melting tube (encountered at loadings between 3 and 5 wt % ^{252}Cf-equivalent). This problem could be alleviated by sintering rather than melting or by melting less cermet material at a time. Additional problems were encountered with melting furnace operation partway into this project. As a result, most of the scoping work on maximum Cf-analog loading was performed with sintered material.

For melted material, the following were the smallest wires obtainable using terbium oxide as a surrogate for Cf_2O_3: 0.85-mm-diameter wire from 7 wt % ^{252}Cf-equivalent, 0.34-mm-diameter wire from 3 wt % ^{252}Cf-equivalent, and 0.20-mm-diameter wire from 0.6 wt % ^{252}Cf-equivalent. Smaller wires could not be obtained because of increased wire hardness and loss of ductility. These results were obtained based on periodic wire annealings at 800°C. Subsequently, annealing temperatures of 1050°C were used, which significantly improved the workability of the sintered material. These higher annealing temperatures could also be expected to improve the workability of the melted material, but this has not been verified to date.

The most promising results were obtained for sintered material with annealing at 1050°C. Two pressed pellets with nominal loading of 5.8 wt % ^{252}Cf-equivalent were rolled and swaged to 0.66- and 0.46-mm diameters, then sheathed in stainless steel tubing, and swaged to a final diameter of 0.27 mm, which is well within the design limitation of 0.34 mm. Other tests with Pt-10% Ir alloy sheath material indicated easier workability than stainless steel. For recycling purposes a palladium sheath will be used. Palladium workability is expected to be comparable to platinum. These results must be confirmed in cell by the use of ^{252}Cf, rather than terbium, with a Pd sheath. The results for maximum loading are an improvement over the SRL scoping studies using Sm_2O_3 in place of Cf_2O_3 in a Pd matrix (Mosley, et al., 1972). They report that dense cermet pellets on the order of 2 wt %

^{252}Cf-equivalent could be rolled down to 0.76 mm, while ^{252}Cf-equivalent loadings approaching 4 wt % would lead to splintering of the wire during rolling.

The current design scenario for the afterloader source is 10-mm length and 0.34-mm outer diameter. A Pd sheath of approximately 0.05-mm thickness reduces the active cermet core diameter to 0.23 mm. Assuming an inactive length of 1 mm at each end of the encapsulating Pd sheath, the total active volume available for the source material, excluding sheath volume, is approximately 0.33 mm^3. If we reasonably assume an achievable ^{252}Cf loading of 5 wt % in a sheathed wire, based on the results above, then we can expect to produce an afterloader source containing approximately 200 μg ^{252}Cf. For the replacement AT sources, development laboratory work demonstrated that melted material containing 7 wt % ^{252}Cf-equivalent could be rolled into a square wire small enough to fit into an AT source. With >7 mg ^{252}Cf-equivalent, such a source would far exceed the limiting exposures for manually loaded sources.

Ongoing research in the manufacture of an alloy containing a transition metal and Cf-analog has been promising. The synthesis of the alloy has been demonstrated with good initial machinability. If practicality of use with ^{252}Cf is confirmed in follow-up testing, the maximum source strengths indicated above could be significantly increased to more than 1 mg of ^{252}Cf (Rivard, 1996).

A practical concern for licensing the afterloader source as Special Form for transportation and use is the internal pressure buildup from alpha decay of ^{252}Cf. This issue will require evaluation with respect to the actual void volume inside the afterloader wire cavity, the ability of the Pd sheath to retain gas, and the realistic mechanisms and pathways of helium release from the sheathed cermet material.

Equipment design has proceeded parallel to the developmental studies. A swager has been modified and adapted for in-cell use as shown in Figure 1. Initial results with the Cf-analog cermet indicate no problem in swaging wires for the replacement AT sources. Remote positioning and gripping equipment has been developed for the tiny wires required for the afterloader sources. Experience gained from manufacture of the AT sources and remote operation of the swager will augment the fabrication experience and source encapsulation design for the afterloader sources.

Summary

Development laboratory work at the REDC indicates that the ^{252}Cf loading can be increased by more than two orders of magnitude in existing SRL source designs such as the AT and by approximately an order of magnitude over the current REDC standard wires. Remotely operated swaging equipment currently undergoing testing in the hot cells will permit near-term fabrication of AT sources at the REDC, confirmation of the Cf-analog results using ^{252}Cf, and ultimately the fabrication and licensing of small high-activity afterloader sources. The new AT sources could potentially contain several milligrams of ^{252}Cf but will only be licensed for a maximum of 100 μg unless requested otherwise. The afterloader sources can contain up to 200 μg ^{252}Cf based on current designs, with some developmental work indicating a possibility of greater than 1 mg ^{252}Cf. Some design and licensing issues remain to be worked out before prototype afterloader sources are fabricated. In 1997 the relicensed AT sources should become available, and the fabrication and licensing issues for the afterloader source should be resolved.

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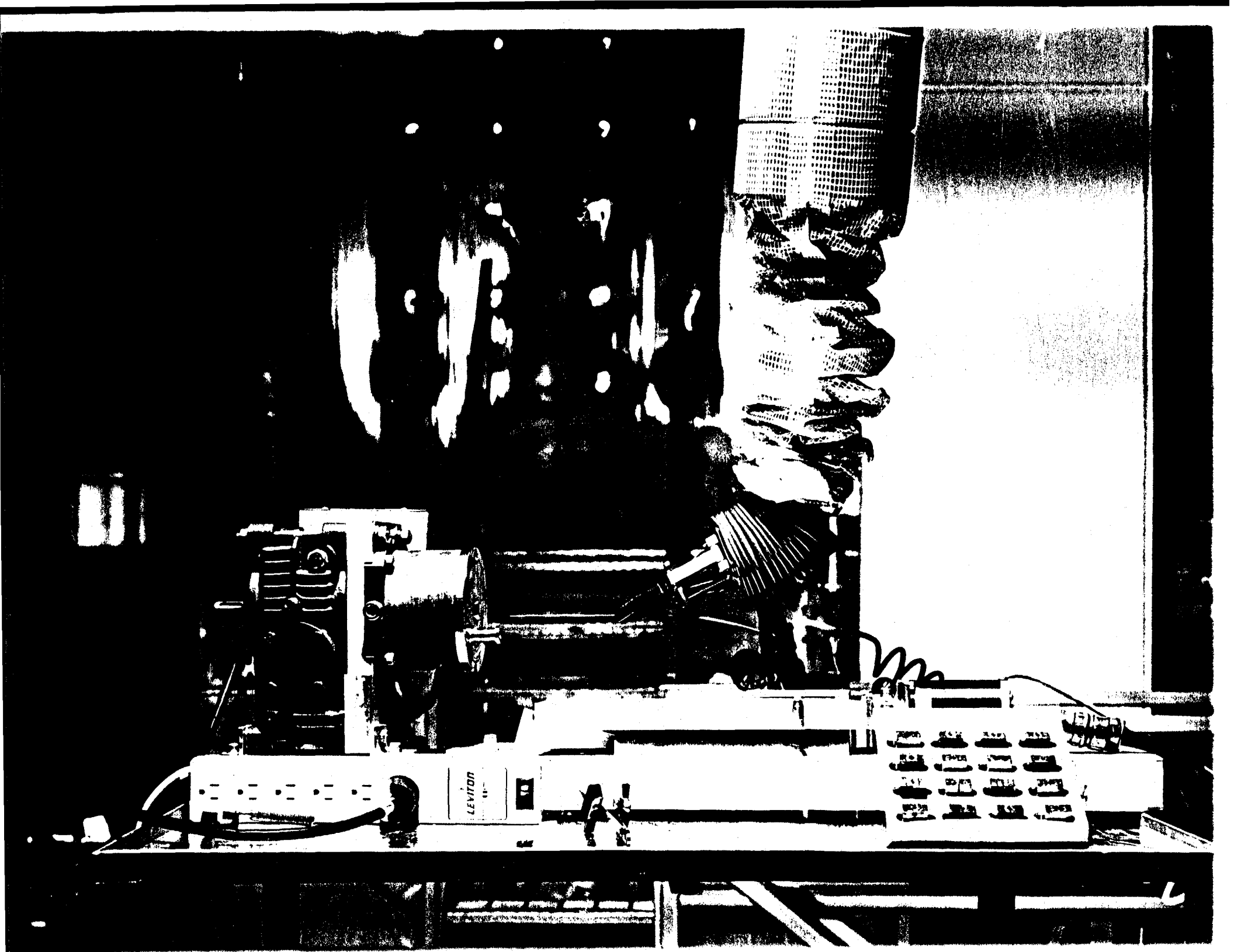
Table 1: Existing Californium-252 Medical Source Designs from Savannah River Laboratory

Source name	SRL Model	Secondary capsule dimensions (mm)		Primary capsule dimensions		Active source length (mm)	Maximum IAEA source strength[(a)] (μg ^{252}Cf)
		Length	Outer/inner diameter	Length	Outer/inner diameter		
Seed	ALC-PXC	-	-	6.05	0.81/0.46	4.0	0.7
Short afterloading cell	SALC	17.9	0.97/0.66	16.0	0.61/0.41	15.0	2.4
Afterloading cell	ALC	32.9	0.97/0.66	31.0	0.61/0.41	30.0	4.8
Applicator tube	AT	23.1	2.79/1.80	17.8	1.75/1.35	15.0	29.8
Toshiba afterloading cell	TALC-PC	9.80	4.70/3.56	6.35	3.45/2.59	4.6	1025

(a) Based on IAEA Certificate of Competent Authority for Special Form Radioactive Materials.

Figure Captions

Figure 1. Swager, designed for remote operation inside the hot cell, to fabricate very thin Pd-Cf_2O_3 cermet wires.


LEVITON